Carbon Sequestration and Linear Models for Individual Tree Biomass Estimation in Bebi Mixed Forest Plantation, Cross River State, Nigeria.

Abstract:

This research was conducted to develop allometric models for estimating aboveground biomass for *Tectona grandis* and *Gmelina arborea*in Bebi Mixed Plantation, Cross River State, Nigeria. Simple random sampling technique was used to lay a total of twenty sample plots; six sample plots for *Gmelinaarborea*and fourteen sample plots for *Tectona grandis*.A total of 606 individual tree species were measured for total height and diameter at breast height (DBH). DBH, total height and specific wood density of each tree species were fitted into allometric equations to determine the green aboveground biomass of each tree species. Conversion factors were then applied to determine stands level green biomass, dry biomass, carbon sequestered and carbon-dioxide (Co_2) emission in the forest. SPSS software version 2.4.1 was used for data analysis. Simple linear regressions of both logarithmic and non-logarithmic models were fitted into the green biomass and growth data (diameter at breast height, tree total height and specific wood density). For *Gmelinaarborea,* mean diameter at breast height, total height and aboveground biomass of 25.2 cm, 11.1m and 40.3kg respectively were obtained. Mean basal area of $18.6m^2ha^{-1}$ was obtained with a mean volume of $40.2629m^3ha^{-1}$. The mean stand level green biomass was determined to be 96.65777 tons/ha^{-1} while mean dry stand level dry biomass was 70.07686 $tonha^{-1}$ and stand level means of carbon stock and carbon-dioxide emission were 35.03843 $tonha^{-1}$and 128.5911 $tonha^{-1}$ respectively. Meanwhile, for *Tectona grandis,* mean diameter at breast height, total height and aboveground biomass of 16.4 cm and 13.8 m and 35.8kg respectively were obtained. Mean basal area of $25.61m^2ha^{-1}$ was obtained with a mean volume of $64.1082m^3ha^{-1}$. The mean stand level green biomass was determined to be 108.4855 ton/ha^{-1} while mean dry stand level dry biomass was 78.6519 $tonha^{-1}$ and stand level means of carbon stock and carbon-dioxide emission were 39.3259 $tonha^{-1}$and 144.3264$tonha^{-1}$ respectively. The developed models were correspondingly validated according to the two tree species. Estimated biases of 2.92367% and 1.65306% for *Gmelinaarborea*and *Tectona grandis*respectively were observed which implies that the model derived can be used to predict green biomass in the study area without any adjustment.

Keywords: Models, Systematic sampling, biomass, Allometric equations and Mixed plantation

INTRODUCTION

Carbon management is a serious concern confronting the world today. Since the beginning of the industrial revolution, carbon dioxide (CO_2) concentration in the atmosphere has been rising alarmingly; ranging from 270ppm prior to the industrial revolution to about 394ppm in December, 2012 (Mauna Loa Observatory, 2013). Furthermore, human activities cause climate change and this often happens when we send gases in greater quantity than required into the atmosphere through activities like cutting down forest, bush burning, manufacturing, driving and use of some house hold equipment. These gases are many and together they are ‘green house gases. The most dangerous of them all is carbon; and when so much of it is released through these various human activities into the atmosphere, it interacts with the sun and increases the earth’s temperature to create ‘global warming’. Climate change worsens as the earth’s temperature increases (UN-REDD, 2012).

Climate change is a condition where the weather has been altered or changed over a long period of time. When this has occurred, it becomes difficult to predict seasons and heat becomes too little or too high and can ultimately affect how crops produce. Forest and forest soils store a lot of carbon more than the amount of carbon found in the atmosphere. In their natural state, primary forest especially absorbs and store carbon from the atmosphere. This means that forest acts as ‘carbon sink’. By taking carbon from the atmosphere, forests help to control weather conditions and prevent the earth from heating up. However, when people cut down forests, the carbon that is stored in the forest will be released into the atmosphere to combine with heat from the sun and warm up the earth thereby increasing the earth’s atmosphere. As the increase of carbon in the atmosphere increases the earth’s atmosphere, it changes the normal weather conditions that human beings usually experience and begins to create unusual weather conditions that in longer term will alter the earth’s climate. Apart from absorbing carbon, forest also maintain cloud cover, reflect sunlight back out of the atmosphere, encourage the transformation from water to vapour which cools the air and creates rainfall (UN-REDD, 2012).

