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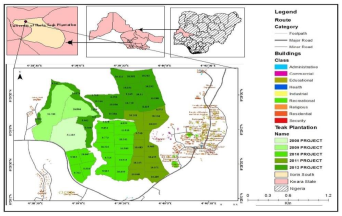

Assessment of carbon sequestration of Teak (*Tectona grandis* Linn. F.) plantation on the campus of University of Ilorin, Nigeria

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Abstract

The study assessed the carbon sequestration of *Tectona grandis* Linn. F. in five age series (11-15 years old), at the University of Ilorin, north-central Nigeria. Data were collected using a stratified sampling technique and twenty square plots of 25 m × 25 m were laid. A non-destructive method was used to determine the biomass of the trees. Tree enumerations were carried out for diameters at the base, top, middle, diameter at breast height (DBH), and height. Soil samples at two different depths (0-15 cm and 15-30 cm) were collected and analyzed to obtain soil organic carbon. The results were summarized using descriptive statistics, while the relationship between tree growth variables and carbon stock was assessed using correlation and regression analysis. The results showed that tree carbon stocks were 230.05 t ha^{-1}, 362.35 t ha^{-1}, 277.48 t ha^{-1}, 216.40 t ha^{-1}, and 126.20 t ha^{-1} for 11 years old (2012), 12 years old (2011), 13 years old (2010), 14 years old (2009) and 15 years old (2008) age series, respectively. The soil organic carbon stocks were 1.1025 t ha^{-1}, 0.6253 t ha^{-1}, 1.2019 t ha^{-1}, 1.4070 t ha^{-1} and 0.7615 t ha^{-1} for 11 years old (2012), 12 years old (2011), 13 years old (2010), 14 years old (2009) and 15 years old (2008) age series, respectively. The study also revealed that the 14-year-old (2009) age series had the highest carbon stock, and the total carbon stock estimate was 151,850.84 t. The potential cash value of the carbon stock was also estimated at $91,894.40 t C ha^{-1} and the total PCV was $56,606,951.50. Correlation analysis showed a strong positive correlation between most of the growth variables and carbon stock. The regression equation ($Y = -596.48 + 27.16\ THT + 1238.34\ DBH$, Adj R^2 = 82.7%) showed that DBH and height of trees are suitable for evaluating the carbon stock in the study area.

Keywords

Global climate change; Afforestation; Teak plantation; Carbon sequestration

Contents

1 Introduction

Global climate change, driven by escalating greenhouse gas emissions, is one of the most pressing challenges of our time. The rise in greenhouse gas concentrations, particularly carbon dioxide (CO_2), is fundamentally altering the Earth's climate, leading to a host of adverse effects, including rising temperatures, extreme weather events, and sea-level upsurge (Masson-Delmotte et al. 2021). For the year 2022, global greenhouse gas emissions (GHG) were estimated at 58 gigatons (GT), the largest annual level ever recorded (Kharas et al. 2022). This came with attendant negative consequences on food, water, health, ecosystem, human habitat, and infrastructure. In response to the global crisis of climate change, therefore, afforestation and reforestation (A&R) programmes have emerged as pivotal mitigation strategies owing to their potential to sequester atmospheric carbon dioxide (CO_2).

Grafton et al. (2021) have suggested that carbon sequestration, especially through A&R programmes could reduce CO_2 emission by up to 55% by 2100, and this would have a great influence on greenhouse gas contribution to the global climate change. Afforestation and reforestation (A&R) programmes involve planting trees on previously non-forested lands (afforestation) or restoring and replanting trees in areas that were once forests (reforestation). These initiatives are widely regarded as valuable tools for mitigating climate change (Simonson et al. 2021). Trees, through photosynthesis, capture CO_2 from the atmosphere and store it as biomass and soil organic carbon, making A&R programmes a powerful means of carbon sequestration (Ravindranath and Ostwald 2008). The effectiveness of A&R programmes in mitigating climate change has actually prompted international initiatives, such as the Bonn Challenge and REDD+ (Reducing Emissions from Deforestation and Forest Degradation), which aim to restore millions of hectares of forests worldwide (Bonn Challenge 2011). These initiatives have the potential to significantly contribute to global climate goals, such as those outlined in the Paris Agreement (United Nations 2015).

However, understanding the carbon dynamics of A&R programmes is crucial for assessing their effectiveness in climate change mitigation efforts (Ravindranath and Ostwald 2008). This is more so, given that different arrays of tree species are used in A&R programmes. Among the diverse array of tree species, *Tectona grandis* Linn. F., commonly known as teak, holds particular importance due to its rapid growth, high timber quality, and substantial potential for carbon sequestration (Amusa and Adedapo 2020). Therefore, as global efforts intensify to combat climate change, assessments of carbon sequestration potential in specific ecosystems, such as teak plantations, become increasingly critical.

