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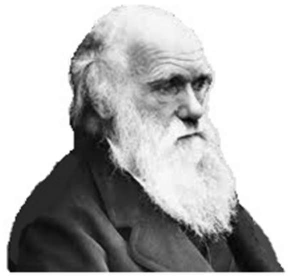

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Growth modelling of *Eucalyptus grandis* W.Hill ex Maiden TOOLUR in the north-western highlands of Cameroon

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ABSTRACT

Eucalyptus grandis W.Hill ex Maiden Toolur is widely grown in the western highlands of Cameroon for fuel wood, charcoal, power transmission and for the construction sector. Its introduction in the area was a community response to increasing demand from adjoining villages and urban centres. In spite of this important economic role, there is little evidence about the application of growth modeling techniques for understanding forest dynamics, productivity and the preparation of feasible and reliable management plans. The objective of this paper was to develop a growth model for *E. grandis* for the Bambui Eucalyptus Plantation of Cameroon. Thirty square plots of 0.04ha each were set-up at 200m intervals in a parallel-cross direction to check within-plot heterogeneity. Data sets for six dominant and co-dominant trees as well as reference diameter were collected from each plot and analysed for the construction of growth models using the SAS non-linear regression technique. Growth performance and tree volumes were adjusted and tested using seven existing models. The Schumacher model gave the best adjustment. We used a site index equation to determine the fertility index, while a guide curve was drawn by substituting the reference age in the equation. Due to ecological similarities, the volume equation models were compared with those of an adjacent plantation. Predicted values were generated from the two plantations and used for a paired *t*-test and graphical illustration. We then simulated a yield table and drew site index curves for the plantation. Apart from environmental factors and site variation,

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growth in height showed rapid increase between 4 and 20 years. 80.5% of variations in reference diameter were explained by the model, while 58.8% of variations in dominant height growth were explained by management practices.

***Keywords*:** Growth modelling, Eucalyptus grandis, forest management, Cameroon

1. INTRODUCTION

Global pressure on forest resources for multiple demands has been on a steady increase (Gustafsson et al. 2012, Ngueguim et al. 2017). This has led to scarcity of high value timber and dwindling productive capacity of the natural forest (Ntabe et al. 2009). Consequently, stakeholders are expressing growing interest in hitherto lesser-used species (Larinde et al. 2005). The importance of plantation forestry as a complementary and alternative source of wood fiber has been highlighted in extant literature as a plausible response to the burgeoning situation (Cossalter and Pye-Smith, 2003, Ntabe et al. 2009; Cristobal, 2014). Among valued plantation species is *Eucalyptus grandis* that is adapted to the tropical and subtropical ecosystems. In Africa, it covers more than 1.7 million hectares (FAO, 2003). Despite its significant global distribution, there is limited scientific knowledge about its growth and productivity within the Congo Basin.

The species is widely grown in the western highlands of Cameroon such as in the Bambui Eucalyptus plantation for fuel wood, power transmission, timber and construction wood. Its introduction to Cameroon dates back to the 1920s (Tchanou, 1975), but it was only towards 1930 that sizeable afforestation started in the North West and West Regions of the country. It has been successfully tested for pulpwood and its potential for pallets, veneer and other products has equally been demonstrated.

The introduction of *Eucalyptus grandis* in the western highlands of Cameroon was a community response to an unmet demand for fuel wood and charcoal from adjoining villages and the urban centres (Fogwe et al. 2019). Today, forest plantations play a frontline role in the supply of poles, charcoal and fuel wood to adjacent communities. There is equally growing interest in its use in the construction industry and multiple commitments in the region. In spite of this important economic role, there is little evidence about the management history of the Bambui Eucalyptus plantation. Absence of such forest management data makes it challenging in proposing an effective management plan. The application of growth modeling techniques can help in understanding forest dynamics, productivity and the preparation of feasible and reliable management plans.

