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Thinning scenarios for *Gmelina arborea* plantations in south-western Nigeria using density management diagrams

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Abstract
Thinning scenarios were developed for *Gmelina arborea* plantations in south-western Nigeria using density management diagram. Data were collected from even-aged plantations of 5 to 25 years. The youngest stand had well-developed crown canopies, indicating that canopy closure occurred at a younger age. Density (number of trees ha^{-1}) decreased with increase in tree size. Density management diagram, with upper and lower growing stock lines, was developed. With references to these lines, three thinning scenarios *A (no-thinning), B (moderate thinning)* and *C (heavy thinning)* were developed. At the end of 20 years rotation, volume production under *scenarios A, B* and *C* would be 1050.3, 784.2 and 751.7 m^3ha^{-1}, respectively while mean diameter would be 29.8, 49.6 and 47.0 cm, respectively. This result indicates that *Gmelina* would react strongly to thinning by way of diameter increase, which only applies if thinning commences at early ages. Net present value (NPV) at interest rates between 5 and 8% revealed *scenarios B* and *C* to be similar but superior to *scenario A*. Only scenarios B and C are judged for appropriate for timber production.

Key words: *Gmelina arborea*, plantation, density management diagram, scenario, thinning, density, net present value.

Introduction
A density management diagram is a stocking chart based on natural development of stands and on the fact that trees die in the process of self-thinning when stands near the maximum density for given tree sizes [3, 17]. It shows the changes in density (number of trees ha^{-1}) as average tree size increases. The higher the average tree size, the lower the density. After establishment, trees in a stand grow to the extent that site resources can support. Growth beyond this point is only possible if resources are released through mortality in the process of self-thinning. Increased average tree size and the associated reduction in the density during this phase form boundary relationship that closely approximates a straight and negatively sloped line when the data are plotted on logarithmically scaled axes [3]. This boundary forms the upper or self-thinning line of the density management diagram and shows the highest possible combination of average trees size and density. Another important line in the diagram is the lower growing-stock line. It represents adequate site occupancy of a species at which competition between individual trees is reduced to minimum. Below this line, the production capacity of the site will be underutilised. Between the upper and the lower lines, some authors (e.g. [10, 21]) added a third line: the line of imminent competition mortality. Density management diagrams have been used in developing thinning programmes for species like *Pseudotsuga menziesii*, *Pinus taeda*, *Pinus elliottii* and*Tectona grandis* [3, 25]. No known density-management diagram exists for *Gmelina arborea*. *Gmelina arborea* has been highly favoured in plantations due to its adaptability to a wide range of soil and climatic conditions, vigorous growth rate, good pulping characteristics and short rotation length [7, 16]. By 1996, the area of *Gmelina* plantations in Nigeria was 112,000 ha [15], a high percentage of which exists in the south-west. The bulk of *Gmelina* plantations in this region were established to provide pulpwood at rotation of 8 – 12 years, thus thinnings were not intended. Unfortunately, a high percentage (70%) of the plantations have exceeded 12 years, mainly due to the inability of Iwopin paper mill to function. Consequently, *Gmelina* resources that are no longer suitable for pulpwood abound. Timber appears to be the only economically appealing alternative management objective for the stands, in which case thinning is necessary. Our objective is therefore to develop thinning scenarios for *Gmelina arborea* plantations in south-western Nigeria, using density management diagram.

Materials and Methods
This study was carried out in unthinned even-aged plantations of *Gmelina* in Oluwa forest reserve in the humid tropical rainforest zone of south-western Nigeria. Oluwa is situated between latitude 6° 55' and 7° 20'N and longitude 3° 45' and 4° 32'E. Large-scale planting of *Gmelina* in Oluwa commenced in the early 1970s. Today, a total of 20,716 ha of *Gmelina* plantations, which account for 89% of the total plantations in the reserve, have been established. The plantations were planted at the spacing of 2.5 m x 3 m to supply pulpwood to Iwopin paper mill. Rainy season last March to November while dry season is from December to February. Annual rainfall is between 1,700 and 2,200 mm. Annual mean temperature, relative humidity and Mean elevation are 26°C, 84% and 100 m, respectively. Soils were formed from sedimentary rocks of the undifferentiated basement complex of the pre-cambrian rock series. Majority of the soils are representative of soils in the Ondo Association, which comprises of well drained, mature, red, stony and gravely soils in the upper sequence, grading into the hill wash overlying original parent material in the valley bottom [24]. The texture of the topsoil is sandy loam and subsoil consists of clay with gravel in some areas. Data were collected from twelve plantations ranging from 5 to 25 years. Each chosen stand (age) was divided into blocks of one-hectare equivalent from which three blocks were randomly selected. A 25 m x 25 m temporary sample plot was laid at the centre of each block, resulting to a total of 36

sample plots (12 ages x 3 sample plots within each age). Within each plot, the number of trees was recorded and measurements of various growth parameters were made on all trees.

