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ABSTRACT

Shortages of wood for burning and construction have begun to create serious environmental problems in sub-Saharan Africa. Kenya is of particular interest both because of its high population pressure and its commitment to an active reforestation movement. This paper examines the contribution that the fast-growing species, Leucaena leucocephala, can make in this effort. A simple statistical model was used to determine the soil and climatic factors that affect its growth; these results are then compared with existing conditions in Kenya. Estimated coefficients for growth and estimated output prices were used to derive a function relating the present value of net revenue to rotation length. It is demonstrated that the economically optimal rotation is just under three years. Implications for the role of L. leucocephala in addressing the projected demand for fuel and wood in Kenya are indicated.

I. Introduction[1]

The dearth of wood for burning and construction is a widely documented phenomenon in sub-Saharan Africa (Leach and Mearns, 1987; FAO, 1981). Figures indicate that area under forest for the most densely populated countries in Africa has decreased in the past two decades by 15-25% (Lele and Stone, 1989). Rapid environmental degradation, declining per capita food production and a steady loss in per capita GDP have characterized much of the last two decades.

This paper focuses on the potential for growing trees in a managed rotation to increase overall supply of fuelwood, the primary source of energy used in sub-Saharan Africa. In particular, it will look at the fast-growing tree, Leucaena leucocephala, which has been genetically improved to yield a highly productive variety known as the Hawaiian Giant.[2] It has gained the reputation of being a potential solution to deforestation and fuelwood shortages because of its ability to grow quickly (up to 9 meters in three years) and to produce large amounts of good quality firewood: according to one source, the specific gravity of a 6 to 8 year old Leucaena averages 0.54, a density found in oaks, ash, and sugar maple (National Research Council, 1984 -- hereafter NRC, 1984). It also has the ability to fix nitrogen in the soil.

Kenya was chosen as a case study because it is at the forefront of the fuelwood crisis, both in terms of its intense population pressure and demand for fuelwood, and its commitment to reversing these trends with an active reforestation movement. It is a useful case study because it contains climatic zones representative of most sub-Saharan Africa.

After review of the literature on the economics of agroforestry and Leucaena in particular, the paper evaluates growing conditions for Leucaena using a simple regression model, and will then analyze the prevailing agro-climatic conditions in Kenya to sketch out prospective areas where the tree can grow. The analysis draws on available data to estimate a volumetric growth function using a dynamic optimization technique in discrete time in order to determine an optimal rotation for harvesting the trees.

It is assumed that trees are grown in stands as opposed to an alley-cropping approach since this is more appropriate for maximizing yield for firewood rather than using them as a source of "green manure."

Nevertheless, the analysis represents an important point of departure for future research on the economics of short-rotation leguminous trees, in that it provides a basic methodology useful for addressing these issues.

II. Review of Literature

Several early attempts were made to apply economic theory to the growth and production processes of trees and other agricultural crops over time. Filius (1982) is credited with introducing the concept of complementarity between crops and trees to expand the production possibilities frontier. Etherington and Mathews (1983, 1987) show how the dynamic interaction of leguminous trees and soil shifts the production possibilities frontier; the effect is to introduce new optimal allocations of land, labor and time. Likewise, Hoekstra (1985) applies similar concepts -- including risk minimization -- in their basic forms.

More sophisticated applications include Hosier (1989) who provided a thorough overview of the economic literature on agroforestry, with application to cases in Kenya and Haiti. Other significant contributions to the literature include Dvorak's (1990) comprehensive review of alley-cropping data and her attempt to model the benefits of planting trees in the alley-cropping technique using dynamic production functions. Christophersen (1988) conducted a study of agroforestry options for the Sahel that showed the different break-even costs and estimated net present value (NPV) for several types of interventions.

Blandon (1985), in bringing portfolio theory to agroforestry, shows how weak or negative response correlation between trees and crops to changes in weather patterns can spread risk across different farm operations. Advocates within large donor institutions such as the World Bank emphasize that growing trees can be profitable (Spears, 1987), arguing that rapid increases in fuel and construction pole prices relative to other commodities will increase the profitability of growing trees.

Though previous work paints Leucaena as a miracle tree, (e.g., Ngambeki, 1985; Cobbina et al. 1989) it is important to recognize that there are some problems associated with it (National Academy of Sciences, 1977). For instance, it is commonly known that Leucaena leaves and pods contain a toxic alkaloid, mimosine, that when ingested in large quantities causes depilation, or loss of hair, in non-ruminants (ibid.). The genus Leucaena as a whole and the species L. leucocephala in particular is poorly adapted to acidic soils (Ahmad and

Ng, 1981)[3]. Further, it has been suggested that like Eucalyptus, Leucaena may (because of mimosine) have allelopathic effects on other plants (Tawata and Hongo, 1987). Some varieties are prolific and are considered weeds (Sorensson, 1989). Problems of pest control threaten wider application and have shown the vulnerability of Leucaena when introduced as an exotic species.

Nevertheless, Leucaena has demonstrated ability to yield copious amounts of wood under the right conditions. At a spacing of 1m x 0.5m (or 20,000 trees per ha.), for instance, volumetric growth of up to 83 cubic meters/ha of wood after the 2nd year was recorded (Van den Beldt and Brewbaker, 1980). Other studies have shown that annual growth rates of 30-40 cubic meters per annum are not uncommon at spacings ranging from 1m x .5m, to 1.5m x 1.5m (Hu and Kiang, 1982; Hu and Shih, 1982). This level of production is necessary for commercial viability: An earlier study suggested that growing Leucaena as a wood crop in Taiwan will only be more profitable than the traditional cash crops of maize, sugarcane or pineapple when volumetric growth rates exceed 40 m^3/ha/yr (Jen, 1980).[4] It is unclear, however, whether high yields can be maintained over time, especially if all the biomass is removed from the site (Hall and Coombs, 1983).[5]

Returns vary according to how labor is invested in production. For instance, a study by the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) found that sole cropping was more profitable than alley cropping, primarily because of high labor inputs (Walker, 1987).[6] Little data is available on labor requirements for harvesting wood (fuel or poles) from stands of giant type Leucaena. However, it appears that the demands are substantial and may be a hurdle to wider adoption of the plant. Intensive weeding during the first year and subsequent plot management and harvest in following years have been recorded by a number of researchers (Dvorak, 1990; Ngambeki, 1985). A method called the "barestem" technique has been developed that may significantly reduce planting and weeding demands on labor (Trees For the Future, 1990). This technique involves starting the seedlings on raised nursery beds during the dry season; and just before the rains, pulling up the roots, stripping the leaves, and packing them into bundles for transplanting.

