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Growth modeling of short rotation coppice teak (*Tectona grandis* L.f) stands in Republic of Bénin

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ABSTRACT

African farmers have being involved in reconverting part of their lands into coppice teak stands for decades. Available studies have pointed out the need for technical assistance, to achieve sustainable production. This work was aimed at developing growth model for coppice teak stands in other to provide management guidelines for stands' owners and decision makers. The study was based on 321 circular plots of a factorial test design which consisted of three factors: Plant community, the age of shoots and the number of shoots per stump. Stand density, circumference at breast height and height were collected periodically for six months in each circular plot. Seven candidate models were fitted and their parameters were estimated with R software using the Generalized Linear Models and the Non-linear Least Squares. Performances of models were compared and the best model was chosen. Findings obtained revealed that the mean quadratic diameter of coppice teak stands could be accurately predicted using non-linear model based on shoots age and the number of shoots per stump. In addition, trees mean height could be calculated based on the mean quadratic diameter through simple linear regression. From this study, first models were developed for predicting quadratic mean diameter and mean height in coppice teak stands. They could be used by managers and stands owners to make sound decisions as well as to plan their production.

INTRODUCTION

Artificial forests or planted stands play an important role in the limitation of natural forests depletion and in the satisfaction of population's firewood and timber needs (FAO, 2011). Teak (*Tectona grandis* L.f.) is among the most planted forest tree species because of its good wood properties (Vernay, 2000; Bekker et al., 2004; Iamtasna et al., 2010; Soumya et al., 2011). Farmers in West Africa are involved in reconverting part of their croplands into coppice teak stands for many reasons such as: Diversification of income sources, lands security as well as wood and poles production (Aoudji et al., 2011, 2012). The provision of management tools to farmers and decision makers for sustainable management of coppice

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Table 1. Distribution of plantations across plant communities.

Plant community	Number of plantations recorded
Mallotus oppositifolius - Paullinia pinnata	5
M. oppositifolius - Macrosphyra longistyla	5
M. oppositifolius - Reissantia indica	3
M. oppositifolius - Combretum sordidum	1
M. oppositifolius - Dichapetalum madagascariense	1
Chromolaena odorata - Imperata cylindrica	3
C. odorata - Panicum maximum	1
Dichapetalum madagascariense - Cnestis ferruginea	1
R. indica - Combretum sordidum	1

teak stands will contribute to environment protection and farmers' revenue improvement. However, several studies have been undertaken in teak plantations while there are scarce studies on coppice teak stands. The few studies done on coppice teak stands have revealed problems of stump and shoot over-density, inadequate sites choices and bad management practices (Maldonado and Louppe, 1999; Mittelman, 2000; Quenum, 2002; Ganglo and Yéssoufou, 2003; Demenois et al., 2005).

Growth modeling has been used to monitor stands dynamic and develop productivity tables as well as provide guidance for managers in smart decision making (Dupuy et al., 1999; Ganglo et al., 1999). In literature, no growth model has been developed for coppice teak stands. While in many studies, height and/or diameter growth models have been developed (Bermejo et al., 2004; Sánchez-González et al., 2005; Adame et al., 2006; Rugmini and Jayaraman, 2009) but the models are based on Richards' equation ($Y = A\left(1-e^{-kt}\right)^{\frac{1}{1-n}}$) and Lundqvist-Korf's equation ($Y = A\left(e^{t}\right)^{\frac{k}{n}}$) (Amaro et al., 1998) which unfortunately contain only "age (t)" as independent variable whereas there are much more independent variables (age, site quality, stump density, shoot density, etc.) which are able to influence growth in coppice teak stands (Yêvidé et al., 2011a, 2011b).

The main objective of this study was to develop primary models to predict diameter growth in coppice teak stands as well as elaboration of allometric equation between height and diameter.

MATERIALS AND METHODS

Sampling and experimental design

This study was based on a representative sample of 21 private teak plantations belonging to nine plant communities (Table 1) and spread in the Department of Atlantic located between 6°18' and 6°58' of North latitude and 1°56' and 2°30' of East longitude (Figure 1). The study area is under the tropical climate. The mean annual rainfall is 1200 mm and the monthly mean temperature varies from 27 to 31°C. Because of agriculture the natural vegetation has been degraded and nowadays fallows and croplands dominate the landscape.

