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Research article

FOREST TRANSITION AND CARBON STOCK DYNAMICS IN AKAMKPA LOCAL GOVERNMENT AREA, CROSS RIVER STATE, NIGERIA

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ABSTRACT

Forest transition, the shift from net forest loss to recovery or structural change, has direct implications for soil carbon dynamics and climate regulation, yet Akamkpa Local Government Area, one of Nigeria's remaining tropical rainforest zones, lacks baseline data on how tree characteristics and land-use-driven forest transition affect soil carbon stock. This study quantified carbon stock dynamics across different tree canopies representing forest transition stages in Akamkpa Local Government Area, Cross River State, Nigeria. A survey research design was adopted, with six sample plots randomly established under each of four tree canopies, gmelina, teak, rubber, and oil palm; tree height, girth, and basal cover were measured, and twenty-four composite soil samples (twelve topsoil, twelve subsoil) were analysed for bulk density, organic carbon, total nitrogen, available phosphorus, and carbon stock, alongside descriptive statistics, one-way analysis of variance, Spearman correlation, and multiple regression analysis. Results showed that oil palm recorded the greatest mean tree height (24.0 m) and girth (1.19 m), while teak recorded the lowest height (15.4 m) and gmelina the lowest girth (0.65 m); differences in tree biomass across species were not statistically significant ($p > .05$). Soils were acidic (pH 4.8-5.2) with topsoil bulk density ranging from 1.07 to 1.29 g/cm³. Topsoil organic carbon and total nitrogen were highest under gmelina and teak, while available phosphorus was highest under rubber (4.87 mg/kg). Carbon stock was greatest under gmelina (0.044 t/ha), followed by teak (0.031 t/ha), and lowest under rubber (0.026 t/ha), although these differences were not statistically significant. Tree biomass variables showed positive but non-significant associations with carbon stock, and multiple regression explained only 21% of the variation in carbon stock. The study concludes that gmelina and teak canopies offer greater carbon sequestration potential than rubber and oil palm, and recommends protecting tree biomass, conserving litter, and integrating trees with crops or grasses to enhance carbon sequestration in the study area.

KEYWORDS

Forest transition; Carbon stock; Soil organic carbon; Tree biomass; Tropical rainforest; Akamkpa; Cross River State; Nigeria

INTRODUCTION

Forest transition describes the shift in forest area trends from decline to recovery, often driven by socio-economic and environmental factors. Over the past two decades, global forest cover has notably decreased, with Latin America, the Caribbean, and Africa experiencing the most significant losses, while regions such as Europe and North America have seen forest stabilisation or growth, influenced by agricultural intensification, changing market values of forest products, policy reforms, rural-to-urban labour shifts, and evolving societal views on forest resources. Historical examples include Scotland in the 1750s, France in the 1830s, Ireland in the 1920s, Denmark, and the United States in the early 1900s, where forest cover was critically low at the point of transition (Lingchao et al., 2021; Bruggeman et al., 2016).

Parallel to forest dynamics, soil carbon sequestration plays a pivotal role in climate mitigation. This process involves capturing atmospheric CO2 and storing it in soil through organic residues, making soil the largest terrestrial carbon reservoir, holding 1,500-2,000 PgC in the top metre, over three times the atmospheric pool and four times the biotic pool. Forests and wetlands are key contributors, with boreal and temperate forests sequestering approximately 6 tonnes of carbon per hectare annually (IPCC, 2007; Wolde et al., 2014). Soil organic carbon (SOC) is essential for regulating greenhouse gases, and its depletion through human activity significantly elevates CO_2 levels (Lal, 2004; Stockmann et al., 2013). The '4 per 1000' initiative aims to increase SOC by 0.4% annually to enhance food security and reduce emissions, though concerns persist regarding nutrient demands and the long-term stability of stored carbon (Minasny et al., 2017; Chen et al., 2018).

Land use and vegetation cover directly affect SOC levels, with agriculture contributing up to 29% of global greenhouse gas emissions while also offering potential for mitigation through improved land management (Vermeulen et al., 2012; Asumadu-Sarkodie & Owusu, 2016). Despite international attention, sub-Saharan Africa has seen limited integration of carbon-conscious farming systems. Initiatives such as REDD+ and the Clean Development Mechanism support emission reductions through land-use change, but progress is hindered by insufficient data on soil carbon stocks and CO_2 emissions in tropical regions (Verchot et al., 2012; Yao et al., 2010; FAO & ITPS, 2015).

