Maderas-Cienc Tecnol 24(2022):19, 1-25
Ahead of Print: Accepted Authors Version
DOI:10.4067/S0718-221X2022005XXXXXX

INFLUENCE OF GROWTH PARAMETERS ON WOOD DENSITY OF *Acacia auriculiformis*

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Received: March 01, 2021
Accepted: January 09, 2022
Posted online: January 10, 2022

ABSTRACT

Understanding the drivers of wood density variation both within a tree and between trees is important in predicting the quality of wood logs and improving this quality through adequate forestry management. This study examined the effect of the diameter growth of *Acacia auriculiformis* on its wood density variation. The study was conducted in the South of Benin in four plantations of *Acacia auriculiformis*. Near infrared spectroscopy (NIRS) method was used to predict the basic density of 225 tree wood cores of *Acacia auriculiformis*. A predicting model of the average tree density using the diameter as predictor was established. The relationship between wood density and tree diameter was best described by a linear mixed-effect model. The average wood density of trees increased with the diameter. The study concluded that the quality of the species logs can be improved through regular thinning and genetic selection.

Keywords: *Acacia auriculiformis*, log, NIRS, tree diameter, wood characteristics,

1- INTRODUCTION

Density is a major functional trait of wood (Hietz *et al.* 2013, Ducey 2012). It is related to the physico-mechanical characteristics and natural durability of the wood (Hietz *et al.* 2013, Pérez-Peña *et al.* 2020) and is correlated with the longevity of trees. Trees with low wood density usually have higher mortality risks (Hietz *et al.* 2013). Also, wood density represents a good indicator of forest biomass and the rate of carbon sequestered in wood (Morel *et al.* 2018, Nabais *et al.* 2018). Wood density is among the most important parameters used in tree breeding programs (Alves *et al.* 2010). It varies inside species with the height and the radial position (Guller *et al.* 2012, Hietz *et al.* 2013). Hence, wood density is a combined effect of several intrinsic and extrinsic factors, including the environment, genetic factors, age and growth parameters (Nabais *et al.* 2018, Morel *et al.* 2018, Mevanarivo *et al.* 2020).

Tree growth is usually expressed in several ways, including height increment, and diameter growth (DeBell *et al.* 1994, Silva *et al*. 2019). Tree growth influence several characteristics of wood such as wood density. The effect of tree growth on wood density is not consistent across species. In general, fast-growing species have low density (DeBell *et al.* 1994). The increase in tree growth would lead to an increase in the ring's width, a low wood density (Wang *et al.* 2000, Gapare *et al.* 2010) and an inter-annual variability in the wood density. On the contrary, DeBell *et al.* (2001) found that the wood density of *Eucalyptus saligna* increased with the diameter, particularly on nutrient rich soil whereas Jakubowski *et al.* (2020) found no significant effect of tree growth on wood density for *Betula pendula*. The relation between tree growth and wood density is apparently site-specific (e.g. climatic factors and soil water reserve) and species-specific (Bouriaud *et al*. 2005).

Several methods are used to estimate wood density. Direct measurements from felled trees, with wood density corresponding to the mass over the volume of a sample, provide quite accurate results (Alves *et al.* 2010). Still, indirect measurements through near infrared spectroscopy (NIRS) could be used for predicting wood properties with high precision based on calibrated and validated Partial Least Squares (PLS) regression models (Alves *et al.* 2010, Cooper *et al.* 2011, Diesel *et al.* 2014). This method allows to evaluate a large amount of data very quickly and efficiently (Cooper *et al.* 2011). It also has the advantage of using samples from un-felled trees to determine wood characteristics.

Knowledge on the distribution of wood density in individual trees and its formation process is required to improve both the silvicultural processes and the wood production so as to obtain a wood of the desired quality (Guller *et al.* 2012, Mäkinen and Hynynen 2012). But the complexity of the wood density formation usually limits the interpretation of the models because a similar average density of two woods can result from different anatomical parameters and environmental factors. Thus, understanding the intraspecific variability of wood density can enable the identification of appropriate silvicultural practices to produce wood at a higher yield and of a better quality (Hai *et al.* 2010).

Acacia auriculiformis is native to Asia (Wickneswari and Norwati 1993) where its wood shows distinct rings. The number of rings may be inconsistent with the age of the tree (Chowdhury *et al*. 2009) and the determination of the radial variation of its wood is of definite interest. In West Africa, the species was introduced in 1980 (Tandjiekpon and Dah-Dovonon 1997) mainly for firewood production but also currently include timber prospects (Tonouéwa *et al.* 2019). The species produces a wood with quite good characteristics (Hounlonon *et al.* 2018,Tonouéwa *et al.* 2020). Determining the variability of its wood density within and between trees and understanding the influence of tree diameter on the wood density will allow for the improvement of the species growth parameters and wood physico-mechanical characteristics through appropriate silvicultural treatments. The main objective of this study is to identify patterns and drivers of wood density variation in *A. auriculiformis* grown in plantations in South Benin. More specifically it aims to (i) determine the relationship between the diameter and wood density of *A. auriculiformis*; and (ii) determine the radial variation of the wood density of *A. auriculiformis*.

