

# Evaluation of the Aerial Biomass of Three Sahelian Species in the Ferlo (North Senegal): *Acacia tortilis* (Forsk.) Hayn essp. *Raddiana* (Savi) Brenan, *Acacia senegal* (L.) Willd and *Balanites aegyptiaca* (L.) Del

Daouda Ndiaye<sup>1,2</sup>, Moustapha Bassimbé Sagna<sup>1,2</sup>, Ramata Talla<sup>1,2,3</sup>, Aly Diallo<sup>4</sup>, Jean Luc Peiry<sup>5</sup>, Aliou Guisse<sup>1,2,3\*</sup>

<sup>1</sup>Department of Plant Biology, Cheikh Anta Diop University, Dakar, Senegal

<sup>2</sup>Observatoire Homme-Milieus international de Tessekere, CNRS/Universite Cheikh Anta Diop, Dakar, Senegal

<sup>3</sup>UMI 3189 "Environnement, Sante, Societes" UGB, UCAD, CNRS, CNRST, USTTB, Dakar, Senegal

<sup>4</sup>Assane Seck University, Department of Agroforestry, Nema, Ziguinchor, Senegal

<sup>5</sup>Department of Geography, Clermont Auvergne University, GEOLAB UMR 6042 CNRS, Clermont-Ferrand, France

Email: \*aliou.guisse@ucad.edu.sn

**How to cite this paper:** Ndiaye, D., Sagna, M.B., Talla, R., Diallo, A., Peiry, J.L. and Guisse, A. (2021) Evaluation of the Aerial Biomass of Three Sahelian Species in the Ferlo (North Senegal): *Acacia tortilis* (Forsk.) Hayn essp. *Raddiana* (Savi) Brenan, *Acacia senegal* (L.) Willd and *Balanites aegyptiaca* (L.) Del. *Open Journal of Ecology*, 11, 183-201.

<https://doi.org/10.4236/oje.2021.112015>

**Received:** December 23, 2020

**Accepted:** February 19, 2021

**Published:** February 22, 2021

Copyright © 2021 by author(s) and Scientific Research Publishing Inc.

This work is licensed under the Creative Commons Attribution International License (CC BY 4.0).

<http://creativecommons.org/licenses/by/4.0/>



Open Access

## Abstract

In a context of climate change characterized by rising temperatures, increased greenhouse gases and frequent droughts, the Sahel is presented as one of the most vulnerable areas to the adverse effects of climate change. The Sahel is presented as one of the most vulnerable areas to the adverse effects of climate change. The objective of this study is to assess the above-ground biomass and carbon stock of three Sahelian species: *Acacia raddiana* *tortilis* (Forsk.) hayne ssp. *raddiana* (savi) Brenan, *Acacia senegal* (L.) Willd and *Balanites aegyptiaca* (L.). The study was carried out in northern Senegal commonly known as Ferlo. Biomasses of the populations of the three target species were first assessed by harvesting the entire epigenetic part of the species and then modelled by correlation using dendrometric parameters measured on each individual of the sample. Two models, mono-specific and multi-species, were used. The results obtained showed that the diameter at breast height ( $x$ ) and the parameter best correlated to the epigeal biomass ( $y$ ). The dry biomass of woody plants was  $31.4 \pm 15.2$  kg/tree for *B. aegyptiaca*,  $30.6 \pm 13.2$  kg/tree for *A. senegal* and  $26.2 \pm 11.1$  kg/tree for *A. raddiana*; *i.e.* carbon equivalents of 14.75 - 14.38 - 12.31 kg/tree respectively. The amount of carbon contained in the above-ground woody biomass is estimated at 4.48 t/ha. The carbon equivalent, atmospheric CO<sub>2</sub> is estimated at 16.44 tons of CO<sub>2</sub>/ha and based on the actual density of Ferlo ( $108.08 \pm 49.79$  ind/ha) the sequestered carbon of the

area is estimated at 1777.008 tons of CO<sub>2</sub>. The comparison between the models developed in this study and the multispecific or mono-specific models from the literature showed substantial differences. This study contributes to a better understanding of the contribution of Sahelian woody species to carbon sequestration and the results could be used in the framework of adaptation to climate change.

## Keywords

*Acacia*, *Balanites*, Biomass, Allometric Model, Ferlo

---

## 1. Introduction

From the drought years of the 1970s to the 1990s, the Sahel region underwent profound ecological and socio-economic changes [1] [2]. Recent studies on the evolution of Senegal's ecosystems in the Ferlo zone have shown a detrimental change in the floristic composition and structure (density, stratification and cover) of the vegetation [3] [4] [5].

In Sahelian ecosystems, the plant biomass produced decreases when the annual rainfall is less than 250 mm; even though soil conditions and human activities have a great influence [6]. This biomass provides important information on the functioning and economic productivity of agrosystems as well as their potential for sequestering atmospheric carbon [6].

Thus, under conditions of optimal management of Senegal's Sahelian ecosystems in a Great Green Wall (GGW) context, knowledge of its functioning and the services it provides is necessary in order to enhance its potential. According to the Intergovernmental Panel on Climate Change [7], significant terrestrial carbon stocks are vulnerable to the impacts of climate change and/or land-use change. To address these concerns, it is important to provide this international community with recent scientific information useful in the fight or mitigation of climate change due to the emission of greenhouse gases, especially carbon.

In the Ferlo area, relatively few studies have focused on estimating woody biomass. The few existing works are the subject of studies correlating aerial biomass and their dendrometric characteristics [8]-[14].

This work is approached at the population scale of three species reforested in the Ferlo in the area of the Great Green Wall; these are *Acacia tortilis* (Forsk.) hayne ssp. *raddiana* (Savi) Brenan, *Acacia senegal* (L.) Willd and *Balanites aegyptiaca* (L.) Del. It aims at taking stock of the carbon sequestration capacity of these woody species with a view to monitoring their dynamics with the evolution of carbon stocks as an indicator.

The selected species have strong economic potential for the local population. In addition to their fodder role, these trees play an important role in the balance of the Sahelian ecosystem. They play a role in maintaining soil fertility and production [2] [3] [6], protecting the soil against bad weather (wind, run-off water,

heat), the floristic composition of herbaceous plants and providing shade [6]. Apart from their ecological and fodder importance, these three species contribute to the socio-economic resources of rural and urban populations. They are often used to satisfy needs in the fields of food (direct consumption of leaves and fruits), clothing (dyeing), energy (firewood), medicine (care of human and animal diseases), agriculture (tool handles, nitrogen fixation in the soil, restoration of depleted soils, regeneration of soils sterilized by salinity or alkalinity), and combating desertification (dune stabilization).

The estimation of the quantity of carbon sequestered by these woody trees is based on the principle of allometry according to which the relationship between certain parameters (height, diameter, crown size and biomass), obeys a rule that is the same for all trees living under the same conditions, from the smallest to the largest [15] [16]. The approach adopted in this study consists first of evaluating the biomass of woody trees by the destructive method and then of establishing some allometric equations allowing to predict the biomass of woody trees from the dendrometric characteristics and finally to deduce the quantity of sequestered carbon.