The forest landscape in Akamkpa Local Government Area, Cross River State, Nigeria, is undergoing structural alteration due to intensified land-use activities. Logging, fuelwood extraction, agricultural expansion, and infrastructure development have accelerated deforestation, producing a measurable shift in forest cover consistent with the concept of forest transition. Akamkpa, previously identified as one of Nigeria's remaining tropical rainforest zones, is experiencing rapid vegetation loss (Speranza, 2022). Unlike regions such as the Amazon, where forest transition and carbon dynamics are extensively documented, Akamkpa lacks baseline data on forest cover variation, transition stages, and carbon stock levels, a data deficiency that limits the ability to quantify environmental impacts, formulate conservation frameworks, and implement climate-related interventions.

This study therefore sought to quantify carbon stock dynamics across different tree canopies representing forest transition stages in Akamkpa Local Government Area, Nigeria. Specifically, the study set out to characterise tree height, girth, and basal cover across the dominant tree canopies in the area; to determine topsoil and subsoil bulk density, organic carbon, total nitrogen, available phosphorus, and carbon stock under each canopy; and to assess the association and predictive influence of tree biomass characteristics on soil carbon stock.

LITERATURE REVIEW

Global Evidence on Forest Transition and Soil Carbon Dynamics

International research has firmly established soil as the largest active terrestrial carbon pool, with even minor shifts in soil carbon capable of significantly altering atmospheric CO_2 concentrations (FAO & ITPS, 2015; Lal, 2004). Forests and wetlands sequester substantial quantities of carbon annually, and soil organic carbon plays an essential regulatory role in the global carbon cycle, such that its depletion through land conversion and mismanagement measurably elevates atmospheric CO_2 levels (Lal, 2004; Stockmann et al., 2013; IPCC, 2007; Wolde et al., 2014). Global policy responses, including the '4 per 1000' initiative, seek to increase soil organic carbon stocks as a climate mitigation and food-security strategy, although questions remain about the nutrient demands and long-term stability of additional stored carbon (Minasny et al., 2017; Chen et al., 2018).

Land use is consistently identified as a primary driver of soil organic carbon variation. Agriculture alone contributes up to 29% of global greenhouse gas emissions, yet improved land management within agricultural systems also offers considerable mitigation potential (Vermeulen et al., 2012; Asumadu-Sarkodie & Owusu, 2016). Historical forest transition episodes in Scotland, France, Ireland, Denmark, and the United States demonstrate that forest cover can recover following periods of decline once socio-economic drivers, such as agricultural intensification, labour migration, and policy reform, shift in favour of forest retention (Lingchao et al., 2021; Bruggeman et al., 2016). This global evidence establishes both the theoretical basis for forest transition and the mechanistic link between land use, vegetation cover, and soil carbon dynamics.

Regional and African Evidence

Within sub-Saharan Africa, the integration of carbon-conscious farming systems has remained limited, and international carbon-financing mechanisms such as REDD+ and the Clean Development Mechanism have been constrained by insufficient data on soil carbon stocks and CO_2 emissions across tropical landscapes (Verchot et al., 2012; Yao et al., 2010). Within Nigeria specifically, a body of research has examined how land use and tree cover shape soil fertility and carbon-related properties. Offiong and Iwara (2011, 2012) documented the build-up of soil nutrients and organic carbon stock across fallow generational cycles in the Cross River rainforest, while Aweto (1981, 2001, 2013) established, across several studies in south-western Nigeria, that secondary succession and shifting cultivation systematically restore soil fertility as fallow vegetation matures. Ekukinam (2010) and Ekukinam, Iwara, and Gani (2014) found that rubber plantations of different ages in south-eastern Nigeria showed distinct phosphorus and exchangeable-base profiles linked to monoculture management, while Odewumi, Iwara, and Ogundele (2013) reported that teak cultivation measurably altered soil physical and chemical properties relative to other land covers in south-western Nigeria.