The University of Ilorin teak plantation, with its unique characteristics and geographical location, offers a valuable opportunity to contribute to our understanding of tropical tree-based carbon sequestration. The teak plantation is an ambitious A&R programme covering 616 hectares of land. It is the largest known plantation programme in any university campus in sub-Sharan Africa if not the entire globe. It is located within the highly deforested savanna zone of Kwara State, Nigeria, representing a valuable asset in the context of climate change mitigation and sustainable forest management. The assessment of its carbon sequestration is essential for understanding the role this plantation plays in sequestering carbon, enhancing ecosystem services, and contributing to the broader objectives of climate change mitigation and environmental sustainability in the region.

In view of the foregoing, this study examined the carbon stock in both above- and belowground biomass, as well as soil organic carbon within the University of Ilorin teak plantation, considering the growth dynamics of the trees over time. It seeks to determine the carbon stock and sequestration rate of the teak plantation. The research endeavors to understand how carbon sequestration of the teak plantation change over time. By considering the growth dynamics of the teak trees across different age series, we aim to provide a better understanding of the plantation's contribution to mitigating climate change. Through these efforts, our overarching goal is to bridge existing knowledge gaps and offer insights that can effectively guide sustainable forest management and climate change mitigation strategies, not only in the immediate region but with broader applicability in Nigeria and beyond. The research seeks to contribute to the discourse on the vital role of teak plantations in addressing contemporary environmental challenges.

2 Material and methods

2.1 Study area

The University of Ilorin Teak Plantation (Figure 1) is situated within the campus of the University of Ilorin on Latitude 08° 27’ 24.6” N - 08° 29’ 54” N and Longitude 04° 39’ 56.7” E - 04° 40’ 01” E. It falls within the Southern Guinea Savanna ecological zone of the country. The teak plantation was initiated in 2008 and spanned a 5-year planting period (2008–2012). It covers a total land area of 616 ha in five age series (15-11 years; Amusa and Adedapo 2020). The study location has a tropical climate with distinct wet and dry seasons. The rainfall pattern exhibits a double maximum, with an annual range of 1000–1500 mm. The temperature ranges between 25° C and 30° C during the wet season and between 33° C and 37° C during the dry season. The relative humidity is between 75% and 80% during the wet season and between 35% and 80% during the dry season (Olanrewaju 2009). The plantation’s terrain is characterized by east and west-facing slopes that drain into the central part to create a major river channel that flows northwards. The land surface is gently to strongly undulating, with an average elevation that varies from 273 m to 333 m above sea level. The soil is underlain by Precambrian basement complex rock and composed of loamy soil with medium-to-low fertility (Ajibade and Ojelola 2004).

The principal objectives of the teak plantation project were: protection of the environment, provision of aesthetic value to the vast landscape of the university, development of wood capital for poles and timber that can significantly contribute to the internally generated revenue of the university at maturity and provision of model field laboratories for teaching, research and innovations for academic staff and students of the university (Amusa et al 2022). The initial stocking of the plantation during each phase of establishment was 1,100 trees ha^{-1} at 3 × 3 m escapement. However, study by Amusa and Adedapo (2020) showed that the plantation had a stand density of 672, 832, 656, 592, and 688 trees ha^{-1} for the 2008, 2009, 2010, 2011 and 2012 planting years, respectively. This shows that stocking density has reduced considerably in all the age series, depicting the level of survival of planted stocks and management efforts. Accordingly, there has been several call for improved management activities such as beating up, thinning, pruning, and weeding operations on the plantation (Amusa and Adedapo 2020).

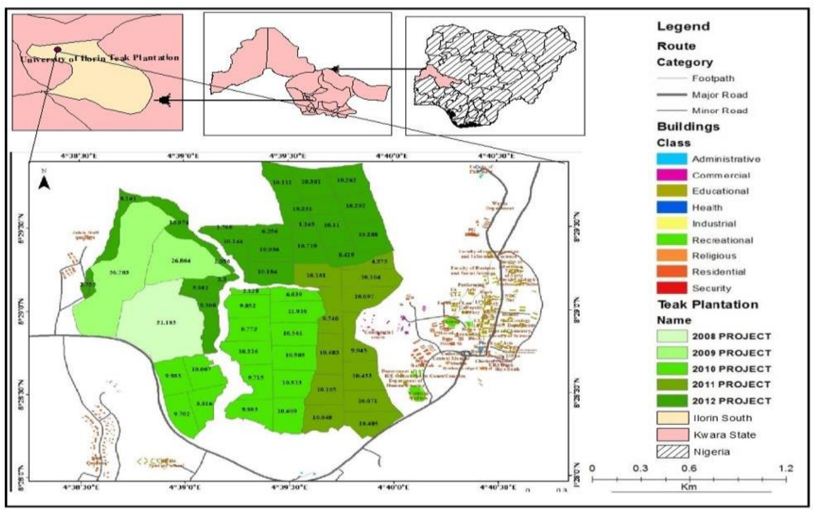

Figure 1. University of Ilorin Teak Plantation (Inset: Maps of Ilorin South Local Government Area, Kwara State, and Nigeria showing Kwara State), (Source: Amusa and Adedapo 2020).

