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Aboveground Biomass Estimation of *Avicennia marina* (Forssk) Vierh. and *Rhizophora mucronata* Lam. in the Mangoky Delta, SW Madagascar

Andriamparany Rakotomavo

Higher Institute of Sciences, Environment and Sustainable Development (ISSEDD), University of Toamasina, Toamasin, Madagascar
Email: andri.savaivo@blueline.mg

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Abstract

Forty-three trees (23 *Rhizophora mucronata* and 20 *Avicennia marina*) were studied for the establishment of allometric relationships between the aboveground biomass "y" and the following dendrometric variables "x": diameter at breast height DBH, $(DBH)^2$ product Ht (where Ht is the total height), and the basal circumference Cb of the trees. The Log y = A Log $[(DBH)^2 \cdot Ht]$ + B equation gives a fairly satisfactory regression coefficient ($R^2 > 0.9$) for the woody compartments. For *A. marina*, it is the equation Log y = A Log Cb + B that is the best correlated for the estimation of less woody compartments ($R^2 = 0.826$ to 0.847). As for *R. mucronata*, these are much more related to DBH. For trees of 8 - 10 m height, the aboveground biomass of the delta is higher (171 $t \cdot ha^{-1}$ for *R. mucronata*) than that of Puerto Rico, but quite comparable to that of Australia (110 $t \cdot ha^{-1}$ for *A. marina*). The first tools for estimating aboveground biomass are given for these two characteristic species of the Indo-Pacific Region and East Africa. Because of the low values of the regression coefficients for some allometric relationships obtained, precautions should be taken in case of extrapolation.

Keywords

Avicennia marina, Aboveground Biomass, Mangoky Delta, Mangrove, Allometric Relationships, *Rhizophora mucronata*

1. Introduction

Covering nearly 327,000 ha [1] [2] to 340,300 ha (according to the map by [3]), the Malagasy mangroves belong to the Indo-Pacific region [4]. Recent evaluations by [5] shed light on these spatial uncertainties by advancing the figure of 213,000 ha of remaining mangroves for the entire Big Island, representing 2% of global mangroves [6] [7]. Those of Madagascar are poor in floristic diversity: only 5 Mangrove families, according to [2], and 9 characteristic species of East Africa, according to [8]. 98% of the Malagasy mangroves are located on the West coast of Madagascar [7] [9] [10] [11].

According to [5], Madagascar lost 57,359 ha of its mangroves, which is 21% of their total area between 1990 and 2010, and this with an annual deforestation rate of 1.06%. This spatial loss follows the global trend described by [12] [13] [14] that Malagasy mangroves are degraded due to anthropogenic and natural pressures. Reactions to this degradation, various forms of preservation such as REDD+ and the financial valuation of carbon from Mangroves are proposed by various authors, despite the associated challenges [14] [15] [16] [17]. To do this, knowledge of the carbon sequestration potential of a Mangrove is unavoidable, and as a corollary, it is important to know the amount of biomass produced in the roots, leaves, stems, as well as through the different aerial and underground compartments of the plant.

Very few reliable scientific data exist on Malagasy mangroves [18]. Apart from the remote sensing work undertaken by [19] in the region, mangroves in the Mangoky Delta remain unexplored and much effort is still needed in ecological diagnosis [11]. Data on their productivity are lacking [11] despite current national and international concerns for the sound management of coastal resources. No baseline study on specific tools for biomass modeling exists for the country and the use of allometric equations developed elsewhere remains for the moment the only way to know the biomass potential of Malagasy Mangroves in general and those of Mangoky Delta in particular. Having confirmed this gap on the East African Mangrove ecosystem, [20] has studied the *Rhizophora mucronata* Lam (Rhizophoraceae) biomass in Gazi Bay [21]; for their part, advanced allometric relationships for the estimation of the aboveground biomass of this same species, still in Gazi. [22] has studied the *Bruguiera gymnorhiza* (L.) Lamk Mangrove biomass in South Africa. Thus, the formula developed by these authors, as well as those advanced by [23] [24] [25] [26], and recently by [21] are the main reference available for the aboveground biomass estimation of the Kenyan and Eastern African *R. mucronata* [27]. However, the global basic equations established by [28] and [29] remain benchmarks, in spite of the possible stationary and structural differences between the Malagasy Mangroves and those of other countries.

To compensate for these shortcomings, the present article tries to provide quantitative data on the aerial phytomass of the two species characteristic of the Mangoky Delta, namely *Avicennia marina* Vierh. (Avicenniaceae) and *Rhizophora mucronata*. It tries to establish allometric relationships between the aboveground biomass, the diameter at breast height, and the total height and basal circumference of trees. The mathematical models thus established will constitute specific tools for the practical estimation of the production potential in above-ground biomasses of the two Mangrove species of the Mangoky Delta—SW Madagascar.

2. Materials and Methods

2.1. The Study Area

Located on the South-West coast of Madagascar, the study area concerns the Mangoky Delta (**Figure 1**). Crossed by the Mangoky River, it lies between 43˚26' and 43˚44' East longitude, 21˚15' and 21˚35' South latitude. With decreasing precipitations of 600 to 400 mm per year from North to South, its climate is dry, which can even be described as semi-arid in the boreal part of the delta. The average annual temperature of the Mangoky Delta oscillates between 24.3˚C and 24.9˚C, with a high annual evapotranspiration of 455 to 755 mm, and a high annual insolation of 3551 to 3724 hours. With a tidal range of about 3 m, the delta comprises 11,790 ha of mangrove, according to satellite images of 2000 [11] [30].