A factorial test design with three factors (plant community, age of shoots and number of shoots per stump) was established. Plantations were of different shoots' age; each was divided into two parts and all the trees in one of them were cut. Four numbers of shoots per stump were considered with three replications: control treatment (T_0) with respect to famer's practice; two shoots per stump (T_1); three shoots per stump (T_2) and four shoots per stump (T_3). Each treatment was applied in circular plot of 100 m² to give a minimum of ten to twelve stumps per plot as recommended by Duplat and Perrotte (1991). Thus, 321 circular plots were installed and used for data collection.

Data collection and parameters calculation

Data were collected at periodicity of six months during two years. In each circular plot, shoots were numbered and the point of circumference measurement materialized. The number of stump (*Nc*) and shoots (*Nt*) were counted; they were used to calculate the initial density of plantation ($Dp = 100 \times Nc$) and the density of shoots ($Dr = 100 \times Nt$). The circumferences at breast height (*Ci*) of all shoots were measured as well as the height (*Hi*) of shoots of the ten first stumps. The data collected allowed computing parameters as follow:

- mean quadratic diameter, that is $Dg = \sqrt{\sum (Ci/\pi)^2 / n}$ and

- mean height, that is $Hg = \sum Hi/n'$

Where *n* is the number of shoots circumference measured

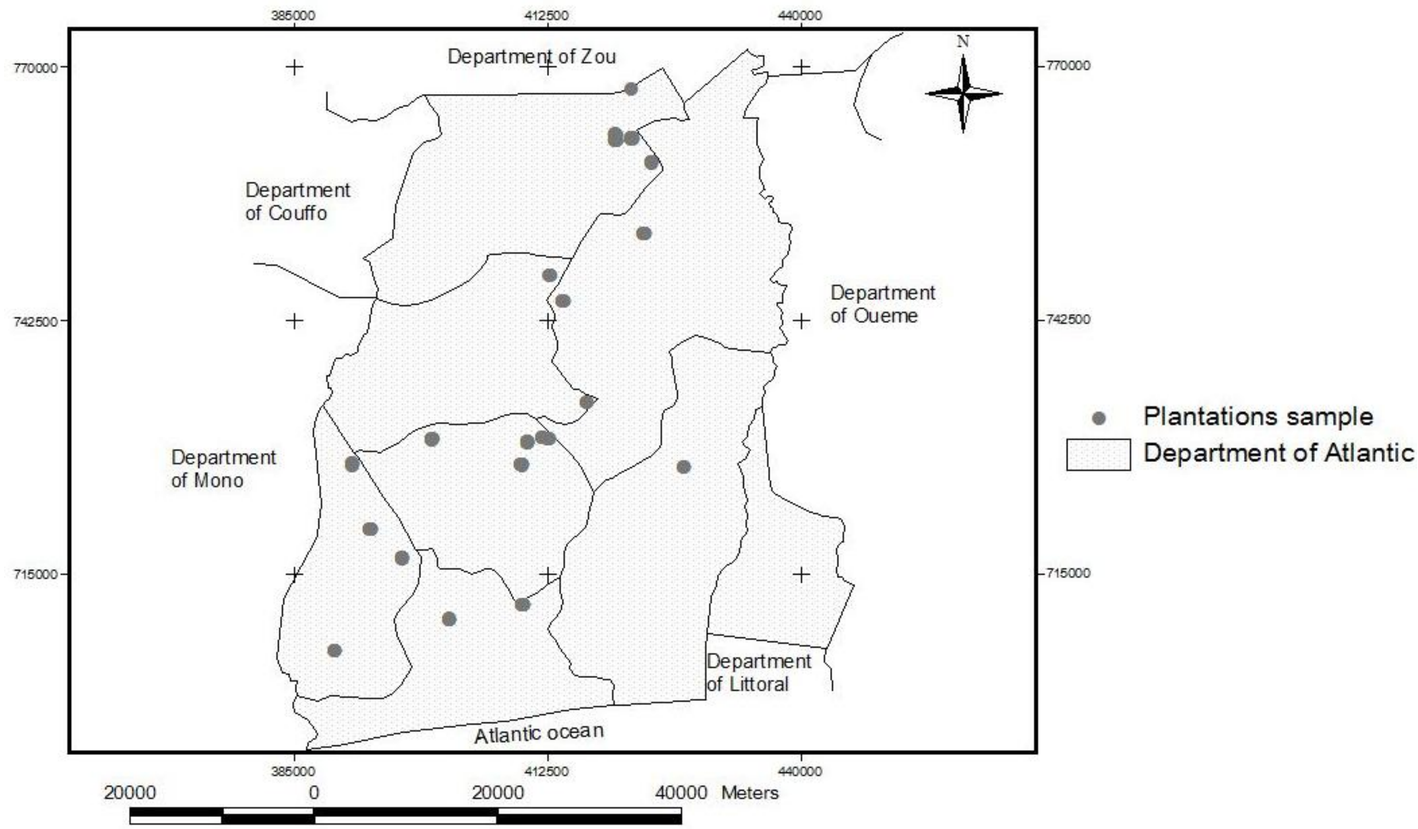

Figure 1. Distribution of studied plantations in the Department of Atlantic.

and *n'* the number of shoots height measured.

After the two years of data collection, 1013 observations were recorded and used to develop diameter growth models and allometric equation between height and diameter of the coppice teak stands. The plantations were at most ten years old.

Growth model choice and data analyses

To predict the mean quadratic diameter of teak in coppice plantations, two different groups of models were used in this study: linear model ($Y = \beta + \sum a_i \times X_i$) and non-linear models with power function ($Y = a_1 \times X_1{}^b + a_2 \times X_2 + ... + a_n \times X_n$) and exponential function ($Y = a_1 \times \exp(b \times X_1) + a_2 \times X_2 + ... + a_n \times X_n$), where *Y* is the dependent variable (mean quadratic diameter); β, a_i and *b* are parameters to be estimated and X_i are independent variables.

The age of the shoots, the number of shoots per stump and the initial density of the plantation were taken as potential independent variables in the development of the diameter growth model. These independent variables were chosen due to their influence on trees growth in coppice stands.

