Stand Density Regulation in Even Aged Teak Plantations

BY
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THESIS

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Dedicated to

Dr.J.P.Srivastwa

DECLARATION

I hereby declare that this thesis entitled "stand density regulation in even-aged teak plantations" is a bonafide record of research work done by me during the course of research and that the thesis has not previously formed the basis for the award to me of any degree, diploma, associateship, fellowship, or other similar title, of any other University or society

Place Vellanikkara
Date . 7 / 1991

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CERTIFICATE

Certified that this thesis, entitled "stand density regulation in even-aged teak plantations" is a record of research work done independently by Shri Prasoon Kumar under my guidance and supervision and that it has not previously formed the basis for the award of any degree, fellowship or associateship to him

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1. INTRODUCTION

1. INTRODUCTION

Teak (<u>Tectona</u> <u>grandis</u> Linn. f.) is the paragon among oriental timbers It is used for various kinds of works such as house building, carpentry, furniture making, wood carving etc In its natural habitat, teak forms a part of the moist and dry deciduous forests Teak plantations were extensively raised throughout Kerala, since the beginning of the last century The state has currently a total area of 72,415 8 hectares under teak (KSFD, 1988) Many of these plantations are, however, in a state of neglect (Karunakaran, 1970; Iyer, 1982)

With regard to plantation management in teak, longer rotations were practised in several forest divisions in the Kerala State, eg Wynad (Adiyodi, 1973) in order to produce larger sized logs, for which there was great demand Afterwards, these rotations were reduced and now a general rotation age of 60 years is being prescribed for teak in many parts of the state It is felt that the motivation for the reduction of the rotation age was only to get yield in a shorter period of time This system is not based on any scientific considerations

Again, thinning schedules, which, ideally, must depend on initial spacing, site, topography, product output, utilization standards, management objectives, availability of labour and equipment, nearness to market etc , are surprisingly uniform in many parts of the state 4,8,13,20,30 and 45 years or its slight variants are common (Karunakaran, 1970; Adiyodi, 1973, Iyer, 1982) In this connection, Sagreiya and Chacko (1962) have found that a rotation age of 45 years is the best for producing poles of 12 inch diameter in the quality class II forests with initial 233 elites per acre with tending

The fixed rotation system as well as the rigid thinning cycles currently in vogue are perhaps consistent with the regulation of yield by area (Vasudevan, 1966), but certainly inconsistent with site-specific stand density management What is required today is the management of plantations on scientific lines to fulfil the various forest management objectives

Density management is the manipulation and control of growing stock to achieve specific stand management objectives. These management objectives must be converted into stand level prescriptions. The first step in density management is to translate the stand management objectives into appropriate level of growing stock consistent with these objectives In this context, the control of growing stock to achieve a certain management objective is of critical importance The control of density levels (growing stock) in a stand has tremendous impact on the stand structure, productivity, and ability to produce a varity of resources (Daniel et al., 1979) Density management is the single most influential activity the silviculturist can perform between successive regeneration periods (Long, 1985) The manipulation of density (perhaps without affecting the stem form) would probably be the surest means for achieving diverse stand management objectives, such as producing large sized logs quickly (sudden sawlog regimes) or maximization of volume growth (as in the case of poles, small timber etc.).

Designing appropriate density management regimes to meet specific management objecties would therefore, be the logical course of action, considering the time value of money. Therefore, stand density management for specific management situation would be worth considering. This aspect has been completely ignored in the past in our country.

Various graphical aides have been developed for use in density management in other parts of the world using indexes based on size-density relationships (Gingrich, 1967, Wilson, 1979). The pioneer in this context is Ando (1968), who has developed "Stand Density Control Diagram" for most of the important commercial timber species of Japan Similar diagrams have been produced for coastal Douglas-fir

2. REVIEW OF LITERATURE

(*Pseudotsuga m ~iesii* Mirb Franco.) (Drew and Flewelling, 1979) and lobl y pine (*Pinus taeda* L) (Flewelling, 1981) and lodgepole pine (*Pinus contorta* var *latifolia* Dougl) (Mc Carter and Long, 1986) in North America These diagrams are also being adopted to suit different management objectives like wildlife habitat improvement (Smith and Long, 1987) and traditional forestry (Long, et al., 1988) Density Management Diagrams incidentally are simple stand average models that represent dimensional relationships in a graphical form. These diagrams help resource specialists predict and display the consequences of stand density manipulation and also, translate the management objectives into practical density management regimes (Long et al , 1988).

In the present study an attempt is made to develop a density management diagram for teak to facilitate stand density management for diverse objectives and also to demonstrate its utility for designing alternate density management regimes compatible with different management objectives

2. REVIEW OF LITERATURE

2.1. Density Ma   ement

Density management is the manipulation and control of growing stock to achieve specific management objectives While the actual control of growing stock is relati ly easy to achieve through initial spacing and intermediate cuttings, the determination of appropriate levels of growing st ck at the stand level is a complex process involving biological, technological and economic factors specific to a particular management situation (Davis, 1966). The control of density levels in a stand has tremendous impact on stand structure, productivity and its ability to produce multiple outputs.

2.2. Biological Basis of Density Management

Small initial difference in seed size, time of germination, growth rate etc leads to greater differences as the monoculture stand develops (Black, 1958; Black and Wilkinson, 1963) After sometime, it results in very dominant and suppressed individuals in the stand As the over - crowded stand grows, the death of the suppressed individuals occur and this, in turn, reduces the plant density. The death may occur because of catastrophic causes namely, disease, fire or wind throw, or due to the competitive interaction between individuals

2.2.1. Competition: The plant competition may be defined as "the tendency of neighbouring plants to utilise the same quantum of light, ion of a mineral nutrient, molecule of water, or volume of space " (Grime,1973) Under competitive conditions the form or size of plant may be modifie without leading to death of the plant These modifications are known as plastic responses (Hutchings and Budd, 1981).

Competition that trees experience early in stand development influences not only the rate of growth but also the form and general appearance of their boles (Baker, 1934) As the population continues to grow, a point is reached when the habitat may support no more biomass, the carrying capacity has been reached and any further growth can occur only at the expense of some biomass already present Thus, parts of plants or even whole plants will be lost from the population. These are usually the smallest and most suppressed individuals (Ford, 1975, Harper, 1977)

Even in a line thinned crop, those trees not adjacent to a removed line will have a relatively higher stocking density and hence higher mortality rates than those which are adjacent to a removed line (Rennolls and Peace, 1986) Generally speaking, increase in stand density causes a decrease in tree growth According to Sakai et al (1987) even an increase of one tree would reduce the dimeter (d b h) growth of neighbouring trees to the tune of about 0 75 cm This me hat growth of one tree occurs at the expense of the other trees growing within a given distance. To sum up, competition in a plant community is a density dependent natural phenomenon and has a marked effect on the diameter growth

2.2.2. Self - thinning: All stands, whether of artificial or natural origin, start their life with a very much larger number of seedlings per unit area, compared to the number of trees that remain at maturity This reduction in number of plants is due to the fact that the area has limited resources for tree growth Therefore, as the seedlings grow, they compete amongst them for the limited site resources In this struggle for existence only the most vigorous and the best adapted to the environment forge ahead leaving behind the rest The plants that are dying in this struggle are generally those which occupy lower layers of the canopy of a regular crop or smaller individuals (Ford, 1975, Harper, 1977; Khanna, 1984) This type of reduction in population is called self-thinning The self-thinning may, therefore, be defined as "mortality imposed by crop on itself" (Westoby, 1984)

The self-thinning in young teak (<u>Tectona grandis</u> Linn.f.) plantation was reported as early as in the 30's, and it was referred to as natural thinning. It was found that the number of trees reduced naturally and the suppressed and dominated trees were victims of this process (Shirley, 1929) After a period of 20 years mortality reduced the number of trees to an extent of 36-52% of the initial number of trees per hectare (Hellinga, 1939)

The relationship between size and density of individuals in populations experiencing density related mortality has been characterised by the "self-thinning rule" (Yoda et al , 1963). The self-thinning law quantified the relationship between number and average diameter on a double logarithmic scale. Ohn Moung (1968) found a closer linear correlation between the logarithm of number of stem per acre and logarithm of average diameter, which could be used to calculate the stem number as given in the yield table for a given average diameter with direct reference to plantation age.

The characteristic equation of the rule $B=CN^{-1/2}$ (Westoby, 1984) (where B = Biomass per unit area, N = density of survivors, C is a constant) defines a straight thinning line of slope -1/2 on double logarithmic scale Yoda's law, $W=CN^{-3/2}$ defines the thinning line of slope - 3/2 on a gragh of log W Vs log N Stands of small plants tend to accumulate biomass until they approach the thinning line Then they suffer mortality in relation to biomass accumulation as they travel along this line (trajectory) The thinning line, therefore, represents a sort of dynamic upper equilibrium condition (Westoby, 1984).

The simple geometric model, developed by Yoda et al (1963) to explain interspecific weight/density relationship during self thinning of over - crowded stands of individual plant species seems also to apply to interspecific weight/density relationships among diverse species of similar morphology (White and Harper, 1970) or two contrasting species (Bazzaz and Harper, 1976) or ranging in shoot weight and in shoot density (Gorham, 1979). Kumar et al. (1989) reported that in a mixture of two dissimilar species, the self-thinning behaviour of the whole population is dictated by the dominant species in the size heirarchy and the size density relationship of the sub-ordinate species assumed a shallower slope prior to its elimination from the population Adherence of the self-thinning rule is a characterstic of shoots but not of whole plants of Lolium perenne (Lonsdale and Watkinson, 1982) They found that the thinning line for shoot plus root per plant was shallower than the thinning line for shoot weight per plant They further added that population grown in deep shade underwent thinning, but along a line of slope of minus one, when sown at low density However, those sown at very high densities underwent an initial period of thinning following the rule but then followed a slope of minus one It has been suggested that the self-thinning rule might be better stated in terms of canopy volume rather than weight (Lonsdale and Watkinson, 1983; Long and Smith, 1984) Carleton and Wannamaker (1987) in their study identified the ecosystem processes related to changes in nutrient relations during stand growth which has a profound influence on the self-thinning behaviour in natural black spruce (Picea mariana) stand The tolerant species have also the same mortality as intolerant species (Zeide, 1985)

Weller (1987) on reanalysing many published data in support of thinning rule found that about one-third of them did not show any significant relationships between stand biomass density and plant density and out of the rest two-third, almost half were significantly different from the slope of minus half, the value predicted by thinning rule Deviations of the thinning slope from the predicted values are particularly important because it is the exponent of the power relationship So even small differences in slope represent large differences in the predictions of the equation. In the light of his and some other studies Weller (1987) suggested that the thinning rule as a qualitative law should be discarded, and the many claims made for the generality, theoretical importance, and [illegible]icability of the rule should be carefully re-evaluated

Lonsdale (1990) after re-analysing the evidences put forward by the supporters (Lonsdale and Watkinson, 1982, Westoby, 1984) and opponents (Zeide, 1985, Weller, 1987) of the -3/2 self-thinning rule has reached the conclusion that the relationship between shade tolerance or taxonomic groups and the slope of the thinning exponents are weak. However, he was of the view that more experiments are required for the final rejection of the idea that there is an ideal slope

The relationship between size and density of individuals in population experiencing density related mortality has been characterised by the self-thinning rule Self-thinning reduces the number of stems in a population due to the mortality of the suppressed and dominated individuals However, of late, several workers have questioned the universal constancy of the self-thinning exponent

2.2.3.Spacing: In the past, stands have commonly been established and maintained at high densities to develop certain desirable bole characteristics (Baker, 1934) The recent trend towards lower initial stand densities (eg "sudden sawlog regimes") has caused concern that stem quality may decline, for example, increased taper, larger branch diameter, and greater volume of juvenile wood (Brazier, 1977, Bendtsen, 1978, Senft et al , 1985) Trees in plots with low stand density was found to have more large and fewer small branches than when stand density was high (Ballard and Long, 1988) They have also found a similar relationship between number and diameter of green branches of lodgepole pine and have suggested that as density management cannot eliminate branches and, therefore, eliminate knots, but it can control their sizes The initial density may be then based on the largest acceptable knot size for a particular product

Some authors suggest artificial pruning to improve the quality of logs in widely spaced plantation (Ware and Stahelin, 1948, Box et al , 1964, Brender, 1965, Bennett, 1969, Feduccia and Mosier, 1977) Intermediate spacings (1500 - 2000 trees per hectre (TPH) depending on site) coupled with thinning was suggested as the best compromise where multiple products are the objectives (Nebeker et al , 1985).