2.2. Quantification of Aerial Phytomass

Forty-three trees (23 *Rhizophora mucronata* and 20 *Avicennia marina*) were selected and fell to the ground on October 2009. These operations were preceded by a floristic inventory of the trees, which was carried out in four 100 m linear transects (**Figure 1**), arranged randomly and perpendicular to the stream lines, each containing ten plots of 10 m × 10 m. For each of the two species studied, the selection of trees was made on the basis of diameter at breast height (DBH at 1.30 m; **Table 1**), with five to eight individuals per diameter class of 5 cm. The trees for which the DBH was less than 5 cm were not selected [11] [30]. It should be noted that in addition to the pre-identification of *in situ* species, using some morphological identification keys of the leaves, roots, stems, flowers and fruits, herbarium collections were collected on site in order to confirm real scientific names of the trees at the Botanical Laboratory of Tsimbazaza in Antananarivo.

After felling the trees, the following main dendrometric parameters were measured on the site itself:

- Height of the stem "Hf";
- Height of the crown "Hh";
- Total height of the tree "Ht = Hf + Hh";
- Width of the crown "Lh";
- Circumference of the stem at the base, on the ground "Cb";
- Diameter of the tree at 1.30 m from the ground "DBH".

The entire aerial part of each tree was weighed on site, distinguishing foliage, boughs (less than 2 cm in diameter), branches (woody part of more than 2 cm in diameter located above first branch) and the stem (woody part below the first branch). The weight of hard wood (whole stem and branches) was calculated.

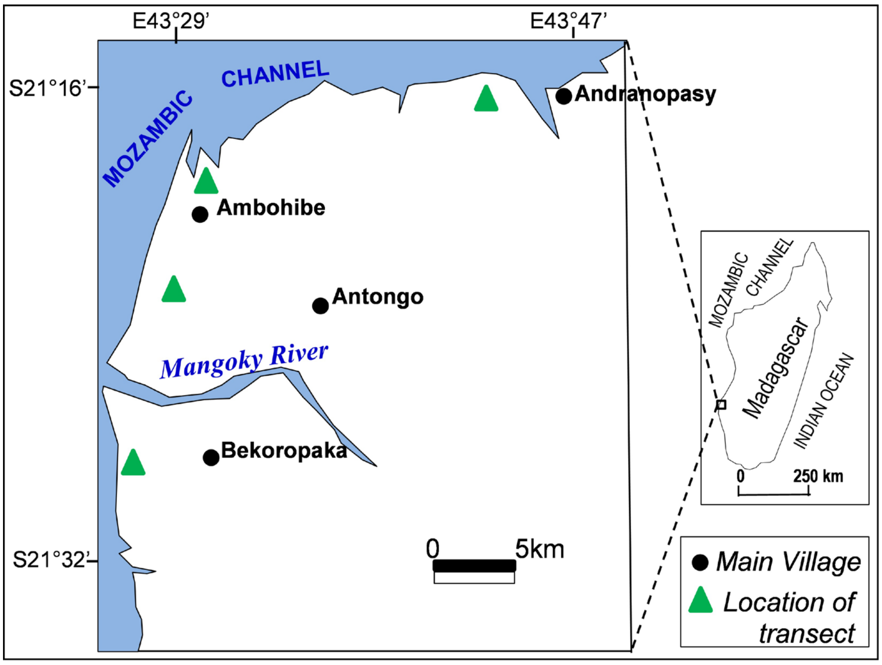

Figure 1. Location of the study site (Mangoky Delta—SW Madagascar).

Table 1. Number of trees felled during sampling.

	5 cm < DBH < 10 cm	10 cm < DBH < 15 cm	15 cm < DBH < 20 cm	20 cm < DBH < 25 cm	TOTAL
Avicennia marina	5	5	5	5	20
Rhizophora mucronata	5	5	8	5	23
TOTAL	10	10	13	10	43

The aerial roots of *Rhizophora mucronata* were also weighed. The fruits and the flowers, not very abundant on the felled trees, were not taken into account. For each tree and for each compartment, samples were taken, weighed and placed in an oven (105˚C) during 72 hours, and this, in order to deduce the weight of dry phytomass.

2.3. Mathematical Modeling of Dry Biomass

The modeling of the dry biomass of felled trees was carried out from the logarithmic equation:

$$\text{Logy} = \text{ALogx} + \text{B} \tag{1}$$

or whether:

$$y = Kx^{A} \text{ with } B = \text{LogK} \tag{2}$$

where y represents dry biomass, x a variable defined from the measured dimensions of the tree such as DBH, $(DBH)^2 \cdot Ht$ and Cb.

The linearity of established logarithmic regressions was verified from the correlation coefficient R^2, which is considered significant from 0.9.

3. Results

3.1. Structures and Aboveground Biomass

At least 6 species of Mangrove are present in the studied delta: *Avicennia marina, Xylocarpus granatum* Koen. (Meliaceae), *Ceriops tagal* C. B. Rob. (Rhizophoraceae), *Rhizophora mucronata, Bruguiera gymnorhiza*, and *Sonneratia alba*. The average height of trees varies from 8.3 to 9.2 m, respectively for the facies with *A. marina* and *R. mucronata.* Their average diameter is 14 cm (with a minimum of 6.37 cm and a maximum of 23.57 cm) for the first and 15 cm (with a minimum of 6.05 cm and a maximum of 21.34 cm) for the second.

