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Development of Silvicultural Management Models for *Gmelina arborea* Roxb. Stands in Area J4, Omo Forest Reserve, Nigeria

Aturamu, O. A. [1*]; Alo, A. A[2]. and Ige P. O[2]

Bamidele Olumilua University of Education, Science and Technology, Ikere Ekiti, Ekiti State.
[2]Department of Social and Environmental Forestry, University of Ibadan, Nigeria
**Corresponding Author: Email:* aturamu.oluyede@bouesti.edu.ng: *Phone No.:* 08036686186

Abstract

Plantation establishment of fast-growing species such as *Gmelina arborea* has been suggested as a quick fix to the perennial problem, especially in Omo Forest Reserve. Management models have been identified as tools for sustainable management and monitoring of Gmelina plantation. Hence, silvicultural management models were developed for sustainable management of Gmelina plantation in Omo Forest Reserve. Nine *Gmelina arborea* age series (34, 32, 30, 26, 24, 22, 20, 18 and 16 years old) stands were purposively selected in Area J4 of Omo forest reserve. A total of Sixty-five temporary sample plots were demarcated proportionate to size across the age series. In each plot, diameter at breast height and stem height were measured to estimate stand basal area and volume. Silvicultural management models were developed to estimate the optimum rotation volume, area and number of stock to harvest using the linear programme option of the R package to obtain the solutions of the planning model for 20 years at 5 years period. It was observed that the mean tree dbh and stem height ranges from 21.50 to 70.61 cm and 16.08 to 24.98 m respectively. The mean basal area and stem volume had the respective values which range from 33.31 to 413.78 m^2/ha and 423.19 to 8413.52 m^3/ha. At the individual tree level, mean annual growth is attained at 27 years. This represents the optimal rotation age of any *Gmelina arborea* stand in Omo forest reserve. If selective logging is applied for timber purpose, a rotation age of 27 years will be the appropriate rotation age. However, if clear-felling is opted for, the appropriate rotation age will be 25 years. The logging plan that optimizes volume in terms of area cut in each stand and period revealed that in 16 years old stands, whole logging will take place only during the last period of the plan, removing 5.00ha. The respective area to be cut during the 1st, 2nd, 3rd and 4th periods are 451.70ha, 517.50ha, 250.80ha and 140.00ha. The harvesting schedules obtained in this study have shown that the management planning model provides rational and practicable results.

Keywords: *Harvesting schedule, linear programme, management models and rotation age*

Introduction

Nigeria is well endowed with forest resources, accounting for about 2.5 percent of the Gross Domestic Products (FAO, 2010). Forest Resources Assessment (2010) reported that these resources provide employment for over 2 million people through the supply of fuelwood and poles and more than 80,000 people working in the log processing industries, especially in the forest zones of the south. The resources abound in the High Forests, woodlands, bushlands, plantations and trees on farmlands. The forests occupy about 10 million hectares representing almost 10 percent of the total land area of 92,377 hectares. This total is made up of about 445 gazetted reserves, distributed over the five main ecological zones of Freshwater/mangrove, the lowland rainforest, the derived savanna and the sahel/sudan savanna (FAO, 2021). More than 5 percent of the total land area is devoted to wildlife conservation which is also distributed across the major ecological zones. The forests provide a wide range of non-wood products and environmental functions, though not adequately quantified and are under-estimated in national accounting. These products include bush meat, medicine, watershed protection, stabilization of the hydrological regimes and carbon sequestration. The forest estates from which wood and other products are obtained have been subjected to severe encroachments, vegetation degradation and dereservation for agriculture, industrial development, urbanization etc (FAO, 2021).

Plantation forests have often been considered as a "quick fix" solution to the perennial problems of overexploitation of the natural forest resources. Plantation forestry in Nigeria started in the early 1900s (Ajayi, 2013). Large-scale plantation forestry in Nigeria was preceded by many successful species and provenance trials, mainly of exotic species. FAO (2011) reported that the annual planting rate is about 58,000 ha.

Gmelina arborea is a fast-growing deciduous tree occurring naturally in India, Thailand, Cambodia and southern provinces of China but planted extensively in Nigeria, Sierra Leone and Malaysia (Ajayi, 2013). It is commonly planted as avenue trees, in gardens and villages along with agricultural land, on village community lands and on wastelands. It is light-demanding, tolerant of excessive drought but moderately frost hardy and has a good capacity to recover in case of frost injury (Duke, 1983). In Nigeria, large investments in *Gmelina arborea* plantations have been made particularly to provide raw materials for pulp and paper mills (Ajayi *et al.*, 2004). The species is now being converted for timber production as a result of the failure of the mills to utilize them (Adetogun and Omole, 2007). These plantations have outgrown the pulpwood production rotation of 8 years (Akachuku 1981; Evans, 1992).

Methodology

The study was carried out in the plantation section (Area J4) of Omo Forest Reserve (Fig 1). It is situated between latitudes 6º 42' and 7º 00'N and longitude 4º 17' and 4º 35'E. The reserve shares its northern boundary with Osun and Ago Owu forest reserves in Osun State and Oluwa forest reserves in Ondo State. The Omo and Oni rivers mark the southern boundary. The reserve had a total area of approximately 130,550 ha with 65km of enclaves. Major communities present include: Aberu, Abititun, Oloji, Osoko, and Ajebamidele, The topography of the reserve is generally gently undulating with an average elevation of 12 m above sea level (Akindele and Abayomi, 1993). The main study area is generally low-lying. It is neither lower than 20m nor higher than 61m, maintaining a landform, which can be regarded as flat to undulating (Chijioke, 1988). It has a mean annual temperature of 26.5ºC with a minimum of 19.5ºC and a maximum of 32.5ºC reported for rainy season and dry seasons respectively (Ige, 2017).

Furthermore, silvicultural treatments have been limited; leaving stands untended.

Sustainable management of forest resources requires a large amount of supporting information. Especially when managing a forest for the production of commercially valuable materials, estimation of present growth of variables, which are not possible to measure easily (such as timber volume), and to estimate the growth values in the future are essential. Vanclay (1994) defined stand growth models as abstractions of the natural dynamics of a forest stand, which may encompass growth, mortality and other changes in stand composition and structure. Therefore, forest models can be used as very successful research and management tools. The models designed for research require much complicated and not readily available data, whereas the models designed for management use simpler and more readily accessible data (Johnsen *et al.*, 2001). The process of developing a growth model may offer interesting new insights into stand dynamics such as stand growth competition models. Hence, management model was developed for sustainable harvest of G. arborea in Area J4, Omo forest reserve, Nigeria.

