Jurnal Ilmu Kehutanan

https://jurnal.ugm.ac.id/v3/jik/

ISSN: 01264451 (print); EISSN: 24773751 (online)

Empirical Data-Based Carbon Stock Projection in Agroforestry for Climate Change Mitigation

Proyeksi Cadangan Karbon Berbasis Data Empiris dalam Agroforestri untuk Mitigasi Perubahan Iklim

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RESEARCH ARTICLE

DOI: 10.22146/jik.v19i2.20118

MANUSCRIPT:
Submitted : 1 March 2025
Revised : 16 August 2025
Accepted : 24 September 2025

KEYWORD
greenhouse gas reduction, sustainability, allometry, biomass, conservation

KATA KUNCI
penurunan emisi, keberlanjutan, alometrik, biomassa, konservasi

ABSTRACT

Deforestation from monoculture farming significantly contributes to greenhouse gas emissions and ecosystem degradation, highlighting the need for sustainable land management. Agroforestry presents a viable solution for enhancing carbon sequestration. However, many project models rely on assumptions or secondary data, leading to limited accuracy. This research aimed to enhance projections of carbon stock changes by utilizing empirical data from a 12.7-ha tea plantation in West Java, Indonesia. This research established baseline carbon stocks through direct field measurements in a monoculture scenario. Agroforestry interventions involved hardwood species, such as *Toona sureni, Altingia excelsa, and Manglietia glauca*, in conjunction with coffee crops. Carbon stock accumulation was then projected over ten years using allometric equations and annual growth increments derived from field observations. Results indicated that agroforestry increased carbon sequestration by threefold compared to monoculture, reaching 472.77 t CO_2eq/ha by 2032. The findings demonstrated that empirical data-driven modeling resulted in more realistic and reliable projections, enhanced the accuracy of carbon stock predictions, and established agroforestry as a sustainable approach for mitigating climate change.

INTISARI

Deforestasi akibat pertanian monokultur berkontribusi secara signifikan terhadap peningkatan emisi gas rumah kaca dan degradasi ekosistem sehingga diperlukan solusi pengelolaan lahan berkelanjutan. Agroforestri menawarkan potensi besar dalam meningkatkan penyerapan karbon, tetapi banyak permodelan proyeksi masih mengandalkan asumsi atau data sekunder yang kurang akurat. Penelitian ini bertujuan untuk menghasilkan proyeksi cadangan karbon yang lebih tepat melalui pemanfaatan data empiris dari perkebunan teh seluas 12,7 ha di Jawa Barat, Indonesia. Penelitian ini menentukan faktor emisi baseline *berdasarkan pengukuran lapangan langsung terhadap diameter pohon pada skenario monokultur yang berjalan. Intervensi agroforestri dilakukan dengan menanam pohon kayu keras (*Toona sureni, Altingia excelsa, Manglietia glauca*) dengan tanaman kopi. Proyeksi akumulasi cadangan karbon dihitung selama sepuluh tahun dengan menggunakan persamaan alometrik dan data pertumbuhan tahunan hasil pengukuran lapangan. Hasil penelitian menunjukkan bahwa agroforestri dapat meningkatkan kapasitas penyerapan karbon hampir tiga kali lipat dibandingkan sistem monokultur mencapai 472,77 t CO_2eq/ha pada tahun 2032. Penelitian ini menyimpulkan bahwa permodelan berbasis data empiris menghasilkan proyeksi yang lebih realistis dan tepercaya, meningkatkan akurasi prediksi cadangan karbon, dan membuktikan agroforestri sebagai strategi berkelanjutan yang efektif untuk mitigasi perubahan iklim.*

Introduction

Climate change is a phenomenon driven by increasing concentrations of greenhouse gases (GHGs), which become trapped in the Earth's atmosphere, leading to adverse effects on ecosystem services and biodiversity. Rising temperatures and habitat loss threaten various species due to the depletion of essential environmental resources, necessitating urgent action to mitigate GHG emissions (Kabisch et al. 2017). Forests, as vital terrestrial ecosystems, provide crucial environmental services, including biodiversity conservation, commodity production, and carbon sequestration. These ecosystems also provide nature-based solutions, such as integrated land-use systems, which are now increasingly recognized as sustainable strategies for mitigating climate change (Karuniasa & Prambudi 2019; Tiemann & Ring 2022; Pan et al. 2025). Previous research demonstrated that agroforestry, which combines trees with crops, offered considerable potential to enhance carbon sequestration, restore degraded forest ecosystems, and ensure long-term sustainability.

In Indonesia, land use change driven by monoculture plantation expansion remains a major contributor to GHG emissions. BPS-Statistics Indonesia reported that 48.8% of the land area is non-forest land, with the primary utilization for agriculture. Although monoculture systems have historically contributed to carbon loss, integrating trees into such landscapes could help reverse this trend. The purpose of this transformation must be clearly defined, whether to emphasize the environmental risks of current practices or the potential advantages of adopting sustainable alternatives, such as agroforestry.