The total above ground biomass varies between 9 and 235 kg per tree for *Avicennia marina*. It is from 11 to 360 kg for *Rhizophora mucronata*. The arithmetic averages obtained are respectively around 110 kg and 173 kg per tree for both species (Table 2 and Table 3).

Table 2. Partial and total dry aerial phytomass of *Avicennia marina* (Hf: Height of the stem; Hh: Height of the crown; Ht = Hf + Hh = Total height of the tree; Lh: Width of the crown; Cb: Circumference of the stem at the base; DBH: Diameter of the tree at 1.30 m from the ground).

Tree N°	DBH (cm)	Hf (cm)	Hh (cm)	Ht (m)	Lh (cm)	Cb (cm)	Stem (kg)	Branches (kg)	Hard wood (kg)	Boughs (kg)	Leaves (kg)	Total (kg)
38	6.37	90	420	5.10	400.00	25.00	2.90	4.74	7.64	0.58	0.83	9.05
39	6.69	180	400	5.80	300.00	30.00	6.44	4.43	10.87	1.46	1.65	13.98
27	7.32	200	400	6.00	400.00	39.00	7.73	6.01	13.74	1.75	2.27	17.76
36	7.64	110	540	6.50	160.00	34.00	7.09	15.81	22.90	1.46	2.68	27.04
40	8.60	100	370	4.70	250.00	27.00	3.87	7.59	11.46	0.88	0.62	12.95
10	12.74	350	620	9.70	270.00	59.00	27.70	26.56	54.27	2.34	3.10	59.70
32	14.33	200	500	7.00	350.00	52.00	19.97	39.21	59.19	5.26	4.95	69.40
12	14.97	320	620	9.40	350.00	70.00	41.88	31.62	73.50	11.10	11.97	96.57
17	14.97	300	500	8.00	375.00	124.00	90.20	92.97	183.17	14.02	14.03	211.23
23	14.97	600	650	12.50	450.00	55.00	75.38	16.44	91.83	1.75	2.89	96.47
35	15.29	210	500	7.10	400.00	72.00	31.57	49.33	80.90	4.09	4.54	89.53
31	16.24	250	550	8.00	450.00	58.00	30.93	46.17	77.10	4.67	5.37	87.14
16	16.88	290	390	6.80	500.00	100.00	51.54	56.92	108.47	12.27	11.97	132.70
30	16.88	200	600	8.00	400.00	63.00	32.21	36.68	68.90	3.80	3.71	76.41
34	18.15	150	600	7.50	450.00	50.00	39.95	84.12	124.07	6.43	7.02	137.51
11	20.38	350	700	10.50	550.00	80.00	74.09	69.57	143.67	8.76	9.08	161.51
13	20.70	320	700	10.20	620.00	123.00	96.64	98.03	194.68	15.19	23.53	233.39
26	21.34	310	1000	13.10	520.00	90.00	70.87	139.15	210.02	4.67	6.60	221.29
15	21.97	310	750	10.60	550.00	85.00	103.08	104.99	208.08	13.44	13.62	235.13
18	23.57	370	600	9.70	550.00	97.00	96.64	88.55	185.19	13.44	11.14	209.77

Table 3. Partial and total dry aerial phytomass of *Rhizophora mucronata* (Hf: Height of the stem; Hh: Height of the crown; Ht = Hf + Hh = Total height of the tree; Lh: Width of the crown; Cb: Circumference of the stem at the base; DBH: Diameter of the tree at 1.30 m from the ground).

Tree N°	DBH (cm)	Hf (cm)	Hh (cm)	Ht (m)	Lh (cm)	Cb (cm)	Stem (kg)	Branches (kg)	Hard wood (kg)	Boughs (kg)	Leaves (kg)	Roots (kg)	Total (kg)
37	6.05	120	350	4.70	250.00	25.00	3.39	4.11	7.50	1.42	1.70	0.60	11.23
7	6.69	260	140	4.00	160.00	24.00	8.15	6.32	14.47	0.47	0.85	6.03	21.82
41	6.69	180	330	5.10	230.00	31.00	6.11	8.22	14.33	1.66	4.68	6.03	26.69
6	7.64	470	250	7.20	250.00	29.00	15.62	6.32	21.93	1.19	1.06	6.03	30.21
14	8.92	340	340	6.80	300.00	28.00	15.62	10.11	25.73	2.37	2.55	14.46	45.12
1	10.19	440	600	10.40	450.00	33.00	30.21	13.90	44.12	3.09	4.89	12.96	65.05
3	10.19	600	450	10.50	400.00	40.00	42.77	18.33	61.10	2.85	2.55	15.07	81.57
2	10.51	550	400	9.50	400.00	36.00	32.59	7.90	40.49	1.66	1.91	9.04	53.10
8	12.10	580	450	10.30	280.00	48.00	51.60	30.97	82.56	4.75	5.32	16.87	109.50
4	14.97	550	450	10.00	550.00	47.00	69.93	42.34	112.27	10.45	9.36	43.39	175.47
22	15.29	420	600	10.20	450.00	57.00	64.50	56.88	121.37	6.65	8.08	66.29	202.39
24	15.29	700	550	12.50	400.00	55.00	90.98	41.08	132.05	5.22	7.66	66.89	211.83
9	15.92	320	400	7.20	550.00	52.00	46.85	74.57	121.42	13.77	14.47	43.39	193.04
21	17.20	480	550	10.30	400.00	59.00	75.36	48.03	123.39	4.27	10.21	90.39	228.27
5	18.15	570	400	9.70	500.00	65.00	101.84	31.60	133.44	8.07	6.38	42.18	190.07
20	18.15	800	450	12.50	450.00	66.00	152.08	22.12	174.20	2.85	5.11	75.33	257.48
28	18.79	550	550	11.00	550.00	64.00	135.78	82.15	217.94	5.70	9.79	113.29	346.72
33	19.75	210	550	7.60	600.00	65.00	43.45	119.44	162.89	14.72	18.72	75.93	272.26
25	20.38	640	470	11.10	450.00	66.00	127.64	60.04	187.67	8.07	9.79	66.29	271.82
19	20.70	550	700	12.50	450.00	63.00	116.77	88.47	205.25	6.65	11.49	90.39	313.78
42	20.70	210	550	7.60	600.00	65.00	42.77	119.44	162.21	14.72	18.72	38.57	234.22
29	21.34	670	500	11.70	550.00	73.00	175.84	69.52	245.36	7.12	9.79	97.62	359.89
43	21.34	400	550	9.50	500.00	72.00	112.70	86.58	199.28	13.77	15.74	42.79	271.58