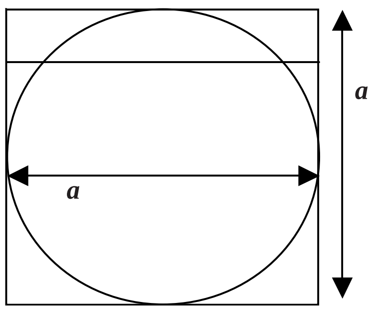
Development of density management diagram and thinning scenarios: In developing the thinning scenarios, the basic silvicultural questions considered were:

1. What is the viable management objective(s) for the species?
2. What is the optimum rotation age?
3. Is thinning desirable? If yes, when should it commence and end?
4. What kind of thinning should be done and what should be its intensity?

Decision on management objective was based on information on growth characteristics of the species and the market survey conducted by [15]. Rotation age was based on the culmination age of mean annual increment (MAI) as practised in plantations [5]. However, where MAI at culmination is approximately equal with that at a higher age and if by allowing the trees to grow to the latter age, better timber candidate trees will be obtained, the higher age was chosen as the rotation age. The ages at which thinning should commence and end were guided by the age of canopy closure and culmination of MAI respectively [26].

In simulating the thinning scenarios, it was necessary to establish the upper and lower growing-stock lines. The relationship between density in unthinned stand and the quadratic mean diameter (QMD) [19, 20], was used to define the upper growing-stock line. Since the growth of dominant trees is presumably not affected by competition, they were used in determining the lower line. It became necessary to determine the density of dominant trees ha^{-1} that will fully occupy the site. To accomplish this, it was assumed that the basal area of a tree is proportional to the area occupied by its crown [1]. The procedures used are:

1. The ratio of the basal area of the dominant trees ha^{-1} to that of the stand was obtained. This indicates the proportion occupied by dominant trees in the unthinned stand.



**The figure 7854 was obtained from the following consideration: Assuming each dominant tree occupies the area represented by a the circle within the space represented by square block in a stand. The area effectively occupied by the trees will be given by*:

$$\frac{a^2 * \frac{\pi}{4}(area\ of\ a\ circle)}{a^2(area\ of\ a\ square)} = \frac{\pi}{4} \approx 0.7854$$

2. The area occupied by the dominant trees ha^{-1} was obtained by multiplying the result from (1) by 10,000 m^2.
3. To obtain the mean area occupied by a dominant tree, the result in (2) was by divided by 100.
4. Dividing 7854* by the result in (3), the number of dominant trees ha^{-1} that will fully occupy each stand was obtained.

The three thinning scenarios (options) considered are *A (No thinning); B (Heavy thinning) and C (Moderate thinning). Scenario A* corresponded to the self-thinning line and involved no-thinning operation from establishment to clear felling. *Scenario B* maintained density close to the lower production line and aimed at maintaining a no-competition status from first to last thinning operation. *Scenario C* began by maintaining density close to the upper line and ended with density close to lower line. For scenario C, diameter limit was used to define when to thin.

Since no information on volume and basal area removed by either mortality or thinning between two time intervals was available, the *k* value-concept suggested[13] was used for this purpose. [13] maintains that with information like density, volume, basal area, mean dbh, it is possible to calculate (eqn. 1) total volume production between two points in time.

$$G_t = V_a + \sum_a^t \Delta V_a + \sum_a^t \Delta N_s * v_{m(\frac{s}{2})} * k$$

(eqn.1)

where: G_t = total volume production at age t; V_a = initial volume production; ΔV_s = difference in production in period s; ΔN_s = difference in number of stems in period s; $v_{m(s/2)}$ = volume of mean tree in the middle of the period (s/2); k = correction factor which ranges from 0.4 to 0.8. Lower values are for very low or no-thinning while high values are for very heavy thinning operations.

Based on the recommendation of [13], *k* value of 0.4 was used in estimating the volume removed by mortality in *scenario A*. For the first thinning recommendation in *scenario B*, *k* value of 0.8 was used, while *k* value of 0.5 was used for subsequent thinning recommendations under this scenario. For *scenario C*, *k* value of 0.5 was used for all thinning recommendations.