III. Volumetric Growth of Leucaena: An Econometric Model

The purpose of this section is to identify the conditions that critically affect the volumetric growth rate of Leucaena. It draws on results from a model using planting density, soil pH, rainfall and temperature as the explanatory variables (Stone, 1990). These results are compared to actual conditions existing in Kenya to determine the most suitable locations for growing Leucaena. A Cobb-Douglas model was selected to estimate the volume function for Leucaena.[7] The model used is:

$$(1) \quad \log Y = \log \alpha + \beta_1 \log X_1 + \beta_2 \log X_2 + \beta_3 \log X_3 + \beta_4 \log X_4 + (\mu_i)$$

Where: Y = growth in volume (meters^3/ha/yr) in year 2;
α = scaling term;
X_1 = spacing (trees per hectare);
X_2 = soil acidity (pH);
X_3 = mean annual rainfall (millimeters/year);
X_4 = mean annual temperature (°C);

As a pragmatic approach to the short growth cycle, the population regression function covers estimated growth in volume between the second and third years. The sample was drawn from experimental data in Hu and Kiang (1982) and is given in Table 1. Soil pH varied from most acid (4.0) in group 3 to least acid (6.8) in group 1. Rainfall varied from a low of 1708 mm per annum in group 4 to a high of 2514 mm/year in group 3. Similarly, temperature was also highest in group 4 (23.2 °C) but substantially lower in group 2 (13.9 °C).[8]

The results are highly significant, both for the individual estimators and collectively for the regression as a whole. The estimated regression function with standard errors given in parentheses is:

$$(2) \quad \log Y = \underset{(5.325)}{-28.246} + \underset{(0.037)}{.217} \log X_1 + \underset{(0.338)}{2.628} \log X_2 + \underset{(0.528)}{2.350} \log X_3 + \underset{(0.326)}{2.360} \log X_4$$

$$F = 38.6 \qquad \bar{R}^2 = 0.89$$

The results confirm the range of temperature, rainfall, and soil pH that is desirable for growing Leucaena. The estimated value of β_2 indicates that, holding all other factors constant, the average volumetric growth will increase by 2.63 percent given a 1 percent increase in soil pH (over the pH range 4.0 - 6.8). Similarly for mean annual rainfall and temperature, the volume elasticities are 2.35 and 2.36, respectively, over the range 1700-2500 mm. and 14-24 degrees Celsius.

IV. Will it Grow in Kenya?

Kenya is marked by extreme variability in its landscape; within its borders are housed some of the most fertile, and most barren, land in Africa. Of its 56,412 square kilometers, over two-thirds are arid and there are wide variations in temperatures (see Table 2).[9]

The land in Kenya is divided into seven moisture availability zones, ranging from humid to very arid. Based on the availability of moisture, different agricultural potentials are ascribed to the zones. Zone I, which covers approximately 4 percent of the land area in Kenya, is classified as humid and having high agricultural potential. Zones II and III cover about 8% of the land area, are sub-humid and semi-humid, and are of high to medium potential. Zone IV is transitional, and covers about 5 percent of total area. Progressively more land comes under zones V to VII; but this land receives below 600-1100 mm per annum in rainfall and is considered unsuitable for Leucaena.

Because of the tremendous elevation changes in Kenya, temperature zones vary as widely as do those corresponding to moisture. For instance, in the "Afro-Alpine Highlands," mean annual temperature is below 10 degrees Celsius and the mean maximum temperature is below 16 degrees. Roughly 4.3 percent of the land area of Kenya is classified as being highlands in zones 9 through 6. Zone 5 is also considered a (lower) highland, and covers around 5 percent of total area. Average temperatures in these zones are still too cold for many species of Leucaena. Zones 4 through 1 are more conducive to growth and in these zones moisture becomes the limiting constraint. In fact, over half the land in Kenya is covered by zone 1, with a mean annual temperature of 24 to 30 degrees Celsius.

Combining the above, a table was constructed to illustrate the potential areas for growing Leucaena. Of the zones mentioned above, over 5 million hectares are suitable. Given the water requirements of the plant, Zones I-3 and I-4 are the most desirable with an average of 1100-2700 mm. of rain per year and temperatures ranging from 14° to 26° on average. Area under zones I-3 and I-4 exceeds 1 million hectares, occuring primarily in southwest Kenya (see Table 3). Zones II-3 and II-4, which are less humid, are also found in the southwest, covering about 1 million hectares of land in the Nyanza and Western Provinces. Zone III, with 800-1400 mm mean annual rainfall, also covers over a million hectares in combination with the temperature regimes 1, through 4. These semi-humid midlands and lowlands occur along Coast Province in the east and Nyanza, Central, and to a lesser extent, Rift Valley Provinces (see Figure 1). Finally, zone IV, which receives on average only 600-1100 mm of rainfall per year and is therefore less suited for raising Leucaena, covers about 2 million hectares in the Rift Valley, Coast, Eastern and Nyanza Provinces.

Having defined areas of high potential and areas potentially suited to growing Leucaena, it is now possible to show how the high potential land is distributed in Kenya, and how it corresponds to population densities. The issue of population pressure is critical to understanding the dynamics of resource use in Kenya. At the simplest level, areas of high population concentration typically will have a higher demand for fuelwood. However, higher population densities may also signal an adequate supply of labor to intensify agricultural production through the adoption of new technologies, such as nitrogen-fixing trees, given the correct incentives.

Table 4 shows how high, medium, and low potential land is spread across the various provinces and districts, and gives the average hectares per person of arable land as of 1979. As can be seen, Central, Western, Nyanza, and part of the Rift Valley contain a large share of the best agricultural land and have the lowest per capita land availability. However, the most fertile land is in the cooler highlands, and thus Leucaena would not compete with higher value crops like coffee and tea.