Six non-linear models and one linear model were tested (Table 2). The evaluation of all potential equations was based on model performance evaluation criteria (Table 3) by Amaro et al. (1998) and Adame et al. (2006).

Potential equations parameters were estimated with R software by using the Generalized Linear Models (GLM) for fitting linear model and the Nonlinear Least Squares (NLS) for fitting non-linear models. All the collected data were used to fit the potential equations and the details of their characteristics are presented in Table 4.

Site index construction and height-diameter relation development

Most of the techniques for site index curves construction can be viewed as special cases of three general methods: The guide curve, the parameter prediction and the difference equation (Clutter et al., 1983). The difference equation method has been the preferred form for developing site index curves (Sánchez-González et al.,

Table 2. Types of model and potential equations for diameter modeling.

Type of model	N°	Equation	Parameters to be estimated
Linear	(1)	$Y = \beta + a_1 \times T + a_2 \times NR + a_3 \times Dp$	β, a_1, a_2 and a_3
Nonlinear	(2)	$Y = a_1 \times T^b$	a_1 and b
	(3)	$Y = a_1 \times T^b + a_2 \times NR$	a_1, a_2 and b
	(4)	$Y = a_1 \times T^b + a_2 \times NR + a_3 \times Dp$	a_1, a_2, a_3 and b
	(5)	$Y = a_1 \times \exp(b \times T)$	a_1 and b
	(6)	$Y = a_1 \times \exp(b \times T) + a_2 \times NR$	a_1, a_2 and b
	(7)	$Y = a_1 \times \exp(b \times T) + a_2 \times NR + a_3 \times Dp$	a_1, a_2, a_3 and b

NB: *Y* is dependent variable; *T* is shoot age; *NR* is the number of shoots per stump; *Dp* is the initial density of the plantation.

Table 3. Parameters for model performance evaluation.

Performance criterion	Symbol	Formula	Ideal value
Mean residual	Mres	$\sum_{i=1}^{n} \frac{est_i - obs_i}{n}$	0
Variance ratio	VR	$\frac{\sum_{i=1}^{n}\left(est_i - \overline{est}\right)^2}{\sum_{i=1}^{n}\left(obs_i - \overline{obs}\right)^2}$	1
Residual mean of squares	RMS	$\frac{\sum_{i=1}^{n}\left(est_i - obs_i\right)^2}{n-p}$	0
Absolute mean residual	Amres	$\sum_{i=1}^{n} \frac{\lvert est_i - obs_i \rvert}{n}$	0
Coefficient of determination	R^2	$1-\frac{\sum_{i=1}^{n}\left(est_i - obs_i\right)^2}{\sum_{i=1}^{n}\left(obs_i - \overline{obs}\right)^2}$	1
Linear regression between observed values and estimated values	α, β and R_{adj}	$obs_i = \alpha + \beta \times est_i$	$\alpha = 0$; $\beta = 1$; $R_{adj} = 1$

NB: est_i: i[th] estimated value; obs_i: i[th] observed value; *n*: number of observations; *p*: number of parameters of the model.
Source: Amaro et al. (1998) and Adame et al. (2006).

