East African Journal of Forestry & Agroforestry
eajfa.eanso.org
Volume 6, Issue 1, 2023
Print ISSN: 2707-4315 | Online ISSN: 2707-4323
Title DOI: https://doi.org/10.37284/2707-4323

EAST AFRICAN NATURE & SCIENCE ORGANIZATION

Original Article

Allometric Equation for Aerial Carbon Estimation (AGC) of Rhizophora racemosa and Avicennia germinans Mangroves of Olende and Ozouri in the Ogooué Delta in Gabon

Igor Akendengue Aken[1], Marjolaine Okanga-Guay[1], Madi Abaker[2], Estelle Dumont[2], Silas Davy Mbadinga Boubala[2], Lauriss Ngombi-Pemba[2] & Adelaïde Nieguitsila[2]*

[1] Université Omar Bongo, B.P. 17043, Libreville, Gabon.
[2] Université des Sciences et Techniques de Masuku, B.P. 901, Franceville, Gabon.
[*] Author for Correspondence ORCID ID https://orcid.org/0009-0000-2312-2252; email: m_okanga_guay@yahoo.fr

Article DOI: https://doi.org/10.37284/eajfa.6.1.1228

Date Published:

24 May 2023

Keywords:

Mangroves, Aboveground biomass (AGB), Carbon (C) stock, Allometric equation, Gabon.

ABSTRACT

The global carbon is determined by forests at 45%. Mangroves sequester more carbon per area unit than the dry land forest. The carbon sequestration capacities of mangroves in the Ogooue Delta are still unknown. Thus, this study aims to set up a carbon estimation equation for the species Rhizophora racemosa and Avicennia germinans of the Ogooué Delta mangroves in Gabon. Data was collected in 25 m * 25 m square plots in four sites. The dendrometry parameters collected were mainly diameter at breast height (DBH) with a forest meter and height from the laser rangefinder. The individual basal area and volume of each tree was determined using the Husch et al. (2003) method. This resulted in a fractal-shaped equation of the type: y=αxβ, i.e., AGC = 0.000112*DBH2.466 with a determination rate of 96%, a relative bias of 0.007 and an RMSE of 1.2. This model was developed with a dataset of 47 individuals and validated with 41 individuals, i.e., 53% versus 47%. This study also allowed us to understand that the DBH structure of Ozouri and Olendé mangroves is stable without external disturbance.

APA CITATION

Aken, I. A., Okanga-Guay, M., Abaker, M., Dumont, E., Boubala, S. D. M., Ngombi-Pemba, L. & Nieguitsila, A. (2023). Allometric Equation for Aerial Carbon Estimation (AGC) of Rhizophora racemosa and Avicennia germinans Mangroves of Olende and Ozouri in the Ogooué Delta in Gabon *East African Journal of Forestry and Agroforestry*, *6*(1), 148-162. https://doi.org/10.37284/eajfa.6.1.1228

CHICAGO CITATION

Aken, Igor Akendengue, Marjolaine Okanga-Guay, Madi Abaker, Estelle Dumont, Silas Davy Mbadinga Boubala, Lauriss Ngombi-Pemba and Adelaïde Nieguitsila. 2023. "Allometric Equation for Aerial Carbon Estimation (AGC) of Rhizophora racemosa and Avicennia germinans Mangroves of Olende and Ozouri in the Ogooué Delta in Gabon". *East African Journal of Forestry and Agroforestry* 6 (1), 148-162. https://doi.org/10.37284/eajfa.6.1.1228

HARVARD CITATION

Aken, I. A., Okanga-Guay, M., Abaker, M., Dumont, E., Boubala, S. D. M., Ngombi-Pemba, L. & Nieguitsila, A. (2023), "Allometric Equation for Aerial Carbon Estimation (AGC) of Rhizophora racemosa and Avicennia germinans Mangroves of Olende and Ozouri in the Ogooué Delta in Gabon", *East African Journal of Forestry and Agroforestry*, 6(1), pp. 148-162. doi: 10.37284/eajfa.6.1.1228.

Article DOI: https://doi.org/10.37284/eajfa.6.1.1228

IEEE CITATION

I. A., Aken, M., Okanga-Guay, M., Abaker, E., Dumont, S. D.M., Boubala, L., Ngombi-Pemba & A., Nieguitsila, “Allometric Equation for Aerial Carbon Estimation (AGC) of Rhizophora racemosa and Avicennia germinans Mangroves of Olende and Ozouri in the Ogooué Delta in Gabon”, *EAJFA*, vol. 6, no. 1, pp. 148-162, May. 2023.

MLA CITATION

Aken, Igor Akendengue, Marjolaine Okanga-Guay, Madi Abaker, Estelle Dumont, Silas Davy Mbadinga Boubala, Lauriss Ngombi-Pemba & Adelaïde Nieguitsila. “Allometric Equation for Aerial Carbon Estimation (AGC) of Rhizophora racemosa and Avicennia germinans Mangroves of Olende and Ozouri in the Ogooué Delta in Gabon”. *East African Journal of Forestry and Agroforestry*, Vol. 6, no. 1, May. 2023, pp. 148-162, doi:10.37284/eajfa.6.1.1228

INTRODUCTION

Forests around the world sequester about 45% of the world's active carbon (Houghton et *al*., 2013). Coastal forest ecosystems, commonly referred to as "blue carbon", including mangroves, are important biological carbon sinks capable of sequestering large amounts of carbon per area unit, more so than terrestrial forests (Komiyama et *al*., 2008; Donato et *al*., 2011; Mcleod et *al*., 2011; Jachowski et *al*., 2013). Mangroves inhabit 24% of tropical coastlines and are present in 123 countries (Spalding et *al*., 2010). They have a total of 68 typical species and 268 associated species (Giesen et *al*., 2007). They cover an area of 140,000 km², 19% of which is along the African coast. As a result, the high woody potential of mangroves gives them the highest carbon levels, more than seagrass beds and salt marshes, other components of blue carbon (Alongi, 2014).

The mangrove sequesters about 32% of anthropogenic emissions each year (Mcleod et *al*., 2011). This sequestration capacity gives it a prominent place in the process of reducing anthropogenic carbon emissions by the Intergovernmental Panel on Climate Change (IPCC, 2022). The mangrove thus plays an essential role in mitigating climate change, but it remains fragile and unique. Fragile because the slightest disturbance can transform it from sequester to producer, and unique because of its valuable ecological and economic-environmental benefits. From an ecological point of view, the mangrove serves as a nursery for animal, avifaunal and fish species (Tomlinson, 1986). In this respect, Donato and Kauffman (2011) point out that 75% of fish catches in tropical areas have lived at some point in mangroves. Estimated at 2500 km² in 1990, including 1000 km² in the Ogooué Delta (Lebigre, 1990), the Gabonese mangrove was reduced to 1890 km^2 in 2015, including 570 km^2 in the Ogooué Delta (AGEOS, 2020; Nzigou Boucka et *al*., 2021), results that remain underestimated, due to the confusion between flooded forests, dense forests, and mangroves.

