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Establishing Allometric Relationships Using Crown Diameter for Estimating Above Ground Combustible Fuels in Southern Nigerian Mangrove Vegetations

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Abstract– **Allometric equations, which predicts the above ground dry combustible fuels of a tree from its Diameter at Breast Height (DBH), are needed to estimate wildfire behavior in southern Nigerian Mangrove vegetations. Although several biomass equations have been developed for different vegetations, but none could fit in for the estimation of crown combustible fuels in southern Nigerian mangroves. In previous studies, we have tried estimating wildfire behaviour, but saw that our predictions will depend on estimating the above ground biomass of combustible fuels. To achieve this aim, we measured the above ground biomass of 20 sample trees belonging to three species of Rhizophora's (Rhizophora Mangal, Rhizophora Harrizoni, and Rhizophora Racemosa) which are the species that dominates the lower Niger Mangrove Vegetations in southern Nigeria. Using the data collected, we developed specific biomass equations which can aid in estimating the above ground combustible fuels in southern Nigeria mangroves. This study was conducted during the peak of the region's dry seasonal period (December – February), which usually is the period of devastating wildfires and the equations developed are within 96% accuracy because it aided in predicting the behaviour, and attacking / suppression of the January 13th – 15th wildfire that occurred in the region.**

Keywords – **Allometric Equations, Crown Combustible Fuels, Mangrove Vegetations, Southern Nigeria and Wildfires**

I. INTRODUCTION

Mangrove wildfires in southern Nigeria represent one of the most catastrophic situations for wildfires in Nigeria. They involve biannual vegetation with very high energy release when compared to other wildfires. Its crown fires affect all of the vegetation strata with a very high energy release rate, which is much larger than a surface fire in a grass land.

However, these devastating wild mangrove fires usually occur during the peak of the region's dry season (December-February). Because of its devastating nature, a reliable technique to predict its behaviour in order to ensure proper attack and suppression was needed. This has been achieved via previous models that have been modified and validated to suit the nature of wildfires in Southern Nigeria. These fires originate from the surface fuels which are usually very dry with moisture content less than 10% and with its crown characteristics. It is often characterized with very large rate of spread (ROS) and is usually subject to certain variations in flame length or rate of spread resulting from wind gusts.

These mangrove forests are characterized by three Rhizophora species of plants (Rhizophora Racemosa, Rhizophora Harrizoni and Rhizophora Mangal) on a flat and slopy terrain, for which the conditions of propagation are quite reproducible. The area in the region which houses the larger part of these mangrove vegetations is the home to a large population of people (farmers, Fishermen, Civil servants) living mainly in small villages and camps scattered along the banks of the rivers and creeks and are interconnected by wooden bridges. In between these mangrove swamps are earth ponds which are of ecological and economic importance to the people. These ponds sometimes dry up when the vegetation surrounding them experiences wildfire, thereby bringing hunger and hardship to the people.

It is usually during the peak of the longer dry season between early December and late February that the regions mangrove vegetations experience this uncontrollable wildfire. These wildfires are caused mainly by Nomadic Farmers crop farmers, Hunters and Honey collectors who usually set mangrove twigs on fire to drive away honey bees with the smoke.

Because of the devastating effects these uncontrolled wildfires have on the regions ecosystem (mangrove vegetations), it is of paramount importance that reliable techniques which will aid in estimating crown combustible fuels to predict wildfire propagation in these mangroves be developed. This is the aim of this research.

II. STUDY AREA AND SITE DESCRIPTIONS

The study area is located in Ndokwa East Local Government Area of Delta State, Nigeria, coordinates 5.30^{o}N to 6.00^{0}E, Tidal height (< 1m to > 4m), the climate is of warm temperature in both arid and wet regions. The annual rainfall totals vary from 2400 to over 4000 millimeters(Feller et al,2000).The forest is characterized by three(3) species of Rhizophora's, which are Rhizophora Harrizoni, Rhizophora Mangal and Rhizophora Racemosa. Fig. 1 and Fig. 2 describe the study area and nature of the site. Fig. 3 shows the Arial view showing Geographic coordinates of the study area, lower Niger mangrove forest, river Niger & some revering villages *(Captured using Google Earth).*

In this study, we have established common allometric relationships for the weight of mangrove trees (Rhizophora species) in south – south Nigerian Mangrove forest. We also discussed the physical aspects of the common allometric relationships, and proposed common equations for estimating mangrove tree Dry leaf biomass (W_{LF}), Dry Branch Biomass (W_{BR}) and Dry Stem Biomass (W_{ST}).

III. SAMPLE COLLECTION AND PROCESSING

Twenty (20) samples of the three (3) mangrove species in the study area were collected. Individuals with straight trunks that showed no obvious signs of damage were chosen. Stunted, dwarfed, or multi – stemmed specimens were not included in the collected samples because they may have different allometric relations (Clough et al 1997). After each sample was collected, its Diameter at Breast Height (DBH) was measured above the surface for the Rhizophora's. Each specimen was cut at ground level and the total stem height was measured. All above-ground biomass was harvested and separated into 3 components: Leaves, Branches and Stem. We measured these components in the field using spring scale of appropriate size to get the Wet – Weight Biomass. They were then left in the field for 7days so that they could lose their moisture content to a reasonable extent before they were taken to the laboratory and dried using standard drying oven and re-weighed to get the Dry – Weight Biomass for the leaves, branches and stems as shown in Table 1. The Table 3, Table 4 and Table 5 show the obtained values for the three Rhizophora species.

A) Moisture Content (µ)

From Table 1, the average moisture content (µ) was obtained thus:

$\mu = W_{\text{FRESH SAMPLE}} / W_{\text{WET SAMPLE}}$ (Ebuy et al 2008).

