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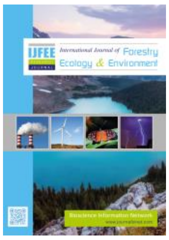

Determination of mean annual increment and optimal rotation age for sustainable management of eucalyptus species in Afaka forest reserve, Nigeria

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ABSTRACT

The study evaluates the mean annual increment (MAI) and optimal rotation age for the sustainable management of eucalyptus plantation in Afaka Forest reserve, Nigeria. To achieve the objectives of this study, the forest reserve was stratified into four age series. Fifty (50) sample plots (20 m X 20 m) were randomly laid across the four age series in the entire plantation. Variable of interest were measured in each of the compartments. The species volume per plot was estimated using Newton's formula, and the yield (volume) with age of the species was generated using an exponential function, while the optimal rotation age was obtained when MAI was maximum. The annual allowable cut was determined using both area and volume control methods. The results show that E. camaldulensis has the highest mean volume (392.841 m^3*), while the least species volume of 281.217m*^{3}* was estimated for E. cloeziana. The maximum mean annual increment (MMAI) ranges between 7.321 to 19.323 (m*^{3}*/ha/yr) across the four sampled compartments. The optimal rotation age ranges between 19 and 42 years, while the total number of trees available for cut ranges between 794 and 7,408 for E. cloeziana and E. camaldulensis species, respectively. This study has shown that mean annual increment and rotation age are of fundamental importance in forest business and shaping of stands future (harvest regulation) for sustainable management.*

Key Words: *Stratified, Evaluates, Plantation, Allowable cut, Age series and Compartment.*

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I. Introduction

Intensive growth and provenance trials of exotic tree species commenced in the savanna region of Nigeria in the late 1950's; such an effort was geared towards meeting the demand of wood and its products, as well as for desertification control in the country. Among the trialed introduced exotic species then were pines and eucalyptus species. Eucalyptus plantations are considered one of the

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fastest growing and most productive forests in the world (Xiaoguo et al., 2019; Cao et al. 2010; Forrester, 2013; Du et al., 2015), covering more than 20 million ha worldwide, thus having significant impacts on global carbon cycling (Booth, 2013; Wink et al., 2013). Eucalyptus is a diverse genus of flowering plants which belongs to myrtle family (Myrtaceae). They comprise approximately seven hundreds (700) species and one percent (1%) of the species is used for industrial purposes (Quoirin and Quisein, 2006). Eucalyptus species are extensively used world-wide in commercial a forestation programs. The main advantages include, their fast growing rates, short rotations and their wood properties, which allow production of high quality wood pulp, timber and veneer (Rockwood et al., 2008). These species are also used for essential oil production and serve as bee's habitat for honey production. Each species thrive well in a particular region depending on the climate, soil fertility and water availability in the area.

Recently, only limited or few amounts of research work have been carried out on the growth of the species (eucalyptus) in the area. Eucalyptus, being one of the worlds' most important species, is used for timber production due to its hardness and resistance to termite's attacks, while, at an early stage, it can be used for pulping and paper production. The decrease of forest area in the country may be due to population explosion, urbanization, anthropogenic and road construction; however, this situation calls for information on how to manage the eucalyptus species in the area for timber and fuelwood production sustainably in the region.

The rapid expansion of forest plantations in the tropics and sub-tropics plays a very important role in the future world wood supply (FAO, 1999). Eucalypts and pines are the most commonly used species in tropical timber plantations (Evans, 1992); they account for 43 percent of all tropical plantation areas (FAO, 1999). Despite their high productivity and importance of eucalypts to the wood industry, the management of these plantations is far from optimal (Robak, 2008). The most common management for eucalypt species usually uses the area control method to achieve the normal age-class distribution of the fully regulated forest (Davis et al., 2001) after a given planning horizon and the harvested units are regenerated through the simple coppice system. In this system, even-aged stands developed from planted seedlings are clear cut at the end of the first rotation interval and repeated crops secured from stump-sprouts are coppiced on seedling rotation (Diaz-Balteiro et al., 2009).

Experience has shown that optimal stand management is highly sensitive to the management objective (Rautiainen et al., 1999). The newly emerged forest in a country may need different management, be it national, community or private forests. In community forestry, a steady flow of fuelwood and small sized poles may be of greater importance than obtaining large sized timber. Concerning state forestry, the traditional criterion has being to maximize sawlog production. In the present situation, in which several wood products have some value, the criterion may also change in state forestry. The inability of the indigenous tree species to meet the wood demand or wood requirements of the user's in this region necessitated this study and it is focused on the determination of mean annual increment and rotation age for sustainable management of the wood yield of the available plantation-grown eucalyptus species, which will help in maintaining a regulatory and even wood flow in reserve.

