Density management diagram as a tool for thinning recommendations in even-aged *Nauclea diderrichii* plantations in Omo forest reserve, Nigeria.

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Abstract

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Density management diagram was developed and used as a tool for thinning recommendations for *Nauclea diderrichii* (Opepe) unthinned even-aged plantations of 5 to 30 years in Omo Forest Reserve, Nigeria. Ten different age series were chosen for this study and three temporary sample plots of 25m x 25m were selected from each age series for detailed assessment. Growth data (e.g. dbh, total height, crown height, etc) were collected on all trees as well as on the six dominant trees in all the 30 sample plots. The upper growing-stock line of the denisty management diagram was established using the relationship between density (trees ha^{-1}) in unthinned stand and quadratic mean diameter (QMD) of all trees in the stand. The lower growing-stock line was developed using the relationship between density and QMD of dominant trees. With reference to these two lines, three thinning scenarios: *A (no-thinning)*, *B (heavy thinning)* and *C (moderate thinning)* were simulated. Volume production in *scenarios A, B* and *C* after 30 years rotation would be 473.9, 418.3 and 407.9 m^3ha^{-1}, respectively, while mean dbh would be 31.2, 45.2 and 42.0cm, respectively. Net present value (NPV) of *scenarios B* and *C* at interest rates of between 5 and 8% were similar but superior to that of *scenario A*. Thus, the financial viability of *scenario B* is comparable to that of *scenario C* though they are both better than that of *scenario A*. Based on the comparable mean dbh, financial viability and final product expected at the end of rotation from *scenarios B* and *C*, Opepe timber plantations in the study area can be managed using either the thinning recommendation under *scenario B* or *scenario C*.

Key words: Density management diagram, *Nauclea diderrichii*, plantation, thinning scenario, Net Present Value.

Introduction

Nauclea diderrichii (Opepe) is a major indigenous plantation species in Nigeria that is economically important for timber and transmission poles (Abayomi, 1983; Kindele and Abayomi, 1993). Although records indicate that until the 1960s, Opepe was one of the dominant plantation species in Nigeria (FAO, 1981), the advent of large-scale plantations with exotic species resulted to a situation where the species was neglected. Consequently, little attention was devoted to understanding the growth characteristics of Opepe and developing thinning strategies for its plantations. Recently, there has been renewed interest in establishing Opepe stands in leading industrial plantations sites in south-western Nigeria, which is an indication that large-scale plantations of the species are being planned. For example, Opepe accounts for about 62% of the 1353.6 ha indigenous species (e.g. *Nauclea diderrichii, Terminalia ivorensis, Cedrela odorata, Triplochiton scleroxylon,* Mansonia species and *Anarcardium occidentale*) trial plots established by the African Development Bank (ADB) Forestry IIB project (1989 to 1996) in Omo and Oluwa forest reserves (Onyekwelu, 2001). It is expected that the results of these trials will pave the way for large-scale plantations of the species.

This development calls for the formulation of forest management plans, especially silvicultural decision-making processes such as time of first and subsequent thinning, so that trees suitable for timber would be obtained at the end of rotation. Density management diagrams have been adopted in developing thinning programmes for species like *Pinus elliottii, Pinus taeda, Pseudotsuga menziesii, Tectona grandi* in USA, Brazil, India, etc (Dean and Baldwin, 1993; Kumar *et al*, 1995; Spathelf and Schneider, 2000). This study aims at developing thinning scenarios for Opepe plantations in south-western Nigeria using the density management diagram as a tool.