Recent studies on Gabon's mangroves have shown that they have not finished revealing their mysteries. Indeed, the country has the greatest floristic diversity of mangroves in the sub-region (Congo and Democratic Republic of Congo, 2 species; Cameroon, 5 species; Gabon, 8 species) (UNEP, 2007; Ajonina et *al*., 2014; Ondo Assoumou, 2017). Sampled measurements in Gabon, Senegal and Liberia revealed that Gabon and Liberia are among the states with the highest mangrove carbon stocks potential on the West African coast (Kauffman and Bhomia, 2017), with only estimates of the Ndougou Lagoon and the Mondah Estuary in Gabon. Other studies have found that Gabon has the highest mangroves in the world (Simard et *al*., 2019; Stovall et *al*., 2021; Akendengué Aken, 2021; Akendengué Aken et *al*., 2021b).

Nevertheless, if knowledge on the carbon storage capacities of Gabon's estuarine mangroves is still embryonic (Ajonina et *al*., 2014; Kauffman and Bhomia, 2017; Akendengué Aken, 2021; Akendengué Aken et *al*., 2021a, Akendengué Aken et *al*., 2021b), those of deltaic mangroves are still unknown. Mangrove studies that have taken place in the region (Fromard and Fontes, 1994; Ondo Assoumou, 2006; Rabenkogo, 2007) focused respectively on the impact of oil activity on the structure and spatial extent of mangroves. No study reports biomass and carbon stocks in the mangroves of the Ogooué Delta, as initiated in estuaries (Akendengué Aken, 2021; Akendengué Aken et *al*., 2021a; Akendengué Aken et *al*.,

Article DOI: https://doi.org/10.37284/eajfa.6.1.1228

2021b). The objective of this work is the establishment of an allometric equation for the prediction of aerial carbon (AGC) of *Rhizophora racemosa* and *Avicennia germinans* of the mangroves of Ozouri and Olendé in the Ogooué Delta.

MATERIALS AND METHODS

Study Area

The Ogooué Delta, which covers 5100 km² (Mombo, 2017), is made up of 20% mangroves. They are established on a geological base consisting of the Ikando, Ozouri, Mandorové and N'Tchengué series, dating respectively from the Paleocene for the first two and the Neogene for the last two (Hourcq and Devigne, 1950). Located between the main outlet (Ozouri) of the Ogooué River and the lagoon formed by the sandy spire of the secondary outlet (Olendé), the Ozouri-Olendé enclave is the hinge between Mandji Island and the Etimboué department. Isolated to the west by the Atlantic Ocean, to the north and east by the Ogooué, and to the south by the Mpolounè River, Ozouri-Olendé Island is home to a lush mangrove whose extent is occasionally interrupted by forests of *Pandanus candelabrum* and *Raphia farinifera* (*Plates 1* and *2*).

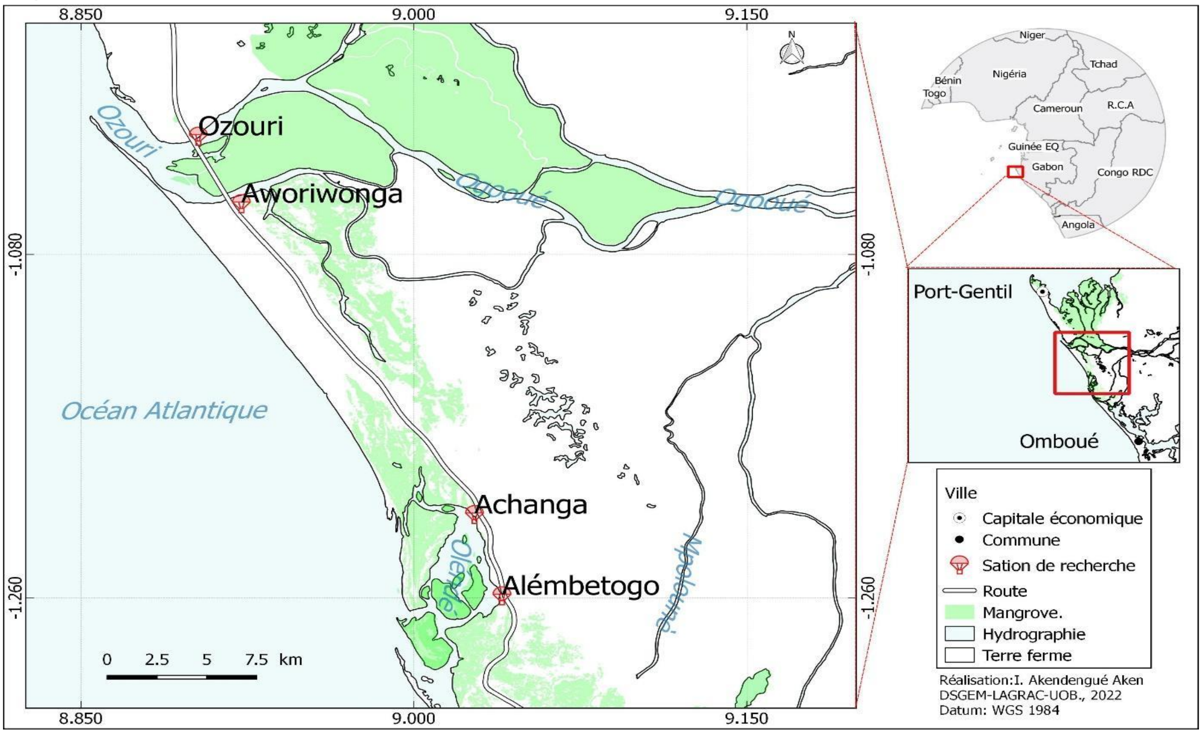
Plate 1: *Pandanus candelabrum* in front, and *Rhizophora racemosa* in back

Plate 2: *Raphia farinifera* in front, *Rhizophora racemosa* in back

This mangrove, which extends over about 44 km in length, is located between two cities: Port-Gentil in the north with its 200,000 inhabitants, and Omboué in the south with 2057 inhabitants (Direction Générale de la Statistique, 2015). The Ozouri-Olendé enclave, which was once accessible only by water, is now accessible by land via the Port-Gentil-Omboué road (*Figure 1*). The mangrove largely dominates the two bridges that stretch to a length of 4.5 km and a height of 50 m each. The impressive size of the local mangroves stands out in Ozouri, at Aworiwonga and Olendé around Alémbetogo, where the bridge is barely half the height of the trees.

Article DOI: https://doi.org/10.37284/eajfa.6.1.1228

Figure 1: Location of the Ozouri-Olendé enclave and sampled stations



Data Collection

Data were collected in georeferenced 25 m x 25 m square plots. The dendrometry parameters collected are mainly the diameter at breast height (DBH), measured with a forest meter, and the height measured with the laser rangefinder. Each species was identified from its morphological characteristics and inflorescence. From the data collected, secondary data were produced.

Data Analysis

Structural Characterization of Mangrove Ecosystems

Several parameters were calculated from the collected data, after it was entered in an Excel spreadsheet. The individual basal area (g), volume (v) and aerial carbon (AGC) of each tree were determined using the method of Husch et *al*. (2003), applied in mangroves by Ajonina (2008); (equations 1, 2, 3 and 4). The model was developed under R.4.0.5 through the lme4 package for modelling, and the metrics package for validation, using the least squares method.

