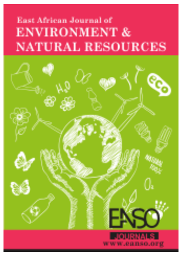

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Original Article

Allometry and Aboveground Biomass of Acacia auriculiformis A. Cunn.ex Benth Based Agroforestry Systems in Yangambi Landscape, Democratic Republic of Congo

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Acacia Auriculiformis, Allometric Models, Above-Ground Biomass, Agroforestry System

ABSTRACT

Most of the population living near the Yangambi Biosphere Reserve lives mainly from slash-and-burn agriculture which causes deforestation. The agroforestry system (AFS) is reputed to stabilise agriculture, store carbon in plant biomass and in the soil, and improve soil fertility. Acacia auriculiformis is a fast-growing leguminous tree that has been planted in AFS in the Yangambi landscape, but few or no studies assessed its aboveground biomass storage. This study aims to determine the aboveground biomass storage of AFS-based Acacia auriculiformis when intercropped with cassava, maise, and peanut food crops at different tree planting densities in the Yangambi landscape. The experimental device is a multifactorial trial of 36 plots of 400 m2 each one; with 4 treatments and 3 repetitions for each of these tree species in association with maise, groundnut, and cassava. Therefore, for assessing the aboveground biomass, the stem circumference and tree height were taken in each plot. Moreover, to study the A. auriculiformis allometry, 30 trees were cut and the aboveground biomass was estimated from the local allometric model set up in this study. Through this work, we have developed the three best allometric models for estimating the aboveground biomass of A. auriculiformis. The result showed that the aboveground biomass of A. auriculiformis varies between 0.49 and 10.54 t/ha (0.25 to 5.27 t/ha of carbon) depending on tree planting density and food crops. By comparing the results of the current study with those of others who worked on A. auriculiformis biomass, it was noted that the local models developed in this study contribute to increasing the precision of carbon estimation in the Congo basin. This is important for the implementation of REDD+ projects

(Reducing emissions from deforestation and forest degradation) in the DRC. In conclusion, agroforestry plantations contribute to storing carbon in plant biomass.

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INTRODUCTION

According to several studies, the agroforestry system (AFS) contributes to the storage of carbon in plant biomass and in the soil (Nair et al., 2009). AFSs are very important in the global carbon cycle and contain approximately 12% of the world's terrestrial carbon (Albrecht & Kandji, 2003). Located in the Democratic Republic of Congo (DRC), the Yangambi Biosphere Reserve is one of the main protected areas threatened by anthropisation in the Congolese central basin region (Kyale et al., 2019). Most of the local population lives mainly from slash-and-burn agriculture. This does not contribute enough to development and is the basis of deforestation (Kyale et al., 2019).

Agroforestry systems are considered to be a solution for limiting anthropogenic pressures on natural forest ecosystems and stabilising agriculture (Sanchez, 2002). It is in this perspective that the Centre for International Forestry Research (CIFOR) and its partners have initiated, since 2020, the project "Yangambi Pôle Scientifique au service de l'homme et de la forêt (YPS)". This project set up two experimental agroforestry farms in the Yangambi landscape, one in Yanonge and the other in Yangambi. On these farms, a local legume tree species (*Pentaclethra macrophylla* Benth) and other exotic (*Acacia auriculiformis*) were planted in association with staple food crops, including maise, cassava, and groundnut. The objective was to explore the different potentialities of agroforestry systems to find a reliable and viable model of sustainable agriculture that can be adapted by the local population.

Most studies on AFS in the Congo Basin have focused on the effect of exotic species, specifically Acacia sp., on carbon storage and have been conducted in old plantations (Drechsel et al., 1991; Sente, 2011; Abdou et al., 2013; Proces et al., 2017; Kachaka, 2020). Despite all this multitude of studies mentioned, we see that, in the Yangambi landscape, the allometry and aboveground biomass of *A. auriculiformis* are not documented. However, in the

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plantation, the allometry of trees varies according to the species, the age of the stand, the quality of the site, the climate, and the silviculture (Zianis & Mencuccini, 2004).

In addition, the aboveground biomass in young plantations of Acacia is less studied, whereas young agroforestry plantations constitute a real carbon sink in the Philippines (Lasco & Suson, 1999), in Kenya (Albrecht & Kandji, 2003) and in Bateke Plateau in the DRC (Dubiez et al., 2018). Moreover, studies relating to the impact of tree planting density and food crops on tree biomass storage are not documented in the landscape. However, according to Fayolle et al. (2016), the spatial variations of the aboveground biomass could be explained by several parameters including the density of stems per hectare.