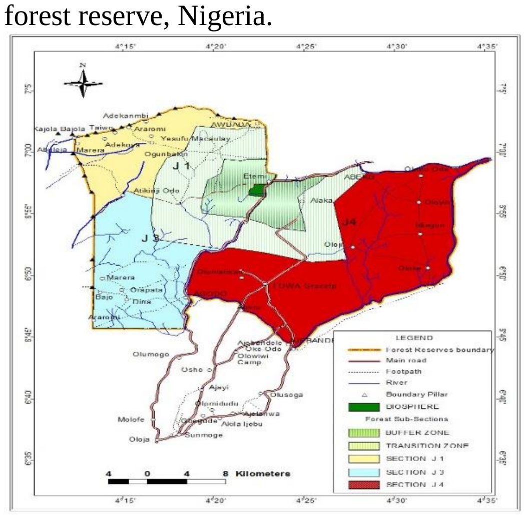


Fig 1: Map of Omo Forest Reserve showing the study area (Area J4)

***Gmelina arborea* Plantation in Omo Forest Reserve**

Omo forest reserve happens to be one of the notable sites in South Western Nigeria where plantations of *Gmelina arborea* were established. Plantation efforts for this species started in 1966. An annual planting target of 500 hectares was planted to serve as a steady source of raw materials for Iwopin Pulp and Paper Mill, located 500km from the reserve. In 1972, the former Western State Government, the original owner of the forest, secured financial assistance from the Federal Government. The purpose was to increase the annual planting target of *Gmelina* and to enhance the maintenance and management of existing plantations that were established through direct labour and Taungya system which took place between 1969 and 1979. In 1989, a loan was secured from the African Development Bank (ADB) for the establishment of more plantations of *Gmelina* at an annual planting target of 1000ha out of which 100ha should be plantations of indigenous species. Since then, there is a continual plantation establishment of *Gmelina* by Ogun State Government through Ogun State Forestry Plantation Project Area J4.

Data Collection

Plot Sampling

Temporary Sample Plots (TSP) were demarcated using the proportionate size in a simple random sampling technique in each of the available age stand (Table 1). Each TSP were 20m x 20m (i.e 0.04) in size. Table 1 below shows the distribution of sample plots used in each age stand

Table 1: Stands selected for the study

Age (Years)	Area planted (ha)	**Number of sample plots**
34	1600.00	10
32	1230.00	10
30	1000.00	10
26	330.00	5
24	78.70	5
22	1360.00	10
20	33.00	5
18	103.00	5
16	5.00	5
Total		65

Measurement of Tree Variables

The following tree variables were measured in each TSP:

- Diameter at breast height (dbh) over bark of all trees (cm). This is measured at a standard position of 1.3m above the ground.
- Diameter over bark at the base (db), middle (dm) and top (dt) of all the trees (cm).
- Total height (Ht) of all the trees (m)
- Merchantable height (Hm) of all the trees (m)

Data Analysis

Basal area estimation

The Basal Area (BA) of individual trees was estimated using the formula according to Husch *et al*, (2003)

$$BA = \frac{\pi}{4} D^2 \qquad \text{…… 1}$$

Where BA = Basal area (m^2), D = dbh (cm) and π = 3.142 (constant)

In each plot, the total area of all the trees will be computed and use to estimate the basal area per hectare. This will be achieved by multiplying the plot basal area by 25 (being the number of 0.04 ha sample plots in an hectare). In addition, the annual tree basal area growth and stand basal area growth per hectare were obtained by dividing individual tree basal area and basal area per hectare by the corresponding plot age respectively.

Stem Volume estimation

The volume of individual trees was estimated using Newton equation developed for trees volume estimation (Husch *et al*, 2003):

$$V = \pi H \left[\frac{Db^2 + 4Dm^2 + Dt^2}{24} \right] \qquad \text{…… 2}$$

Where V = Total volume (m^3), H = height (m), Db = Diameter at the base, Dm = Diameter at the middle, Dt = Diameter at the top and π = 3.142 (constant)

In each plot, the total stem volume of trees was computed and used to estimate the stem volume per hectare (m^3/ha). This was done by multiplying the plot stem volume by 25. Also, annual stem volume growth for individual trees and on stand basis was computed by dividing tree volume and stem volume per hectare by the corresponding plot age.

Site quality assessment

The linear regression model was fitted to the dominant height and age data in this study, as suggested by Schumacher (1939), is of the form:

$H_d = exp^{(\beta_0 + \beta_1 A^{-1})}$ ……………………… 3

Where: H_d = average height of dominant trees

A = stand age

β_0 = intercept value associated with each particular site index.

β_1 = slope with the same value for all site indices.

In this form, it is only possible to produce anamorphic site index equations. This implied that the site index curves to be generated will be a family of parallel lines with constant slope but varying intercepts. The equation for a particular site index line was obtained bearing in mind that such a line has the form:

$lnH_d = b_0 + b_0 A^{-1}$ ……………………… 4

Where lnHd and A are as earlier defined while b_0 and b_1 are sample estimates of β_0 and β_1, respectively. The equation was fitted to the dominant height-age data to obtain estimates of the regression parameters. By definition, when A equals the index age (i.e. 20 years for this study), Hd will be equal to site index (SI), so that:

$b_0 = \ln(SI) - b_1 (20^{-1})$ …………………….. 5

Note: $20^{-1} = 0.05$

By substituting equation 5 into equation 4, the following equation was obtained:

$\ln Hd = \ln(SI) - 0.05b_1 + b_1 A^{-1}$ thus,

$\ln Hd = \ln(SI) - b_1 (A^{-1} - 0.05)$ …………… 6

When SI is made the subject of equation 6, site index equation obtained is:

$\ln(SI) = \ln Hd - b_1 (A^{-1} - 0.05)$

Therefore, $SI = \exp[\ln Hd - b_1 (A^{-1} - 0.05)]$ …. 7

With known values of age and dominant height, this equation can be used to estimate the site index value for each plot.

Forest Management Planning Models

Models for Determining Optimum Rotation Age

The biological model of optimal rotation age determination maximizes the mean annual growth (MAG) of the stand. The mean annual growth is the total volume (at stand or tree level) divided by the age of the stand at that time. This is expressed mathematically as:

$MAG = {}^{Y}/_{A}$ ………………………………… 8

MAG = Mean Annual Growth (m^3/ha/yr or m^3/yr at tree level)

A = Stand or tree age (yrs) and Y = Yield or volume of wood at age A

Wood yield is maximized over perpetual rotations if the stands are cut at the age where MAG reaches a maximum. Avery and Burkhart (2002) have pointed out the mathematical relationship between growth and yield. To obtain the age of maximum mean annual growth, one divides the yield function by age, takes the first derivative with respect to age. Then, the result is equated to zero and solved for age. The yield function used is of the form:

$\ln Y = a + bA^{-1}$ ………………………… 9

The yield function and mean annual growth (MAG) can thus be written as:

$Y = e^{a+bA^{-1}}$ ………………………….. 10

$MAG = \left(e^{a+bA^{-1}}\right)(A^{-1})$ ………………. 11

Management Planning Models

The development of logging scheduling models in this study was achieved through linear programming model. The management needs considered in this study area are: the need for rational and organized forest utilization through sensible logging sequence that aims at sustained production of the best quality stem at a lesser possible time (i.e optimal management plan). Linear programming model formulation used (Leuschner, 1990) involves the following steps:

i. **Choice of decision variables**

The decision variables that define the future logging sequence most simply are the areas cut from each initial compartment (or stand) in every period of the plan. A period of 20 years was chosen as the planning horizon for this study. To keep the number of variables relatively small, a sufficiently long lapse of time for each period was chosen. Thus we have four 5 – year operating periods. This led to the decision variables of the form: X_{ij}.

