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Application of Allometric Models in Estimating Above- and Below-Ground Biomass Carbon Stock in Planted Forests of Congo

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Abstract

In Republic of Congo, the forest plantations are dominated by both exogenous and endogenous tree species. This study estimated carbon stocks for above- and below-ground biomass around the Bambou-Mingali forest plantations, in the Republic of Congo. It applied allometric equations to measure above- and below-ground biomass carbon stocks in six rectangular plots of 5000 m^2 (200 m × 25 m). About 1763 trees were measured and recorded where 1360 trees were within the 10 - 20 cm diameter class, 385 trees within the 20 - 30 cm diameter class and 18 trees within the 30 - 40 cm diameter class. Furthermore, the average carbon stock was 144.9 t C ha^{-1} for aboveground biomass (AGB) or 81% and 33.8 t C ha^{-1} for belowground biomass (BGB), or 19%. Similarly, results also showed total carbon stocks in all biomass to be 869.7 t C for AGB and 203.3 t C for BGB. Bambou-Mingali forest plantations are an important carbon sink and can therefore play a key role in the creation of carbon sinks, climate change mitigation and emergence of the green economy in the Republic of Congo.

Keywords

Biomass Carbon, Forest Carbon Climate Change, Forest Plantations, Above- and Below-Ground Biomass, Congo

1. Introduction

Within the past two decades, climate change research has likened greenhouse gas (GHG) emissions to human activities, such as industrialization, land-use change and over-exploitation of natural resources (Ekoungoulou et al., 2015; Mannan et al., 2021; Ma et al., 2023) Generally, climate change impacts environments thus affecting agriculture, crop yields, hence household livelihoods and incomes (Mukete et al., 2024). In the global carbon balance, terrestrial ecosystems are recognized as playing an essential role, absorbing nearly 30% of the total anthropogenic CO_2 emitted (IPCC, 2013). Allometric model in forest ecosystem context is an equation that utilizes the genotypical relationship among tree components to estimate characteristics of one tree component from another (ForestPlots.net et al., 2021). Allometric equations are mathematical relationships that relate an animal's or plant's size (length, mass, volume, etc.) to its biomass (dry weight). "Allometry" refers to the study of how an organism's size affects its physiology and morphology (see http://www.afritron.org).

REDD+ (Reducing emissions from deforestation and forest degradation), is a climate change instrument that encourages developing countries with large forest areas to conserve and manage them sustainably. It primarily focuses on reducing emissions from deforestation, reducing emissions from forest degradation, sustainable forest management, conserving forest carbon stocks and enhancing forest carbon stocks (CNIAF, 2015). The Congo Basin with 200 million ha of forest, is the second largest tropical forest ecosystem after Amazonia. If relatively conserved, it should play an important role in regulating the continental and global climate system (Ekoungoulou, 2014). Similarly, tropical forests spread over an area of 13.76 million km^2 representing 60% of the world's forests and play a key role in the global carbon (C) cycle, both in terms of C fluxes and the volume of C stored (IPCC, 2013).

The Global Forest Resources Assessment reports make an important distinction between the total loss of forest land over a given period and the net change in forest area. Against this backdrop of declining natural forest resources and availability, plantations represent a major option for meeting growing demand for forest products and reducing pressure on natural forests. As a result, an accurate and verifiable estimate of carbon stocks in this type of forest have become an urgent necessity (Lewis et al., 2013; Ekoungoulou et al., 2021). However, the carbon stock of these forest ecosystems is not yet known in a satisfactory way, to enable countries with this heritage to access carbon credit, which is another way of benefiting from the forest. Moreover, very little information exists on the forest carbon content of planted forests in the Republic of Congo. According to the IPCC (2006), estimating the carbon stock in forest ecosystems requires estimates for the following carbon pools: aboveground biomass, belowground biomass, coarse woody debris, litter and soils (Ekoungoulou et al., 2021). The objectives of the present study were to: 1) identify measurable dendrometric variables influencing carbon stock; 2) assess woody biomass in the different study plots; 3) assess age-dependent carbon stock in the different forest plantations.