Bearing in mind that *k* in eqn. 1 defines the ratio of the volume of mean tree to be removed to that of mean tree after thinning, which is approximately the same for basal area (eqn. 2), volume of mean trees to be removed by thinning were estimated from eqn. 1.

$$k = \frac{v_r}{v_a} \approx \frac{g_r}{g_a}; \quad thus, \quad g_a = \frac{g_r}{k} \quad \text{(eqn. 2)}$$

Where v_r = volume of mean tree removed by thinning; v_a = volume of mean tree after thinning; g_r = basal area of mean tree removed by thinning; g_a = basal area of mean tree after thinning

Basal area of mean tree before thinning is given by:

$$g_t = \frac{N_r * g_r + N_a * g_a}{N_r + N_a} \quad \text{(eqn. 3)}$$

where: N_r and N_a = number of trees removed and number of trees after thinning, respectively. g_t = basal area of mean tree before thinning

By substituting g_a in eqn. 3 by eqn 2 and by solving for g_r, basal area of mean tree to be removed is:

$$g_t = \frac{N_r * g_r + N_a * \frac{g_r}{k}}{N_r + N_a}; \quad g_r = \frac{g_t(N_r + N_a)}{N_r + \frac{N_a}{k}} \quad \text{(eqn. 4)}$$

The total basal area to be removed by thinning was obtained by multiply the result of eqn. 4 by number of trees to be removed, while the total basal area after thinning was obtained by subtracting the basal area removed by thinning from the basal area before thinning.

Income at the end of rotation was estimated for each scenario using information from market survey conducted by Onyekwelu[15] as well as information from Formecu[6]. Net present value (NPV) was calculated using the method stipulated by Clutter et al.,[2]. The African Development Bank (ADB) average interest rate of 7% was used in NPV estimation. Interest rates below and above 7% were also used.

Results

Summary of the growth data for unthinned *Gmelina* plantations is presented in Table 1. It reveals that *Gmelina* has an impressive growth rate, even in unthinned stands. Mean annual volume increment (MAI) ranged from 40 to 51.7 m^3 ha^{-1} $year^{-1}$ (Fig. 1). It culminated at the age of 17.5 years but between 15 and 20 years, MAI was almost equal (Fig. 1). However, Table 1 reveals that mean dbh at 20 years was higher than that at 15 years. Consequently, 20 years was chosen as the rotation age for timber production. The upper and lower growing-stock lines are presented in Figure 2. Figure 2 reveals a steady decrease in density as QMD increased. *Scenario A* (no-thinning) is characterised by high density and high volume (Tab. 2). At the end of 20 years rotation, product distributions under *Scenario A* are expected to be 10, 43 and 47% fuelwood, poles and timber respectively. About 51% of products categorised as timber would be between 30 and 40 cm in dbh. About 400 trees (31% of trees ha^{-1}) would be lost to mortality, most of which would die between 10 and 20 years. At the end of rotation, *scenario A* will yield a slightly higher income than *scenarios B* and *C*. However, at the various interest rates considered, *scenario A* gave the lowest net present value (NPV) (Tab. 3).

Scenario B maintains density close to the lower line from first thinning to final harvest (Fig. 2a). Contrary to this, thinning under *scenario C* moved gradually from the upper to the lower line (Fig. 2b). Under the two scenarios, thinning from above is used to remove undesirable trees in dominant canopy (e.g. forked trees, bent trees etc.), while thinning from below removes trees in the suppressed crown class. Thinning chart for S*cenarios B* and *C* are presented in Table 2. Under Scenario B, first, second and third thinning operations at 5, 10 and 15 years, respectively are to be administered at the respective mean dbh of 15.9, 30.0 and 39.2 cm (Table. 2; Figs 2a and b). For Scenario C, first, second and third thinning should be done at mean dbh of 15.9, 24.0 and 34.0 cm, respectively at the respective ages of 5, 11 and 16 years (Table. 2; Figs 2a and b). Under *scenarios B* and *C*, product from the first and second thinning would be fuelwood and pulpwood and/or poles respectively. Products from third thinning are expected to be predominantly poles and pulpwood, but some timber-sized trees are expected. After the third thinning operation, an impressive mean dbh of about 41 and 40 cm would be obtained under *scenarios B* and *C* respectively (Table. 2). S*cenario B* would yield its highest thinning income from the first thinning, while the highest thinning income under *scenario C* will be obtained from the third thinning (Table. 3). At the end of rotation, basal area of 54.1 and 52.1m^2 ha^{-1} would be harvested under *scenarios B* and *C* respectively (Tab. 2). Although *scenario A* yielded higher basal area and volume than *scenarios B* and *C* at the end of rotation, mean dbh of *scenarios B* and *C* were appreciably higher (Table. 2). *Scenario C* would provide higher thinning income than *B*. Total income and NPV at various interest rates of *scenarios B* and *C* would be comparable (Table. 3).