Where X_{ij} = area cut from stand i in period j. There are 36 of such variables in this study, since the study covered nine stands and there are four 5-year operating periods.

ii. **Stating the objective function**

The objective function of this study was based on optimizing volume. The objective function therefore, expresses the total volume of timber cut during the period of the plan (which is 20 years in this study) as a linear function of the decision variables. The object of the management planning model is to find the values of the decision variables such that the total amount of timber produced throughout the plan is optimum. The general form of this objective function is given as:

$$Max\ Z_{sv} = \sum_{i=1}^{m=9}\sum_{i=1}^{p=4} V_{ij}X_{ij} \quad \ldots\ldots\ldots\ldots\ldots\ldots..\ 12$$

Where Z_{sv} = stem volume per hectare, V_{ij} = expected volume per hectare in the stand I and period j, X_{ij} is as earlier defined.

iii. **Stating the Constraints**

There are five kinds of constraints to be considered in this study for modeling. These are: The constraints that refer to the limited land availability, The constraints expressing the desired pattern (or policy) of production during the plan, The constraints subjecting the management alternatives to either area-control or volume control management, The constraints that refer to limited manpower available and the constraints that express limited finances available. However, the first three were built into the linear programming model (because they are compatible with the decision variables and the objective function). The last two served as useful guides for decision-making on the solution of the linear programming model.

a. Land availability constraints

The land availability constraints state that the area of land that is cut in each stand (or compartment) cannot exceed the area available. These are mathematically expressed as:

$$\sum_{j=1}^{p=4} X_{i,j} \leq a_i \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ 13$$

i = 1, 2, 3, 4, ………., 9 and a_i = area (in hectare) of ith stand.

In the model formulated, an area that has been cut cannot be cut again before the end of the plan. This gives room for monitoring and evaluation of the output of the management plans. Evaluation results at the end of the plan will enhance decision on whether the management plan needs revision or should be maintained.

b. Time flow constraints

These constraints express the desired pattern of the flow of timber that is harvested during the plan. Timber flow that ensures a regular increase of 10% every 5 years was used in this study. Let f_j be the fraction by which the cut in j must exceed that in j-1, then, the general expression of the flow constraint is

$$\sum_{i=1}^{m=9} V_{i,j}X_{i,j} - (1 + f_j)\sum_{i=1}^{m=9} V_{i,j-1}X_{i,j-1} = 0 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ 14$$

j = 2, 3 and 4. There are p – 1 constraints of this kind. Where p = number of periods or intervals.

c. Area control constraints

The area control system stipulates that the total area cut cannot exceed (y/r) A, where y is the length of the plan and r is the rotation age (expressed in the same unit of time) and A is the entire area of the forest. In terms of the decision variables, this gives:

$$\sum_{i=1}^{m}\sum_{i=1}^{p} X_{i,j} \leq y\left(A/_r\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..\ 15$$

iv Use of appropriate software package

The linear programme option of R Development Core Team (2012) software package was used to obtain the solutions of the planning model.

Results

General Growth Estimates

Table 2 provides important whole stand variables estimated for *G. arborea* in the study area. The number of tree stands per hectare ranges from 875 to 1000. Mean tree dbh and stem height range from 21.50 to 70.61 cm and 16.08 to 24.98 m respectively. The same trend was observed for mean basal area, stem volume and merchantable volume with the respective values which range from 33.31 to 413.78 m^2/ha, 423.19 to 8413.52 m^3/ha and 297.14 to 6375.21 m^3/ha. Meanwhile, basal area growth and volume range from 1.85 to 12.17 m^2/ha/yr and 23.51 to 247.46 m^3/ha/yr respectively while stem quality growth ranged respectively from 174.17 to 322.18 m/ha/yr. The trees' vigour was very high as values observed for the crown projection area ranges from 54466.80 to 151094.00 m^2/ha.

Meanwhile, the site index estimates for *Gmelina* stands in this study ranged from 11.62 to 28.70m. The same trend was followed at the individual tree level (Table 3) as a number of stem per plot ranged from 35 to 40 while basal area and stem quality ranged from 0.15 to 0.42m^2 and 11.12 to 18.09 m respectively. Stem basal area, volume and stem quality growth ranged from 0.002 to 0.017 m^2/yr, 0.027 to 0.250 m^3/yr and 0.506 to 0.749 m/yr. These ranges indicate that *Gmelina* trees in this study area are growing well. Generally, the diameter distribution (Fig 2) shows that the diameter of the tree, which usually follows a normal distribution pattern, is basic and very useful means of characterizing an even-aged stand for all the age series considered in this study. The results of linear correlation coefficient between growth variables and other parameters at the whole and individual stand levels are presented in Tables 4 and 5 respectively. At the individual stand level, there were significant linear relationships between stand volume and the following variables: age, density, dbh, stem heights, basal area, basal area growth and stem quality. At the whole stand level, a notable significant correlation was observed between the stand volume and basal area growth, stem quality growth and site index.

Model for Site Quality Estimation

Site index equation obtained in this study is presented as

$$SI = \exp\left[\ln H_d \text{ - } 5.81(\mathrm{A}^{-1} \text{ - } 0.05)\right] \ldots\ldots\ldots 16$$

(R^2 = 0.8871, MSE = 0.0013)

Where SI = Site index (m), H_d = Dominant height (m), A = Stand age (years), R^2 = Coefficient of determination, MSE = Mean square error.

This equation was used to obtain the site index values (Tables 2 and 3) for each plot used in the whole stand estimation. The site index estimates for the *Gmelina* stands in this study ranged from 11.6189 to 28.6951m. These ranges indicate that *Gmelina* trees in Omo forest reserve are doing well.

Silvicultural Management Planning Models

The silvicultural management recommended is an even age management, with clear-cutting, followed by coppice system. Provisions were made for inter-planting where coppices fail. The management-planning model for the sustainable management of *Gmelina* stands in Omo forest reserve is presented as follows:

Find $X_{1,1}$, $X_{1,2}$, .., $X_{9,4}$, all non-negative, such that:

$$\text{Max } Z_{sv} = 13491.85X_{1,1} + 18115.82X_{1,2} + 22904.71X_{1,3} + 27728.57X_{1,4} + 11727.12X_{2,1} + 16237.54X_{2,2} + 20978.72X_{2,3} + 25801.32X_{2,4} + 10031.22X_{3,1} + 14395.56X_{3,2} + 19065.24X_{3,3} + 23870.05X_{3,4} + 6909.05X_{4,1} + 10869.63X_{4,2} + 15311.30X_{4,3} + 20019.91X_{4,4} + 5516.94X_{5,1} + 9213.87X_{5,2} + 13491.85X_{5,3} + 18115.82X_{5,4} + 4260.91X_{6,1} + 7650.63X_{6,2} + 11727.12X_{6,3} + 16237.54X_{6,4} + 3157.58X_{7,1} + 6197.08X_{7,2} + 10031.22X_{7,3} + 14395.56X_{7,4} + 2221.12X_{8,1} + 4870.84X_{8,2} + 8419.63X_{8,3} + 12601X_{8,4} + 1461.13X_{9,1} + 3689.19X_{9,2} + 6909.05X_{9,3} + 10869.63X_{9,4} \ldots\ldots 17$$

(Note: The coefficients of equation 17 are the expected volumes at 5-years time steps presented in Table 2).