Basal area (m^2ha^{-1}) $(g) = \pi \frac{d^2}{4}$ [1]

Volume (m^3) $(v) = g \times h \times f$ [2]

Where π = 3.14; d = diameter in meters, g = basal area in m^2ha^{-1}, h = height in meters and f = shape factor (f = 0.6; Ajonina and Usongo, 2001). Individual aboveground biomass (AGB) (Equation 3) was obtained by the standard formula of Husch et *al*. (2003).

Biomass $(AGB) = p \times V \times BEF$ [3]

Where AGB = aboveground biomass, p = average density of mangrove wood [(0.88 for *Avicennia germinans*, 1.17 for *Rhizophora spp* (Akendengué et *al*., 2021b)] and BEF = biomass expansion factor in mangroves (determined at 1.18; Ajonina, 2008; Ajonina et *al*., 2013).

Aerial Carbone $(AGC) = AGB \times 0.48$ [4]

Where 0.48 is the carbon biomass expansion factor in mangroves (Donato et Kauffman, 2011).

Development and Evaluation of Allometric Equations

The modelling data includes 47 trees, or 53% of the measured population, while the validation data accumulates 41 trees, or 47% of the entire database. The modelling DBH varies between 2 cm and 110 cm and the height from 2 m to 60 m. One must note that there is a gap in the DBH class

Article DOI: https://doi.org/10.37284/eajfa.6.1.1228

[100-110[cm in the validation data. In general, classes between [2 and 40] cm cumulate 48.93% of individuals. The height for these same classes represents 76.58% of the modelling base. For validation data, the dominant classes of DBH are between [10 and 40] cm, i.e., a quota of 54.53%. The dominant height classes are between [2 and 30] m, i.e., a rate of 92.68% (*Table 1*).

Table 1: Modelling and validation data

Class	Modelling				Validation			
	DBH (cm)	**F (%)**	**Height (m)**	**F (%)**	**DBH (cm)**	**F (%)**	**Height (m)**	**F (%)**
[2 - 10[	4	8.51	5	10.63	3	6.81	4	9.75
[10 - 20[	16	34.04	21	44.68	12	27.27	21	51.22
[20 - 30[	7	14.89	10	21.27	7	15.90	13	31.71
[30 - 40[	6	12.76	8	17.02	5	11.36	1	2.43
[40 - 50[	2	4.25	2	4.25	2	4.54	1	2.43
[50 - 60[	1	2.12	1	2.12	3	6.81	1	2.43
[60 - 70[	3	6.38	0	0	3	6.81	0	0
[70 - 80[	2	4.25	0	0	2	4.54	0	0
[80 - 90[	2	4.25	0	0	3	6.81	0	0
[90 - 100[	1	2.12	0	0	1	2.27	0	0
[100-110[	3	6.38	0	0	0	0.000	0	0
Total	47	100	47	100	41	100	41	100
	53%				47%			

The model is generated (Picard et al., 2012) using the alpha (α) and beta (β) parameters applied to the dataset (equations 5 and 6).

$$\alpha = \frac{COV(Y;Y')}{V(Y)} = \frac{\bar{Y}\bar{Y}' - \bar{Y}.\bar{Y}'}{\bar{Y}^2 - (\bar{Y})^2} \quad [5]$$

$$\beta = \bar{Y}' - \alpha.\bar{Y} \quad [6]$$

The validation of the allometric equation produced is done by comparing the predicted carbon and the carbon measured by checking the root mean square error (RMSE; equation 7), the bias (equation 8) and the percentage bias (equation 9).

$$RMSE = \frac{1}{N}\sum_1^n\left(\frac{((P_i - O_i)^2)}{N}\right) * 0.5 \quad [7]$$

$$bias = \frac{1}{N}\sum_1^n(P_i - O_i) \quad [8]$$

$$bias\ (\%) = \frac{1}{N}\sum_1^n \frac{(P_i - O_i)}{absolue}(O_i) \quad [9]$$

Where RMSE = root mean square error, P = predicted biomass, O = observed biomass and N = the number of observations. RMSE is used to measure the dispersion of predictions from observations (Chave et *al*., 2005).

RESULTS

Dendrometry Features

The DBH of *Rhizophora racemosa* varies between 2 and 100 cm with a predominance of the [10 - 20[class which represents 32.65%, followed by the [20 - 30[class with 18.36% and [2 - 10[and [30 - 40[classes, each having 12.24%. The height varies between 2 and 60 m with predominance of the [10 - 20[class which cumulates 42.85%. It is followed by the [20 - 30[and [2 - 10[classes having respectively 20.41% and 16.33%. The DBH of *Avicennia germinans* varies between 2 and 110 cm. The dominant DBH classes for *Avicennia germinans* are [10 - 20[with 30.77%, [20 - 30[and [30 - 40[with 12.82% each. The height of this same species varies between 2 and 40 m with a dominance of [10 - 20[and [20 - 30[classes with respectively 53.85% and 33.33% (*Table 2*). It appears that *Rhizophora racemosa* grows the highest, while *Avicennia germinans* grows the largest.

Article DOI: https://doi.org/10.37284/eajfa.6.1.1228

Table 2: Distribution of DBH and height according to classes

Species	*Rhizophora racemosa*				*Avicennia germinans*			
Classes	**DBH (cm)**	**F (%)**	**Height (m)**	**F (%)**	**DBH (cm)**	**F (%)**	**Height (m)**	**F (%)**
[2 - 10[	6	12.24	8	16.33	1	2.56	1	2.56
[10 - 20[	16	32.65	21	42.85	12	30.77	21	53.85
[20 - 30[	9	18.36	10	20.41	5	12.82	13	33.33
[30 - 40[	6	12.24	5	10.20	5	12.82	4	10.25
[40 - 50[	2	4.08	3	6.12	2	5.12	0	0
[50 - 60[	1	2.04	2	4.08	3	7.69	0	0
[60 - 70[	4	8.16	0	0	2	5.12	0	0
[70 - 80[	1	2.04	0	0	3	7.69	0	0
[80 - 90[	3	6.12	0	0	2	5.12	0	0
[90 - 100[	1	2.04	0	0	1	2.56	0	0
[100-110[	0	0	0	0	3	7.69	0	0
Total	49	100	49	100	39	100	39	100

Mangrove Biomass and Aboveground Carbon Stock per Site

The DBH of the trees at the Ozouri site is between 2.2 cm and 95 cm, with an average of 35.55 ± 5.27 cm. The cumulative DBH is 1102.2 cm and the median is 20 cm. The height is between 6.6 m and 51.8 m with an average of 22.68 ± 2.53 m. The basal area is 0.16 ± 0.04 m^2ha^{-1} and the total basal area is 5.10 m^2ha^{-1}. The total volume of mangroves sampled at Ozouri is 107.09 m^3 with an average of 3.45 ± 0.87 m^3. The aboveground biomass (AGB) of the Ozouri site varies between 0.003 and 22.148 Mg, with an average AGB of 4.76 ± 1.2 Mg and a total of 147.85 Mg for 31 trees sampled. This represents 72.45 Mg of airborne carbon (AGC) (*Table 3*).