Traditionally, local land management practices are primarily aimed at economic welfare, often relying on monoculture farming systems due to their relatively straightforward cultivation methods (Sudiana et al. 2009). However, monoculture farming carries inherent risks, including low carbon sequestration capacity, land degradation due to disrupted soil hydrology, and financial vulnerability from crop failures caused by pests and climate variability (Miller & Spoolman 2016). To mitigate these risks, some communities have begun to adopt integrated land-use practices by incorporating forestry and crops within the same area through agroforestry systems. Agroforestry enhances food security, diversification, economic value, competitiveness, sustainable resource utilization, and ecosystem stability through increased carbon stock (Edwin 2016; Murniati et al. 2022). Ensuring sustainable agroforestry-based land management presents challenges beyond economic feasibility, as it also requires optimizing environmental viability. Environmental sustainability is achieved when ecological functions are maintained to support present and future generations, particularly in mitigating global surface temperature rise through carbon sequestration and storage (Pratama et al. 2015).

Research by Siarudin (2021) and Lestari (2023) found that agroforestry systems could serve as a sustainable land management model by enhancing carbon sequestration through the integration of timber trees with crops (Siarudin et al. 2021; Lestari & Dewi 2023). Recent research indicates that in tea-based agroforestry, older stands exhibit significantly higher biomass and carbon stocks than younger stands, with shade trees enhancing carbon contributions by up to 25% (Kalita et al. 2020). However, most projections still rely on secondary data or generalized carbon stock, with few incorporating direct field measurements of tree diameters or accounting for variation in growth patterns across different species and growth cycles. This methodological gap limits the accuracy of projection and the ability to design site-specific interventions.

This research addressed this gap by developing a carbon stock projection model based on empirical data, explicitly accounting for species diversity and growth increments in a tea-based agroforestry system. The tea plantation was selected as the setting for both ecological and socio-economic reasons. Although tea is at risk of growth retardation from shading, which can lead to yield loss, research in Sri Lanka and southern India shows that carefully managed shade trees can provide various benefits. These include improving the microclimate, enhancing soil fertility, reducing pest pressure, and sustaining long-term productivity (Mohotti et al. 2020). Jayamekar Village in Garut, West Java, was chosen for its extensive monoculture landscapes, making it an ideal place to test the feasibility of integrating hardwood species to enhance carbon sequestration without compromising tea yields.

By combining field-based measurements with specific allometric equations, this research provided a more accurate projection of carbon stock changes in tea-based agroforestry. The research specifically focused on carbon stock change projection by applying the Business-as-Usual (BaU) scenario in monoculture tea plantation areas and the enhanced scenario through agroforestry management practices. This research also quantified the cumulative land carbon stock by adding biomass from forestry and crops managed under an agroforestry system. Using empirical data, this research aimed to develop a more realistic, site-specific carbon stock projection model that accurately reflects physical environmental conditions.

Methods

Approach

This research used a quantitative approach to assess the feasibility of land management through agroforestry systems by analyzing the impact of this management on carbon sequestration. The quantitative method involved a comparative analysis of baseline carbon stock calculations conducted prior to the research, followed by projections of carbon stock increases resulting from agroforestry implementation.

Research Area

The research was conducted in Jayamekar Village, Pakenjeng Subdistrict, Garut Regency, West Java, covering a total land area of 12.7 ha (Figure 1). The land belonged to four farmers and was used exclusively for monoculture tea plantations, which established approximately three years before the research. This research employed multiple sequential phases. The initial phase, carried out in 2022, focused on characterizing the location and collecting baseline data of carbon stocks before agroforestry intervention, followed by the interplanting initiation of selected tree species among existing tea crop. Subsequent work consisted of year-long maintenance, such as fertilization, watering, pest control, weeding, and pruning, to ensure optimal plant development. The second phase, in 2023, focused on collecting empirical diameter-increment data across several plant species to estimate biomass, providing the basis for carbon stock change projection. In addition, this phase collected empirical data on diameter increments and the ages of comparable plant species cultivated by local communities prior to the research period to determine the average growth patterns of diameter increments from the first year of planting.

The characteristics of this research area, as presented in Table 1, comprised diverse topography ranging from lowlands to mountainous areas, making it rich in natural resource potential, particularly in the agricultural sector. The elevation ranged from 800 m to 900 m above sea level (masl) with an average annual rainfall of approximately 1,572 mm/year and air temperatures ranging from 24 °C to 27 °C. This situation offered a valuable opportunity to improve land productivity and ecological benefits by implementing agroforestry-based management practices.

Table 1. Research area characteristics

Climate classification	Unit	Description
Elevation	masl	800—900
Rainfall	mm/year	1,572
Air temperature	°C	24—27

The agroforestry system integrated forest tree species, such as suren (*Toona sureni*), rasamala (*Altingia excelsa*), and manglid (*Manglietia glauca*), alongside crops, particularly coffee (*Coffea robusta*). The selection of these forestry and crop species was based on a vegetation inventory that identified plant species that had naturally grown in the area over the past few years. This research conducted an initial assessment of baseline carbon stock before implementing the agroforestry intervention to evaluate its impact on carbon stock, as shown in Table 2. One year after planting the coffee and forest tree species, this research collected data to assess changes in carbon sequestration and overall ecosystem transformation, including natural regeneration of native species, such as grasses and shrubs.