Many studies were made to quantify the effect of spacing of plantation on diameter and height growth (Rudolf 1951; Guilkey and Westing, 1956, Wilde et al , 1968, Zavitkovski and Dawson, 1978) Zavitkovski and Dawson (1978) observed that height growth was depressed in higher density plantations compared to the average height at wider spacings and concluded that the main reason for height growth depression was competition for light However, Lanner (1985) observed that the additional resources made available due to the increased spacing were not drawn to the leader, but were used else where in the tree as in the vascular cambiumm So, the height growth was not affected by the change in spacing but the radial growth increased Again, Zavitkovski and Dawson (1978) reported that basal diameter and breast height diameter growth were more in wider spacings Results of Barrett (1981) also indicate the same trend He found that the average rate of diameter and basal area growth were approximately twice in the widest spacing (i e. 62 trees/acre) than that of the narrowest spacing (i e. 500 trees/acre). However, the average height of trees on low density plots was greater than that of those on the high density plots. These results also hold good for <u>Eucalyptus cloezina</u> (Saramaki and Sekeli, 1984) They found significant difference in diameter development but height growth was not significant.

Although volume production may be independent of initial spacing, stocking will have a marked effect on the diameter growth, as well as the length of time necessary to produce a product of a desired size (Nebeker et al , 1985) Therefore, several workers (Ek and Dawson, 1976, Zavitkovski and Dawson, 1978, Outcalt, 1986) have attempted fixing rotation length according to the density of the stand A rotation of 20-25 year has been recommended for *Pinus clausa* var. *immuginata* for a density of 600 stems per acre (Outcalt, 1986). It was found that the total merchantable volume was greater at this density He has also found significant differences in diameter development. At lower density, it was significantly greater but the net volume was less

Several workers suggested that although total volume was less, wide spacing (10 x 10 feet or more) produced more board foot volume in a relatively short rotation of 25-35 years than closer spacings (Bennett, 1963, 1969, 1971, Shepard, 1973, Arnold, 1978, Shelton and Switzer, 1980, Burton, 1982)

The effect of spacing on different tree characters has been studied. One important tree characteristic that depends both on height and diameter is the slenderness ratio or taper (Assamann, 1970). Zavitkovski and Dawson (1978) indicated that the dominant trees taper more rapidly and also survival increased with increasing spacing The average tree weight as well as weight of all tree components - stems, branches and needles - increased with increasing spacing for Jack pine (*Pinus banksiana*)

Pearson et al (1984) found that the ratio between sapwood area and foliage area was influenced by stand density The ratio, was quite different for an open stand

(400 to 1300 TPH) in comparison to that of a dense stand (more than 9000 TPH) In contrast, Hungerford (1987) did not find any influence of stand density on the ratio of foliage area · basal sapwood area for lodgepole pine Studies in a natural forest of Ohi (Albizia chinesis Osbeck Merr) showed that density was inversely related to bark per cent and diameter (Sagwal and Gupta, 1987)

Theoretical stability calculations for unthinned plantation of Sitka spruce (Picea sitchensis) at different spacing showed that the increase in resistance of uprooting or stem breakage as a result of incresing the mean tree size outweighed the greater drag force on the crown (Blackbury and Petty, 1988) They concluded that incrasing the spacing beyond the currently accepted norm of 2 meters would appear to improve stability

It can be summarised that spacing, either inital or after thinning, has a pronounced effect on height, diameter growth and biomass increment and thus affects the volume increment Spacing indirectly affects all those tree characters that depend on height and diameter (e g.taper) and also the rotation length required to produce a desired dimension log or timber Resistance to stem breakage and uprooting can also be improved with correct spacing between trees

2.2.4. Thinning: Stand Self - thinning confers advantages such as increased height growth of the survivors, retention of more vigorous and in most cases, straight and more cylindrical stems However, it adversely affects the growth of even the dominant trees (Khanna, 1984) Therefore, it is necessary that the number of plants per unit area in stands is gradually reduced as the crop advances in age i.e the stands should be thinned as they grow with age

Thinning may, therefore, be defined as "a felling made in an immature stand for the purpose of improving the growth and form of the trees that remain, without permanently breaking the canopy" (Khanna, 1984) Thinning is done only to regulate the distribution of the growing space for the purpose of improving the growth

It was seen that heavy thinning, in suppressed forests of good or better site quality, increased volume of standing timber than low light thinning due to higher radial growth rate, but not height Heavy thinning of dominant trees and heavy partial clearance of forest stimulated diameter growth, but later affected the yield, form and branching adversely (Beumee, 1922) It is now generally accepted that teak requires ample room for its development and that once the crown have been allowed to be restricted they do not respond rapidly to a thinning The aim of thinning must, therefore, be to allow a healthy development of the crown while at the same time retaining as many trees per acre as possible It is found that once a teak plantation has been allowed to get congested, the annual increment is not only reduced but that it takes a number of years after thinning have been carried out to bring the current annual increment up to what it would have been if the stand was correctly thinned (Blanford, 1923)

Shirley (1928) reported that neglect and delay of thinning results in congestion of crown, poor under growth, erosion and slow growth increment and deficient volume Less diameter growth is the common features of unthinned stands than the thinned plantation However, the number and the total basal area per hectare was generally more in those stands Hellinga (1939) had reported a 5-25 per cent reduction in volume of the unthinned stand when total volume was taken into consinderation. Thinning intensities have negligible influence on height of trees in dominant and codominant positions (Wilson, 1946, FRI, 1955) Thinning affects the radial growth of individual tree positively and tree height growth negatively (Hibbs et al , 1989)

The average diameter of thinned crop and the main crop were independent on site quality and thinning grade for teak within the range of C and D grade of ordinary thinning

(Mathauda, 1954) Studies at FRI (1955) revealed that heavier grades of thinning gave progressively higher diameter increments But at the end of 16 years, the yield of useful basal area and that of total volume produced decreased as intensity of thinning increased Similar results have been reported by Pongsopha (1962) also However, he observed significant height growth in 80% more removal than normal He sugested that a heavy thinning for teak is desirable Sarlin (1966) considered selection thinning better than mechanical thinning since the increment after first thinning of about 50% in the tenth year was grater Even in coppice forest of teak, it was found that the volume increased greatly in thinned shoots than unthinned ones (Edie, 1916) He recommended the thinning out of inferior coppice shoots of teak only after 10 years.

Early heavy thinning is not advisable for teak because the young crop will become branchy and the danger of storm damage to young shallow rooted trees will be grater As the tree becomes branchy, pruning becomes necessary which is too expensive. Again, weed control will be difficult and also the thinned material at the age of first four years are too small to be merchantable Drastic opening of the canopy also can cause site degradation (Khalil, 1943) But frequent light thinnings may yield a better quality product and perhaps more board foot volume than heavier thinnings

(Farrar, 1968; Fender, 1968, Feduccia and Mosier, 1977).

Bryndum (1987) found that yield per hectare was independent of stand density in stands thinned lightly. He recommended an early moderate thinning followed by a slightly more intense thinning for beech which would produce good quality timbers. Leduc and Zeide (1987) reported that density and pruning intensity had direct and inverse relationship with volume, respectively It was found that different intensities of thinning had no significant effect on average wood density of Cupressus lusitanica (Malende and Dingo, 1987).

Thinning affects the diameter growth, yield and branching Neglect or delay of thinning causes adverse effect on undergrowth, erosion and growth increment and volume Thinning has negligible influence on height growth of trees

2.2.5. Stand density indices: Drew and Flewelling (1979) has given a relative density index (the ratio of actual stand density to the maximum stand density attainable in a stand with the same mean tree volume) as a basis for quantifying tree growth and stand yield The accepted measures of stand density (the number of stems per unit area, basal area and biomass) are satisfactory only when the average tree size is identical in the compared stands Hence, indices of stand density that combine some expression of mean size (e.g mean weight, volume, height and d b h) and density (Curtis, 1970, 1971; Long and Smith, 1984) are relevant Perhaps the most familiar of these indices is Reineke's (1933) stand density index (SDI), based on the predictable relationship between quadratic mean diameter and trees per unit area in dense stands. Other indices that have been suggested as meaures of growing stock include mean volume-density (Drew and Flewelling, 1977) and mean height-density (Wilson, 1979). The Reineki's and other density indexes are independent of site quality and stand age (Daniel et al , 1979, Curtis, 1982, Long 1985)

Similar to Reineke (1933), Sterba (1987) has suggested a stand density index to give potential density of sites This approach is found to be suitable for evaluation of difference in gross volume hat would not have been detected from yield tables alone

It was found that the Slenderness index, which is defined as the height in feet divided by d.b.h in inches, decreased with increasing spacing of 10 year old jack pine trees (Rudolf, 1951) Zavitkovski and Dawson (1978) found that slenderness index followed the same trend for dominant trees also but the values were lower

Kikuzawa (1983) has calculated compactness index for deciduous broad leaved forest. He drew Equivalent Diameter curves which show the number and volume of trees larger then a certain diameter at three levels of stand compactness and argued that most of the variation in the equivalent diameter points of each of the tree groups (grouped according to stand compactness levels) can be explained by the difference in stand compactness levels

Stand density index is an ideal measure of growing stock A good index should combine mean size and density One of the widely used indexes is Reineke's stand density index which combines quadratic mean diameter and trees per unit area This index is independent of site quality and stand age.

2.3. Empirical Approaches for Density Regulation

There are different approaches to regulate density and yield from different forests as described below Fundamentally, thinning consists of removing some trees from the places they occupy, to assure the survivors adequate growing space. Also it is evident that no stand density formula can be written which does not include that basic item - the stem count - or the number of trees per unit of area (Wilson, 1979)

2.3.1. Percentage height approach: Some workers have related the percentage of height with the space left after thinning

For red pine, 16 to 24% of height with thinning interval of 3 years and 17-30% of height with thinning interval of 3 years have been suggested by Day and Rudolph (1971) and Day and Rudolph (1972) Handler (1984) has given 10-20% of mean height for sitka spruce for average stem distance and 18% of that for beech These relationships are very useful

2.3.2. **Height and density approach:** Sagreiya (1963) has proposed a relationship of stand density to height represented by the equation $NH^2 = 510{,}000$ (where H is the top height of stand and N is the number of stems per acre) He found that the height, within reasonable limits, was unaffected by the intensity of thinning In other words, his study was based on the fact that top height is more or less independent of stand density He argued that this relationship is independent of age for all practical purposes and valid for the usual thinning period of a crop It has been contended that Sagreiya's formula of thinning results in heavy removals (Ram Prasad, 1973). He suggested that in early stages at least more stem per unit area be retained and crop can be opened up more at later stages for higher diameter increments

2.3.3. **Diameter and density approach:** Sagreiya and Chacko (1962) have given three equations relating height with site quality and age, secondly, normal diameter with top height and lastly normal number of trees per acre at given mean diameter These three equations summarise the yield table for even aged teak forests They have suggested that 150-163 elites per acre with a rotation of 60-65 years is preferrable to growing large number of poles of a specified size of 15 inch diameter Liu (1984) developed equations, for natural larch stand and china fir plantation, relating diameter and stand density

2.3.4. Density management diagrams: There are different stand control diagrams (as a guide for thinning schedules) Some of them are functions which use crown competition factor (CCF) as a measure of density (Yang and Lin, 1981). The site quality could also be introduced as a further independent variable in the variable density yield tables and stand control diagrams Often dynamic programming procedures are given for optimizing thinning schedule and rotation of even-aged plantations using, age, basal area, number of trees and time since thinnings (Ritters et al., 1982). They argued that forage and timber production can both be optimised because both are functions of stand density in ponderosa pine (Pinus ponderosa) Many diagrams used mean height, diameter, number of dead standing trees, basal area and stem wood volume as functions of planting and of stand density (Kikuzawa, 1983, Merzlenko, 1983, Kisilev and Atroshchenko, 1985, Nigi, 1986)

There are many management diagrams, which are based on the self-thinning rule, for different species, namely, Douglas fir (Pseudotsuga menziesii) and Ponderosa pine (Pinus ponderosa) (Riitters and Brodie, 1984) The geographical model of Dzedzyulya (1985) for regulating yield and size by changes in stand density is based on the law of competitive self-thinning and relative density index.