Given the socioeconomic importance of *E. grandis* in the study area, this study focused on options that could improve management planning and the prediction of harvestable volumes within the plantation. While site index studies play an important role in forest science, only few attempts have been conducted in the country. A majority of methods that are used in the computation of forest productivity, available for tropical plantations are based on yield tables, adapted to pure and even-aged plantations and coppice rotations (Henry et al. 2011). They however fail to portray the actual growth of a particular stand and cannot be used in predicting the effects of alternative silvicultural and harvesting options. This could be mitigated by developing local growth models for *Eucalyptus* species, traditionally planted or suitable for planting in the region (Delgado-Matas and Pukkala, 2014). Consequently, the objective of this paper was to develop a growth model for *E. grandis* for the Bambui Forest plantation.

2. MATERIALS AND METHODS

2. 1. Study area

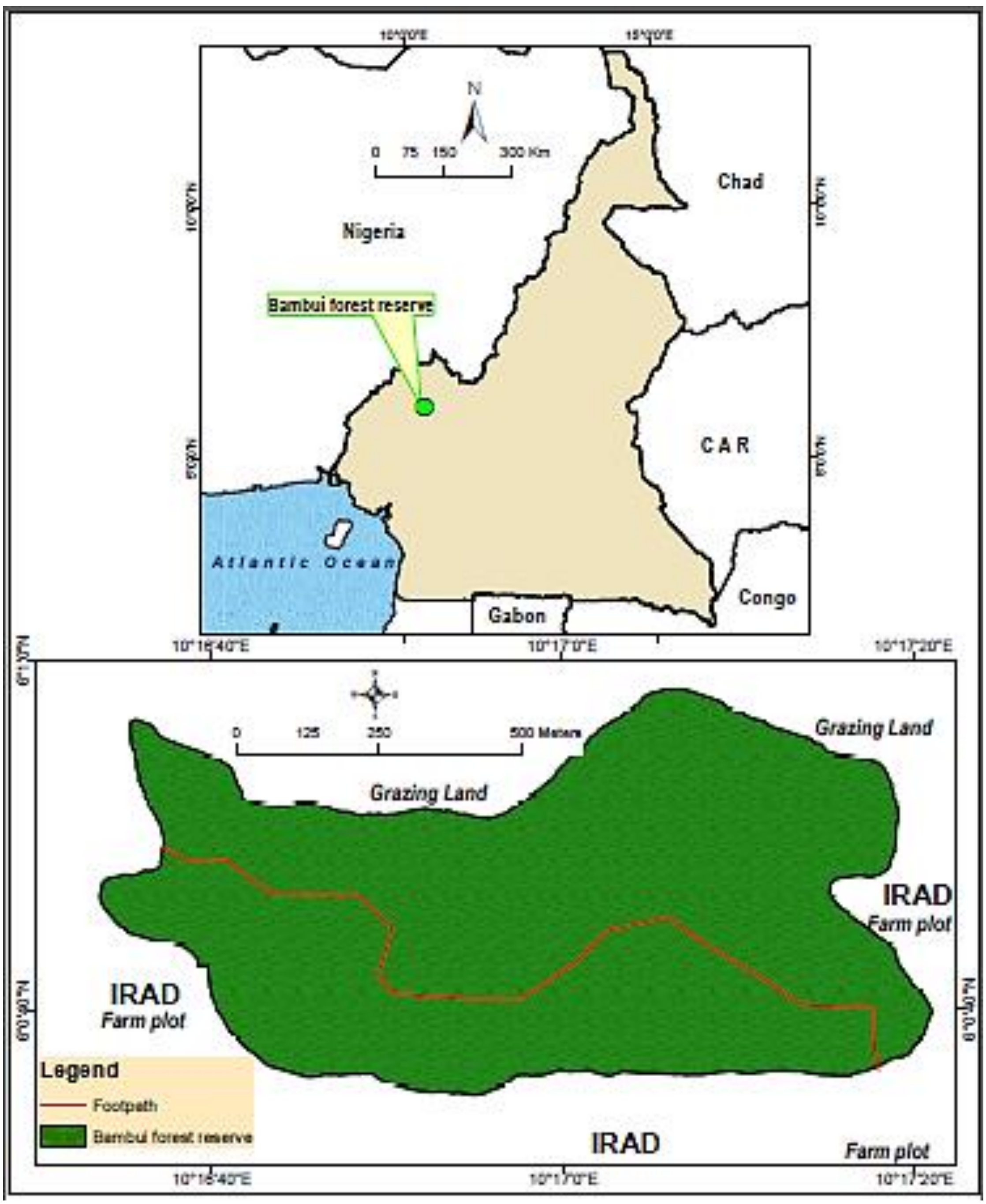

Figure 1. Bambui Eucalyptus Plantation

Bambui Eucalyptus plantation is located in the western highlands of Cameroon (Figure 1). It extends over an 85 ha surface with an altitude of 1400 – 2500 m above sea level (Fubah, 2014). The region is characterised by a rainy season that runs from mid-March to October (Fubah, 2014). It is washed by the southwest Monsoon winds that increase rainfall index between June and October (CTFC, 2013). Rainfall is frequent and heavy with a peak between July and September, during which time, it hits 4000 mm. Within the plantation, it is estimated at 3000mm per year. Bambui Eucalyptus plantation serves as catchment for five streams criss-crossing in southwest and southeast directions. With the regularity of rainfall and adequate soil moisture content, the period between June and August is usually set aside for transplanting of seedlings from the nurseries. The dry season runs from November to mid-March and is characterised by the dry harmattan winds. The season is set aside for the establishment of seed nurseries and fire tracing. Mean annual temperature for Bambui is 22 °C with a maximum of 34.6 °C (CTFC, 2013). The plantation is made up of ferralitic soils (MINADER, 2015) which are highly weathered and reddish brown in colour, consisting mostly of hydrated iron and aluminium oxides. They are highly permeable and are heavily leached of bases and silica (MINAT, 2012). This soil type is common around the uphill slopes while the valleys and lowlands are composed of ferruginous soils.