FAO (2005), defined biomass as the organic material both above and below the ground, and both living and dead, e.g., trees, grasses, tree liters, roots etc. Aboveground biomass, belowground biomass, dead wood, liter, and soil organic matter are the main carbon pools in any forest ecosystem (FAO, 2005; IPCC, 2003; IPCC, 2006).Above-ground biomass(AGB) includes all living biomass above the soil, while below-ground biomass (BGB) includes all biomass of live roots excluding fine roots (<2mm diameter). Forest biomass is measured either in terms of fresh weight or dry weight. For the purpose of carbon estimation, dry weight is preferred as dry biomass roughly contains 50% carbon (Brown, 1997; IPCC, 2003). Majority of biomass assessment are done for aboveground of trees because these generally account for the greatest fraction of total living biomass in a forest and do not pose too many logistical problems in the field measurement (Brown, 1997). Biomass assessment is important for national development planning as well as for scientific studies of ecosystem productivity, carbon budgets, etc. (Parresol 1999; Zheng *et al.,* 2004; Zianis&Mencuccini 2004, Pandey *et al.,* 2010). Biomass analysis is an important element in the carbon cycle especially, carbon sequestration. Recently, biomass is increasingly used to help quantify pools and fluxes of greenhouse gases (GHG) from terrestrial biosphere associated with land use and land cover changes (Cairns *et al.,* 2003). The importance of terrestrial vegetation and soil as significant sinks of atmospheric CO_2 and its other derivatives is highlighted under Kyoto Protocol (Wani *et al.*, 2010). Therefore, estimating aboveground biomass is a critical step to quantify and monitor changes in the tropical forests and plantations.

METHODOLOGY

Study Area

The study was carried out in Bebi Mixed Plantation, Cross River State, Nigeria. The plantation was established in 1972 covering an area of fifty four (54) hectares, comprising *of Pinus caribaea*(planted in 1972), *Tectona grandis* (planted in 1973) *and Gmelina arborea*, (planted in 1978), *and* managed by the Cross River State Forestry Commission. The plantation falls along Latitude 6^0 32`N $9^0$ 16`E and Longitude 6.5^0 33'N 9.267'E (http://www.bioone.org/doi/full/10.1896/1-881173-82-8.17). The climate of the area is comparatively cold, experiencing a semi-temperate climate, with temperatures going between 26 °C to 32 °C during the dry season of November to January. The rainy season in June to September with temperature as low as between 4 °C to 10 °C (Obudu Cattle Ranch Info,2011).Due to the high level of human activities in the plantation, the population of pine stands is scanty, therefore, the research only concentrated on Teak and Gmelina.

Sampling Technique and Data Collection

Simple random sampling technique was used to lay a total of twenty sample plots; six sample plots for *Gmelinaarborea*and fourteen sample plots for *Tectona grandis*. Diameter tape and Sunto clinometers were used for diameter and height measurements respectively. Diameter at breast height (10.5cm above ground) and tree total height were measured for all trees across plot and species. Density of each of the tree measured was determined from the default values of the Pan tropical table (Chudoff, 1984) and wood density for tropical tree species (Gisel *et al*, 1992). The obtained values were used to estimate the biomass of each tree within the sample plots in the plantation (Ajayi and Adie, 2018; Bassey and Ajayi, 2020).

DATA ANALYSIS

Basal Area Estimation

The diameter at breast height was used to calculate the basal area.

$$\text{Basal Area}(BA) = \frac{\pi D^2}{4} \qquad \text{eq.1}$$

where: D = diameter at breast height (cm)

π = 3.142

BA = Basal Area.