The growth models of Smith and Hann (1986) suggested a maximum relative density of 40 and 50% for Alnus rubra and Pinus resinosa respectively The model of Lloyd and Harms (1986) consists of the relationships between maximum plant size, time and density incorporating a function for survival Drew and Flewelling (1979) developed a simple stand management diagram for Douglas fir (Pseudotsuga menziesii). The most comprehensive of the graphical models are density management diagrams (Long, 1985). Hara and Oliver (1988) developed a three dimensional model with the help of three variables, tree per hectare, breast height age and either mean tree volume or stand volume. This model is a reasonably accurate representation of unthinned stand growth The density management diagram together with site index table can be used to estimate average stem diameter and total yield produced with various stand densities of lodgepole pine (Pinus contorta) (Mc Carter and Long, 1986) Smith and Long (1987) has modified the lodgepole pine density management diagram of Mc Carter and Long (1986) and suggested the use of this graphical tool for the evaluation of wildlife habitat Hibbs (1987) found that the relative density value for crown closure, mortality and the lower thinning limit for red alder (Alnus rubra Bong) correspond to those for other species

Many statistical methods are available to regulate density and yield from different forests Commonly, the percentage height approach or diameter and density approach are in common use Density management diagrams are simple stand average models that represent dimensional relationships in a graphical form These diagrams help resource specialists to predict and display the consequences of stand density manipulation and also, translate the management objectives into practical density management regimes These could be used in a variety of management situation, including traditional wood production as well as wildlife habitat improvement

3. STUDY AREA

3. STUDY AREAS

Stand inventory data were collected from the teak plantations at three locations, namely, Parambikulam (Wildlife Sanctuary), Thrissur and Chalakudy Forest Divisions during the period from October 1989 to May 1990

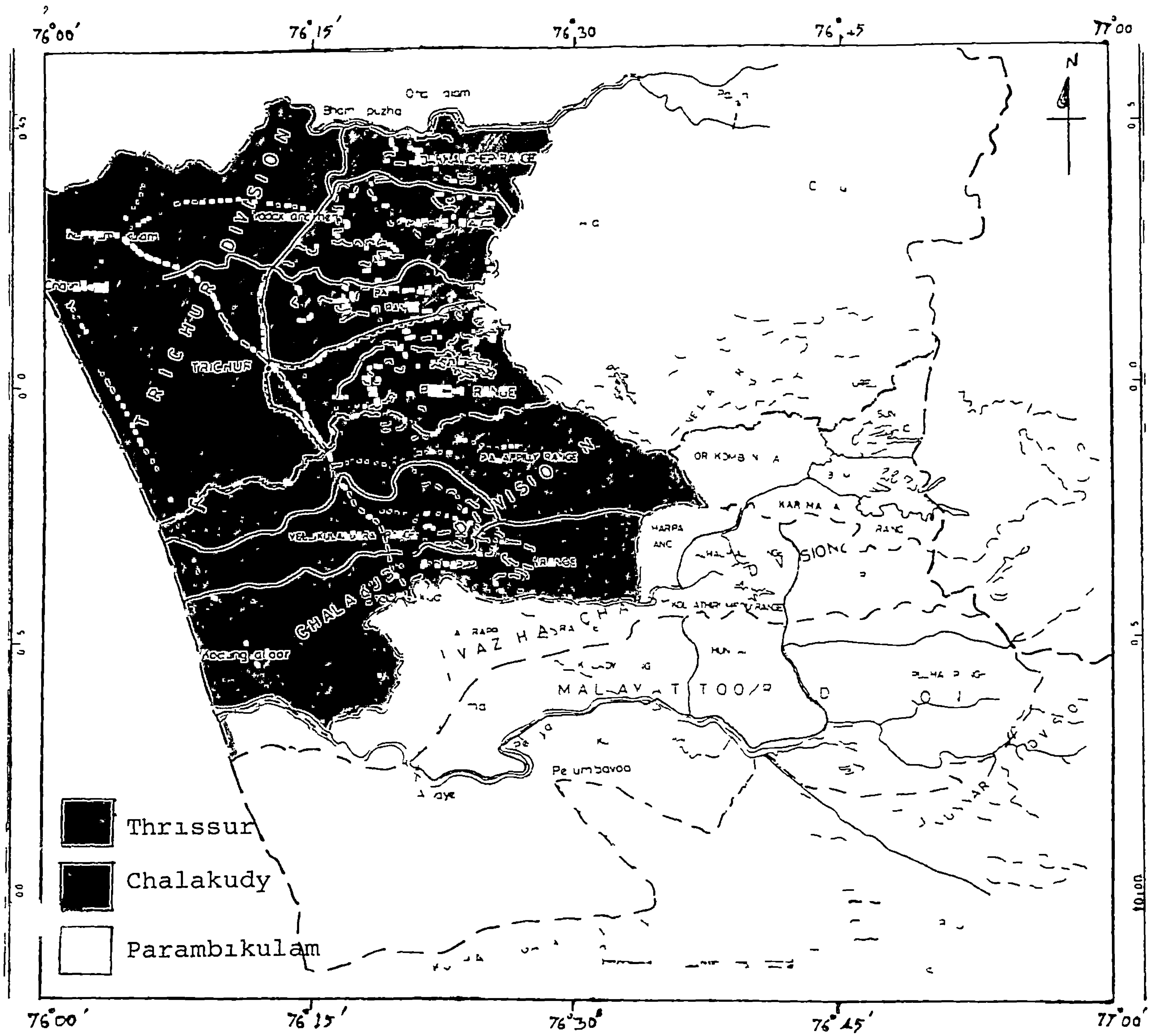
3.1. <u>Parambikulam (Wildlife Sanctuary)</u>

Teak was extensively planted in the erstwhile Parambikulam Forest Division (between $76^{\circ}31'$ and $76^{\circ}50'$ east longitude and $10^{\circ}21'$ and $10^{\circ}26'$ north latitude [Map 1]) ever since 1921, until 1983 At present, no planting and harvesting operations are undertaken after the conversion of the division into a Wildlife Sanctuary Table 1 contains the details concerning forest plantations in different ranges of the division

Table 1 Plantation details of the erstwhile Parambikulam Forest Division

Range	Area under plantations (Hectare)		
	Teak	Eucalyptus	Teak + *Ailanthus malabaricum*
Karaimala	3254 27	-	-
Sungam	1796 00	71 51	30 09
Orukomban	1702 54	-	-
Parambikulam	1752 00	-	-
Total	8504 81	71 51	30 09

(Source Uniyal, 1988)



Map 1. Location map of Thrissur, Chalakudy and Parambikulam Divisions

Teak plantations in the Karaimala and Sungam ranges of the Wildlife Sanctuary were selected for the present study Tropical Evergreen forests, Tropical Semi-Evergreen forests and Moist Deciduous forests are the other prominent vegetation types occuring in this area Topographically, the area exhibits a hilly terrain with characteristic distribution of undulating plains and marsh lands interspersed in the valleys The valleys are low lying, having a gentle undulating surface and are covered with artificially regenerated teak The altitude varies between 300 m to 1430 m

3.1.1. Geology, Soil and Climate: The main geological formation in the area are hornblende, biotite gneisses, charnockites which had been intruded by granitic-orthogenisses and Plagioclase-porphyry-dykes (GSI, 1964) Major constituents of these rocks are quartz, biotite, orthoclase and plagioclase feldspar. The soil on the slopes are chocolate coloured, sandy loam which is rich in organic matter and supports a good vegetation. In the valley, it is clayey loam

The area gets both the south west and north east monsoons, south west being the most effective The mean monthly rainfall ranges from 1 cm to 36 cm in plains (Fig 1) In hills, it ranges from 1 cm to 46 cm (Fig 2) The maximum

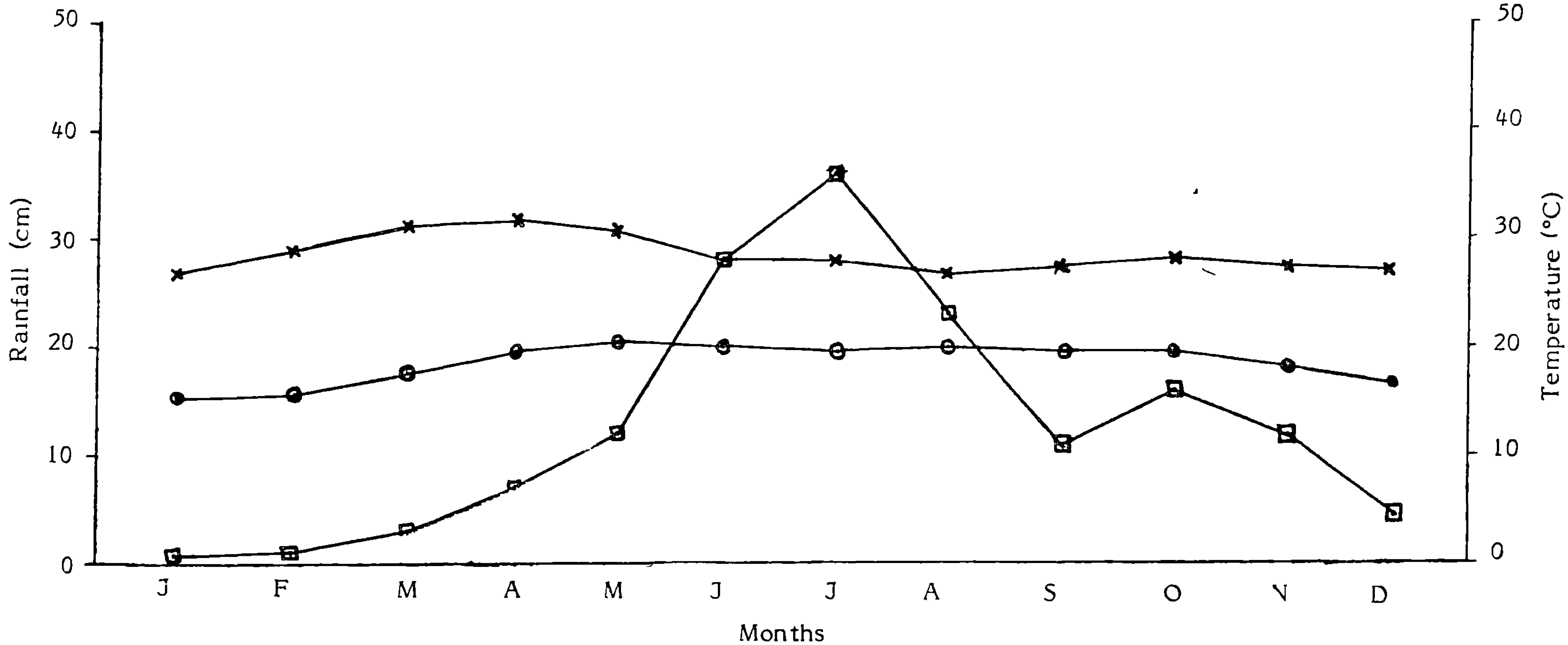


Fig.1 Mean monthly rainfall, maximum temperature and minimum temperature at Tuncadavu for the period from 1965 to 1985 (□-□-□:Rainfall; x-x-x : maximum temperature and o-o-o · minimum temperature)