Closer to the present study area, Speranza (2022) reported that Akamkpa, long recognised as one of Nigeria's remaining tropical rainforest zones, is experiencing rapid vegetation loss driven by logging, fuelwood extraction, agricultural expansion, and infrastructure development. This regional evidence agrees with the global literature in confirming that land use and tree-cover type systematically shape soil carbon-related properties, and it further shows that Cross River State's forest and fallow soils have been reasonably well studied in relation to nutrient build-up and fertility restoration. What this regional evidence does not provide, however, is canopy-specific data connecting tree structural characteristics directly to soil carbon stock within an active forest-transition landscape such as Akamkpa.

Local Research Gap

Unlike regions such as the Amazon, where forest transition and carbon dynamics are extensively documented, Akamkpa lacks baseline data on forest cover variation, transition stages, and carbon stock levels beneath the specific tree canopies that now dominate its transitioning landscape. This data deficiency limits the ability of local and national agencies to quantify environmental impacts, formulate conservation frameworks, and implement climate-related interventions. The present study therefore addresses this gap by quantifying, across four dominant tree canopies in Akamkpa, gmelina, teak, rubber, and oil palm, the tree structural characteristics, soil physicochemical properties, and carbon stock levels that together describe how this transitioning tropical landscape is currently functioning as a carbon reservoir.

METHODOLOGY

Study Area

Akamkpa Local Government Area is situated in the southern part of Cross River State, Nigeria, bordering Biase, Calabar Municipality, and Odukpani Local Government Areas, and extending toward the Cameroon border. It encompasses a broad landscape and is home to the Cross River National Park, a vital biodiversity hotspot. The area features hilly terrain, dense rainforest, and flowing rivers that support both wildlife and communities, with a tropical climate marked by high humidity, annual rainfall of 2,000-3,000 mm, distinct wet and dry seasons, and temperatures consistently ranging from 25°C to 30°C. The soils, primarily ferrallitic and lateritic, are deep and fertile, fostering agriculture and forest growth, though they are prone to erosion if not well managed. The vegetation is rich in tropical rainforest species, including valuable timber such as mahogany and iroko, and provides habitat for endangered species such as the Cross River gorilla. Agroforestry practices in the area combine crops such as cocoa, cassava, and oil palm with trees to improve soil quality and carbon retention.

Research Design

A survey research design was applied, integrating field observation, measurement, and structured sampling for the assessment of vegetation and soil characteristics across forest transition zones. A systematic and random sampling framework was applied for vegetation and soil assessment across the four tree-canopy land-use categories, gmelina, teak, rubber, and oil palm, with six sample plots randomly established within each canopy category for vegetation and soil sampling.

Data Collection

Recorded vegetation variables included tree height, diameter at breast height (DBH), girth, and basal cover. Soil sampling was conducted at two depths, 15 cm and 30 cm, using augers and core samplers. Three sub-samples per plot were pooled into a composite sample, yielding six composite samples per quadrat, three surface and three subsurface, and 24 soil samples overall across the four canopy categories. Soil analyses were carried out at the Soil Science Laboratory, University of Calabar. Samples were air-dried, sieved, and processed for physical and chemical properties, including texture, bulk density, particle size, pH, electrical conductivity, organic carbon, nitrogen, phosphorus, exchangeable bases, and cation exchange capacity. Soil organic carbon was analysed using the Walkley-Black method, and CO2 emissions were measured using a gas-entrapment technique with PVC chambers followed by titration. Carbon stock was estimated from soil organic carbon, bulk density, and sampling depth using the allometric equation of Yasin et al. (2023), Komal et al. (2022), and Yasin et al. (2021):

$$\text{C stock (t ha}^{-1}) = \text{SOC content (g kg}^{-1}) \times \text{bulk density (g cm}^{-3}) \times \text{depth (cm)} \times 10^{-1}$$

Data Analysis

Both descriptive and inferential statistical techniques were used to analyse the data. Descriptively, tables, means, and standard deviations were used to summarise tree and soil characteristics across the four canopy categories. Inferentially, one-way analysis of variance (ANOVA) was used to test for differences in tree biomass and soil carbon stock across canopies, Spearman's correlation was used to examine the association between tree biomass variables and carbon stock, and multiple regression analysis was used to assess the combined and individual influence of tree height, girth, and basal cover on carbon stock, all tested at the .05 level of significance.