2- MATERIALS AND METHODS

2.1 Study area

The study was conducted in Southern Benin around 6º22 'to 6º54'N latitude and 2º05 'to 2º8'E longitude (Figure 1) and precisely in twelve state-owned plantations of *A. auriculiformis*. These plantations were located at Lama (on vertisol), Pahou (on ferruginous soil), Ouedo (on ferralitic soil) and Sèmè-kpodji (on sandy soil). The climate is similar across the study sites (Amoussou *et al*. 2016). The average annual rainfall is 1100 mm and the average annual temperature 27 °C.

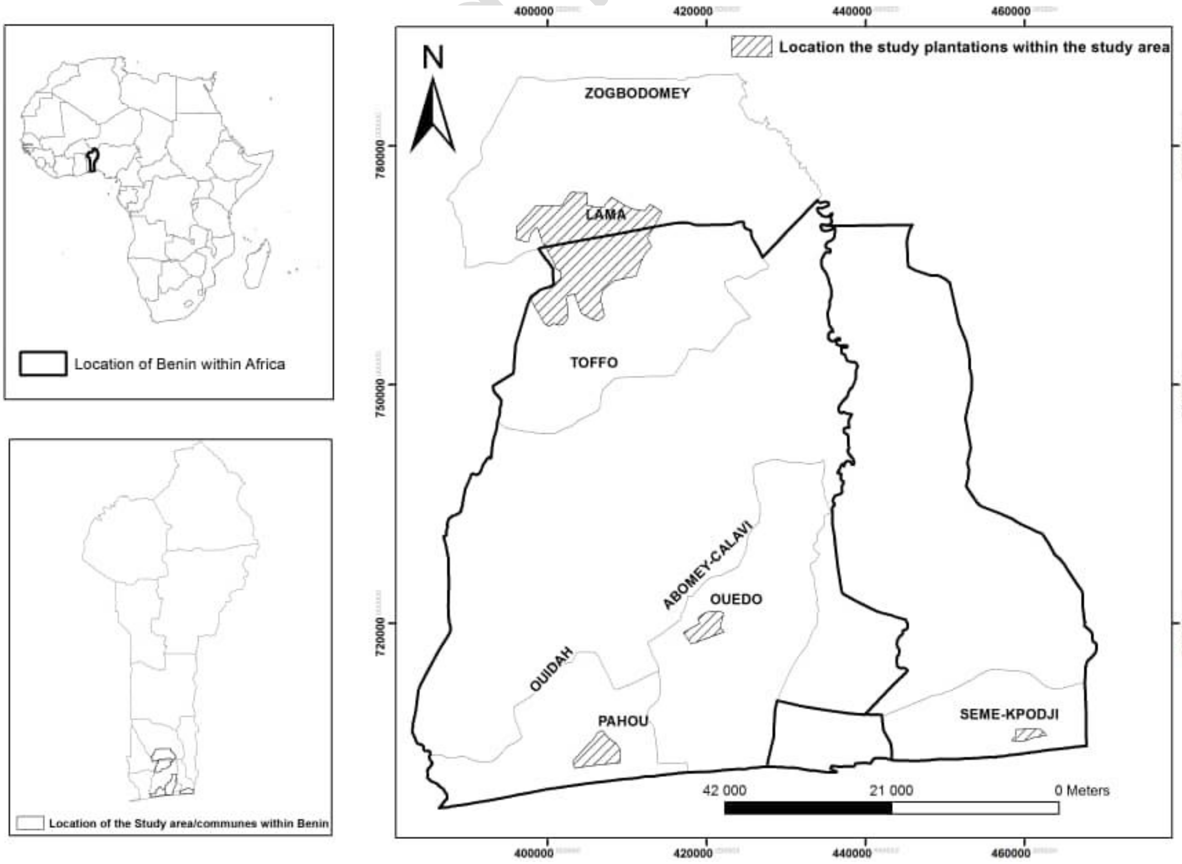

Figure 1: Map of study area and location of the study plantations.