Table 4. Mean quadratic diameter and mean height per shoot age classes for developing models.

Age class	Number of observations	Mean quadratic diameter (Dg)					Mean height (Hg)				
		Min	Max	Mean	SD	CV (%)	Min	Max	Mean	SD	CV (%)
[0 - 2]	663	1.49	6.5	3.24	0.99	30.6	0.96	8.51	3.54	1.31	37.0
[2 - 4]	135	3.98	7.67	5.59	0.81	14.6	3.7	10.03	6.71	1.19	17.8
[4 - 6]	158	4.61	8.96	6.33	0.91	14.4	4.65	11.66	7.68	1.47	19.1
[6 - 8]	36	5.47	9.32	7.33	1.03	14.1	4.53	11.15	7.77	1.67	21.5
[8 - 10]	21	6.53	9.71	7.77	0.74	9.6	5.88	9.72	8.47	0.85	10.0
Total	1013										

NB: Dg is mean quadratic diameter; Hg is mean height; SD is standard deviation; CV is coefficient variation.

Table 5. Potential models' parameters and their degree of significance.

Model	Fitted models' parameters				
	Mean quadratic diameter				
	a1	*a2*	*a3*	*b*	*β*
1	0.6689***	-0.3334***	-0.0001**		3.9260***
2	3.2223***			0.4242***	
3	4.0716***	-0.2761***		0.3371***	
4	4.9360***	-0.3228***	-0.0003***	0.2872***	
5	3.0527***			0.1271***	
6	4.3334***	-0.4477***		0.0940***	
7	4.8800***	-0.4735***	-0.0002***	0.0859***	

Signification codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Table 6. Models' performances criteria for each potential equation.

Model	Mean quadratic diameter								
	Model performances criteria					Linear regression			Normality of the residue
	Mres	R²	VR	RMS	Amres	α	β	Radj	
1	0.0821[2]	0.7818	0.7837	0.6759	0.6471	-0.082	**1.000**	0.784	No
2	0.0091[2]	**0.8292**	**0.8031**	**0.5281**	**0.5677**	**-0.078**	1.016	**0.829**	No
3	**0.0041[1]**	**0.8474**	**0.8354**	**0.4723**	**0.5279**	**-0.034**	**1.007**	**0.847**	No
4	0.0177[2]	**0.8566**	**0.8475**	**0.4443**	**0.5139**	**-0.041**	**1.005**	**0.856**	No
5	**0.0270[1]**	0.6782	0.6006	0.9948	0.8018	-0.305	1.064	0.681	No
6	**0.0114[1]**	0.7331	0.6990	0.8260	0.7206	-0.116	1.024	0.733	**Yes**
7	**0.0265[1]**	0.7374	0.7098	0.8135	0.7113	-0.110	1.019	0.737	**Yes**

[1] Non-significant at P>0.05; [2] significant at P<0.05.

2005; Diéguez-Aranda et al., 2005; Adame et al., 2006). The most common indicator of site productivity is site index; generally defined as top height at reference age. In this study, site index is defined as the mean quadratic diameter at reference age of 5-years and the guide curve method has been used. This is explained by the high frequency of logging and the short rotation length observed in coppice teak stands in Bénin Republic. In addition, it is on basis of the diameter size that farmers decide to log their trees and the logging is sometimes done by selecting trees with the widest diameter. This makes inappropriate the use of top height as site index because there is no true top height.

Based on the pattern of the scatter plot of diameter (*Dg*) and height (*Hg*), a linear model $Hg = a \times Dg + c$ was used to develop height-diameter equation. In the equation, *a* and *c* are parameters to be estimated.

RESULTS

Estimation of models' parameters

Parameters in all candidate equations were significantly (P<0.01) different from the null hypothesis (Table 5). The age of shoots, the numbers of shoots per stump and the initial density of plantation influenced significantly the mean quadratic diameter in coppice teak plantations.