Subject to:

Land availability:

$X_{1,1} + X_{1,2} + X_{1,3} + X_{1,4} \leq 1600.00$ …………… 18

$X_{2,1} + X_{2,2} + X_{2,3} + X_{2,4} \leq 1230.00$ …………… 19

$X_{3,1} + X_{3,2} + X_{3,3} + X_{3,4} \leq 1000.00$ …………… 20

$X_{4,1} + X_{4,2} + X_{4,3} + X_{4,4} \leq 330.00$ …………....... 21

$X_{5,1} + X_{5,2} + X_{5,3} + X_{5,4} \leq 78.70$ ………………. 22

$X_{6,1} + X_{6,2} + X_{6,3} + X_{6,4} \leq 1360.00$ ……………. 23

$X_{7,1} + X_{7,2} + X_{7,3} + X_{7,4} \leq 33.00$ ………………. 24

$X_{8,1} + X_{8,2} + X_{8,3} + X_{8,4} \leq 103.00$ …………….. 25

$X_{9,1} + X_{9,2} + X_{9,3} + X_{9,4} \leq 5.00$ …………...….. 26

Timber flow:

$$18115.82X_{1,2} + 16237.54X_{2,2} + 14395.56X_{3,2} + 10869.63X_{4,2} + 9213.87X_{5,2} + 7650.63X_{6,2} + 6197.08X_{7,2} + 4870.84X_{8,2} + 3689.19X_{9,2} - 14841.04X_{1,1} - 12899.83X_{2,1} - 11034.34X_{3,1} - 7599.96X_{4,1} - 6068.63X_{5,1} - 4687.00X_{6,1} - 3473.34X_{7,1} - 2443.23X_{8,1} - 1607.24X_{9,1} = 0 \ldots 27$$

$$22904.71X_{1,3} + 20978.72X_{2,3} + 19065.24X_{3,3} + 15311.30X_{4,3} + 13491.85X_{5,3} + 11727.12X_{6,3} + 10031.22X_{7,3} + 8419.63X_{8,3} + 6909.05X_{9,3} - 19927.40X_{1,2} - 17861.29X_{2,2} - 15835.12X_{3,2} - 11956.59X_{4,2} - 10135.26X_{5,2} - 8415.69X_{6,2} - 6816.79X_{7,2} - 5357.92X_{8,2} - 4058.11X_{9,2} = 0 \ldots. 28$$

$$27728.57X_{1,4} + 25801.32X_{2,4} + 23870.05X_{3,4} + 20019.91X_{4,4} + 18115.82X_{5,4} + 16237.54X_{6,4} + 14395.56X_{7,4} + 12601X_{8,4} + 10869.63X_{9,4} - 25195.18X_{1,3} - 23076.59X_{2,3} - 20971.76X_{3,3} - 16842.43X_{4,3} - 14841.04X_{5,3} - 12899.83X_{6,3} - 11034.34X_{7,3} - 9261.59X_{8,3} - 7599.96X_{9,3} = 0 \ldots.. 29$$

Area control:

$X_{1,1} + X_{1,2} + X_{1,3} + X_{1,4} + X_{2,1} + X_{2,2} + X_{2,3} + X_{2,4} + X_{3,1} + X_{3,2} + X_{3,3} + X_{3,4} + X_{4,1} + X_{4,2} + X_{4,3} + X_{4,4} + X_{5,1} + X_{5,2} + X_{5,3} + X_{5,4} + X_{6,1} + X_{6,2} + X_{6,3} + X_{6,4} + X_{7,1} + X_{7,2} + X_{7,3} + X_{7,4} + X_{8,1} + X_{8,2} + X_{8,3} + X_{8,4} + X_{9,1} + X_{9,2} + X_{9,3} + X_{9,4} \leq 5716.97$ ……………. 30

Optimal Management Plan for *Gmelina* Stands in Omo Forest Reserve

Discussion

A forest is considered healthy when its growth variables are in the expected range of meeting management objectives. All the growth variables considered in this study were of the expected range at a whole stand and individual tree levels (Tables 2 and 3). The tree dbh trend follows the trend often obtained for tropical plantation species (Figure 2). The tree's dbh is highly correlated with the plantation age, no of stem, basal area and the stem volume (Tables 4 and 5). According to Husch *et al* (2003), basal area per hectare is computed from the number of trees per hectare and the dbh of the standing trees.

Hence, timber production appears to be the feasible alternative management objective for the existing *Gmelina* plantations in the study area. The plantations selected for this study are older than 12 years which are no longer suitable for pulp production due to lower pulp yield, higher lignin content and shorter fibre length of old *Gmelina* trees (Yuchang, *et al*; 1995). In addition, there is no indication that the mill meant to utilize the *Gmelina* resources will function in the nearest future and the market for *Gmelina* timber is emerging in Nigeria (Onyekwelu, 2001). The result of site quality estimation model also confirms the suitability of the study area for optimum growth and yield of *Gmelina*. Clutter *et al*. (1983) noted that ferruginous tropical soils, which are found in this study area, are among the most fertile soils in southwestern Nigeria. The high growth rate of *Gmelina* can also be attributed to the fact that the extremes of the temperature of 31.3ºC and 21.0ºC and annual rainfall of 1257 mm are required by the species for optimum growth (Lamb, 1968) is adequately met in the study area. Hence, the trends shown in these ranges correspond to the common trend often reported in tropical plantation growth studies (Abayomi, 1986; Adesoye, 2002; Onyekwelu, *et al*., 2006).

The final solution of the linear programming model for stem volume optimization is presented in Tables 6, 7 and 8. The result in Table 6 expresses the area cut in each stand by period. Table 7 reveals the volume of *Gmelina* to be harvested in each stand by period while Table 8 shows the number of stems to be harvested in each stand by period. Figure 3 shows the area that must be cut in each stand and period that will lead to the optimal volume.

A timber rotation period is simply the time between the establishment of a stand of trees and when that same stand is ready for a final cut. This period of years often called the "optimum" rotation period is especially important when forest managers try to determine the most advantageous harvest condition in an even-aged stand of trees. When a stand is either economically mature or reaching beyond natural maturity, the "rotation period" has been reached and a final harvest can be planned. Most past studies (e.g. Adegbehin, 1985; Onyekwelu, 1995; Onyekwelu, 2003) have based the estimation of optimum rotation age through mean annual growth on stand statistics without consideration of the tree level implications. But Adesoye (2002) explores both the tree level and stand-level estimations of the rotation age for *Nauclea diderrichii*.

Hence this study assessed the optimal rotation age for this tree species on nine age series presently available in the study area at both individual and whole stand levels. The models developed in this study were found very suitable. At the individual tree level, the results reveal that mean annual growth is attained at approximately 27 years. This represents the optimal rotation age of any *Gmelina arborea* stands in Omo forest reserve. In some African countries (Nigeria, Ghana, and Sierra Leone), between 15 and 25 years of rotation age have been for *Gmelina* timber stands (FORMECU, 1999; Schneider 1997; Onyekwelu, 2003). Hence, this study still follows the same trend observed in the previous studies. At the whole stand level, the mean growth per hectare culminates at 25 years. It represents the optimum rotation age of the species at the stand level. The choice of 25 or 27 years will depend on the type of logging embarked upon. If selective logging is applied for timber purposes, a rotation age of 27 years will be the appropriate rotation age. Therefore, selective logging will imply a longer rotation age. However, if clear-felling is opted for, the appropriate rotation age will be 25 years.