Volume Estimation

Individual tree volume was estimated using the regression model below:

$LnV = -8.2525 + 2.209 LnD$ (Bassey and Ajayi, 2021) eq2

Where, V= Tree volume (m^3)

D= Diameter at breast height (cm)

Ln = natural log

Aboveground Live Green Biomass Estimation per Hectare

To estimate the above-ground live biomass, the equation of Brown (1997) for tropical wet climate zone was adopted. The equation is given as

$$Y = 21.297 - 6.952(D) + 0.740(D^2) \qquad eq3$$

Where; Y = biomass per tree in kg and D = diameter at breast height (dbh) in cm.

The summation of the biomass calculated for all trees in a sample produced the total plot biomass (AGBplot). This per plot estimate of aboveground (in kg) was divided by 1000 to express it in metric tons. This was then converted to per hectare estimate (AGBha) by using the equation

$$AGBper\ ha = \left(\frac{Ah}{Ap}\right) \times AGBplot \qquad eq.4$$

where: AGBha= aboveground biomass (metric tons per hectare)

Ah= area of one hectar in m^2

Ap= area of the plot (m^2)

Aboveground Dry Biomass Estimation

Aboveground dry biomass estimation was calculated from:

$$W = \frac{AGBh \times 0.725}{1000} \qquad eq.5$$

where W= aboveground dry biomass (metric tones)

AGB_h = aboveground green biomass (kg ha^{-1})

Estimation of Carbon-dioxide equivalent from Carbon Stock

The content of carbon in woody biomass of any forest is generally 50% of the tree total volume. Hence, to compute the weight of carbon stock in a tree was obtained by multiplying the dry weight of the tree by 50% (Eneji*et al.*, 2014). Therefore the equation for the measurement of carbon sequestered per hectare is given as:

$$Sc = W \times 0.5 \qquad eq. 6$$

where; Sc = sequestered carbon (tha^{-1})

W= aboveground dry biomass ($t\ ha^{-1}$)

Biomass Model Formulation for the Two Species

Log and non-log equations for the two tree species advanced for screening include:

i. $Y = \alpha + \beta DBH^2$
ii. $Y = \alpha + \beta_1 DBH^2 + \beta_2 H$
iii. $LogY = \alpha + \beta logDBH^2$
iv. $LogY = \alpha + \beta_1 logDBH^2 + \beta_2 logH$
v. $LogY = \alpha + \beta logDBH^2 * H$
vi. $LogY = \alpha + \beta logDBH^2 + \beta_2 H$
vii. $Y = \alpha + \beta logDBH^2 + \beta_2 6H$
viii. $LogY = \alpha + \beta logDBH^2 * WD$
ix. $LogY = \alpha + \beta logDBH^2 * H * WD$

Where: α, β, β_1, β_2 and β_3 are the regression coefficients

Y= Aboveground biomass (kg)

DBH = diameter at breast height

H = total height

WD = specific wood density.

Criteria for Model Selection

Five indicators were considered for the assessment of goodness of fit of individual equationfitted:

i. a goodness of fit with high coefficient of determination (R^2)
ii. significant variable ratio (F) at 5% probability level
iii. Standard error of parameter estimate of the predictor variables
iv. Least Root mean square error
v. High Durbin-Watson value.
vi. **Biomass Model Validation**

Paired T-test and test of bias were carried out on the errors associated with the final prediction to test for model validity.

Null (H0) = paired observations are not different

Alternative (H1) = paired observations are different

$$t = \frac{\overline{D}}{SD/\sqrt{n}}$$

where: T= t-statistics

$\overline{D}$= mean of the difference between pairs (ton)