3.2. Allometric Relationships

With *Avicennia marina*, the Log y = A Log [$(DBH)^2 \cdot Ht$] + B equation has a correlation coefficient greater than 0.9 for the more woody compartments such as hardwood (R^2 = 0.931) and the stem (R^2 = 0.908). The use of the variable $(DBH)^2$. Ht is also quite satisfactory (R^2 = 0.92) in the case of the total aboveground biomass (Figure 2, Table 4).

This observation is verified in *Rhizophora mucronata* (Figure 3, Table 5), although the R^2 value for the roots is less significant (0.839) under the formula Log y = A Log [$(DBH)^2 \cdot Ht$ + B]. As for the total aboveground biomass, the coefficient remains the same (R^2 = 0.959) as well as with Log y = A Log [$(DBH)^2 \cdot Ht$] +

B and Log y = A Log DBH + B.

It is the Log y = A Log Cb + B equation that is the most correlated for the estimation of less woody compartments such as the leaves and boughs of *A. marina*, and this, despite the low value of R^2 (respectively 0.847 and 0.826). It is the same for the branches where $R^2 = 0.876$.

Despite the low value of R^2 (0.734 to 0.865), it is with the DBH variable that we obtain the best correlation for estimating the weight of branches, leaves and boughs of *R. mucronata.* With a regression coefficient of 0.93 for both hard woods and total aboveground biomass, the use of basal circumference coefficient Cb is not as conclusive as the use of DBH or $[(DBH)^2 \cdot Ht$.

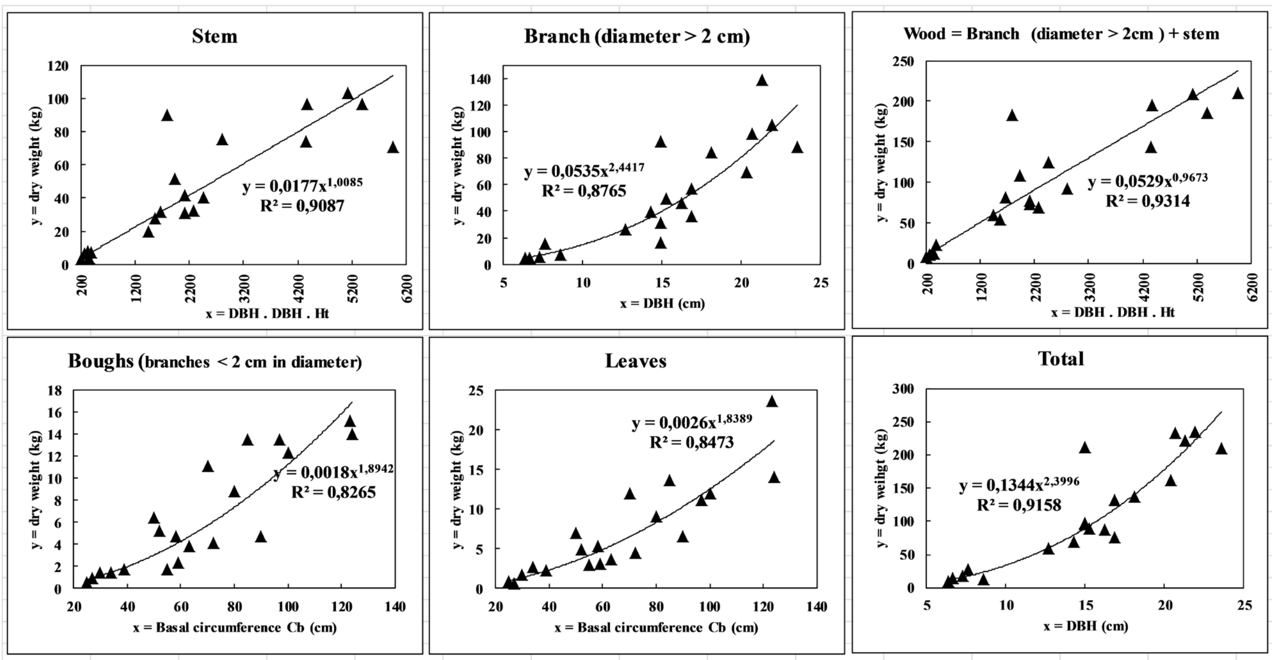

Figure 2. Allometric relationship on the different aerial compartments of *Avicennia marina*.