## 2. Methods

### 2.1. Presentation of the Study Area and Study Sites

This study was conducted in Senegal in the sylvopastoral zone commonly known as Ferlo (Figure 1). The Ferlo covers an area of 70,000 km<sup>2</sup> [17] and is crossed from east to west by the route of the Great Green Wall project in Senegal. Climatically, the annual rainfall of the Ferlo varies between 100 mm and 350 mm [1]. Relative air humidity is very low (annual average 35%) with high evapotranspiration ranging from 1800 to 2200 mm/year [1] [18]. The Ferlo has a woody to shrubby steppe dominated by woody trees such as *Balanites aegyptiaca*

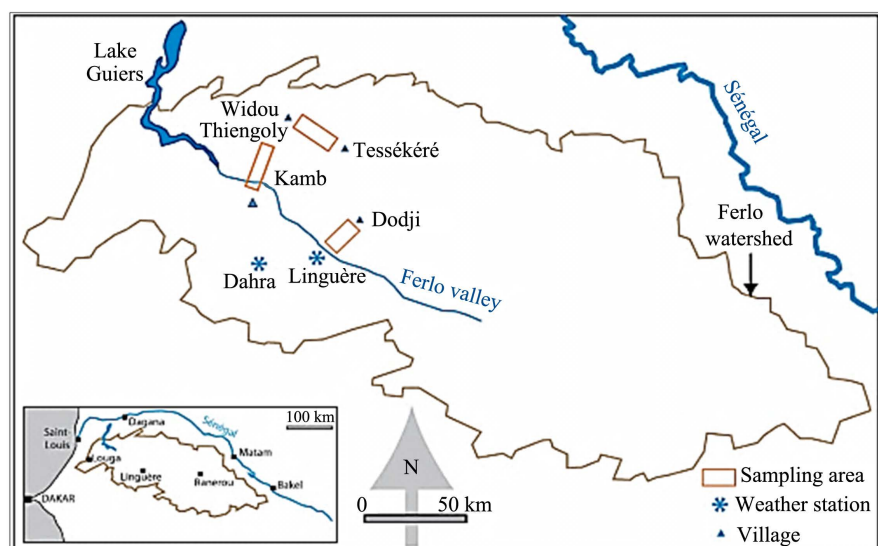


Figure 1. Location of the study area and study sites.

(L.) Del, *Boscia senegalensis* (Pers.) Lam. Ex Poir, *Acacia senegal* (L.), *Acacia tortilis* (forsk.) Hayne ssp. *raddiana* (Savi) Brenan, and *Calotropis procera* (Aiton) W. T. Aiton [17] [18] [19].

This vegetation is inferred from two types of soils [20]: sandy iso humic soils of the dune system consisting of sandy red-brown clayey-sandy soils and poor in organic matter; and sandy to sandy red clayey-sandy tropical ferruginous soils, more or less leached and poor in organic matter.

The study was carried out in the western Ferlo center, in the environment circumscribed by five localities: Linguere, Dodji, Tsetsere, Widou Thiengoly and Kamb (Figure 1).

## 2.2. Wood Sampling

Samples of *Balanites aegyptiaca* (L.) Del, *Acacia senegal* (L.), *Acacia tortilis* (Forsk.) Hayne ssp. *raddiana* (Savi) Brenan were collected in August 2012 along three transects: the first one connects Widou to Kamb (15°32.533N - 15°25.769W); the second Widou to Tessékéré (15°51.940N - 15°12.695W); and the last is on the Dodji-Linguère axis (15°28.079N - 14°59.891W). The sampling was carried out at the individual level and generally concerns shrubs and trees. Individuals of variable diameter were chosen to cover a range of sizes and thus widen the dendrometric variability. The selected individuals were coded and georeferenced using a GPS (GARMIN MAP64). The sample size was calculated from the formula in [21], which takes into account the density of the wood:

$$n = U_{1-\alpha/2}^2 \frac{P(1-P)}{d^2} \quad \text{with } U_{1-\alpha/2} = 1.96 (\approx 2) \quad \text{and } 1 \leq d \leq 15$$

( $P$  = percentage of the species;  $a$  = the ratio of the density of the species studied to the total density of woody plants;  $d$  = is the error rate;  $U$  = is the  $u$  of the normal law which is read from the table;  $n$  = number of feet to be sampled).

Based on this calculation, a total of 132 individuals were counted on the three transects (Table 1).

The sample size in the elaboration of allometric models is variable, depending on the study areas, the density of trees and the spatio-temporal variability of precipitation [15] [16] [22] [23]. Allometric models have been developed with a number of trees greater than 100 [24] [25]. However, other models focused on tree numbers below 20 [26] [27] [28] [29]. Stratified sampling was used following the transects, with sampling at the individual level for shrubs and trees.

**Table 1.** Sample size justified in the method section (Dagnélie's formula).

Sites	<i>A. raddiana</i>	<i>A. senegal</i>	<i>B. aegyptiaca</i>
Widou-Kamb	10	25	10
Widou-Tessekere	17	20	20
Dodji-Linguere	10	10	10
<b>Total</b>	37	55	40

### 2.3. Dendrometric Measurements

The dendrometric parameters measured on each individual were trunk diameter at 0.30 m and 1.30 m from the ground, and crown diameter on the N-S and E-W axes (Baskerville, 1965). Tree diameters were measured with a forest compass (Mantax black model A060). A tape measure was used for circumference measurements. For the feet of irregular and branched trunks, measurements were taken on the whole trunk; the individual values were then summed. The total heights of the individuals were measured on the ground after felling.

### 2.4. Felling, Cutting and Sampling of Trees

The selected individuals were cut down with a chainsaw. After felling, the aerial part of each individual was cut into pieces and divided into four categories or compartments: trunk, branches, twigs, and twigs and leaves [30]-[38].

To measure the dry biomass of the trees, branch samples were taken in all four directions (N, E, W and S); for twigs and leaves, one sample was taken in the northern direction only, since there was no significant difference in moisture content in the direction of sampling [39]. In this study, the underground biomass was not studied despite the fact that it constitutes a significant part of the Sahelian environment where the deep growth of trees would be very determining.

### 2.5. Weighing and Monitoring the Moisture Content of the Biomass in the Different Compartments

After slaughter, the total fresh mass of each compartment of an individual was weighed with a 200 kg  $\pm$  0.1 scale and then added to obtain the total fresh mass epigraphed. Samples from each compartment were taken and weighed more accurately with a precision balance (7 kg  $\pm$  0.05) and reported to the laboratory. At the laboratory, the samples were oven dried: leaves at 70°C and wood at 105°C until constant mass. To measure the moisture content of the trunks, washers at 0.30 m and 1.30 m from the ground were used.

### 2.6. Data Processing

The ratio of fresh and dry masses made it possible to calculate the moisture content of the different compartments of each individual. The following formula was used:

$$Th = \frac{Pf - Ps}{Pf} \times 100$$

With:

- $Th$  = Moisture content of the sample (%);
- $Pf$  = fresh mass of the sample (kg);
- $Ps$  = dry mass of the sample (kg).