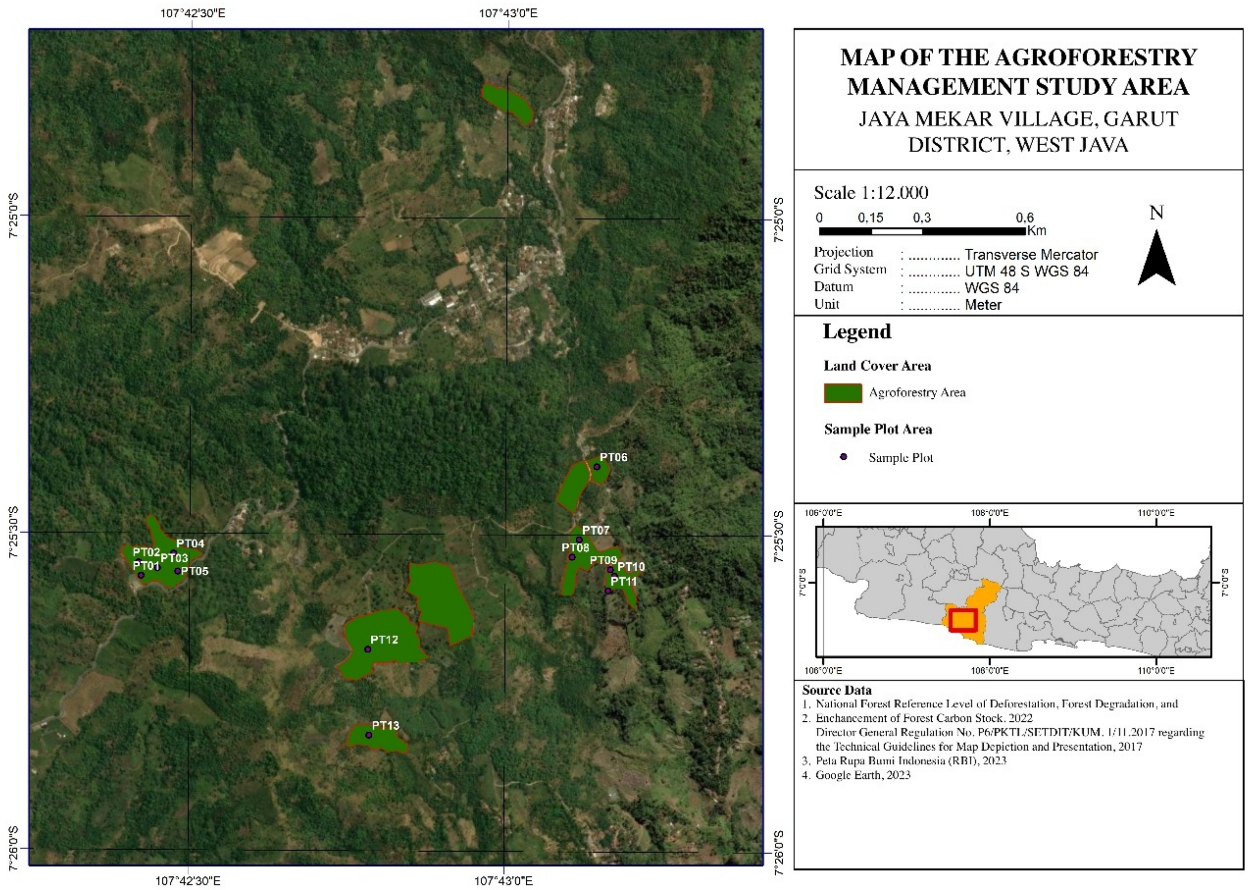

Figure 1. Research area

Sample

The sample collection followed SNI 7724:2019 and used stratified random sampling due to the differences in the composition of forestry and agricultural plant species within the location. The variation in composition included species and ages of both forestry and crop species present in the research area, managed under an agroforestry system. The stratification yielded 13 sample plots that represent the extent of land cover and species composition within the research area. In addition, the carbon stock projection over ten years adopted the standard methodologies established by the United Nations Framework Convention on Climate Change (UNFCCC), the Project Design Document for Afforestation and Reforestation Project Activities (CDM-ARPDD), and the Forest Reference Level (FRL) documents, which commonly use baseline emission evaluations and climate change mitigation targets over ten years.