2.2 Sampling procedure and data collection

A stratified random sampling technique was adopted for the study. The stratification was done according to the age series (11, 12, 13, 14, and 15 years) respective to the year of establishment of the various compartments obtained on the plantation. A total of twenty (20) temporary sample plots of 25 m × 25 m were used in the study. The number of sample plots in each stratum was based on the area covered by each of the age series (Table 1). The optimum allocation of sample plots for each stratum was determined using equation 1.

$$(1)\ \mathrm{ni} = \frac{\mathrm{n} \times \mathrm{Ai}}{\sum \mathrm{Aj}}$$

Where ni = the number of sample plots allocated to stratum i; n = the total number of sample plots; Ai = the area covered by age series i and $\sum\mathrm{Aj}$ = the sum of areas covered by all age series.

Table 1. Sample plots allocation in the different age series in the study area.

Year of establishment	Age series	Size (ha)	Number of sample plots
2008	15	57	2
2009	14	130	4
2010	13	150	5
2011	12	157	5
2012	11	122	4
TOTAL		**616**	**20**

In each sample plot, measurements of all individual trees were carried out. The data of trees collected include the diameters at the base, middle, top, and breast height (1.3 m above the ground) using diameter tape, as well as the total height of trees (THT) measured with the aid of a Spiegel Relaskop.

The soil organic carbon was assessed for each age series by collecting soil samples from two depths (0-15 and 15-30 cm) using a soil auger. Soil samples of the same depth were bulked into labelled polybags. The soil organic carbon was determined using the wet oxidation method (Walkley and Black 1934). Sub-samples (1g) of the soil composites consisting of the two different depths were oxidized using 10 ml of 1 N potassium dichromate ($K_2Cr_2O_7$) solution. Thereafter, 20 ml of concentrated sulphuric acid (H_2SO_4) was added to the solution while swirling the flask gently in a fume cupboard and was left to stand for 30 minutes. Then 100 ml of distilled water was added to cool the reaction. About 3-4 drops of Ferroin indicator were further added and titrated with 0.5 N ferrous sulphate ($FeSO_4$) solution in the burette. As the endpoint approached, the solution took a greenish colour and then changed to a dark green. A blank without soil was prepared alongside the sub-samples and titrated in the same manner. Readings were recorded at the titration phase and the percentage of organic carbon in the soil samples was calculated using equation 2:

$$(2)\quad \text{Percentage of Total Carbon Content } = \frac{(\mathrm{B}-\mathrm{T})\times \mathrm{M} \times 0.003 \times 1.33 \times 100}{\text{weight of sample}}$$

Where B = Blank titre value; T = Test sample value; M = Molarity of $FeSO_4$; 1.33 = Correction factor; 0.003 = mg equivalent of carbon.

2.3 Basic computation

Stand density was determined for each age series using the estimated number of trees and basal areas of the species per hectare (Etigale et al. 2014). The estimated number of trees of each age series per hectare within the plantation was obtained by extrapolating the total number of trees enumerated in the respective sample plots. The basal area for each tree in the sample plots was calculated using the measured DBH of the tree. The mean basal area per plot was determined by dividing the total basal trees in sample plots by the density of trees.

The stem volume of each tree within sample plots was determined using Newton's formula (equation 3) which generally yields a more accurate result than other volume equations because it involves making use of more information to calculate the total volume.

(3) $V = \pi h\left(\frac{Db^2+4Dm^2+Dt^2}{24}\right)$

Where V = stem volume (m^3); π = 3.142; h = total height of the tree; Db = diameter at the base of the tree; Dm = diameter at the middle of the tree; Dt = diameter at the top of the tree.

The above-ground stem biomass of individual trees in sample plots was estimated by multiplying the respective volume of trees with the density (Fearnside 1997). The value of specific gravity or density of the *Tectona grandis* (teak; 0.55 g cm^{-3}) was obtained from the list of wood densities of tropical tree species (Gisel et al. 1992). Below-ground biomass of trees in the sample plots was calculated by multiplying the above-ground biomass of each tree by 0.25 root ratio, which means the root system weight is about 25% of the above-ground weight (Ravindranath and Ostwald 2008).

Total green weight is the weight of the tree when it is alive. Thus, the total green weight of the trees was calculated by multiplying 1.25 by the above-ground biomass. The dry weight of trees was determined by multiplying the total green weight of the tree by 0.725 which is 72.5% of the total green weight since an average tree is usually considered to be 72.5% dry matter and 27.5% moisture.

Carbon content refers to the weight or amount of carbon sequestered in a tree which is generally 50% of the tree's dry weight. Therefore, in calculating the weight of carbon of individual trees in sample plots, the dry weight of the trees was multiplied by 0.5.