The concept of density management diagram

Density management diagram, also known as density control diagrams, is a tool used increasingly in quantitative silviculture (Jack and Long, 1996). A density management diagram shows the changes in density (number of trees ha^{-1}) as average tree dimension (*e.g.* dbh) increases. The higher the tree dimension, the lower the density and vice versa. It is a stocking chart based on natural stand development and on the fact that trees die in the process of self-thinning when stands near the maximum density for given tree sizes (Dean and Baldwin, 1993; Pretzsch, 2000). After establishment, trees in a stand grow to the extent that site resources can support. Beyond this point, growth is only possible if resources are released through mortality. Density-induced mortality or self-thinning is the result of competition between the individual trees in a forest stand, which takes place if one or more of the resources needed for tree development is insufficient for the needs of individual trees and the stand as a whole (Rio *et al*, 2001). Increased tree dimension and the associated reduction in density form boundary relationship that closely approximates negatively sloped straight line when the data are plotted on logarithmically scaled axes (Dean and Baldwin, 1993). This boundary forms the self-thinning or the upper growing-stock line of the density management diagram. Another important line in the diagram is the lower growing-stock line, which shows adequate site occupancy at which competition between individual trees is reduced to minimum. Below this line, the production capacity of the site will be under-utilised. Thinning is usually restricted between these two lines. Some authors have added a third line between the upper and lower growing-stock lines (Hibbs *et al*, 1989; Rytter, 1995). The Density management diagram has been found valuable in forest management (Zeide, 1995). Areas where the diagram has been found useful include: estimation of stand density and stocking, determination of optimal thinning intensity, degree of site occupancy and calculation of the degree of disturbance, rate of self thinning and other forest processes (Dean and Baldwin, 1993; Zeide, 1995). The diagram has been described as "a simple tool, which is useful in the design, display and evaluation of alternative density management regimes" (Jack and Long, 1996).

Materials and Methods

The study area

This investigation was conducted in unthinned even-aged plantations of *Nauclea diderrichii* in Omo Forest Reserve, situated between latitude 6°35' and 7°05'N and longitude 4°05' and 4°40'E in south-western Nigeria. The establishment of Opepe plantations in Omo Forest Reserve dates back to the early part of the 20th century (Horne, 1966). Stands planted till 1979 were established through the taungya system, while plantations from 1980 to 1996 were established through mechanised planting at the initial planting spacing of 4 x 4m *i.e.* 625 trees ha^{-1}). Prior to this investigation, thinning has not been conducted in the stands under study.

The climate of Omo Forest Reserve is comprised of distinct dry and rainy seasons. Rainy season spans from April to November while dry season begins in December and ends in March. Mean annual rainfall varies from 1,750 to 2,200mm. Mean annual temperature is 26.5°C while average daily relative humidity is 80%.

Mean elevation is 123m above sea level. Soils were formed from crystalline rocks of undifferentiated basement complex of the pre-cambrian series. They are ferruginous tropical and are comprised of well-drained, mature, red, stony and gravely soils in the upper parts of the sequence (Smyth and Montgomery, 1962). The texture of the topsoil is loamy and sandy, subsoil consists of clay with gravel at 30-60cm depth.

Data collection

Ten age classes were randomly selected from stands spanning from 5 to 30 years. Each selected stand (age class) was divided into one-hectare blocks from which three were randomly selected. A 25m x 25m temporary sample plot was laid within each block. Measurements made on all trees in each plot were diameter at breast height (dbh), total height, diameter at various points along the bole of the tree and crown height. Six largest trees per plot (which represents the 100 largest trees ha^{-1}) served as dominant trees. Also, the number of trees per plot was taken while stand age was obtained from plantation records.

Development of density management diagram and thinning scenarios

Management objective(s), rotation age, time of first and last thinning and thinning intensity were taken into consideration in developing the thinning scenarios. Decision on management objective was based on information from literature (Abayomi, 1983; Onyekwelu, 2001). Rotation age was based on the culmination age of mean annual increment (MAI) as practised in forest plantations (Evans, 1992). The ages of the first and last thinning were guided by the recommendation of Strin (1990), who recommended that thinning should occur anytime between canopy closure and the culmination age of MAI (i.e. within divisions I, II and III in Fig. 1).

The upper growing-stock line of the density management diagram was established using the relationship between density in unthinned stand and quadratic mean diameter (QMD) of all trees in the stand (Reineke 1933; Rio *et al*, 2001) while the lower growing-stock line was developed using the relationship between density and QMD of dominant trees. The lower growing-stock line was constructed using the procedures outlined by Onyekwelu (2001) and Onyekwelu *et al* (2003).