Baseline Carbon Stock Determination

The determination of baseline carbon stock followed the Business as Usual (BaU) scenario, based on routine activities conducted by the local community on the monoculture tea plantation. This research used the Tier 2 carbon stock obtained from the 2022 Forest Reference Level (FRL) document issued by the Government of Indonesia as a benchmark for measuring the performance of climate change mitigation activities based on land cover classification. The baseline carbon stock was estimated from empirical measurements of tea plants' diameter (Tier 3) and in accordance with SNI 7724:2019 and allometric equations. In this study, allometric equations were applied to estimate aboveground biomass (AGB), following the guidelines of SNI 7724:2019 which recommends using models that incorporate diameter and wood density to estimate the carbon stock. For tea (*Camellia sinensis*), the equation from Ketterings (2001) was used due to its relevance to tropical agroforestry systems and its frequent application in similar plantation management (Ketterings et al. 2001). The equation by Arifin et al. (2001) for coffee (*Coffea robusta*) was selected based on its empirical derivation from coffee stands in Indonesia. For forestry species, suren (*Toona sureni*) and rasamala (*Altingia excelsa*), equations by Krisnawati (2012) and Latifah (2018) were used which include wood density and were derived from Indonesian forest plots. For manglid (*Manglietia glauca*), a generalized tropical model from Chave (2005) was used. The selection of these equations was based on species availability and ecological relevance.

The measurement used circle plots with a 25 m^2 plot of a radius of 2.82 m for small stems (diameter: 2 cm—9.9 cm), a 100 m^2 plot of a radius of 5.64 m for medium stems (diameter: 10 cm—19.9 cm), a 400 m^2 plot of a radius of 11.29 m for large stems (diameter > 20 cm), as illustrated in Figure 2.

The baseline of above-ground biomass (AGB) and below-ground biomass (BGB) from each sample plot in the tea plantation was summarized in Table 2. The tea plantation had above-ground biomass (AGB) of 62.53 t/ha and below-ground biomass (BGB) of 15.64 t/ha, based on a 4:1 ratio of AGB to BGB from previous research (Hairiah et al. 2011). In total, the tea plantation biomass was 78.16 t/ha.

Carbon Stock Projection

The estimation of above-ground biomass (AGB) and below-ground biomass (BGB) used a specific allometric equation for each plant species, including tea, coffee, suren, rasamala, and manglid (Arifin et al. 2001; Ketterings et al. 2001; Chave et al. 2005; Krisnawati et al. 2012; Latifah et al. 2018; Luth & Setiyono 2018), as summarized in Table 3. The selection of the allometric equations considered the similarity of species and site conditions of the research

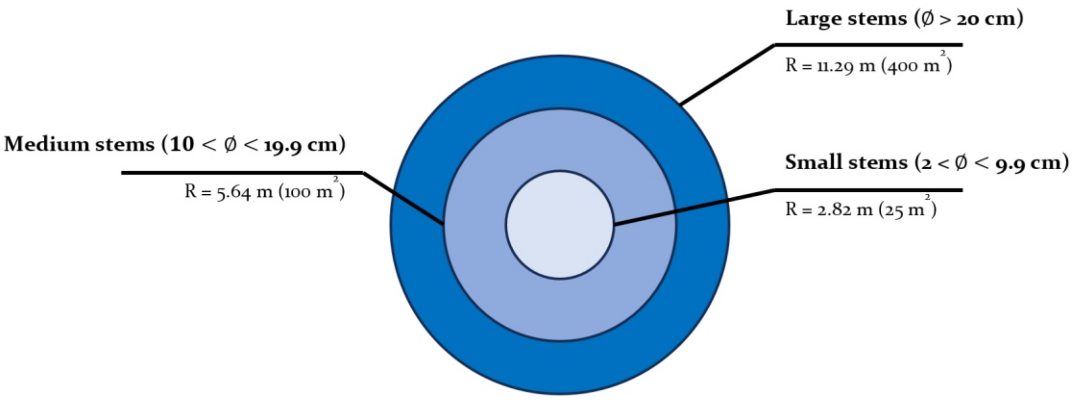

Figure 2. Sample plot size

Table 2. Carbon stock baseline initial assessment

Sample Plot Code	Above-Ground Biomass (AGB) (t/ha)				Below-Ground Biomass (BGB) (t/ha) (*25% of AGB*)	Biomass Total (t/ha)
	Small Stems (*a*)	Medium Stems (b)	Large Stems (c)	Total		
PT01	5.41	3.22	-	8.63	**15.63**	**78.16**
PT02	-	65.59	-	65.59		
PT03	-	69.31	-	69.31		
PT04	-	68.10	-	68.10		
PT05	11.21	38.08	-	49.29		
PT06	-	9.65	-	9.55		
PT07	10.12	44.79	-	4.92		
PT08	-	81.88	-	81.88		
PT09	17.27	40.72	-	57.99		
PT10	38.49	82.22	-	120.71		
PT11	23.96	26.80	-	50.77		
PT12	56.74	79.34	-	136.08		
PT13	16.72	23.22	-	39.95		
Average	**13.84**	**48.69**	-	**62.53**		

area. BGB was calculated using a biomass ratio, with root biomass set at 25% (4:1 AGB:BGB) based on existing literature (Hairiah et al. 2011).