Table 3: Statistical parameters of mangroves sampled at Ozouri

Statistical parameters	DBH (cm)	Height (m)	G (m^2h^{-1})	V (m^3)	AGB (Mg)	C (Mg)
Mean	35.55	22.68	0.16	3.45	4.76	2.33
Standard error	5.27	2.53	0.04	0.87	1.20	0.58
Median	20	16.4	0.031	0.59	0.83	0.41
Type deviation	29.34	14.11	0.22	4.84	6.69	3.28
Amplitude	92.8	45.2	0.71	16.04	22.15	10.85
Minimum	2.2	6.6	0.000	0.002	0.003	0.001
Maximum	95	51.8	0.71	16.04	22.148	10.85
Total	1102.2	703.1	5.10	107.09	147.85	72.45
N	31	31	31	31	31	31

The tree DBH of the Aworiwonga site oscillate between 20 and 82 cm, with an amplitude of 62 cm for an average of 53.1 ± 6.09 cm. The average height is 38.06 ± 3.13 m for a total of 380.6 m. The height varies between 21.4 m and 51.8 m, with an amplitude of 30.4 m. The basal area gravitates between 0.031 $m^2.ha^{-1}$ and 0.53 $m^2.ha^{-1}$, i.e., an amplitude of 0.49 $m^2.ha^{-1}$. The average is 0.25 ± 0.05 $m^2.ha^{-1}$ for a total of 2.48 $m^2.ha^{-1}$, representing the 10 trees inventoried. The average volume is 6.11 ± 1.384 m^3 with a minimum and maximum threshold of 0.59 and 14.44 m^3 respectively. This represents an amplitude of 13.84 m^3 for a total of 61.06 m^3. The biomass varies between 0.83 Mg and 19.94 Mg, with an amplitude of 19.11 Mg and an average of 8.43 ± 1.910 Mg. Carbon varies between 0.41 and 9.77 Mg, with an average of 4.13 ± 0.94 Mg, for a total carbon of 41.30 Mg for the 10 trees sampled at Aworiwonga (*Table 4*).

Article DOI: https://doi.org/10.37284/eajfa.6.1.1228

Table 4: Statistical parameters of mangroves sampled at Aworiwonga

Statistical parameters	DBH (cm)	Height (m)	G (m^2h^{-1})	V (m^3)	AGB (Mg)	C (Mg)
Mean	53.1	38.06	0.25	6.11	8.43	4.13
Standard error	6.09	3.13	0.05	1.384	1.910	0.94
Median	55.5	35.9	0.24	6.340	8.75	4.29
Type deviation	19.28	9.90	0.16	4.38	6.04	2.96
Amplitude	62	30,4	0,49	13,84	19,11	9.36
Minimum	20	21.4	0.031	0.59	0.83	0.41
Maximum	82	51.8	0.53	14.44	19.94	9.77
Total	531	380.6	2.48	61.06	84.29	41.30
N	10	10	10	10	10	10

At the Achanga site, 18 trees were sampled. The DBH of this site varies between 10 and 43 cm, with an amplitude of 33 cm and an average of 22.17 ± 2.13 cm. The minimum and maximum height is 7.4 m and 32.6 m respectively, giving an amplitude of 25.2 m for an average of 18.67 ± 1.68 m. The average basal area is 0.05 ± 0.008 $m^2.ha^{-1}$, with a total of 0.80 $m^2.ha^{-1}$. The minimum and maximum basal area is 0.008 $m^2.ha^{-1}$ and 0.15 $m^2.ha^{-1}$ respectively. The average volume of trees sampled in Achanga is 0.63 ± 0.17 m^3 with a total of 11.27 m^3 and a minimum and maximum threshold of 0.04 m^3 and 2.84 m^3 respectively. The average aboveground biomass (AGB) is 0.86 ± 0.23 Mg for a total value of 15.56 Mg, representative of the 18 trees sampled. The average aerial carbon (AGC) is 0.42 ± 0.11 Mg with a minimum and maximum threshold of 0.03 Mg and 1.92 Mg respectively (*Table 5*).

Table 5: Statistical parameters of mangroves sampled at Achanga

Statistical parameters	DBH (cm)	Height (m)	G (m^2h^{-1})	V (m^3)	AGB (Mg)	C (Mg)
Mean	22.17	18.67	0.05	0.63	0.86	0.42
Standard error	2.13	1.68	0.008	0.17	0.23	0.11
Median	20.5	17.5	0.03	0.34	0.47	0.23
Type deviation	9.04	7.15	0.04	0.71	0.98	0.48
Amplitude	33	25.2	0.13	2.79	3.86	1.89
Minimum	10	7.4	0.008	0.04	0.06	0.03
Maximum	43	32.6	0.15	2.84	3.92	1.92
Total	399	336.1	0.80	11.27	15.56	7.62
N	18	18	18	18	18	18

The average DBH of the Alémbetogo site is 41.41 ± 4.86 cm with a minimum and maximum threshold of 9 cm and 110 cm respectively, i.e., an amplitude of 101 cm. The maximum height in Alémbetogo is 34.8 m and the minimum height is 8.4 m, which is an amplitude of 26.4 m. The average is around 19.98 ± 1.09 m and the median is 19.2 m. A resemblance of the mean and the median emerges from the site of Alémbetogo. The average basal area is 0.21 ± 0.041 $m^2. ha^{-1}$ and the median is 0.08 $m^2.ha^{-1}$. The minimum and maximum threshold of land area are 0.006 $m^2. ha^{-1}$ and 0.95 $m^2.ha^{-1}$ respectively. The number of trees sampled in Alémbetogo is 39, for a total volume of 118.95 m^3 with an average of 3.05 ± 0.686 m^3. The average aboveground biomass (AGB) is 3.17 ± 0.71 Mg for an amplitude of 17.59 Mg and a total aboveground biomass of 123.52 Mg. The average aerial carbon is 1.55 ± 0.34 Mg with a minimum and maximum threshold of 0.02 Mg and 8.63 Mg respectively (*Table 6*).