The influence of shoots' age is positive but the effect of the number of shoots per stump and the effect of the initial density of the plantation are negative. This means that, the more the number of shoots per stump, the less the growth in diameter of the coppice teak stands and, the more the number of initial density of plantation, the less the growth in diameter.

Models comparison

The model performance evaluation criteria are shown in Table 6. It revealed that the mean residues (Mres) of all fitted models are around zero. The Mres are not significantly different from zero for models 3, 5, 6 and 7. The coefficient of determination (R^2) associated with the diameter estimation, was generally over 65%, but the highest value was obtained with the models 4 and 3. These were also among models which have the best

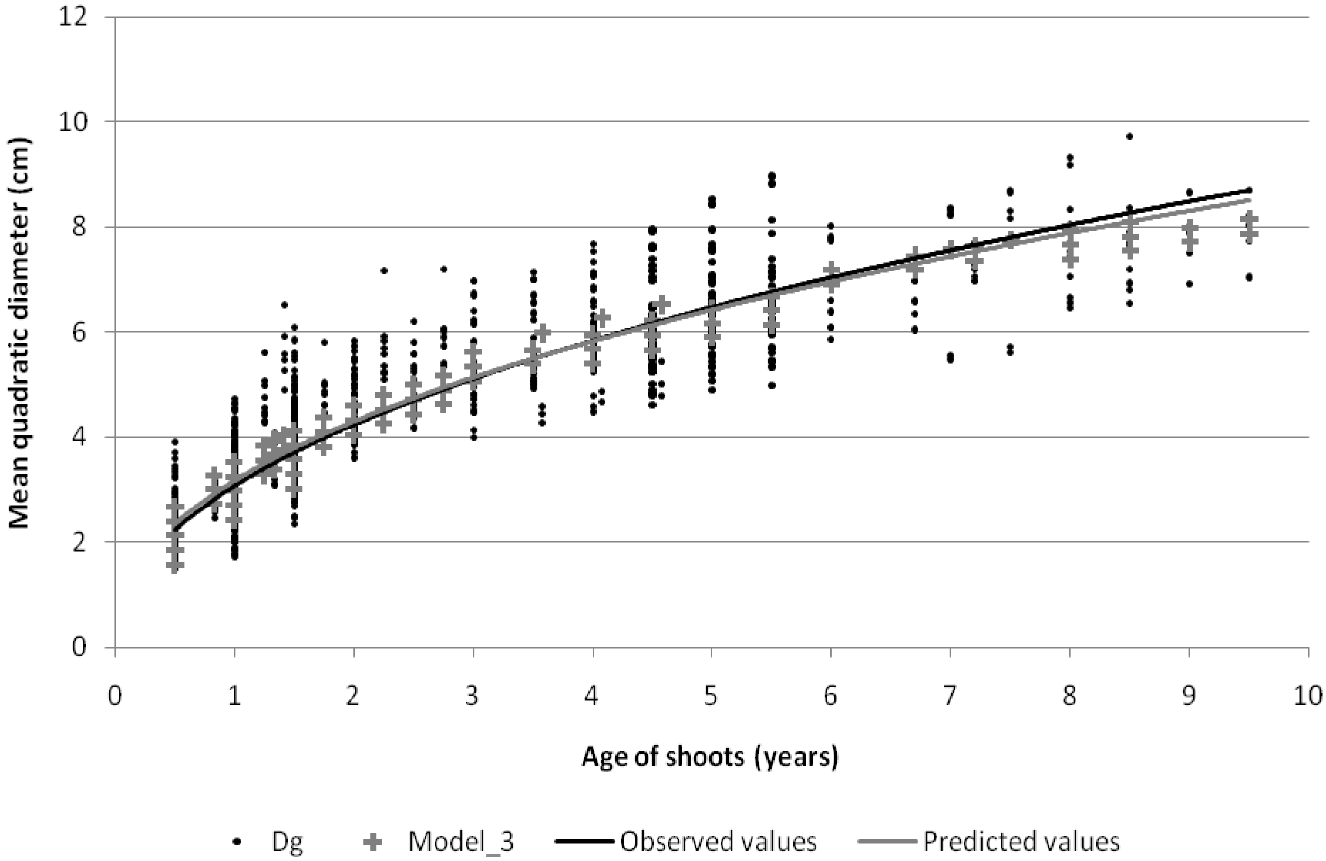

Figure 2. Observed and predicted mean quadratic diameters and their curves.

performance according to the linear regression between the observed values and the estimated values. Model 3 allowed to estimate with 0.5 cm of absolute mean residual (Amres), the mean quadratic diameter of coppice teak plantations. Despite the non-normality of residues, model 3 is the most appropriate to predict the mean quadratic diameter in coppice teak stands because it has recorded the best model performance criteria. Furthermore, values of predicted and observed mean quadratic diameter were closer and their curves easily superimposed (Figure 2).