The management planning model developed and solved in this study is equation 17 (based on stem volume optimization). The model was also used to obtain harvest schedules (in terms of the area cut per period per stand) that optimize the stem volume of *Gmelina* throughout the period of the management plan (i.e. 20 years). Linear programming models obtained for management planning in this study were similar to Lappi (1992), Jonsson *et al* (1993), Adesoye (2002) and Millie *et al* (2010). The solutions of equations 17 to 30 are given in tables 6 to 8. This is an improvement to linear programming solutions that merely specify area to be cut or volume to be cut which may be difficult to quantify during implementation. The solutions obtained in this study, therefore, provide tripartite fronts for practical implementation of the optimal management plan.

The logging plan (Fig 3) that optimizes volume in terms of area cut in each stand and period revealed that in 16 years old stands, whole logging will take place only during the last period of the plan, removing 5.00 ha. During the last period of the plan, the stand will be 36 years old. This solution is similar to that reported by Buongiorno and Gilless (1987), Adesoye (2002) and Millie *et al* (2010). They reported solutions that left the first age class (being younger) un-cut. The 24, 20 and 18 years old stands will be cut during the second, third and fourth periods. Meanwhile, 22 years old stand is the only stand that will be cut throughout the period of the plan. The respective area to be cut during the 1st, 2nd, 3rd and 4th periods are 451.70 ha, 517.50 ha, 250.80 ha and 140.00 ha. The whole of 34, 32 and 30 years old stands (the oldest set) will be cut during the first period of plan.

The column totals in table 6 show that four blocks of 4586.70 ha, 553.15 ha, 328.20 ha and 248.92 ha are created during the first, second, third and fourth periods respectively. These values have two implications. First, they show a reducing timber flow during the period of the plan. Second, they show areas available for regeneration. Hence, forest managers can plan the number of seedlings to raise and the amount it will cost or the various operations necessary to ensure good coppices. This is in accordance with the work of Manoel (1995) and Millie *et al* (2010) that the only real way to ensure proper management with economic purpose is through rational utilization, which transforms silviculture in a self-sustainable economic activity.

Table 7 shows the volume of *Gmelina* that will be logged in each stand per period. The total volume produced by the stands is 38,436,546.66 m^3. This is the maximum that can be obtained with respect to the various constraints imposed. The column totals in Table 7 shows the production level by period from 34,871,563.67m^3 in the first period to 1,025,297.73m^3 in the last period of the plan. Table 8 reveals the number of stems which is the equivalent of the volume values in table 7. A total of 5,534,552 stems amounting to 38,436,546.66 m^3 of wood volume will be obtained throughout the plan. With the data in table 8, the implementation of the plan becomes practically apparent.

Conclusion and Recommendation

The optimum rotation age determined in this study are useful in determining the actual time such plantation can be harvested without compromising the out-door uses (e.g. furniture making, roofing, etc) of the tree species. This will also ensure the maximum use and yield of the land/soil.

The management planning models are useful for establishing strategic logging goals with spatially feasible plan that can be implemented. The information on number of stems to be harvested ensures practical implementation. The logging schedules, which best satisfy the objective of maximizing the total yield from a forest will be governed by some factors. These are: the area of the forest available, the present volume and growth on the area, the optimal rotation age, the number of cutting schedules and whether it is desirable to have the yields increased, decreased or remain constant in succeeding cutting periods. The harvesting schedules obtained in this study have shown that the management planning model provides rational and practicable results.

References

Abayomi, J.O (1986). Stocking and forest productivity. *In:* A.B. Oguntala (Editor). *The Challenge of deforestation in Nigeria.* Proceedings of 1986 Annual Conference of

Forestry Association of Nigeria, Minna, 1986, 310 – 318p

Adesoye, P.O (2002). Integrated system of forest stand models for *Nauclea diderrichii* in Omo forest reserve, Nigeria. Ph.D thesis, Department of Forest Resources Management, University of Ibadan, Nigeria. 174p.

Adetogun A.C and Omole A.O. (2007). Treatment of *Gmelina arborea* with CCA using thermal process. *Journal of Tropical Forest Science* 19: 186–187.

Ajayi. S; Ogar N.E; Anyaorah C.N (2004). A Mathematical Programming Approach to Sustainable Management of *Gmelina arborea* (Roxb) Plantations in a Nigerian rain forest. *International Journal of Education*, 2 (1&2): 146 – 157.

Ajayi, S (2013). Diameter Distribution for *Gmelina Arborea* (ROXB*)* Plantations in Ukpon River Forest Reserve, Cross River State, Nigeria. An *International Journal of Science and Technology* Bahir Dar, Ethiopia Vol. 2 (1) January, 2013:64-82

Akachuwku, A. E. (1981). Estimation of volume and weight growth in *Gmelina arborea* with X-ray densitometry. *In forest site and productivity*. Netherlands pp 153 – 59.

Adegbehin, J. O. (1985). Growth Prediction in Some Plantation of Exotic Tree Species in the Northern Guinea and Derived Savanna Zones of Nigeria. Unpublished Ph. D Thesis, Dept. of Forest Resources Management, University of Ibadan. 328p.

Akindele, S. O. and Abayomi, J. O. (1993). Stem Diameter Distribution in a Permanent Sample Plot of *Nauclea diderrichii* in South-western Nigeria. In: Proceedings, IUFRO. Conference. Held in Copenhagen, 14 – 17 June, 1993. 118 – 193pp.

Avery, T. E. and Burkhart, H. E. (2002). *Forest Measurements*. McGraw-Hill Book Company, New York. 337pp.

Buongiorno, J and J.K. Gilless (1987). Forest Management and Economics. Macmillan Publishing Company, New York 285p.

Chijioke, E.O. (1988). Soil Factors and growth of *Gmelina arborea* in Omo forest reserve. *Forest Ecology and Management*, Volume 23: 245 – 251.

Clutter, J. L., J. C. Fortson, L. V. Pienaar, G. H. Brister and R. L. Bailey (1983). Timber Management: A Quantitative Approach. John Wiley and Sons, New York. 333pp.

Duke, J.A., (1983). *Gmelina arborea* Roxb. Handbook of Energy Crops. Centre for New Crops and Plant Products, Purdue University, USA.

Evans, J. (1992). The suitability of wood production in plantation forestry. *Unasylva* 192 (49), 47–52.

FAO (2010). Global Forest Resources Assessment (2005 & 2010) and the State of the World's Forests.

FAO (2011). State of the World's Forests 2011. 15BN 978-92-5-106750-5. Published by the food and Agriculture Organization of the United Nations, Rome.

FRA (2010). Global Forest Resources Assessment 2010. Main report FAO Forestry Paper163.

FRA (2021). Global Forest Resources Assessment 2021. Nigeria report FAO Forestry Paper206.