V. Optimizing Leucaena Production over Time: A Bioeconomic Model

The purpose of this section is to determine an optimal rotation for harvesting Leucaena leucocephala based on prevailing prices, costs and growing conditions. It will also estimate the present value of land under Leucaena for comparison with other possible revenue-generating activities. The optimal rotation length can in turn be used to analyze the potential supply of Leucaena in meeting the projected demand for fuelwood in Kenya. Finally, secondary benefits associated with raising Leucaena, such as soil improvement through nitrogen fixation and organic matter decomposition, are briefly examined.

To arrive at an optimal rotation period, T^*, one needs to estimate a growth function, Q(t), to describe production over time. In this case, production is measured in cubic meters; hence the production function yields volume at future time, t. A commonly used functional form in this case is:

(3) $$Q(t) = e^{\gamma - \eta/t}$$

where:

$Q(t)$ = volume of <u>Leucaena</u> in m^3 on one hectare of land;
e = base "e" (2.71282)
t = time in months;
γ & η = parameters such that $\eta > \gamma > 0$.

To estimate the equation, the natural log is taken of both sides. The resulting equation is:

(4) $$\ln Q(t) = \gamma - \eta/t$$

Five separate equations were fitted using data from Table 1. Each equation corresponds to a different planting density. The estimated parameters and corresponding t-statistics are given in Table 5 and presented graphically in Figure 2. Although the higher planting density of 20,000 trees per hectare yields the highest incremental growth in the short run, the quality of the product for purposes of timber is inferior. At higher density, volume increases due to the proliferation of many small branches and trunks as opposed to increases in diameter of individual trees. Also, it is easier to manage a less densely planted stand. For the purposes of the following exercise, a planting density of 5,000 trees per hectare will be assumed. The estimated volume function that will be used is therefore:

(5) $$Q(t) = e^{5.61 - 36.18/t}$$

Figure 3 shows volumetric growth at a density of 5,000 trees per hectare. It can be seen that maximum mean annual growth for one rotation is achieved at approximately 36 months.

The Faustmann-Pressler-Ohlin Theorem (FPO) develops criteria for finding the optimal length of an infinite rotation of trees based on prevailing interest rates, net price of timber, and time to maturity for the stand. Several assumptions are implicit in the model:

1.) a "perfect" capital market exists; farmers can lend or borrow any amount of money at the prevailing interest rate which is known with certainty over all future periods;

2.) future wood prices and future prices of inputs are constant and known with certainty;

3.) future wood yields are known;

4.) land can be bought, sold and rented in a perfect market.

These simplifying assumptions are needed to extend the model over an infinite series of rotations; doing so allows the analyst to determine net present value of all future rotations and optimal time to harvest.

Having estimated the volumetric growth equation, it is possible to use that relationship to derive the optimal rotation of Leucaena. From equation 5 and Figure 3, the time to harvest that maximizes mean annual increment (MAI) is equal to the estimate η coefficient, here, 36.18 months. The present value of a single rotation can be calculated based on prevailing prices of output, costs of production c, and the interest rate, δ:

(6)

$$\pi_s=[pQ(T)\rho^T-c]$$

where $\rho = 1/(1+\delta)$. For an infinite series of rotations, the expression for is:

(7)

$$\pi^*=[pQ(T)\rho^T-c](1+\rho^T+\rho^{2T}+...+\rho^{\infty T})$$

which converges to:

(8)

$$\pi^{*}=[pQ(T)\rho^{T}-c](1-\rho^{T})^{-1}=\frac{[pQ(T)-c(1+\delta)^{T}]}{(1+\delta)^{T}-1}$$

If planting costs are assumed to be zero (which may not be a poor assumption if seedlings are raised in the dry season), equation 8 reduces to:

(9)

$$\pi^{*}=\frac{[pQ(T)]}{(\rho^{-T}-1)}=\frac{[pQ(T)]}{(1+\delta)^{T}-1}$$

since $\rho = 1/[1+\delta]$. This is the formula used to calculate the NPV for each rotation length, over an infinite series of rotations.

At yearly interest rate of 5%, a wood price of $16.77 per cubic meter (a figure taken from Hosier's 1989 study in Kenya), and zero cost of harvest (implying a zero opportunity cost of labor), equation 9 generates the profit curve in Figure 4. The economically optimal T^{*} occurs where the slope of the present value function equals zero. It can be quickly seen that T^{*} is slightly less than T_{MAI}, 34 as compared to 36 months. These values are consistent with other estimates in the literature (Van den Beldt and Brewbaker 1980; Hu and Kiang 1982). At $\delta = .05$, the NPV of all future rotations is US $4,344.

When δ is increased, the optimal rotation length decreases. Specifically, when δ was doubled to 10%, the T^{*} decreased by two months, to 32 months. Furthermore, NPV of all future rotations dropped to just over $2,000. Increasing δ to 20% resulted in an even shorter optimal rotation length of $T^{*} = 29$ months. At $\delta = .20$, NPV of an infinite series of rotations fell to only $893. Thus, the solution is sensitive to changes in the discount rate, but remains between two and three years over a reasonable range of observed interest rates.

Secondary benefits of producing Leucaena can be quantified to determine at what point they alter the optimal rotation. For instance, soil improvement through nitrogen and organic matter accumulation were included in the model to determine what effect they had on the optimal rotation time (Stone, 1990). Assuming that Leucaena is planted at t = 0, a specified amount of nitrogen will pass into the soil from leaf litter, root nodulation, and fine root decomposition. If the flow of nitrogen is treated as a proxy for soil improvement, and denoted N_t, and the amount of nitrogen available in period t is denoted X_t, then the following equation describes their relationship over time:

(10)

$$X_{t+1}=(1-\lambda)X_t+N_t$$

where λ is a rate at which nitrogen passes out of the root zone. Once X_t is determined, its value or shadow price is estimated using the fertilizer price equivalent, q. In discrete time, the objective function is to:

(11)

$$\text{Max}[pQ(T)+qX_T]\rho^T-c$$

subject to:

$$X_{t+1}=(1-\lambda)X_t+N_t$$

where ρ again is equal to $1/[1+\delta]^{10}$. Assuming a zero initial stock of nitrogen, a value for λ of 0.23,[11] and a fertilizer price of \$240/ton[12] the optimal rotation time does not change. The solution found above still holds: it remains constant at 34 months for an infinite series of rotations, even including the estimated benefits from soil improvement. This result is primarily a function of λ, the rate at which nitrogen passes out of the root zone.