The annual carbon stock growth rate for the tea plantation baseline scenario was set at 1.8 t C/ha/year, based on IPCC guidelines. However, the carbon stock projection for the agroforestry scenario was calculated using allometric equations for each forest and crop species in the system. Annual diameter growth for each species was estimated from nearby trees of the same species under similar conditions. This data included diameter measurements and tree ages, which were used to calculate the average annual growth for each species. Carbon stock values were calculated by converting biomass to carbon using the default IPCC carbon fraction of 0.47. The total projected carbon stock for each year was obtained by summing the contributions from AGB and BGB for all species across agroforestry plots. This method provided a transparent and replicable framework for estimating potential carbon sequestration benefits under the proposed agroforestry management scenario.

Carbon Stock Changes with Agroforestry Intervention

Modeling commenced one year after planting, based on the measured growth rates of the agroforestry tree diameters. Annual diameter growth was then predicted using empirical data, specifically, annual diameter growth increments collected for each species in the research area. The initial diameter is the average stem diameter at planting, and the measured diameter is the average stem diameter at the time of measurement. The landowners reported the age of each tree based on their planting year. Diameter deviation was calculated as the difference between these two values for each sample, and the average annual diameter growth rate per species was then determined (Table 4).

Table 3. Allometric equations

Plant Type	Allometric Equation	Source
Tea (*Camellia sinensis*)*	$AGB = 0.11 \times \rho \times D^{2.62}$	(Ketterings et al. 2001)
Coffee (*Coffea robusta*)	$AGB = 0.281 \times D^{2.06}$	(Arifin et al. 2001)
Suren (*Toona sureni*)**	$AGB = 0.00013 \times \ \times D^{2.5017}$	(Krisnawati et al. 2012; Latifah et al. 2018)
Rasamala (*Altingia excelsa*)	$AGB = 0.199 \times D^{2.148}$	(Krisnawati et al. 2012)
Manglid (*Manglietia glauca*)***	$AGB = \rho \times e^{(-1.499+2.148\ln D+0.207(\ln D)^{2+0}.^{0281(\ln D)^{3)}}}$	(Chave et al. 2005)

Remarks: * = Tea wood density, 0.4 g/cm^3; ** = Manglid wood density, 0.41 g/cm^3; AGB: Above-Ground Biomass (t/ha); Wood carbon content = 47%; Carbon stock conversion: 44/12

Table 4. Empirical data on plant diameter growth increment

Plant Type	Age (years)	Initial Diameter/d_o (cm)	Measured Diameter/d_t (cm)	Diameter Deviation/Δd (cm)	Average Diameter Growth Increment (cm)
Coffee (*Coffea robusta*)	3	0.75±0.15	1.8±0.3	1.05±0.3	0.35±0.1
	4	0.75±0.15	2.7±0.7	2.0±0.5	0.5±0.12
	5	0.75±0.15	6.5±0.4	5.7±0.5	1.14±0.09
	6	0.75±0.15	7.25±0.5	6.3±0.6	1.05±0.1
	7	0.75±0.15	9.0±0.4	8.3±0.7	1.18±0.1
Average per year					**0.84±0.1**
Suren (*Toona sureni*)	4	2.0±0.05	9.3±2.9	7.3±2.9	1.82±0.73
	5	2.0±0.05	11.4±2.3	9.4±2.3	1.88±0.46
	6	2.0±0.05	14.2±3.1	12.2±3.1	2.03±0.52
	7	2.0±0.05	19.2±3.2	17.2±3.2	2.45±0.46
Average per year					**2.04±0.54**
Rasamala (*Altingia excelsa*)	4	1.25±0.1	13.5±1.5	12.2±1.35	3.05±0.33
	6	1.25±0.1	15.5±1.1	14.2±1.15	2.36±0.19
	17	1.25±0.1	21.8±6.32	20.55±6.32	1.21±0.37
	19	1.25±0.1	25.2±2.9	23.95±2.95	1.26±0.15
Average per year					**1.97±0.26**
Manglid (*Manglietia glauca*)	3	1.5±0.1	5.8±1.2	4.1±1.4	1.36±0.47
	4	1.5±0.1	8.3±1.4	6.8±1.4	1.7±0.35
	8	1.5±0.1	14.9±3.4	13.4±3.4	1.67±0.43
	16	1.5±0.1	28±1.6	26.5±1.6	1.65±0.1
Average per year					**1.6±0.33**

Results and Discussion

Agroforestry-Based Land Management

Local communities developed agroforestry by integrating crops, such as coffee (*Coffea robusta*), with forest species, including suren, rasamala, and manglid. Species selection hinged on three factors: maintaining biophysical stability, maximizing carbon sequestration, and providing competitive economic value through high-value commodities. Tree planting used specific patterns and spacing to optimize density, promote ideal growth, and achieve high survival rates, as illustrated in Figure 3.