SD= standard deviation of the difference between pairs (ton)

n= number of paired observation (degree of freedom is n-1)

$$Bias = \frac{\sum residual}{\sum Actual\ observation} \times \frac{100}{1}$$

RESULTS

Parameters of Aboveground Biomass in Bebi Mixed Plantation

The result presented in Table 1 indicates that a total of 606 individual tree species were measured for both diameter at breast height (DBH) and tree total height in the mixed plantation. An average dbh of 16.4cm and 25.2cm were respectively measured for *Tectona grandis* and *Gmelina arborea*. Average total heights of 13.8cm and 11.1 were obtained respectively for *Tectona grandis* and *Gmelina arborea*, however, average aboveground biomass of 40.3kg and 35.8kg was obtained for *Gmelina arborea* and *Tectona grandis* respectively. While mean basal area for *Tectona grandis* was 25.61m^2ha^{-1} and 18.56m^2ha^{-1} for *Gmelina arborea*. The mean volume for *Tectona grandis* was 64.1082 m^3ha^{-1};while mean volume for *Gmelina arborea* was 40.2629 m^3ha^{-1} in the Bebi Mixed Plantation.

Table 1: Parameters of Tree Volume and Aboveground Biomass in Bebi Mixed Plantation

S/N	Parameters	*Tectona grandis*	*Gmelina arborea*
1	No. of sample plots measured	14	6
2	No of trees measured	442	164
3	Average DBH (cm)	16.4	25.2
4	Average height (m)	13.8	11.1

5	Mean biomass (kg)	35.8	40.3
6	Mean basal area (m^2ha^{-1})	25.61	18.56
7	Mean volume (M^3ha^{-1})	64.1082	40.2629
8	Sampling intensity 0.3%		

Biomass and Carbon Stock for *Gmelina arborea* in Bebi Mixed Plantation

Results in Table 2 show volume, aboveground green and dry biomasses, and carbon stock and carbon emission per stand for *Gmelina arborea* in Bebi Mixed Plantation of Cross River State, Nigeria. Stand aboveground green biomass ranged from 85.8527t ha^{-1} to 105.691 t ha^{-1}, dry biomass ranged from 62.2432t ha^{-1} to 76.62612 t ha^{-1}, carbon stock range from 31.1216 t ha^{-1} to 38.31306t ha^{-1} and carbon-dioxide emission ranged from 114.2163 t $ha^{-1}$to 140.6089 t ha^{-1}. Meanwhile, stand basal area ranged from 15.2475m^2ha^{-1} to 18.7464m^2ha^{-1} while volume ranged from 30.7022 m^3 $ha^{-1}$to 52.6059m^3ha^{-1}. Also, number of stem per hectare ranged from 271.493 Nha^{-1} to 475.113 Nha^{-1}.

Table 2: Biomass and Carbon Stock for *Gmelina arborea* in Bebi Mixed Plantation

S/N	Number of stem per hectare (N ha^{-1})	Basal Area (M^2ha^{-1})	Volume (M^3ha^{-1})	Green Biomass (ton ha^{-1})	Dry Biomass (ton ha^{-1})	Carbon Stock (ton ha^{-1})	Carbondioxide emission (ton ha^{-1})
1	407.24	17.2458	40.6267	85.8527	62.2432	31.1216	114.2163
2	452.489	20.8659	52.6059	102.113	74.03164	37.01582	135.8481
3	271.493	15.2475	30.7022	96.2393	69.77351	34.88676	128.0344
4	294.118	15.9584	30.823	91.713	66.49193	33.24597	122.0127
5	475.113	18.7464	45.5234	98.3376	71.29477	35.64739	130.8259
6	429.864	17.3258	41.2963	105.691	76.62612	38.31306	140.6089
Total	2330.31	105.389	241.577	579.9466	420.4612	210.2306	771.5463
Average	388.386	17.5649	40.2629	96.65777	70.07686	35.03843	128.5911

Fitted Models for Biomass Estimation of *Gmelina arborea* in Bebi Mixed Plantation

The results in Table 3 show a linear regression analysis used in developing allometric models for estimating *Gmelina arborea*biomass in the study area using basal area, specific wood density, tree total height and their logarithmic transformations as predictor variables. Model 1 was judged best and selected for biomass estimation because it has the highest F-ratio value (17878.037),) highest Durbin Watson value (1.297) with R^2 value of 99% , R^2_a value of value of 99% and a very low standard error of estimate (0.001378). Ranked very closely was model 2 with R^2 value of 99% and F-ratio value of 14015.132.