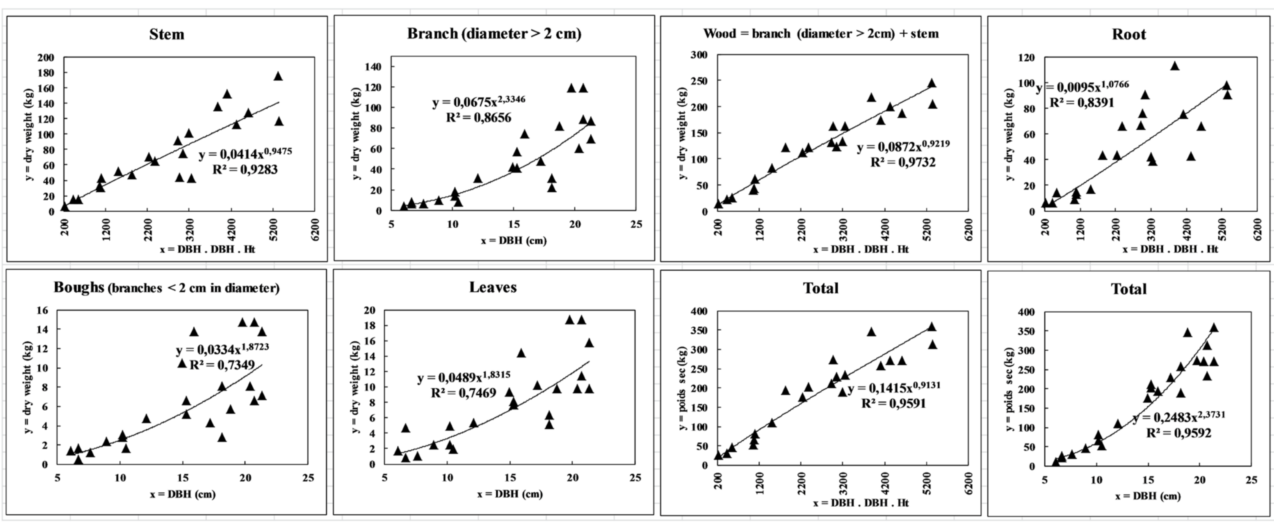

Figure 3. Allometric relationship on the different aerial compartments of *Rhizophora mucronata*.

Table 4. Value of parameters A and B in the relation Log y = A Log x + B according to dendrometric variables x of the *Avicennia marina* species.

VARIABLE x	COMPARTMENT	A	B	R^2	n
DBH	Hard wood	2.47	−1.018	0.924	20
$(DBH)^2 \cdot Ht$	Hard wood	0.967	−1.284	0.931	20
Cb	Hard wood	2.06	−1.854	0.853	20
DBH	Branches	2.441	−1.276	0.876	20
$(DBH)^2 \cdot Ht$	Branches	0.928	−1.444	0.833	20
Cb	Branches	1.999	−2.046	0.78	20
DBH	Leaves	1.89	−1.481	0.674	20
$(DBH)^2 \cdot Ht$	Leaves	0.73	−1.658	0.661	20
Cb	Leaves	1.838	−2.699	0.847	20
DBH	Stem	2.526	−1.432	0.867	20
$(DBH)^2 \cdot Ht$	Stem	1.008	−1.770	0.908	20
Cb	Stem	2.186	−2.523	0.862	20
DBH	Boughs	2.019	−1.699	0.707	20
$(DBH)^2 \cdot Ht$	Boughs	0.755	−1.796	0.65	20
Cb	Boughs	1.894	−3.000	0.826	20
DBH	Total	2.399	−0.873	0.915	20
$(DBH)^2 \cdot Ht$	Total	0.938	−1.125	0.92	20
Cb	Total	2.032	−1.745	0.872	20

LEGEND: y = phytomass of dry matter in kg; DBH in cm; Ht in m; Cb in cm; R^2: regression coefficient of the equation Log y = A Log x + B, *i.e.* $y = kx^A$ such that B = Log k; n = number of trees felled during sampling.

Table 5. Value of parameters A and B in the relation Log y = A Log x + B according to dendrometric variables x of the *Rhizophora mucronata* species.

VARIABLE x	COMPARTMENT	A	B	R^2	n
DBH	Hard wood	2.382	−0.799	0.962	23
$(DBH)^2 \cdot Ht$	Hard wood	0.921	−1.060	0.973	23
Cb	Hard wood	2.679	−2.699	0.934	23
DBH	Branches	2.334	−1.174	0.865	23
$(DBH)^2 \cdot Ht$	Branches	0.851	−1.268	0.777	23
Cb	Branches	2.603	−3.000	0.826	23
DBH	Leaves	1.831	−1.319	0.746	23
$(DBH)^2 \cdot Ht$	Leaves	0.661	−1.367	0.658	23
Cb	Leaves	2.074	−3.000	0.735	23
DBH	Stem	2.334	−0.987	0.834	23
$(DBH)^2 \cdot Ht$	Stem	0.947	−1.387	0.928	23

Continued

Cb	Stem	2.633	−3.000	0.815	23
DBH	Roots	2.779	−1.721	0.828	23
$(DBH)^2 \cdot Ht$	Roots	1.076	−2.046	0.839	23
Cb	Roots	3.084	−3.699	0.782	23
DBH	Boughs	1.872	−1.481	0.734	23
$(DBH)^2 \cdot Ht$	Boughs	0.682	−1.553	0.659	23
Cb	Boughs	2.081	−3.000	0.697	23
DBH	Total	2.373	−0.606	0.959	23
$(DBH)^2 \cdot Ht$	Total	0.913	−0.851	0.959	23
Cb	Total	2.668	−2.398	0.930	23

LEGEND: y = phytomass of dry matter in kg; DBH in cm; Ht in m; Cb in cm; R^2: regression coefficient of the equation Log y = A Log x + B, *i.e.* $y = kx^A$ such that B = Log k; n = number of trees felled during sampling.