II. Materials and Methods

Study area

The study was carried out in the FRIN/JICA *Eucalyptus* plantation site in October 2011. Afaka forest reserve is located in Igabi Local Government Area, Kaduna State (Figure 01). The plantation lies along Latitude ($9^0$00'' and $11^0$30"N) and Longitude ($6^0$30" and $8^0$30"E) and covers up to 2,700 hectares extending in a Southern-Easterly direction within the reserve of almost ten thousand hectares (10,000 ha).

Kaduna State experiences two distinct seasons that reflected the influences of tropical continental and equatorial maritime air masses which sweep over the entire country (Britannica, 2019). This seasonality in the state is pronounced with the cool to hot dry season, with hot season being longer, than the rainy season. Also, the spatial and temporal distribution of the rain varies, decreasing from an average of about 1,530mm in Kafanchan-Kagoro areas in the Southeast to about 1,015mm in lkara Makarfi districts in the northeast. Generally, the soil type in the State consists of red brown to red

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yellow ferruginous tropical soils which are heavily weathered and markedly laterized. They are mostly formed on granite and gneiss parent materials and on Aeolian and many sedimentary deposits (Abaje, et al., 2016). The geology of the study area is underlain by gneisses, migmatites and meta sediments of the Precambrian to lower palaezoic age (McCurry, 1989). In the southeastern corner, younger granites and batholiths are evident of deep chemical weathering and fluvial erosion, which was influenced by the bioclimatic nature of the environment.

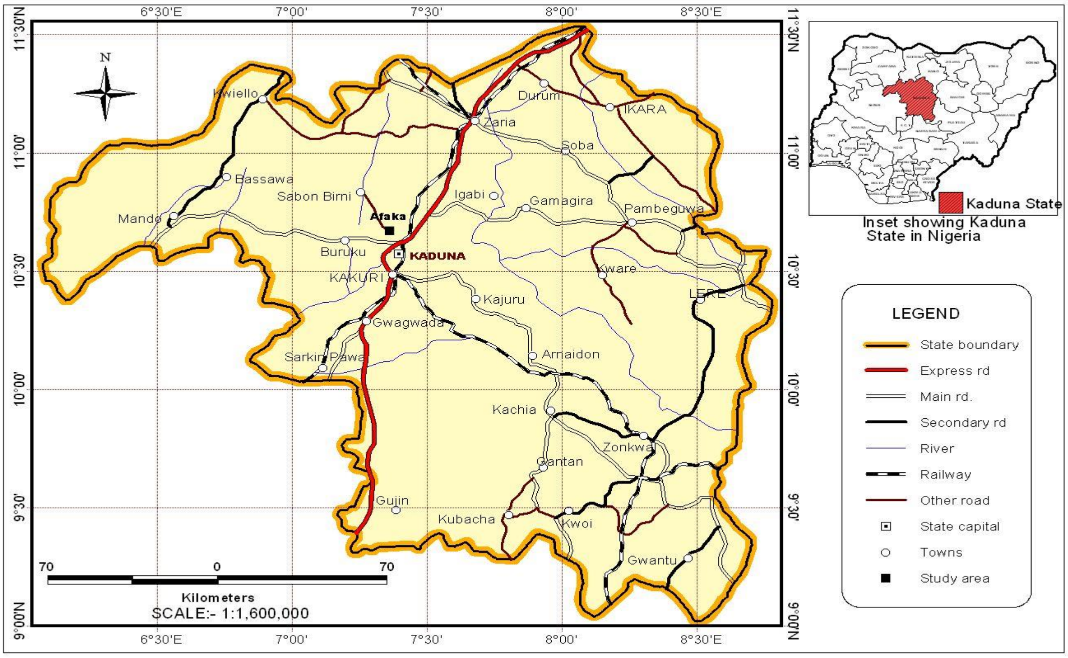

Figure 01. Map of Kaduna state showing the study area (Afaka forest reserve)

Sampling technique and data collection

A stratified sampling technique was adopted in obtaining information for this study. In each of the species stand, a sample plot size of 20 m x 20 m was laid, in which complete enumeration was carried out in each of the sampled plots and all the trees encountered were counted and the diameter at breast height for all biotic trees was measured at 1.3 m above the ground level, while other diameter measurements were measured at various section of the tree. Data obtained on the height and the diameter at breast height (dbh) was used in deriving other variables such as basal area, yield, density, etc.