RESULTS

Tree Characteristics across Canopies

Tree height is an essential parameter for estimating biomass and understanding growth dynamics, but accurate measurement is often constrained in forests with dense, tall canopies and broad crowns (Yrttimaa et al., 2024; Larjavaara & Muller-Landau, 2013). Results in Table 1 indicate that oil palm recorded the greatest mean height (24.0 m), followed by gmelina (22.4 m) and rubber (22.2 m), while teak exhibited the lowest mean height (15.4 m). Tree height is a critical structural attribute that regulates light interception, reduces soil erosion, and enhances carbon sequestration (Kuyah et al., 2024; Buba, 2013), and its role in reducing the erosive effect of raindrops and contributing to carbon storage has been separately established (Iwara, 2014a; Offiong & Iwara, 2012; Lal, 2005).

Tree girth, a fundamental parameter for assessing growth, performance, and volume (Iqbal et al., 2016), was greatest under oil palm (1.19 m) and rubber (1.15 m) and lowest under gmelina (0.65 m). Variations in girth are linked to anthropogenic disturbance, tree age, and site conditions such as soil fertility, with larger tree sizes generally associated with minimal disturbance and older stand age (Iwara et al., 2014b; Martinez-Meza & Whitford, 1996). Girth strongly influences nutrient cycling and carbon sequestration, since large-diameter trees store substantial amounts of carbon and thereby contribute to climate mitigation (Lutz et al., 2018), suggesting that the wider-girthed oil palm and rubber trees sampled here may carry higher carbon storage potential in their standing biomass than gmelina.

Table 1. Tree characteristics (height, girth, and basal cover) across the four tree canopies in Akamkpa Local Government Area

Descriptive Statistic	Gmelina	Teak	Rubber	Oil Palm
Tree height (m) - Mean	22.4	15.4	22.2	24.0
Tree height (m) - SD	4.5	6.3	3.3	4.1
Girth (m) - Mean	0.65	1.06	1.15	1.19
Girth (m) - SD	0.51	0.62	0.07	0.10
Basal cover (m) - Mean	0.53	0.54	0.55	0.72
Basal cover (m) - SD	0.22	0.07	0.08	0.21

Basal cover, defined as the portion of the tree stem in contact with the soil, is an important structural attribute that influences carbon sequestration (Gorte, 2009), nutrient distribution, and soil structure through enhanced infiltration (Iwara, 2014b). Table 1 shows that oil palm recorded the highest mean basal cover (0.72 m), while the other three species exhibited relatively similar values between 0.53 and 0.55 m, a pattern linked in earlier work to plantation age and climax-species presence (Offiong et al., 2012; Aweto, 2001; Makana & Thomas, 2006).

Spatial Variation in Tree Biomass across Canopies

A one-way ANOVA of tree biomass variables across the four canopy categories, presented in Table 2, showed no statistically significant variation in basal cover, girth, or height, with p-values ranging from .197 to .493, all exceeding the .05 threshold. This outcome suggests structural uniformity among the sampled tree species, reflecting comparable vertical growth, trunk thickness, and ground coverage across canopies. Such uniformity is attributable to stable site conditions, including consistent soil fertility, light availability, and moisture distribution, which minimise disturbance factors such as logging, grazing, and erosion, combined with broadly similar physiological traits, such as growth rate and canopy structure, across the species sampled. This finding agrees with Ozondu et al. (2019), who reported that low-disturbance environments encourage biomass homogeneity, and it carries a practical implication for management: structural uniformity across canopies simplifies carbon-stock estimation and modelling and gives afforestation and agroforestry programmes flexibility in species selection without compromising carbon-sequestration goals.

Table 2. One-way ANOVA of the variation in tree biomass across the four tree canopies

Biomass Variable	Source of Variation	Sum of Squares	df	Mean Square	F	Sig.
Basal cover	Between groups	.068	3	.023	0.877 ns	.493
Basal cover	Within groups	.207	8	.026		
Basal cover	Total	.276	11			
Girth	Between groups	.553	3	.184	1.123 ns	.396
Girth	Within groups	1.313	8	.164		
Girth	Total	1.866	11			
Height	Between groups	130.403	3	43.468	1.971 ns	.197
Height	Within groups	176.453	8	22.057		
Height	Total	306.857	11			

ns = Not significant at the 5% alpha level.