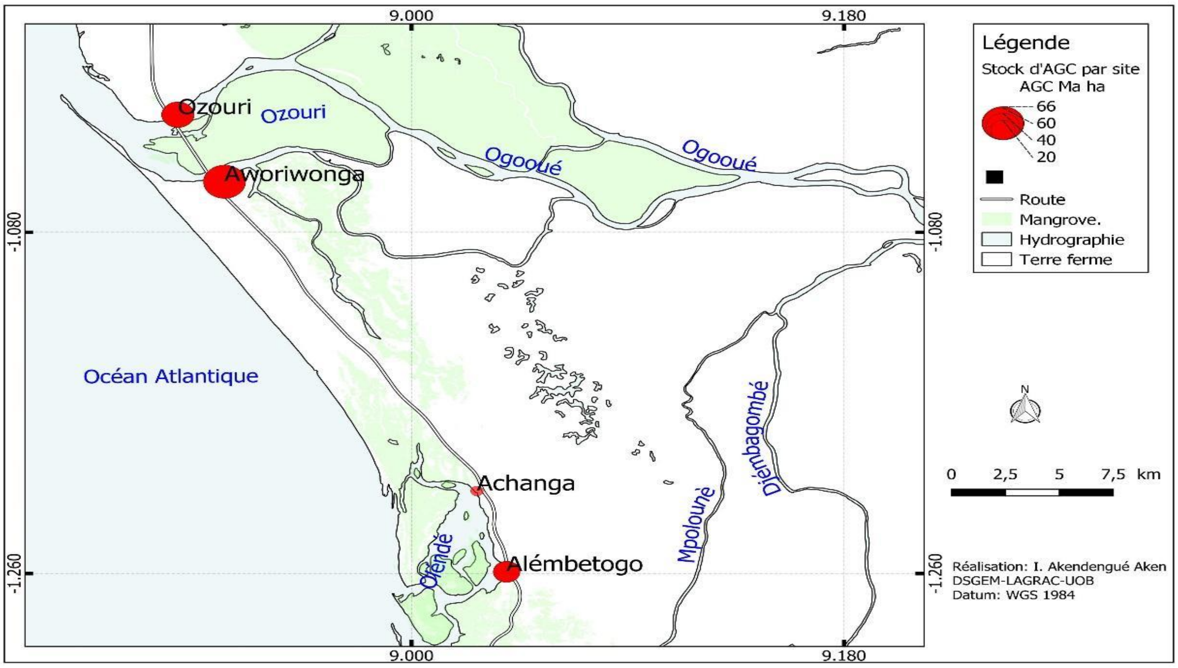
Article DOI: https://doi.org/10.37284/eajfa.6.1.1228

Table 6: Statistical parameters of mangroves sampled in Alémbetogo

Statistical parameters	DBH (cm)	Height (m)	G (m^2h^{-1})	V (m^3)	AGB (Mg)	C (Mg)
Mean	41.41	19.98	0.21	3.05	3.17	1.55
Standard error	4.86	1.09	0.041	0.686	0.71	0.34
Median	31	19.2	0.08	0.86	0.89	0.43
Type deviation	30.32	68.53	0.258	4.28	4.44	2.18
Amplitude	101	26.4	0.94	16.94	17.59	4.22
Minimum	9	8.4	0.006	0.04	0.04	0.02
Maximum	110	34.8	0.95	16.98	17.64	8.63
Total	1615	779.1	7.99	118.95	123.52	60.52
N	39	39	39	39	39	39

Stock mapping reveals a predominance of aerial carbon (AGC) in the Ozouri region, which has 66 ± 15.4 Mg ha-1 in Aworiwonga and 60 ± 9.28 Mg ha-1 in Ozouri. The Olendé region has a maximum AGC of 40 ± 5.44 Mg ha^{-1} in Alémbetogo and 20 ± 1.76 Mg ha^{-1} in Achanga (*Figure 2*). The predominance of aerial carbon stocks at the Ozouri and Aworiwonga sites is related to the high density of individuals at these sites. On the other hand, at Achanga and Alémbetogo, that is to say in Olendé, the densities are lower because the individuals are more voluminous and therefore far from each other. Indeed, the average DBH in Olendé are respectively 22.17 cm and 41.41 cm in Achanga and Alémbetogo, while, in the vicinity of Ozouri, in Aworiwonga and Ozouri, the average DBH are respectively 35.55 cm and 53.1 cm.

Figure 2: Distribution of AGC stocks ($Mg.ha^{-1}$) per site



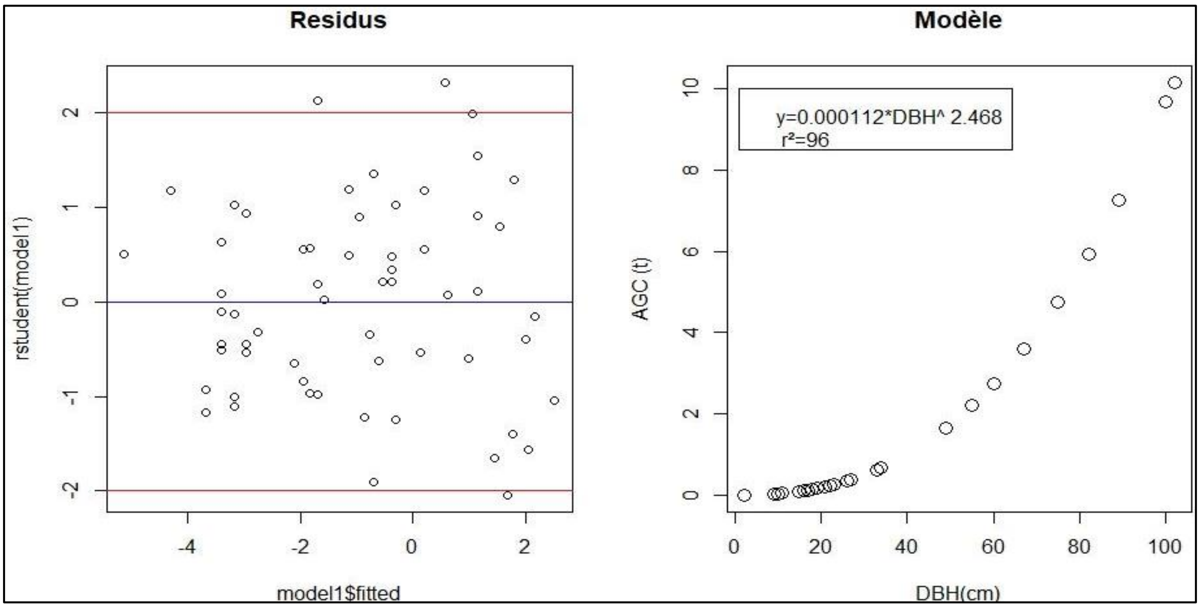
Modelling

The equation $AGC=0.000112DBH^{2.468}$ was calibrated in a DBH range between [2 and 110] cm. It includes *Rhizophora racemosa* and *Avicennia germinans* which are the most widespread mangrove species in the Ozouri and Olendé region. The sequestration of aerial carbon from these mangroves obeys a model of power form: y = αxβ. This model is adjusted with a coefficient of determination (r^2) of 96%. The residuals of the model are symmetric [-2 and 2],

Article DOI: https://doi.org/10.37284/eajfa.6.1.1228

and randomly distributed around the regression axis y=0 (*Figure 3*).