VI. Potential Contribution to Projected Demand for Fuelwood

Using the results found above, the potential for using L. leucocephala to meet projected fuelwood demand in Kenya can be demonstrated. The World Bank estimates that the demand for woodfuel will rise from 31.0 to 57.3 million cubic meters from 1985 to the year 2000 (1988: 21). If L. leucocephala were planted on half of the potentially suitable land (5.49 million hectares), and a steady-state yield of 30 m^3/ha./yr. on a three-year rotation is assumed, then the annual yield would meet 48 percent of the projected demand in the year 2000 (see Table 6).

Clearly, one needs to be cautious in interpreting these results. The yield of 30 m^3/ha./yr. from L. leucocephala in Kenya is somewhat optimistic. In the cooler parts of Kenya, it has been suggested that L. diversifolia is better adapted (Brewbaker, 1987). Also, the opportunity costs of devoting one-eighth of the arable land in Kenya to Leucaena as opposed to food or other crops may be unacceptably high. However, the calculations illustrate the potential of high-yielding tree varieties for supplying the anticipated demand in the woodfuel market. Alternatively, meeting this demand through kerosene imports would cost Ksh. 2 billion per annum by the year 2000 or approximately 8% of export earnings (World Bank, 1988: 4).

VII. Conclusion

This paper has attempted to set an economic analysis of Leucaena production in the context of increasingly urgent wood and fuel shortages in sub-Saharan Africa. It reviewed previous studies on the subject, with particular emphasis on Leucaena, and found that to date many of the studies have used rudimentary models of the actual processes involved. These are important points of departure, but they indicate the scope for innovation in both technique and theory. This paper builds on earlier efforts by bringing the Faustmann-Pressler-Ohlin Theorem to bear on fast growing tree species.

The model developed in this paper, in conjunction with information on agro-climatic conditions on Kenya, suggests that L. leucocephala could potentially play a significant role in addressing the future demand for fuelwood. The evidence shows that over one-quarter of Kenya's arable land is suitable for producing L. leucocephala. Further, its nitrogen-fixing properties, while not affecting the economically optimal rotation length, may nevertheless improve overall agricultural productivity. More data is needed to determine its growth performance in Kenya, to assess alternatives, and to determine what role it may play in meeting the future demand for fuelwood.

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Notes

1. This paper has benefitted tremendously from comments by Greg Nagale of the Department of Natural Resources and Jennifer Phillips, of the Department of Agronomy.

2. It is important in weighing the advantages and disadvantages of Leucaena to understand the different species within the genus and the purpose for which it is selected. According to NRC (1984), there are three main varieties:

   a.) Common type: short (3-5 m) bushy type that flowers year round. Because of swift propagation it is thought of as a weed. It can be used to reclaim barren hill slopes in the tropics, among other things;

   b.) Giant type: tall (15-20 m), this variety has become the focus of more recent research experiments on biomass and wood production. The higher-yielding varieties are known as "Hawaiian Giants" and are given the names K8, K28, K67;

   c.) Peru type: shorter than the giant types (10-15 m), this variety is useful mainly for the production of fodder. It is said to be much more productive than Hawaiian types, and may have lower mimosine content than giant and common types.

3. Ahmad and Ng write that, "At soil pH 4.75-4.95, the growth performance of Leucaena could be considered satisfactory. The critical level appears to be between 4.45 and 4.70, below which the species cannot be satisfactorily established." (1981: 7).

4. In a later study (1988) the same author found that even at high rates of volumetric growth, Leucaena plantations have a lower average internal rate of return (IRR) (7.4%) than other traditional cash crops, though the production risk for many cash crops may still make the trees an atractive alternative.

5. For instance they write, "Suggested spacings of about 1 m^2 to each rootstock, coupled with frequent harvesting, at cycles between 2 and 10 years, put considerable pressure on the soil in terms of nutrient removal as compared with conventional forestry with harvesting after 30 to 100 years. Studies (Steinbeck, 1981) in the USA have suggested a removal rate of around 50 kg ha^{-1} nitrogen, 10 kg P, 20 to 30 kg Ca and 5 to 8 kg Mg, in such intensive systems" (1983: 147).

6. Alley cropping with Leucaena substantially increases demands on labor. It is estimated that "on average, the maize crop leucaena treatment increased labor inputs by 52%..."(Ngambeki, 1985: 247).

7. The following formula is used to derive volume:

   $\text{Volume} = .5 * \text{dbh}^2 * \text{height}$

   where dbh = diameter at breast height. This formula is suitable for the range of dbh 2.5 - 10 cm, a planting density of 5,000 - 40,000, and for the first four years of growth (Van den Beldt, 1983; Kanazawa et al. 1982).

8. Although not included in the model, elevation may have had a significant dampening effect on growth. Group 2 had the highest elevation (320 m above sea level), whereas group 1 had an elevation of only 30 m.

9. Soil pH, although critically important as demonstrated above, will not be explicitly considered as it is highly variable throughout the country but will likely fall within the range given in Table 1. Also, acidity can be corrected to some extent by treating the soil with lime.

10. Equation 4.17 describes a point-input, point-output process; it assumes that the accumulated nitrogen is used at the same time the trees are harvested. However, it can be easily modified to reflect a cropping sequence (similar to alley-cropping) where the nitrogen is used prior to harvesting the trees:

$$\pi\,(T) = pQ\,(T)\,\rho^{T} + \sum_{t=0}^{T} \rho^{t} q X_{t} - c$$

at time t.

11. This figures calculated from data in Coleman et. al., (1989). It is relatively high, reflecting rapid leaching due to heavy rainfall.

12. Based on a 1990 price of urea in Kenya of 300 Ksh/50 kg. bag at an exchange rate of 25 Ksh/US$1. Since urea contains 46% nitrogen, X_t is scaled up by a factor of 2.17 (1/0.46) to arrive at the shadow price of pure nitrogen in the ground.