4. Discussions

4.1. The Equations

The types of Equations (1) and (2) have been used by many authors to estimate aboveground biomass in Kenya [20] [21] [31], in French Guiana [23], in South Florida [32] and in Malaysia [25], where DBH is the main variable. [20] uses the tree circumference to model the aboveground biomass of *Ceriops tagal* and *Rhizophora mucronata*. Others such as [24] [33] [34] use $(DBH)^2 \cdot Ht$ to estimate it.

The present study tries to value the gains of the equations developed by these various authors by adapting them with the variables of the different compartments of a Mangoky Delta tree (**Table 6**). It tries to check for any discrepancies between the values of the allometric parameters established elsewhere in the world and those obtained on a smaller scale as the delta.

4.2. Productivity

With 60 $t \cdot ha^{-1}$ of total aboveground biomass, (all species combined, average tree height = 5.83 m, mean DBH = 8 cm), the Mangoky Delta Mangrove is comparable to that of West Africa where [35] [36] found 55 to 60 $t \cdot ha^{-1}$ at Saloum, for trees of 5.65 m high. It should be noted that in Puerto Rico, Mangrove yields 58 $t \cdot ha^{-1}$ $year^{-1}$ of raw primary products and 9 $t \cdot ha^{-1}$ $year^{-1}$ of net primary products [37].

As part of this study, where tree total heights were 8.3 m and 9.2 m, respectively for *Rhizophora mucronata* (DBH = 15 cm) and *Avicennia marina* (DBH = 14 cm), the respective total biomass values of 110 $t \cdot ha^{-1}$ and 171 $t \cdot ha^{-1}$ are important compared to the figures found by [38] in Puerto Rico where Ht = 8 m and y = 62.9 $t \cdot ha^{-1}$ for *R. mucronata*. However, they are comparable to those measured in Australia where [39] found y = 99.7 $t \cdot ha^{-1}$ for trees of *A. marina* of

8.5 m high; and where [40] obtained y = 104.1 $t \cdot ha^{-1}$ for strata of 7 m. In the USA, [41] found y = 136 $t \cdot ha^{-1}$ for the species *Rhizophora spp.* of 9 m high. Those differences are surely linked to latitudinal and longitudinal variations of the studied ecosystems [42]. Indeed, [43] found 240 $t \cdot ha^{-1}$ for the *R. mucronata* species in Sri Lanka (8˚2'S), compared to 452.02 $t \cdot ha^{-1}$ in Kenya (4˚25'S) according to [21].

The data on the share of the different compartments in the biomass constitution are comparable to the figures obtained by [20] in Kenya, namely for the stems and roots of *R. mucronata* (**Table 7**). However, it seems that the Gazi trees have more leaves than the delta ones where about one-third of the total aboveground biomass is provided by the branches.

4.3. Allometric Relationships on the Total Aboveground Biomass

For *Rhizophora*, the expression of total aboveground biomass can be written in two forms:

$\text{Log } y = 2.371 \text{ Log DBH} - 0.606$;

$\text{Log } y = 0.913 \text{ Log } [(\text{DBH})^2 \cdot \text{Ht}] - 0.851$.

In either equation, the regression coefficient remains the same ($R^2 = 0.959$). The values of A and B presented in this study are substantially similar to those found by [24] in Southern Japan and [44] in Indo-Pacific. It is the same for the case of *Avicennia* where in French Guiana, [23] found A = 2.4 and B = −0.8539 respectively, compared to 0.399 and −0.873 in the Mangoky Delta. In addition to the longitudinal and latitudinal factors reported by [42], these slight differences seem related to the productivity of the ecosystems studied as we have mentioned above. The physiognomic difference between the species *R. apiculata* and *R. mucronata* on one hand and between *A. germinans* and *A. marina*, on the other hand also influences the weight of the trees studied.

4.4. Allometric Relationships on Hard Wood

Regarding hardwood (=stem + branches), the most significant allometric relationships established in this study are:

$\text{Log } y = 0.921 \text{ Log } [(\text{DBH})^2 \cdot \text{Ht}] - 1.060$ for *R. mucronata* where $R^2 = 0.973$;

$\text{Log } y = 0.967 \text{ Log } [(\text{DBH})^2 \cdot \text{Ht}] - 1.284$ for *A. marina* where $R^2 = 0.931$.

Using the variable DBH, the relationship becomes less significant ($R^2 = 0.962$ for *R. mucronata* and 0.924 for *A. marina*); the differences in value between [21] parameters A and B and those of this study are respectively 0.14 and −1.9 for *R. mucronata*. Indeed, the trees studied in Kenya include much more stem (50.2% ± 7.3% of the total biomass) than those evaluated in the Mangoky Delta (40% ± 12.4% of the total biomass) (**Table 7**).