Soil Bulk Density across Canopies

Bulk density is an important indicator of soil structure, defined as the dry weight of soil per unit volume (Rabot et al., 2018; Walter et al., 2016; Singer & Munns, 2002); high bulk density indicates compact soils with restricted water movement and root penetration, while low bulk density enhances water retention and aeration. Table 3 shows relatively similar bulk-density values across the canopies, with higher topsoil values under rubber (1.29 g/cm³) and oil palm (1.25 g/cm³), and a lower value under teak (1.07 g/cm³), a pattern repeated in the subsoil. All recorded values fall below the 1.4 g/cm³ threshold considered suitable for plant growth (Donahue, Miller, & Shickluna, 1990; Dong et al., 2021), indicating that the soils can support vegetation by providing adequate aeration and reducing mechanical resistance to root penetration. The comparatively low bulk density under tree canopies, and particularly under teak, is attributable to root activity that loosens the soil and increases macroporosity, consistent with earlier observations in fallow soils (Aweto, 1981).

Table 3. Topsoil and subsoil bulk density (g/cm³) across the four tree canopies

Depth	Canopy	Mean	SD
Topsoil	Rubber	1.29	0.06
Topsoil	Oil palm	1.25	0.03
Topsoil	Gmelina	1.20	0.23
Topsoil	Teak	1.07	0.06
Subsoil	Rubber	1.40	0.17

Depth	Canopy	Mean	SD
Subsoil	Oil palm	1.41	0.09
Subsoil	Gmelina	1.43	0.14
Subsoil	Teak	1.12	0.03

Soil Organic Carbon and Total Nitrogen across Canopies

Soil organic carbon is a key component of soil organic matter and a major contributor to atmospheric CO2 concentrations (Ozondu et al., 2019). Table 4 shows that topsoil organic carbon was highest under gmelina (2.49%), followed by teak (1.92%), and lowest under rubber (1.33%), while subsoil organic carbon was highest under rubber, followed by oil palm, with the lowest values recorded under teak. The elevated topsoil organic carbon under gmelina and teak is attributable to greater litter accumulation and decomposition, consistent with Iwara (2018) and Dolle and Schmidt (2009), who reported that soil carbon levels rise in environments with high biomass inputs.

Table 4. Topsoil and subsoil organic carbon (%) across the four tree canopies

Depth	Canopy	Mean (%)	SD
Topsoil	Rubber	1.33	0.34
Topsoil	Oil palm	1.53	0.54
Topsoil	Gmelina	2.49	1.16
Topsoil	Teak	1.92	0.43
Subsoil	Rubber	1.62	1.14
Subsoil	Oil palm	1.50	0.45
Subsoil	Gmelina	1.45	1.26
Subsoil	Teak	1.37	0.51

Table 5 shows a corresponding pattern for total nitrogen, with higher topsoil values under gmelina (0.22%) and teak (0.17%) than under rubber (0.11%). Because nitrogen content is closely linked to organic carbon, soils with higher organic matter tend to show correspondingly higher total nitrogen (Mashi et al., 2015), and organic inputs such as leaf litter and plant residues are known to enhance the availability of nitrogen alongside other nutrients including phosphorus and potassium (Bokhtiar & Sakurai, 2005). Increased total nitrogen, like organic carbon, improves soil quality and supports long-term agricultural and ecological productivity (Tahat et al., 2020; Shah & Wu, 2019; Aweto & Dikinya, 2003).

Table 5. Topsoil and subsoil total nitrogen (%) across the four tree canopies

Depth	Canopy	Mean (%)	SD
Topsoil	Rubber	0.11	0.04
Topsoil	Oil palm	0.13	0.04
Topsoil	Gmelina	0.22	0.10
Topsoil	Teak	0.17	0.04
Subsoil	Rubber	0.14	0.10
Subsoil	Oil palm	0.13	0.04
Subsoil	Gmelina	0.12	0.11
Subsoil	Teak	0.12	0.05