Volume estimation

The volume/yield of the species was estimated using Newton's formula Eq (1)

$$V = H\frac{(A_b + 4A_m + A_t)}{6} \quad \ldots\ldots. \qquad \text{Eq. (1)}$$

where,

V = Volume (Yield)

H = Tree height

A_b= Cross sectional area at the base

A_m= Cross sectional area at the middle

A_t = Cross sectional area at the top

Mean annual increment estimation

The mean annual increment (MAI) was estimated by dividing the yield by their corresponding ages, while the yield functions, was generated using Eq.2 (Pancel and Köhl, 2016).

$$Y = exp^{b0 - b1A^{-1}} \quad \ldots\ldots\ldots. \qquad \text{Eq. (2)}$$

Linearization of (Eq. 2) produces (Eq.3) of the form:

$$\text{Ln MAI} = b_0 + b_1A^{-1} \quad \ldots\ldots\ldots\ldots \qquad \text{Eq. (3)}$$

To obtain the current annual increment (CAI), derivative of yield with respect to the age of the species was estimated i.e. $\left({dY}/{dA}\right)$ and MAI was computed using Equation 4.

$$MAI = {Y}/{A} \qquad \ldots\ldots\ldots\ldots \qquad \text{Eq. (4)}$$

The age at which the Mean annual increment (MAI) was at maximum was obtained from the derivative of MAI for age, which is equivalent to the slope (b_1) of the equation.

Annual allowable cut estimation

To ensure sustainability and productivity of forest stands, a certain number of trees per hectare has to be cut over a specified period, especially in the area, where wood sales are based on stumpage method and specified prices for each size class. The annual allowable cut for *Eucalyptus* species in the region was estimated, using both area control and volume methods:

Area control method

This requires cutting of equal areas or areas of equal productivity annually or periodically. Allowable hectare cut formula is given as:

$$\mathrm{A_{HA}} = \frac{\mathrm{T_{ha}}}{\mathrm{Y}} \qquad \ldots\ldots\ldots\ldots \qquad \text{Eq. (5)}$$

Where,

T_{ha} = Total hectares of the Forest
A_{HA} = Annual allowable hectare (ha/yr)
Y = Year of management

The annual allowable cut volume is calculated by multiplying the allowable hectare cut per year with the mean yield per hectare i.e.

$$V_A = A_{HA} \times \bar{Y} \qquad \ldots\ldots\ldots\ldots \qquad \text{Eq. (6)}$$

Where,

V_A = Annual allowable volume (m^3/yr)
A_{HA}= Annual allowable hectare (ha/yr)
$\bar{Y}$ = Mean yield per hectare (m^3/ha).

Volume control method

Volume control requires cutting of equal volumes of trees annually or periodically. As pointed out by Leuschner (1984) Von Mantel's formula was used to estimate the allowable cuts of the species and is of the form:

$$\mathrm{Y_a} = \frac{2(\mathrm{G_a})}{\mathrm{R}} \qquad \ldots\ldots\ldots\ldots \qquad \text{Eq. (7)}$$

where,

Y_a = Actual yield
G_a = actual growing stock
R = Rotation age

III. Results and Discussion

Attributes of measured variables for Eucalyptus species in Afaka forest reserve

The summary of the statistics of the measured variables (Table 01) shows that the average diameter at breast height (dbh) across the four age series in the stand varies from 13.4 to 18.2 cm, while the average total height and dominant height varied from 23.6 to 31.2 m in the study area. In terms of species stocking, it was revealed that *E. citriodora* has the highest stock density of 925 trees per hectare; this was followed by *E. cloeziana* with a total number of 923 trees per ha, while the least stocked compartment (*E. terreticornis*) has 831 trees/ha. The average basal area ranges between

14.08 m^2 and 26.85 m^2, while the site index ranges between 29 to 31 years across the four compartments. The compartment with highest volume per hectare was *E. camaldulensis* with a total volume of 340.798 m^3; this was followed by *E. citriodora* with a volume of 310. 265 m^3, while the least *E. cloeziana* gave a volume of 211.770 m^3 per hectare.