In estimating the average moisture content (**µ**), we made use of the values obtained from the branches and the leaves. This is because they were observed to have great effect on rate of fire spread. We neglected that of the stem because the stem's moisture content hardly influences crown rate of spread.

$\sum \mu_{\text{leaves}} = 11.10$ while,

$\sum \mu_{\text{branches}} = 14.23$

The average moisture content for the field was calculated thus**;**

$$\sum \mu_{\text{leaves}} + \sum \mu_{\text{branches}} \div (N_{\text{R.SPP}}) \qquad 1$$

$$\mu_T = 11.10 + 14.23 \div 3 = 8$$

where $N_{\text{R.SPP}}$ is the number of Rhizophora species used in developing the Allometric equation.

B) The Allomertric Models

Using the data from the 20 samples of Rhizophora trees, the allometric relationships for W_{LF}, W_{BR} , and W_{ST} (kg) were examined with the variables of Diameter at Breast Height (DBH) (m). Statistical analysis was undertaken using statistical product and service solutions (SPSS). The coefficients of regression R^2 for each of the Allometric equations were obtained after mathematical analysis of 'The Line of Regression' as shown:

The line of regression of W_L on DBH mathematically is expressed thus:

$$W_{LF} = a_1\, DBH + a_0 \qquad 2$$

$a_{1\,=}$ coefficient of regression on DBH

but; $\overline{DBH} = \frac{\sum DBH}{N}$ & $\bar{W}L = \frac{\sum WL}{N}$

Equation (2) when summed gives:

$$\sum W_{LF} = a_0 N + a_1 NDBH \qquad 3$$

Multiplying equation (2) by DBH & summing both sides gives

$$\sum DBH.W_{LF} = a_0 \sum DBH + a_1 \sum DBH^2 \qquad 4$$

Solving equations (3) & (4) gives

$$a_1 = \frac{\sum DBH.WL - N\,\overline{DBH}\;.\overline{WL}}{\sum DBH^2 - N\;\overline{DBH}^2} \qquad 5$$

The regression of DBH on $W_{L\,F}$ gives :

$$DBH = b_1\, W_{LF} + b_0 \qquad 6$$

$$\therefore b_1 = \frac{\sum WLF * DBH - N\,(\overline{DBH}\,.\overline{WLF})}{\sum WLF^2 - N\,(.\overline{WLF})^2} \qquad 7$$

For the regression of W_{ST} on DBH

$$W_{ST} = a_1 DBH + a_0 \qquad 8$$

Following similar steps as described above

$$a_1 = \frac{\sum DBH * WST - N\,\overline{DBH}\;.\overline{WLF}}{\sum DBH^2 - N(\,\overline{DBH^2})} \qquad 9$$

The regression on DBH on W_{ST} gives:

$$\sum DBH\,.\,W_{ST} = b_0 \sum W_{ST} + b_1 \sum W_{ST}^{\;2}$$

So that $b_1 = \frac{\sum WST\ DBH - N\,\overline{DBH}\;.\overline{WLF}}{\sum WST^2 - N\;\overline{(WLF)}^2}$ $\qquad 10$

For the regression of W_{BR} on DBH

$$W_{BR} = a_1\, DBH + a_0 \qquad 11$$

So that:

$$a_1 = \frac{\sum DBH.WBR - N\,\overline{DBH}\;.\overline{WLF}}{\sum DBH^2 - N\;\overline{DBH}^2} \qquad 12$$

while,

$$\sum DBH \,.\, W_{BR} = b_0 \sum W_{BR} + b_1 \sum W_{BR}{}^{2}$$

$$\text{So that: } b_1 = \frac{\sum WS\ DBH\ - N\ \overline{DBH}\ .\overline{WLF}}{\sum WH^2 - N\ \ (\overline{WBR})^2} \qquad 13$$

The coefficient of linear correlation (R^2) which is the relationship between the coefficient of regression of W_{LF} on DBH & that of DBH on W_{LF}, W_{ST} on DBH & DBH on W_{ST}, W_{BR} on DBH & DBH on W_{BR} was assumed between pairs of random variables of W_{LF}, W_{BR}, W_{ST} & DBH.

If (W_{LF1}, DBH_1) $_{....}$(W_{LFn}, DBH_n); (W_{ST1}, DBH_1) $_{....}$(W_{STn}, DBH_n); (W_{BR1}, DBH_1) $_{....}$(W_{BRn}, DBH_n) are n different values of these random variables, then the coefficient of correlation 'R^2' can be mathematically expressed thus:

$$R^2 = a_1 b_1 \qquad 14$$

$$\text{Or}\quad R = \left\{ \frac{\sum WL\ DBH - N(\overline{WL}\ .\overline{DBH})}{\left(\sum(DBH^2)\right) - N\ \ \overline{DBH}^2\ (WL^2 - N\overline{Y}^2)\ \ \frac{1}{2}} \right\} \qquad 15$$

Such is applicable for W_{BR} & W_{ST} respectively.

These values of the coefficient of regression 'R^2' lies between -1 & +1

IV. RESULTS AND DISCUSSIONS

Leaf Weight (W_{LF})