Table 1: Data on Volumetric Growth of Different 2-Year Old *Leucaena* Varieties

	Annual Growth (m^3/ha/yr)	Spacing (trees/ha)	Soil Acidity (pH)	Rainfall	Temperature	Variety (K28=1)
Group 1	30.7	2500	6.8	1740	22.2	1
	43.2	5000	6.8	1740	22.2	1
	38.1	10000	6.8	1740	22.2	1
	42.2	20000	6.8	1740	22.2	1
	37.9	40000	6.8	1740	22.2	1
Group 2	8.4	2500	5.6	2234	13.9	1
	13.4	5000	5.6	2234	13.9	1
	14.5	10000	5.6	2234	13.9	1
	15.6	20000	5.6	2234	13.9	1
	18.6	40000	5.6	2234	13.9	1
Group 3	9.1	2500	4.0	2514	19.0	0
	11.8	5000	4.0	2514	19.0	0
	18.0	10000	4.0	2514	19.0	0
	18.5	20000	4.0	2514	19.0	0
	25.5	40000	4.0	2514	19.0	0
Group 3	13.3	2500	5.0	1708	23.2	1
	17.0	5000	5.0	1708	23.2	1
	18.4	10000	5.0	1708	23.2	1
	18.2	20000	5.0	1708	23.2	1
	25.4	40000	5.0	1708	23.2	1

Source: Hu, Ta-Wei and Tao Kiang, 1982.

Table 2: Extent of Moisture Availability/Temperature Zones in Kenya

	Temperature Zone									in 1000 Ha.	in Percent
	1	2	3	4	5	6	7	8	9		
Moisture Availability Zone											
I	-	-	530	520	530	250	350	200	160	2540	4.4%
II	20	50	610	400	450	510	280	60	-	2380	4.1%
III	230	70	580	490	650	480	70	-	-	2570	4.4%
IV	480	360	840	450	590	150	-	-	-	2870	4.9%
V	3230	1940	1460	1260	840	-	-	-	-	8730	15.0%
VI	9540	2700	240	160	-	-	-	-	-	12640	21.7%
VII	26360	170	-	-	-	-	-	-	-	26530	45.5%
in 1000 Ha.	39860	5290	4260	3280	3060	1390	700	260	160	58260	100.0%
in percent	68.4%	9.1%	7.3%	5.6%	5.3%	2.4%	1.2%	0.4%	0.3%		

Source: Sombroek et al. 1982.

Table 3: Temperature and Moisture Zones Suitable for Growing Leucaena

Zone	Classification	Hectares ('000)	% of Total	Province	District
I-3	Humid Midlands	530	0.9%	Nyanza	S. Nyanza
				Western	Kakamega, Busia
I-4	Humid Midlands	520	0.9%	Nyanza	Kisii
				Western	Kakamega, Bungoma
				Rift Valley	Nandi
				Central	Murang'a
				Eastern	Meru
II-3	Sub-Humid Midlands	610	1.0%	Nyanza	S. Nyanza, Siaya
				Western	Busia
II-4	Sub-Humid Midlands	400	0.7%	Nyanza	Kisii, Kisumu
				Western	Bungoma
III-1	Semi-Humid Lowlands	230	0.4%	Coast	Kwali
III-3	Semi-Humid Midlands	580	1.0%	Nyanza	Siaya, Kisumu S. Nyanza
III-4	Semi-Humid Midlands	490	0.8%	Central	Murang'a, Kirirnyaga
				Rift Valley	Narok
IV-1	Semi-Humid/Semi-Arid Lowlands	480	0.8%	Coast	Kilifi, Tana River Lamu
IV-2	Semi-Humid/Semi-Arid Midlands	360	0.6%	Eastern	Embu, Meru
IV-3	Semi-Humid/Semi-Arid Midlands	840	1.4%	Nyanza	S. Nyanza, Siaya
				Rift Valley	West Pokot
				Eastern	Machakos
IV-4	Semi-Humid/Semi-Arid Midlands	450	0.8%	Rift Valley	Narok
Totals 1/		5,490	9.4%		

Source: Sombroek et al., 1982.

Note: 1/ Total Area used to calculate percentages is 58,260,000 Ha.

Table 4: Agricultural Land Potential and Population Densities in Kenya, By Province and District

PROVINCE	DISTRICT	AREA (Sq. Km.)	POP. DENSITY 1979	(Zones I & II)	% of Total	(Zones III & IV)	% of Total	(Zones V & VI)	% of Total	ARABLE LAND (ha.)	ARABLE AS PERCENTAGE OF TOTAL	HECTARES PER PERSON 1979
NAIROBI		684	1210									
CENTRAL	Kiambu	2,448	280	778	54.7%	470	33.1%	174	12.2%	1,422	58.1%	0.21
	Kirinyaga	1,437	203	285	29.8%	665	69.6%	5	0.5%	955	66.5%	0.33
	Muranga	2,476	262	961	53.2%	847	46.8%			1,808	73.0%	0.28
	Nyandarua	3,528	66	763	36.6%	1225	58.8%	97	4.7%	2,085	59.1%	0.89
	Nyeri	3,284	148	695	43.7%	685	43.1%	209	13.2%	1,589	48.4%	0.33
	SUB-TOTAL	13,173	178	3482	44.3%	3892	49.5%	485	6.2%	7,859	59.7%	0.34
COAST	Kilifi	12,414	35			2541	35.7%	4572	64.3%	7,113	57.3%	1.65
	Kwale	8,257	35	235	3.2%	1850	25.3%	5228	71.5%	7,313	88.6%	2.54
	Lamu	6,506	7			3887	70.5%	1630	29.5%	5,517	84.8%	13.04
	Mombasa	210	1625									
	Taita/Taveta	16,959	9	40	0.7%	663	11.3%	5139	88.0%	5,842	34.4%	3.96
	Tana River	38,694	2			418	4.9%	8132	95.1%	8,550	22.1%	9.25
	SUB-TOTAL	83,040	16	275	0.8%	9359	27.3%	24701	71.9%	34,335	41.3%	2.56
EASTERN	Embu	2,714	97	161	8.0%	639	31.7%	1213	60.3%	2,013	74.2%	0.76
	Isiolo	25,605	2									
	Kitui	29,388	16			2902	14.5%	17162	85.5%	20,064	68.3%	4.32
	Machakos	14,178	72	131	1.2%	3526	31.3%	7616	67.6%	11,273	79.5%	1.10
	Marsabit	73,952	1									
	Meru	9,922	84	743	14.0%	2127	40.0%	2447	46.0%	5,317	53.6%	0.64
	SUB-TOTAL	155,759	17	1035	2.7%	9194	23.8%	28438	73.5%	38,667	24.8%	1.42
NORTH EASTERN	Garissa	43,931	3									
	Mandera	26,470	4									
	Wajir	56,501	2									
	SUB-TOTAL	126,902	3									
NYANZA	Kisii	2,196	396	1914	99.4%	11	0.6%			1,925	87.7%	0.22
	Kisumu	2,093	230	605	37.9%	992	62.1%			1,597	76.3%	0.33
	Siaya	2,522	188	985	47.8%	1054	51.2%	20	1.0%	2,059	81.6%	0.43
	South Nyanza	5,714	143	2033	45.2%	2091	46.5%	375	8.3%	4,499	78.7%	0.55
	SUB-TOTAL	12,525	211	5537	54.9%	4148	41.2%	395	3.9%	10,080	80.5%	0.38