Table 3: Fitted Models for Biomass Estimation of *Gmelina arborea* in Bebi Mixed Plantation

S/N	Models	R^2	Adjusted R^2	F-ratio	Durbin Watsin	SEE	Remark
1	$Y = 0.002 + 0.383DBH^2$	0.99	17878.037	0.99	1.297	0.001378	Selected
2	$Y = 0.008 + 0.369DBH^2 + 0.001H$	0.99	14015.132	0.99	1.270	0.001102	Suitable
3	$LogY = 0.394 + 2.096log DBH^2$	0.76	532.422	0.76	1.935	0.18550	Suitable
4	$LogY = 1.761 + 1.272log DBH^2 - 1.7681 DBH^2$	0.92	957.815	0.92	1.134	0.10727	Suitable
5	$LogY = 0.240 + 0.106 logDBH^2 * H$	0.69	375.730	0.69	1.258	0.21080	Suitable
6	$LogY = -1.216 + 0.109log DBH^2 + 0.101H$	0.85	457.356	0.84	1.406	0.14904	Suitable
7	$Y = 0.005 + 0.004log DBH^2 * H$	0.88	622.902	0.88	1.729	0.004938	Suitable
8	$LogY = -2.290 + 18.028DBH^2 * WD$	0.66	323.774	0.66	1.779	0.22179	Suitable
9	$LogY = -2.249 + 1.391log DBH^2 * H * WD$	0.64	291.575	0.64	1.800	0.22952	Suitable

T-calculated = 0.0920, T-tabulated = 0.690, Bias = 2.92367%

However, 30% *Gmelina arborea*field data set aside for its model validation. Paired T-test was used to validate the model by comparing the actual green biomass and predicted biomass. The equation selected recorded non-significant difference (P>0.05) with the actual biomass computed from the field. Again, with a low estimated bias of 2.9236%, the selected model can be used to predict *Gmelina arborea*biomass in the mixed plantation.

Fitted Models for Biomass Estimation of *Tectona grandis*in Bebi Mixed Plantation

Result in Table 5 shows volume, aboveground green and dry biomasses, and carbon stock and carbon emission per stand for *Tectona grandis*in Bebi Mixed Plantation of Cross River State, Nigeria. Stand aboveground green biomass ranged from 55.4716t ha^{-1} to 172.9464 t ha^{-1}, dry biomass ranged from 40.21691t ha^{-1} to 125.3861t ha^{-1}, carbon stock range from 20.10846t ha^{-1} to 62.69307t ha^{-1} and carbon-dioxide emission ranged from 62.69307t ha^{-1}to 230.0836 t ha^{-1}. Meanwhile, stand basal area ranged from 15.2475m^{2}ha^{-1} to 45.5301m^{2}ha^{-1} while volume ranged from 30.7022 m^{3} ha^{-1}to102.8329 m^{3} ha^{-1} and number of stem per hectare ranged from 271.4932Nha^{-1} to 1199.0950Nha^{-1} with a mean number of stem of 714.2856 Nha^{-1}.

Table 4: Biomass and Carbon Stock for *Tectona grandis* in Bebi Mixed Plantation

S/N	Number of stem per hectare (N ha^{-1})	Basal Area (M^{2}ha^{-1})	Volume (M^{3}ha^{-1})	Green Biomass (ton ha^{-1})	Dry Biomass (ton ha^{-1})	Carbon Stock (ton ha^{-1})	Carbondioxide emission (ton ha^{-1})
1	407.2398	17.2458	40.6267	76.8635	55.72604	27.86302	102.2573
2	452.4886	20.8659	52.6059	88.6251	64.2532	32.1266	117.9046
3	271.4932	15.2475	30.7022	55.4716	40.21691	20.10846	73.79803
4	294.1176	15.9584	30.8230	58.7241	42.57497	21.28749	78.12507
5	475.1131	18.7464	45.5234	89.7363	65.05882	32.52941	119.3829
6	429.8642	17.3258	41.2963	80.7621	58.55252	29.27626	107.4439
7	1108.5972	33.6186	82.5416	167.964	121.7739	60.88695	223.4551
8	859.7285	23.7201	65.9564	122.4352	88.76552	44.38276	162.8847
9	1199.0950	35.7320	125.8612	172.9464	125.3861	62.69307	230.0836
10	746.6063	32.3258	64.9048	109.6351	79.48545	39.74272	145.8558
11	1131.221	45.5301	102.8329	160.284	116.2059	58.10295	213.2378
12	837.1040	26.4188	55.9751	91.0258	65.99371	32.99685	121.0984