2. Materials and Methods

2.1. Study Area

The study was carried out in the village of Bambou-Mingali (latitude 3˚53'S, longitude 15˚28'E) Ignié District, Pool division, Republic of Congo some (site 80 km from Brazzaville, the capital city (**Figure 1**).

The region exhibits the low-Congolian equatorial climate characterized by a relatively cool, well-marked dry season extending over three months from June to September, and a more accentuated rainy season from November to April. This is interrupted by a short, more or less regular dry season lasting a few weeks and occurring between December and February (Ekoungoulou et al., 2018), a low amplitude of temperature variations, not exceeding 10˚C and where average temperature oscillates between 30˚C during the hot season, and 22˚C during the cool season (**Figure 2**).

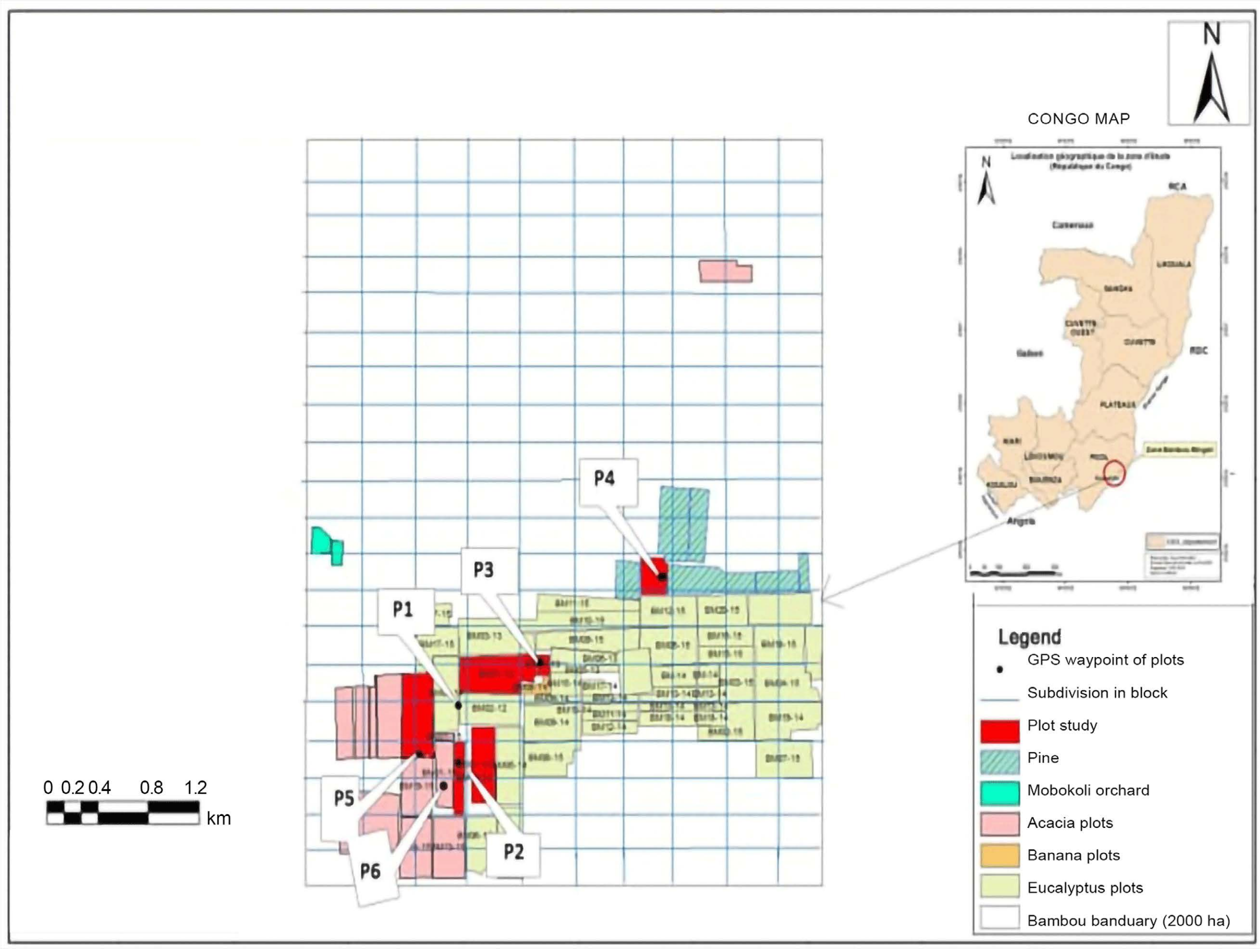


Figure 1. Location of study area.

2.1.1. Climate

The study area is under the influence of a low-Congolian equatorial climate that prevails in southwestern Congo (Ekoungoulou, 2014; ANAC, 2021). This climate is characterized by:

- A relatively cool, well-marked dry season extending over three months from June to September, and a more accentuated rainy season from November to April, interrupted by a short, more or less regular dry season lasting a few weeks and occurring between December and February (**Figure 2**);

- A low amplitude of temperature variations, not exceeding 10˚C: the average temperature oscillates between 30˚C during the hot season, and 22˚C during the cool season (**Figure 2**).