Site index and height-diameter relation

The most appropriate model in predicting the mean quadratic diameter is:

$$Dg = a_1 \times T^b + a_2 \times NR \Rightarrow \ln(Dg - a_2 \times NR) = \ln(a_1) + b \times \ln(T).$$

The mean quadratic diameter (Dg_r) at reference age (*Tr*) is computed as:

$$Dg_r = a_1 \times Tr^b + a_2 \times NR \Rightarrow \ln(Dg_r - a_2 \times NR) = \ln(a_1) + b \times \ln(Tr)$$

so, $\ln(a_1) = \ln(Dg_r - a_2 \times NR) - b \times \ln(Tr)$. It can be deduced that:

$$\ln(Dg - a_2 \times NR) = [\ln(Dg_r - a_2 \times NR) - b \times \ln(Tr)] + b \times \ln(T)$$

or $\ln(Dg - a_2 \times NR) = A + b \times \ln(T)$ with $A = \ln(Dg_r - a_2 \times NR) - b\ln(Tr)$. So $\ln(Dg - a_2 \times NR) = A + b \times \ln(T) = A + \ln(T^b)$ and $\exp[\ln(Dg - a_2 \times NR)] = \exp(A) \times \exp[\ln(T^b)]$ $\Leftrightarrow$

$$Dg - a_2 \times NR = \exp(A) \times T^b$$

$$Dg = \exp(A) \times T^b + a_2 \times NR.$$

Taking 5-year for the reference age (*Tr*) and 2 shoots per stump, the estimated Dg_r from the equation above is equal to 6.5 cm. Amplitude of 1 cm chosen to cover scales of sites productivity allow identifying five site indexes (Table 7) and the Figure 3 shows the curves of site indexes.