Discussion

Although real time series data were not available for this study as the plantations have not been thinned, our results are plausible when compared with that of thinning trials with the species in some tropical countries [4, 14]. However, it is necessary to test the practicality of our results by conducting thinning experiments with *Gmelina*.

Timber production appears to be the feasible alternative management objective for the existing *Gmelina* plantations in the study area. The over 70% of plantations older than 12 years are no longer suitable for pulp production due to lower pulp yield, higher lignin content and shorter fibre length of old *Gmelina* trees [27]. In addition, there is no indication that the mill meant to utilise the *Gmelina* resources will function in the nearest future and market for *Gmelina* timber is emerging in Nigeria [15]. The approximately equal MAI between 15 and 20 years implies that rotation age for timber can lie between this range. In some African countries (Nigeria, Ghana, Sierra Leone), between 15 and 23 years rotation have been used timber in *Gmelina* timber stands [12, 22, 8]. However, 15 years does not seem appropriate because trees that will be produced at this age will be small-dimension trees. To produce large-dimension trees after 20 years, thinning is inevitable.

Table 1. Summary of growth data for unthinned *Gmelina arborea* plantations.

Age	Density	Dbh (cm)			Mean height	BA	Vol
(years)	(N ha^{-1})	Min.	Mean	Max.	(m)	(m^3ha^{-1})	(m^3ha^{-1})
5	1232	5.0	15.1	31.4	14.1	24.3	242.7
6	1291	3.8	15.6	33.0	16.4	28.4	370.3
8	1259	4.3	16.4	34.7	15.8	30.8	350.7
10	1147	5.0	18.0	37.5	17.0	33.8	418.0
13	1189	3.8	18.8	41.4	18.0	39.8	559.0
15	1184	6.0	21.1	53.0	18.0	48.3	630.7
16	1024	4.7	23.3	47.7	17.8	51.9	741.3
17	992	4.5	25.5	62.3	20.6	60.7	943.0
19	837	9.8	28.7	57.0	21.4	61.0	935.3
21	864	7.1	30.2	61.3	22.9	71.5	1165.0
23	891	8.9	31.6	63.6	22.7	79.1	1176.3
25	874	7.0	33.6	71.2	23.2	89.5	1519.3

Table 2. Thinning scenarios for *Gmelina arborea* plantations.

Silvicultural operations	Mean crop in unthinned stands/Before thinning						Yield from thinning/Mortality				Mean crop in unthinned stands/ after thinning				
	Age Years	N (ha^{-1})	D_g (cm)	H_t (m)	G (m^2 ha^{-1})	V (m^3 ha^{-1})	N (ha^{-1})	G (m^2 ha^{-1})	V (m^3 ha^{-1})	V_{ea} (m^3 ha^{-1})	N (ha^{-1})	D_g (cm)	H_t (m)	G (m^2 ha^{-1})	V (m^3 ha^{-1})
SCENARIO A:	*No Thinning*														
	5	1300	15.9	14.6	25.7	252.6	-	-	-	-	1300	15.9	14.6	25.7	252.6
	10	1200	19.4	16.8	36.5	418.2	100	1.0	10.9	10.9	1200	19.4	16.8	36.5	418.2
	15	1050	23.0	19.1	52.5	630.6	150	2.4	28.5	39.4	1050	23.0	19.1	52.5	630.6
Final harvest	20	900	31.3	21.3	69.1	1050.3	100	2.5	34.1	73.5	900	29.8	21.3	62.8	1050.3
SCENARIO B:	*Heavy Thinning*														
1st thinning	5	1300	15.9	14.6	25.7	252.6	900	6.2	54.4	53.4	400	24.9	20.9	19.5	199.2
2nd thinning	10	400	30.0	22.9	28.3	394.4	70	2.2	28.4	82.8	330	31.7	23.2	26.1	366.0
3rd thinning	15	300	39.2	25.5	39.9	583.2	50	2.7	38.2	121.0	280	41.1	25.7	37.2	545.0
Final harvest	20	280	49.6	27.5	54.1	784.2	0.0	0.0	0.0	121.0	280	49.6	27.5	54.1	784.2
SCENARIO C:	*Moderate Thinning*														
1st thinning	5	1300	15.9	14.6	25.7	252.6	400	4.6	38.1	38.1	900	17.3	17.4	21.1	214.5
2nd thinning	11	600	24.0	20.6	40.7	445.6	300	8.1	45.4	83.5	600	26.5	21.5	32.6	400.2
3rd thinning	16	600	34.0	23.9	54.5	678.3	300	15.7	114.6	198.1	300	39.9	25.3	37.8	563.7