With reference to the upper and lower growing-stock lines, three thinning scenarios (*A: No thinning; B: Heavy thinning and C: Moderate thinning*) were simulated. The *k* value-concept, suggested by Magin (1963) was used to estimate volume or basal area removed by

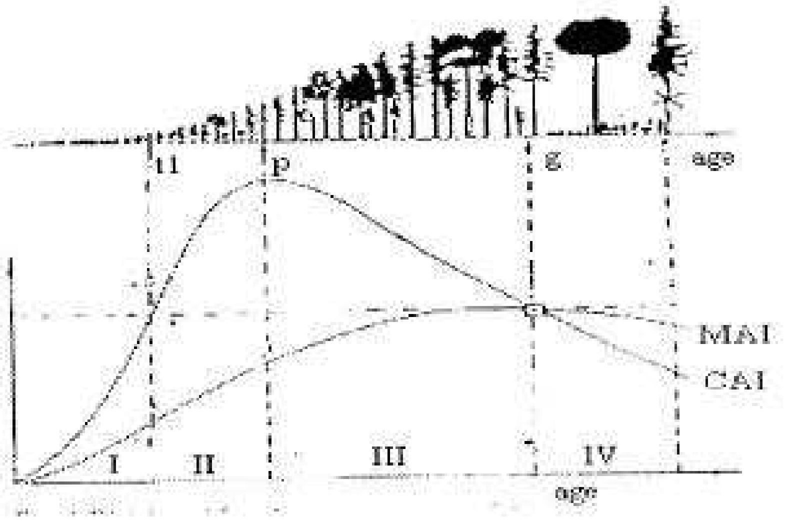

Figure 1: Division of forest management area into groups ***(Source: Strin, 1990)***

mortality or thinning. Detailed computational procedures using this concept have been given by Onyekwelu *et al* (2003). Margin (1963) gave 0.4 as the lowest *k value*, which represents trees removed by mortality in a stand. The higher the *k value*, the higher the thinning intensity and vice versa. Based on Magin's recommendation, *k* value of 0.4 was used in estimating the volume removed by mortality in *scenario A*. The *K* value of 0.8 was used for the first thinning recommendation in *scenario B*, while the *k* value of 0.5 was used for subsequent thinning recommendations under this scenario. The *K* value of 0.5 was used for all thinning recommendations under *scenario C*.

Income at the end of rotation was estimated using information from market survey conducted by Onyekwelu (2002) and information from FORMECU (1989). The method stipulated by Clutter *et al* (1983) was used in calculating Net present value (NPV). The African Development Bank (ADB) average interest rate of 7% was used in NPV estimation. Also, interest rates below and above 7% were used.

Results and discussion

Mean dbh varied from 9.6 to 31.2cm between 5 and 30 years while mean height ranged from 9.0 to 22.3m within the same period (Tab. 1). Volume production varied from 24.0 to 552.0 $m^3 ha^{-1}$ between 5 and 30 years, while basal area increased from 4.1 to 40.0 $m^2 ha^{-1}$ within the same period. Current annual increment ranged from 7.4 to 21.9$m^3 ha^{-1} year^{-1}$ [illegible] AI varied from 5.7 to 15.9 $m^3 ha^{-1} year^{-1}$. Maximum MAI was attained at the age of 28 years, at which age MAI and CAI were equal (Fig. 2). Only little differences existed in MAI values between ages 23 and 30 years (Fig. 2).