The overall objective of this study is to determine the impact of *A. auriculiformis* tree plantation on the storage of aboveground biomass in the agroforestry system of the Yangambi landscape. Specifically, the study aims to determine the allometry of *A. auriculiformis* one-year-old and its variation according to the type of associated crop; determine the aboveground biomass of *A. auriculiformis* according to tree planting density depending on the type of crop.

The information presented in this study contributes to a better understanding of the contribution of young agroforestry plantations on carbon storage based on aboveground biomass in the Congo basin. This is important for the implementation of REDD+ projects (Reducing emissions from deforestation and forest degradation) in the DRC.

MATERIALS AND METHODS

Study Site

The Yangambi agroforestry farm is located in the Yangambi Landscape, Yangambi Biosphere Reserve (YBR), in the Tshopo Province in the DRC. The Yangambi ecological region covers 440,000 hectares with more than 76,000 people (Likoko et al., 2018). As part of this region, the YBR covers an area of 236,000 ha. Its geographical coordinates are between 24°18’ and 25°08’ East longitude and 00°43’ and 01°08’ North latitude. The altitude varies between 400 and 500 m above sea level. The climate of Yangambi Landscape is equatorial type (Af type according to the Koppen classification) (Kottek et al., 2006).

The soils are ferralitic of the Yangambi structural catena (Kombele, 2004), acidic and poor in fertilising elements (Likoko et al., 2020). In Yangambi, a large part of the forests corresponds to the definition of tropical evergreen rainforests (Lebrun & Gilbert, 1954). These forests are characterised by variable dominance of *Scorodophleus zenkeri*, *Pericopsis elata* and *Brachystegia laurentii* (Boyemba, 2011; Likoko et al., 2018).

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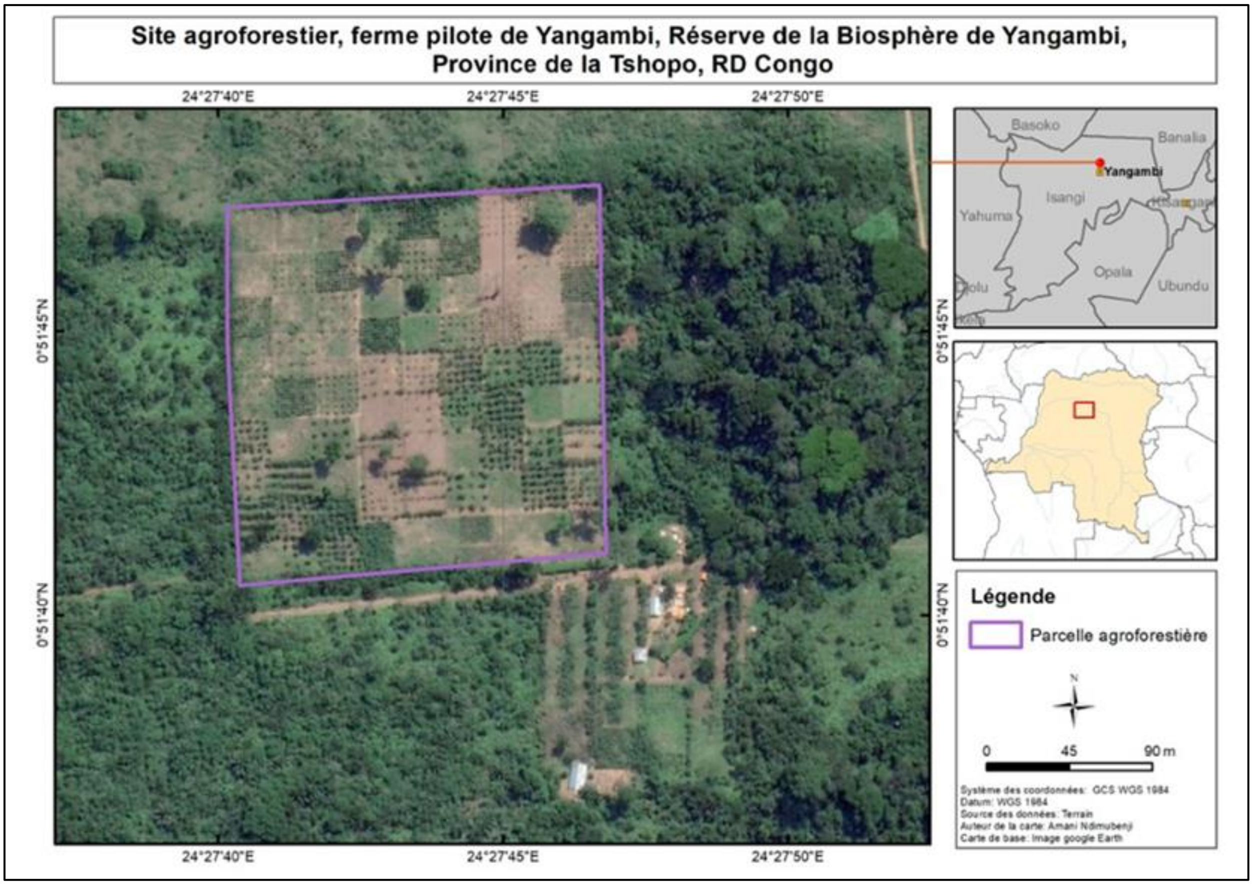
Figure 1: Yangambi agroforestry site, Yangambi Biosphere Reserve from Google Earth terrain and image data, GCS WGS 1984 coordinate system