FORMECU (1999). Forest Resources Study, Nigeria: Revised National Report Volume 1. Federal Department of Forestry. Abuja, Nigeria. 108p.

Husch, B., I. M. Charles and W. B. Thomas (2003). *Forest Mensuration*. The Ronald Press Company, New York, U. S. A. pp 120-123.

Ige, P.O. (2017). Inter-tree competition models using *Gmelina arborea* Roxb. Stands in Omo Forest Reserve, Ogun State, Nigeria. Ph.D Thesis, Department of Forest Resources Management, University of Ibadan, Nigeria. 179p.

Johnsen, K., Samuelson, L., Teskey, R., McNulty, S and Fox, T. (2001). Process-based models as tools in forestry research and management. *Forest Science* 47, 2-7.

Jonsson, B., J. Jacobsson and H. Kallur (1993). The forest Management Planning Package. Theory and application. *Studia Forestalia Suecica* 189. 56p

Lamb, R. (1968): Forests, fuel and the future. Forestry Topics Reports No 5. FAO Forestry.

Lappi, J. (1992). JLP: a linear programming package for management planning. *Research Paper* 414. The Finish Forest Research Instiitute. 134p

Leuschner, W.A. (1990). Forest Regulation, Harvesting Scheduling and Planning Techniques. Wiley, New York. 281p.

Manoel, de Freitas (1995). Planted Forests in Brazil. *In:* E. Korpilahti, H. Mikkela and T. salonen (Editors), *Caring for the Forest: Research in a changing world.* Congress Report, Volume II, IUFRO XX World Congress, 6 – 12th August 1995, Tampere, Finland. 147 – 154.

Millie Pant, Radha Thangaraj, Deepti Rani, Ajith Abraham, Dinesh Kumar Srivastava (2010). Estimation of optimal crop plan using nature inspired metaheuristics. *World Journal of Modelling and Simulation.* Vol. 6 (2010) No. 2, pp. 97-109

Onyekwelu, J.C., (2003). Choosing appropriate index age for estimating site index of *Gmelina arborea* timber plantations in Oluwa forest reserve, Nigeria. *Journal of Food, Agric. & Environment*, 1(3&4): 286 – 290.

Onyekwelu, J.C. (1995). Growth and yield studies for *Gmelina arborea* (Roxb.) plantations in Oluwa Forest Reserve, Nigeria. Unpublished M. Tech. Thesis, Department of Forestry and Wood Technology, Federal University of Technology, Akure, Nigeria. 105p.

Onyekwelu, J.C., (2001). Growth characteristics and management scenarios for plantation-grown *Gmelina arborea* and *Nauclea diderrichii* in southwestern Nigeria. Hieronymus Verlag, Munich, 196 pp.

Onyekwelu J.C, Mosandl R and Stimm B (2006). Productivity, site evaluation and state of nutrition of *Gmelina arborea* plantations in Oluwa and Omo forest reserves, Nigeria. *Forest Ecol Manag* 229:214–227

R Development Core Team (2012). R: A language and environment for statistical computing, R Foundation for Statistical Computing, Vienna, 2500p.

Schneider, K. (1997). Waldbau mit *Gmelina arborea* im Regenwaldgebiet Ghanas. AFZ/DerWald 4: 185-188.

Schumacher, F.X. (1939). A new growth curve and its application to timber yield studies. *Journal of forestry*.37: 819 – 820.

Vanclay J. K. (1994). Modelling forest Growth and Yield. Applications to mixed Tropical forests. CAB, International publisher, Wallingford UK. ISBN0851989, 136 – 312pp.

Yuchang, S., K. Yantong, K. Yunchuan, Y. Hanming, Y.C. Su, Y.T. Kuo, Y.C. Ku and H.M Yo, (1995). Studies on the fast-growing wood species *Gmelina arborea*. Part II. Relationships between wood characteristics and pulping potentials. Quarterly Journal of Chinese Forestry 28(2): 69 – 86.

Table 2: Summary of whole stand growth variables

Age (yrs)	**No of stem/ha**	**Mean dbh (cm)**	**Mean Stem height (m)**	**Mean BA (m^2/ha)**	**Mean SVol (m^3/ha)**	**Mean MVol (m^3/ha)**	**Δdbh (cm/ yr)**	**ΔBA (m^2/ ha/yr)**	**ΔSVol (m^3/ ha/yr)**	**ΔSQ (m/ ha/yr)**	**SI (m)**
34	1000	70.61	24.10	413.78	8413.52	6375.21	2.08	12.17	247.46	174.17	28.70
32	925	67.36	24.98	335.81	6200.62	4403.12	2.11	10.49	193.77	187.72	28.39
30	1000	64.51	22.73	333.29	6802.33	5030.71	2.15	11.11	226.74	219.94	20.38
26	975	61.51	21.57	263.38	4623.86	3224.52	2.37	10.13	177.84	241.87	27.23
24	975	58.46	21.52	296.05	5199.51	3622.05	2.44	12.34	216.65	267.08	26.72
22	950	41.64	22.06	138.19	1793.46	1791.86	1.89	6.28	81.52	268.68	26.14
20	975	22.71	17.72	41.21	549.87	349.08	1.14	2.06	27.49	322.18	20.00
18	875	22.88	16.60	33.31	423.19	297.14	1.27	1.85	23.51	235.47	11.62
16	900	21.50	16.08	38.40	535.64	387.22	1.34	2.40	33.48	256.41	13.95

BA = Basal area, dbh = Diameter at breast height, SVol = Stem volume, MVol = Merchantable volume, SI = Site index, ΔSQ = Stem quality growth, ΔBA = Basal area growth, Δdbh = diameter growth and ΔSVol = Stem volume growth.

Table 3: Summary of individual tree growth variables

Age (yrs)	**No of stem/plot**	**Mean dbh cm)**	**Mean Stem height (m)**	**Mean BA(m^2)**	**Mean SVol (m^3)**	**Mean MVol (m^3)**	**Δdbh (cm/yr)**	**ΔBA (m^2/yr)**	**ΔSVol (m^3/yr)**	**SQ (m)**	**ΔSQ (m/yr)**	**SI (m)**
34	40	70.61	24.10	0.42	8.50	6.41	2.08	0.012	0.250	18.09	0.532	28.70
32	37	67.36	24.98	0.36	6.76	4.80	2.11	0.011	0.211	16.19	0.506	28.39
30	40	64.51	22.73	0.34	6.84	5.06	2.15	0.011	0.228	18.36	0.612	20.38
26	39	61.51	21.57	0.27	4.79	3.34	2.37	0.010	0.184	15.00	0.577	27.23
24	39	58.46	21.52	0.30	5.33	3.72	2.44	0.013	0.222	15.00	0.625	26.72
22	35	41.64	22.06	0.15	1.90	1.90	1.89	0.007	0.086	15.80	0.718	26.14
20	39	22.71	17.72	0.04	0.56	0.36	1.14	0.002	0.028	11.12	0.556	20.00
18	35	22.88	16.60	0.04	0.48	0.34	1.27	0.002	0.027	11.29	0.627	11.62
16	36	21.50	16.08	0.04	0.60	0.44	1.34	0.003	0.038	11.98	0.749	13.95

BA = Basal area, dbh = Diameter at breast height, SVol = Stem volume, MVol = Merchantable volume, SI = Site index, SQ = Stem quality, ΔSQ = Stem quality growth, ΔBA = Basal area growth, Δdbh = diameter growth and ΔSVol = Stem volume growth.