Climatological data (temperature (˚C) and rainfall (mm)) were collected at the Agence Nationale de l'Aviation Civile (ANAC) unit in the Pool Department, located at Maya Maya in the city of Brazzaville. During August and September, when we carried out our study, the average temperature was 25.4˚C and 26.0˚C respectively. However, monthly rainfall was 58.3 mm in September (Ekoungoulou, 2014; ANAC, 2021). All in all, no month is ecologically dry in this area.

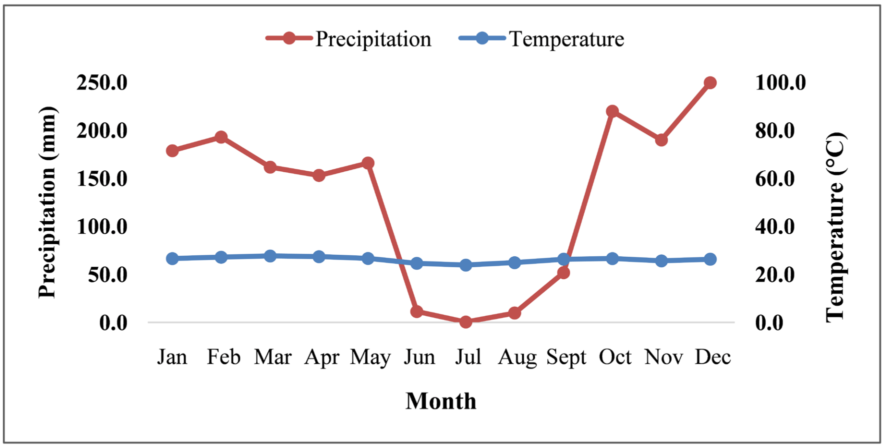


Figure 2. Climograph of the main meteorological station around the study area (average from 2010-2020).

2.2. Data Collection

Using the non-destructive method, data collection was carried out in six rectangular plots, each measuring 0.5 ha (i.e., 200 × 25 m). A compass (Eyeskey Military Sighting Compass model) was used to determine the cardinal points (North-South and East-West) and the orientation of each plot.

Finally, a Garmin 64S for the Global Positioning System (GPS) was used to record the plot location (coordinates) in minutes, degrees and seconds. Latitude, longitude and altitude were then recorded using the GPS at the center of each plot. Diameter at breast height (DBH) was determined from the circumference measured with a tape meter at 1.30 m above ground level. This circumference was then divided by 3.14 to obtain the diameter at breast height.

Only trees with DBH ≥ 10 cm were identified and measured thus trees with DBH < 10 cm (Ekoungoulou et al., 2017) were excluded because these trees hold a small fraction of the aboveground biomass in the woodland forest, and would otherwise dominate the signal in regression models (Lopez-Gonzalez et al., 2011; Chave et al., 2014; Ekoungoulou et al., 2015). Measurements were carried out taking tree locations into account. For trees with obstacles, 30 cm were added at 1.3 m to the normal size measurements (ForestPlots.net et al., 2021).