2.2 Data collection

The data comes from twelve state-owned plantations of *A. auriculiformis* (Table 1; Figure 2). A total of 255 cores of 5 mm diameter were sampled, at 1.30 m height from 255 tree individuals (1 core per tree), using a Pressler auger. The transverse surface of the cores was sanded with sandpaper (fine grits) to obtain a flat and smooth surface for the measurements. The cores moisture was stabilized at 12%. The near infrared spectrometry (NIRS) method was used to determine the wood density on each core sample at 1 cm interval (Figure 3) and the radial variation of the wood density of *A. auriculiformis* was described. Near infrared spectra were obtained with a Bruker Vector 22/N spectrometer run by OPUS 200 software version 5.5.

Figure 2: *A. auriculiformis* plantations of 4 years old, South-Benin.

Table 1: Wood samples distribution across soil types and age of the selected plantations.

Type of soil	Ferrallitic			Ferruginous			Vertisol			Sandy			Total
Age of the selected plantation (years)	4	5	6	6	9	15	7	9	11	27	27	29	
Thinning regime						a				b	c	UH	
Number of trees/hectare (Tonouéwa *et al.* 2019)	970	910	827	790	407	323	707	530	420	190	293	187	
Number of plots	3	3	3	3	3	3	3	3	3	3	3	3	36
Number of cores extracted	21	21	21	21	21	21	22	22	21	21	21	21	253
Cores with validated measures	20	20	21	14	16	12	21	22	21	21	18	19	225

UH=Uncontrolled Harvesting; a= thinning at 9 years; b= thinning at 7 years+ Uncontrolled Harvesting; c= Thinning at 14 years + Uncontrolled Harvesting

On each core, the number of measures in the heartwood was ≤ 20 (20th radial position, Figure 3 and 6).

After removing broken and poorly preserved cores from the samples and after removing outliers, 225 cores translating into 2869 measurements (430 on sapwood and 2439 on heartwood) were validated (Table 1). However, the wood density of *A. auriculiformis* was predicted using only the 2439 measurements on heartwood because wood density is always higher in heartwood than in sapwood (Githiomi and Kariuki 2010). This is due to the high proportions of carbon, lignin and extractives in the heartwood (de Aza *et al.* 2011, Bertaud and Holmbom 2004). In addition, heartwood is the most interesting part of the tree for use as timber.

For the prediction of wood density, we used a pre-established NIRS model of the basic density of *A. auriculiformis* in South Benin (Tonouéwa *et al.* 2020). The model had a root-mean-square error (RMSE) of 50.33 kg/m^3 ($R^2 = 0.75$) for the prediction model and 45.88 kg/m^3 ($R^2 = 0.79$) for the calibrated model. The Unscrambler software, version 9.7 CAMO (The Unscrambler 2007) was used to estimate the basic density and the standard deviation for each measured point. The value of the basic density at a given point on a wood core is an average of 16 measurements with the spectrometer at this point. The standard deviation of the 16 measurements at each point was ≥ 60 Kg/m^3.

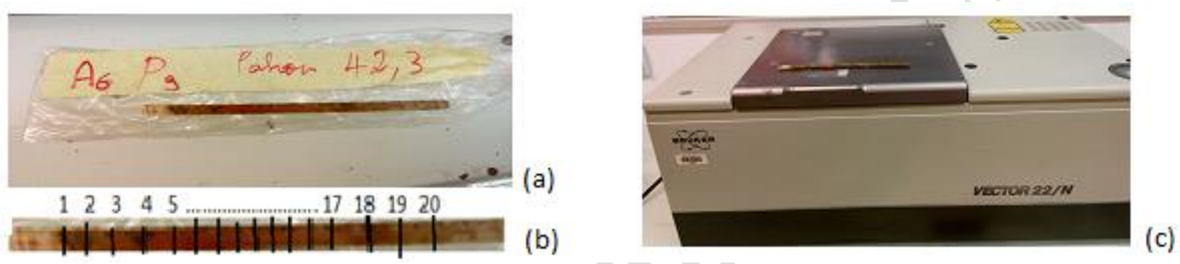

Figure 3: *A. auriculiformis* wood core packed within the field with codes indicating the location, the tree and tree diameter (a); a wood core marked for measurements (b) and the spectrometer used to make the measurements (c).

The basic density of *A. auriculiformis* trees was evaluated as a function of the radial position in the tree and as the ratio between the dry mass of a sample and its saturated volume (Rybníček *et al.* 2012, Diesel *et al.* 2014).

2.3 Statistical analysis

A first exploratory analysis of the predicted wood density of *A. auriculiformis* on cores was done. Samples with standard deviations greater than or equal to 200 kg/m^3 (i.e. 1.5 times the interquartile range above the third quartile or below the first quartile; Crawley 2007) were considered as outliers and excluded from the batch for the subsequent analyses.