The carbon dioxide equivalent (CO_2e) of each tree was calculated by comparing the relationship between the carbon content value of the tree and the molecule and atomic weight of carbon dioxide. Carbon dioxide (CO_2) has one molecule of carbon and two molecules of oxygen. The atomic weight of Carbon is 12 and the atomic weight of Oxygen is 16. The weight of CO_2 of trees was determined by the ratio of CO_2 (44) to C (12), which means 44 was divided by 12 to give 3.67. The weight of carbon dioxide sequestered in the tree was determined by multiplying the weight of carbon in the tree by 3.67 (Renasingbe and Abasari 2008).

The soil organic carbon stocks at each of the depths (0-15 cm and 15-30 cm) were estimated using equation 4, as proposed by Poeplau et al. (2017).

(4) Organic Carbon Stock (t/ha) = OC × BD × Soil Depth

Where OC = Organic Carbon; BD = Bulk Density

Total carbon stock was estimated by summing the carbon contents of all trees per hectare in each age series (which is the combination of the above-ground carbon and the below-ground carbon of trees) and the soil carbon (Adeyemi and Adeleke 2020).

The potential cash value estimate is based on the European Emission Allowance (EUA) market (Jantawong et al. 2022). As of August 2023, the trading price of 1 ton of CO_2 on the European Union Allowance's (EUA) carbon market was 94.05 EUR tCO_2^{-1}, which is 372.78 USD tC^{-1} when converted (CO_2 × 44/12 (ratio molecular weight of CO_2 to C), at 1.08 USD EUR^{-1}.

2.4 Data analysis

A multiple linear regression model was developed to determine the relationship among the tree variables. Specifically, it examined the relationship between two independent variables (DBH and THT) and a dependent variable (carbon stock). The multiple linear regression model is expressed as:

$$(5)\quad Y = \alpha + \beta_1 X_1 + \beta_2 X_2$$

Where Y = Carbon Stock; β = Coefficient; X_1 = THT; X_2 = DBH; α = Intercept.

Pearson Product Moment Correlation (PPMC) was used to determine the strength and magnitude of the relationship between the tree growth parameters and carbon stock. The formula is given as:

$$(6)\quad r = \frac{N\sum xy-(\sum x)(\sum y)}{\sqrt{[N\sum x^2-(\sum x)^2][N\sum y^2-(\sum y)^2]}}$$

Where r = Pearson correlation coefficient; N = number of pairs of the stock; ∑xy = sum of products of the paired stocks; ∑x = sum of the x scores; ∑y = sum of the y scores; $\sum x^2$ = sum of the squared x scores; $\sum y^2$ = sum of the squared y scores.

3 Results and discussion

3.1 Tree growth variables in the different age series in the study area

Table 2 presents the stand density, mean DBH, mean basal area, and stem volume in the different age series in the study area. The 15 years (2008), 14 years (2009), 13 years (2010), 12 years (2011) and 11 years (2012) old age series had 864 trees ha^{-1}, 784 trees ha^{-1}, 736 trees ha^{-1}, 688 trees ha^{-1}, and 672 trees ha^{-1}, respectively. The results show a consistent decline in tree density with the decreasing age of the compartments in the teak plantation. The result agrees with the finding of Adeyemi and Moshood (2019) who observed a decline in tree density with decreasing age in *Triplochiton scleroxylon* stands in Onigambari forest reserve, Oyo State. Furthermore, the result shows a relatively understocked plantation considering the observed spacing (3 × 3 m) which is supposed to yield over a thousand stands per hectare.

Meanwhile, the 14 years (2009) age series had individual trees with the highest mean total height of 12.72 m, followed by the 15 years (2008) age series with mean total height of 12.06 m while 11 years (2012) old age series had the least (9.18 m). The trend in the mean height reveals that the age of the teak trees has a substantial impact on their growth, which is expected. Apart from the age factor, however, the 14 years (2009) age series likely experienced optimal growth conditions, leading to its impressive height. In contrast, the while 11 years (2012) old age series may have faced less favorable conditions or environmental stressors that hindered its growth. These results underscore the importance of monitoring and managing teak plantations with consideration for their age.

Results obtained on DBH also shows that the 14 years (2009) age series had the highest mean DBH of 0.56 m, followed by the 13 years (2010) and 12 years (2011) with 0.53 m each, while the 11 years (2012) old age series had the least (0.42 m). The mean diameter in all the age series is lower than what was obtained in the University of Ibadan teak plantation (Adesoye and Oluwadare 2008), teak stands in Osho Forest Reserve (Popoola and Adesoye 2012) and teak plantation in Nimba forest reserve (Shamaki et al. 2011).

Table 2. Tree growth variables for different age compartments in teak plantations.