Source: (Author: Amani, 2022).

Biological Material

Acacia auriculiformis A. Cunn. ex Benth., synonym *Racosperma auriculiforme* (A. Cunn. ex Benth.) Pedley is a species belonging to the family Fabaceae, subfamily Mimosoideae according to the APG III classification, native to northern Australia, Papua New -Guinea and Indonesia (Gnahoua & Louppe, 2003). It has been widely planted throughout the tropical and subtropical world. It is a large tree that can reach under good conditions, 30 m in height with a straight and long bole 60 cm in diameter (Gnahoua & Louppe, 2003). It is a fast-growing species and adapts to a wide variety of soils ranging from sandy soils to clay soils and soils with temporary hydromorphy. It tolerates pH from 3.0 to 9.5 and can grow on particularly poor soils (Gnahoua & Louppe, 2003).

Research Design

The research design is presented in *Figure 2*.

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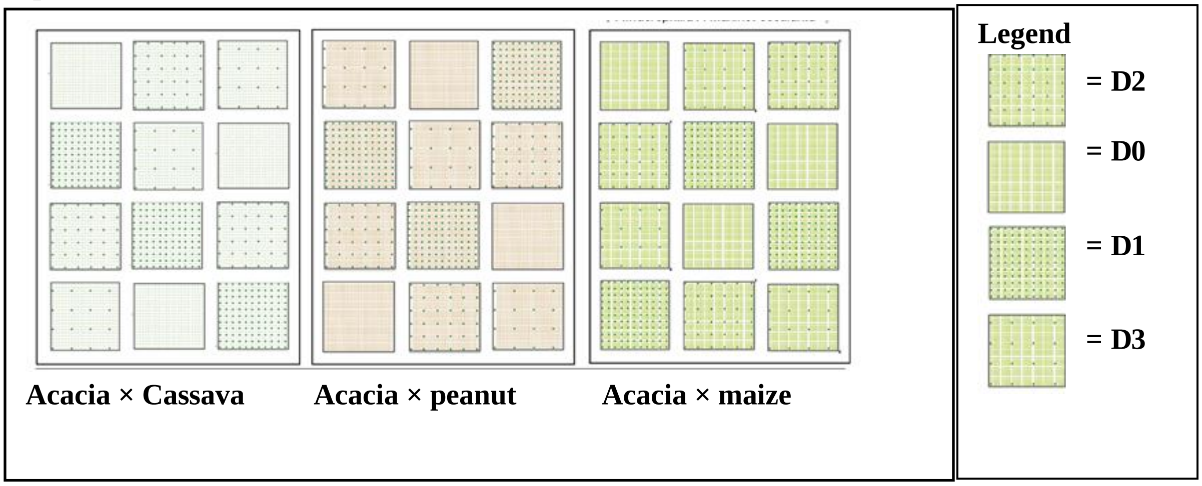
Figure 2: Multifactorial trial design of *A. auriculiformis* planted with crops in the Yangambi experimental site



The experiment was set in multifactorial trial design (*Figure 2*) of *Acacia auriculiformis*, with three replicates; under 4 different tree planting densities (spacing): 2500 trees×ha-1 (D1), 625 trees×ha-1 (D2), 278 trees×ha-1 (D3) and crop-only plot. Each tree density was intercropped separately with 3 food crops: cassava (*Maniho tesculenta* var. Obama 2), maise (*Zea mays* var. Samaru) and peanut (*Arachis hypogaea* var. G17). The plot size was 400 m2 (one experimental unit), constituted by the combination of planting density and food crop.