Where N = Number of trees; D_g = Mean diameter; H_t = mean height; G = stand basal area,
V = stand volume ; V_{ea} = Volume removed by successive thinning operations

Table 3. Expected products and income from the different thinning scenarios for *Gmelina arborea* plantations.

Scenarios	Operations	Age of Operation (years)	Name of Product	product Yield m^3 ha^{-1}	income (N ha^{-1})	Net present value (NPV) Interest rate (5%)	Interest rate (6%)	interest rate (7%)	interest rate (8%)
A (No-thinning)	Final Harvest	20	1. FW	104.0	673	254	210	174	144
		20	2. PW/PL	453.7	223.144	84.101	69.577	57.665	47.875
		20	3. TB	492.6	283.772	106.951	88.481	73.332	60.883
	Total			**1050.3**	**507.589**	**191.305**	**158.269**	**131.171**	**108.902**
B (Heavy thinning)	1st thinning	5	FW	54.4	16.156	12.659	12.073	11.519	10.996
	2nd thinning	10	PW/PL	28.4	13.447	8.255	7.509	6.836	6.229
	3rd thinning	15	PW/PL	38.2	15.128	7.277	6.312	5.483	4.769
	Final Harvest	20	TB	784.2	457.592	172.462	142.679	118.250	98.176
	Total			**905.2**	**502.323**	**200.652**	**168.573**	**142.088**	**120.169**
C (Moderate thinning)	1st thinning	5	FW	38.1	5.705	4.470	4.263	4.068	3.883
	2nd thinning	11	PW/PL	45.4	26.984	157.77	14.215	12.820	11.573
	3rd thinning	16	FW/PL	114.6	48.275	221.15	19.003	16.352	14.091
	Final Harvest	20	TB	751.7	420.788	158.591	131.204	108.740	90.279
	Total			**949.8**	**501.752**	**200.953**	**168.685**	**141.980**	**119.826**

Where: FW = Fuelwood; PW/PL = Pulpwood/poles; TB = Timber.

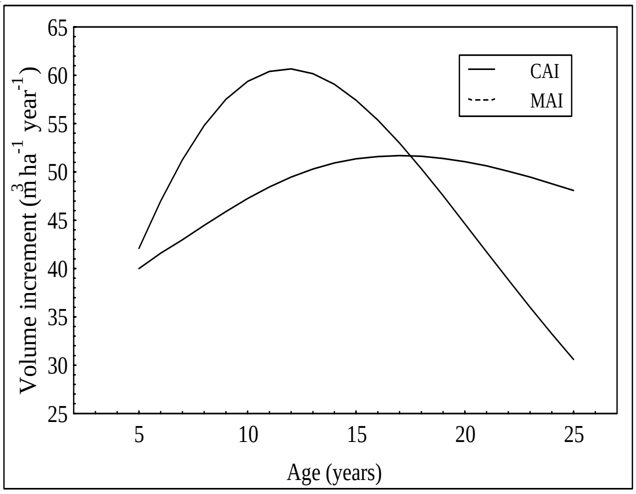


Figure 1. Current (CAI) and mean annual volume increment (MAI) for *Gmelina* plantations.