They possess a high content of iron compounds especially oxides whose accumulation sometimes results in the formation of an iron crust. They are equally acidic and low in nutrient content due to heavy leaching of bases and are vulnerable to wind and water erosion. The ecological characteristics of the area are conducive for the growth of *E. grandis* where they can attain 55m in height with a diameter ≥1m at breast height (FAO, 1982).

2. 2. Description of *E. grandis*

Etymologically, the name *Eucalyptus* comes from the Greek word eukalyptos and the species' name *grandis* which means large or covering tree relates to its large size. It belongs to the Myrtaceae family (Myburg et al. 2014) and is classified in the subgenus *Symphyomyrtus*, Section *Latoangulatae*, Series *Transversae* (Ritter, 2014). It counts about 700 species and subspecies today (Brooker, 2000). *E. grandis* supplies high-quality woody biomass for multiple industrial applications (Grattapaglia and Kirst, 2008). It also moderates pressure on local species by adjacent communities (Wang et al. 2013). Its natural environment is the high altitude zones between latitude 7°N and 43°39'S (Ladiges et al. 2003). Dry season within this fringe is relatively short while annual rainfall varies between 1000-1800mm. It grows best within the humid subtropical or warm temperate climate, especially with fertile loam or clay loam soils (Kellison et al. 2013). Most of the species worldwide in artificial plantations today occur south of the tropic of Capricorn. However, recent trials have established that provenances growing north of Capricorn are of increasing importance in the low latitude countries (FAO, 1982). *Eucalyptus* is native to Australia (Grattapaglia and Kirst, 2008) but has proven to be particularly successful in tropical and sub-tropical regions (Stanturf et al. 2013). They now occupy almost half of the artificial plantations around the world (Dhakad et al. 2018) and their fast growth and multiple uses significantly reduce pressure on the natural forest.