Knowing the moisture content ( $Th$ ), the dry biomass of the different compartments was calculated by the following formula:

$$BS = \sum_{i=1}^k Pf_i - (Pf_i - Th_i) \text{ with } k = \text{number of compartments measured.}$$

The calculation of the amount of carbon ( $C$ ) stored by each species was determined from the dry biomass ( $BS$ ). It is also based on the work of [40] which considers that 47% of the dry biomass of woody species is made up of carbon.

$$C = \frac{BS}{100} \times 47 = \frac{\sum_{i=1}^k Pf_i - (Pf_i - Th_i)}{100} \times 47$$

Above-ground carbon stock (ton/ha) of woody species in the Ferlo area was assessed using the average carbon stock of the three species, but also based on the actual density of Ferlo ( $108.08 \pm 49.79$  ind/ha) according to [41]. The estimation of the carbon equivalent, atmospheric  $CO_2$ , of the area was carried out by multiplying the volume of carbon by 3.67 according to the method used by [42] according to the equation: Equivalent stock (Téq) = carbon stock  $\times$  3.67.

Data analysis was performed with Xlstat version 2015 and Minitab 14 demo version 14.1. Simple regression analyses allowed the construction of statistical models linking dry mass and dendrometric parameters for each species.

The construction of the models required the verification of a certain number of validation criteria: 1) the significance of the coefficients (Student's t-test); 2) the overall significance of the model (Fisher's F-test); 3) the normality of the residuals (Shapiro Wilk test); 4) the independence of the residuals (Durbin Watson test); 5) the homoscedasticity of the residuals (Breush Pagan test); 6) the null mean of the residuals (Univariate test of null mean); 7) the linearity between the explained variable and the explanatory variable(s) (Reset test of non-linearity).

However, three criteria were used to select the best fitted models: 1) The Akaike Information Criterion (AIC) which selects the best model through the lowest AIC; 2) the Residual Standard Deviation (RSE) which selects the best model through the lowest RSE; 3) the Adjusted Determination Coefficient ( $R^2$ ) which reflects both the quality of fit and the complexity of the model, its value varies from 0 to 1. A value close to 1 indicates a good fit of the model.

A comparison of generic and mono-specific models from the literature with the models constructed in this study was then carried out. They are used to determine the relationship between biomass and wood scaling [14] [43] [44]. This is the model integrating the power function and the model integrating the polynomial function (from degree two to three).

### 3. Results

#### 3.1. Relationship between Dry Biomass and Dendrometric Parameters

In this study, the dry biomass of each of the three species is correlated to three dendrometric parameters: diameter at breast height (DBH), total tree height and crown diameter. Thus thanks to the selection and validation criteria, the best models are selected (Table 2).

The analysis in Table 2 shows that the selected models met the conditions of

**Table 2.** Characteristics of the statistical tests of the selected biomass predilection models.

Species	Models of biomass Dried in (Kg)	F	TSG Biomass	TNR	THR	TIR	TLR	TNMR	R <sup>2</sup> adjusted	RSE	AIC
<i>A. raddiana</i> n = 37	$y = 0.3939x^2 - 0.7051x + 2.4551$	F <sup>1.75</sup> 5619	p < 0.001	0.44	0.27	0.65	0.52	0.78	0.78	0.12	13.56
<i>A. senegal</i> n = 55	$y = 0.4475x^2 - 2.3777x + 14.408$	F <sup>1.92</sup> 8680	p < 0.001	0.63	0.36	0.73	0.71	0.89	0.75	0.13	15.42
<i>B. aegyptiaca</i> n = 40	$y = 0.6595x^2 - 13.092x + 89.419$	F <sup>1.87</sup> 7719	p < 0.001	0.47	0.29	0.64	0.56	0.85	0.84	0.10	10.22

(AIC: Akaike Information Criterion; RSE: Residual Standard Error; TIR: Test of Residual Independence; TNR: Test of Residual Normality; TNMR: Test of Nullity of Residual Mean; THR: Test of Residual Homoscedasticity; TLR: Test of Linearity of the Relationship between the Explained Variable and the Explanatory Variable; TSG: Test of Overall Significance n: Sample Size).

normality, independence, homoscedasticity and null mean of the residuals (p-value greater than 0.05). In addition, the estimated coefficients of the models are highly significant, which was translated into an overall significance (p < 0.001).

The dry biomass distribution trend curves as a function of DHP show determination coefficients (R<sup>2</sup>) of 0.78; 0.75 and 0.84 respectively in *A. raddiana*, *A. senegal* and *B. aegyptiaca* (Figure 2). These coefficients of determination show a strong correlation between biomass and DHP.

The final equations from the regression model for the three species are:

- *raddiana*:  $y = 0.3939x^2 - 0.7051x + 2.4551$  with R<sup>2</sup> = 0.7851 and p value = 0.001
- *senegal*:  $y = 0.4475x^2 - 2.3777x + 14.408$  with R<sup>2</sup> = 0.7508 and p value = 0.001
- *aegyptiaca*:  $y = 0.6595x^2 - 13.092x + 89.419$  with R<sup>2</sup> = 0.8451 and p value = 0.001

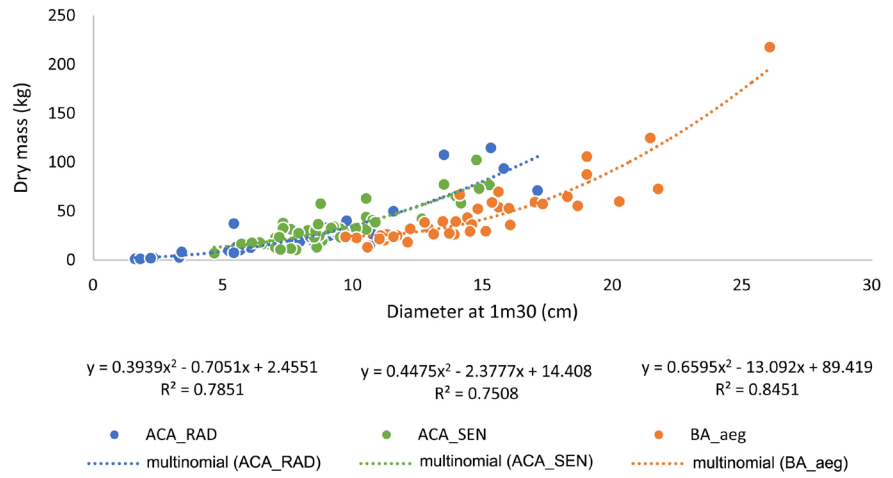
### 3.2. Comparison of the Results of This Study with Models in the Literature

The results of this study are compared on the one hand with generic models [12] [24] [44] and on the other hand with mono-specific models developed by [8] [45] (Table 3).

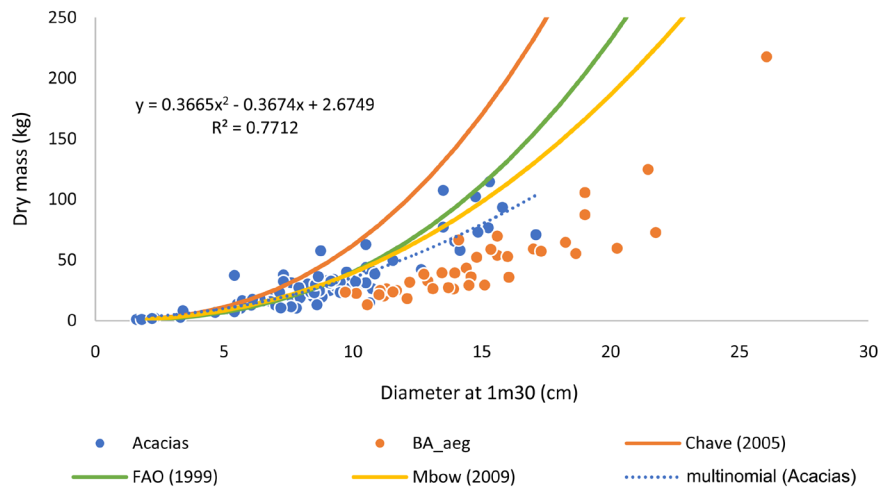
The presentation of its allometric models in graphical form visually illustrates the degree of similarity between the models proposed in the literature and those from this study (Figures 3-6).