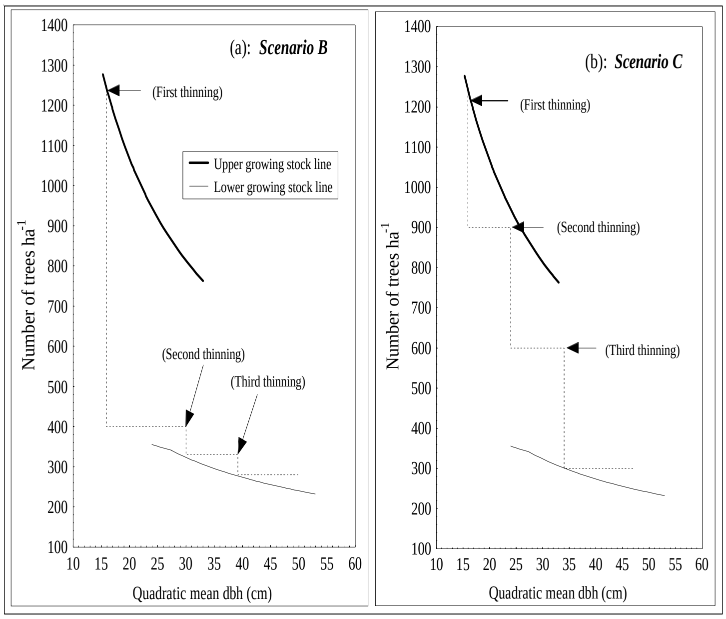


Figure 2. Schematic presentation of thinning *scenarios B and C* for *Gmelina* plantations.

Timing of thinning operations, especially the age at which it commences, is a very important management and silvicultural decision. Making an early start will affect stem quality and crown development and trees respond too slowly when stands are thinned late [1, 3]. Thinning operations are usually administered between canopy closure and culmination of MAI [26]. In this study, 5 years was chosen as the time of first thinning because stands would have closed canopy between 3 and 4 years and crown dominant classes would have been distinct. First thinning in *Gmelina* plantations between ages 3 and 5 years are practiced in some tropical countries [4, 8, 14]. However, first thinning at 3 years seems too early as this might slow down self-pruning.

Thinning operations using density management diagrams are restricted between the upper and lower growing-stock lines [3, 25]. The upper line represents the maximum production capacity of *Gmelina*, given the initial stocking of 1333 trees ha^{-1} while the lower line represents the stand development line below which the site will be under-utilised. Thus, thinning below the lower line should be avoided. Depending on the objective of management and thinning intensity, thinning can be conducted such that the stand development continues (a) very close to the upper line, (b) very close to the lower line or (c) moves gradually from the upper to the lower line. Although, some authors [21] prefer option (c), the forest manager is free to decide how to thin between the two lines. *Scenario A* is appropriate for fuelwood, pulpwood, or pole production but to be economically viable, rotation age must be considerably lower than 20 years. S*cenario A* will not be appropriate for timber production because a high percentage (47%) of trees will be small-sized at the end of rotation. Processing logs from *scenario A* will result in high wastage due to low log recovery rate [15]. The lower NPV of *scenario A* when compared to those of *sce-*

narios B and C (Table. 3) implies that *scenarios B and C* are more financially viable than *scenario A.*

Early and heavy stem removal is being practiced in *Gmelina* stands. Up to 57% stem removal during first thinning is practised in Costa Rica [14]. Depending on site quality, [4] prescribed between 55 and 64% stem removal. Heavy stem removal is also practiced in *Gmelina* stands in Sierra Leone [12]. However, there is empirical evidence that heavy stem thinning at an early age might result in stand instability [9]. Also, heavy stem removal at an early age might promote lateral branch growth [8, 11]. These problems are envisaged under *scenario B* but are not envisaged under *scenario C* because of the moderate stem removal.

Residual trees in *scenarios B* and *C* will react positively to thinning by way of increased diameter growth. Our results show that when thinned, the gain in mean dbh growth after 20 years will range from 68 to 58% over that of unthinned stand. Thinning leads to increased diameter growth of residual trees [23, 18]. [9] reported a 100% increase in diameter of residual trees after thinning in *Aucoumea klaineana* stands in Gabon. Available information reveals that when thinned, *Gmelina* stands can attain mean dbh of 50 to 72cm after 15 to 20 years [4, 8, 12]. However, the more the first thinning is delayed, the lower the expected gain in diameter growth.

With regards to the current emphasis in plantation management, which is provision of diverse products during a rotation (i.e. multiple-use plantation management [5, 18], *scenario C* appears to be more attractive than *scenario B.* Unlike *scenario B*, *scenario C* will have fairly distributed thinning products of fuelwood, pulpwood and poles. *Scenario C* will provide higher revenue from thinnings than *scenario B* but the cost of thinning is expected to be higher in *scenario C*. Going by NPV of *scenarios B* and *C*, the financial viability of the two scenarios will be comparable. The product at the end of rotation from *scenarios B* and *C* will be adequate for sawlog. Consequently, the plantation manager can either manage the plantations for timber at the rotation age of 20 years using either Scenario B or Scenario C.

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