Available Phosphorus across Canopies

Table 6 shows that available phosphorus was highest in topsoil under rubber (4.87 mg/kg), followed by gmelina (3.29 mg/kg), and lowest under teak (1.39 mg/kg), while subsoil values ranged more narrowly from 0.66 to 0.91 mg/kg, with the highest value under oil palm. The elevated topsoil phosphorus under rubber is plausibly linked to synthetic fertiliser inputs commonly used to enhance rubber-plantation fertility (Ekukinam, 2010; Ekukinam et al., 2014), whereas the comparatively high value under gmelina is more consistent with litter accumulation and associated organic-matter enrichment together with soil pH conditions that favour phosphorus release (Liu et al., 2024; Osemwota, 2010). These results suggest that both management practices, such as fertiliser use in rubber plantations, and natural processes, such as litter decomposition under gmelina, contribute to the variation in phosphorus observed across the canopies.

Table 6. Topsoil and subsoil available phosphorus (mg/kg) across the four tree canopies

Depth	Canopy	Mean (mg/kg)	SD
Topsoil	Rubber	4.87	3.77
Topsoil	Oil palm	2.41	3.43
Topsoil	Gmelina	3.29	4.40
Topsoil	Teak	1.39	1.71
Subsoil	Rubber	0.66	0.16
Subsoil	Oil palm	0.91	0.08
Subsoil	Gmelina	0.67	0.19
Subsoil	Teak	0.72	0.28

Carbon Stock across Canopies

Soil organic carbon, expressed here as carbon stock, represents one of the largest active carbon pools, existing as an integral part of soil organic matter and biomass, and its storage is central to climate change mitigation and sustainable land use (Bessah et al., 2016). Table 7 indicates no statistically significant variation in carbon stock across canopies, in either topsoil ($F = 1.040$, $p > .05$) or subsoil ($F = 0.190$, $p > .05$). Despite this lack of statistical significance, mean values were higher under gmelina (0.044 t/ha) and teak (0.031 t/ha) than under rubber (0.026 t/ha), pointing to the comparatively greater carbon-sequestration potential of gmelina and teak canopies, a pattern consistent with Pütsep (2021), who identified teak as a high carbon-sequestering species in India.

Table 7. Topsoil and subsoil carbon stock (t/ha) across the four tree canopies

Depth	Canopy	Mean (t/ha)	SD
Topsoil	Rubber	0.026	0.005
Topsoil	Oil palm	0.029	0.012
Topsoil	Gmelina	0.044	0.023
Topsoil	Teak	0.031	0.008
Subsoil	Rubber	0.036	0.029
Subsoil	Oil palm	0.031	0.008
Subsoil	Gmelina	0.031	0.030
Subsoil	Teak	0.023	0.008

The elevated topsoil carbon stock beneath gmelina and teak canopies is linked to greater litter accumulation, which promotes soil carbon build-up through decomposition. This is consistent with Webber (2024), who observed that around 48% of forest carbon is stored in litter and soil rather than in tree biomass alone, and with Singh et al. (2022), who stressed the influence of litter quality on soil organic carbon accumulation. These findings also broadly agree with Ruslim, Sandalayuk, Kristiningrum, and Alam (2021), who reported high organic carbon stocks in gmelina and teak stands in Indonesia, although that study found teak to have somewhat greater sequestration potential than gmelina, whereas the present study found the reverse ordering, a difference plausibly attributable to site-specific differences in stand age, litter quality, and soil conditions between the two locations. Conversely, the comparatively low topsoil carbon stock under rubber is consistent with its reduced litter accumulation, underscoring the significance of species-specific litter production in determining soil carbon-storage capacity.

Association between Tree Biomass and Carbon Stock

Spearman's correlation analysis was used to examine the relationship between tree biomass variables and topsoil carbon stock. Table 8 shows positive but statistically non-significant associations between basal cover and carbon stock (rho = .247, $p > .05$), height and carbon stock (rho = .358, $p > .05$), and girth and carbon stock (rho = .021, $p > .05$). These positive, if non-significant, coefficients indicate that increases in tree height, girth, and basal cover tend to correspond with increases in carbon stock, consistent with earlier studies linking tree size to carbon storage (Gebrewahid & Meressa, 2020; Ozondu et al., 2019; Behera et al., 2017). Large trees in particular have been shown to exert a disproportionate influence on carbon storage, with Lutz et al. (2018) reporting that trees with diameters above 60 cm contribute about 41% of global aboveground biomass, and Stephenson et al. (2014, as cited in Mildrexler et al., 2020) reporting that a single large tree can store carbon equivalent to or greater than several medium-sized trees of the same species.