A linear relationship was recognized between W_L & DBH (fig 4) with R^2 = 0.62 and W_L & $DBH^{1.5}$ (fig 5) with R^2 = 0.625. Transforming the relationship W_L & DBH and W_L & $DBH^{1.5}$, the common allometric equation for leaf weight of Mangroves was determined as:

$$\mathbf{W_{LF\,=}\ 0.707DBH + 1.226} \qquad 16$$

$$\mathbf{W_{L\,F} = 0.188\ DBH^{1.5} + 2.668} \qquad 17$$

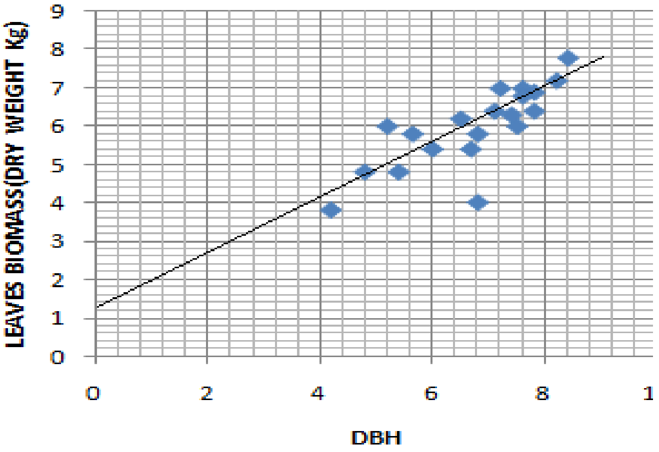

Fig. 4: Allometric graph of DLB V_S DBH

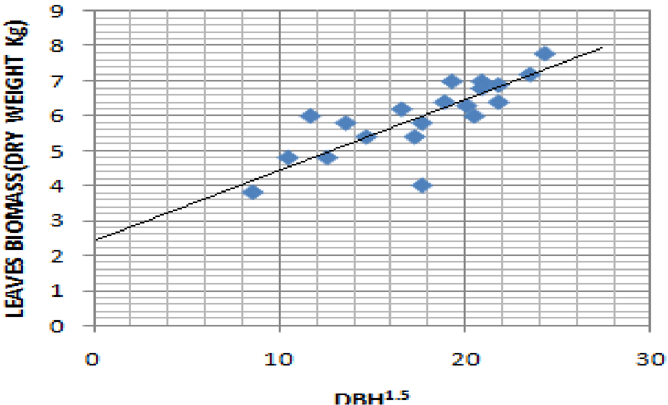

Fig. 5: Allometric graph of DLB Vs $DBH^{1.5}$

Branch Weight (W_{BR})

A linear relationship was recognized between W_B & DBH (Fig. 3) with R^2 = 0.981 and W_B & $DBH^{1.5}$ (Fig. 4) with R^2 = 0.982. Transforming the relationship W_B & DBH and W_B & $DBH^{1.5}$, the common allometric equation for leaf weight of Mangroves was determined as:

$$\mathbf{W_{BR\,=}\ 1.977\ DBH + 0.401} \qquad 18$$

$$\mathbf{W_{BR} = 0.524\ DBH^{1.5} + 4.460} \qquad 19$$

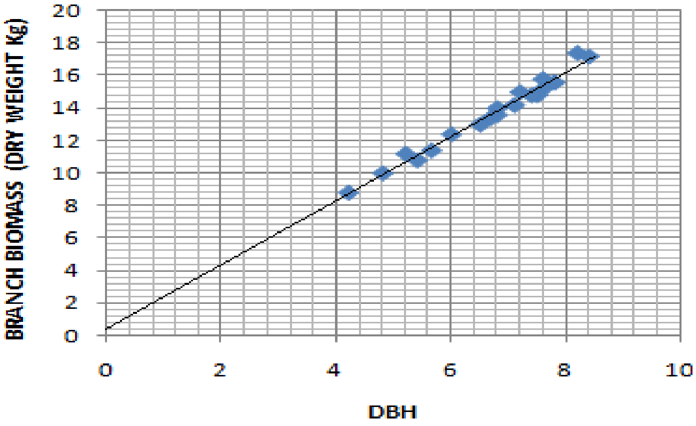

Fig. 6: Allometric graph of DBB Vs DBH

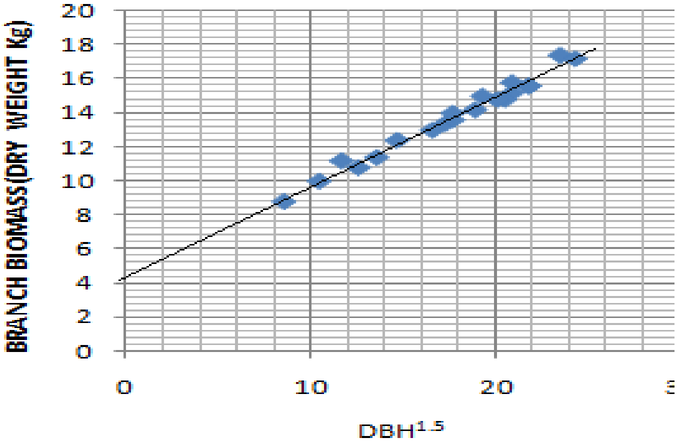

Fig. 7: Allometric graph of DBB Vs $DBH^{1.5}$

Stem Weight (W_{ST})

A linear relationship was recognized between W_S & DBH (Fig. 5) with $R^2 = 0.758$ and W_S & $DBH^{1.5}$ (Fig. 6) with $R^2 = 0.766$. Transforming the relationship W_S & DBH and W_L & $DBH^{1.5}$, the common allometric equation for leaf weight of Mangroves was determined as:

$$W_{ST} = 2.875\ DBH + 6.657 \qquad 20$$

$$W_{ST} = 0.765\ DBH^{1.5} + 12.49 \qquad 21$$

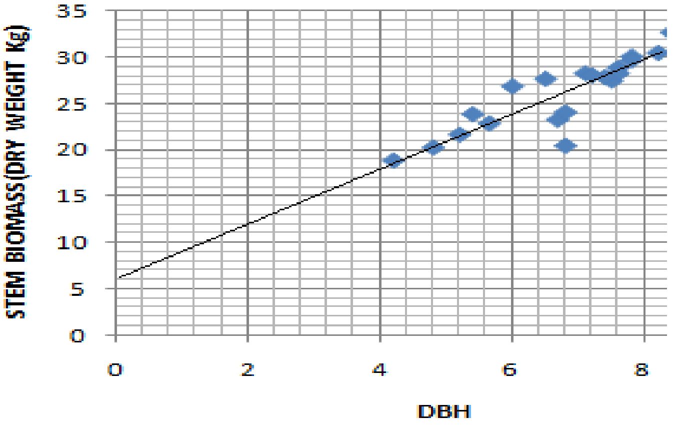

Fig. 8: Allometric graph of DSB Vs DBH

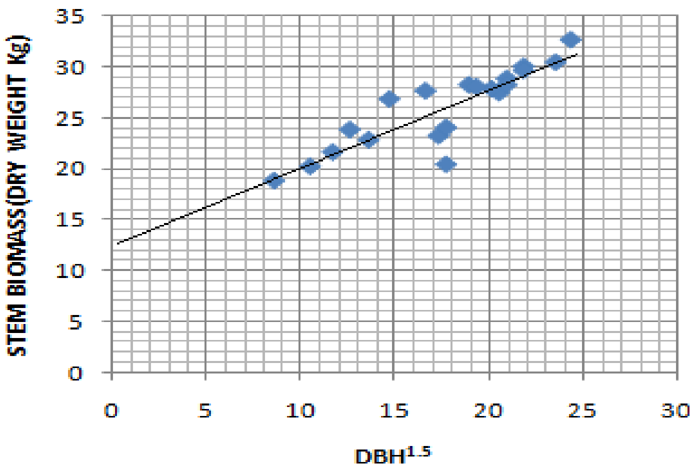

Fig. 9: Allometric graph of DSB Vs $DBH^{1.5}$

RHIZOPHORA HARRIZONI

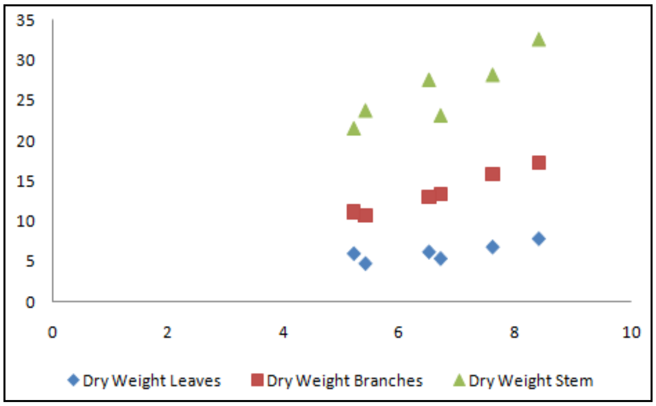

Fig. 10a: GRAPH OF W_{LF}, W_{BR}, W_{ST} Vs DBH

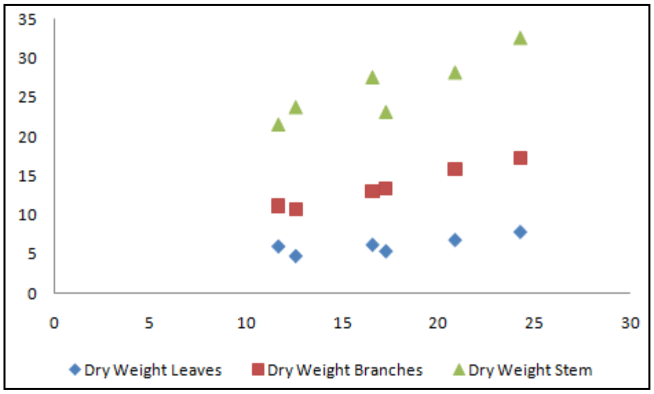

Fig. 10b: GRAPH OF W_{LF}, W_{BR}, W_{ST} Vs $DBH^{1.5}$

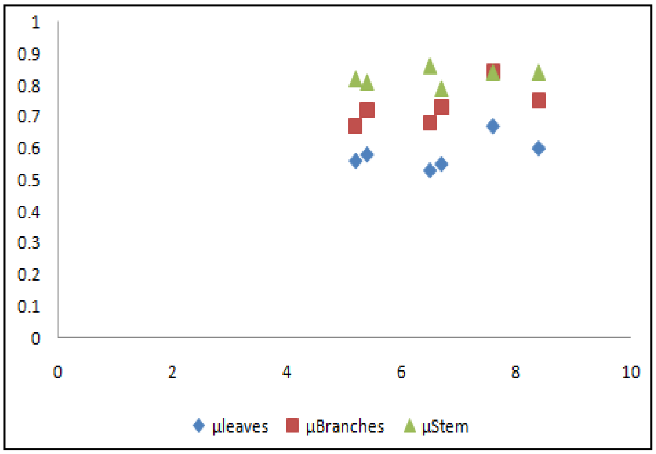

Fig. 10c: Graph of $\mu_{LF,}$ $\mu_{BR,}$ $\mu_{ST,}$ Vs DBH

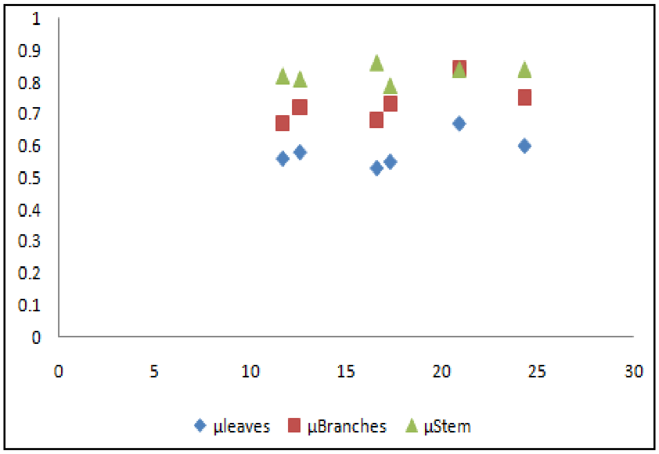

Fig. 10d: Graph of $\mu_{LF,}$ $\mu_{BR,}$ $\mu_{ST,}$ Vs DBH$^{1.5}$

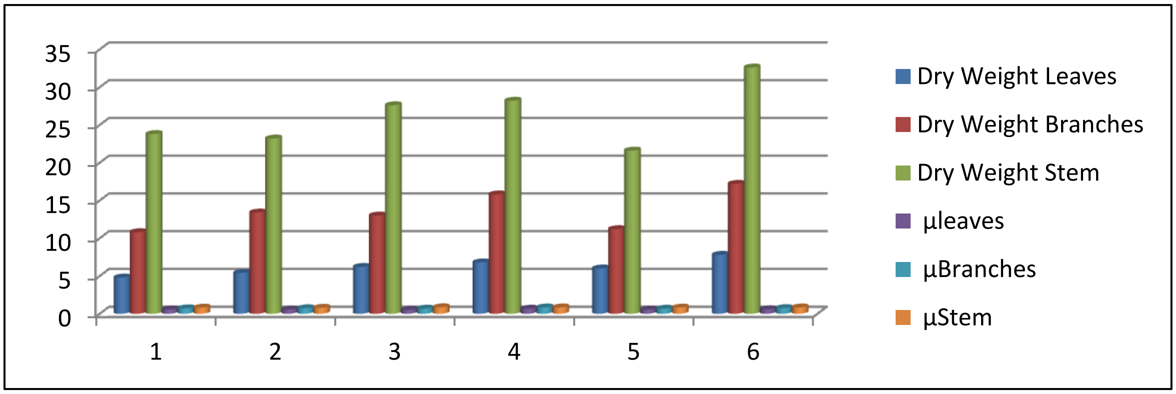

Fig. 10e: Chart showing the biomass properties of Rhizophora Harrizoni specie

RHIZOPHORA MANGAL

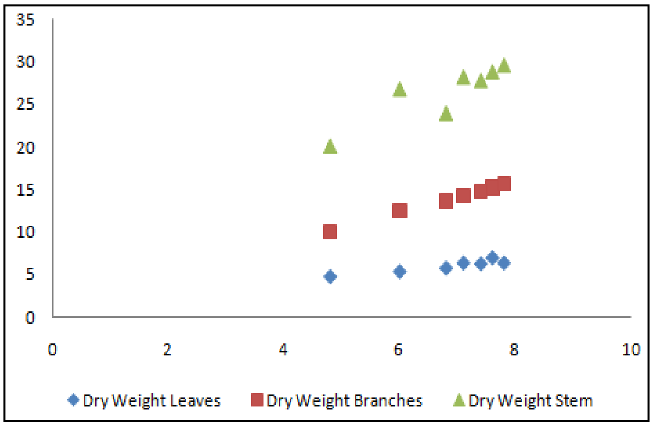

Fig. 11a: Graph of $W_{LF,}$ $W_{BR,}$ W_{ST} Vs DBH

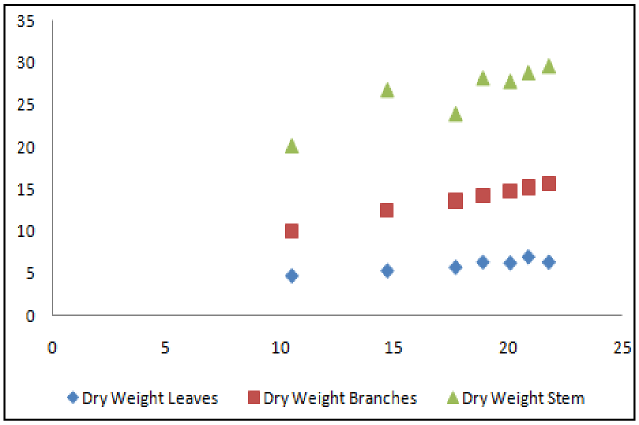

Fig 11b: Graph of W_{LF} ,$W_{BR,}$ W_{ST} Vs DBH$^{1.5}$

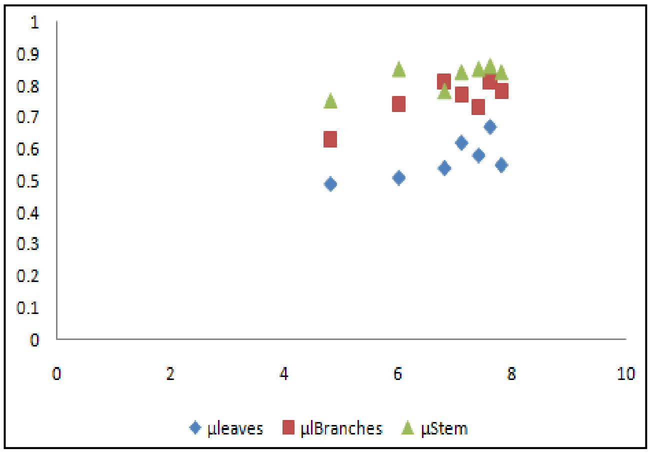