2. 3. Experimental Design

An experimental design consisting of 30 square plots of 0.04 ha each, established in 9 compartments and aged between 4 and 44 years was employed for this application. They were established at intervals of 200m each in a parallel-cross direction to check within-plot heterogeneity. The plantation was divided into eight productivity sites, ranging from S16 to S44 with S28 being the mean productive site, covering 26.67% of the study area. S16 was the poorest site, covering 3.33% of the area. Data collection instruments included; a peg, a Blume-Leiss, a wide band Spiegel Relaskop, and a 30m tape. A white mark at 1.3m above the ground was placed on a 2m peg to locate the breast height for DBH measurements. These instruments were used in estimating DBH and the heights of six dominant and co-dominant trees within each sample plot. The concept of dominance and co-dominance refers to the tallest trees that form the main canopy of a stand. Dominance and co-dominance are qualitative measures of the position of a tree crown in relation to its neighbours (Ward et al. 1999). Dominant height within each plot was defined as the six tallest trees within the plot. They are important in the measurement of the productivity or tree growth potential of a site. Dominant and co-dominant trees are important indicators of site index (Fonweban, 1995). In total, 180 trees were sampled in the 30 plots for diameter and height measurements using a one degree systematic sampling at 0.5% intensity.

2. 3. 1. Height measurement

Total height measurements for 6 individual dominant and co-dominant trees within each plot were determined using the equation:

$$Ht = Hd \cos\theta(\tan\alpha + \tan\beta)$$

Ht = Total height
Hd = Horizontal distance between the tree and the observer
θ = Angle from observer to white mark on the peg
α = Angle from eye to tree base
β = Angle from eye to tree top

The respective arithmetic means of the six trees that were sampled from each plot gave the dominant heights (Ho) for each plot. Dominant height within each plot was defined as the six tallest trees within the plot.

2. 3. 2. Diameter measurement

Each reference diameter (DBH) was deduced from its reference circumference (C) for the individual tree using the relation;

$$DBH = {}^{C}/_{\pi}$$

The plot level basal area (g) was determined by computing the individual basal area of each of the six dominant and co-dominant trees of the plot. For every individual dominant and co-dominant tree, basal area was obtained using the relation;

$$g = \frac{\pi D^2}{4}$$

where: D = DBH of sampled tree (cm) and g (m^2/ha).

Data sets collected were analysed using Excel and growth models were developed using the SAS system (SAS Institute, 2016) non-linear regression technique in fitting the functions. Growth performance and tree volume were tested using seven existing models to obtain the most fitting models for the data sets. The tested existing models were:

Growth function	Reference
$Y = ae^{(-b/x)}$	Schumacher growth model
$Y = a\left[1 - be^{(-cx)}\right]$	Mitscherlisch monomolecular growth model
$Y = a[1 - b^{x}]$	Simplified monomolecular model
$Y = a\left[1 - e^{(bx^{c})}\right]$	Chapman-Richard growth model
$Y = ae^{[-b(x-c)]}$	Gompertz modified growth model
$Y = a\left[1 + be^{(cx)}\right]^{-1}$	Verhulst Logistic growth model
$Y = a\left[1 - e^{(-bx^{c})}\right]$	Weibull modified model

where:

Y = Height or diameter or volume or basal area of individual tree
x = Age of stand
e = exponential function
$a,\ b$ c = coefficients determined from data
a = An asymptote to the regression curve
b = A constant that determines the slope of the curve
c = A constant that determines the form of the curve.

The most efficient model was chosen based on the highest coefficient of determination (R^2), simplicity of the model in terms of number of coefficients and entries or variables and lowest Root Mean Square Error (RMSE). Since we had just a single parameter (age), the complexity of the model was not taken into account.

2. 3. 3. Determination of site quality (S)

The chosen reference age for *E. grandis* in the plantation was 10 years. An established equation was used in determining the site index of the plantation while a guide curve, Ho=S was obtained by substituting age in the equation.
By considering the Schumacher model

$$H_0 = Ae^{\left(\frac{-B}{x}\right)} \text{.......................................Eq.1}$$

when: $\chi = \chi_0$ (eg 10 years), $H_o = S$.