Successful plant growth relied on optimized spacing, composition, and community care. As shown in Table 5, the average survival density after one year showed promising results. This outcome can be attributed to the agroforestry design, which strategically positioned coffee plants at the interface between tea and forest tree species (see also Figure 3) to enhance sunlight penetration and improve coffee survival rates. Prior research indicated that coffee requires 35%—66% shade for optimal growth (Marques et al. 2022). Regular community maintenance and care activities also influenced plant growth in the agroforestry system. These included the

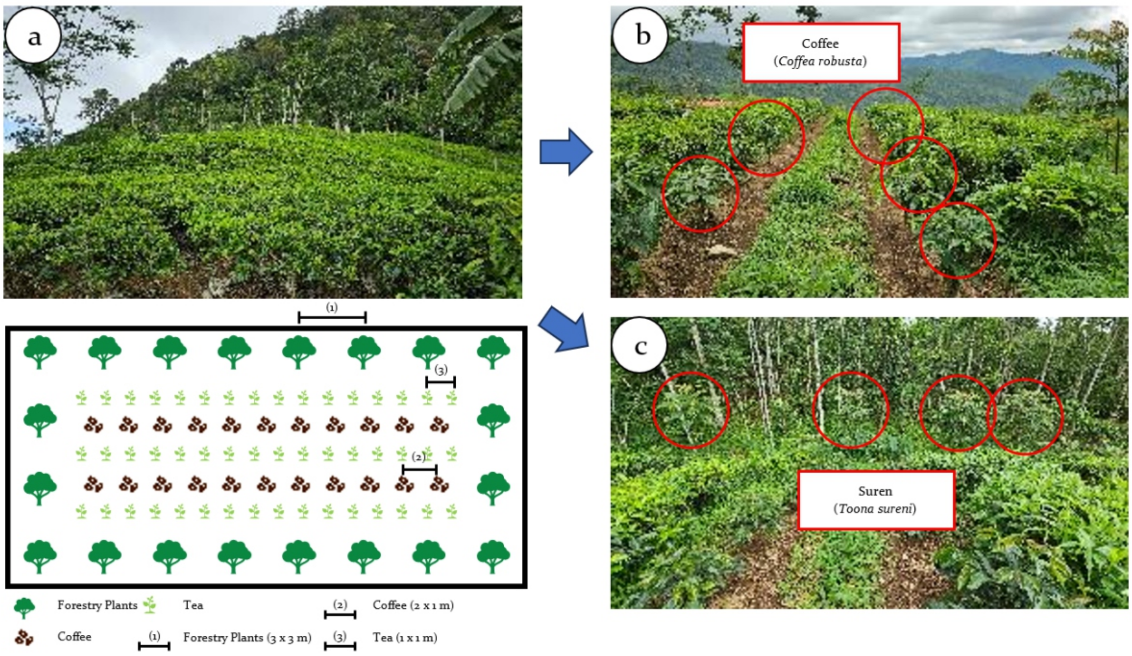

Figure 3. Planting pattern of the agroforestry-based land management: before (a) and after (b and c)

Table 5. Growth of forest species in agroforestry-based land management after a year of planting

Sample Plot Code	Coffee (*Coffea robusta*)		Suren (*Toona sureni*)		Rasamala (*Altingia excelsa*)		Manglid (*Manglietia glauca*)	
	Individu/ Plot	Individu/ ha	Individu/ Plot	Individu/ ha	Individu/ Plot	Individu/ ha	Individu/ Plot	Individu/ ha
PT01	32	10,146.81	4	1,268.35	2	634.18	3	951.26
PT02	87	27,586.64	7	2,219.61	3	951.26	1	317.09
PT03	59	18,708.18	2	634.18	4	1,268.35	1	317.09
PT04	44	13,951.87	7	2,219.61	5	1,585.44	6	1,902.53
PT05	56	17,756.92	5	1,585.44	1	317.09	1	317.09
PT06	77	24,415.76	9	2,853.79	3	951.26	2	634.18
PT07	59	18,708.18	9	2,853.79	4	1,268.35	4	1,268.35
PT08	56	17,756.92	5	1,585.44	5	1,585.44	4	1,268.35
PT09	59	18,708.18	6	1,902.53	3	951.26	3	951.26
PT10	89	28,220.82	8	2,536.70	3	951.26	4	1,268.35
PT11	52	16,488.57	7	2,219.61	4	1,268.35	2	634.18
PT12	99	31,391.70	8	2,536.70	3	951.26	4	1,268.35
PT13	99	31,391.70	8	2,536.70	4	1,268.35	1	317.09
Average	**67**	**21,172**	**7**	**2,073**	**3**	**1,073**	**3**	**878**

application of organic and chemical fertilizers, irrigation, pest control, weeding, and pruning. As a result, after one year of planting, the plant survival rate reached 90%.

Carbon Stock Baseline

The establishment of a carbon stock baseline for tea plantations employed biomass data from the Forest Reference Level Indonesia 2022 (FRL) document and compared it with direct field measurements. According to the FRL document, tea plantations were classified as pure dry agriculture, with an average AGB of 14.08 t/ha. However, field measurements showed that the actual biomass of tea plantations was 78.16 t/ha. This discrepancy arose because tea plants were classified as perennial crops, with longer life cycles and continuous growth compared to annual crops such as rice and corn. As a result, tea plants accumulated biomass over time, allowing the storage of a significant amount of carbon both above and below ground.