Table 8. Spearman correlation between tree biomass variables and topsoil carbon stock

Variable	rho	p-value
Basal cover (m)	0.247 ns	.438
Girth (m)	0.021 ns	.948
Height (m)	0.358 ns	.253

ns = Correlation not significant at the .05 level (2-tailed).

Through photosynthesis, trees capture atmospheric $CO2$ and store it in stems, branches, and roots, later contributing to soil carbon pools through litter fall and decomposition (Bai & Ding, 2024; Wolf et al., 2020; Nowak & Crane, 2002), and tree biomass has similarly been shown elsewhere to function as a major sink for atmospheric $CO2$, with net storage dynamics shifting as trees grow, die, and decay (Tang et al., 2016). The present correlations therefore suggest that tree height, girth, and basal cover are relevant, if individually modest, predictors of organic carbon storage in soils under the canopies sampled.

Influence of Tree Biomass on Carbon Stock

Multiple regression analysis was applied to assess the combined influence of tree height, girth, and basal cover on soil carbon stock, following an approach comparable to that of Edmondson et al. (2014) in evaluating the contribution of urban trees to soil organic carbon in the United Kingdom. Table 9 shows a weak multiple correlation ($R = .458$) between the biomass variables and carbon stock, with a coefficient of multiple determination ($R^2 = .210$) indicating that only 21% of the variation in carbon stock was explained by the combined effect of tree height, girth, and basal cover. None of the individual predictors, basal cover ($t = 0.560$), girth ($t = 1.345$), or tree height ($t = 0.659$), reached statistical significance at the .05 level, and the overall ANOVA F-ratio of 0.710 was likewise not significant.

Table 9. Multiple regression analysis of the influence of tree biomass characteristics on carbon stock

Predictor Variable	b	β	t-value
Basal cover (BC)	0.008	0.188	0.560 ns
Girth (G)	0.012	0.452	1.345 ns
Tree height (TH)	0.001	0.210	0.659 ns
F-value	0.710		
R	0.458		
R^2	0.210		
Constant	0.032		

ns = Not significant at the 5% level; the fitted equation is $Y = 0.032 + 0.188BC + 0.452G + 0.210TH$, where Y = carbon stock (t/ha).

Although none of the three predictors reached individual statistical significance, all three regression coefficients were positive, indicating that tree biomass characteristics, both individually and collectively, contribute in direction, if not in statistically confirmed magnitude, to the quantity of carbon stored in the soil.

The standardised coefficients (β) show that girth exerted the greatest relative influence (β = .452), followed by tree height (β = .210), with basal cover exerting the least influence, a pattern consistent with earlier work establishing diameter at breast height as a strong correlate of soil organic carbon (Attua, 2009; Lal, 2005; Gorte, 2009). The absence of statistical significance may partly reflect the limited sample size used in the regression, and it further suggests that other environmental and edaphic factors, such as soil texture, microclimate, litter quality, and decomposition rate, may exert stronger control over carbon stock than tree structural attributes alone, a conclusion broadly consistent with Edmondson et al. (2014) and Bessah et al. (2016).

DISCUSSION OF FINDINGS

Taken together, the results show that Akamkpa's transitioning forest landscape is functioning as a modest but measurable carbon reservoir whose capacity varies systematically, if not always statistically significantly, with tree-canopy type. Gmelina and teak canopies consistently outperformed rubber and oil palm on the carbon-relevant soil properties examined, organic carbon, total nitrogen, and carbon stock, a pattern the study attributes to greater litter accumulation and decomposition beneath these two species. This agrees with global evidence that litter and soil, rather than tree biomass alone, account for a substantial share of forest carbon storage (Webber, 2024; Singh et al., 2022), and it extends the regional evidence on Nigerian fallow and plantation soils (Offiong & Iwara, 2011, 2012; Aweto, 1981, 2001) by showing that the same litter-driven carbon-accumulation mechanism operates across the specific tree canopies now dominating Akamkpa's transitioning landscape.