Regarding the *Avicennia marina* species, the equation $\text{Log } y = 2.47 \text{ Log DBH} - 1.018$ obtained in the Mangoky Delta is relatively similar to that established by [26] in Queensland for *R. apiculata* and *R. stylosa*. Indeed, the values of A and B respectively are around 2.5 and −1 (**Table 6**).

Table 6. Allometric relationships between dry phytomass and the variables DBH and $(DBH)^2 \cdot Ht$, according to some authors.

Authors	Site	Species	DBH	Compartment	Equation	A	B	R^2	n
[25]	Perak, Malaysia	*Rhizophora apiculata*	3.5 to 88	Total	Log y = A Log DBH + B	2.318	−1.671	0.98	73
[25]	Perak, Malaysia	*Rhizophora apiculata*	15 to 88	Total	Log y = A Log DBH + B	2.420	−1.832	0.98	57
[21]	Gazi Bay, Kenya	*Rhizophora mucronata*	2.3 to 23.3	Total	$y = B\ (DBH)^A$	2.5154	−0.8069	0.9799	15
[23]	French Guiana	*Rhizophora mangle*	1 to 42	Total	$y = b\ (DBH)^A$ where B = Log b	2.6	−0,8928		
[44]	Indo-West Pacific	*Rhizophora apiculata*	5 to 31	Total	Log y = A Log DBH + B	2.516	−0.767		
[26]	North-Eastern Queensland	*Rhizophora apiculata* and *R. stylosa*	3 to 25	Total	Log y = A Log DBH + B	2.6848	−0.9789	0.995	23
The present study	**Mangoky, SW Madagascar**	***Rhizophora mucronata***	**6.05 to 21.34**	**Total**	**Log y = A Log DBH + B**	**2.373**	**−0.606**	**0.959**	**23**
The present study	**Mangoky, SW Madagascar**	***Rhizophora mucronata***	**6.05 to 21.34**	**Total**	**Log y = A Log $[(DBH)^2 \cdot Ht]$ + B**	**0.913**	**−0.851**	**0.959**	**23**
[24]	Ishigaki Island, South Japan	*Rhizophora mucronata*	16.2	Total	$y = b\ [(DBH)^2 \cdot Ht]^a$ where B = Log b	0.931	−0.9956		9
The present study	**Mangoky, SW Madagascar**	***Rhizophora mucronata***	**6.05 to 21.34**	**Total**	**Log y = A Log $[(DBH)^2 \cdot Ht]$ + B**	**0.913**	**−0.851**	**0.959**	**23**
[23]	French Guiana	*Avicennia germinans*	1 to 32	Total	$y = b\ (DBH)^A$ where B = Log b	2.4	−0.8539		
The present study	**Mangoky, SW Madagascar**	***Avicennia marina***	**6.37 to 23.57**	**Total**	**Log y = A Log DBH + B**	**2.399**	**−0.873**	**0.915**	**20**
The present study	**Mangoky, SW Madagascar**	***Avicennia marina***	**6.37 to 23.57**	**Total**	**Log y = A Log $[(DBH)^2 \cdot Ht]$ + B**	**0.938**	**−1.125**	**0.92**	**20**
[26]	North-Eastern Queensland	*Rhizophora apiculata* and *R. stylosa*	3 to 25	Hard wood	Log y = A Log DBH + B	2.5621	−1.0528	0.991	23
[25]	Perak, Malaysia	*Rhizophora apiculata*	3.5 to 88	Hard wood	Log y = A Log DBH + B	2.550	−2.175	0.99	70
[25]	Perak, Malaysia	*Rhizophora apiculata*	15 to 88	Hard wood	Log y = A Log DBH + B	2.477	−2.050	0.98	54
[21]	Gazi Bay, Kenya	*Rhizophora mucronata*	2.3 to 23.3	Hard wood	$y = B\ (DBH)^A$	2.5299	−1.1264	0.9703	15
The present study	**Mangoky, SW Madagascar**	***Rhizophora mucronata***	**6.05 to 21.34**	**Hard wood**	**Log y = A Log DBH + B**	**2.382**	**−0.799**	**0.962**	**23**
The present study	**Mangoky, SW Madagascar**	***Avicennia marina***	**6.37 to 23.57**	**Hard wood**	**Log y = A Log DBH + B**	**2.47**	**−1.018**	**0.924**	**20**
The present study	**Mangoky, SW Madagascar**	***Avicennia marina***	**6.37 to 23.57**	**Hard wood**	**Log y = A Log $[(DBH)^2 \cdot Ht]$ + B**	**0.967**	**−1.284**	**0.931**	**20**
[25]	Perak, Malaysia	*Rhizophora apiculata*	3.5 to 88	Leaves	Log y = A Log DBH + B	1.378	−1.632	0.73	71
[25]	Perak, Malaysia	*Rhizophora apiculata*	15 to 88	Leaves	Log y = A Log DBH + B	1.616	−1.969	0.73	71
[21]	Gazi Bay, Kenya	*Rhizophora mucronata*	2.3 to 23.3	Leaves	$y = B\ (DBH)^A$	2.5628	−1.8069	0.8996	15