Comparison between the generic models and the model developed in this study shows that the former overestimate woody biomass (Figure 2). However, it can be noted that the model in [12] is closer to the model developed in this study, followed by the model in [45]. With the model of [25], the predicted biomass increases very rapidly when the diameter reaches 7 cm. At 15 cm diameter, the biomass is largely overestimated compared to that predicted by the other models.

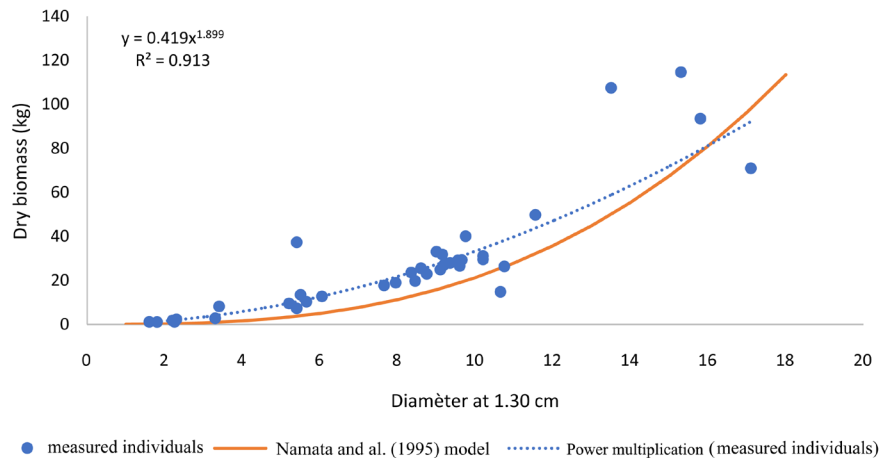
For the monospecific models, the model of [8] also overestimates the biomass of *A. senegal* (Figure 6) compared to the model developed in this study. Only



**Figure 2.** Allometric relationships for estimating above-ground biomass as a function of diameter at chest height (DBH) for *A. raddiana*, *A. senegal* and *B. aegyptiaca*.

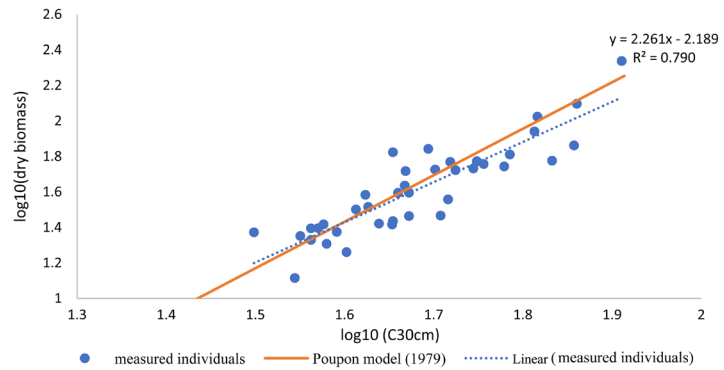


**Figure 3.** Comparison of the results of this study with multi-species models from the literature [12] [24] [44].

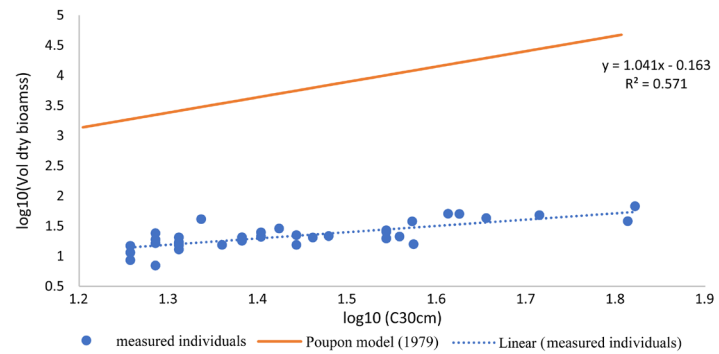


**Figure 4.** Comparison of the monospecific model developed for *B. aegyptiaca* with that developed by [8].





**Figure 5.** Comparison of the monospecific model developed for *A. raddiana* with that developed by [45].



**Figure 6.** Comparison of the monospecific model developed for *Acacia senegal* with that developed by [8].

**Table 3.** Generic models and mono-specific models from the specialized literature with the models developed in this study.

Species	Models
<b>Plurispecific (generic)</b>	FAO (1997)
	$PST = \exp(-2.134 + 2.530 \ln D)$
	Mbow (2009)
	$PST = 0.229 D^{2.237}$
	Chave and al., (2005)
	$\ln(PST) = -1.589 + 2.284 \ln D + 0.129 \ln D^2 - 0.0197 \ln D^3$ (I)
	Models of this study
	$y = 0.3665x^2 - 0.3674x + 2.6749$
<b>A. raddiana</b>	Namata et al., (1995)
	$PST = 0.03 * (DBH)^{2.85}$
	Models of this study
	$y = 0.3939x^2 - 0.7051x + 2.4551$
<b>A. senegal</b> Mono-specifics	Poupon (1979)
	$\log_{10} PST = -2.76 + 2.62 * \log_{10} (Cb)$
	Models of this study
	$y = 0.4475x^2 - 2.3777x + 14.408$
<b>B. aegyptiaca</b>	Poupon (1979)
	$\log_{10} PST = -2.76 + 2.62 * \log_{10} (Cb)$
	Models of this study
	$y = 0.6595x^2 - 13.092x + 89.419$

PST: Total Dry Weight; Cb: Circumference at Base; D: Diameter; DBH: Diameter to Chest Height.

those developed by [8] on *B. aegyptiaca* (Figure 4) and by [46] on *A. raddiana* (Figure 5) corroborate this study.

### 3.3. Assessment of Biomass and Carbon Stock by the Destructive Method

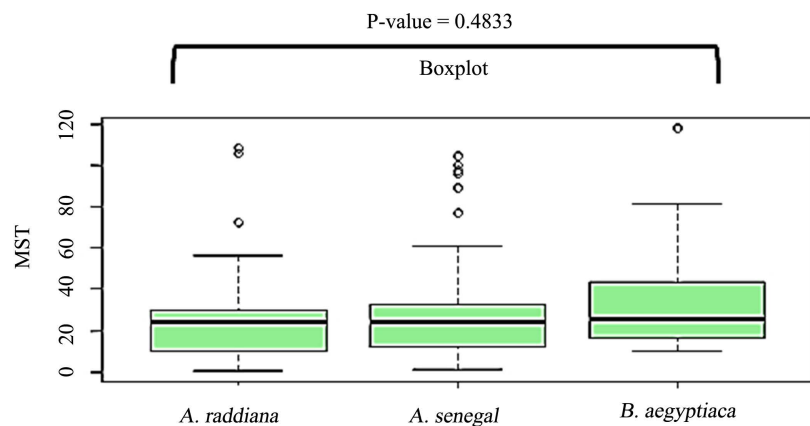
The biomass obtained by the destructive method after drying the samples is  $31.4 \pm 15.2$  kg/tree for *B. aegyptiaca*,  $30.6 \pm 13.2$  kg/tree for *A. senegal*, and  $26.2 \pm 11.1$  kg/tree for *A. raddiana* (Figure 7). Comparative analysis of the biomass of the three species indicates that their difference is not significant ( $p$ -value = 0.4833). The conversion of this biomass to carbon stock shows a sequestration potential of 12.31 kg/tonne/tree for *A. raddiana*; 14.38 kg/tonne/tree for *A. senegal* and 14.75 kg/tonne/tree for *B. aegyptiaca*.