The general checklist of species composing the flora procession has been established after digital processing of six sample plots, on the basis of The African plants database (v.3.4.0) of Conservatory and Botanical Garden of Geneva, Switzerland and South African National Biodiversity Institute, Pretoria (Accessed 20 June 2024 at http://www.ville-ge.ch/musinfo/bd/cjb/africa/recherche.php), The Global plants database (Accessed June 18, 2024 at http://plants.jstor.org), The working list of all plant species database (Retrieved 5 July 2024 from http://www.theplantlist.org), and The Xycol database (The list of scientific and vernacular woods names: Accessed June 12, 2024 at http://www.xycol.net/index.php?categorie=0&sess_langue=430). All trees have been also checked and confirmed by The Missouri botanical garden's herbarium database, which is the one of world's outstanding research resources for specimens and information on plants (see http://www.missouribotanicalgarden.org).

A laser Hypsometer (Brand Nikon vision Co., Ltd., Forestry Pro No WJ072214) was used to measure the height of trees with a DBH ≥ 10 cm. The selection criteria for the six plots studied and field inventory have been performed with accordance to forest plots (see http://www.forestplots.net) protocol (ForestPlots.net et al., 2021), and the African tropical rainforest observation network protocol (AfriTRON), which is an international network of researchers engaged in on-the-ground long-term monitoring of tropical forests (see http://www.afritron.org).

2.3. Data Analysis

2.3.1. Trees Processing Overview

The database for the presentation of tables and graphs was created using Microsoft Excel 2016, a database was created in which scientific names, DBH, total height, specific tree density was recorded. The variation of biomass stock within and between vegetation types was analyzed and correlated with parameters including tree density, basal area and stem height. Density refers to the average number of trees per plot and basal area is the sum of the cross-sectional area at 1.3 m above the ground level of all trees in a plot. To perform this analysis, all data (diameter at breast height, stem density and tree height) were distributed in six studied rectangular plots of Bambou-Mingali planted forest ecosystem.

2.3.2. Estimation of Biomass and Carbon Stock

i) Aboveground biomass (AGB)

Aboveground biomass was estimated using the standard allometric Equation (1) from Chave et al. (2014), and used with success by Ekoungoulou (2014). This equation was chosen for two reasons: 1) This model considers three measurable dendrometric variables (Diameter at breast height, Total height of trees and their specific density); 2) This model is adapted to the tropical area and has been recommended by the Republic of Congo's national REDD+ coordination. The allometric equation of Chave et al. (2014) has been used successfully and repeated in numerous works (Djomo et al., 2016; Fayolle et al., 2016; Ekoungoulou et al., 2018). The allometric equation suggested by Chave et al. (2014) is presented as follows:

$$AGB_{est} = 0.0673 \times \left(\rho D^2 H\right)^{0.976} \quad (1)$$

ρ = wood density ($g \cdot cm^{-3}$)

D = diameter at breast height (cm)

H = height of tree (m)

AGB = aboveground biomass ($t \cdot ha^{-1}$)

However, the specific wood density for each tree (Zanne et al., 2009) was provided by DRYAD's Global wood density database (accessed on September 16, 2021, at https://doi.org/10.5061/dryad.234). Regarding the species for which specific densities could not be found, the default value for specific wood density of 0.5 g/cm^{-3} was used (IPCC, 2006).

ii) Belowground biomass (BGB)

Belowground biomass was estimated from aboveground biomass using the allometric Equation (2) & (3) developed by Mokany et al. (2006) which is as follows:

$$BGB_{est} = 0.205 \times AGB \text{ if } AGB \leq 125\ \mathbf{t \cdot ha^{-1}} \quad (2)$$

$$BGB_{est} = 0.235 \times AGB \text{ if } AGB > 125\ \mathbf{t \cdot ha^{-1}} \quad (3)$$

BGB = aboveground biomass ($t \cdot ha^{-1}$).