Continued

The present study	**Mangoky, SW Madagascar**	***Rhizophora mucronata***	**6.05 to 21.34**	**Leaves**	**Log y = A Log DBH + B**	**1.831**	**−1.319**	**0.746**	**23**
The present study	**Mangoky, SW Madagascar**	***Avicennia marina***	**6.37 to 23.57**	**Leaves**	**Log y = A Log DBH + B**	**1.89**	**−1.481**	**0.674**	**20**
The present study	**Mangoky, SW Madagascar**	***Avicennia marina***	**6.37 to 23.57**	**Leaves**	**Log y = A Log Cb + B**	**1.838**	**−2.699**	**0.847**	**20**
[26]	North-Eastern Queensland	*Rhizophora apiculata* and *R. stylosa*	3 to 25	Leaves	Log y = A Log DBH + B	2.1072	−1.8571	0.857	23
[26]	North-Eastern Queensland	*Rhizophora apiculata* and *R. stylosa*	3 to 25	Branch	Log y = A Log DBH + B	2.6844	−1.8953	0.912	23
[21]	Gazi Bay, Kenya	*Rhizophora mucronata*	2.3 to 23.3	Branch	$y = B\,(DBH)^A$	2.4606	−1.4634	0.9860	15
The present study	**Mangoky, SW Madagascar**	***Rhizophora mucronata***	**6.05 to 21.34**	**Branch**	**Log y = A Log DBH + B**	**2.334**	**−1.174**	**0.865**	**23**
[26]	North-Eastern Queensland	*Rhizophora apiculata* and *R. stylosa*	3 to 25	Root	Log y = A Log DBH + B	3.1353	−2.1663	0.968	23
[21]	Gazi Bay, Kenya	*Rhizophora mucronata*	2.3 to 23.3	Root	$y = B\,(DBH)^A$	2.5263	−1.3270	0.9649	15
[25]	Perak, Malaysia	*Rhizophora apiculata*	15 to 88	Root	Log y = A Log DBH + B	2.546	−2.94	0.84	41
The present study	**Mangoky, SW Madagascar**	***Rhizophora mucronata***	**6.05 to 21.34**	**Root**	**Log y = A Log DBH + B**	**2.779**	**−1.721**	**0.828**	**23**
The present study	**Mangoky, SW Madagascar**	***Rhizophora mucronata***	**6.05 to 21.34**	**Root**	**Log y = A Log [$(DBH)^2 \cdot Ht$] + B**	**1.076**	**−2.046**	**0.839**	**23**

LEGEND: y in kg of dry matter; DBH in cm; R^2: correlation coefficient; n = number of trees felled during sampling.

4.5. Allometric Relationships on Leaves

The most significant allometric relationships found in the Mangoky Delta are:

Log y = 1.831 Log DBH − 1.319 for *R. marina* where $R^2 = 0.746$;

Log y = 1.838 Log Cb − 2.699 for *A. marina* where $R^2 = 0.847$.

The regression coefficient on *R. marina* obtained in the delta has a mean value compared to that found by [25] at Perak in Malaysia and [21] in Kenya. Be as it may, the results of the different authors show that with the equation of the type Log y = A Log x + B, the R^2 values remain insignificant for the *Rizophora* and *Avicennia* leaves. Constituting 2% to 10% of the total biomass, leaf weight is insignificant and variable (**Table 7**).

4.6. Allometric Relationships on Branches

The most significant allometric relationships found in the Mangoky Delta are:

Log y = 2.334 Log DBH − 1.174 for *R. marina* where $R^2 = 0.865$;

Log y = 2.441 Log DBH − 1.276 for *A. marina* where $R^2 = 0.876$.

The equation of [21] differs from that established in the Mangoky Delta due to the physiognomy of the trees studied: 26% ± 9.6% of the aerial weight of *R. mucronata* of the Delta are made up of branches, compared to 9.7% ± 4.8% only for Gazi in Kenya.

4.7. Allometric Relationships on *R. mucronata* Roots

It is with the variable $(DBH)^2 \cdot Ht$, more precisely with the allometric relationship Log y = 1.076 Log $[(DBH)^2 \cdot Ht]$ − 2.046 (where $R^2 = 0.839$) that the best correlation was found for the roots of *R. mucronata* of the study area.

5. Conclusion

Based on a destructive method experimented directly *in situ*, this study has an interest that lies in the availability of the first tools for estimating the aboveground biomass of *R. mucronata* and *A. marina*, two main Mangrove species of the Indo-Pacific Region and East Africa, including the Mangoky Delta. The first more targeted equations adapted to sub-regional contexts are now available to

Table 7. Constitution as % of the aboveground biomass.

Compartment	Based on this study, Mangoky Delta in Madagascar		According to [20], Gazi Bay in Kenya	
	Rhizophora mucronata	*Avicennia marina*	*Rhizophora mucronata*	*Ceriops tagal*
Stem	40 ± 12.4	40 ± 11.2	50.2 ± 16.3	27.0 ± 7.3
Branch > 2 cm	26 ± 9.6	47 ± 11.6	9.7 ± 4.8	28.5 ± 6.9
Boughs < 2 cm	4 ± 2.5	6 ± 2.5		
Leaves	6 ± 3.8	7 ± 3	15.2 ± 4.8	14.2 ± 6.7
Aerial roots	24 ± 7.6		24.9 ± 15.4	30.3 ± 8.0

complement those already established at larger scales. However, given the lack of baseline data on the productivity of Malagasy Mangroves on the one hand, and because of the small values of the regression coefficients obtained on certain allometric relationships, precautions should be taken in case of extrapolation. It is therefore essential to multiply allometric studies and those on the productivity of Malagasy and East African Mangroves. In any case, the results of this paper can already serve as the first modeling tools for the two main and most widespread species in Madagascar, East Africa and the Indian Ocean.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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