To assess the relationship between the wood density and tree diameter, several Linear and Non-Linear Mixed Effects Models (NLME) were tested in R.3.5.2 (R Core Team 2018) with the nlme package (Pinheiro *et al.* 2018). The random effects were: plots nested within zone of data collection and the fixed effect was tree diameter. Based on the inspection of the scatterplots and models previously used for explaining the relation between tree diameter or tree age and wood density, a linear (Silva *et al.* 2019) and four nonlinear functions (Table 3) were assumed to potentially fit well the data. The nonlinear functions include the second-degree polynomial function (Githiomi and Kariuki 2010), the first exponential function (Oddi *et al.* 2019), the Michaelis-Menten asymptotic function (Oddi *et al.* 2019) and the second exponential function (Oddi *et al.* 2019).

The appropriate model was selected based on the Akaike Information Criterion (AIC) (Akaike 1973) and the random effect. The best model is the one that minimizes the AIC value (Chave *et al.* 2005) and shows a high random effect (i.e. variance in the wood density explained by the random effect). The general equation of the NLME model developed in R.3.5.2 is showed below:

```
Model=nlme(ER,
           data=WDdata,
           fixed=a+b+c~1,
           random=a~1|zone/plot,
           start=c(a=u, b=v, c=w))
```

ER: the linear or nonlinear regression equation used (Table 2); WDdata: the database containing the dependant (wood density) and the explanatory variables; a + b + c ~ 1: the parameters of the function (Table 2) used for the fixed effect of the model; a ~ 1 | zone / plot: the random effect; *u*, *v*, *w*: the list of initial estimates for the values of *a*, *b*, and *c* respectively.

When the function has two parameters (a, b), the fixed effect takes the form a + b ~ 1.

Regarding the type of linear or nonlinear relationship, parameters *a*, *b* and *c* were calculated with an adjustment in R (R.3.5.2).

Concerning the linear function, parameters *a* and *b* were determined by solving in R the following matrix equation (1):

$$\begin{cases} Y1 = ax1 + b \\ Y2 = ax2 + b \end{cases} \tag{1}$$

Considering the second-degree polynomial function, parameters a, b, and c were calculated by solving in R the following matrix equation (2):

$$A\begin{pmatrix} y1 \\ y2 \\ y3 \end{pmatrix} = B\begin{pmatrix} a \\ b \\ c \end{pmatrix} * \mathrm{C}\begin{pmatrix} x1^2 & x1 & 1 \\ x2^2 & x2 & 1 \\ x3^2 & x2 & 1 \end{pmatrix} \tag{2}$$

Regarding the first exponential function (3), *a* and *b* were calculated as follow:

$$\mathrm{b} = \log\left(\frac{\mathrm{y1.x2}}{\mathrm{y2.x1}}\right)/(\mathrm{x2} - \mathrm{x1}) \text{ and } \mathrm{a} = \frac{\mathrm{y1}}{\mathrm{x1e^{-bx1}}} \tag{3}$$

For the Michaelis-Menten asymptotic function, *a* and *b* were calculated using the SSmicmen function of the package stats.

For the second exponential function (4), *a* and *b* were calculated as follow:

$$\mathrm{b} = \log\left(\frac{\mathrm{y_2}}{\mathrm{y_1}}\right)/\log\left(\frac{\mathrm{x_2}}{\mathrm{x_1}}\right) \text{ and } \mathrm{a} = \frac{y_1}{x_1^b} \tag{4}$$

After the selection of the best model, normality quantile, modelling variance, correlation structure, residuals wood density as function of tree diameter, and a plot of the predicted vs observed wood density were analysed to evaluate the model assumptions.

In addition, the relations between the wood density and the age of the plantation, and the radial position in the tree were determined using a mixed effect model in R.3.5.2 (R Core Team 2018) with the lmerTest package. The average values of the wood density were eventually regressed against the radial position for each age of plantation.

3- RESULTS

3.1- Variation in wood density of *A. auriculiformis* in relation to tree diameter

Among the models tested (Table 2) for expressing the wood density as a function of tree diameter, the linear mixed effect model was the most suitable for *A. auriculiformis* (low AIC, high random effect). This model validity is restricted to *A. auriculiformis* trees with at least 10 cm diameter at breast height and growing in conditions similar to those of south Benin. The model is in the form of: $WD = a * D + b$, with D = tree diameter, WD = wood density,

a =1.2335, b= 537.6931 from solving Equation (1). With a Root-Mean-Square Error (RMSE) of 51.79 Kg/m3 and a Bias of 0.2%, the quality of the model is suitable.

Table 2: Results from the five linear and nonlinear models tested for the prediction of *A. auriculiformis* wood density (WD) in kilograms per cubic meter (Kg/m3) with tree diameter (D) in centimetre (cm) as the predictor.