While the dbh and height data in this study are comparable with those reported for the species by Abayomi (1983), Dupuy and Mille (1993) and Onifade (1998), the dbh values for Opepe reported by Akindele and Abayomi (1993) and Fonweban *et al* (1994) were higher. Fonweban *et al* (1994) reported mean dbh of about 14 and 17cm for 4 and 7 years stands in Cameroon as against about 11 and 13cm for 5 and 7 years stands in this study. The higher dbh growth reported by Fonweban *et al* (1994) and Akindele and Abayomi (1993) could be explained by the lower density (wider planting spacing) in their study. Opepe showed evidence of moderate growth rate when compared with exotic species like *Gmelina arborea*, *Eucalyptus sp.* However, its growth rate (especially height) compares favourably with that of indigenous plantation species like *Terminalia spp*, *Khaya* spp, *Lophira alata*, *Cedrela odorata*, *etc.* as well as Teak (Okojie *et al*, 1988; Dupuy and Mille, 1993; Butterfield, 1996).

Although MAI culminated at about the age of 28 years, the approximately equal MAI between 23 and 28 years (Fig. 2) implies that thinning should not be administered beyond 23 years. Strin (1990) has shown that thinning operation(s) should not be extended beyond the

Table 1: Summary of growth data for unthinned *Nauclea diderrichii* plantations at Omo Forest Reserve.

Age (years)	Density ($N ha^{-1}$)	Dbh (cm) Min.	Mean	Max.	Mean height (m)	BA ($m^2 ha^{-1}$)	Vol ($m^3 ha^{-1}$)
5	667	4.9	9.6	14.5	9.0	4.1	24.0
6	587	5.0	11.2	16.9	9.1	6.2	27.4
7	624	4.1	11.8	21.7	11.1	7.5	58.9
9	587	7.4	16.7	26.8	13.1	13.9	120.8
15	443	7.5	19.6	35.6	15.0	15.1	153.4
19	517	8.8	21.2	38.0	16.3	20.7	253.9
24	485	6.1	23.3	43.8	21.1	22.9	344.3
26	491	9.5	26.2	42.4	22.1	28.6	399.7
28	496	11.9	27.2	47.5	22.4	30.7	433.1
30	496	15.0	31.2	52.2	22.3	40.0	552.0

age of culmination of MAI, which is probably based on the assumption that stands thinned after the age of MAI culmination will react slowly to thinning in terms of little gain in diameter growth. In addition, it also implies that rotation age for timber can lie between 23 and 30 years, since the main objective is usually maximum volume production over the rotation period. FORMECU (1999) recommended rotation age of 23 years for the best site and 30 years for moderate and poor sites in Nigeria. It is however doubtful if good timber size trees would be obtained after 23 years rotation. Depending on site quality, Dupuy and Mille (1993) recommended rotation age of 30 to 40 years. Onyekwelu (2001) recommended 30 years for Opepe plantations in the study area, which is adopted in this study.

Onyekwelu (2002) reported that a high percentage of logs from an unthinned 30-year-old Opepe plantations in south-western Nigeria were mainly small dimension trees which are not suitable for the pre-dominant log conversion technology (CD5 and CD6) in Nigeria. Consequently, thinning in Opepe stands is inevitable if large dimension trees are to be produced after of 30 years rotation. The need for thinning is further underscored by the mean dbh of 31.2cm of unthinned 30 years stand (Tab. 1). Timing of thinning operation is very important in silviculture. When administered too early, thinning affects stem quality (e.g. development of lateral branches) and crown development. Trees respond too slowly, in terms of low increase in diameter growth, if stands are thinned late (Assmann, 1970; Dean and Baldwin, 1993). Usually, thinning operations in forest plantations are administered between canopy closure and culmination of MAI (Strin, 1990). Opepe plantations in the study area closes canopy between four and five years (Onyekwelu, 2001). Consequently, 5 years was adopted as the age of first thinning operation in this study.

The upper and lower growing-stock lines for Opepe plantations in the study area are shown in Figure 3, which reveals steady decrease in density as mean diameter increased. *Scenario A* is characterised by high density and high volume production at the end of 30 years rotation, which is higher than what will be produced under *scenarios B and C*. For example, at the end of 30 years rotation, standing volume in *scenario A* is 473.9m^3ha^{-1} as against 418.3 and 407.9m^3ha^{-1} under *scenarios B and C* respectively (Tab. 2). About 150 trees (24.6% of trees ha^{-1}), corresponding to volume of 23.6$m^3 ha^{-1}$, were lost to mortality in *scenario A* between 5 and 30 years. Loss of trees to mortality is not expected under *scenarios B and C* since the weaker individual trees, which would have been lost to mortality, are expected to be salvaged through thinning operations.