Age series	Stand density (per ha)	Mean THT (m)	Mean DBH (m)	Mean BA (m^2)	Volume (m^3 ha^{-1})
2008	864	12.06 ± 0.12	0.44 ± 0.01	0.16 ± 0.01	923.08
2009	784	12.72 ± 0.06	0.56 ± 0.01	0.26 ± 0.01	1453.94
2010	736	11.39 ± 0.10	0.53 ± 0.01	0.24 ± 0.01	1113.39
2011	688	10.51 ± 0.11	0.53 ± 0.01	0.24 ± 0.01	868.31
2012	672	9.18 ± 0.11	0.42 ± 0.01	0.14 ± 0.01	506.37
TOTAL					**4865.09**

NB: DBH = Diameter at breast height; THT = Total height of tree; BA = Basal area

The results on average basal area across age series revealed that the 14 years (2009) age series had 0.26 m^2 which is the highest, followed by 13 years (2010) and 12 years (2011) both having 0.24 m^2, while the while 11 years (2012) old age series had the least (0.14 m^2). The 14 years (2009) age series stands out with the highest average basal area suggesting that the trees in this series have occupied more space on the forest floor and have larger trunk diameters. This observation aligns with the idea that older teak trees tend to grow wider trunks. The 13 years (2010) and 12 years (2011) age series both exhibit an average basal area of 0.24 m^2, indicating similar growth patterns. These series likely share similar growth conditions and management practices during their development. Contrastingly, the 11 years (2012) old age series had the lowest average basal area indicating less trunk diameter. The higher average basal area in older age series suggests that they are more suitable for timber production, and they sequester more carbon due to the larger tree dimensions. Other factors such as soil quality, climate, and management practices could have aided the development of the trees in one age series better than others.

In terms of tree volume, the results further show that the tree volume per hectare were 923.08 m^3 ha^{-1}, 1,453.94 m^3 ha^{-1}, 1,113.39 m^3 ha^{-1}, 868.31 m^3 ha^{-1}, and 506.37 m^3 ha^{-1} for the 15 years (2008), 14 years (2009), 13 years (2010), 12 years (2011) and 11 years (2012) old age series respectively (Table 2). The diameter differences affected the distribution of volume in the different age series. For instance, the 14 years (2009) age series had the highest diameter and the highest volume yield, while the 11 years (2012) age series had the least diameter and volume yield. This can be explained by the strong positive correlation (0.90) between diameter at breast height and volume in the study. Furthermore, the 14 years (2009) age series with the highest tree volume expectedly sequestered more carbon compared to other years because higher tree volumes indicate greater carbon sequestration ability, and this explains the perfect positive correlation between stem volume and carbon in the study. The differences in volume could also be attributed to the age of the plantation. The observed volumes in all the age series were higher than what was reported in some teak plantations in Nigeria (e.g Dantani et al. 2019 in Kanya Forest plantation, Kebbi State, Nigeria) and this may be a result of several factors such as location, silvicultural practices, and soil factors, etc.

3.2 Above ground biomass and below ground biomass

The trend in Above Ground Biomass (AGB) and Below Ground Biomass (BGB) of trees per hectare are presented in Figure 2. The 14 years (2009) age series had the highest estimate of AGB with 799.67 t ha^{-1}, followed by the 13 years (2010; 612.36 t ha^{-}

[1]), 15 years (2008; 507.69 t ha^{-1}), and 12 years (2011; 477.57 t ha^{-1}) age series, while the 11 years (2012; 278.50 t ha^{-1}) age series had the least. The BGB follows the same pattern with estimates of 199.92 t ha^{-1}, 153.09 t ha^{-1}, 126.92 t ha^{-1}, 119.39 t ha^{-1}, and 69.63 t ha^{-1} for the 14 years (2009), 13 years (2010), 15 years (2008), 12 years (2011) and the 11 years (2012) age series, respectively. Above Ground Biomass comprises the biomass of plant parts above the soil, such as stems, branches, leaves, and fruits (Gielen et al. 2018), while Below Ground Biomass includes the biomass of plant parts below the soil surface, primarily roots (Rovai and Twilley 2018). AGB is essential for estimating the carbon content of forests and plays a crucial role in carbon sequestration and climate regulation (Behera et al. 2017; Meena et al. 2019; Chen et al. 2023). BGB on the other hand is vital for understanding plant nutrient uptake, soil stabilization, and carbon storage in terrestrial ecosystems (Zeng et al. 2017). The findings of this study show that AGB and BGB distribution in trees per hectare vary significantly across different age series. The trend shows that the 14 years (2009) age series displayed the highest AGB and BGB estimate while the 11 years (2012) age series accumulated the least AGB and BGB suggesting that a young forest plantation holds less biomass compared to older forest. Although, an old forest may not be capturing any new carbon but can continue to hold large volumes of carbon as biomass over long periods (Yusuf et al. 2019). This result is contrary to the findings of Adeyemi and Adeleke (2020) who reported a low AGB and BGB for teak in the J4 sector of Omo Forest Reserve, south-west Nigeria. This may be influenced by factors such as tree growth rates, environmental conditions, or management practices.