At the scale of the Ferlo landscapes, *B. aegyptiaca* which is the most prosperous species (32.02 ind/ha) constitutes an enormous reservoir of carbon stock (1.7329 tC/ha) compared to *A. raddiana* (3.68 ind/ha) and *A. senegal* (1.05 ind/ha) and whose carbon stocks are evaluated respectively at 0.16625 tC/ha and 0.05615 tC/ha (Table 4).

### 3.4. Preference of Woody Biomass with Developed Models

#### 3.4.1. Model Developed in This Study

The biomass prediction models developed in this study were used to calculate the biomass of the three species. The results obtained show a total biomass of



**Figure 7.** Aerial total dry mass (TDS) of *A. raddiana* (a); *A. senegal* (b); and *B. aegyptiaca* (c).

**Table 4.** Estimated potential for atmospheric carbon sequestration.

Species	Actual density of Ferlo ind/ha	Average dry biomass per foot in kg	Average carbon Per feet in kg	Carbon stock in t/ha	Carbon equivalent (tC/ha)
<i>Acacia raddiana</i>	3.68	26.2	12.31	0.0453	0.16625
<i>Acacia senegal</i>	1.05	30.6	14.38	0.0153	0.05615
<i>Balanites aegyptiaca</i>	32.02	31.4	14.75	0.4722	1.7329

1046.29 kg for *A. raddiana*, 1626.86 for *A. senegal* and 1966.75 kg for *B. aegyptiaca* (Table 5). Comparison of the masses obtained with those obtained by the destructive method shows that the differences are not significant (p-values greater than 0.05).

### 3.4.2. Existing Generic Models

Biomass predictions from the generic models compared to the destructive method (2,370,709 kg); show values twice as important for the model of [45] and [12] with respectively 5818/844 kg and 4,510,332 kg; and four times as important for the model of [25], i.e. 8,658,737 kg. For these comparisons, the Kruskal Wallis test showed highly significant differences (p-values less than 0.001) (Table 6).

### 3.4.3. Existing Single-Species Models

Biomasses obtained by prediction with monospecific models appear to be higher than those obtained by the destructive method (Table 7).

**Table 5.** Comparison between destructive observed masses and masses derived from the model predilection.

Species	Allometric equations	R <sup>2</sup> adjusted	Mass (kg-MS)		p-value
			MP	MOD	
<i>A. raddiana</i>	$y = 0.3939x^2 - 0.7051x + 2.4551$	0.785	1046.29	1006.27	8.77
<i>A. senegal</i>	$y = 0.4475x^2 - 2.3777x + 14.408$	0.750	1626.86	1538.30	4.37
<i>B. egyptiaca</i>	$y = 0.6595x^2 - 13.092x + 89.419$	0.845	1966.75	1300.20	3.95

MP = Predicted mass; MOD = Observed destructive mass; p-value at the end of the Kruskal Wallis test.

**Table 6.** Validation of the generic models developed.

Statistical Parameters	Observed mass (Kg-MS)	Mass predicted by the models		
	Validation sample (30 trees)	FAO (1997)	Mbow (2009)	Chave and et al., (2005)
	2370.709	5818.844	4510.332	8658.737
Estimation		16.58	11.26	15.79
Erreur standard		1.29	0.44	1.16
test value		12.87	25.32	13.59
p-value		4.9E-13***	2E-16***	1.37E-13***

\*\*\*Very highly significant differences.

**Table 7.** Validation of the mono-specific models developed.

Statistical Parameters	Validation sample	Observed mass (Kg-MS)	Mass predicted by the models	Erreur Standard	Test value	p-value
Poupon (1979) on <i>B. egyptiaca</i>	30 trees	2089.791	5358.737	7.67	0.294	0.771
Poupon (1979) on <i>A. senegal</i>	30 trees	2915.084	9645.780	0.26	2.67	0.013
Namata et al. (1995) on <i>A. raddiana</i>	40 trees	6621.505	9564.450	5.23	0.275	0.655

However, the statistical tests carried out have shown that there is no significant difference between the biomasses obtained by the destructive method and those predicted by the model of [8] for *B. aegyptiaca* (p-value = 0.771 > 0.05) and the model of [45] for *A. raddiana* (p-value = 0.655 > 0.05). Only the biomass predicted by model [8] for *A. senegal* seems to give results slightly different from those obtained by the destructive method (p-value = 0.013 < 0.05).

#### 4. Discussion

The allometric relationships that were the subject of this study were compared to existing models. The three (3) allometric models developed in this study each have an adjusted R<sup>2</sup> coefficient of determination close to 1 and meet the various preliminary statistical tests. The CSR values ranged from 0.10 to 0.13 as did the AIC values, which ranged from 10,223 to 15,423. These criteria are taken individually or combined in the choice of the best models by many authors [43] [44] [47]. For the latter, the best model is the one with the lowest AIC and CSR values. The same approach has been used by [48], who selected cubage tariff models by combining these two parameters. On the other hand, [49] developed allometric equations whose selection was based mainly on the low value of CSR. Thus, biomass prediction from these three models produced results very close to those of the destructive method.

The highly significant differences between the mass obtained by the destructive method and that obtained from the generic models developed by [12] [25] [45] indicate that it would not be appropriate to use these models in the context of Ferlo. Rather, his models tend to overestimate dry biomass.

Monospecific prediction models seem to better predict the biomass of the species studied, notably the model of [8] for *B. aegyptiaca* and that of [46] for *A. raddiana*; even if the biomasses predicted by these models are relatively slightly higher compared to those obtained with the validation sample.

Thus, in tropical, intertropical or temperate zones, most of the authors who have studied the question of biomass estimation [8] [12] [50]-[59], agrees on the fact that there are no universal rules, due in particular to the diversity of the stands studied and especially to the high number of problems to be solved (sample size, choice of prediction models, etc.). However, it should be pointed out that the estimation of dry biomass of Sahelian woody species from approved generic models generally differs from what is observed elsewhere. Indeed, in wetter regions, these models are generally developed on large-diameter species.

According to [12], the use of a generic model amounts to introducing a prediction bias that can be seen as interspecies variability. His study shows that merging data for several species is of interest if the gain in intra-species variability brought by this merger compensates for the interspecies variability introduced. However, it is necessary to ensure that: 1) this merging makes sense and 2) the proportions within the sample of the different species present in the stand are respected. When constructing an all-species tariff from the outset (as is often

the case with natural stand tariffs), care must be taken to ensure that the choice of individuals in the sample is independent of their species, so as not to bias the tariff in favour of a particular species [12]. However, the best strategy to achieve the tariff for a stand is to construct monospecific allometric equations for the main species present; and then to carry out the interspecific assessment of dry biomass by applying the monospecific allometric equations while respecting the characteristics of the stand under study (species composition and proportion, but also distribution of tree diameters and sizes). By merging the data, the sample size is increased, which is of interest if it compensates for the increase in variability due to the mixing of different species [12]; but this is a rather cumbersome task to carry out.