Fig. 11c: Graph of $\mu_{LF,}$ $\mu_{BR,}$ $\mu_{ST,}$Vs DBH

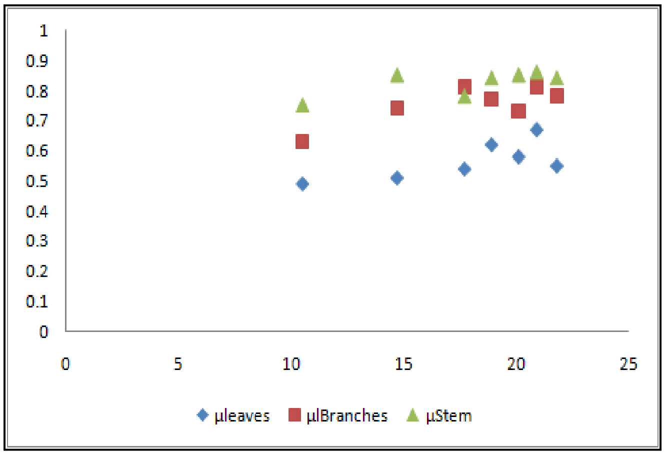

Fig. 11d:Graph of $\mu_{LF,}$ $\mu_{BR,}$ $\mu_{ST,}$ Vs DBH$^{1.5}$

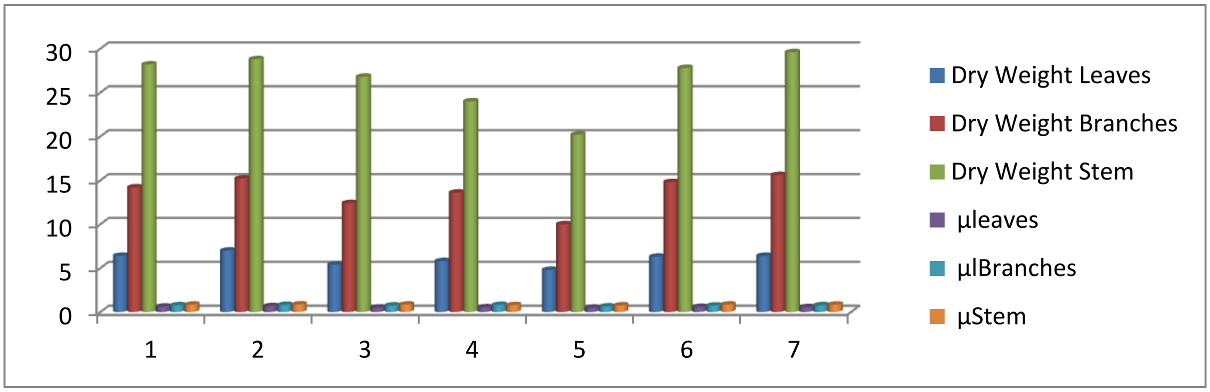

Fig 11e: Chart showing the biomass properties of Rhizophora Mangal specie

RHIZOPHORA RACEMOSA

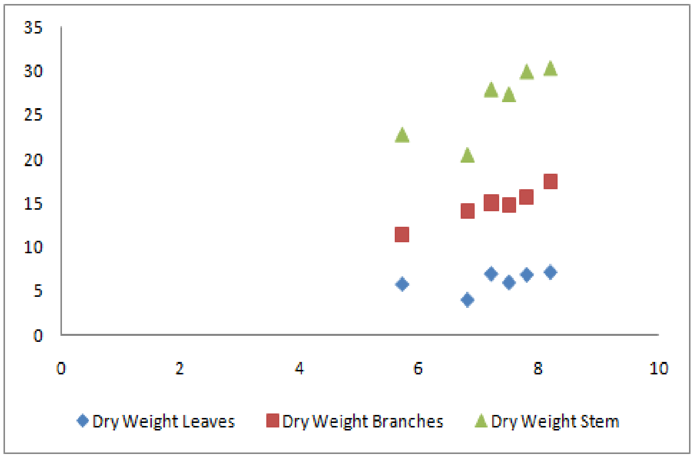

Fig. 12a: Graph of $W_{LF,}$ $W_{BR,}$ W_{ST} Vs DBH

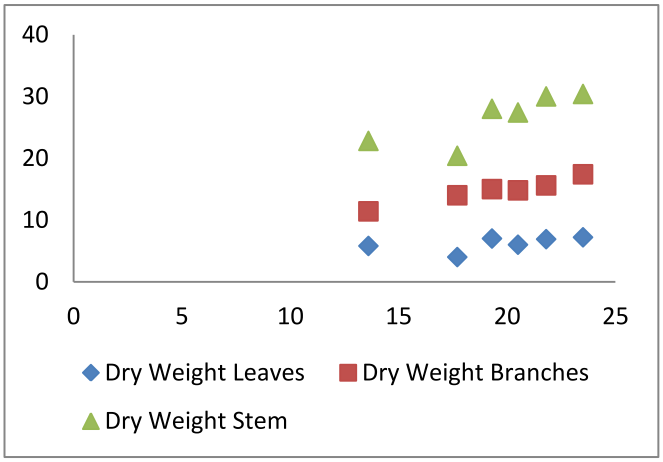

Fig. 12b: Graph of $W_{LF,}$ $W_{BR,}$ W_{ST} Vs DBH$^{1.5}$

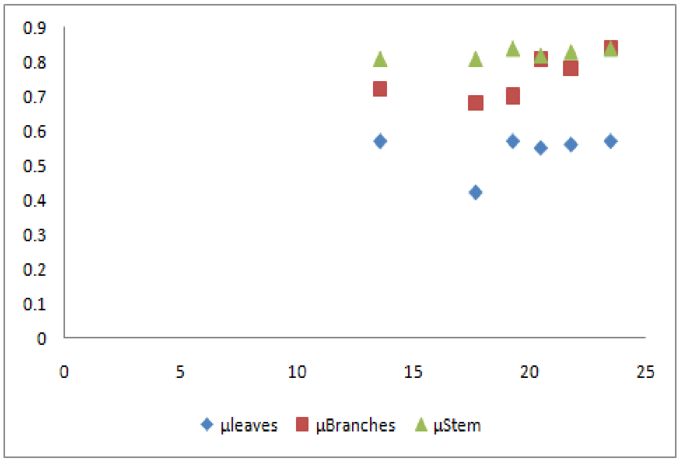

Fig. 12c: Graph of μ_{LF}, μ_{BR}, μ_{ST}, Vs DBH

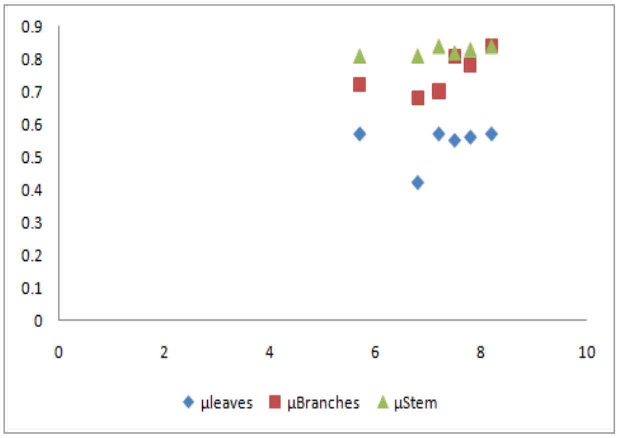

Fig. 12d: Graph of μ_{LF}, μ_{BR}, μ_{ST}, Vs DBH$^{1.5}$

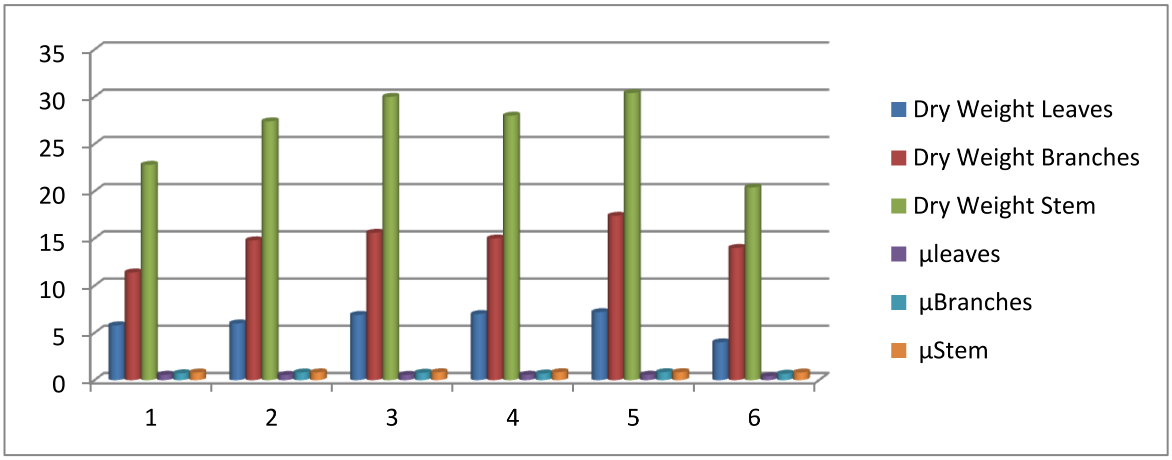

Fig. 12e: Chart showing the biomass properties of Rhizophora Racemosa specie

V. CONCLUSIONS

The Allometric equations developed in this research were developed based on the close linear relationship exiting between DBH, W_{LF}, W_{BR}, and W_{ST}. This proves that Diameter at breast height is an important parameter for estimating crown combustible fuels of