Model	Equation	Fixed coefficient	Random effect	AIC	log-Likelihood	ΔAIC
Linear	$WD = a * D + b$	a=1,23 b= 537,69	38,21	2218,89	-1104,447	0
First exponential	$WD = a * D * e^{(-b*D)}$	a=71,48 b=0,05	4,57	2251,77	-1120,887	32,88
Polynomiale	$WD = a * D^2 + b * D + c$	a= -0,20 b=9,63 c= 455,68	0,06	2251,15	-1119,575	32,26
Asymptotique	$WD = a * \frac{D}{1 + (b * D)}$	a= 586,02 b= 0,79	34,44	2226,91	-1108,453	8,02
Second exponential	$WD = e^{b*D}$	a=533,51 b= 0,003	30,73	2228,1	-1109,05	9,21

WD = wood density; a, b and c are the parameters of the function used for the fixed effect of each model (see Table 2); AIC = Akaike Information Criterion; ΔAIC = difference between the AIC of the best model (smallest AIC) and each of the alternate models, for ease of comparison.

The characteristics of the linear model obtained indicate a distribution of the data close to normal (Figure 4-a), a homogeneity of the variance (Figure 4-b), a weak autocorrelation structure (Figure 4-c), and a coherent and uniform distribution of wood density residues as a function of the diameter of the trees (Figure 4-d). The scatter plot between the real data and those predicted is not perfect (Figure 4-e), however we observe that the predicted values are averages of the real values.