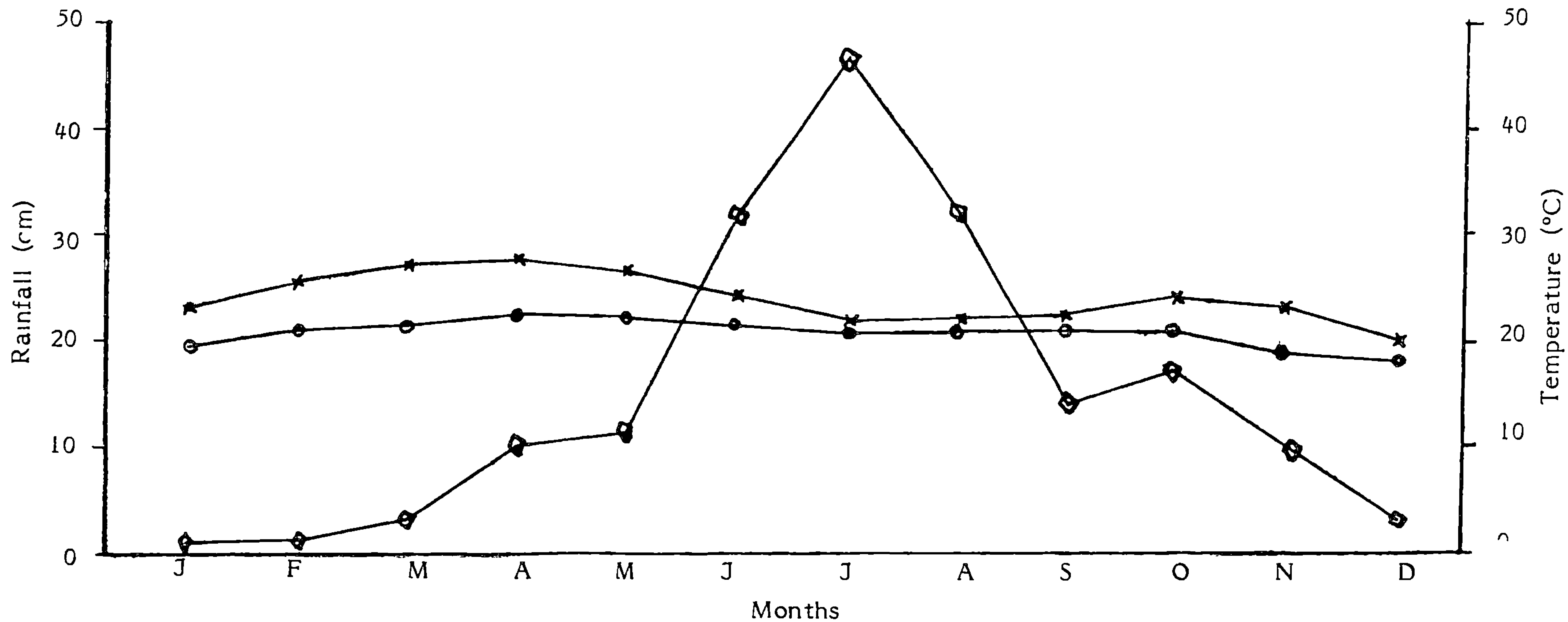


Fig.2 Mean monthly rainfall, maximum temperature and minimum temperature at Parambikulam for the period from 1965 to 1985 (□-□-□ Rainfall, x-x-x : maximum temperature, o-o-o : minimum temperature)

mean monthly temperatures fluctuates between 26 5^{o}C to 32.0^{o}C, whereas the minimum ranges from 15 5^{o}C to 20 5^{o}C in the valley (Fig 1) March and April are the hottest months

3.1.2. Management of Teak Plantations: Regarading thinning, the general principle followed was to thin early and heavily provided that no lasting gaps in the canopy are made. 'C' garde thinning was recommended A thinning cycle of 4,8,12,20,29 and 40 years was fixed taking into account the faster girth increment (Uniyal, 1988). However, c rently no intermediate operations are being carried out in these plantations

3.2. <u>Thrissur Forest Division</u>

Thrissur Forest Division is situated on the 'T' shaped strip of the Western Ghat, south of Palghat gap (between 76^{o}5' and 76^{o}45' east longitude and 10^{o}20' and 10^{o}45' north latitudes [Map 1]) The altitude varies from 30 m to 1515 m

3.2.1. Geology, Soil and Climate: The prevailing geological formation is metamorphic rocks of the gneiss series Laterites occur in places The soil is fairly deep, blackish sandy loam which tends to be reddish in places on the lower slopes (George, 1954)

The climate is generally equable in the low country and fairly cool higher up March, April and May are the hottest months when the maximum mean monthly temperature goes up to about 38 0 ^{o}C, in the hills The maximum mean monthly temperature ranges between 32 0 ^{o}C to 38 0 ^{o}C and the minimum ranges from 20 0 ^{o}C to 23 5 ^{o}C in hills (Fig 3) However, in plains it varies from 29 0 ^{o}C to 36 0 ^{o}C and 20 3 ^{o}C to 25 0 ^{o}C respectively (Fig 4) The coolest months are December, January and February Average annual rainfall is 268 cm in hills and 301 cm in the plains

3.2.2. Teak Plantations: The first teak plantation in the division was raised in the year 1872 This was followed by continuous annual planting up to 1889 except during the year 1874, 1875, 1881 and 1886 Regular plantings were resumed in the year 1923 (George, 1954) There are about 3219 56 hectares of teak plantations in the division (Table 2)

Table 2. Details of plantations in Thrissur Froest Division

Ranges	Area under plantations (Hectare)		
	Teak	Teak + Bombax ceiba	Teak + Bamboo
Wadakanchery	510 76	-	-
Machad	1738 68	571 36	-
Peechi	309 08	-	361 04
Pattikad	661 04	-	-
Total	3219 04	571 36	361 04

(Source George, 1954)

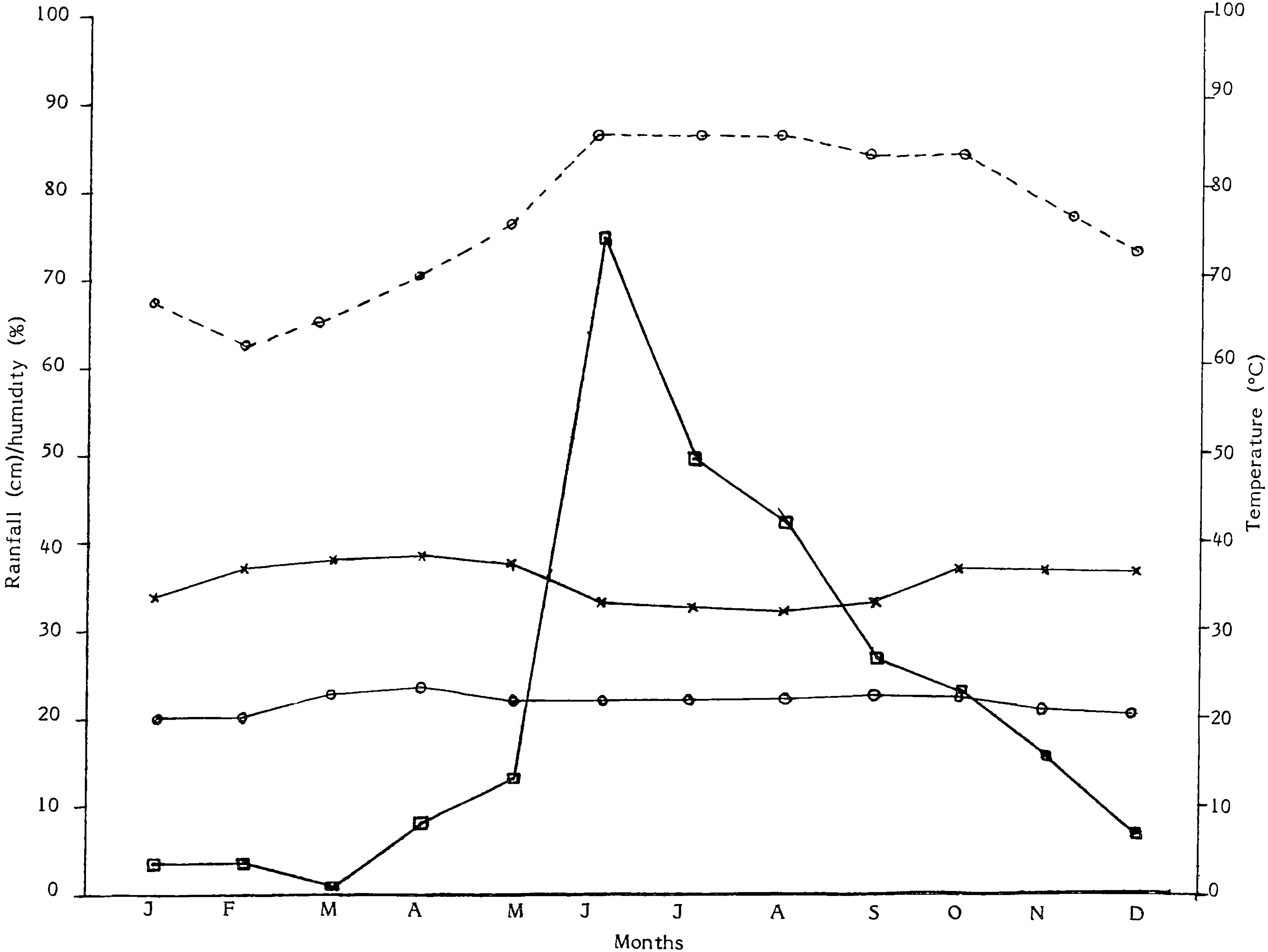


Fig.3 Mean monthly rainfall, maximum temperature, minimum temperature and relative humidity • at Peechi for the period from 1985 to 1990 March (□-□: rainfall; x-x-x : maximum temperature; o-o-o : minimum temperature and o--o--o · relative humidity)

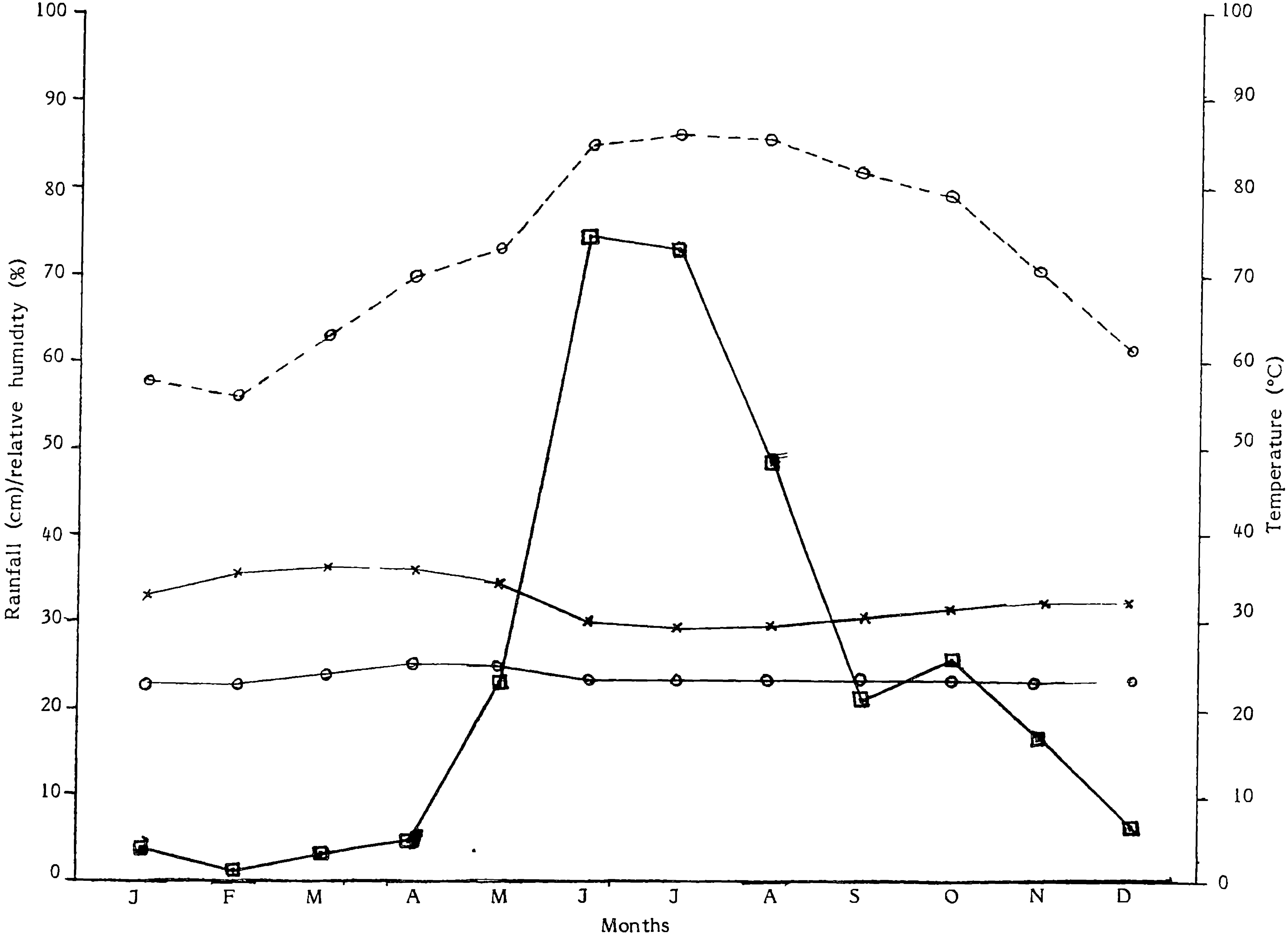


Fig.4 Mean monthly rainfall, maximum temperature, minimum temperature and relative humidity at Vellanikkara for the period from 1985 to 1990 July (x-x-x : Maximum temperature; o-o-o : Minimum temperature; o--o--o : Relative humidity and □-□-□ : Rainfall)

There is considerable variation in the quality of the crop in different plantations Thinning cycle was different for different sites depending on site quality (George, 1954).