Table 01. Summary statistics of the measured variables for eucalyptus species plantation at Afaka forest reserve

Stand attributes	*E. camaldulensis*				*E. terreticornis*				*E. citriodora*				*E. cloeziana*			
	Mean	Min	Max	SD	Mean	Min	Max	SD	Mean	Min	Max	SD	Mean	Min	Max	SD
Age (yrs)	25.8	24.0	27.0	1.668	25.7	24.0	27.0	1.078	25.6	24.0	27.0	1.333	25.4	24.0	27.0	0.961
Diameter at breast height (cm)	13.4	9.9	16.9	2.059	13.9	10.0	17.9	2.165	14.9	12.9	16.9	1.176	18.2	12.9	23.3	3.038
Total height (m)	28.2	20.2	35.1	4.003	23.6	19.1	31.0	3.352	24.1	21.1	27.2	1.825	26.6	23.1	29.6	1.772
Merchantable height (m)	20.9	14.2	26.6	3.356	16.5	13.1	23.4	2.643	17.5	15.4	19.2	1.339	18.8	15.8	20.8	1.315
Dominant height (m)	31.2	27.2	33.7	2.0757	29.1	23.5	35.6	1.5988	28.7	26.9	30.3	1.0989	27.3	25.7	29.2	10188
No. of Trees per Compartments	36	30	42	4.002	33	30	37	1.635	37	31	41	3.082	39	34	42	2.183
Stem per hectare (N/ha)	907	750	1050	100.057	831	750	925	49.582	925	775	1025	77.055	923	850	1050	48.501
Basal area per hectare (m^2/ha)	14.13	7.78	20.06	3.719	14.08	7.98	21.88	4.146	17.88	14.38	20.15	2.162	26.85	13.10	45.15	8.598
Site Index (m)	28.9	33.6	36.7	3.0511	30.7	30	32	0.962	30.8	30	32	1.221	30.9	30	32	0.880
Stand Volume (m^3/ha)	340.798	227.841	392.805	76.015	258.644	161.065	386.453	99.075	310.265	266.579	352.505	35.750	211.770	105.562	281.217	75.396

Total volume production (TVP) for Eucalyptus species plantation in Afaka forest reserve

The result in Table 02 shows the TVP for eucalyptus species at Afaka forest reserve. It was revealed that *E. citriodora* had the highest number of stems per hectare (3,763). This was followed by *E. cloeziana* and *E. camaldulensis* with 3,742 and 3,694, respectively. The highest total volume production (TVP) species was *E. camaldulensis,* with a total volume of 91,535.246 m^3 per stand, while *E. cloeziana* has the least volume of 4,936.692 m^3 per stand.

Optimum rotation age and mean annual increment (MAI) for Eucalyptus species plantation in Afaka Forest Reserve

The rotation age of the species occurred when the mean annual increment is at maximum (MMAI), i.e., the point where mean annual increment (MAI) and current annual increment (CAI) intersect. Table 03 display the parameter estimates, fit statistics and optimum rotation age of the eucalyptus species. It was revealed that there are variations in the rotation age of the species; *E. tereticornis* and *E. cloeziana* had the highest rotation age of 42 years; while, *E. camaldulensis* and *E. citriodora* has a rotation age of

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19 and 27 years, respectively. This point is of considerable significance in forest management, as it helps determine the harvesting period (chosen the rotation age of species for maximum volume production). This result was contrary to that of Muhammad (2002), who suggested a rotation age of 8 -9 years in their study on the growth and price trend of *Eucalyptus camaldulensis* in Central Punjab. The maximum mean annual increment for *E. camaldulensis, E. citriodora and E. cloeziana* are 19.323 m^3/ha 16.993 m^3/ha and 16.030 m^3/ha, respectively, which occur at the age of 20, while that of *E. terreticornis* was 18.705 m^3/ha and occur at 21 years of age. The maximum MAI for *E. camaldulensis, E. terreticornis* and *E. citriodora was 18.705, 19.323* and 16.786 m^3/ha/yr, respectively, while *E. cloeziana* had the least (10.982 m^3/ha/yr).