Based on farmers' cropping practices and recommendations, food crops were planted at the spacing of 1 m × 1 m for cassava, 1 m × 0.5 m for maise, and 0.2 m × 0.2 m for peanuts. The experiment was thus constituted of 36 plots (4 planting densities × 3 food crops and × 3 replications). The agroforestry tree selection was based on wood density for carbonisation, rapid growth, atmospheric nitrogen fixation and disease resistance; the food crop selection was based on local food preferences, while the varieties choice was motivated by precocity, disease resistance and crop yield.

The experiment was led from March 2020 to March 2021 by planting at the same period trees and food crops. Moreover, with regards to the crop's cycles and practices, maise and peanut were sown in each cropping season, i.e., twice a year (from March to July and from September to January), while cassava was planted only once a year. Concerning the food crops yield, grain yield was considered for maise and peanuts, while root yield was considered for cassava.

Determination of Tree Allometry

Measurements of the circumference at the base of the trunk/collar (at 10 cm from the ground) were taken on all the trees in the plot with the tape measure or the calliper (for the diameter) and the height of the trees (on 25 % of individuals in the plot) using a graduated board (Chave et al., 2003) (*Plate 1*). The circumference data were converted into diameter by the equation (1): $D=C/\Pi$ *(1)*

Equation (1) is the relation between collar diameter and circumference, D is the diameter at the collar (in cm), C is the circumference (in cm) and Π=3.14.

To determine the allometry of trees of *A. auriculiformis*, the following six allometric models divided into two groups according to the predictors were compared (Fonton et al., 2014). *Table 1* contains the above-ground biomass estimation equation models.

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Table 1: Aboveground biomass estimation equation models

N°	Model
1	ln(AGB)=a+b*ln(D)
2	ln(AGB)=a+b*ln(D)+c*(ln(D))^2
3	ln(AGB)=a+b*ln(D)+c*(ln(D))^2+d*(ln(D))^3
4	ln(AGB)=a+b*ln(D)+c*ln(H)
5	ln(AGB)=a+b*(ln(D))^2+c*ln(H)
6	ln(AGB)=a+b*ln(D^2*H)

Note: AGB is the aboveground biomass (in kg), ln is the function of the natural logarithm, D is the diameter at the collar (in cm), and H is the total height (in m)

The criteria for evaluating the quality of adjustment of each model are the adjusted coefficient of determination R_a^2 , the Root square Error (RSE) and the Akaike Information Criteria (*AIC*). The prediction quality of the model was assessed by calculating the cross-validation error through the sum of the squares of the prediction errors (PRESS: "predictive residual square error") (Sclove, 1968; Katembo, 2020).

The best equations are those characterised by high values of R_a^2 and small values of RSE and AIC. Using the least squares method with the R software, the values of these different criteria were determined. The study of the residuals helps to evaluate the models established by regression diagnostic techniques serving as a posteriori verification of the assumptions on the residuals.

According to the choice of the best model, three models were chosen respectively; one with predictor (D) and two with two predictors (D and H) according to AIC and PRESS criteria. In addition, the choice was supported by the significance of the estimated coefficients of the established models. Indeed, the model may fit well and be characterised by a large uncertainty on the regression coefficients.

Aboveground Estimation

To collect aboveground biomass data, 30 trees evenly distributed over the diameter range were cut (Pardé & Bouchon, 1988; Picard et al., 2012; Péroches, 2012). Before felling, measurements of the circumference at the base of the trunk/collar (at 10 cm from the ground) and the height of the trees were taken.

The felling of trees (distant from the edges of the plot by at least two rows to avoid the edge effect) was done by a hand saw. Tarpaulin was extended on the ground to avoid loss of leaves. After identification of the main axis, the branches were removed with a machete and/or pruning shears; thereafter, leaf stripping was done with pruning shears or by hand, as recommended by Picard et al. (2012).

For each tree, the fresh biomass of all the compartments (stem, branches, and leaves) was measured directly on the site by a mechanical load cell or a precision balance (0.01 g) (*Plate 1a*). Aliquots were taken for each tree. For the stem, two slices (carrots) were systematically taken from the trunk (large and fine ends). For the branches, sections (4 in total) and leaves, two composite samples of about 100 g each were taken. These samples were immediately weighed after collection in the field with a precision balance (0.01 g) before being brought back to the Laboratory of Ecology and Forest Management (LECAFOR), Faculty of Sciences, "Université de Kisangani" to analyse the biomass.

In the laboratory, each fresh biomass sample was weighed to determine its fresh weight before drying in the oven. Drying was done in an oven (70 °C for the leaves and 105 °C for the branches and stems) to constant weight. The anhydrous mass of each

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sample was then weighed using a precision balance (0.01 g) (*Plate 1b*).