3.3. <u>Chalakudy Forest Division</u>

The Chalakudy Forest Division lies south of Thrissur Forest Division (between 76°10' and 76°40' east longitudes and 10°15' and 10°30' north latitudes [Map 1]) within the Thrissur Revenue District The altitude varies from 30 m in the plains to over 1116 m in the hills Most of the area is hilly in character and the ground is undulating, the eastern portion being more rugged and having many valleys of which Chimany-Mooply, Seenikuzhi-Idukkupara etc are important.

3.3.1. Geology, Soils and Climate: The underlying rock formation is metamorphic gneiss of a complex crystalline structure In the foot hills and over a greater part of the plains, the rock is foliated to a great degree. Veins of quartz and feldspar appear in varying thickness and out-crops of mica and granite are not uncommon, laterite is more commonly met with on the foot hills than on the higher ridges (Akkara, 1984)

Soils have been formed from archaean rocks which include gneisses, charnockites and basic dykes Soils have been formed under sub-humid climate and under evergreen, semi-evergreen and moist deciduous types of vegetation Soils under evergreen and semi-evergreen forests are dark brown to brown in colour. Most of the soils are deep and the surface horizons of these soils have the following characteristics sandy loam to loam texture, slightly acid reaction and fairly high organic carbon (Akkara, 1984)

The climate is fairly equable with very little seasonal and diurnal temperature variations The dry season is from December to April and humid season from May to November The hottest months are March, April and May and the coldest are December to January In the hot months of March, April and May the average temperature will be 32 0 ^{o}C to 36 0 ^{o}C in the low country and about 24 0 ^{o}C to 30.0 ^{o}C in the hills During the cold season (December, January and February) the temperature in the low country falls to 20 0 ^{o}C whereas in the hills it drops to less than 15 0 ^{o}C (Akkara, 1984) The mean average rainfall is 298 cm and is derived from both South West and North East monsoons (Fig.5).

3.3.2. Teak Plantations: Plantations were raised in groups at Palapilly, Vellikulangara and Pariyaram ranges Apart from pure plantations of teak, bombax and cashew mixed plantations were also raised The earliest plantation activity dates back to 1905, though regular annual planting started only in 1912 Total extent of plantation in the division is 6172 0 hectares

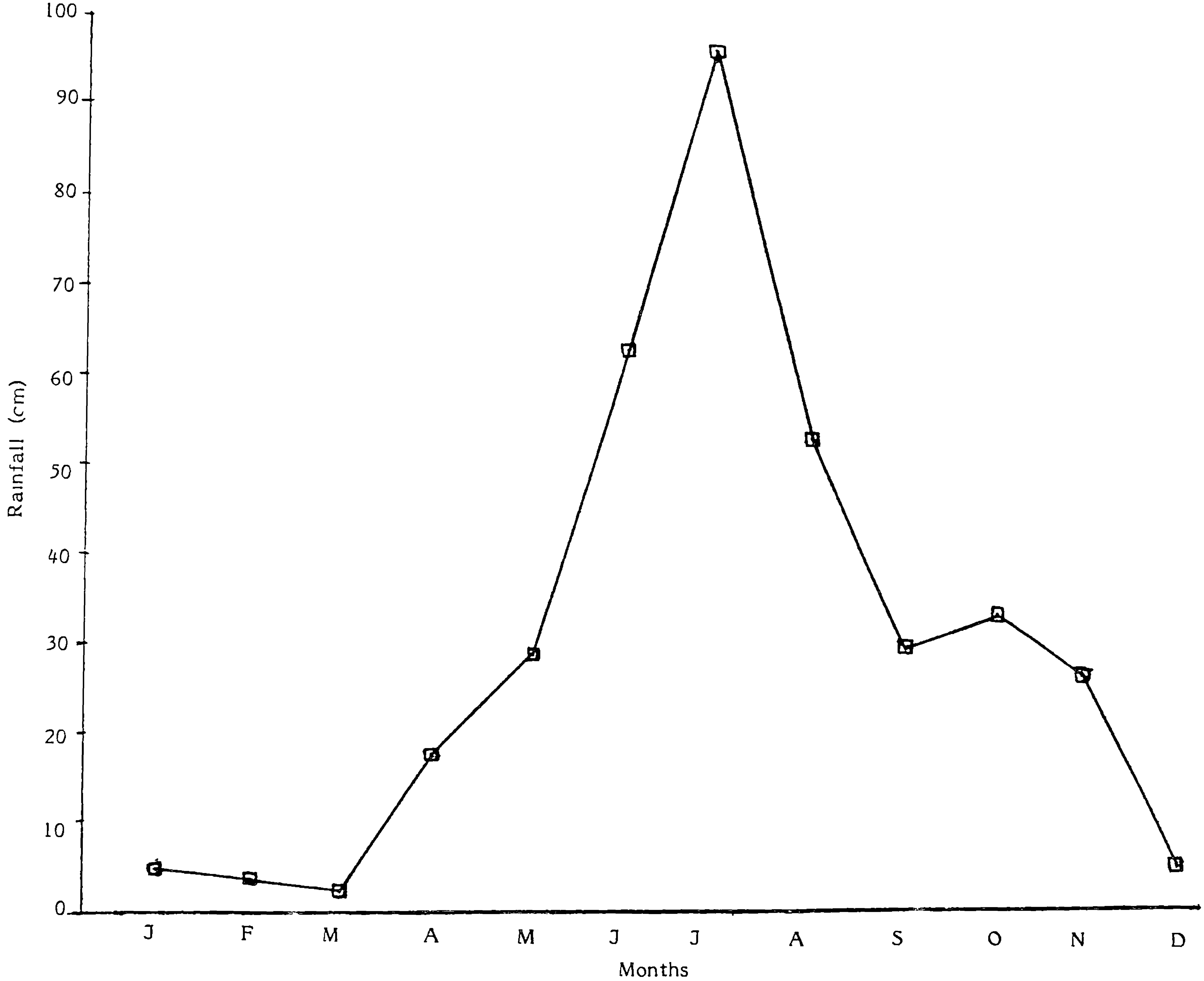


Fig.5 Mean monthly rainfall at Chalakudy for the period from 1971 to 1980

Table 3. Details of plantations in Chalakudy Forset Division.

Ranges	Area under plantations (Hectare)		
	Teak	Teak + Bombax ceiba	Acacia + Teak
Palappilly	506 98	800 19	-
Vellikulangara	1096 40	-	-
Pariyaram	2923 24	-	20 64
Total	4526 62	800 19	20 64

(Source. Akkara, 1984)

A thinning cycle of 5th, 10th, 15th, 20th, 30th and 40th year has been prescribed (Akkara, 1984) However, for want of adeqate timely tending operation the plantations are in a degraded condition

4. MATERIALS AND METHODS

4. MATERIALS AND METHODS

Teak plantations of different thinning intensities and age classes (average class interval = 5 years) starting from the 75 year old (1915 plantation) were selected from Parambikulam, Thrissur and Chalakudy Forest Divisions

Plots of size 63 25 x 63.25 m (one acre) were established in selected stands in the following manner First a base line was marked using a compass and a metre tape. On the base line a point was selected and a distance of 63 25 m was measured Using the compass a 90^{o} line was marked which formed the second side of the square plot The third and fourth sides were also determined in this fashion. A total of 116 such plots were established in the Thrissur (19 plots) Chalakudy (79 plots) and Parambikulam (18 plots) divisions.

All trees in the 116 plots were enumerated Top height (height of a tree up to the tip from the base) in meter and girth at breast height over bark (1.3m from the base) in centimeter were measured using a Ravi Multimeter (Ravi Vygyanik Yantra Nirmata, Dehradun) and DBH-tape respectively

Using these variables, average diameter at breast height (DBH), quadratic mean diameter (Dq), mean height (Ht), density per hectare, basal area (BA), total volume, mean annual increment (MAI) for diameter (DMAI), height (HMAI) and for gross volume (GVMAI), stand density index (SDI) and relative density (ρr) were calculated using the equations given in Table 4. The age of the plantation was calculated as on 1990 from the year of plantation establishment

The data indicate that trees per hectare (TPH) ranged from 20 to 760 between the age of 10 to 75 years The total volume varied from 62 0076 $m^3 ha^{-1}$ to 519 7161 $m^3 ha^{-1}$ whereas the basal area (BA) variation was from 3 1309 $m^2 ha^{-1}$ to 21 4758 $m^2 ha^{-1}$ Tree height varied between 8 1687 m to 28.8507 m (Table 5 and Appendix I)

4.1. Statistical Models Used

The following models were used for the present study

$$\hat{Mvol} = e^{bo} \, e^{b1} \, Den \, e^{b2} \, Ht$$

$$\hat{Dq} = e^{bo} . e^{b1} \, Mvol \, e^{b2} \, Den$$

The models are logarithmically linear and were fitted by the principle of least squares (with SPSS/PC).

The transformed equations are as follows·

$$\ln \hat{Mvol} = bo + b1 \ln Den + b2 \ln Ht$$

$$\ln \hat{Dq} = bo + b1 \ln Mvol + b2 \ln Den$$

Where bo is the intercept, b1 and b2 are the partial regression co-efficients, Den is the density per hectare, Mvol is the mean volume per tree.

The models were also examined for the pattern of residuals to detect the possibility of any model violations

Table 4. Equations used for the calculation of variables.