Table 02. Estimates of eucalyptus species total volume production and mean annual increment (MAI)

Species	Age (Yrs)	Stand size (ha)	Stems (N/ha)	Volume (m^3/ha)	MAI (m3/ha/yr)	Compartmental total volume (m^3)
Eucalyptus Camaldulensis (ECM)	20	65.9	988	227.841	11.392	15,014.721
	21	70.7	975	392.805	18.705	27,771.310
	22	123.0	850	373.854	16.993	45,984.040
	23	7.5	881	368.690	16.030	2,765.180
Total		**267.1**	**3,694**			**91,535.246**
Eucalyptus terreticornis (ETC)	20	52.4	838	386.453	19.323	20,250.137
	21	43.4	825	276.581	13.171	12,003.615
	22	105.5	858	161.065	7.321	16,992.358
	23	5.0	820	203.946	8.867	1,019.730
Total		**206.3**	**3,341**			**50,265.840**
Eucalyptus citriodora (ECT)	20	12.3	958	266.579	13.329	2,278.922
	21	6.9	975	352.505	16.786	2,432.285
	22	8.4	988	319.366	14.517	2,682.674
	23	3.0	842	287.566	12.503	862.698
Total		**30.6**	**3,763**			**8,256.629**
Eucalyptus Cloeziana (ECL)	20	24.0	967	105.562	5.278	2,533.488
	21	4.9	925	230.618	10.982	1,130.282
	22	5.9	900	182.425	8.292	1,076.308
	23	1.0	950	196.622	8.549	196.622
Total		**35.8**	**3,742**			**4,936.692**

Table 03. Estimates, fit statistics and optimum rotation age for Eucalyptus species plantation in Afaka forest reserve, Nigeria

Species	Coefficients	Estimates	Fit statistics		Optimum rotation age (Years)
			R^2	RMSE (%)	
Eucalyptus camaldulensis	β_0	0.651	67.2	0.0451	19
	β_1	18.798			
Eucalyptus terreticornis	β_0	3.358	89.8	0.0488	42
	β_1	42.089			
Eucalyptus citriodora	β_0	2.809	84.1	0.0409	27
	β_1	27.342			
Eucalyptus cloeziana	β_0	-0.251	61.9	0.1127	42
	β_1	41.759			

Annual allowable cut for eucalyptus species plantation in Afaka forest reserve

Using area control method, the number of trees and volume of trees to be harvested for each of the species is depicted in Table 04. For example, in *E. terreticornis* stand with a rotation age of 42 years, 80 trees/ha with a total volume of 2,393m^3/ha/yr for trees with Dbh < 30cm will be available for harvest in 0.63 hectares of land, while only 4 trees/ha with a volume of 13.5m^3/ha/yr for trees with Dbh > 30 cm will be available for cut at the same rotation age and hectarage. The characterization of the species by diameter girth limit (30 cm) will enable proper management for the number and volume of trees to

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be harvested at a particular period, and this will assist in regulating the forest for continuous wood flow in the area.

Table 04. Annual allowable cut for Eucalyptus species plantation at Afaka forest reserve

Species	Rotation age (Years)	Stand size (ha)	Area control (ha)	Annual allowable cut			
				Number of trees (N/ ha)		Volume of trees (m^3/ha/yr)	
				< 30cm	>30cm	< 30cm	>30cm
E. camaldulensis	19	267.1	14.06	193.4	-	9,635.3	-
E. terreticornis	42	206.3	0.63	79.5	4.1	2,393.6	13.5
E. citriodora	27	30.6	1.13	139.1	0.9	611.6	3.3
E. cloeziana	42	35.8	0.85	86.1	13.4	235.1	24.1

IV. Conclusion

Summarily, both area control and volume control methods can be used to regulate the Eucalyptus species at Afaka forest reserve at any specific rotation age as demonstrated by this study, but area control method is by far the simplest and most easy means of regulating the forest at any specific rotation age. Thus, applying the area control method involves strongly limiting the harvest alternatives and variations in land productivity between succeeding rotation intervals, as Luiz et al. (2009) suggested. The rotation ages of 19 and 27 years were suggested for *E. camaldulensis* and *E. citriodora,* respectively, while 42 years were suggested for both *E. terreticornis* and *E. cloeziana*. For any forest estate to be managed sustainably, a reliable amount of the wood in a particular area that can grow annually at the minimum level of forest management must be estimated. The principal disadvantages of volume control method are variations that may occur in the harvest volume during the conversion period. The growing of the forest for a short rotation period would ensure early and maximum income generation and sustainable management of the reserve, which may not harm crop production. Furthermore, this study has proved that mean annual increment and rotation age are of fundamental importance in forest business and shaping of stands future (harvest regulation) for sustainable management.

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