The humidity rate (stem, foliage, and branches) was calculated from the ratio between the dry biomass of the sample and its fresh biomass. The leaf and ligneous dry biomasses were finally obtained by multiplying their fresh biomass by the humidity rate calculated from the aliquots. The total dry mass of the tree was finally obtained by the sum of the dry leaf biomass and the dry woody biomass (Procès, 2017; Fayolle et al., 2018).

Plate 1: Collection and measurements of fresh biomass from leaves, stems, and branches of *A. auriculiformis* by precision balance at the Yangambi pilot farm site (a) and oven drying of stem, branch, and leaf aliquots in the laboratory (b)

Source: (Photo: Amani, 2021)

The estimated total aboveground biomass (kg) was converted to carbon stock (kg) by multiplying it by a carbon fraction. Numerous studies have shown that the wood carbon content varies between 0.47 and 0.51; by convention, 0.5 was used, according to Mille & Louppe (2015).

Thus, the total aboveground biomass was converted into carbon quantity using *equation 2* in accordance with the recommendations of the Intergovernmental Panel on Climate Change (IPCC) (GIEC, 2003) as well as with the methodological approach used by Saïdou et al. (2012):

$$\text{Carbon stock} = AGB \times 0.5 \quad (2)$$

Equation 2 is the relation between carbon stock and the aboveground biomass; carbon stock is the volume of carbon, and AGB is the aboveground biomass.

The carbon equivalent, atmospheric CO_2, of the forest was estimated by *equation 3* according to the method used by Tsoumou et al. (2016):

$$\text{Equivalent stock (Teq)} = \text{carbon stock} \times 3.67 \quad (3)$$

Equation 3 is the relation between carbon stock and the atmospheric CO_2, carbon stock is the volume of carbon, and equivalent stock is the atmospheric CO_2.

Statistical Analyses

All the statistical tests were carried out using the R software "version R-4.0.5". The significance of the tests was judged at variable thresholds (0.001, 0.01 and 0.05).

First, the normal distribution of residuals was verified by Shapiro's test.

As regards the allometry of the trees and the analysis of the aboveground biomass, by the method of least squares with the R software, the adjusted values of the parameters (a, b, c, and d) and values of the different evaluation criteria of adjustment quality (R_a^2, RSE, AIC, PRESS) were determined for each model. Thanks to the *lm* function

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incorporated in the R software, the linear models were adjusted.

The Pearson or Spearman correlation test (if there is no normal distribution of residuals) was used to determine the correlation between diameter, height, and aboveground biomass. Using a local (specific to the site) allometric equation fitted in this research, the total biomass of each tree was finally determined. The aboveground biomass of the plot was obtained by the sum of the biomass of all the trees in the plot. This aboveground biomass was converted to a hectare (Procès *et al.*, 2017). The Tukey-Kramer (HSD) test was also used to group plots with similar values.

The ANOVA test was used to determine the variations in above-ground biomass according to planting density and/or the type of associated crop. In the case where the data distribution does not follow a normal law, the Kruskall-Wallis test was used to determine these variations.

RESULTS

Allometry of *Acacia auriculiformis* in the Yangambi Landscape

Table 2 shows the dendrometry characteristics of the 30 trees cut for the development of allometric equations. For these trees, the total height ranges from 1 to 5 m, the base diameter is between 1.7 and 8.1 cm, and the total biomass varies between 0.51 to 11.3 kg.

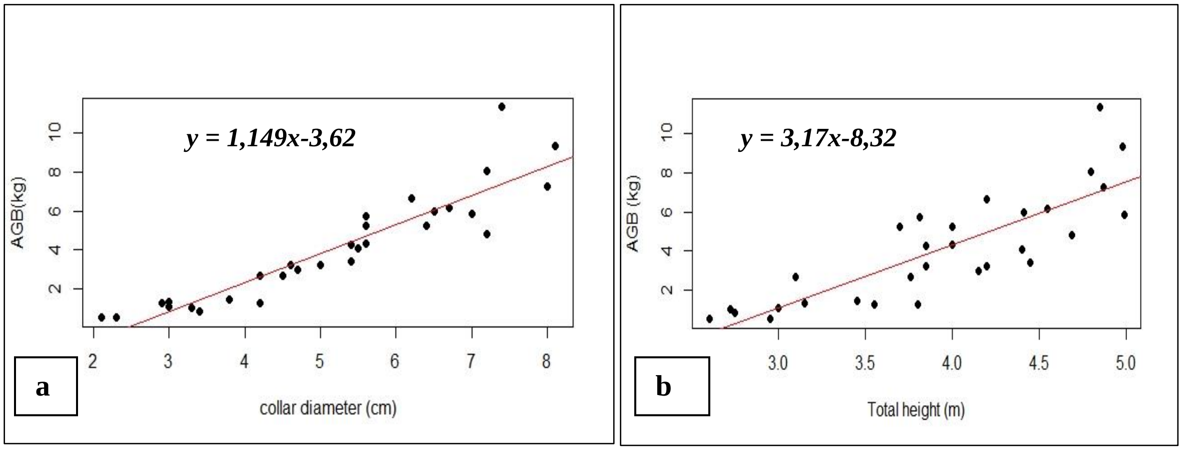
Table 2: Dendrometry characteristics of the 30 *Acacia auriculiformis* trees cut