Rhizophora species in southern Nigeria mangrove vegetations. These equations are only applicable in estimating the above ground biomass of Rhizophora species in Southern Nigerian Mangroves. They have been found to aid in the estimation of combustible fuels during wildfire spread. However, in developing these Allometric relationships, ladder fuels were not considered separately. They were integrated into leaf biomass estimations.

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Fig. 1: Swampy region of the mangroves

Fig. 2: pipelines running through the mangroves

Fig. 4: Arial view showing Geographic coordinates of the study area, lower Niger mangrove forest, river Niger & some revering villages *(Captured using Google Earth)*

Table 1: Table of Leaf, Branch and Stem weights for 20samples of Rhizophora's

Sample	Height (ft)	DBH	DBH$^{1.5}$	DW$_{LF}$ (kg)	WW$_{LF}$ (kg)	μ_{LF}	DW$_{BR}$ (kg)	WW$_{BR}$(kg)	μ_{BR}	DW$_{ST}$ (kg)	WW$_{ST}$ (kg)	μ_{ST}
1	5.8	5.4	12.6	4.8	8.2	0.58	10.8	14.8	0.72	23.8	29.3	0.81
2	6.1	7.1	18.9	6.4	10.3	0.62	14.2	18.3	0.77	28.2	33.7	0.84