The upper and lower growing-stock lines are usually used as uppermost and lowest boundaries in thinning operations using density management diagrams. Based on the objective of management and thinning intensity, thinning can be conducted such that stand development continues (i) very close to the upper line, (ii) very close to the lower line or (iii) moves gradually from the upper to the lower line (Onyekwelu *et al*, 2003). The upper line in Figure 3a & b represents the maximum production capacity of Opepe plantation, given the initial stocking of 625 trees ha^{-1} while the lower line represents the stand development below which the site will be under-utilised. The main objective in setting the lower growing stock line is to maintain adequate site occupancy (Dean and Baldwin, 1993), thus thinning below it should be avoided. *Scenario B* maintained density close to the lower line from first thinning to final harvest while thinning in *scenario C* moved gradually from the upper to the lower line (Fig. 3a & b). Although *scenario B* prescribed a heavier first thinning (50.8%) than *scenario C* (26.2%), subsequent thinning recommendations were heavier in *scenario C* than *B* (Tab. 2; Fig. 3). Thinning recommendations under *scenarios B and C* were made bearing in mind that thinning from above and thinning from below will be used to remove unwanted trees (e.g. forked trees, trees with big low branches, bent trees) in dominant canopy and trees in the suppressed crown class, respectively. First, second and third thinnings in *scenario B* are to be administered at 5, 10 and 15 years, respectively at the respective mean dbh of about 10.0, 22.0 and 30.0cm (Tab. 2; Fig 3a). For *scenario C*, first, second and third thinnings should be undertaken at 5, 10 and 15 years respectively when the respective mean dbh of about 10.0, 19.0 and 25.0cm, would have been be attained (Tab. 2; Fig 3b). Dupuy and Mille (1993) recommended three thinning regimes for Opepe plantations at 5, 9 and 15 years within a rotation of 30 years. Heavy (54.5%) first thinning operation at 5 years, similar to that under *scenario B*, was prescribed by Dupuy and Mille (1993). FORMECU (1999) recommended only two thinning regimes at 7 and 17 years for Opepe stands in Nigeria within a rotation of between 23 and 30 years. Although the fear that heavy early thinning might result in stand instability and promote lateral branch growth has been raised (FORMECU, 1999; Fuhr *et al*, 2001; Onyekwelu, 2001), there is no empirical evidence to show that this will be the case with heavy early thinning in Opepe plantations in the study area.

Research workers have demonstrated that thinning leads to increased diameter growth of residual trees (Dean and Baldwin, 1993; Smith *et al*, 1997; Rautiainen *et al*, 2000; Fuhr *et al*, 2001). Onyekwelu *et al* (2003) have shown that increase in dbh of residual trees in *Gmelina arborea* plantations in Nigeria is expected to be between 58 and 68% after thinning. The results of this investigation indicates that when thinned, gain in mean dbh in Opepe plantations will range from 34.6 to 44.9% over that of unthinned stands. Thus, at the end of 30 years rotation, mean dbh of trees under *scenario A* (unthinned stand) is 31.2cm, which is smaller than 45.2 and 42.0cm mean dbh expected from *scenarios B* and C, respectively (Tab. 2).

Based on the diameter limits for Opepe wood products recommended by FORMECU (1999), products from thinning operations and final harvest were categorised into fuelwood, poles and timber. Under *scenarios B* and *C*, product from first thinning would be fuelwood, while product from the second and third thinning operations would be poles (Tab. 3). At the end of rotation, product distribution under *scenario A* is 41.5% poles and 58.5% timber (Tab. 3). Contrary to this, products at the end of rotation under *scenarios B* and *C* will be 100% timber (Tab. 3), which when compared to the size of logs processed in sawmill in Nigeria will fall into the medium size-log category (Onyekwelu, 2002).