Table 4: Agricultural Land Potential and Population Densities in Kenya, By Province and District (cont.)

PROVINCE	DISTRICT	AREA (Sq. Km.)	DENSITY 1979	(Zones I & II)	% of Total	(Zones III & IV)	% of Total	(Zones V & VI)	% of Total	ARABLE LAND (ha.)	ARABLE AS PERCENTAGE OF TOTAL	HECTARES PER PERSON 1979
RIFT VALLEY	Baringo	9,885	21	207	2.9%	1769	24.6%	5209	72.5%	7,185	72.7%	3.53
	Elgeyo Marakwet	2,279	65	603	41.5%	501	34.5%	350	24.1%	1,454	63.8%	0.98
	Kajiado	19,605	8	3	0.1%	308	9.2%	3019	90.7%	3,330	17.0%	2.23
	Kericho	3,931	161	2553	75.6%	801	23.7%	21	0.6%	3,375	85.9%	0.53
	Laikipia	9,718	14	75	0.9%	1255	15.5%	6757	83.6%	8,087	83.2%	6.01
	Nakuru	5,769	91	1138	30.3%	1540	41.1%	1073	28.6%	3,751	65.0%	0.72
	Nandi	2,745	109	1136	59.0%	790	41.0%			1,926	70.2%	0.64
	Narok	16,115	13	2179	18.4%	3256	27.4%	6438	54.2%	11,873	73.7%	5.65
	Samburu	17,521	4									
	Trans Nzoia	2,078	125	344	22.1%	1206	77.4%	9	0.6%	1,559	75.0%	0.60
	Turkana	61,768	2									
	Uasin Gishu	3,378	89	328	11.8%	2453	88.2%			2,781	82.3%	0.92
	West Pokot	9,090	17	522	10.8%	846	17.4%	3487	71.8%	4,855	53.4%	3.06
	SUB-TOTAL	163,883	20	9115	18.2%	14725	29.3%	26363	52.5%	50,203	30.6%	1.55
WESTERN	Bungoma	3,077	164	1210	60.7%	782	39.3%			1,992	64.7%	0.40
	Busia	1,626	183	927	68.7%	422	31.3%			1,349	83.0%	0.45
	Kakamega	3,495	295	1918	75.3%	630	24.7%			2,548	72.9%	0.25
	SUB-TOTAL	8,196	224	4055	68.9%	1834	31.1%			5,889	71.9%	0.32
	TOTAL	564,162	27	23500	16.0%	43152	29.3%	80382	54.7%	147,034	26.1%	0.96

Source: Jaetzold and Schmidt, 1982.

Table 5: Estimated Volumetric Growth at Various Planting Densities

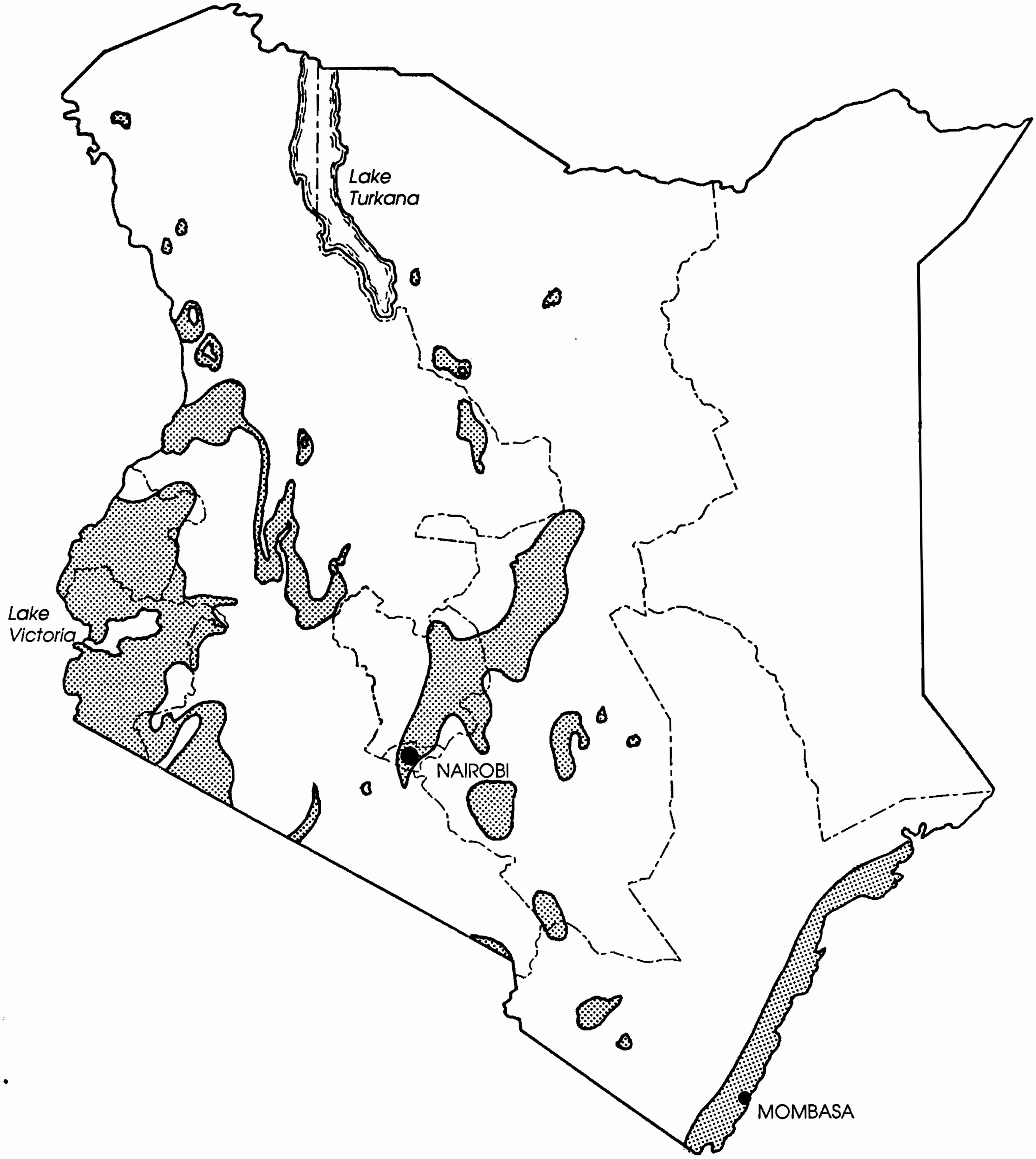
Density	Spacing	----- Parameter Estimates -----			
trees/ha		γ	η	t-ratio	R^2
2,500	2m x 2m	5.42	41.86	(53.18)	0.99
5,000	2m x 1m	5.61	36.18	(21.31)	0.99
10,000	1m x 1m	5.18	25.65	(13.15)	0.99
20,000	1m x .5m	5.45	25.25	(11.02)	0.98
40,000	.5m x .5m	5.33	24.21	(10.10)	0.98