13	859.7285	27.2718	68.1951	115.8016	83.95616	41.97808	154.0596
14	927.6018	28.5427	89.6702	128.5221	93.17852	46.58926	170.9826
Total	9999.999	358.5497	897.5148	1518.797	1101.128	550.5639	2020.569
Average	714.2856	25.6106	64.1082	108.4855	78.6519	39.3259	144.3264

Fitted Models for Biomass Estimation of *Tectona grandis*in Bebi Mixed Plantation

The result in Table 6 shows a linear regression analysis used in developing allometric models for estimating *Tectona grandis* biomass in the study area using basal area, specific wood density, tree total height and their logarithmic transformations as predictor variables. Model 3 was judged best and selected for biomass estimation because it has the highest F-ratio value (21515.867), highest Durbin Watson value (0.938) with R^2 value of 98% R^2_a value of value of 98% and a very low standard error of estimate (0.05036). Ranked very closely was model 4 with R^2 value of 98% and F-ratio value of 12926.178.

Table 5: Fitted Models for Biomass Estimation of *Tectona grandis*in Bebi Mixed Plantation

S/N	Models	R^2	Adjusted R^2	F-ratio	Durbin Watsin	SEE	Remark
1	Y = -0.001 + 0.457DBH^2	1.000	1.000	27840.01	1.363	0.00126	Unsuitable
2	Y = -0.008 + 0.457DBH^2 + 0.001H	1.000	1.000	24277.60	1.601	0.00096	Unsuitable
3	LogY = -0.258 + 1.093 logDBH^2	0.98	0.98	21515.867	0.938	0.05036	Selected
4	LogY = -0.168 + 1.147logDBH^2- 0.001DBH^2	0.98	0.98	12926.178	0.957	0.04602	Suitable
5	LogY = -0.827 + 0.74 logDBH^2 *H	0.44	0.44	355.067	0.911	0.26463	Unsuitable
6	LogY= -0.876 + 0.996 logDBH^2 + 0.045H	1.000	1.000	975502.976	1.153	0.00534	Unsuitable
7	Y= 38.878 + 2.294 logDBH^2*H	0.53	0.52	496.696	1.743	6.89665	Suitable

8	LogY = 0.000+ 1.093log DBH^2 *WD	0.98	0.98	21515.867	0.938	0.05036	Suitable
9	LogY = -0.827 + 0.074log DBH^2*H * WD	0.44	355.037	0.44	0.911	0.26463	Unsuitable

T-calculated = 0.0871, T-tabulated = 1. 166, Bias = 1.65306%

Similarly, 30% *Tectona grandis*field data was set aside for its model validation. Paired T-test was used to validate the model by comparing the actual green biomass and predicted biomass.The equation selected recorded non-significant difference (P>0.05) with the actual biomass computed from the field. Again, with a low estimated bias of 1.65306%, the selected model can be used to predict *Tectona grandis*biomass in the mixed plantation.