2.3.3. Estimation of Carbon Stock

To estimate carbon stock, aboveground biomass was divided by two to obtain the carbon stock of each plot (Fayolle et al., 2016; Basuki et al., 2009). In addition, a carbon stock is generally derived from aboveground biomass, if 50% of the biomass is carbon, as stated by Basuki et al. (2009). The carbon stock of belowground biomass was estimated from the belowground biomass, which was divided by two to obtain the carbon of each plot (Mokany et al., 2006). It was assumed that 50% of belowground biomass is composed of the carbon stock (Ekoungoulou et al., 2015).

2.3.4. Statistical Analysis

Data collected were subjected to analysis of variance (ANOVA) to determine if differences between each variable were statistically significant. The data of this study were compiled with SigmaPlot v. 10.0 and PAST v .3.05 statistical software. The statistical analysis was performed using the software PAST v 3.05 including standard statistical tests at $p < 0.05$.

3. Results

3.1. Flora Inventorying and Basal Area

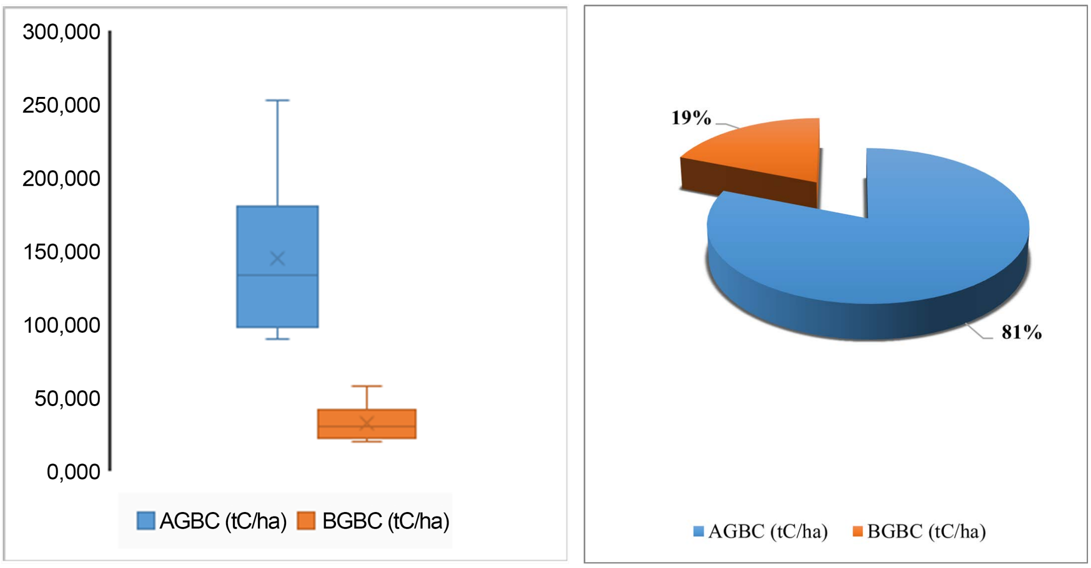
At the end of the inventory, 1763 trees with DBH ≥ 10 cm were recorded and measured. The identified species were mainly planted trees divided into 4 species and 3 families. The calculated basal area ranged from 7.6 $m^2 \cdot ha^{-1}$ to 19.9 $m^2 \cdot ha^{-1}$, with an estimated average of 13.4 $m^2 \cdot ha^{-1}$ (**Table 1**). Plot 1 had the highest value (19.9 $m^2 \cdot ha^{-1}$), followed by plot 3 (17.8 $m^2 \cdot ha^{-1}$) and plot 4 (7.6 $m^2 \cdot ha^{-1}$).