Scenario C is expected to yield higher income from the sale of thinning products than *scenario B* (Tab. 3). Total income from *scenario A* would be slightly higher than those of *scenarios B* and C (Tab. 3). However, *scenario A* is expected to give the lowest net present value (NPV) at the various interest rates (Tab. 3). As interest rate increased, the NPV of *scenario A* became smaller than those of *scenarios B* and *C*. The lower NPV of *scenario A* implies that *scenarios B and C* are more financially viable. Total income from *scenario B* would be slightly higher than that from *scenario C* but the NPV of *scenario C* would be slightly higher than that of *scenario B* at all interest rates considered (Tab. 3). However, the total income and NPV of the two scenarios (i.e. *B* and *C*) are comparable. The similar NPV of *scenarios B* and *C* reveal that both scenarios have comparable financial viability.

Conclusion

Density management diagram proved to be a useful tool in making thinning recommendations for *Nauclea diderrichii* plantations in Omo Forest Reserve, Nigeria. The product distribution from *scenario A* (*no thinning*) reveals the necessity for thinning in Opepe plantations in the study area, if timber-sized logs must be attained at the end of 30 years rotation. The higher mean dbh and NPV expected from *scenarios B and C* (*heavy* and *moderate thinning*, respectively) than from *scenario A* reveals the superiority of the two *scenarios* (*B & C*) over *scenario A*. Going by the comparable mean dbh, financial viability and comparable final product expected at the end of rotation from *scenarios B* and *C*, the thinning recommendation under both scenarios can be adopted for Opepe timber plantations in the study area. Consequently, the plantation manager can manage the plantations for timber using either *scenario B* or *C*.

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Table 2: Thinning scenarios/recommendations for *Nauclea diderrichii* plantations at Omo Forest Reserve

		Mean crop in unthinned stand/before thinning					Yield from thinning/Mortality				Main crop in unthinned stand/after thinning				
Thinning/ Harvest	Age (years)	N (ha^{-1})	D_g (cm)	H_l (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_{Δ} (m^3 ha^{-1})	N (ha^{-1})	D_g (cm)	H_l (m)	G (m^2 ha^{-1})	V (m^3 ha^{-1})
SCENARIO A: No Thinning															
-	5	610	9.7	9.4	4.5	28.3	-	-	-	-	610	9.7	9.4	4.5	28.3
-	9	560	17.7	13.7	14.6	121.4	50	0.7	2.6	2.6	560	17.7	13.7	13.9	121.4
-	15	520	19.3	15.6	15.7	185.9	40	0.4	4.6	7.2	520	19.3	15.6	15.2	185.9
Final harvest	30	460	33.3	23.2	40.5	473.9	60	1.1	16.4	23.6	460	31.2	23.2	40.0	473.9
SCENARIO B: Heavy Thinning															
1st thinning	5	610	9.7	9.4	4.5	28.3	310	1.4	6.8	6.8	300	11.5	11.0	3.1	21.5
2nd thinning	9	300	21.8	18.5	11.2	106.3	80	1.7	15.6	22.4	220	23.4	19.4	9.5	90.7
3rd thinning	15	220	29.6	22.1	15.2	170.8	40	1.9	20.0	42.4	180	30.7	22.6	13.3	150.8
Final harvest	30	180	45.2	27.1	28.9	418.3	0.0	0.0	0.0	42.4	180	45.2	27.1	28.9	418.3
SCENARIO C: Moderate Thinning															
1st thinning	5	610	9.7	9.4	4.5	28.3	160	0.7	4.2	4.2	450	10.4	9.8	3.8	24.1
2nd thinning	10	450	19.0	16.9	12.8	130.6	150	2.6	26.1	30.3	300	20.8	18.0	10.2	104.5
3rd thinning	15	300	25.0	20.2	14.7	172.8	100	2.6	33.4	63.7	200	28.0	21.5	12.3	139.4
Final harvest	30	200	42.0	26.3	27.7	407.9	0.0	0.0	0.0	63.7	200	42.0	26.3	27.7	407.9