Dendrometry characteristics	Minimum	Maximum	Average
Collar diameter (cm)	1.7	8.1	5.3±1.7
Total height (m)	0.7	5	3.9±0.7
Stem biomass (kg)	0.17	3.9	1.4±1
Branches biomass (kg)	0.09	3.8	1.2±1
Leaves biomass (kg)	0.24	4.1	1.7±1.1
Total biomass (kg)	0.51	11.3	4.3±3

Note: The numbers preceded by ± correspond to the standard deviation.

The correlation between collar diameter and aboveground biomass and also between total height and aboveground biomass is presented in *Figures 3a* and *3b*.

Figure 3: Relationship between collar diameter (a), total height (b) and total biomass of 30 trees of *A. auriculiformis* collected and weighed in the Yangambi agroforestry farm



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A strong correlation between collar diameter and aboveground biomass ($R^2 = 0.92$, $\alpha<0.05$) (*Figure 3a*) and also between total height and aboveground biomass of trees of *A. auriculiformis* ($R^2 = 0.83$, $\alpha<0.05$) (*Figure 3b*) was observed.

Table 3 shows the allometric equations for estimating the aboveground biomass of *A. auriculiformis* in the Yangambi landscape. These equations associate the aboveground biomass (AGB in kg), the diameter at the collar (D in cm) and the total height (H in m). For each equation is given the values of the coefficient R_a^2, the RSE, the AIC, PRESS, and the adjusted values of the parameters (a, b, c, and d). Three best equations were retained for estimating the aboveground biomass of the species *A. auriculiformis* in the Yangambi landscape. In the case of a single predictor, the best was equation 1, whose RSE is 0.232. Whereas in the case of two predictors, the best are equations 5 and 6 with an RSE of 0.234 and 0.235, respectively. However, all six models fit the data well.

Table 3: Allometric models for estimating aboveground biomass of *A. auriculiformis*

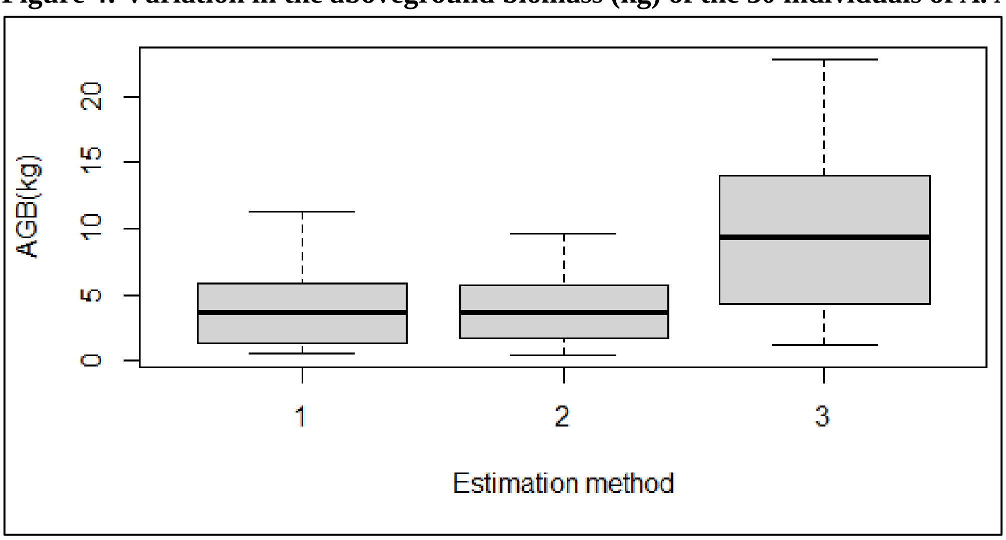
Models	a	b	c	d	R_{aj}^2	RSE	AIC	PRESS
Model with a single predictor								
1	-2.406	2.225	-	-	0.926	0.232	1	1.7
2	-2.357	2.154	0.024	-	0.923	0.236	3	1.8
3	0.413	-4.260	4.685	-1.077	0.925	0.233	3	1.8
Model with two predictors								
4	-2.614	2.062	0.346	-	0.924	0.234	3	1.9
5	-1.273	0.672	0.456	-	0.909	0.256	8	2.2
6	-2.929	0.896	-	-	0.924	0.235	2	1.7

Note: The best models are presented in bold.