Figure 3: Residue distribution and model regression curve



Validation

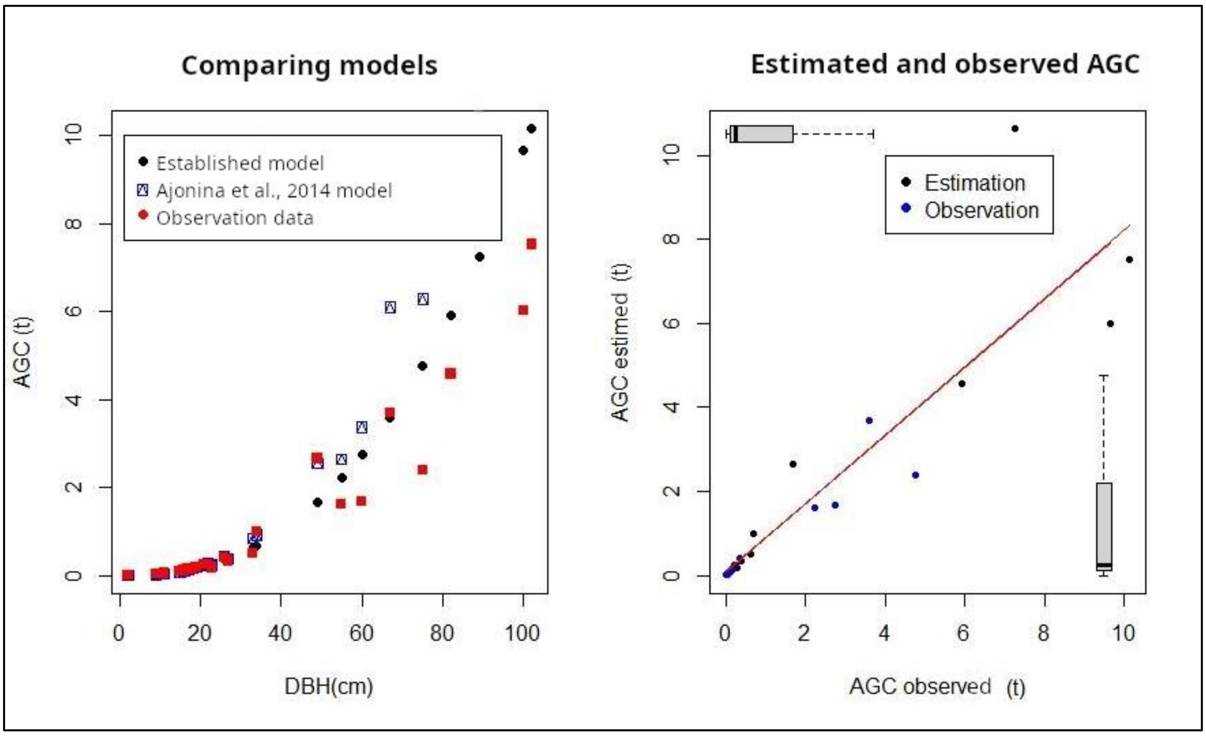
The cross-referencing of the model results and the observed data shows a RMSE of 1.20 and a relative bias of 0.007% (*Table 7*). The $0.000112DBH^{2.468}$ model is capable of predicting mangrove carbon (AGC). The cross-referencing of the results of the established model, the Ajonina et *al.* (2014) model and the observed data have a perfect superposition in the range of [0 – 38[cm (*Figure 4*). Beyond that, the next three predictions are close, but no longer overlap. From 58 cm, the model of Ajonina et *al.* (2014) overestimates the predictions. From a DBH of 70 cm no prediction of the established model is superimposed on the observed data.

Table 7: Model parameters and assessment criteria

Model	α	β	RSE	bias	bias %	RMSE
y=αx^β	0.000112	2.468	0.376	0.240	0.007	1.200

East African Journal of Forestry and Agroforestry, Volume 6, Issue 1, 2023
Article DOI: https://doi.org/10.37284/eajfa.6.1.1228

Figure 4: Model comparison and regression between estimated AGC and observed AGC



DISCUSSION

The mangrove structure encountered in Ozouri, Aworiwonga, Achanga and Alémbetogo is different from that encountered by Ondo Assoumou (2006) in Aléwana and N'Tchengué which are located north and northwest of the Ogooué delta. Indeed, in the Aléwana and Ntchengué sites, the DBH rarely exceeds 10 cm in mangroves. The same applies to heights that vary between 4 and 6 m in Aléwana and between 10 and 12 m in Ntchengué. The Aléwana site consists of *Rhizophora harrisonii* while that of Ntchengué is composed of *Rhizophora racemosa*, as in Ozouri, Achanga and Alémbetogo. They are close to the structure mentioned by Lebigre (1990) in the Remboué area of the Komo estuary, where we find 100 cm DBH and 40 m high *Rhizophora racemosa*. Ajonina et *al*. (2014), Simard et *al*. (2019), Akendengué Aken (2021) observed mangroves, mainly *Rhizophora racemosa*, 41, 62 and 60 m high at the Remboué River. It is certainly premature to say that *Rhizophora racemosa* tends to grow the highest, but for the moment, these field observations match with other observations in Bolokouboué, Mamboumba, Remboué, Aworiwonga and Ozouri (Lebigre, 1990; Ondo Assoumou, 2006; Ajonina et *al*., 2014; Akendengué Aken, 2021).

Structural DBH analysis of the *Rhizophora racemosa* and *Avicennia germinans* populations showed a strong representation of young individuals, and a progressive decrease of individuals in the classes of large DBH or size. These species show a regular distribution, indicating little environmental disturbance. However, an absence of *Rhizophora racemosa* individuals is observed in the class [100-110[while the same class is provided with 3 individuals in *Avicennia germinans*. This fact is explained by the stilt root morphology of *Rhizophora* which does not favour their upright position above a certain DBH threshold (Ondo Assoumou, 2006). Indeed, from the DBH class [100-110[, *Rhizophora* falls under the effect of its own weight and soil structure. According to field observations and literature, *Rhizophora*'s DBH rarely exceeds the [100-110[cm class. These limitations were also observed in Benin, Congo Brazzaville, and Cameroon, where the largest *Rhizophora racemosa* observed has a diameter of 102 cm (Ajonina et *al*., 2014). However, mangroves in the Philippines have large diameters: the DBH of *Rhizophora mucronata* exceeds 150 cm and other mangrove species reach 300 cm of DBH (Gonzaga et *al*., 2022). On the contrary, mangroves in arid regions, such as the *Avicennia marina* of the Arabian Peninsula, are generally small (less than 3 m tall) (Chatting et *al*., 2020).

The developed model overestimates carbon by 0.007%. The margin of error predicted in allometric models by over- or underestimation is in the order of 5% (Chave et *al*., 2005). Thus, the developed model is well below this threshold and therefore meets the standards for assessing an allometric equation. This is similar to Akendengué Aken et *al*. (2021a) who present a nonlinear model for *Rhizophora*, located south of Libreville (Gabon), with an RMSE of 0.0014 and a bias of -0.35%. The Ajonina et *al*. (2014) model applied to our data, has a relative margin of error of 0.017% and a RMSE of 2.326. The RMSE between the model established here and the model of Ajonina et *al*. (2014) is 1.426 for a relative bias of -0.098. This negative relative bias reflects the fact that the predictions of the developed model are closer to the theoretical values. However, this small margin of error of the model established by Ajonina et *al*. (2014) is not surprising because this is a fractal model just like the one developed in this research. This type of model is not subject to geographical endemism, i.e., it can be delocalized to other geographical spaces and predict correctly (Zianis and Mencuccini, 2004). Although the established model represents only 25% of the mangrove species found in Gabon, it nevertheless takes into account the highest, largest, and most widespread species, namely *Rhizophora racemosa* and *Avicennia germinans*.