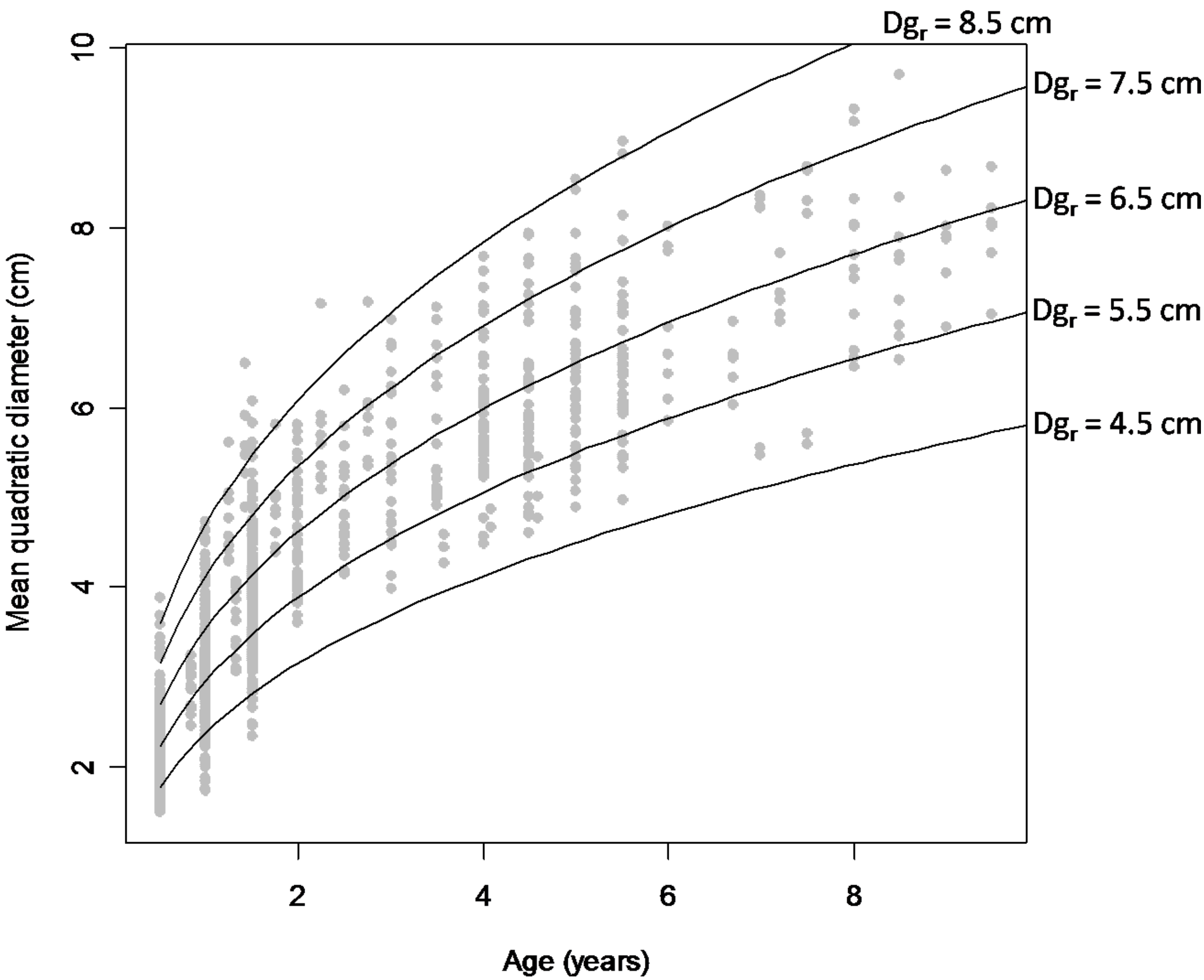

Figure 3. Site index curves of coppice teak stand for model 3.

Table 7. Deduced site indices for coppice teak stands in the Department of Atlantic with 5 as reference age and 2 as number of shoots per stump.

Productivity class	Site index	Equation of the mean quadratic diameter
First	8.5	$Dg = 5.2618 \times T^{0.3371} - 0.5522$
Second	7.5	$Dg = 4.6805 \times T^{0.3371} - 0.5522$
Third	6.5	$Dg = 4.0992 \times T^{0.3371} - 0.5522$
Fourth	5.5	$Dg = 3.5180 \times T^{0.3371} - 0.5522$
Fifth	4.5	$Dg = 2.9367 \times T^{0.3371} - 0.5522$

NB: *T* is the shoot age.