Based on *Table 3*, the best equations for estimating the aboveground biomass of *A. auriculiformis* are as follows: ln(AGB)= -2.406+2.225ln(D) (equation 1), ln(AGB)= -2.614+2.062ln(D) +0.345ln(H) (equation 4) and ln(AGB)=-2.929+0.896ln(D^2H) (equation 6).

The comparison was made between the aboveground tree biomass values obtained from the destructive data, the biomass data predicted by the local model and that predicted by the model established by Procès *et al.* (2017) on the Mampu site in the DRC (*Figure 4*).

Figure 4: Variation in the aboveground biomass (kg) of the 30 individuals of *A. Auriculiformis*



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The dark black bar in the middle indicates the median, while the light black bars indicate the lower and upper extreme values. 1 = biomass from destructive data, 2= biomass predicted by the local model and 3 = biomass predicted by the model from Procès et al. (2017)

By comparing the aboveground tree biomass values obtained from the destructive data, the biomass data predicted by the local model and that predicted by the model Btot = $2{,}2279 \times D^{2{,}2020}$ of Procès et al. (2017) established on the Mampu site in the DRC, there is a significant difference ($p<0.001$). The model of Procès *et al*. (2017) overestimates the biomass of *A. auriculiformis* in the forest region of Yangambi.

Biomass Storage in *A. Auriculiformis* Plantations

Plantation density has no significant impact on average tree biomass for various crop types ($p>0.05$). On the other hand, the average biomass per tree varies significantly according to the type of crop associated with *A. auriculiformis* ($p < 0.001$).

In these 27 plots of *A. auriculiformis*, the total aboveground biomass stock was calculated from the local equation $\ln(AGB) = -2.929 + 0.896\ln(D^2H)$ implemented in the Yangambi landscape. Aboveground biomass was later converted into carbon stock (*Table 4*). High aboveground biomass and carbon stock values were observed in plots associated with groundnut, followed by maise. Cassava plots were characterised by low aboveground biomass and carbon stock.

Table 4: Stocks of aboveground biomass, of carbon and atmospheric carbon sequestration potential of plots of *A. auriculiformis* (t/ha) by crop type according to planting density

Planting density	*A. auriculiformis* aboveground biomass (t/ha)			Carbon stock (t/ha)			Carbone equivalent (tCO_2/ha)		
	Groundnut	Maize	Cassava	Groundnut	Maize	Cassava	Groundnut	Maize	Cassava
D1	10.54	8.46	2.47	5.27	4.23	1.24	19.34	15.52	4.53
D2	3.53	2.73	0.9	1.76	1.36	0.45	6.48	5.01	1.65
D3	1.71	1.05	0.49	0.86	0.53	0.245	3.14	1.93	0.90

Figure 5 presents the aboveground biomass stock of the plots according to tree planting density and crop type.