Table 4: Correlation matrix for the whole stand growth variables

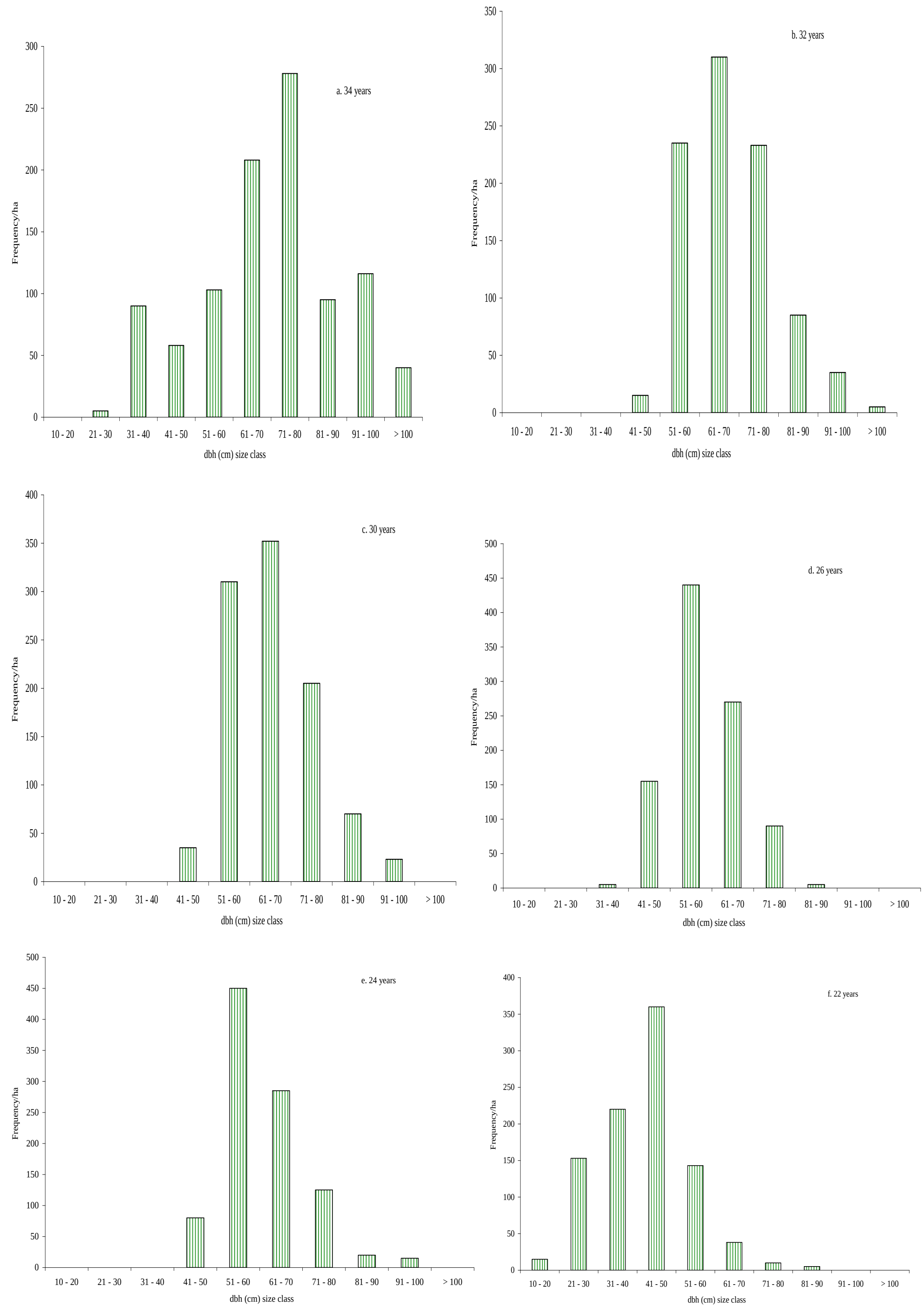
	Age	**No/ha**	**dbh**	**Stem height**	**BA**	**SV**	**Mvol**	**ΔSQ**	**SI**	**ΔBA**	**ΔSV**
Age	1										
No/ha	0.620	1									
dbh	0.935	0.634	1								
Stem height	0.927	0.584	0.937	1							
BA	0.948	0.653	0.986	0.912	1						
Svol	0.954*	0.656*	0.964*	0.876*	0.993*	1					
Mvol	0.958	0.667*	0.959	0.891	0.989	0.996	1				
ΔSQ	-0.747*	-0.046	-0.684*	-0.627	-0.712*	0.740*	-0.746*	1			
SI	0.746*	0.646	0.813	0.878	0.774*	0.709*	0.718*	-0.323	1		
ΔBA	0.856	0.669*	0.974	0.883	0.970	0.941*	0.933	-0.583	0.803	1	
ΔTVol	0.895	0.683*	0.974	0.863	0.987	0.978	0.968	-0.643	0.739*	0.987	1

*Significantly different at 5% probability level.

Table 5: Correlation matrix for individual tree growth variables

	Age	**No/plot**	**dbh**	**Stem height**	**BA**	**Svol**	**Mvol**	**Δdbh**	**ΔBA**	**ΔSVol**	**SQ**	**ΔSQ**	**SI**
Age	1												
No/plot	0.521	1											
dbh	0.932	0.561	1										
Stem height	0.931	0.509	0.926	1									
BA	0.938	0.542	0.992	0.916	1								
Svol	0.943*	0.540*	0.975*	0.878*	0.992	1							
Mvol	0.948	0.553	0.979	0.908	0.993	0.994*	1						
Δdbh	0.744	0.557	0.934	0.820	0.909	0.867	0.874	1					
ΔBA	0.820	0.577	0.959	0.866	0.962	0.935*	0.939	0.972	1				
ΔSVol	0.881	0.586	0.975	0.852	0.986	0.982	0.976	0.932	0.978	1			
SQ	0.848	0.575	0.887	0.889	0.884	0.868*	0.914	0.817	0.852	0.855	1		
ΔSQ	-0.648	-0.290	-0.476	-0.462	-0.482	-0.509	-0.458	-0.246	-0.324	-0.430	-0.166	1	
SI	0.704	0.587	0.782	0.859	0.742	0.671	0.688	0.792	0.783	0.707	0.641	-0.414	1

*Significantly different at 5% probability level.


a. 34 years
b. 32 years
c. 30 years
d. 26 years
e. 24 years
f. 22 years
Frequency/ha
dbh (cm) size class
10 - 20
21 - 30
31 - 40
41 - 50
51 - 60
61 - 70
71 - 80
81 - 90
91 - 100
> 100