Variables	Equations	Unit
1. Average diameter at breast height (DBH)	$(\Sigma\, GBH/\pi)/N$	cm
2. Quadratic mean diameter (Dq)	$\sqrt{\Sigma(GBH/\pi)^2/N}$	cm
3. Mean height(Ht)	$\Sigma\, Hts/N$	m
4. Density (TPH)	N/Plot area (ha)	Trees ha^{-1}
5. Basal Area (BA)	$\Sigma(GBH^2/4\pi \times 10000)$/Plot area	$m^2\ ha^{-1}$
6. Total Volume	$\dfrac{\Sigma[(GBH^2/4\pi \times 10000)(Htbar)]}{\text{Plot area (ha)}}$	$m^3\ ha^{-1}$
7. Diameter Mean Annual Increment (DMAI)	$\Sigma\,(GBH/\pi \times Age)/N$	$cm\ yr^{-1}\ acre^{-1}$
8. Height Mean Annual Increment (HMAI)	$\Sigma(Hts/Age)/N$	$m\ yr^{-1}\ acre^{-1}$
9 Gross Volume Mean Annual Increment (GVMAI)	$\dfrac{\Sigma[(GBH^2)(Hts)]}{4\pi / 10000} \Big/ Age\ /\ N$	$m^3\ yr^{-1}\ acre^{-1}$
10 Reineke's Stand Density Index (SDI)(Reineke,1933)	$Density\ (Dq/25)^{1.6}$	—
11. Relative density (ρr) (Drew and Flewelling,1977)	$Density/e^{[\{10.08-\ln Mvol\}/1.5]}$	—

Abbreviations used:

GBH - Girth at breath height overbark
N - Number of trees per acre
Hts - Heights of individal tree
Σ - Summation
cm - Centimeter
m Metre
ha - Hectare
yr - Year
ln - Natural logarithm
π - 3 141592654
Mvol- Mean volume per tree

Table 5 Stand characteristics of teak at different sites

Forest Division	Number of stand	Density (TPH)		Mean height (m)		Basal area (m^2 ha^{-1})		Total volume (m^3 ha^{-1})	
		Min	Max	Min	Max	Min	Max	Min	Max
Parambikulam	18	67 5	440 0	18 13	27 94	11 40	21 50	211 42	519 72
Trichur	19	135 0	345 0	13 23	22 35	4 76	11 92	68 35	267 44
Chalakudy	79	20 0	757 0	8 17	28 85	3 13	16 15	62 01	394 33

Abbreviations used

ha - Hectare
m - Meter
Max - Maximum
Min.- Minimum
TPH - Tree per hectare

4.2. Construction of Density Management Diagram (DMD)

The elements of the density management diagram (DMD) include variables, namely, Dq, Mvol, Ht and SDI Density was represented on the x-axis of the log-log paper and Dq on the y-axis Dq and Density were chosen for the DMD because they are the most commonly used and easiest to estimate in the field.

The maximum SDI for teak was obtained from the scatter diagram for diameter and Density (Fig 7) It is assumed that the maximum SDI is a reasonable approximation of the maximum size-density relation for teak and thus represents the maximum combination of diameter and Density possible in stands of this species

The regression equations for ln Dq and ln Mvol were used to generate two families of curves representing height and volume Use of diagram for designing alternate density management regimes is also illustrated for a hypothetical stand of 2500 TPH

5. RESULTS AND DISCUSSION

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5.1. Stand growth and yield characteristics

The mean stand volume, basal area, density, diameter and height were markedly greater at Parambikulam (Table 6) For instance the total mean stand volume in the 65 year old stand was 470 m^3 ha^{-1} as against 135 m^3 ha^{-1} for Chalakudy Basal area and density also followed a similar trend In the case of 65 year old plantation, the average density was found to be 75 trees per hectare (TPH) and 41 TPH, respectively for Parambikulam and Chalakudy

Average diameter at breast height (DBH) at Parambikulam was also found to be more than that of Chalakudy and Thrissur. In case of the 65 year old plantations, the average DBH was 56 11 cm as against 42 56 cm at Chalakudy Average tree height also followed a similar trend Chalakudy, incidentally, had greater average height than Thrissur at the age of 25 years (Table 6) In general, Parambikulam can be rated as a much better site for teak compared to Thrissur or Chalakudy

Two-way classification of the experimental plots with respect to age and density clearly indicate that the stand density decreased in the higher age classes (Table 7) For example, density observed for 60-65 year age class ranged from 0 to 100 (10 plots over three forest divisons) The

Table 6. Mean Stand Characteristics as a function of age.

Division	Age (Years)	No of plots	DBH (cm)	Dq (cm)	Ht (m)	Den (TPH)	BA ($m^2 ha^{-1}$)	Vol ($m^3 ha^{-1}$)
Chalakudy	75	10	45 9530	46.4179	22 2485	26 0000	4.3765	100.1584
			(4.8407)	(4.8188)	(2.0648)	(3.3747)	(0.7014)	(21 7377)
	65	8	42.5641	42 9509	22 3265	40 9375	5 9039	135.0663
			(1 8923)	(2 2221)	(0 8676)	(7 4327)	(0 9188)	(21 6108)
	56	10	39 8837	40.3051	24.1314	75 2500	9 6418	243 0419
			(2 2701)	(2.2384)	(2.0978)	(4.9230)	(1.3237)	(48.2932)
	50	8	38.1393	39.3877	24.2606	90.9375	11.1030	302.1843
			(2.6872)	(2.3589)	(1 6256)	(14.5736)	(2.1381)	(67.5435)
	45	6	29 7208	30 2837	19.7799	161.6667	11 5533	235 0056
			(1.0165)	(1.0793)	(0.6990)	(10.0830)	(1.0314)	(23.5879)
	40	8	27.1181	27.4381	18.5013	154.3750	9.1270	172 2168
			(0 4849)	(0.4694)	(0 2406)	(9 7970)	(0 6182)	(11.7021)
	25	5	24 4212	25.1736	22.2801	191 0000	9 6582	229 2100
			(3.0883)	(3.1814)	(0.5472)	(8.7678)	(2.4424)	(60.3538)
	20	8	17.8252	18.4406	17.4955	560.9375	14.9818	284.7896
			(0 2465)	(0.2898)	(0 4370)	(28.2191)	(0.8477)	(15 7167)
	15	8	12 1370	13.1786	9.1914	537 8125	7 3067	89.2944
			(0.6603)	(0.5581)	(0 6321)	(75.8339)	(0 8854)	(10.2728)
	10	8	12.5557	13.1369	10.4863	747.8125	10.1423	126 2183
			(0 4078)	(0.3790)	(0.6096)	(8.3919)	(0.5942)	(11.1133)
Parambikulam	74	1	57 5686	58 8325	27.9419	67.5000	18.3491	516.7011
	65	2	56 1144	56 7177	24 6344	75 0000	18 9899	470 3312
			(4 1641)	(3.7455)	(0 5906)	(0 0000)	(2.5027)	(69 8408)

Table 6. contd.

Division	Age (Years)	No of plots	DBH (cm)	Dq (cm)	Ht (m)	Den (TPH)	BA ($m^2 ha^{-1}$)	Vol ($m^3 ha^{-1}$)
Parambikulam	50	2	35 9773	36.4986	20.4755	152 5000	16 0193	328.9795
			(0 8349)	(0.8453)	(0 2724)	(24 7487)	(3 3291)	(74 4513)
	45	4	38 9434	39.3779	22.9429	140.6250	17 1778	397 2619
			(1 2837)	(1.3467)	(0 7551)	(8.7500)	(1.9976)	(34 6618)
	40	2	33 0065	33.7919	19.9000	171.2500	15.1258	306.4177
			(3 3290)	(3.5608)	(0 0732)	(33.5876)	(0 2077)	(6 2733)
	35	2	30 3273	30 8571	22.9475	248 7500	18.6011	433 8799
			(0 1590)	(0 1450)	(0.3014)	(1.7678)	(0.0427)	(5.0467)
	30	4	24 7237	25.3233	19.1754	278.7500	14 3103	289.9404
			(1 4095)	(1.4304)	(1.7859)	(57 8252)	(4 7970)	(128 0682)
	17	1	20 5895	21.1610	20.3474	440 0000	15 4740	322 2316
Thrissur	35	8	25 6633	26 4928	17 0133	166 8750	9 0339	165 9808
			(3 5007)	(3 5573)	(2.5624)	(34 0102)	(1.6476)	(47 8711)
	30	6	22 9697	23.5116	15 3256	181 2510	7 8001	127.7316
			(1 7934)	(1.7743)	(1 1580)	(56 1193)	(2.0131)	(39 6956)
	25	5	18.9517	19.4563	14.1498	326.500	9.7475	146.6192
			(1.2473)	(1.2903)	(0.6329)	(17 9060)	(1.4810)	(26 2005)

Values in parenthesis indicate standard deviation.

Table 7. Two way classification of the experimental plots with respect to Age (year) and Density (DEN) (trees per hectare).

DEN / Age	<50	50 to 100	100 to 150	150 to 200	200 to 250	250 to 300	300 to 350	350 to 400	400 to 450	450 to 500	500 to 550	550 to 600	600 to 650	650 to 700	700 to 750	750 to 1000	Row Total
<10															6	2	8
10 to 15									1	3	1	0	3				8
15 to 20									1		3	5					9
20 to 25				5		1	4										10
25 to 30			3	2	2	2		1									10
30 to 35			4	3	3												10
35 to 40			5	5													10
40 to 45			6	4													10
45 to 50		6	3	1													10
50 to 55																	0
55 to 60		10															10
60 to 65	7	3															10
65 to 70																	0
70 to 100	10	1															11
Column	17	20	21	20	5	3	4	1	2	3	4	5	3	0	6	2	116
Total	14.7	17.1	18.1	17.1	4.3	2.6	3.4	0.9	1.7	2.6	3.4	4.3	2.6	0.0	5.2	1.7	100

marked reduction in stand density as a function of age can be attributed to either thinning or self thinning While establishing the experimental plots although care was taken to include stands thinned as per the schedule prescribed in the respective working plan and also unthinned stands, it was often not possible to obtain sufficient number of experimental plots satisfying these criteria Many of the plots, in fact, were not thinned regularly and hence a strict characterisation as to whether the reduction in density is due to mortality induced by man (thinning) or by the crop on itself (self-thinning) is difficult

A similar relationship was visible with respect to the density and quadratic mean diameter also (Table 8) In an attempt to predict stand age (for use in the density management diagram, described elswhere), it was regressed on quadratic mean diameter using a linear regression model The resulting equation was $\hat{Age} = -6\ 8852 + 1\ 5532\ Dq$ ($r^2 = 0\ 89$)

In this context, several workers (Blume, 1961, Leak, 1975, 1985, Tubbs, 1977) suggested that diameter can be used as a surrogate for predicting age This approach will be all the more relevant for old growth stands where the large size of trees and the abundance of hollow or rotten boles poses serious problems in extracting increment cores as a measure of tree age

Table 8. Two way classification of the experimental plots with respect to density (DEN) (trees per hectare) and quadratic diameter (Dq) (cm)

DEN / Dq	Low to <50	50 to 100	100 to 150	150 to 200	200 to 250	250 to 300	300 to 350	350 to 400	400 to 450	450 to 500	500 to 550	550 to 600	600 to 650	650 to 700	700 to 750	750 to 1000	Row Total
Low to <20				1		1	2		1	3	4	5	3		6	2	28
20 to 30			11	14	3	2	2	1	1								34
30 to 40	1	6	9	5	2												23
40 to 50	14	11	1														26
50 to 60	2	3															5
Column Total	17	20	21	20	5	3	4	1	2	3	4	5	3		6	2	116
%	14.7	17.2	18.1	17.2	4.3	2.6	3.4	0.9	1.7	2.6	3.4	4.3	2.6	0.0	5.2	1.7	100

5.2. Mean Annual Increment (M A.I)

The data on volume M A I with respect to Parambikulam, Thrissur and Chalakudy divisions are presented in Table 9 and Fig. 6 The data presented here reiterate the superiority of Parambikulam over Chalakudy and Thrissur Incidentally, the data on Thrissur was not adequate for making an effective comparison The curve (Fig 6) appears to be "wavy" The wide variation, especially observed in Chalakudy with respect to volume MAI could probably be attributed to site quality changes Certain age classes were probably present on "low" sites only The author's observations confirm this For example, all the 1975 plantations enumerated from Chalakudy division were in a very deteriorated condition The average height (9 19 ± 0 63m) as well as average diameter (12 13 ± 0.66cm) were found to be very low (Table 6) These areas were also infected by teak leaf defoliators and stem borers

Parambikulam registered the lowest mean annual increment (MAI) of 0 0338 m^3 $acre^{-1}$ $year^{-1}$ at the age of 30 years and was followed by a sharp increase (Table 9 and Fig 6) The MAI curve for Parambikulam appears to culminate at the age of 74 years only, whereas, in the case of Chalakudy the volume MAI peaks at the age of 50 years (0 0663 m^3 ha^{-1} $year^{-1}$ and 0 0661 m^3 ha^{-1} $year^{-1}$, respectively) (Table 9 and Fig 6)