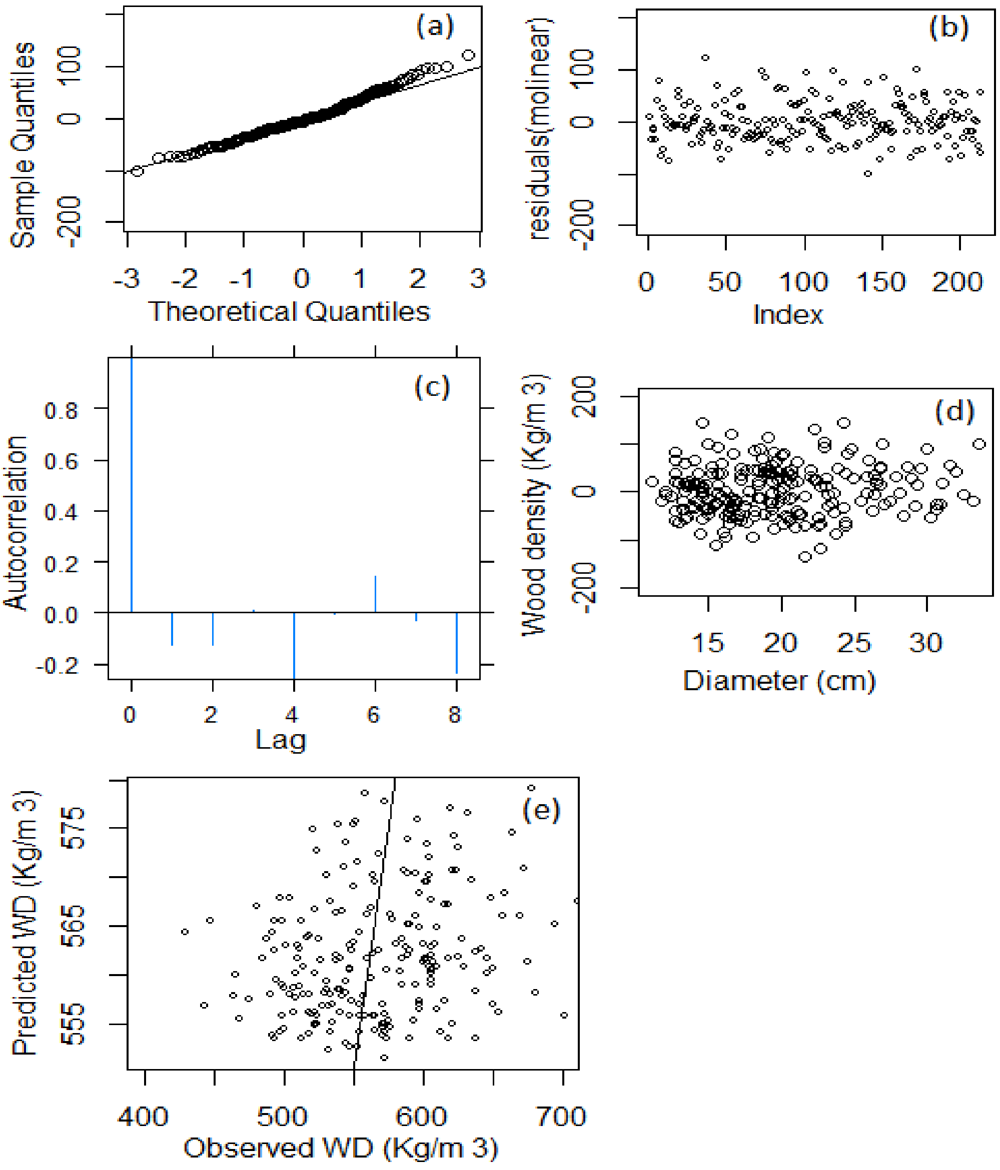

Figure 4: Characteristics of the linear mixed effect model of wood density as a function of tree diameter for *A. auriculiformis* in Benin: a- Normality quantile, b-modelling variance, c-correlation structure, d- Residual wood density as a function of tree diameter, e- Predicted Wood density vs observed wood density, 45° line.

In general, wood density of *A. auriculiformis* increased with the diameter (Figure 5). There is also a significant and positive correlation between tree diameter and wood density of *A. auriculiformis* (r = 0.23; p-value = 0.0006**).

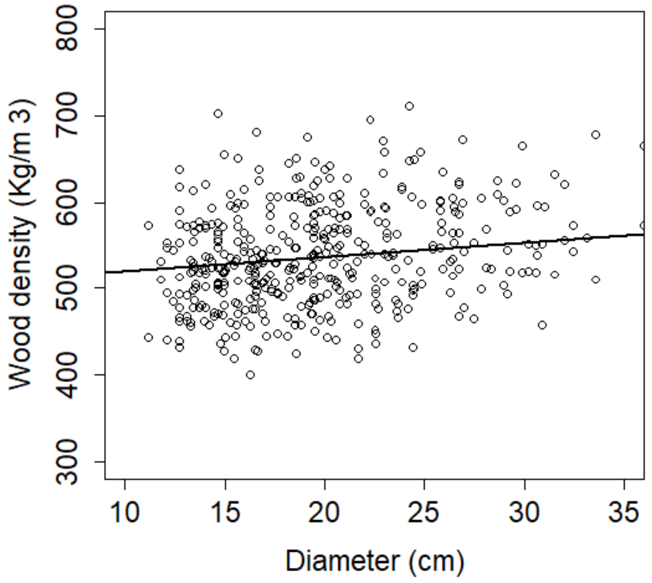

Figure 5: Wood density of *A. auriculiformis* as a function of the tree diameter.

3.2- Intra-species and intra-tree variations in the wood density of *A. auriculiformis*

Wood density varies from one tree to another (Table 3), and the random effect of this parameter explains 25.7% of the variation of *A. auriculiformis* wood density in the study plantations.

Table 3: Results of the mixed effect model predicting wood density as a function of the plantation age and the radial position of the wood in the tree.

Random effects		Variance	Std.Dev.		
	Tree	917,9	30,3		
	Residual	3562,7	59,69		
Fixed effects		Estimate	Std.Error	t.value	p.z
	(Intercept)	566,42	5,27	107,57	0,00***
	Age of plantation	26,11	1,32	19,3	0,00***
	Radial position	-1,58	1,23	-1,28	0,20ns
	Age of plantation:Radial position	0,20	1,22	0,17	0,87ns

****Significant difference at 0,1% level; ns = no significant*

In general, the relation between the wood density of *A. auriculiformis* and the radial position of the wood in a tree was not significant (Table 3, Figure 6). The radial pattern of the wood density of the species did not show the demarcation between juvenile and mature wood. Still, we noted a sawtooth radial variability of wood density, an increase in the density of the wood outwards until a wood density peak is obtained, and a decrease in the wood density towards the ends of the tree. On the contrary, the age of the plantation has a significant and positive effect on wood density (Table 3).