3	5.6	5.7	13.6	5.8	10.1	0.57	11.4	15.8	0.72	22.8	28.2	0.81
4	6.0	6.7	17.3	5.4	9.8	0.55	13.4	18.2	0.73	23.2	29.1	0.79
5	6.4	7.6	20.9	7.0	10.5	0.67	15.2	18.8	0.81	28.8	33.5	0.86
6	5.9	6.5	16.6	6.2	11.6	0.53	13.0	18.9	0.68	27.6	32.1	0.86
7	5.9	6.0	14.7	5.4	10.6	0.51	12.4	16.7	0.74	26.8	31.7	0.85
8	6.3	7.5	20.5	6.0	10.9	0.55	14.8	18.3	0.81	27.4	33.4	0.82
9	6.4	6.8	17.7	5.8	10.7	0.54	13.6	16.8	0.81	24.0	30.6	0.78
10	6.2	7.8	21.8	6.9	12.2	0.56	15.6	20.1	0.78	30.0	36.3	0.83
11	5.1	4.8	10.5	4.8	9.8	0.49	10.0	15.9	0.63	20.2	26.9	0.75
12	6.1	7.6	20.9	6.8	10.2	0.67	15.8	18.8	0.84	28.2	33.7	0.84
13	5.9	7.4	20.1	6.3	10.8	0.58	14.8	20.4	0.73	27.8	32.7	0.85
14	4.6	5.2	11.7	6.0	10.7	0.56	11.2	16.6	0.67	21.6	26.3	0.82
15	5.8	7.2	19.3	7.0	12.2	0.57	15.0	21.3	0.70	28.0	33.5	0.84
16	6.5	8.2	23.5	7.2	12.7	0.57	17.4	20.6	0.84	30.4	36.3	0.84
17	4.1	4.2	8.6	3.8	8.2	0.46	8.8	14.6	0.60	18.8	24.2	0.78
18	6.1	6.8	17.7	4.0	9.6	0.42	14.0	20.4	0.68	20.4	25.3	0.81
19	6.3	8.4	24.3	7.8	12.9	0.60	17.2	22.9	0.75	32.6	38.7	0.84
20	6.2	7.8	21.8	6.4	11.7	0.55	15.6	19.8	0.78	29.6	35.3	0.84
SUM	117.3					11.10			14.23			16.46