The annual projection of baseline carbon stock changes for the research area used the annual carbon stock growth rate for agricultural land, as stated in the IPCC, which was set at 1.8 t C/ha/year. This growth rate was applied to model the increase in land carbon stock as the baseline emission factor. After obtaining the average biomass, the total carbon stock for the entire area was calculated by considering this growth rate, resulting in a projected cumulative baseline emission factor of 2,465.51 tCO_2 by the tenth year of the research, as shown in Figure 4. This result was consistent with previous research, which found that tea plants had denser, larger canopies than seasonal crops, contributing to higher biomass accumulation and greater carbon sequestration potential (Kalita et al. 2015).

Carbon Stock with Agroforestry Intervention

The agroforestry intervention had a significant positive impact on both ecological and local economic sustainability. The measurement indicated that agroforestry significantly increased carbon sequestration capacity, and its carbon stock increased substantially over the next ten-year period, compared to tea plantations. Agroforestry-based land management had a significant impact on soil biomass accumulation with annual increases surpassing those observed in monoculture farming systems. This increase in biomass accumulation was attributed to the integration of hardwood species into agricultural systems, which enhanced soil organic matter accumulation, primarily because of greater root and litter inputs from woody plants compared to tea crops. In addition, these results reinforced previous research showing that agroforestry, through a combination of woody species and food crops, significantly improved carbon sequestration, notably as plant age increased, thereby enhancing AGB and BGB more effectively than monoculture farming systems (Insarullah et al. 2019).

Woody plants contributed significantly to BGB

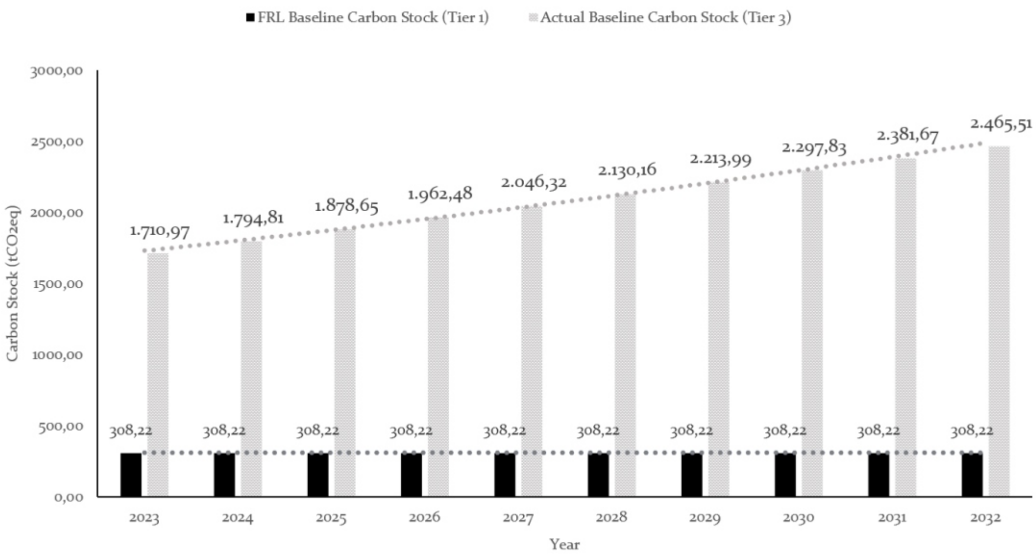

Figure 4. Baseline carbon stock projection of tea agriculture

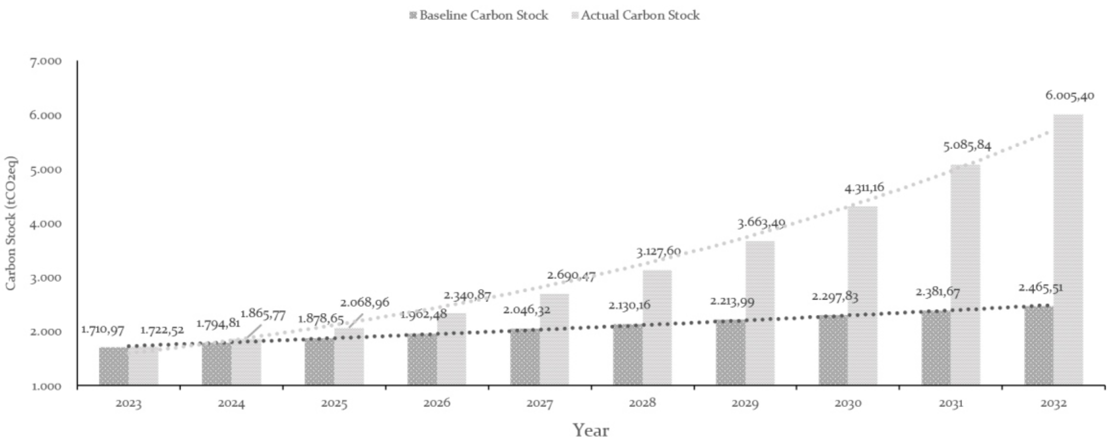

Figure 5. Comparison of actual carbon stock and baseline carbon stock

Table 6. Projection of Biomass Growth by Tree Species

Year	Biomass (t/ha)			
	Coffee (*Coffea robusta*)	Suren (*Toona sureni*)	Rasamala (*Altingia excelsa*)	Manglid (*Manglietia glauca*)
2023	0.15	0.03	0.02	0.32
2024	0.87	0.26	0.13	1.99
2025	2.42	0.71	0.42	5.14
2026	5.00	1.42	1.05	9.82
2027	8.76	2.38	2.23	16.05
2028	13.85	3.63	4.22	23.87
2029	20.39	5.15	7.39	33.29
2030	28.50	6.96	12.19	44.33
2031	38.29	9.06	19.19	56.99
2032	49.86	11.47	29.08	71.29
Total	**168.09**	**41.07**	**75.91**	**263.09**