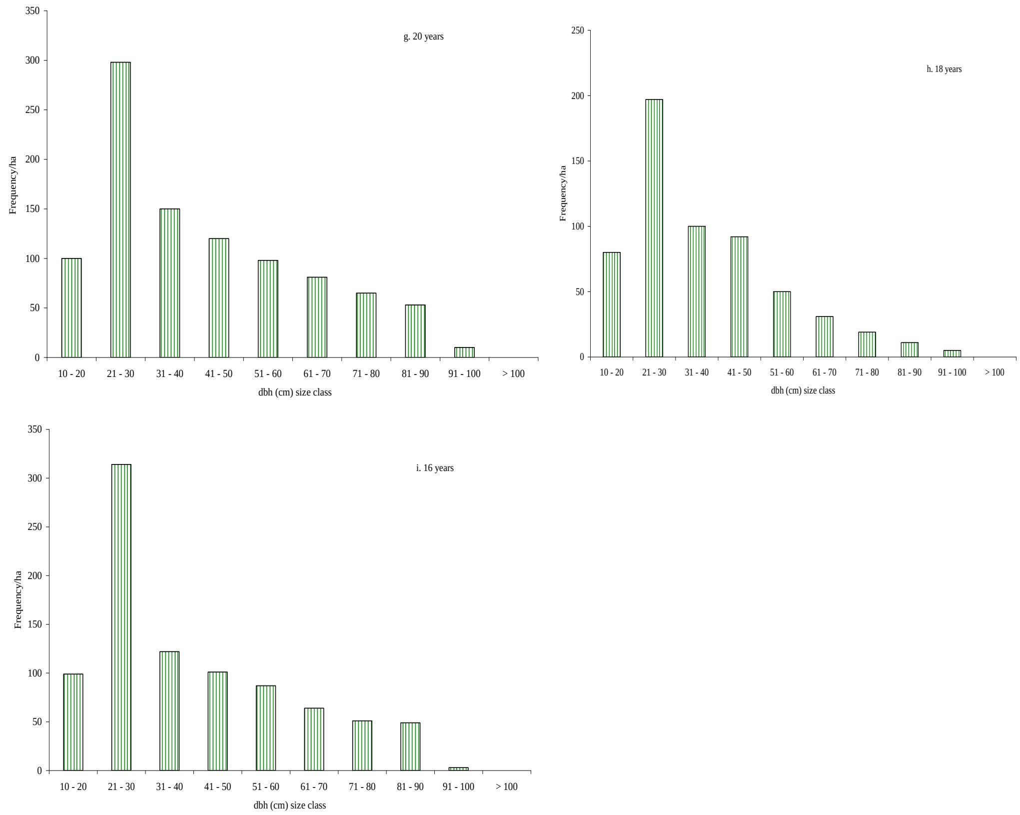


Fig 2: Diameter size class distribution of *G. arborea* in the study area

Table 6: Logging Plan that Optimizes volume: Stock and area to be cut

Stand		**Area cut (ha) per period**				
		1st Period	**2nd Period**	**3rd Period**	**4th Period**	**Total Hectares cut**
34	Stock	1600.00	0	0	0	
	Cut	1600.00	0	0	0	1600.00
32	Stock	1230.00	0	0	0	
	Cut	1230.00	0	0	0	1230.00
30	Stock	1000.00	0	0	0	
	Cut	1000.00	0	0	0	1000.00
26	Stock	330.00	25.00	0	0	
	Cut	305.00	25.00	0	0	330.00
24	Stock	78.70	78.70	72.90	51.30	
	Cut	0	5.80	21.60	51.30	78.70
22	Stock	1360.00	908.30	390.80	140.00	
	Cut	451.70	517.50	250.8	140.00	1360.00
20	Stock	33.00	30.65	28.30	22.50	
	Cut	0	2.35	5.80	18.92	27.07
18	Stock	103.00	103.00	100.50	50.50	
	Cut	0	2.50	50.00	33.70	86.20
16	Stock	5.00	5.00	5.00	5.00	
	Cut	0	0	0	5.00	5.00
Total Area Cut		4586.70	553.15	328.20	248.92	5716.97

Table 7: Logging Plan that Optimizes volume: Volume data

	Volume cut (m^3) Per Period				
Stand	**1st Period**	**2nd Period**	**3rd Period**	**4th Period**	**Total Volume (m^3)**
34	15,441,504.00	0	0	0	15,441,504.00
32	8,818,472.70	0	0	0	8,818,472.70
30	7,935,900.00	0	0	0	7,935,900.00
26	1,681,477.20	160,056.00	0	0	1,841,533.20
24	0	42,723.38	182,505.96	489,022.38	714,251.72
22	994,209.77	1,349,971.20	756,473.00	479,337.60	3,579,991.57
20	0	1,938.05	5,580.47	20,804.44	28,322.96
18	0	1,645.70	38,791.50	30,106.91	70,544.11
16	0	0	0	6,026.40	6,026.40
Total	**34,871,563.67**	**1,556,334.33**	**983,350.93**	**1,025,297.73**	**38,436,546.66**

Table 8: Logging Plan that Optimizes volume: Equivalent Number of Stems to be cut

	Number of Stems Cut Per Period				
Stand	**1st Period**	**2nd Period**	**3rd Period**	**4th Period**	**Total Stems**
34	1,600,000	0	0	0	1,600,000
32	1,137,750	0	0	0	1,137,750
30	1,000,000	0	0	0	1,000,000
26	297,375	24,375	0	0	321,750
24	0	5,655	21,060	50,018	76,733
22	429,115	491,625	238,260	133,000	1,292,040
20	0	2,291	5,655	18,447	26,393
18	0	2,188	43,750	29,488	75,426
16	0	0	0	4,500	4,500
Total	**4,464,240**	**526,134**	**308,725**	**235,453**	**5,534,552**

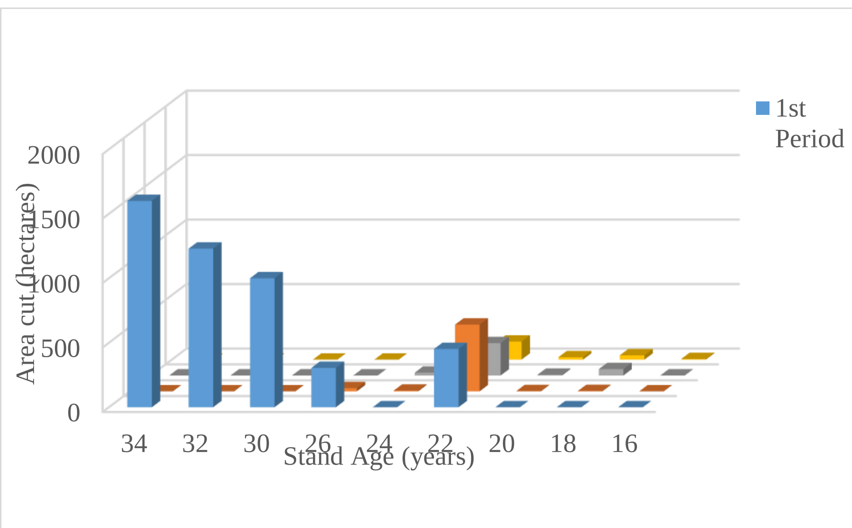


Fig 3: Optimal management plan (volume optimization) for *Gmelina* stands