Table 2: Table of Leaf, Stem, Branch and moisture contents for Rhozophora Harrizoni Species

SAMPLE	HEIGHT	DBH	DBH$^{1.5}$	DW$_{LF}$	DW$_{BR}$	DW$_{ST}$	WW$_{LF}$	WW$_{BR}$	WW$_{ST}$	μ_{LF}	μ_{BR}	μ_{ST}
1	5.8	5.4	12.6	4.8	10.8	23.8	8.2	14.8	29.3	0.58	0.72	0.81
4	6	6.7	17.3	5.4	13.4	23.2	9.8	18.2	29.1	0.55	0.73	0.79
6	5.9	6.5	16.6	6.2	13	27.6	11.6	18.9	32.1	0.53	0.68	0.86
12	6.1	7.6	20.9	6.8	15.8	28.2	10.2	19.8	33.7	0.67	0.84	0.84
14	4.6	5.2	11.7	6	11.2	21.6	10.7	16.6	26.3	0.56	0.67	0.82
19	6.3	8.4	24.3	7.8	17.2	32.6	12.9	22.9	38.7	0.60	0.75	0.84

Table 3: Table of Leaf, Stem, Branch and moisture contents for Rhozophora Mangal Species

SAMPLE	HEIGHT	DBH	DBH$^{1.5}$	DW$_{LF}$	DW$_{BR}$	DW$_{ST}$	WW$_{LF}$	WW$_{BR}$	WW$_{ST}$	μ_{LF}	μ_{BR}	μ_{ST}
2	6.1	7.1	18.9	6.4	14.2	28.2	10.3	18.3	33.7	0.62	0.77	0.84
5	6.4	7.6	20.9	7.0	15.2	28.8	10.5	18.8	33.5	0.67	0.81	0.86
7	5.9	6.0	14.7	5.4	12.4	26.8	10.6	16.7	31.7	0.51	0.74	0.85
9	6.4	6.8	17.7	5.8	13.6	24.0	10.7	16.8	30.6	0.54	0.81	0.78
11	5.1	4.8	10.5	4.8	10.0	20.2	9.8	15.9	26.9	0.49	0.63	0.75
13	5.9	7.4	20.1	6.3	14.8	27.8	10.8	20.4	32.7	0.58	0.73	0.85
20	6.2	7.8	21.8	6.4	15.6	29.6	11.7	19.8	35.3	0.55	0.78	0.84

Table 4: Table of Leaf, Stem, Branch and moisture contents for Rhozophora Racemosa Species

SAMPLE	HEIGHT	DBH	DBH$^{1.5}$	DW$_{LF}$	DW$_{BR}$	DW$_{ST}$	WW$_{LF}$	WW$_{BR}$	WW$_{ST}$	μ_{LF}	μ_{BR}	μ_{ST}
3	5.6	5.7	13.6	5.8	11.4	22.8	10.1	15.8	28.2	0.57	0.72	0.81
8	6.3	7.5	20.5	6.0	14.8	27.4	10.9	18.3	33.4	0.55	0.81	0.82
10	6.2	7.8	21.8	6.9	15.6	30.0	12.2	20.1	36.3	0.56	0.78	0.83
15	5.8	7.2	19.3	7.0	15.0	28.0	12.2	21.3	33.5	0.57	0.70	0.84
16	6.5	8.2	23.5	7.2	17.4	30.4	12.7	20.6	36.3	0.57	0.84	0.84
18	6.1	6.8	17.7	4.0	14.0	20.4	9.6	20.4	25.3	0.42	0.68	0.81

Table 5: Summary table of Allometric Equations

	ALLOMETRIC EQUATIONS	R^2	a_1	a_0
LEAF WEIGHT				
1	$W_{LF} = 0.707$ DBH + 1.226	0.620	0.707	1.226
2	$W_{LF} = 0.188 + DBH^{1.5} + 2.668$	0.625	0.188	2,668
BRANCH WEIGHT				
3	$W_{BR} = 1977$ DBH + 0.401	0.981	1.977	0.401
4	$W_{BR} = 0.524\ DBH^{1.5} + 4.406$	0.981	0.524	4.406
STEM WEIGHT				
5	$W_{ST} = 2.875$ DBH + 6.657	0.758	2.875	6.657
6	$W_{ST} = 0.765\ DBH^{1-5} + 12.49$	0.766	0.765	12.49

Nomenclature

DLB: Dry Leaf Biomass

DBB: Dry Branch Biomass

DSB: Dry Stem Biomass

DBH: Diameter at Breast Height.

$DW_{LF:}$ Dry Weight of Leaf

DW_{BR} : Dry Weight of Branches

DW_{ST}: Dry Weight of Stem

WW_{LF}: Wet weight of leaf

WW_{BR}: Wet weight of Stem

WW_{BR}: Wet weight of Branch

μ_{LF}: Leaf moisture content

μ_{BR}: Branch moisture content

$\mu_{ST:}$ Stem moisture content

a_1 : Slope

a_0 : Intercept

R^2: Coefficient of Correlation