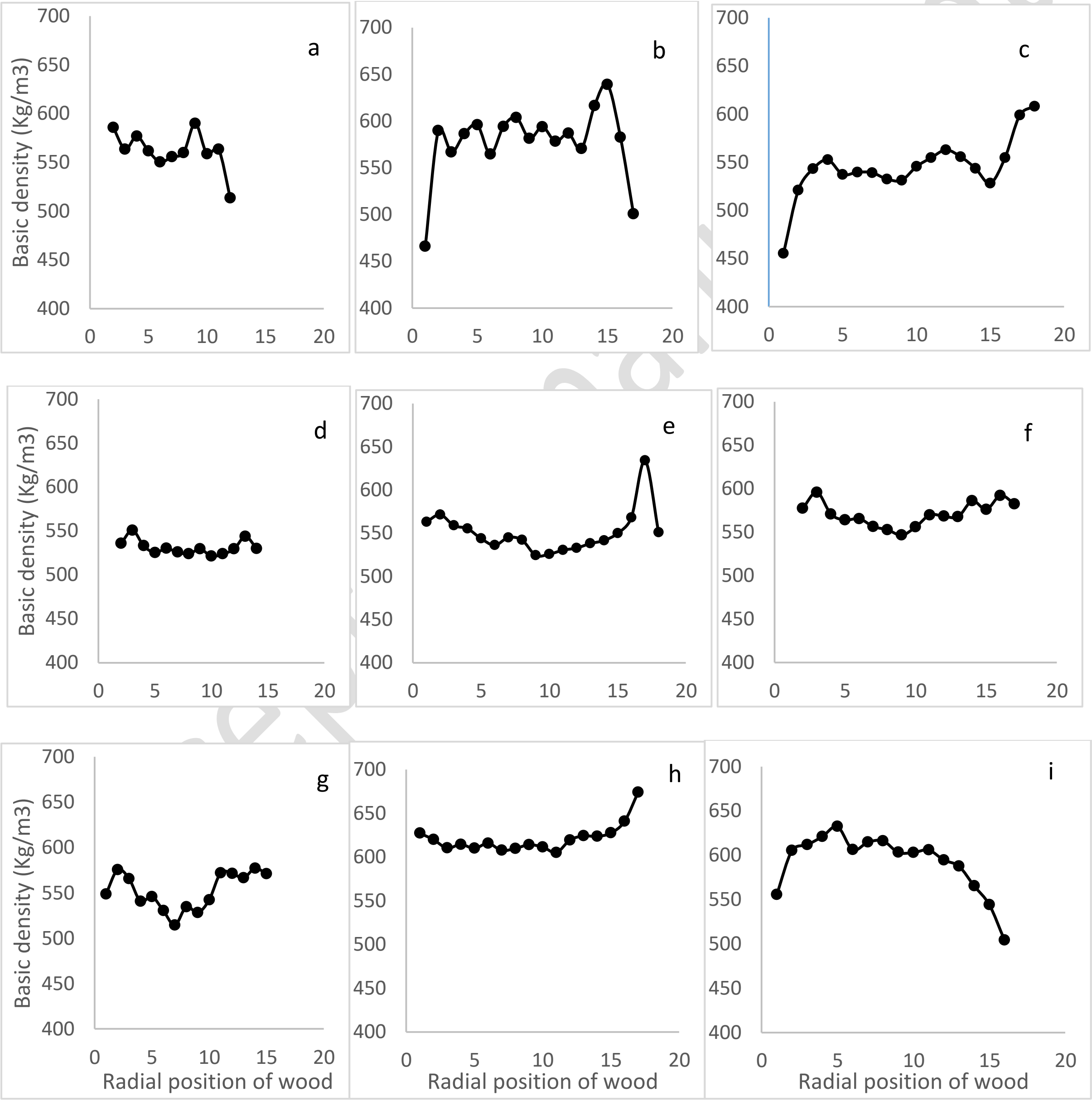

Figure 6: Variations in the wood density of *A. auriculiformis* as a function of the radial position of the wood and the age of the plantation: a = 4 years old plantation; b = 5 years old plantation; c = 6 years old plantation; d= 7 years old plantation; e = 9 years old plantation; f =

11 years old plantation; g = 15 years old plantation; h = 27 years old plantation; i = 29 years old plantation.

4- DISCUSSION

The best model for predicting the wood density of *A. auriculiformis* as a function of diameter is a linear function, and wood density increased with tree diameter within the range of diameters considered for the sample trees in this study (10-35 cm diameter at 1.30 cm). Linear models have been widely applied for the estimation of wood density in various settings and for various species. For example, an estimation of the wood density of Cerrado species (e.g. *Luehea paniculata, Terminalia fagifolia)* was obtained in Brazil with a lineal mixed model (Silva *et al.* 2019) and for several species in Madagascar (Ramananantoandro *et al.* 2016). Similarly, a linear mixed-effect model was used to estimate the wood density of *Quercus petraea* as a function of growth parameters and site quality (Guilley *et al.* 2004). Wood density increased with diameter. Forestry focused on accelerating the growth of *A. auriculiformis* trees is generally recommended for the rapid obtaining of good wood quality and large diameters. As such, regular thinning could be effective in increasing the value of *A. auriculiformis* plantations as shown elsewhere (e.g. Huong *et al.* 2020, Wiersum and Ramlan 1982). However, climate and soil conditions can alter trees response to thinning and post-thinning diameter growth. Thus, further experiments are needed to evaluate the response of the species to frequent thinning practices in the specific conditions of South Benin.