Table 6: Projected Demand for Woodfuel and Potential Supply of Leucaena

Land Suitable	5.49	million ha.
Assumed Planted	2.75	million ha.
Rotation	3.00	years
Harvested Area	0.92	million cubic meters
Assumed Yield	30.00	cubic meters/ha/yr
Total Yield	27.45	million cubic meters
Projected Demand	57.30	million cubic meters
% Demand Met by Leucaena	48%	

Source: Projected Demand: World Bank, 1988.

FIGURE 1. ZONES SUITABLE FOR GROWING LEUCAENA IN KENYA



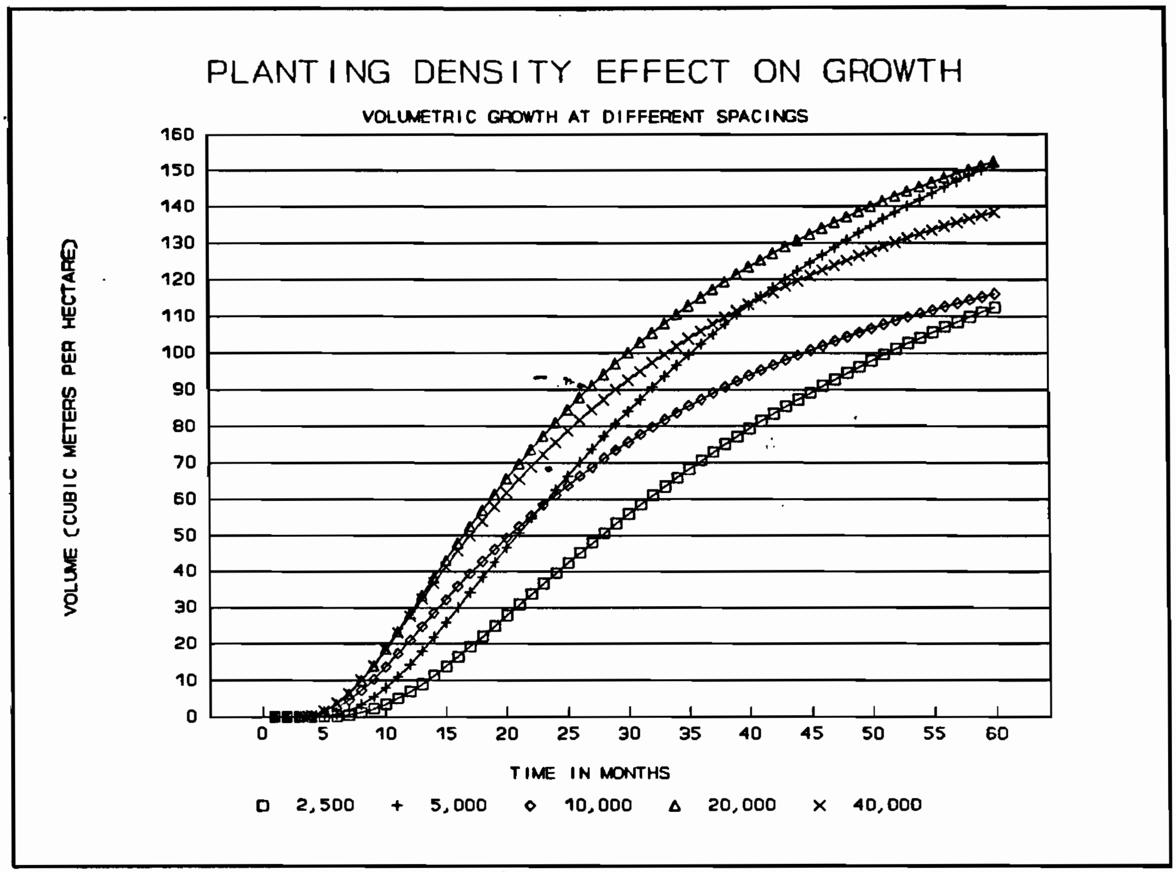


Figure 2: Planting Density Effect on Volumetric Growth of Leuceana

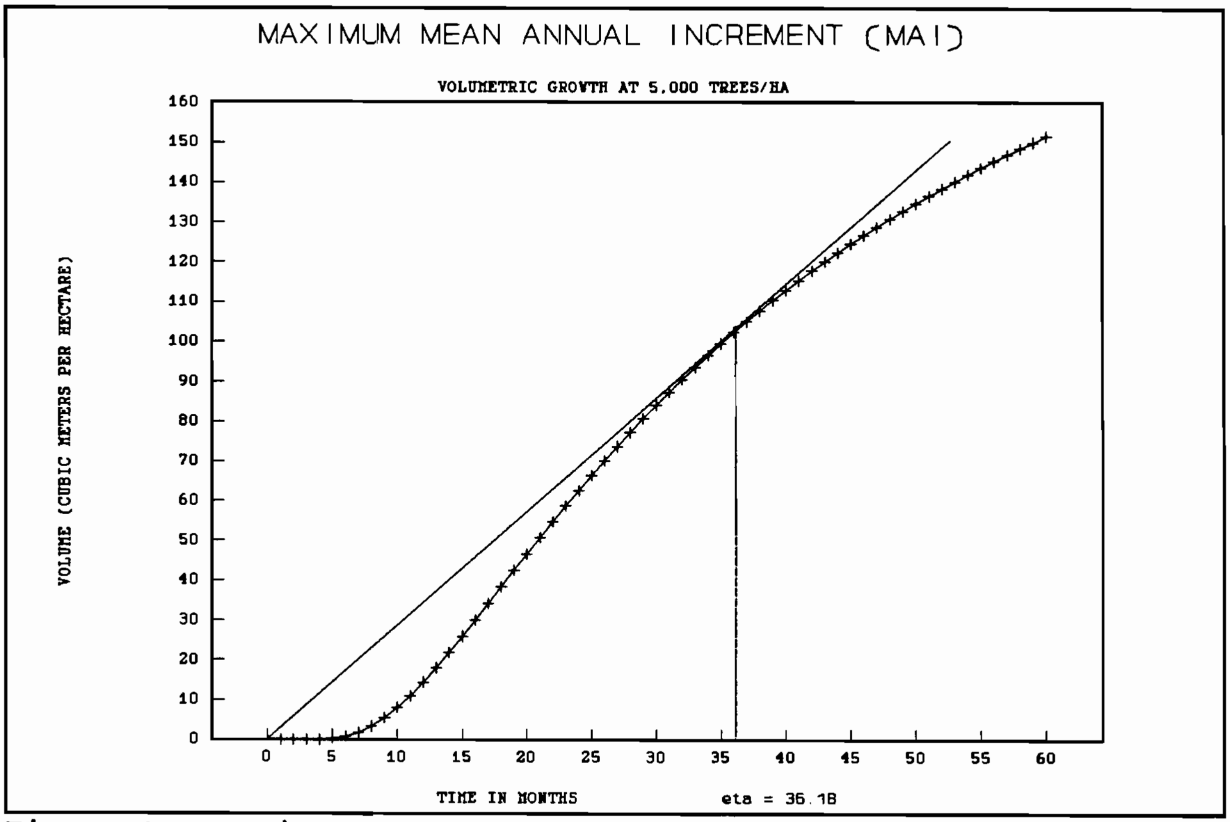


Figure 3: Maximum Mean Annual Increment (MAI) of Leucaena

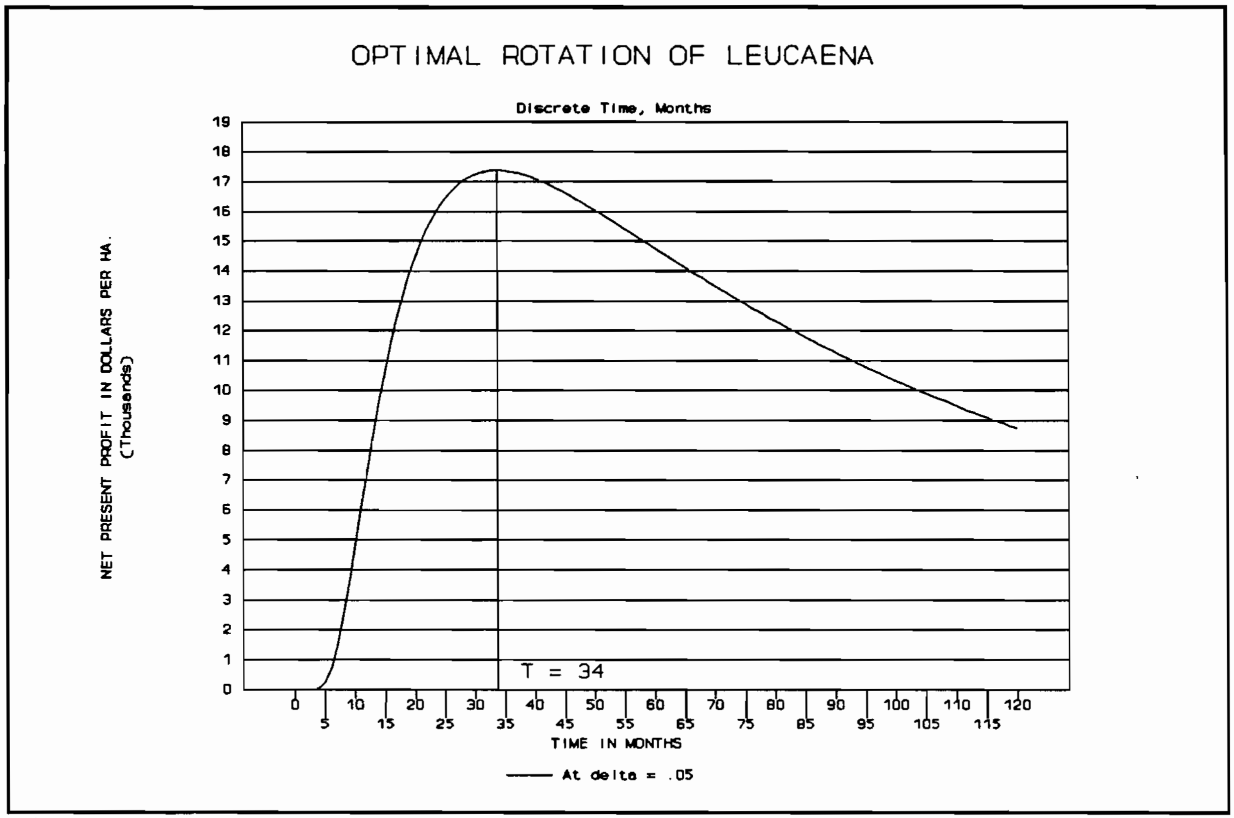


Figure 4. Optimal Rotation of Leucaena in Months (δ = .05)

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