The dry biomass resulting from the destructive method is  $31.4 \pm 15.2$  kg DM/tree for *B. aegyptiaca*,  $30.6 \pm 13.2$  kg DM/tree for *A. senegal*, and  $26.2 \pm 11.1$  kg DM/tree for *A. raddiana*. This result seems to indicate that its three Sahelian species could have the same carbon sequestration capacity; although it should be noted that at the scale of the Ferlo landscapes, *B. aegyptiaca* which is the most prosperous species constitutes a huge reservoir of carbon stock (1.7329 tC/ha) the most important compared to *A. raddiana* (3.68 ind/ha) and *A. senegal* with respectively 0.16625 tC/ha and 0.05615 tC/ha.

Our results are close to those obtained by [12] in the Sudanian and Sudano-Guinean savannas of Senegal (classified forests of Bala, Kantora, Mampaye, Ouli, Patako and Welor) where the biomasses obtained with the polynomial allometric model vary from 7.9 to 102.2 tMS/ha for equivalent carbon stocks from 3.93 to 50.89 tC/ha. In the wetter regions, the amounts of sequestered carbons are between 81.48 and 118.36 tC/ha [60]. These differences would be related to climatic conditions that influence in one way or another the size of the woody plants. [12] had pointed out that the value of biomass and carbon in the savannah is low because of the predominance of small diameter woody trees. Also, logging, which most often targets large trees, drastically reduces biomass stocks over the years.

Highly vulnerable to climate change, the Sahel, and more particularly the Ferlo, nevertheless presents significant assets for reducing the concentration of greenhouse gases in the atmosphere. Firstly, it contains vast areas still available for forest management and favourable to the development of adapted species. Secondly, reforestation combines very well with the fight against poverty, since forest resources weigh heavily on the economy of the population. Finally, the species best adapted to semi-arid climates are also those that provide the highest added value products, such as gum trees [2] [3]. On these bases, the Sahel is a zone of great potential interest in the perspective of promoting carbon sequestration while fostering new sources of income to fight against poverty and improve food security for the populations of the zone. Thus, estimating the quantity of carbon sequestered in Sahelian ecosystems as accurately as possible is of great interest for the development of the zone and its better inclusion in the global balance.

The limits of this study are related to the destructive method used, but also the number of species considered in relation to the important woody diversity in the Ferlo area. However, it is essential to refine a new non-destructive methodology based on major species of the area for a better estimation of the carbon stock.

## 5. Conclusions

This present study carried out in the Ferlo on populations of *A. raddiana*, *A. senegal* and *B. aegyptiaca* allowed building on the one hand, mono-specific allometric models linking dendrometric parameters to the aerial phytomass and on the other hand, evaluating the quantity of carbon sequestered by these species in the Ferlo.

The study confirms previous research on the measurement discrepancies found between mono-specific and generic models established for the estimation of biomass and carbon stock. The woody species of the Senegalese Sahel, due to their small trunk size, have a low carbon sequestration capacity compared to other more humid ecosystems. Differences in the biomass prediction results can be explained by the variability related to ecological conditions, the choice of parameters to be considered in developing the model, and the choice of the mathematical model that best fits the experimental point cloud.

Estimating biomass and quantifying the carbon sequestered by woody plants in the Ferlo will gain in precision and reliability with single-species models, which take more account of the specificities of each species present in its stand.

The best strategy to achieve stand pricing would therefore be to construct monospecific allometric equations for the main species present; and then to carry out interspecific assessment of dry biomass by applying the monospecific allometric equations.

This study contributes to the evaluation of the contribution of Sahelian woody species to carbon sequestration in a context of climate change and to the monitoring of their dynamics with the evolution of woody carbon stocks as an indicator.

## Acknowledgements

This study was carried out with the support of Veolia Environnement and the Observatoire Homme Milieux T  ss  k  r   (OHM), the Scientific Research Center (CNRS, PEPS ECOSAN, INEE) and the Labex DRIIHM.

## Conflicts of Interest

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

## References

- [1] Sarr, M.A. (2009) Recent Evolution of Climate and Vegetation in Senegal (Case of Ferlo). Doctoral Thesis, University Jean Moulin, Lyon, 410 p.

- [2] Diallo, A., Faye, M.N. and Guisse, A. (2011) Structure of Woody Stands in *Acacia senegal* (L.) Willd Plantations in the Dahra Zone (Ferlo, Senegal). *Revue D'Écologie*, **66**, 415-427.. <https://hdl.handle.net/2042/55893>
- [3] Diouf, M. (2003) Basic Characteristics of the Leaves of a Sahelian Woody Species: *Acacia tortilis* (Forsk) Hyane, Variation According to the Topographic Microsites of Ferlo (Nord-Sénégal). Thesis, Université Cheikh Anta Diop de Dakar, Dakar, 103 p.
- [4] Bakhoun, A. (2013) Dynamics of Forage Resources: Indicator of Resilience of Community Rangelands from Tèssékéré to Ferlo (North-Senegal). Unique Doctoral Thesis in Biology, Animal Productions and Pathologies, Option Pastoral Ecology, FST-UCAD, 115 p.
- [5] Ndiaye, O. (2015) Determinants of the Dynamics of the Vegetation of a Grazed Environment in the Sahelian Region of Senegal. Doctoral Thesis, Université Cheikh Anta Diop de Dakar, Dakar, 138 p.
- [6] Brenan, H. and Kessler, J.J. (1995) Woody Plants in Qgro-Ecosystem of Semi-Arid Region, with an Emphasis on the Sahelian Countries. Springer-Verlag, Berlin-Heidelberg, 340 p.
- [7] IPCC (Intergovernmental Panel on Climate Change) (2007) Climate Change Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Core Editorial Team, Pachauri RK and Reisinger A. IPCC, Geneva, 103 p.
- [8] Poupon, H. (1979) Structure and Dynamics of the Woody Stratum of a Sahelian Steppe in Northern Senegal. Natural Sciences, Doctoral Thesis, University of Paris Sud, ORSAY. ORSTOM Works and Document, Paris, 351 p.
- [9] Woomer, P.L., Toure, A. and Sall, M. (2004) Carbon Stocks in Senegal's Sahel Transition Zone. *Journal of Arid Environments*, **59**, 499-510. <https://doi.org/10.1016/j.jaridenv.2004.03.027>
- [10] Tschakert, P., Khouma, M. and Sene, M. (2004) Biophysical Potential for Soil Carbon Sequestration in Agricultural Systems of the Old Peanut Basin of Senegal. *Journal of Arid Environments*, **59**, 511-533. <https://doi.org/10.1016/j.jaridenv.2004.03.026>
- [11] Liu, S., Kairé, M., Wood, E., Diallo, O. and Tieszen, L. (2004) Impacts of Land Use and Climate Change on Carbon Dynamics in South-Central Senegal. *Journal of Arid Environments*, **59**, 583-604. <https://doi.org/10.1016/j.jaridenv.2004.03.023>
- [12] Mbow, C. (2009) Potential and Dynamics of Carbon Stocks in the Sudanese and Sudanese-Guinean Savannas of Senegal. UCAD State Doctorate Thesis in Sciences, Cheikh Anta Diop University (UCAD), Dakar, 319 p.
- [13] Thiam, S. (2011) Development of an Allometric Model on *Acacia senegal* (L.) Willd to Improve the Woody Carbon Analysis of the Great Green Wall (GMV) in Senegal. DEA Dissertation UCAD, Cheikh Anta Diop University (UCAD), Dakar, 69 p.
- [14] Henry, M., Picard, N., Trotta, C., Manlay, R., Valentini, R., Bernoux, M. and Saint-Andre, L. (2011) Estimating Tree Biomass of Sub-Saharan African Forests: A Review of Available Allometric Equations. *Silva Fennica*, **45**, 477-569. <https://www.metla.fi/silvafennica/full/sf45/s453B477> <https://doi.org/10.14214/sf.38>
- [15] Bohlman, S. and O'brien, S. (2006) Allometry, Adult Stature and Regeneration Requirement of 65 Tree Species on Barro Colorado Island, Panama. *Journal of Tropical Ecology*, **22**, 123-136. <https://doi.org/10.1017/S0266467405003019>
- [16] Dietze, M.C., Wolosin, M.S. and Clark, J.S. (2008) Capturing Diversity and Inter-