The various stand density indices such as Reineke's SDI

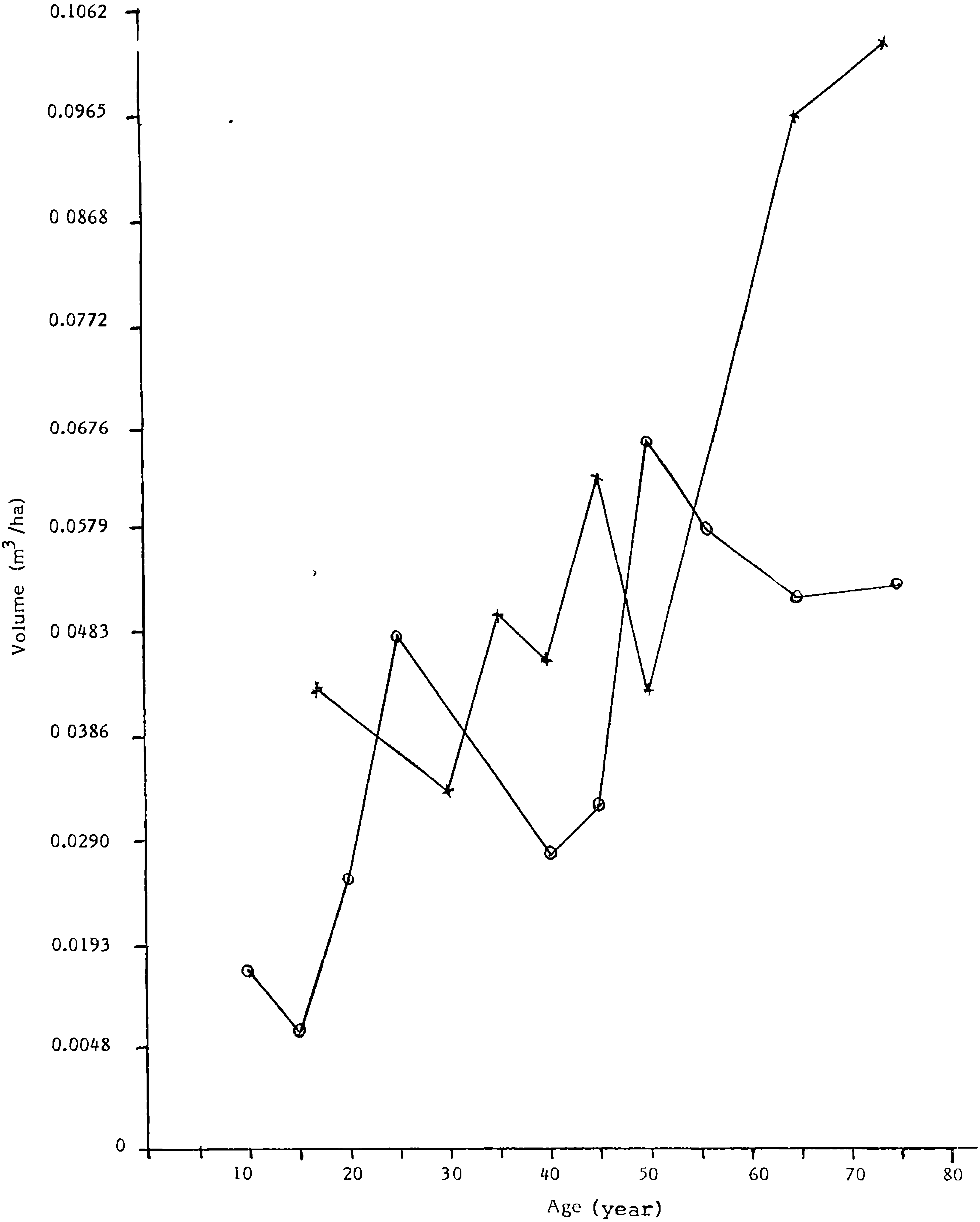

Fig.6 Volume mean annual increment of teak at Parambikulam and Chalakudy (x-x-x : Parambikulam, o-o-o Chalakudy)

Table 9. Mean annual increments and Stand density indices of different Stands as a function of age.

Division	Age (year)	No of plots	DMAI (cm yr^{-1} ha^{-1})	HMAI (m yr^{-1} ha^{-1})	VOLMAI (m^{3} yr^{-1} ha^{-1})	SDI	ρ_r
Chalakudy	75	10	0.6127 (0.0645)	0.2967 (0.0275)	0.0495 (0.0129)	69.4698 (9.3116)	0.1463 (0.2215)
	65	8	0.6529 (0.0310)	0.3435 (0.0134)	0.0513 (0.0072)	96.8796 (15.0125)	0.1092 (0.0166)
	56	10	0.7122 (0.0405)	0.4309 (0.0375)	0.0576 (0.0105)	161.9905 (19.2859)	0.1978 (0.0284)
	50	8	0.7628 (0.0537)	0.4852 (0.0325)	0.0663 (0.0097)	188.3222 (34.0009)	0.2439 (0.0474)
	45	6	0.6605 (0.0226)	0.4396 (0.0156)	0.0323 (0.0020)	218.2618 (17.3529)	0.2502 (0.0212)
	40	8	0.6780 (0.0121)	0.4625 (0.0060)	0.0279 (0.0011)	179.1339 (11.7489)	0.2003 (0.0128)
	25	5	0.9768 (0.1235)	0.8912 (0.0219)	0.0478 (0.0116)	194.8357 (41.4573)	0.2587 (0.0499)
	20	8	0.8913 (0.0123)	0.8748 (0.0219)	0.0254 (0.0009)	344.6964 (18.5822)	0.4307 (0.0219)
	15	8	0.8091 (0.0440)	0.6128 (0.0421)	0.0112 (0.0011)	192.3575 (23.1365)	0.1958 (0.0224)
	10	8	1.2555 (0.0408)	1.0486 (0.0610)	0.0169 (0.0015)	267.1786 (12.4328)	0.2754 (0.0160)

Table 9. contd

Division	Age (year)	No. of plots	DMAI (cm yr^{-1} ha^{-1})	HMAI (m yr^{-1} ha^{-1})	VOLMAI (m^{3} yr^{-1} ha^{-1})	SDI	ρ_r
Parambikulam	74	1	0 7780	0 3776	0 1034	265.4531	0.3163
	65	2	0 8633	0 3794	0.0965	278.4588	0.3074
			(0 0641)	(0 0085)	(0 0144)	(29 3891)	(0 0305)
	50	2	0 7196	0 4096	0 0429	280 2636	0.3072
			(0 0169)	(0 0054)	(0.0028)	(55 7005)	(0 0630)
	45	4	0.8654	0 5099	0.0627	291.5447	0 3390
			(0.0285)	(0.0168)	(0 0021)	(30 5528)	(0 0266)
	40	2	0 8252	0.4975	0 0457	273 5036	0 3037
			(0.0832)	(0.0018)	(0.0099)	(7.7919)	(0.0158)
	35	2	0.8665	0.6557	0.0499	348.3507	0.4349
			(0 0045)	(0 0086)	(0 0009)	(0 1449)	(0 0023)
	30	4	0 8241	0 6392	0 0336	288 6812	0 3440
			(0 0470)	(0.0595)	(0.0070)	(89.1618))	0.1242
	17	1	1.2111	1.1969	0 0431	336.9824	0.4313
Thrissur	35	8	0.7333	0.4861	0.0299	179.5440	0.1976
			(0 1000)	(0.0732)	(0.0125)	(26.7624)	(0.0338)
	30	6	0 7657	0 5109	0.0236	162.9161	0.1727
			(0.0598)	(0.0386)	(0.0040)	(42.9813)	(0 0526)
	25	5	0 7581	0 5660	0.0179	219.0902	0 2304
			(0 0499)	(0 0253)	(0 0029)	(27 6312)	(0 0290)

Values in parenthesis indicate standard deviation.

and relative density (RD) were also consistently and substantially greater for Parambikulam compared to Thrissur and Chalakudy It may be remembered that stand density indexes are independent of age and site quality and hence are ideal parameters for comparing stands of different ages and sites Incidentally the latter, namely, RD is independent of species also Reineke's SDI can be made independent of species by taking the per cent of the maximum SDI for any given species

To sum up, results presented here clearly indicate that Parambikulam, in general, and Karaimala and Sungam ranges of this division, in particular, are very good for teak However, because of the shift in management objectives, consequent on the declaration of this area as a Wildlife Sanctuary, establishment of new teak plantations in this area is probably out of question. The data also reveal that Chalakudy (particularly Vellikulangara and Pariyaram ranges) is not an inherently good site for teak However, with appropriate crop management strategies (eg tending fertilization, plant protection etc) teak plantations can be made viable here also

5.3. Maximum Size-density Relationships

The upper line in Fig 7 corresponds to an SDI of 600 roughly conforming to the maximum SDI represented in the data

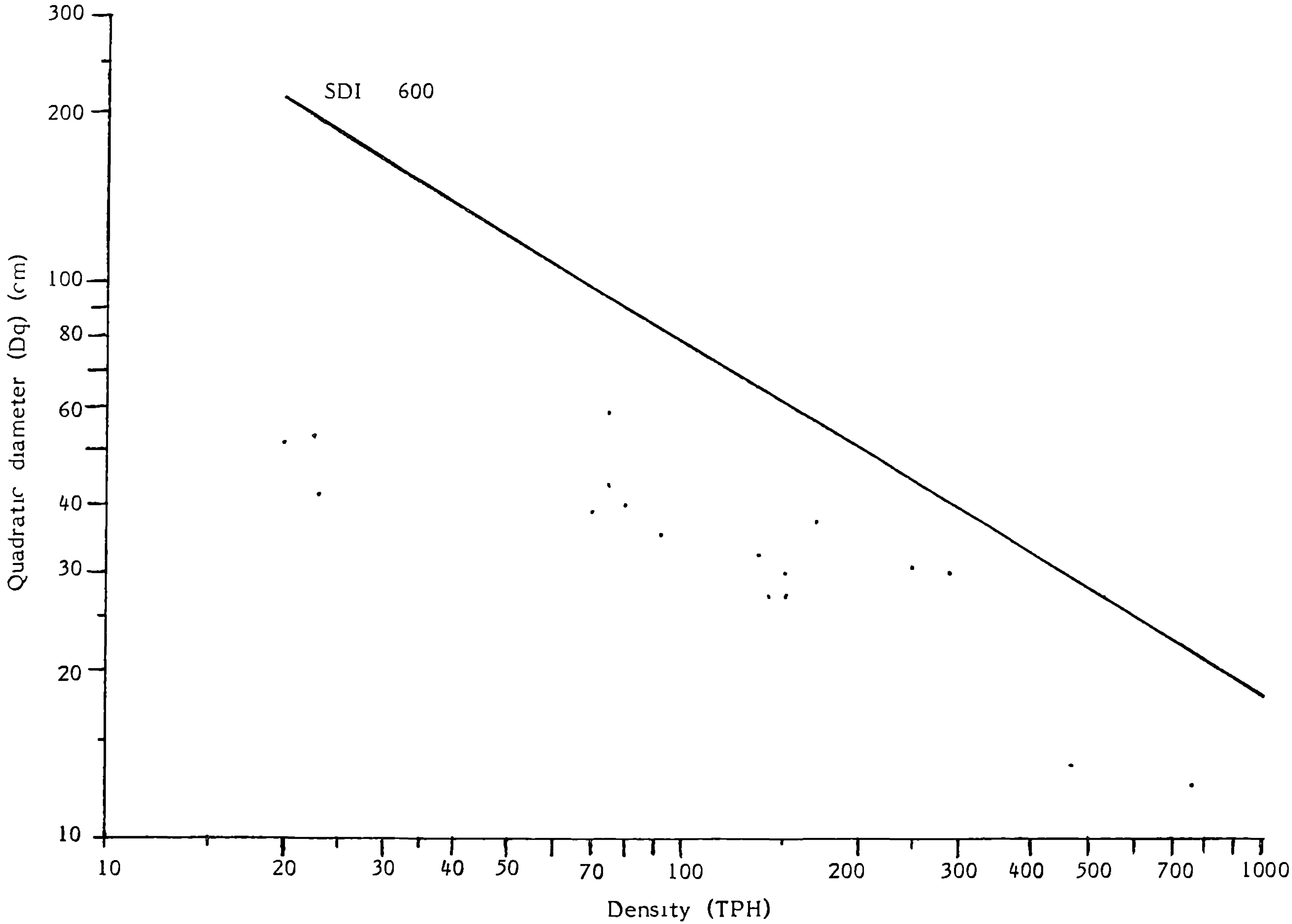

Fig 7 Size-density relationships of teak showing maximum stand density index (SDI)

set (Appendix I) It may be remembered that the data set contains stands under different intensities of thinning and also a cross section of the site qualities in which teak is usually grown and we assume that no real combination of size density would be possible above this line corresponding to an SDI 600