By replacing H_o with its value, we obtain

$$H_0 = S = Ae^{\left(\frac{-B}{\chi_0}\right)}$$

$$\Longrightarrow \quad A = S\left[e^{\left(-\frac{B}{\chi_0}\right)}\right]^{-1} \text{..........................Eq. 2}$$

Substituting equation 2 into 1, we obtain

$$H_0 = Se^{\left[-B\left(\frac{1}{\chi}-\frac{1}{\chi_0}\right)\right]} \text{...............................Eq. 3}$$

Equation 3 was then used in expressing S in terms of other parameters, giving the following equation of productivity index or site quality:

$$S = H_0\left[e^{-B\left(\frac{1}{\chi}-\frac{1}{\chi_0}\right)}\right]^{-1}$$

where

B = Constant given by the model

Productivity indices generated by the above equation were distributed into the following three fertility classes: Productive class (Very fertile), Average class (Moderately fertile), Poor class (Less fertile)

Dominant height model developed for the Bambui Eucalyptus plantation was compared with that of Bafut-Ngemba, an adjacent plantation with similar biophysical characteristics (soils, rainfall, temperature, relative humidity, altitude, winds and seasons) to determine whether or not, volume equations developed for Bafut-Ngemba could be used in Bambui. With respect to age, predicted values from growth models of the two plantations were used for a paired *t*-test and graphical illustration of growth trends. Stand level volume equations V_T = -0.0610 + 0.000886D^2 for the estimation of total volume and V_{bw} = -0.0709 + 0.000887D^2 for volume up to 7cm top-diameter (big wood volume) developed by Pettang (1994) for Bafut-Ngemba were used to estimate those in the Bambui plantation.

3. RESULTS

Out of the seven growth models that were tested, the Schumacher model gave the best results for height (H_o), the coefficient of determination (R^2) and the Root Mean Square Error (RMSE) where;

H_o = 43.465898exp (-4.235439/age)

R^2 = 58.8%

RMSE = 6.87m and

D = 53. 41404exp (-4.991986/age)

R^2 = 80.52%

RMSE = 5.5cm

Growth in total height showed rapid increase between 4 and 20 years. Growth performance was consistent with forest growth theory over the plantation and was affected by environmental factors that varied based on the site (Fig. 2). Mean annual increment for *E. grandis* within the plantation varied between 14.47 m^3/ha and 60.02 m^3/ha. The model explained 58.8% of variation in predicted dominant height while the rest could be attributed to other factors such as planting density, silvicultural practices and thinning that were not considered during the formulation of the model. The results for reference diameter also followed the same trend as in dominant height. 80.5% of variations in diameter growth were explained by the model.