The correlation between the diameter of the trees and wood density, although significant, was moderate in this study and suggests that the diameter of the tree alone does not explain entirely the variation in wood density of *A. auriculiformis*. Indeed, the relationship between wood density and growth rate in a species is generally influenced by environmental, silvicultural and genetic factors (Zobel and van Buijtenen 1989, Zhang and Morgenstern 1995). Consequently, contrasting relations between tree growth and wood density are found in the literature. For example, in Madagascar, Ramananantoandro *et al.* (2016) found that tree diameter did not significantly affect wood density for native hardwood species. Similarly, a lack of correlation between tree growth and wood density was observed for *Eucalyptus globulus* in Portugal (Quilhó and Pereira 2001) and for black spruce (*Picea mariana*) in Canada (Hall 1984), while DeBell *et al.* (2001) found a negligible influence of growth rate on wood density for *Eucalyptus saligna* in Hawai. In contrast, Roque and Fo (2007) and Boyle *et al*. (1988) reported negative correlations between wood density and growth traits, respectively for *Gmelina arborea* in Costa Rica and for black spruce (*Picea mariana*) in Canada. In the present study, the moderate positive correlation between *A. auriculiformis* wood density and tree diameter suggests that diameter growth can be improved with a small gain in the species wood density. This is interesting as most wood mechanical properties are closely related to wood density.

In addition, wood density varies from one tree to another within same plot. This variability of the wood density can find an explanation in the silvicultural practices in Benin. *A. auriculiformis* plantations in Benin are set up from seeds from mother plants chosen mostly randomly, or based on the availability and accessibility of the trees (survey in South Benin). The probability of a large genetic variability between trees on the same plot is thus high. This stress the importance of genetic selection, as the structural characteristics of *A. auriculiformis* wood, such as the wood density, are heritable. The selection of good quality parent material are particularly critical for improving the properties of new plantations (Hai *et al.* 2010, Chowdhury *et al.* 2012, Nabais *et al.* 2018).

Regarding the intra-tree variation of wood density, we found no significant relation between the radial positions of the wood and the wood density for *A. auriculiformis*. Wood density being the main technological parameter of wood, its variation within trees and the magnitude of the variation provide information on the quality of the logs produced (Guilley *et al.* 2004).

As such, our results indicate that the characteristics of *A. auriculiformis* logs are heterogeneous. Bouriaud *et al.* (2005) linked the variability of the radial density of wood to the differences in radial growth of trees. The latter is influenced by climatic variations, thinning and soil fertility (Mäkinen and Hynynen 2012, Hietz *et al.* 2013, Miranda and Pereira 2015, Nabais *et al.* 2018). For *A. auriculiformis* these site-specific constraints could relate to climatic conditions and tree spacing.

Although the intra-tree variation of wood density was not significant in this study, the following patterns could be drawn from the data: (i) a sawtooth radial variability of wood density that possibly reflect the succession of rainy and dry seasons at the study sites; (ii) an increase in the density of the wood outwards until a wood density peak is obtained, suggesting that the wood formed during the last years of the tree's life is of higher density; (iii) a decrease in the wood density from pith to bark, which is potentially linked to the presence of sapwood. Similar variations of radial characteristics were also recorded on *A. auriculiformis* produced in Asia (Chowdhury *et al.* 2012) as well as for other timber species (Hietz *et al.* 2013).

The low radial variability in the wood density indicates that for estimation of wood biomass of *A. auriculiformis* and carbon content in the wood, the samples wood can be taken at any radial position in the tree (Chave *et al.* 2006, Hietz *et al.* 2013). This low radial variability in the wood density also makes it possible to predict low constraints growing of the tree (Curran *et al.* 2008, Nock *et al.* 2009, Nabais *et al.* 2018) predicting good ecological and biological conditions of growing and better quality of the log.

5- CONCLUSIONS

In this study, the best model for predicting the wood density of *A. auriculiformis* as a function of diameter is a linear function, and wood density increased with tree diameter. The moderate positive correlation between *A. auriculiformis* wood density and tree diameter suggests that diameter growth can be improved with a small gain in the species wood density. The suggested opportunities for improvement include the selection of good quality parent and the practice of frequent and regular thinning to reach desirable diameters and produce high-density timber. However, further experiments should evaluate the response of the species to frequent thinning in the specific climate and soil conditions of *A. auriculiformis* grown in South Benin. The study also highlights the need for reducing the intra-tree variability in wood quality, which could also be achieved through improved tree breeding.

ACKNOWLEDGMENTS

The first author received support from the International Foundation for Science (FIS; Grant I-1-D-6154-1), L'Oréal UNESCO (Sub-saharan Africa young Talents program 2019; grant For Women in Science), and IDEA Wild (field equipment). The authors extend their thanks to the French Agricultural Research Centre for International Development (CIRAD-Montpellier, France) for making it possible for the first author to carry out wood samples analyses within its UR BioWooEB laboratory.

Conflicts of interest: The authors declare that they have no conflict of interest

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