3.2. Biomass and Carbon Stock

As shown in Table 1, the average amount of biomass in the aboveground pool was 289.9 t·ha^{-1}, far higher than that of the belowground biomass (67.7 t·ha^{-1}). The average total biomass yield was 357.7 t·ha^{-1} and the highest biomass is represented by plot P1 with 623 t·ha^{-1}. Figure 3 shows the average aboveground biomass carbon stock to be 144.9 t C ha^{-1}, or 81%. In contrast, the average carbon stock of belowground biomass was 33.8 t C ha^{-1}, or 19%. Therefore, AGB is high compared to BGB and the carbon stock estimate for AGB (144.9 t C ha^{-1}) is higher than for BGB (33.8 t C ha^{-1}).

Table 1. Characteristics of the study plots in Bambou-Mingali planted forest. n is the number of sampled trees by plot; DBH is average of diameter at breast height (in cm) of trees measured using forestry meter tape; Height is average of trees height (in m) of trees per measured plot utilizing hypsometer; AGB is aboveground biomass (in t·ha^{-1}) calculated using the standard equation for all tropical forests developed by Chave et al. (2014); BGB is belowground biomass (in t·ha^{-1}) calculated using the model for tropical forests proposed by Mokany et al., 2006; G is basal area (in m^2·ha^{-1}) calculate for each plot according to ForestPlots (http://www.forestplots.net/). Age is the age of planted trees in each plot (in year). ρ is mean of wood specific gravity (in g·cm^{-3}) values provided by Global Wood Density Database from DRYAD at http://datadryad.org/handle/10255/dryad.235 (Accessed September 16, 2021); P is a sampled plot.

Plots	n	Age	G	Height	DBH	ρ	AGB	BGB
P1	255	9	19.97	18	21.8	0.6	504.5	118.4
P2	292	7	12.36	16	15.8	0.6	247.8	57.6
P3	368	8	17.81	17	17.1	0.6	290.3	67.8
P4	207	5	7.6	12	15.2	0.6	180.7	41.8
P5	284	7	12.14	16	15.9	0.6	314	73.6
P6	357	6	10.84	16	13.6	0.6	202.2	47.1



(a) (b)

Figure 3. Relationship between aboveground biomass (AGB, in t·ha^{-1}) and belowground biomass (BGB, in t·ha^{-1}) for Bambou-Mingali forest (a) using the reference model proposed by Chave et al. (2014). Fitted relationship between aboveground biomass (AGB) and belowground biomass (BGB) in percent (b).

Table 2. Effect of different plantation ages and above- and below-ground biomass carbon stock. AGBC is carbon stock of above-ground biomass (in t·ha^{-1}); BGBC is carbon stock of belowground biomass (in t·ha^{-1}); Age in year.

Species	Age	AGBC	BGBC
Acacia auriculiformis A. Cunn. ex Benth and *Acacia mangium* Willd.	6	101.1	23.5
	7	157	36.8
Eucalyptus urograndis hort.	9	252.2	59.2
	8	145.1	33.9
	7	123.9	28.8
Pinus caribaea Morelet var. *caribaea.*	5	90.3	20.9

As shown in Table 2, the 9 years old plantations of *Eucalyptus urograndis* hort stored more carbon in above- and below-ground biomass (252.2 t C ha^{-1} and 59.2 t C ha^{-1}) than other tree species.

However, one-way ANOVA analysis at P-level < 0.05 showed significant difference in means aboveground biomass for the studied forest ($F = 22.46$, $df = 7.671$, $P = 0.00139$). Levene's test for homogeneity of variance for means shows a significant difference ($P = 0.0174$). Kruskal-Wallis test for equal median shows that there is a significant difference between different 6 plots ($P = 0.0008$). Two-sample paired test were applied on plot 1 and plot 2 and shows a significant difference for t-test (Mean difference: 215.33, confidence interval at 95%: 0.53 - 430.22, $P = 0.031$), for Wilcoxin test (normal approximation inaccurate): $P = 0.08$. One-way ANOVA applied on plot 5 and plot 6 revealed significant difference regarding the test for equal means ($F = 8.48$, $df = 1$, $P = 0.0152$), for the Welch F-test in the case of unequal variance: $F = 8.371$, $df = 3.314$, $P = 0.0428$. Kruskal-Wallis test shows that there is significant difference between plot 3 and plot 4 ($P = 0.02081$).