- pecific Variability in Allometries: A Hierarchical Approach. *Forest Ecology and Management*, **256**, 1939-1948. <https://doi.org/10.1016/j.foreco.2008.07.034>
- [17] Miehe, S., Kluge, J., Wehrden, H. and Retzer, V. (2010) Long-Term Degradation of Sahelian Rangeland Detected by 27 Years of Field Study in Senegal. *Journal of Applied Ecology*, **47**, 692-700. <https://doi.org/10.1111/j.1365-2664.2010.01815.x>
- [18] Akpo, L.E. and Grouzis, M. (1996) Influence of the Cover on the Regeneration of Some Woody Sahelian Species (North-Senegal-West Africa). *Webbia*, **50**, 247-263. <https://doi.org/10.1080/00837792.1996.10670605>
- [19] Ndiaye, O. (2013) Characteristics of the Soils, Flora and Vegetation of Ferlo, Senegal. Doctoral Thesis in Ecology and Agroforestry, EDSEV, UCAD-FST.
- [20] Leprun, J.C. (1971) New Observations on the Fixed Sand Dune Formations of the Northwestern Ferlo (Senegal). *Bulletin de Liaison—ASEQUA*, **31**, 69-78. <https://www.documentation.ird.fr/hor/fdi:05414>
- [21] Dagnelie, P. (1998) Theoretical and Applied Statistics: One-Dimensional and Two-Dimensional Statistical Inference. De Boeck & Larcier, Paris, Brussels, 181-186.
- [22] Picard, N., Henry, M., Mortier, F., Trotta, C. and Saint-Andre, L. (2012) Using Bayesian Model Averaging to Predict Tree Aboveground Biomass. *Forest Science*, **58**, 15-23. <https://doi.org/10.5849/forsci.10-083>
- [23] Talla, R., Sagna, M., Diallo, M.D., Diallo, A., Ndiaye, D., Sarr, O. and Guisse, A. (2020) Development of Allometric Models for Estimating the Biomass of *Sclerocarya birrea* (A. Rich) Hoscht and *Boscia senegalensis* (Pers.) Lam. ex Poir. *Open Journal of Ecology*, **10**, 571-584. <https://doi.org/10.4236/oje.2020.108035>
- [24] Brown, S. (1997) Estimating Biomass and Biomass Change of Tropical Forests: A Primer. FAO Forestry Paper, Rome, 134, 55 p.
- [25] Chave, J., Andalo, C., Brown, S., Cairns, M.A., Chambers, J.Q., Eamus, D., Folster, H., Fromard, F., Higuchi, N., Kira, T., Lescure, J.P., Nelson, B.W., Ogawa, H., Puig, H., Rierab, B. and Yamakura, T. (2005) Tree Allometry and Improved Estimation of Carbon Stocks and Balance in Tropical Forests. *Oecologia*, **145**, 87-99. <https://doi.org/10.1007/s00442-005-0100-x>
- [26] Brown, I.F., Martinelli, L.A., Thomas, W.W., Moreira, M.Z., Victoria, R.A. and Ferreira, C.A.C. (1995) Uncertainty in the Biomass of Amazonian Forests: An Example from Rondônia, Brazil. *Forest Ecology and Management*, **75**, 175-189. [https://doi.org/10.1016/0378-1127\(94\)03512-U](https://doi.org/10.1016/0378-1127(94)03512-U)
- [27] Peltier, R., Forkong, C.N., Mama, F., Ntoupka, M., Manlay, R., Henry, M. and Morillon, V. (2007) Évaluation du stock de carbone et de la productivité en bois d'un parc à karités du Nord Cameroun. *Revue Bois et Forêts des Tropiques*, **294**, 12.
- [28] Larwanou, M., Yemshaw, Y. and Saâdou, M. (2010) Prediction Models for Estimating Foliar and Fruit Dry Biomasses of Five Savannah Tree Species in the West African Sahel. *International Journal of Biological and Chemical Sciences*, **4**, 2245-2256. <https://doi.org/10.4314/ijbcs.v4i6.64943>
- [29] Ebuy, J., Lokombé, Dimandja, J.P., Ponette, Q., Sonwa, D. and Picard, N. (2011) Biomass Equation for Predicting Tree Aboveground Biomass at Yangambi, RDC. *Journal of Tropical Forest Science*, **23**, 125-132.
- [30] Shinozaki, K., Yoda, K., Hozumi, K. and Kira, T. (1964a) A Quantitative Analysis of Plant Form—The Pipe Model Theory. I. Basic Analyses. *Japanese Journal of Ecology*, **14**, 97-104.
- [31] Shinozaki, K., Yoda, K., Hozumi, K. and Kira, T. (1964b) A Quantitative Analysis of Plant Form—The Pipe Model Theory. II. Further Evidence of the Theory and Its