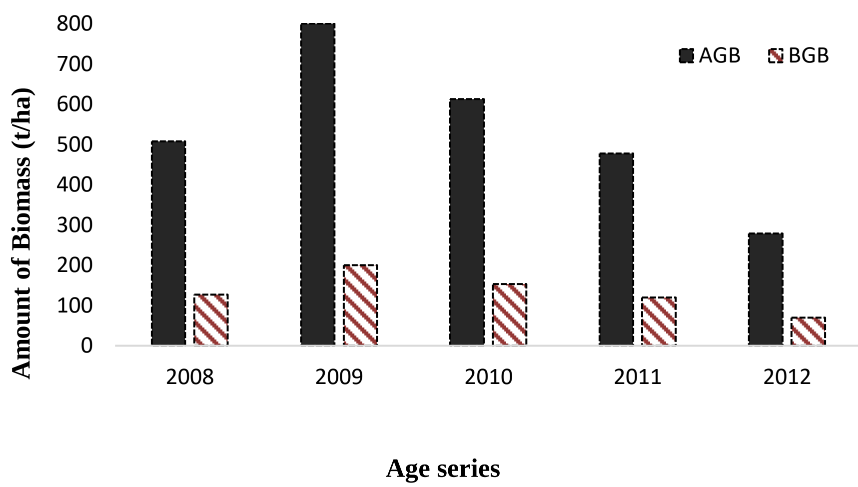

Figure 2. Above and below biomass of trees in the different age series in the study area.

3.3 Tree carbon content and carbon dioxide equivalent in the different age series in the study area

The 14 years (2009) age series had the highest carbon content per hectare with 362.35 t ha^{-1}, followed by the 13 years (2010; 277.48 t ha^{-1}), 15 years (2008; 230.05 t ha^{-1}), and 12 years (2011) (216.40 t ha^{-1}) age series, while the 11 years (2012; 126.20 t ha^{-1}) age series had the least (Table 3). The carbon dioxide equivalent per hectare follows the same trend with 1,329.82 t ha^{-1}, 1018.34 t ha^{-1}, 844.28 t ha^{-1}, 794.18 t ha^{-1}, and 463.14 t ha^{-1} for the 14 years (2009), 13 years (2010), 15 years (2010), 12 years (2011) and 11 years (2012) age series, respectively. The amount of carbon dioxide sequestered per year for the 15 years (2008), 14 years (2009), 13 years (2010), 12 years (2011), and 11 years (2012) age series were 56.29 t ha^{-1}, 88.65 t ha^{-1}, 67.89 t ha^{-1}, 52.95 t ha^{-1}, and 30.88 t ha^{-1}, respectively (Table 3). The 14 years (2009) age series had the highest carbon content per hectare, indicating that teak trees in this series stored the most carbon. In contrast, the 11 years (2011) age series had the lowest carbon content. This suggests that the age of teak trees significantly influences their capacity to sequester carbon which indicates that older trees tend to accumulate more carbon (Kraenzel et al. 2003; Wirabuana et al. 2022). This agrees with the findings of Chanan and Iriany (2014) in Indonesia, Reddy et al. (2014) in Southern India, and Chayaporn et al. (2021) in Thailand. The study suggests that managing and protecting older teak trees can be crucial for maximizing carbon sequestration in teak plantations and contributing to climate change mitigation efforts.

Table 3. Tree carbon and carbon dioxide estimation across age series in the study area.

Age series	Age	Tree Carbon Content (t ha^{-1})	CO_2 (t ha^{-1})	CO_2 (t ha^{-1} yr^{-1})
2008	15	230.05	844.28	56.29
2009	14	362.35	1329.82	88.65
2010	13	277.48	1018.34	67.89
2011	12	216.40	794.18	52.95
2012	11	126.20	463.14	30.88
TOTAL		**1212.48**	**4449.76**	**296.66**

3.4 Soil organic carbon stock

The soil organic carbon stock at depths of 0-15 cm and 15-30 cm are shown in Figure 3. At the 0-15 cm soil depth, the teak plantation had the highest amount of soil organic carbon stock (0.4785 t ha^{-1}) in the 13 years (2010) age series, followed by the 11 years (2012; 0.4445 t ha^{-1}), 15 years (2008; 0.3983 t ha^{-1}), and 12 years (2011; 0.3374 t ha^{-1}) age series, while the 14 years (2009) age series had the least (0.3152 t ha^{-1}). The result differs for the 15-30 cm soil depth, where the 14 years (2009) age series had the highest amount of soil organic carbon stock (1.0918 t ha^{-1}), followed by the 13 years (2010; 0.7234 t ha^{-1}), 11 years (2012; 0.6580 t ha^{-1}), and the 15 years (2008; 0.3632 t ha^{-1}) age series, while the 12 years (2011) age series had the least (0.2879 t ha^{-1}). The SOC increased with depth for the 14 years (2009), 13 years (2010), and 12 years (2011) age series, while it decreased for the 15 years (2008) and 11 years (2012) age series. Meanwhile, Adeyemi and Adeleke (2020) reported that the soil carbon of teak decreased with depths in the J4 sector of Omo forest reserve, while Ashura (2016) submitted that forests have higher SOC compared to other land uses which can be associated with a large annual addition of organic matter in the form of leaf litter, and longer residue time in the soil due to fewer disturbances, which subsequently ends up in higher organic carbon. Generally, the rate of litterfall and dynamics associated with it regulate the litter decomposition in soil and assist in organic carbon storage (Lugo et al. 1990).