The finding that tree biomass characteristics were positively but only weakly and non-significantly associated with carbon stock, explaining just 21% of its variation, agrees with Edmondson et al. (2014) and Bessah et al. (2016), both of whom found that structural tree attributes alone offer limited explanatory power for soil organic carbon variation, and it disagrees with the stronger, statistically significant tree-size-carbon relationships reported in some other tropical settings (Behera et al., 2017; Gebrewahid & Meressa, 2020). This apparent tension is best read as a difference in scale and site homogeneity rather than a genuine contradiction: because tree biomass in Akamkpa showed no significant variation across canopies in the first place, there was correspondingly little biomass-driven variation available to explain differences in carbon stock, so soil-level factors such as litter quality, microclimate, and decomposition rate necessarily carry more of the explanatory burden here than in more structurally heterogeneous forest stands.

The comparison with Ruslim et al. (2021), whose Indonesian gmelina and teak stands showed teak outperforming gmelina in carbon storage while the present study found the reverse ordering, illustrates a broader point emerging from this discussion: species-level carbon-sequestration rankings reported in the global literature should be treated as context-dependent rather than universal, since local differences in stand age, planting density, litter management, and soil fertility can plausibly reorder which species sequesters more carbon at a given site. This reinforces the importance of the locally-generated, canopy-specific evidence that this study provides for Akamkpa, rather than relying on carbon-sequestration rankings transferred wholesale from other tropical forest regions.

For climate and land-use policy, the results suggest that where forest transition in Akamkpa proceeds toward gmelina or teak plantation rather than rubber or oil palm monoculture, the resulting land cover is likely to retain somewhat greater soil carbon-sequestration capacity, even though tree biomass itself does not differ significantly across these canopies. This distinction between standing biomass and soil carbon outcome is a useful one for local conservation planning, since it indicates that canopy choice in land-use and afforestation decisions should be informed by species-specific litter and soil-carbon behaviour rather than by tree size alone.

CONCLUSION

This study set out to quantify carbon stock dynamics across different tree canopies representing forest transition stages in Akamkpa Local Government Area, Cross River State, Nigeria. The findings show that forest transition, marked by the establishment of diverse tree species, contributes substantially to soil carbon-stock accumulation and strengthens soil quality, with gmelina and teak plantations recording superior carbon-sequestration capacity relative to rubber and oil palm. Tree biomass characteristics exerted a consistently positive, if statistically modest, influence on carbon accumulation, with litter fall and decomposing biomass emerging as the more important drivers of soil organic-matter enrichment, particularly beneath gmelina and teak canopies.

The contribution of this study lies in providing Akamkpa, and by extension Cross River State's wider tropical rainforest zone, with baseline, canopy-specific data on tree characteristics, soil properties, and carbon stock that were previously unavailable, addressing a data deficiency that had limited the formulation of conservation frameworks and climate-related interventions for the area. By identifying gmelina and teak as the canopies with the greatest carbon-sequestration potential, and by showing that this advantage operates chiefly through litter-driven soil-carbon accumulation rather than through differences in standing tree biomass, the study offers a practical, locally grounded basis for guiding land-use and afforestation decisions as Akamkpa's forest landscape continues to transition.

RECOMMENDATION

Based on the findings, it is recommended that tree biomass in Akamkpa, particularly under gmelina and teak canopies, be managed and protected through non-destructive harvesting practices, and that litter be conserved rather than raked or removed, since litter accumulation was consistently linked to higher soil organic carbon, nitrogen, and carbon stock. Integrating these tree species with crops or grasses is also recommended, as such integration can actively boost carbon sequestration in both aboveground and belowground biomass while offering a sustainable pathway to enrich soils and promote ecosystem resilience.

It is further recommended that plantation owners and land managers in the area be encouraged to register under carbon-offset programmes to support sustainable climate-change mitigation, and that future monitoring in Akamkpa expand the sampling of tree canopies and soil depths so that the modest, non-significant relationships identified here between tree biomass and carbon stock can be tested with greater statistical power, thereby strengthening the evidence base available to local conservation and land-use planning.

DECLARATIONS

Ethical approval: Not applicable; the study involved field vegetation measurement and soil sampling, with no human or animal subjects.

Informed consent: Not applicable.

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Conflict of interest: The authors declare no conflict of interest.

Data availability: The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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