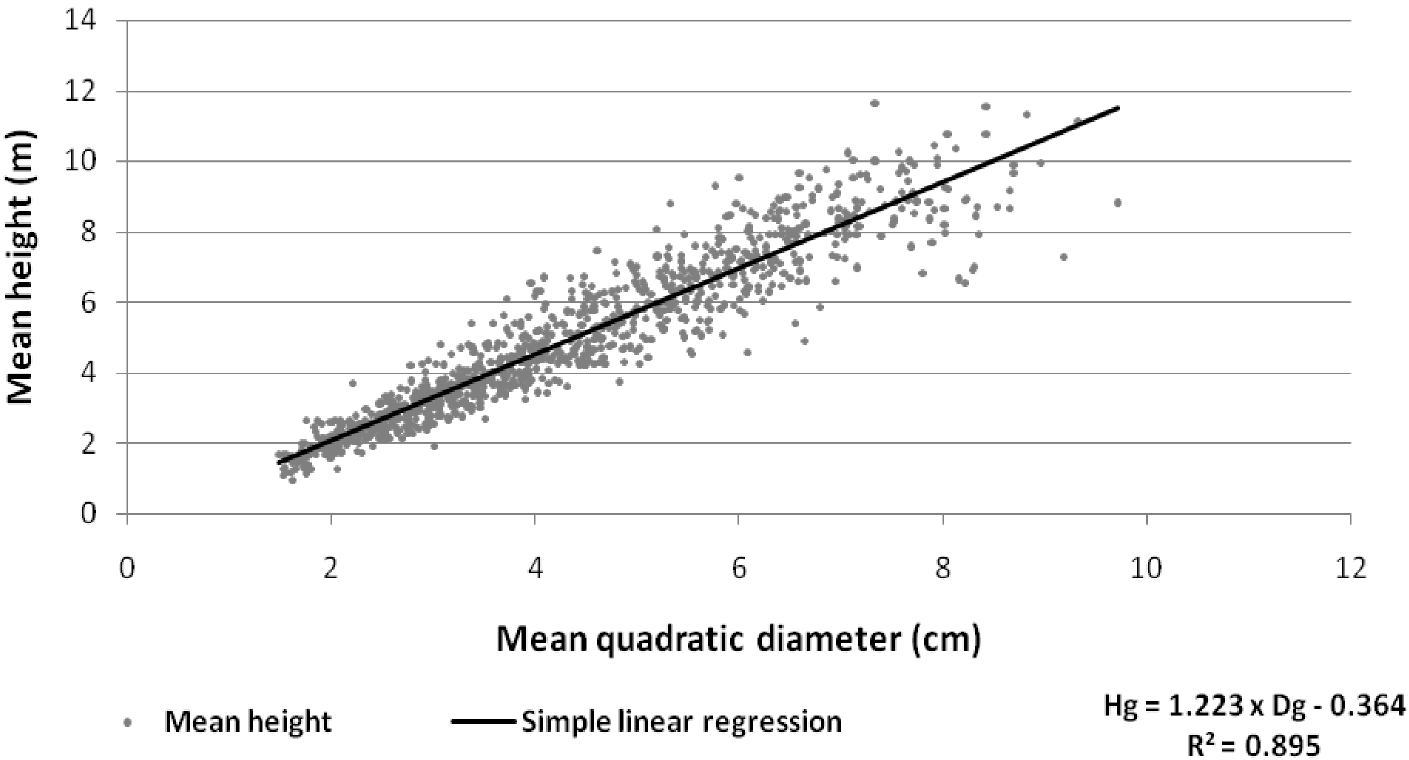

Figure 4. Scatter plot and regression equation of height.

The scatter plot of diameter and height (Figure 4) shows a linear relation between the mean height and the mean quadratic diameter. This relation can be written as follow: $Hg = 1.223 \times Dg - 0.364$, with coefficient of determination R^2 of 0.9. Thus, through the above equation, the mean height can be estimated using the mean quadratic diameter of the stand.

DISCUSSION

In the study, the authors developed primary models to predict accurately the mean quadratic diameter and the mean height of coppice teak stands. Contrary to most models developed which use only age as independent variable to estimate trees growth (Ganglo et al., 1999; Wang et al., 2007; Bravo-Oviedo et al., 2008; Palahi et al., 2008), this model combined not only age but also density in terms of number of shoots per stump. Furthermore, the age used refers to the shoot age which is different from the stump age. In fact, coppice teak stands were made decades ago and farmers were not able to provide accurate plantation date during investigation. It is most likely that the influence of stump age on trees growth (but non-precise data) would have induced bias in the model's parameters.

Influence of shoots' age is positive while the number of shoots per stump has negative effect. This fact points out production and storage of matter over time and the effect of density. Many previous studies have concluded that the high densities observed in coppice plantations of teak grown by farmers are the main factor of their weak growth (Ganglo and Yéssoufou, 2003, Demenois et al., 2005). The results from this study support this fact because the more the number of shoots per stump the less the mean quadratic diameter. In Tanzania, removal of excess stems was proposed and applied when shoots are young and soft, so that only the strongest and straightest stems are left (Bekker et al., 2004). It is suitable to limit the number of shoots per stump and advisable to keep at most three shoots per stump in coppice plantation of teak but two shoots per stump remains the optimal number (Yêvidé et al., 2011b).

Stand initial density influences teak growth, that is why in seed origin plantations, it is recommended to reduce the stand density to facilitate tree growth (Dupuy et al., 1999; Ganglo, 1999; Ganglo et al., 1999). Akhtar et al. (2008) made the same observations for *Eucalyptus camaldulensis* plantations. So the spacing or the reduction of stand initial density improves tree growth. For coppice teak stands, the same trend was found.

With regard to the site index curves, plantations on soils

with intermediate fertility achieved 6.5 cm of diameter in five years (Figure 3). Therefore to obtain shoots with quadratic mean diameter of 10 cm, it will take more than 15-years. This explains why farmers in the Atlantic department uses short rotation (3 to 6-years) in their coppice teak plantations to produce lumber generally used for home construction or firewood. Most of the farmers' plantations were also established on *Mallotus oppositifolius* - *Paullinia pinnata*-community; *M. oppositifolius* - *Reissantia indica*-community and *C. odorata* - *Imperata cylindrical*-community. These plants communities are indicators of low fertile soils which are not adequate for producing timber for small joinery unless farmers wait for a period of about 15-year.

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