Mapping of the aboveground carbon stocks has revealed that the Ozouri area is more important than the Olendé area. Despite the similarity of the two mangrove ecosystems, they differ in the absence of *Avicennia germinans* in Ozouri but their presence in Olendé. This differentiation is certainly due to the environmental conditions that favour the development of these species, including the fundamental contribution of nutrients. The Ozouri mangrove is of fluvial type while the Olendé mangrove is of the lagoon type. In theory, sediment input is greater in river areas than in lagoon areas. The main river (Obando), linking the Ogooué to the Nkomi lagoon which flows into the ocean through the Olendé outlet, is subdivided into two subarms, Mpolounè and Djémbagombé, less important. In addition to this complex hydrographic configuration, there is a low topography, with average altitudes under 50 m (Mombo, 2017) that favour significant sedimentary inputs from surrounding rivers. Indeed, the lagoon current is not consistent, it brings less continental sediments, but rather marine aggregate from the Atlantic Ocean. Under such unique conditions, the growing conditions of the Olendé lagoon mangroves and the Ozouri river mangroves will inevitably impact the AGC stocks in these two areas.

CONCLUSION

This study resulted in a fractal form equation for aerial carbon prediction of the species *Rhizophora racemosa* and *Avicennia germinans*. This equation has a determination rate of 96% with a relative bias of 0.007 and an RMSE of 1.2. In general, the mangroves of the Ozouri and Olendé region have a stable DBH structure without external disturbance. *Rhizophora racemosa* rarely exceeds the DBH of the class [100-110[, which is contrary to *Avicennia germinans*. There is a need to evaluate the ability of this equation to predict the aerial carbon of the species *Rhizophora harrisonii*, *Rhizophora mangle*, *Laguncularia racemosa* and *Conocarpus erectus*. The same is true of the possible application for the southern lagoon mangroves, considering that fractality transcends geographical endemism.

ACKNOWLEDGEMENTS

The teams of LAGRAC (Omar Bongo University, Libreville, Gabon) and LARME (University of Science and Technology of Masuku, Franceville, Gabon) thank the Ogooué Maritime Provincial Directorate of Fisheries and the East Environmental Brigade of Haut-Ogooué for their multifaceted support during data collection. More appreciations are extended to Ogooué-Lolo of the Ministry of Water, Forests, Sea, Environment, in

Article DOI: https://doi.org/10.37284/eajfa.6.1.1228

charge of the Climate Plan, and the Land Use Plan (Port-Gentil and Franceville, Gabon); the Governorate of the province of Ogooué Maritime; and the Chiefs of the Achanga and Ozouri villages where the team stayed.

Conflict Of Interest Statement

None declared.

Data Availability

Data underlying data of this article will be shared on reasonable request to the corresponding author.

Funding

This publication was produced with self-funding (LAGRAC and LARME teams), and a small grant of the Institut de Recherche pour le Développement (IRD, France).

REFERENCES

Agence Gabonaise des Études et Observations Spatiales (AGEOS). (2020). *Occupation du sol du Gabon en 2015*. Données vecteurs, Gabon.

Ajonina, G.N. and Usongo, L. (2001). Preliminary quantitative impact assessment of wood extraction on the mangroves of Douala-Edea Forest Reserve, Cameroon. *Tropical Biodiversity*, 7 (2-3), 137-149.

Ajonina, G.N. (2008). Inventory and modelling mangrove forest stand dynamics following different levels of wood exploitation pressures in the Douala-Edea Atlantic Coast of Cameroon, Central Africa. Mitteilungen der Abteilungen für Forstliche Biometrie, Albert-Ludwigs- Universität: Freiburg. 2008-2. https://doi.org/10.13140/RG.2.2.12879.79526

Ajonina, G.N. (2013). Établissement du bilan carbone des mangroves des zones humides du Complexe Ouest du Sud-Bénin en vue de la préparation d'un projet MDP. Rapport de Consultation. Eco-Bénin et Ecosystem Alliance.

Ajonina, G.N., Kairo, J., Grimsditch, G., Sembres, T., Chuyong, G. and Diyouke, E. (2014). Assessment of mangrove carbon stocks in Cameroon, Gabon, the Republic of Congo (RoC) and the Democratic Republic of Congo (DRC) including their potential for reducing emissions from deforestation and forest degradation (REDD+). *The Land/Ocean Interactions in the Coastal Zone of West and Central Africa*, Eds. Diop S., Barusseau J.P. and Descamps C., Springer International Publishing Switzerland. https://doi.org/10.1007/978-3-319-06388-1_15

Akendengue Aken, I. (2021). *Estimation et spatialisation du stock de biomasse et carbone aérien des mangroves estuariennes au Gabon*. Thèse de doctorat en biogéographie soutenue à l'Université Omar Bongo, Gabon.

Akendengue Aken, I., Okanga-Guay, M., Ondo Assoumou, E. et Mombo, J.-B. (2021a). Estimation de la biomasse aérienne (AGB) du genre *Rhizophora* des mangroves des rivières Lowé et Igoumié à Owendo (Gabon). *Revue Africaine et Malgache de REcherche Scientifiques (RAMRES) : Science de la vie, de la terre et agronomie,* Vol 09, Num 02, 38-46.

Akendengue Aken, I., Okanga-Guay, M., Ondo Assoumou, E., Ajonina, G.N. And Mombo, J.B. (2021b). Local allometric equations for estimating aboveground biomass (AGB) of mangroves (*Rhizophora spp*. and *Avicennia germinans*) from the Komo, Mondah and Rio Mouni estuaries in Gabon. *European Scientific Journal: Natural/Life/Medical Sciences*, 17(34), 172-189. https://doi.org/10.19044/esj.2021.v17n34p172

Alongi, D.M. (2014). Carbon Cycling and Storage in Mangrove Forests. *Annual Review of Marine Science*, 6(1), 195-219. https://doi.org/10.1146/annurev-marine-010213-135020

Chatting, M., LeVay, L., Walton, M., Skov, M.W., Kennedy, H., Wilson, S., Al-Maslamani, I. (2020). Mangrove carbon stocks and biomass partitioning in an extreme environment. *Estuarine, Coastal and Shelf Science*, 244, Elsevier. https://doi.org/10.1016/j.ecss.2020.106940

Chave, J., Andalo, C., Brown, S., Cairns, M.A., Chambers, J.Q., Eamus D., Fölser, H., Fromard, F., Higuchi, N., Kira, T., Lescure, J.-P., Nelson, B.W., Ogawa, H., Puig, H., Riéra, B., Yamakura, T. (2005). Tree allometry and improved estimation of carbon stocks and balance in tropical forests. *Oecologia*, 145(1), 87-99. DOI: 10.1007/s00442-005-0100-x

Direction Générale de la Statistique. (2015). Résultats globaux du Recensement Général de la Population et des Logements de 2013 du Gabon (RGPL-2013). Gabon.

Donato, D.C. and Kauffman, J.B. (2011). *Protocols for the measurement, monitoring and reporting of structure, biomass and carbon stocks in mangrove forests*. Working Paper 86 CIFOR, CIFOR Bogor Indonesia. https://doi.org/10.17528/cifor/003749

Donato, D.C., Kauffman, J.B., Murdiyarso, D., Kurnianto, S., Melanie, S.M. and Kanninen, M. (2011). Mangroves among the most carbon-rich forests in the tropics. *Nature Geoscience,* 4, 293-297. https://doi.org/10.1038/ngeo1123

Fromard, F. et Fontes, J. (1994). Structure et dynamique des mangroves de la région de Port-Gentil (Gabon). Analyse de l'impact lié à l'activité pétrolière. Libreville, rapport scientifique à la demande d'Elf-Gabon.