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

Table 3: Expected products and income from the different thinning scenarios for *Nauclea diderrichii* plantations at Omo Forest Reserve

Scenarios		Operations (year)	Time of operation Product*	Name of ($m^3 ha^{-1}$)	product yield ($N ha^{-1}$)	income 5%	Net present value (NPV) at interest rate of 6%	7%	8%
A (No thinning)	-		-	-	-	-	-	-	-
	-		-	-	-	-	-	-	-
	-		-	-	-	-	-	-	-
	Final Harvest	30	1. PL	196.7	217,492	50,323	37,868	28,571	21,644
		30	2. TB	277.2	228,212	52,803	39,734	29,980	22,679
Total				**473.9**	**445,704**	**103,126**	**77,602**	**58,551**	**44,293**
B (Heavy thinning)	1st thinning	5	6.8	9,358	7,332	6,993	6,672	6,369	
	2nd thinning	9	PL	15.6	16,662	10,740	9,862	9,063	8,335
	3rd thinning	15	PL	20.0	20,190	9,712	8,425	7,318	6,365
	Final Harvest	30	TB	418.3	393,376	91,018	68,491	51,677	39,093
Total				**460.7**	**439,586**	**118,803**	**93,770**	**74,730**	**60,161**
C (Moderate thinning)	1st thinning	5	FW	4.2	4,586	3,593	3,427	3,270	3,121
	2nd thinning	10	PL	26.1	23,721	14,563	13,246	12,059	10,987
	3rd thinning	15	PL	33.4	33,965	16,338	14,172	12,310	10,707
	Final Harvest	30	TB	407.9	370,777	85,789	64,556	48,708	36,847
Total				**471.6**	**433,049**	**120,283**	**95,401**	**76,347**	**61,663**

** FW - Fuelwood; PL - Poles; TB - Timber*

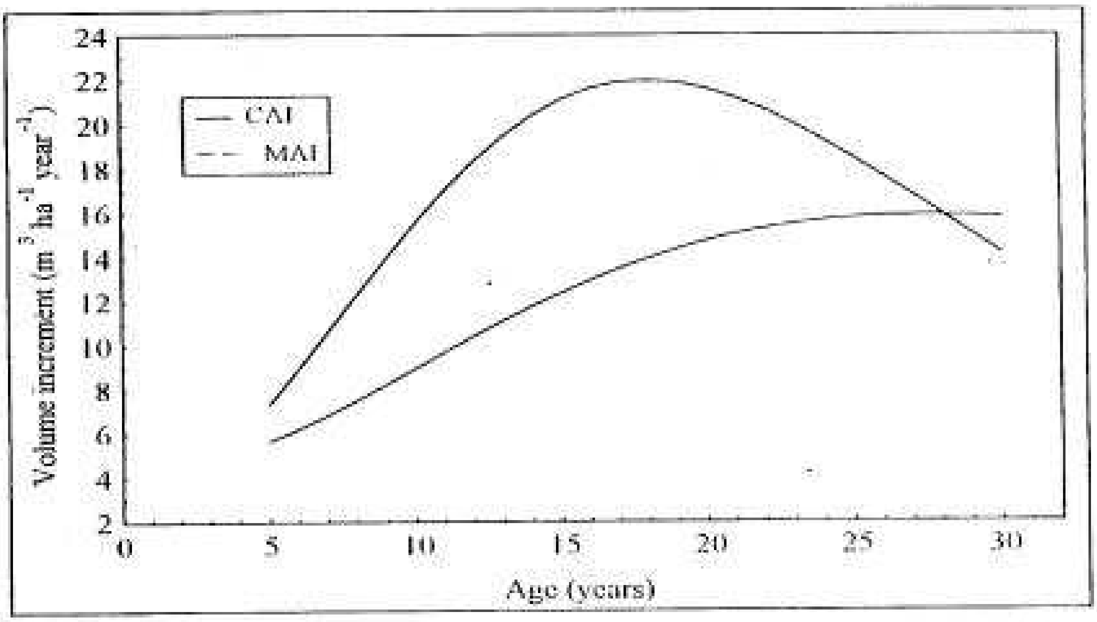

Figure 2: Current and mean annual volume increment for *Nauclea diderrichii* plantations at Omo Forest Reserve.