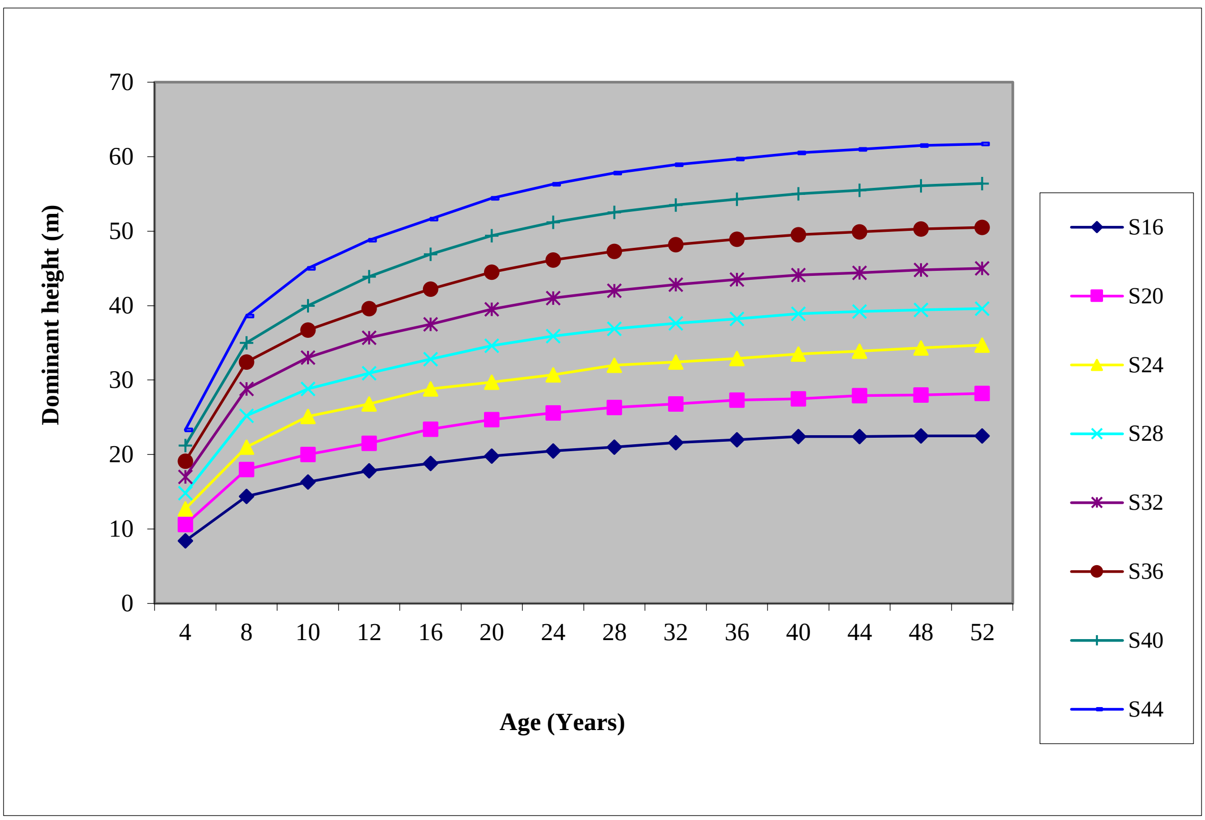

Figure 2. Site index curves for Bambui

Figure 2 shows S28 as the mean productive site of the plantation, covering 26.67% of the sample plots. S44 is most productive while S16 is the poorest. 73% of sample plots were found between S24 and S32. Pettang (1994) observed that 92.13% of sample plots were found between S24 and S32 for the Bafut-Ngemba Eucalyptus plantation. In the Bambui Eucalyptus plantation, Mean quadratic diameter (Dg) was 33.774+0.553434 H_o -0.010519N; R^2 = 0.75; RMSE = 6.76cm; Number of stems per hectare (N) = 3550.529exp (-0.035753 H_o); R^2 = 56.03% and RMSE = 371 trees/ha.

A paired *t*-test comparison in the evolution of dominant height between 4 and 52 years was conducted between Bambui and Bafut-Ngemba and the following results were recorded:

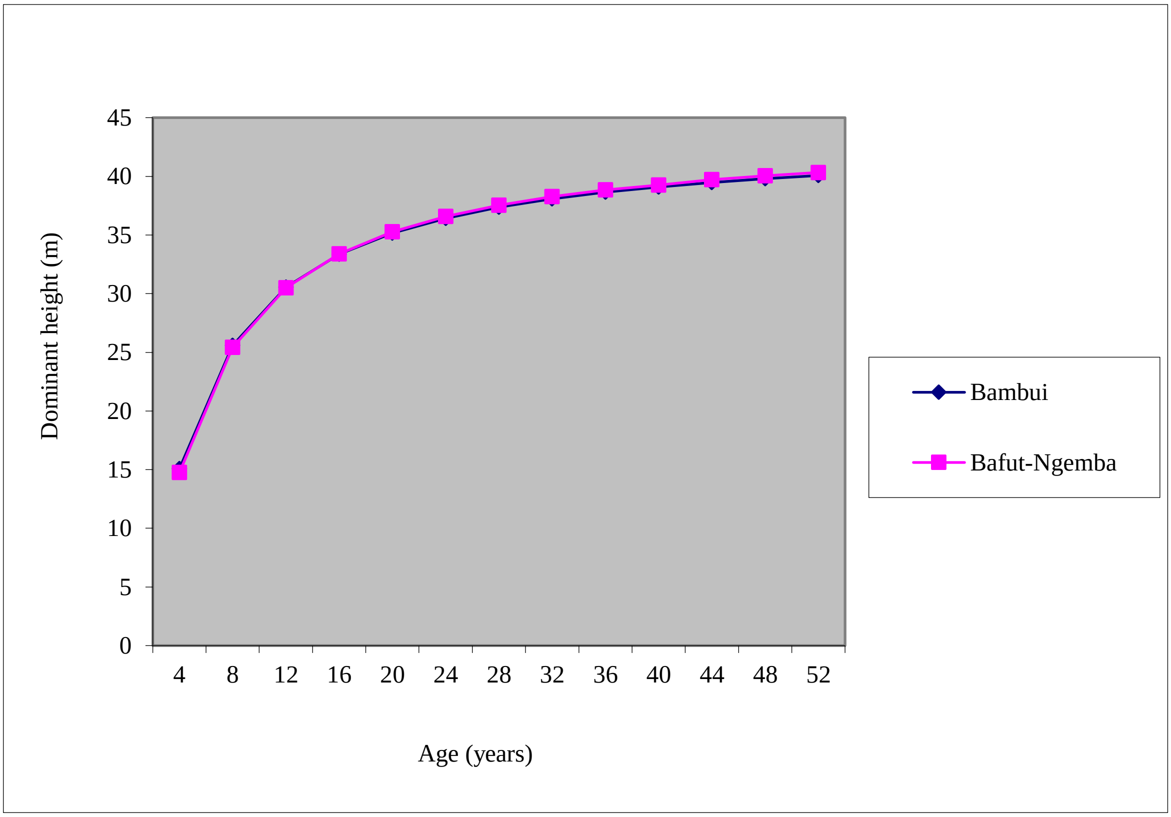

Figure 3. Evolution in dominant height in Bambui and Bafut-Ngemba

Figure 3 shows no difference in the evolution of dominant height for the two plantations. Thus, the growth function developed by Pettang (1994) for Bafut was used for the estimation of tree volume for Bambui. Derived stand volumes were given by the relation:

$\frac{V_T}{ha} = N \text{ x } V_T$ and $V_{bw}/ha = N \text{ x } V_{bw}$

where: N = Number of stems per hectare

Total volume per hectare was adjusted and modelled to the form

Y = 345.23 In(x) -256.4

Table 1. Predicted yield table for Bambui forest.

Age (yrs)	N/ha	H_o (m)/ha	D (cm)	BA (m^2)	V_T	V_{bw}
4	2071	15.08	20.33	67.24	632.2	612.6
21	997	35.53	42.95	144.43	1568.5	1560.5

22	985	35.85	43.25	144.77	1573.1	1565.1
27	941	37.16	44.44	145.91	1588.6	1581.2
31	915	37.92	45.13	146.41	1595.8	1588.6
35	896	38.51	45.66	146.73	1600.6	1593.6
38	884	38.88	45.99	146.89	1603.2	1596.3
42	871	39.30	46.36	147.05	1605.7	1598.9
44	866	39.48	46.52	147.10	1606.7	1600.0

Table 1 & 2 uses a number of parameters to give a panoramic presentation of growth performance of *Eucalyptus grandis* modelled from the data that was collected. The yield table gives predicted values for

Table 2. Mean volume predictions and corresponding MAI (per ha)

Age (yrs)	V_T (m^3)/ha	MAI_T	V_{bw} (m^3)/ha	MAI_{bw} (m^3)
4	74.37	18.59	67.26	16.82
21	902.70	42.99	897.82	42.75
22	1320.49	60.02	1315.99	59.81
27	792.26	29.24	789.03	29.22
31	970.46	31.31	966.56	31.18
35	724.02	20.69	720.72	20.59
38	1173.05	30.88	1170.16	30.79
42	1348.10	32.10	1343.96	31.99
44	636.51	14.47	632.44	14.37