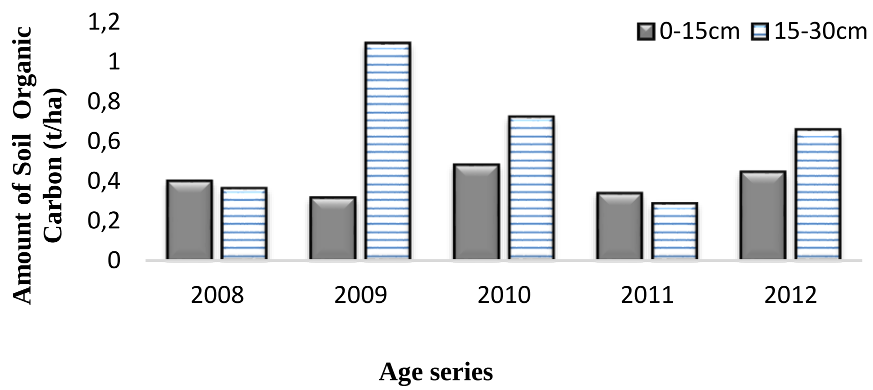

Figure 3. Soil organic carbon at depths 0-15cm and 15-30cm in the different age series in the study area.

3.5 Total carbon stock

Table 4 shows the total estimates of carbon stock in the teak plantation, comprising both the total soil organic carbon stock and tree carbon stock. For the total soil organic carbon stock, the estimates were 43.41 t, 182.91 t, 180.29 t, 98.17 t, and 134.51 t for the 15 years (2008), 14 years (2009), 13 years (2010), 12 years (2011), and 11 years (2012) age series, respectively. The total carbon stock of trees for each age series were 13,112.90 t, 47,105.50 t, 41,622 t, 33,974.80 t, and 15,396.40 t for 2008, 2009, 2010, 2011 and 2012 age series, respectively. The total carbon stock estimated across age series were 13,156.30 t, 47,288.40 t, 41,802.30 t, 34,073 t, and 15,530.90 t for the 15 years (2008), 14 years (2009), 13 years (2010), 12 years (2011), and 11 years (2012) age series, respectively. The gross total estimates of carbon stock in the plantation was 151,850.84 t (Table 4). The variation observed in carbon stock agrees with Chayaporn et al. (2021) who noted that the overall carbon stocks in standing trees strongly varied according to age and tree density that results from thinning treatments. Meshram *et al*. (2016) reported that the higher amount of carbon sequestration that was found in five teak trees among the nine teak trees sampled was attributed to higher above-ground biomass which was due to favorable soil conditions. Also, the tree biomass may be influenced by the level of some tree growth parameters such as age, height, basal area, stand density, diameters, and volume of trees. Adeyemi and Adeleke (2020) also noted that species differences and stand density significantly influenced the amount of carbon sequestered. Generally, the results also support that teak is one of the most important tree species in carbon sequestration as other studies have revealed.

Table 4. Total carbon stock estimation across age series in the study area.

Age series	Area (ha)	SOC (t Cha^{-1})	TCC (t Cha^{-1})	SOC (ton)	TCC (ton)	Total carbon stock (ton)
2008	57	0.7615	230.05	43.41	13,112.90	13,156.30
2009	130	1.4070	362.35	182.91	47,105.50	47,288.40
2010	150	1.2019	277.48	180.29	41,622.00	41,802.30
2011	157	0.6253	216.40	98.17	33,974.80	34,073.00
2012	122	1.1025	126.20	134.51	15,396.40	15,530.90
					TOTAL	**151,850.84**