accumulation in the agroforestry system, which increased in parallel with AGB growth. As shown in Table 6, while coffee plants contributed to high total biomass/ha in the early stages of planting, forest tree species such as suren (*Toona sureni*), rasamala (*Altingia excelsa*), and manglid (*Manglietia glauca*) had greater long-term biomass growth potential due to their longer lifespan compared to short-lived crops. Consequently, these tree species played a crucial role in enhancing carbon stock accumulation. The biomass capacity analysis showed that although coffee plants contributed significantly to carbon sequestration due to their rapid growth, forest tree species were essential for maintaining long-term stability of carbon stocks and ecosystem functions. These results were consistent with previous research showing that agroforestry systems effectively enhance soil carbon through organic matter inputs and root biomass accumulation (Cardinael et al. 2018).

Using empirical data for modeling could accurately project biomass, carbon stocks, and sequestration. The agroforestry system accumulated carbon stock of 6,005.40 tCO_2eq over ten years, nearly three times that of tea monoculture (see Figure 5). This increase was attributed to the integration of trees and crops, which enhance soil carbon through their biomass, roots, and litter, and to the composition of tree stands, especially the presence of larger-diameter trees and diverse species. This combination could lead to a threefold increase in carbon stocks (Getnet et al. 2023). The model showed that sequestration rates in agroforestry increased more rapidly than in monoculture. This superior, long-term carbon storage capacity confirms agroforestry's role as a key strategy for climate change mitigation (Takimoto et al. 2008; Getnet et al. 2023).

This research confirmed a causal relationship between agroforestry and increased carbon stocks. For years, agroforestry has been recognized as a more efficient, sustainable carbon storage system than monoculture (Getnet et al. 2023; Lestari & Dewi 2023). The findings corroborate prior work that integrating forestry plants boosts biomass and soil organic matter, significantly increasing sequestration. In West Java, for instance, agroforestry systems showed above-ground carbon stocks of 2.26 t–66.65 t C/ha/year, far surpassing those of monoculture (13.65 t–18.29 t C/ha/year). This superior performance was due to canopy and species diversity, which optimized light use, extended photosynthetic periods, and enriched the soil, all leading to faster biomass and greater carbon capture (Cardinael et al. 2018; Siagian et al. 2024).

Following Vanneste (2024), the carbon stock projection used Microsoft Excel for calculations to promote transparency and simplicity in modelling spatial and temporal carbon stock dynamics. The results indicated that agroforestry significantly increased carbon stock compared to baseline monoculture tea farming. This finding aligns with Cardinael's (2025) modeling recommendations, highlighting the need for site-specific data to enhance model accuracy.

This research provides empirical evidence for agroforestry's role in enhancing carbon stocks over ten years by integrating forest tree species such as suren, rasamala, and manglid compared with the monoculture tea farming system (Jose 2009). Beyond sequestration, this indicates agroforestry improves ecological resilience for climate change mitigation (Takimoto et al. 2008). The implications of this research were highly relevant to climate change mitigation strategies in Indonesia's non-forest agricultural sector, supporting the country's efforts to reduce GHG emissions. In addition, this research also contributed to the existing literature on the impact of agroforestry management. It emphasized the active role of local communities in climate change mitigation and sustainable natural resource management. The research's key strength was its empirical data, which yielded accurate, field-relevant results that surpassed those of theoretical models. The main limitation, however, was the restricted local scope and single agroforestry type. Validation requires broader research incorporating diverse species and environments. The results opened the door for long-term carbon stock projection modeling. Future research should expand its focus to a broader range of species, climates, and soil types to provide a comprehensive global assessment of agroforestry as a climate mitigation tool.

Conclusion

This research shows that using a specific empirical measurement approach for carbon stock projection in agroforestry management within tea plantations yields more reliable models than approaches based on generalized assumptions or secondary data. Empirical data refers to direct diameter measurements and annual growth data from local trees, enhancing projection reliability. Agroforestry systems that integrate forest tree species with crops significantly improve biomass and soil organic matter, thereby enhancing carbon sequestration capacity. Increasing tree maturity introduces competition for light, nutrients, and water, which can affect productivity and carbon sequestration accumulation. This result shows that gains cannot follow a simple linear trend. In addition, these results address a key research gap in agroforestry carbon stock modeling by demonstrating a locally calibrated, field-based projection method and support the broader applicability of agroforestry as a scalable, data-driven climate change mitigation strategy.

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