4. DISCUSSION

Modelling has been employed in forestry to attain varied management objectives (Ntabe et al. 2015; Yi et al. 2018). Generally, the best model is the simplest (Ntabe et al. 2012). The estimation of tree volume and stand dynamics heavily relies on height and diameter models. Plot sizes were sufficiently large to ensure unbiased results in the data collection process. This is similar to the reference by Lappi (2005) who advises that plot sizes should be large enough to avoid unbiased predictions. Our use of 20m x 20m was reasonable enough to cover intra-plot variation, as the average number of trees was x±SD. Site index was used to measure forest site quality due to the relative ease with which site quality can be estimated from field observations. Silva et al. (2018) also used site index to compare different non-linear models to classify the productive capacity of thinned and non-thinned eucalyptus stands with guide curve and longitudinal measurement modelling methods of the height of dominant and co-dominant trees. While the authors observed that the Chapman-Richards model was more effective in adjusting two data sets (with and without thinning) for Eucalyptus plantations, they observed that the Schumacher model was more suitable for dominant height groups at a reference age 7 years. This observation is similar to the results that were obtained in the Bambui Eucalyptus plantation.

Fonweban and Houllier, (1997) used site index in the development of growth models for *E. saligna* in Cameroon. Growth in total height in the Bambui plantation was similar to results obtained by Pettang (1994) in the development of growth models in the Bafut plantation. This is the first attempt that growth models have been fitted for *E. grandis* in the plantation. The dominant height curve of the plantation was analysed by comparing it to the Bafut-Ngemba model using the guide curve method. Results of the comparison revealed an objectively compatible shape between the growth model of Bambui and that of Bafut-Ngemba. This is also in line with preceding models for *E. saligna* in Cameroon by Fonweban and Houllier (1995) and *E. grandis* in S. Africa by Louw, (1997). While most preceding models for dominant height in *E. grandis* have focused on relatively young stands, we extended the age in this study to 44 years. Ntabe et al. (2012) endorse that once a growth model is constructed for a given site and species, it can be applied in other localities with similar biophysical characteristics. The validity zone of the Bambui Eucalyptus plantation growth model is therefore any region with similar site characteristics that are described under section 2.1.

The set of models developed in this study gives fairly accurate predictions of stand development. The Schumacher model gave the best predictions for *E. grandis*. Height and diameter increments were significant between 4 and 10 years. Delgado-Matas and Pukkala (2014) observed faster dominant height increments between 3 and 7 years which is similar to the results obtained in this study. Faster growth during this period can be explained by the natural process of tree growth which is sigmoidal or s-shaped. The incorporation of sample plots with younger stands helped in improving the dominant height and site index modelling process. The dominant height model was developed based on height data of 180 trees that were investigated.

5. CONCLUSIONS

Growth modelling is an important feature in the management of forest plantations. In this study, seven growth functions were tested for their goodness-of-fit and the Schumacher model gave a perfect adjustment of the data sets. A maximum dominant height of 48m and reference diameter of 53cm respectively were observed at 35 years. Apart from environmental factors and site variation, growth in height showed rapid increase between 4 and 20 years. Mean annual increment (MAI) ranged between 14.47 m^3/ha and 60.02 m^3/ha with the optimum at 22 years. 80.5% of variations in reference diameter and 58.8% of variations in predicted dominant height growth could be explained by the model, while the rest could be explained by random factors such as planting density, silvicultural practices and thinning. The developed model can serve as a decision support tool in the preparation of logging and management plans, the estimation of biomass production, carbon sequestration and the development of stand characteristics for *E. grandis*. Poor sites within the plantation could be used for pole and fuel wood production while more productive sites could be used for timber production. The model developed could also be tested locally and validated for application in adjacent plantations with similar site characteristics. While this study relied on phytocentric metrics, it would perhaps be necessary to focus future investigations on the influence of geocentric measures (physical site properties such as climate and soil) on growth performance of *E. grandis* in the area.

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