Giesen, W., Wulffraat, S., Zieren, M., Scholten, L**.** (2007). *Mangrove guidebook for Southeast Asia. Bangkok*. Food and Agricultural Organisation & Wetlands International.

Gonzaga, L.T.C., De La Cruz, M.T., Gomez, E.J.P., Barbosa, R. and Samson, M.B.G. (2022). Diversity assessment and geospatial mapping of mangroves in Matalom, Leyte, Philippines. *Aswan University Journal of Environmental Studies (AUJES)*, Vol. 3, No. 3, 324- 336. https://doi.org/10.21608/aujes.2022.145108.1072

Houghton, R.A. (2013). The emissions of carbon from deforestation and degradation in the tropics: past trends and future potential. *Carbon Management*, 4:5, 539-546. https://doi.org/ 10.4155/cmt.13.41

Hourcq, V. et Devigne, J.-P. (1950). *Notice explicative sur la feuille Port-Gentil Ouest (carte géologique de reconnaissance au 1/500 000)*. Gouv. Gén. de l'A.E.F.,Direction Mines et Géologie Afrique Équatoriale Française. Paris, Impr. Nat., 24 p., 1 carte géol. coul. (feuille Port-Gentil Ouest, SA-32 NE-0.9).

Husch, B., Beers, T.W. and Kershaw, J.A.J. (2003). *Forest mensuration*. 4th ed. John Wiley Publishers.

IPCC. (2022). *Climate Change 2022: Impacts, Adaptation and Vulnerability*. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press. Cambridge University Press, Cambridge, UK and New York, NY, USA. https://doi.org/10.1017/9781009325844.

Jachowski, N.R.A., Quak, M.S.Y., Friess, D.A., Duangnamon, D., Webb, E.L. and Ziegler, A. D. (2013). Mangrove biomass estimation in Southwest Thailand using machine learning. *Applied Geography*, 45, Elsevier, 311-321. http://dx.doi.org/10.1016/j.apgeog.2013.09.024

Kauffman, J.B. and Bhomia, R.K. (2017). Ecosystem carbon stocks of mangroves across broad environmental gradients in West-Central Africa: Global and regional

Article DOI: https://doi.org/10.37284/eajfa.6.1.1228

comparisons. *PLoS ONE*, 12(11). https://doi.org/10.1371/journal.pone.0187749

Komiyama, A., Ong, J.E. and Poungparn, S. (2008). Allometry, biomass, and productivity of mangrove forests: A review. *Aquatic Botany*, 89, 128- 137. https://doi.org/10.1016 /j.aquabot.2007.12.006

Lebigre, J.M. (1990). Les marais maritimes du Gabon et de Madagascar : contribution géographique à l'étude d'un milieu naturel tropicale. Thèse de doctorat d'État, Géographie tropicale, Université de Bordeaux III.

Mcleod, E., Chmura, G. L., Bouillon, S., Salm, R., Björk, M., Duarte, C.M., Lovelock, C.E., Schlesinger W.H., Silliman, B.R. (2011). A blueprint for blue carbon: toward an improved understanding of the role of vegetated coastal habitats in sequestering CO2. *Frontiers in Ecology and the Environment*, 9(10), 552-560. https://doi.org/10.1890/110004

Mombo, J.B. (2017). Les reliefs des régions littorales du Gabon. In : Eds Pottier, P., Menie Ovono, Z., Faure, F.E. et Bignoumba, G.S., *Les régions littorales du Gabon. Éléments de réflexion pour une planification stratégique du territoire* (pp. 85-103). Coédition LETG-Nantes Géolittomer (Nantes) et Raponda Walker (Gabon).

Nzigou Boucka, F., Obame, C.V., Manfoumbi, F., Nzue Mba, A., Ngui Ondo, M., Ovono, V., Mambimba Ndjoungui, A. (2021). Cartographie de l'occupation du sol du Gabon en 2015 : Changements intervenus entre 2010 et 2015. *Revue Française de Photogrammétrie et de Télédétection*, 223, 118-128. https://doi.org/10.52638/rfpt.2021.567

Ondo Assoumou, E. (2006). Dynamique des paysages végétaux du littoral centre-ouest du Gabon autour de Port-Gentil : approche spatiale et analyse des données de terrain. Thèse de doctorat, Biogéographie, Université de Montpellier 3, France. http://www.mgm.fr/UMR/Ondo/These.pdf

Ondo Assoumou, E. (2017). Les paysages végétaux du littoral gabonais. In Eds Pottier, P., Menie Ovono, Z., Faure, F.E. et Bignoumba, G.S., *Les régions littorales du Gabon. Éléments de réflexion pour une planification stratégique du territoire* (pp. 41-57). Coédition LETG-Nantes Géolittomer (Nantes) et Raponda Walker (Gabon).

Picard, N., Saint-André, L. et Henry, M. (2012). Manuel de construction d'équations allométriques pour l'estimation du volume et la biomasse des arbres : De la mesure de terrain à la prédiction. Food and Agricultural Organization (FAO) of the United Nations.

Rabenkogo, N. (2007). *Le littoral Nkomi (Gabon) : contribution géographique à la conservation des milieux naturels.* Thèse de doctorat : Géographie et Aménagement de l'Espace, Université de Montpellier II.

Simard, M., Fatoyinbo, L., Smetanka, C., Rivera-Monroy, V.H., Castaneda, E., Thomas, N. and Van der stocken, T. (2019). *Global Mangrove Distribution, Aboveground Biomass, and Canopy Height (Gabon Dataset)*. ORNL DAAC, Oak Ridge, Tennessee, USA. https://doi.org/10.3334/ORNLDAAC/1665

Spalding, M., Kainuma, M. and Collins, L. (2010). *World atlas of mangroves*. Routledge, ITTO, ISME, FAO, UNEP-WCMC, UNESCO-MAB and UNU-INWEH.

Stovall, A. E., Fatoyinbo, T., Thomas, N. M., Armston, J., Ebanega, M. O., Simard, M., Trettin, C., Obiang Zogo, R. V., Akendengue Aken, I., Debina, M., Mekui Me Kemoe, A., Ondo Assoumou, E., Kim, J. S., Lagomasino, D., Lee, S.-K., Ndong Obame, J. C., Voubou, G. D., Zame Essono, C. (2021). Comprehensive comparison of airborne and spaceborne SAR and LiDAR estimates of forest structure in the tallest mangrove forest on earth. *Science of Remote Sensing*, 4, 100034. https://doi.org/10.1016/j.srs.2021.100034

Tomlinson, P.B. (1986). *The botany of mangroves.* Cambridge Tropical Biology Series, Cambridge.

UNEP (United Nations Environment Program) - WCMC (World Conservation Monitoring Centre) (2007). *The mangroves of West-Central Africa*. UNEPWCMC report. https://archive.org/details/mangrovesofweste07corc

Zianis, D. and Mencuccini, M. (2004). On simplifying allometric analyses of forest biomass. *Forest Ecology and Management*, 187(2- 3), 311– 332. https://doi.org/10.1016/j.foreco.2003.07.007.