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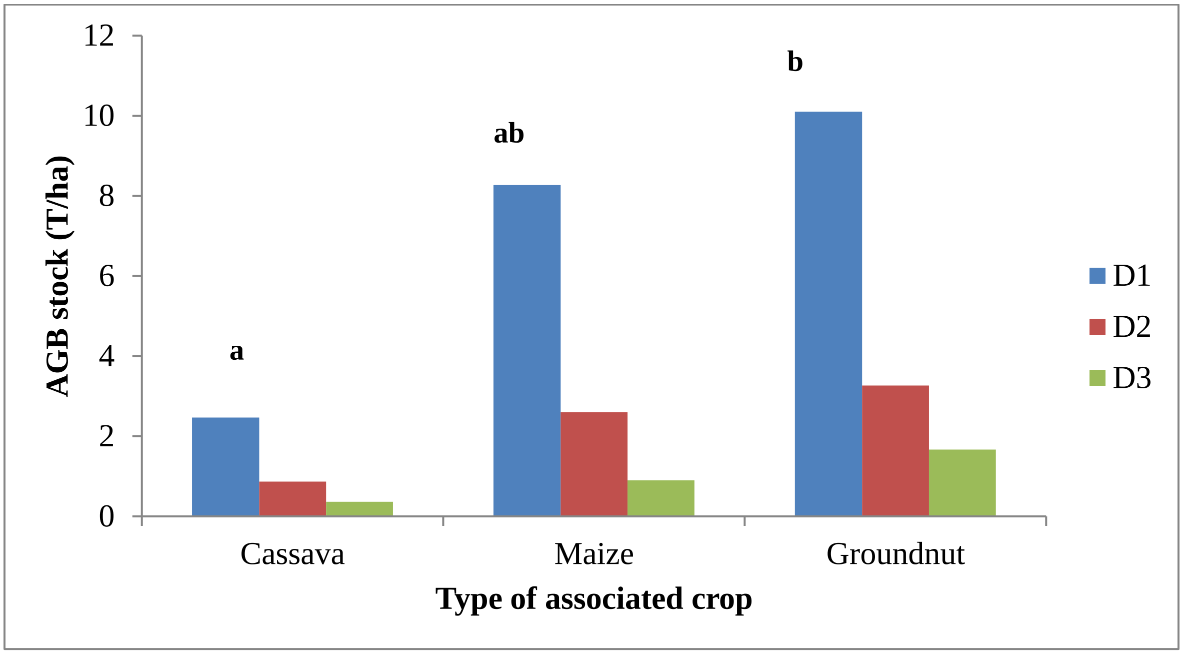
Figure 5: Variation in aboveground biomass stock (T. ha-1) of A. auriculiformis plots aged one year depending on the planting density and the type of associated crop.



Note: a, ab and c provide information on the significance of the statistical test.

With regard to this figure, the trees density and the type of associated crops have a significant impact on the storage of the biomass of a plot ($p < 0.001$, $\alpha=0.001$).

DISCUSSION

The local allometric model better estimates the aboveground biomass of *A. auriculiformis* plantations of the Yangambi landscape.

The results showed the existence of a strong correlation between the collar diameter and the aboveground biomass of *A. auriculiformis*. There is also a positive correlation between the total height and the aboveground biomass of *A. auriculiformis* trees.

These results are correlated with those of Bernhard-Reversat et al. (1993) who showed that in *A. auriculiformis* the total aboveground biomass increases with the diameter at the base of the trunk and the total height of the trees.

This finding confirms several results already obtained in tropical forests. Indeed, in tropical Africa, Lewis et al. (2013) as well as Bastin et al. (2015) indicate that aboveground tree biomass is always positively correlated with tree diameter/basal area.

Several authors have shown the importance of using local allometric models in the estimation of biomass. The Procès et al. (2017) model implemented during the recent study on *A. auriculiformis* agroforestry systems from the Mampu site, Plateau Bateke in the DRC was not efficient for our study. The use of this model gives somewhat high aboveground biomass values.

Through this study, the three best allometric models for estimating the aboveground biomass of *A. Auriculiformis* were set up. Among them, one with a single predictor (basal diameter) and two for basal diameter and height as predictors of aboveground biomass.

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Aboveground Biomass and Carbon Storage in *A. auriculiformis* Agroforestry Plantations

The results confirm that the storage of above-ground biomass and carbon of the plots varies considerably depending on tree planting density and the type of food crop. Fayolle et al. (2016) showed that spatial variations in aboveground biomass could be explained by several parameters, including the density of stems per hectare.

Albrecht &Kandji (2003) also argued that carbon sequestration is linked to the nature of the agroforestry systems in place, their structures, and functions, which depend on socioeconomic and environmental factors, the types of woody species and the management method.

CONCLUSION

This article focused on the impact of one-year-old *A. auriculiformis* plantations on above-ground biomass and carbon storage in the Yangambi landscape.

It is noted that the storage of the total aboveground biomass and carbon of the plots is linked to the density of tree plantations and the type of food crop put in place. Thus, the study recommends that the *A. auriculiformis*-based agroforestry system be vulgarised by planting at most 625 trees per hectare (4 m x 4 m spacing) to avoid competition between trees and crops.

Despite the results obtained, some information deserves to be provided to complete this research. The study recommends that given woody legumes for carbon storage vary according to the age of the plantations, it is necessary to study the biomass and its evolution during the growth of *A. auriculiformis*.

Finally, limits for the smooth running of the collection and/or analysis of samples may have risen from caution on certain hazards in the field. Although all work has limits, the results obtained within the framework of this study constitute a source of relevant data and information concerning the themes addressed therein.

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