Discussion

The observed stocking density of 388.386N ha^{-1} and 927.6018N ha^{-1} for *Gmelinaarborea*and *Tectona grandis* respectively in the Bebi mixed Plantation is very low considering the age range of 40-50years. This is in contrast with the findings (1068) by Ajayi and Adie (2018) for a Teak Mono-Plantation**,** Cross River State. The low stocking density can be attributed to the fact that both stands perhaps were not properly stocked during the plantation establishment and/or due to poor plantation management. Secondly, it reflects very high level of encroachment level into the plantation which calls for urgent management attention. The biomass estimates recorded for both species stands is also very low. The low biomass yield of 96.65777 t ha^{-1} and 108.4855 t ha^{-1} for *Gmelinaarborea*and *Tectona grandis* respectively could be due to low nutrient of the site. This finding also agrees with that of Nwoboshi (2000), who noted that soil types to a great extent determines the growth of trees and detect the type of management required for optimum performance. This result further agrees with the findings of Kannan and Pailiwall (1997) who reported that soil nutrients increased tree growth and performance of *Senna siamea*.

Average dbh of 11.1cm and 18.8cm for *Gmelina arborea* and *Tectona grandis* respectively in this plantation reflected a degree of poor plantation management and to a great extent the inability of the soil to support the tree species since this result is completely at variance with reports of other authors Kannan and Pailiwall (1997). There is urgent need to enrich the stands for optimal utilization of the land resources. This agrees with the report made by (Mishra *et. al*., 2004) that the potential of degraded rainforests including plantation forests to recover from degradation can therefore be enhanced through enrichment planting. However, the stand volume of 40.2629 m^3 ha^{-1} and 64.1082m^3ha^{-1} for *Gmelina arborea* and *Tectona grandis* respectively are way too far to that recommended by Dianyuan Han (2012) as normal for tropical high forest (250m^3ha^{-1}). This shortfall could be as a result of poor stocking, encroachment and/or poor management practices. Therefore, effort should be made to improve the current density and productivity through good management approach such as enrichment planting. This will guarantee steady forest cover for wood production for construction and fuel wood supply, environmental protection and carbon trade.

The selected aboveground biomass models for both species recorded a non-significant difference (P>0.05) with the actual biomass computed from the field, hence, the models are adequate for estimating aboveground biomass in the study area as stated by (Ajayi and Adie, (2018) and Bassey and Ajayi,(2021). The results showed that model with diameter at breast height as the predictive variable gave the best model. This confirms the claim by many authors that considering the sources of error in height measurement, it is necessary to develop volume estimation models using a variable such as DBH which can be accurately measured in the field. Ketterings*et al.,* (2001) also supported the claim that height measurement can be tedious and might not explain more of the variance. By implication therefore, diameter at breast height and its logarithmic form can be judged to be a good predictor variable for aboveground biomass estimation of both species. The percentage biases for the selected models (2.92367% and 1.5630% for *Gmelina arborea* and *Tectona grandis* respectively) agree with the findings of Adekunle (2002) who reported that the percentage bias as low as 30% is an indication of good fit model.

Conclusion

The principal element for the estimation of forest's carbon stocks is the estimation of forest biomass. Forest biomass estimation is also needed for the sustainable planning of forest resources. The study has provided estimates of above-ground biomass for the different species in the Bebi Mixed Plantation. This is useful for wood productivity studies, forest conservation and carbon trade. Estimation of forest carbon stocks will enable the assessment of the amount of carbon loss during deforestation or the amount of carbon that the mixed plantation can store when such forests are regenerated.

Furthermore, remarkable development of models remains a valuable tool on policy, monitoring and supply systems as interventions in combating the challenges of climate issues in the study area. The effectiveness of reducing emissions depends greatly on the formulation of accurate models for proper management of the forest ecosystem. Therefore, models developed in the study area for the estimation of aboveground biomass will significantly enhance the capacity to accurately estimate aboveground biomass without destructive harvest.

Recommendations

Based on the findings of this study, the following recommendations were made:

i. Ensure effective monitoring and actions to reduce encroachment and negative impacts on the forest cover.

ii. The plantation should be restocked according to the required stocking density of both species to ensure efficient utilization of the land resources.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

We hereby state that NO generative AI tools, including text-to-image generators and large language models (ChatGPT, COPILOT, etc.), were used in the development or editing of this paper.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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