4. Discussion

4.1. Dominance of Families and Individuals per Plot

Dominant species included the Myrtaceae such as *Eucalyptus urograndis* hort and Fabaceae such as *Acacia auriculiformis* A. Cunn. Ex Benth. This is due to these families being the oldest (age) and fastest growing in terms of height or diameter across the plantations. In a related study, Ekoungoulou (2014) found Fabacaea-Mimosoidaea (10%), Myrtacaea (10%) and Rubiacaea (10%) to be the most representative families around the Lesio-louna reserve in the Republic of Congo.

4.2. Analysis of Carbon Stock for Above- and Below-Ground Biomass

Carbon stocks in Bamboo-Mingali plantations vary from plot-to-plot with the carbon stock of above-ground biomass (AGB) being higher than that of below-ground biomass (BGB). Therefore, carbon stock is not based on the number of trees, but is rather related to DBH and tree height. In this study area, plot 1 has the highest carbon stock (AGB is 252.2 t C ha^{-1}). In plot one, 255 trees were measured, AGB was 252.2 t C ha^{-1}, BGB was 59.2 t C ha^{-1} and mean DBH was 21.8 cm

(**Table 1**). In addition, the mean trees diameter in plot 1 was greater than in the others plots, which consisted solely of trees planted with *Eucalyptus urograndis* hort. (Myrtaceae). This is because plot 1 is the oldest in terms of plantations (9 years), Tree age influences carbon sequestration capacity, thus all the species recorded in plot 4 are the least aged and have a lower carbon stock. According to Kooke et al. (2019), carbon stock values are observed in decreasing order from the oldest to the youngest plantations.

Furthermore, carbon stock is high in aboveground biomass (AGB) as compared to belowground biomass (BGB), with measurements of 869.7 t C ha^{-1} and 203.3 t C ha^{-1} respectively. The mean comparison test between plots revealed a significant difference between plots. The average carbon stock of 144.9 t C ha^{-1} found in this study is higher than that found by Ekoungoulou et al. (2018), which obtained 73.2 t C ha^{-1}. These differences are probably due to the diversity of environments and tree densities, but also to the different allometric equations used. Regarding a regional allometry for the Congo basin forests based on the largest ever destructive sampling, Fayolle et al. (2016) founded that to test whether, central African tropical forests are really different from other tropical forests with respect to biomass allometry. They tested the performance of pantropical models, which tended to provide significantly biased AGB estimates at the tree level for most sites.

In the three eucalyptus plots, as well as in the two acacia plots planted, carbon stocks were found to vary with age in the different plantations. This difference is probably linked to the dendrometric structure, sequestration capacity and age of the species surveyed. According to Temgoua et al. (2018), the older the tree, the more carbon it sequesters. In a related study on 5- to 15-year-old cocoa agroforestry systems, Temgoua et al. (2018) found biomass to increase with age. Their study concluded that the amount of carbon sequestered by an agroforestry system depends on the species planted, density, structure and function of the system.

5. Conclusion

This study focused on estimating the carbon stock of aboveground biomass (AGB) and below-ground biomass (BGB) in the Bambou-Mingali Land Reserve in the republic of Congo, made up mainly of planted trees. Throughout this area of forest plantations, the carbon stock for above-ground biomass (AGB) was 81% and the carbon stock for below-ground biomass (BGB) was 19%. Plot 1 was the most dominant in terms of carbon stock while that of plot 4 was lower than that of the other plots. A mean comparison test between the plots revealed that the significant difference was 111 t C ha^{-1} thus constituting an important carbon sink, and a key role in mitigating the global climate change. Given that the different carbon stocks are significant, Mingali Bamboo plantations could play a key role in creating carbon sinks throughout the Pool Department in the Republic of Congo. This forest plays a key role to forest carbon sequestration. In addition, this forest plantation can provide a large amount of oxygen to the atmosphere, helping to reduce the greenhouse effect and global climate change.

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Conflicts of Interest

The authors declare no conflicts of interest.

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