Note: SOC = Soil organic carbon, TCC = Tree carbon content

3.6 Potential cash value

Table 5 shows the Potential Cash Value (PCV) of carbon stock for each age series, as well as the total estimate for the plantation. The tree carbon PCV per hectare was estimated at \$85,758.04, \$135,076.83, \$103,439, \$80,699.59 and \$47,044.84 for the 15 years (2008), 14 years (2009), 13 years (2010), 12 years (2011), and 11 years (2012) age series, respectively. For the soil organic carbon, PCV per hectare was estimated at \$283.87, \$524.50, \$448.05, \$233.10, and \$410.99 for the 15 years (2008), 14 years (2009), 13 years (2010), 12 years (2011), and 11 years (2012) age series, respectively. The total PCV for each of the age series were \$4,904,388.92, \$17,628,173.49, \$15,583,055.76, \$12,702,722.54 and \$5,789,610.79, respectively. The total PCV for the teak plantation was \$56,606,951.51 (Table 5). The estimated amount of PCV of carbon stock per hectare revealed that among the age series, 14 years (2009) had the highest (118,573.86 USD ha^{-1}). The estimate of PCV for the study is higher than the PCV of 34,654.95 USD ha^{-1} reported by Jantawong et al. (2022). It was valued at €55.98/ \$242.21 tC^{-1} in August 2021 compared to €94.05 / \$372.78 tC^{-1} in August 2023. Chayaporn et al. (2021) estimated that the teak plantation revenues from carbon-based incentives would be \$2,219 t Cha^{-1} every year. The dynamics of the carbon stock price in the EUA market allowances is generally influenced by higher emission carbons arising from higher energy demand. The price of the permits on the European Union's carbon market rose above €105/\$115 per tonne (\$420.03 tC^{-1}) for the first time at the beginning of 2023, which reflected the growing costs that factories, power plants, and other industries have to bear for their pollution emissions.

Table 5. Potential cash value estimation of carbon stock across age series in the study area.

Age series	Area (ha)	SOC (\$ t ha^{-1})	TCC (\$ t ha^{-1})	SOC (\$)	TCC (\$)	PCV (\$)
2008	57	283.87	85,758.04	16,180.7	4,888,208.22	4,904,388.92
2009	130	524.50	135,076.83	68,185.2	17,559,988.29	17,628,173.49
2010	150	448.05	103,439.0	67,206.6	15,515,849.16	15,583,055.76
2011	157	233.10	80,669.59	36,596.6	12,665,125.94	12,701,722.54
2012	122	410.99	47,044.84	50,140.8	5,739,469.99	5,789,610.79
					TOTAL	**56,606,951.51**

Note: PVC = Potential cash value; SOC = Soil organic carbon; TCC = Tree carbon content; \$ t $ha-^{1}$ = Dollars in tonnes per hectare

3.7 Correlation matrix for tree growth variables in the study area

The correlation matrix for tree growth variables in the study area is shown in Table 6. All the growth variables (and carbon stock) had significant and strong positive correlations with each other except Dm and THT which showed a moderate positive correlation (0.59). However, stem volume showed a perfect positive linear correlation with carbon which indicates that the two variables are in perfect sync with each other. The result is similar to the previous study of Amusa and Adedapo (2021) in the same study area. Similarly, Shamaki et al. (2011) reported a significant positive correlation between DBH, height, and volume in a Teak plantation in Nimbia Forest Reserve, Kaduna State, Nigeria.

Table 6. Correlation matrix for the tree growth variables in the study area.

	D_m	D_b	THT	DBH	BA	Volume	Carbon
D_m	1						
D_b	0.75	1					
THT	0.59	0.78	1				
DBH	0.89	0.82	0.68	1			
BA	0.91	0.79	0.63	0.98	1		
Volume	0.92	0.82	0.72	0.90	0.93	1	
Carbon	0.92	0.82	0.72	0.90	0.93	1	1

3.8 Multiple linear regression model

The regression model Y = -596.48 + 27.16 (THT) + 1238.34 (DBH) was fitted to predict tree carbon stock using total height and diameter at breast height as predictors. The model gave an adjusted R-square value of 82.7% and a significant p-value of 0.00 (p-value < 0.05). Given the regression coefficients (adjusted R^2 = 82.7%) and the strong positive correlation between the variables and carbon stock, the multiple regression model is a good fit and explains that tree height and diameter at breast height are good predictors of carbon stock. It also explains that about 82.7% of the total variation in carbon stock was explained by the equation. The result is similar to the findings of Kraenzel et al. (2002), which reported that 87.0% of the variation in the root biomass and carbon stock can be explained by the DBH of the trees. Contrarily, Simhadri et al. (2021) indicated no significant variations between the tree heights and carbon sequestered. Thus, the result of this study revealed that the tree height and DBH measurements could be used in determining the carbon biomass in future studies.

4 Conclusions

The study has revealed the carbon sequestration of the teak plantation at the University of Ilorin. It showed that the trees accumulated a significant amount of biomass across five age series which yielded the tree carbon stock of 151,211.60 t. The trees of the 2009 age series had the highest carbon stock while 2012 had the lowest. It was also discovered that the tree growth variables of the 2009 age series such as the diameters, heights, and volumes were slightly higher than other age series which influenced the higher estimates of its biomass and carbon stock. The same trend was observed in the soil carbon stock, with the highest carbon stock recorded in 2009. A total of 639.29 tons of soil carbon was estimated. The total carbon stock was 151,850.84 tons. Furthermore, the potential cash value of the total carbon stock across the different age series was estimated to be valued at $56,606,951.50. The study further showed the positive correlation between the tree growth variables and the carbon stock in which a multiple linear regression equation was fitted to establish the relationship. The study provided relevant information and insight on the contribution of the teak plantation in reducing the amount of greenhouse gases in the atmosphere, thereby assisting in the mitigation of the impacts of climate change.

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