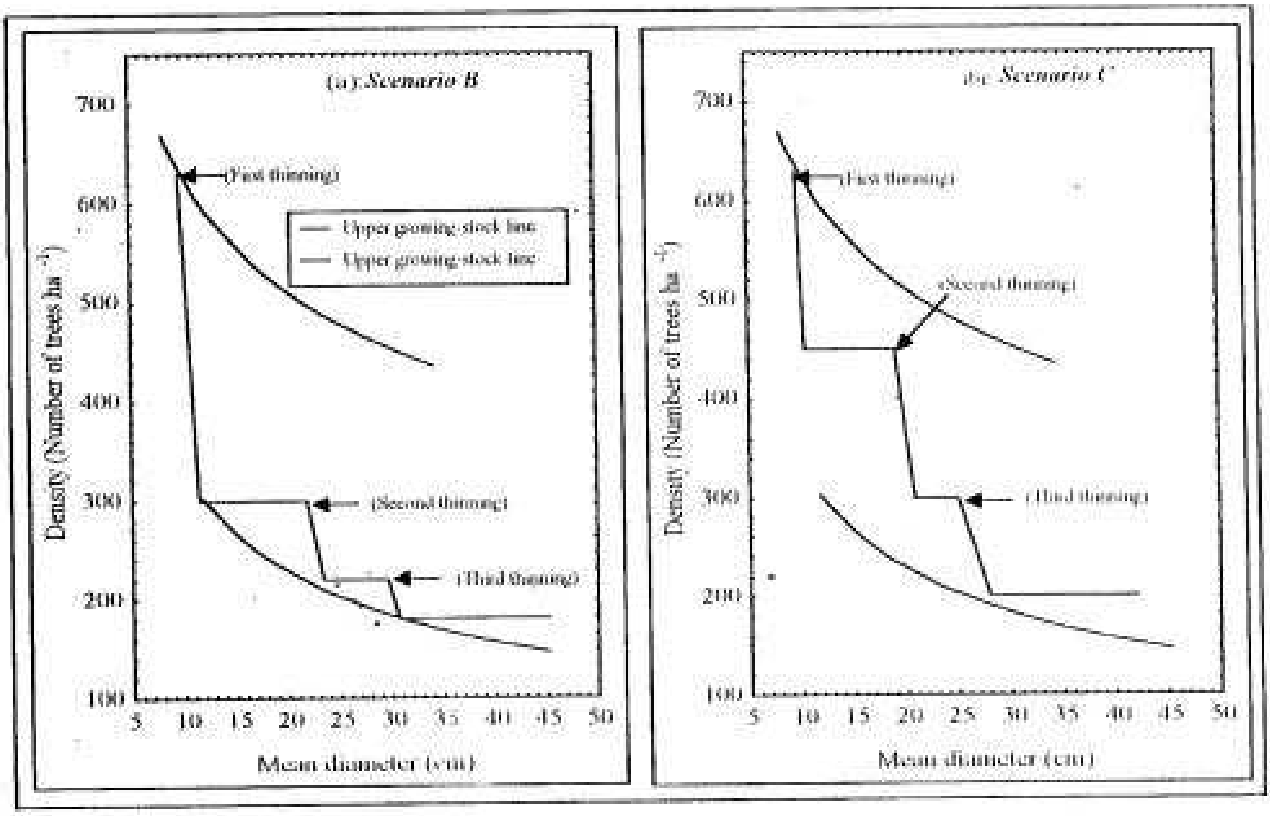

Figure 3: Schematic presentation of thinning *scenarios B and C* for *Nauclea* plantations at Omo Forest Reserve.