- Application on Forest Ecology. *Japanese Journal of Ecology*, **14**, 133-139.
- [32] Thornley, J.H. (1972) A Balanced Quantitative Model for Root: Shoot Ratios in Vegetative Plants. *Annals of Botany*, **36**, 431-441.  
<https://doi.org/10.1093/oxfordjournals.aob.a084602>
- [33] Bloom, A.J., Chapin, F.S. and Mooney, H.A. (1985) Resource Limitation in Plants—An Economic Analogy. *Annual Review of Ecology and Systematics*, **16**, 363-392. <https://www.annualreviews.org>  
<https://doi.org/10.1146/annurev.es.16.110185.002051>
- [34] West, G.B., Brown, J.H. and Enquist, B.J. (1999) A General Model for the Structure and Allometry of Plant Vascular Systems. *Nature*, **400**, 664-667.  
<https://doi.org/10.1038/23251>
- [35] Nicolini, É., Chanson, B. and Bonne, F. (2001) Stem Growth and Epicormic Branch Formation in Understorey Beech Trees (*Fagus sylvatica* L.). *Annals of Botany*, **87**, 737-750. <https://doi.org/10.1006/anbo.2001.1398>
- [36] Savage, V.M., Deeds, E.J. and Fontana, W. (2008) Sizing Up Allometric Scaling Theory. *PLoS Computational Biology*, **4**, e1000171.  
<https://doi.org/10.1371/journal.pcbi.1000171>
- [37] Genet, A., Wernsdörfer, H., Jonard, M., Pretzsch, H., Rauch, M., Ponette, Q., Nys, C., Legout, A., Ranger, J., Vallet, P. and Saint-Andre, L. (2011) Ontogeny Partly Explains the Apparent Heterogeneity of Published Biomass Equations for *Fagus sylvatica* in Central Europe. *Forest Ecology and Management*, **261**, 1188-1202.  
<https://doi.org/10.1016/j.foreco.2010.12.034>
- [38] Gourlet-Fleury, S., Rossi, V., Rejou-Mechain, M., Freycon, V., Fayolle, A., Saint-Andre, L., Cornu, G., Gerard, J., Sarrailh, J.M., Flores, O., Baya, F., Billand, A., Fauvet, N., Gally, M., Henry, M., Hubert, D., Pasquier, A. and Picard, N. (2011) Environmental Filtering of Dense-Wooded Species Controls Above-Ground Biomass Stored in African Moist Forests. *Journal of Ecology*, **99**, 981-990.  
<https://doi.org/10.1111/j.1365-2745.2011.01829.x>
- [39] Ranger, J. (1978) Research on the Comparative Biomasses of Two Corsican Pine Plantations with or without Fertilization. *Annales des sciences forestières, INRA/EDP Sciences*, **35**, 93-115. <https://doi.org/10.1051/forest/19780201>
- [40] IPCC (2006) 2019 IPCC Guidelines for National Green house Gas Inventories. Volume 4 Agriculture, Forestry and Other Land Use.  
<https://www.ipcc-nggip.iges.or.jp/public/2006gl/french/vol4.html>
- [41] Ndiaye, O., Diallo, A., Sagna, M.B. and Guisse, A. (2013) Floristic Diversity of Woody Stands in Ferlo, Senegal. *VertigO—The Electronic Journal in Environmental Sciences*, **13**, 12.
- [42] Tsoumou, B.R., Lumandé, K.J., Kampé, J.P. and Nzila, J.D. (2016) Estimation of the Quantity of Carbon Sequestered by the Dimonika Model Forest (Southwest of the Republic of Congo). *Congo Basin Forest & Environment Scientific and Technical Review*, **6**, 39-45.
- [43] Zianis, D., Muukkonen, P., Mäkipää, R. and Mencuccini, M. (2005) Biomass and Stem Volume Equations for Tree Species in Europe. *Silva Fennica Monographs No. 4*. The Finnish Society of Forest Science and the Finnish Forest Research Institute, Vantaa, 12, 25-44. <https://www.metla.fi/silvafennica/full/smf/smf004.pdf>
- [44] Hofstad, O. (2005) Review of Biomass and Volume Functions for Individual Trees and Shrubs in Southeast Africa. *Journal of Tropical Forest Science*, **17**, 151-162.  
<https://www.jstor.org/stable/2361653>

- [45] FAO (1997) Estimating Biomass and Biomass Change of Tropical Forests. A Primer Par S. Brown. Etude FAO: Forêts n° 134. Rome.
- [46] Namata, S., Adagoye, B., Barke, A., Youssifi, S., Massaoudou, M., Boubacar, M., Amani, A., Issoufou, H.B.A, Kaire, M., Larwanou, M. and Mahamane, A. (2015) The Carbone Sequestration Potential of the Mains Agroforestry Woody Species in Niger Agrosystemes. University Dan Dicko Dankoulodo of Maradi University Abdou Moumouni of Niamey AGRHYMET Regional Center, 17 p.
- [47] Kuyah, S., Dietz, J., Muthuri, C., Jamnadass, R., Mwangi, P., Coe, R. and Neufeldt, H. (2012) Allometric Equations for Estimating Biomass in Agricultural Landscapes: Aboveground Biomass. *Agriculture, Ecosystems & Environment*, **158**, 216-224. <https://doi.org/10.1016/j.agee.2012.05.011>
- [48] Fayolle, A., Rondeux, J., Doucet, J.L., Ernst, G., Bouissou, C., Quevauvillers, S., Bourland, N., Feteke, R. and Lejeune, P. (2013) Revise Scaling Tariffs to Better Manage Cameroon's Forests. *Bois et Forêts des Tropiques*, **317**, 35-49. <https://doi.org/10.19182/bft2013.317.a20521>
- [49] Mbow, C., Chhin, S., Sambou, B. and Skole, D. (2013) Potential of Dendrochronology to Assess Annual Rates of Biomass Productivity in Savanna Trees of West Africa. *Dendrochronologia*, **31**, 41-51. <https://doi.org/10.1016/j.dendro.2012.06.001>
- [50] Baskerville, G.L. (1965) Estimation of Dry Weight of Tree Components and Total Standing Crop in Conifer Stands. *Ecology*, **46**, 867-869. <https://doi.org/10.2307/1934021>
- [51] Whitaker, R.H. and Woodwell, G.M. (1968) Dimension, and Production Relations of Trees and Shrubs in the Brookhaven Forest, New York. *Journal of Ecology*, **56**, 1-25. <https://doi.org/10.1038/2325>
- [52] Whitaker, R.H. and Woodwell, G.M. (1969) Measurement of Net Primary Production of Forests. Colloque sur la productivité des Ecosystèmes forestiers, UNESCO PBI, Bruxelles.
- [53] Riedacker, A. (1968) Méthode d'estimation de la biomasse d'un arbre. D. E. A. Biologie végétale, 31 p., Fac. Sci. Orsay.
- [54] Keays, J.L. (1971) Complete Tree Utilization: An Analysis of the Literature. Part III: Branches. Info. Rep. VP-X-70. Vancouver Forest Products Laboratory. Cdn. For. Ser. 1971, 67p.
- [55] Egunjobij, K. (1976) An Evaluation of Five Methods for Estimating Biomass of an Even Aged Plantation of *Pinus caribaea* L. *Oecologia Plantarum*, **11**, 109-116. <http://pascal-francis.inist.fr/vibad/index.php>
- [56] Young, H.E. (1971) Biomass Sampling Methods for Puckerbrush Stands. *XV IURO Congress University of Florida*, Gainesville, 179-190.
- [57] Clement, J. (1982) Estimation of Volumes and Productivity of Mixed Forests and Tropical Grasses. *Woods and Forests of the Tropics*, **198**, 35-58.
- [58] Sylla, M.L. (1997) Rapid Assessment of the Productivity and Production of Plant Formations: Bamako and Ségou Basins. Mission Report. Bamako, Mali, Republic of Mali, Ministry of Rural Development and Environment, National Directorate of Rural Development and Equipment, 27 p.
- [59] Ichaou, A. (2000) Dynamics and Productivity of Contracted Forest Structures in the Western Nigerian Plateaux. Doctoral Thesis, Paul Sabatier-Toulouse 3 University, Toulouse, 231 p.
- [60] Ibrahima, A. and Fanta, C.A. (2008) Estimation of the Carbon Stock in the Tree and

Shrub Facies of the Sudano Guinean Savannas of Ngaoundéré, Cameroon. *Cameroon Journal of Experimental Biology*, **4**, 1-11.  
<https://doi.org/10.4314/cajeb.v4i1.37970>