The translation of specific managment objectives into appropriate levels of growing stock is the key in Density Management However, this is probably the most difficult step in designing a density managment regime (Davis, 1966) The use of a size-density based index of growing stock such as Reineke's SDI, however, greatly simplifies this process (Long, 1985) Reineke's SDI is the number of trees at an average stand diameter (where the average stand diameter (ASD) is the diameter at breast height of a tree with the average basal area) of 25 cm According to Reineke (1933), this approach of determining density holds good for any pure, fully stocked, even-aged stand of a given species

Since it is a species dependent parameter, the maximum SDI will be different for different species For example, 600 for Douglas-fir (_Pseudotsuga menziesii_, Drew and Flewelling, 1979) and 700 for lodgepole pine (_Pinus contorta_, Mc Carter and Long, 1986) Maximum SDI represents the combination of size and density where self-thinning starts It is assumed to be 100% SDI that can be achieved by the species (Daniel et al , 1979) Maximum SDI is a reasonable approximation of the maximum size density relation for a species and thus represents the maximum combination of diameter and density possible for a particular species

Fig 8, depicting the relationship between SDI and f_r (Relative density) indicates that the two size-density indexes are directly related to each other implying that f_r can also be used for designing density management regimes Relative density index, f_r, is the ratio of actual stand density to the maximum stand density attainable in a stand with the same mean tree volume (Drew and Flewelling, 1979)

5.4. Growth-growing stock relationship

Fig 9a and b present the data concerning mean stand volume, mean tree volume as a function of stand density index (SDI). Table 10 presents some of the key SDI limits at which important processes and events in stand development occur The SDI limits portrayed in the Fig 9 broadly confirm the projections of Long (1985) We used these SDI limits for designing alternate density management regimes for teak described later in this text

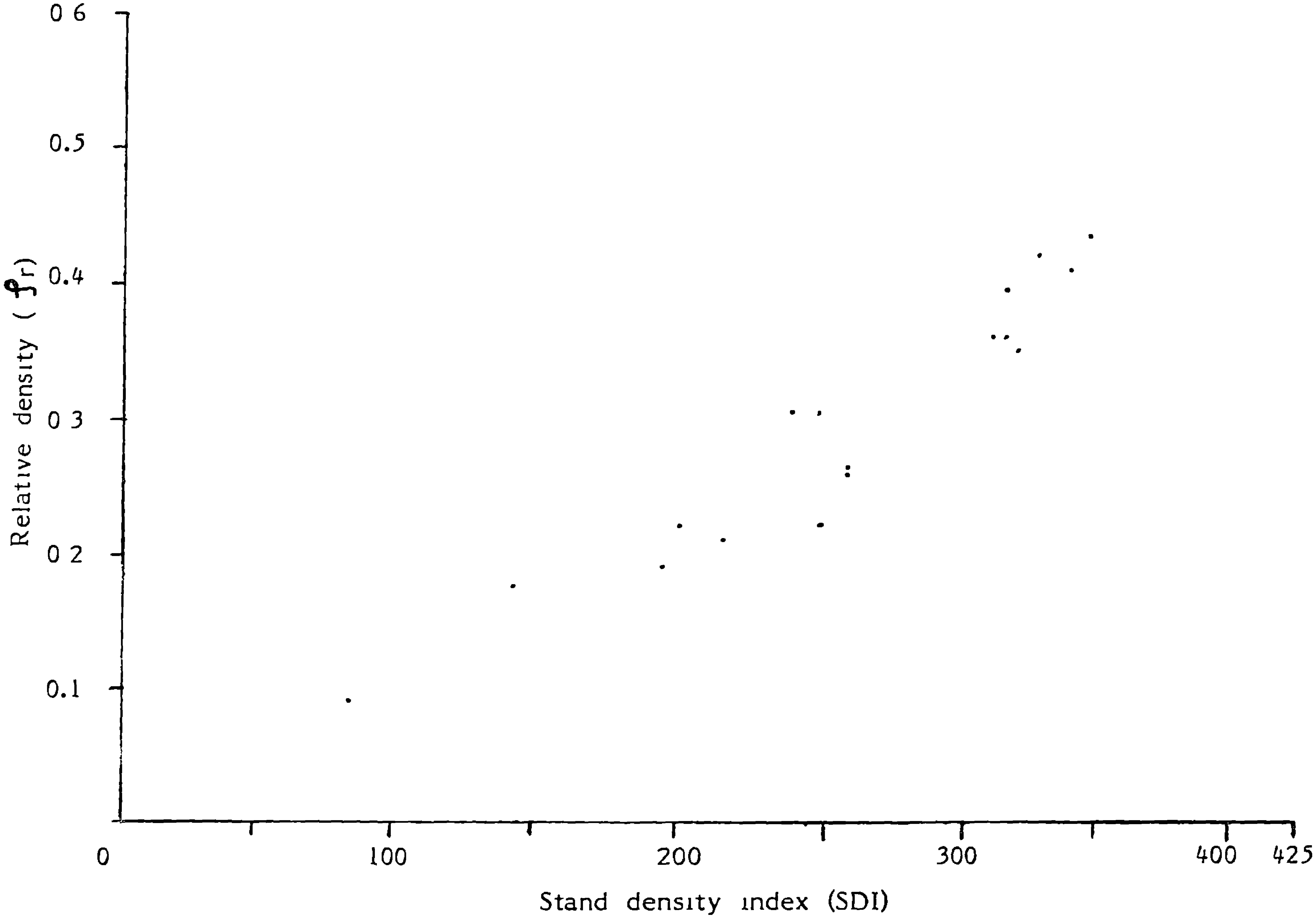

Fig 8 Relationship between stand density index and relative density

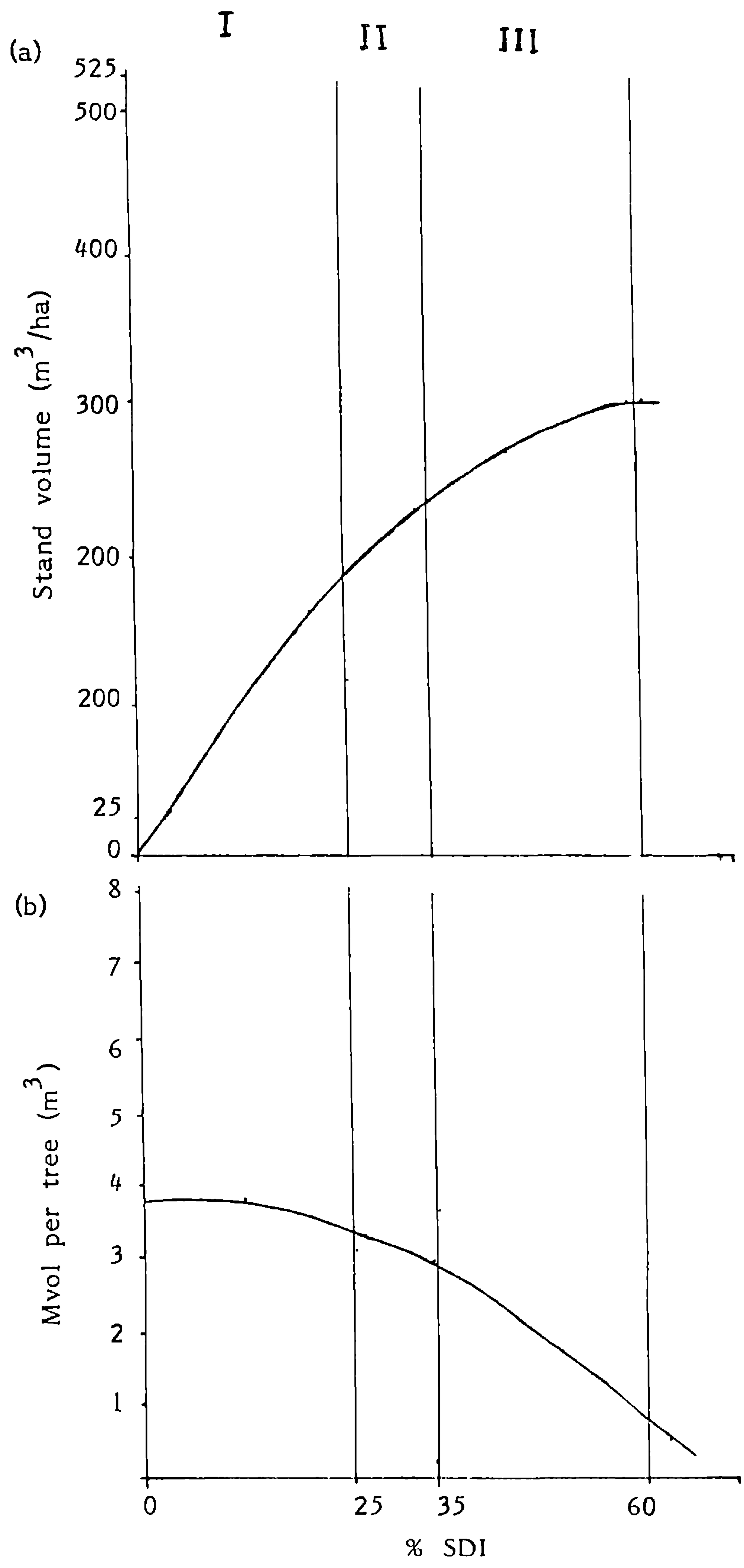

Fig 9 Relationship between stand density index (SDI) and (a) stand volume (b) mean volume per tree

Table 10 Examples of "key" SDI values for teak

Stand development events	% of maximum SDI	Teak
Maximum	100	600
Lower limit of self-thinning	60	360
Lower limit of "full site occupancy"	35	210
Onset of competition	25	150

In this context, Langsaeter (1941), while discussing the effects of thinning on volume growth has described the effects of density (with density given in terms of volume in cubic meters) on volume growth Based on the response of the stand to increase in volume, Langsaeter's curve can be divided into five zones Zone I represents trees growing independent of each other Zone II marks the beginning of competitive interactions between the trees and the growth rate here is below the potential In zone III growth rate changes rather very slowly (plateaus) In zone IV, the annual growth declines at an increasing rate As the stand volume increases further the annual growth declines very rapidly in zone V. These two zones namely, IV and V where the rate of growth decline rapidly were referred to as the "Zones of imminent competition mortality" by Drew and Flewelling (1977) In this zone, the self-thinning or competition-related-mortality is likely to occur (Drew and Flewelling, 1979) Long (1985) has given a schematic characterisation of the Langsaeter's curve by taking percentage of maximum SDI in place of density on the X-axis He hypothesised that zone I can be represented by 25% of the maximum SDI whereas zone II corresponds to 35% of the maximum SDI and zone III corresponds to 60% of the maximum SDI The zone IV and V are probably characterised by more than 60% of maximum SDI (Table 10)

Similarly a ρ_r of 0 to 0 15 corresponds to the zone I of Langsaeter's curve or 0 to 25% of maximum SDI (Drew and Flewelling, 1979) The relative densities between 0 15 to 0.40 represent zone II of Langsaetar's curve and 25% to 35% of maximum SDI The relative density between 0 40 and 0 55 represent the zone between 35% to 60% of maximum SDI or zone III of Langsaeter's curve More than 0 55 ρ_r represents the zone IV and V or zone of imminent competition mortality (more than 60% of the maximum SDI, Drew and Flewelling, 1979).

5.5. <u>Construction of Density Management Diagram (DMD)</u>

5.5.1. Regression models: From the calculated variables two multiple regression models were developed following the least square method These two models explains the relationships among ln Mvol, ln Ht, ln Den and ln Dq Analysis of variance of both the models are presented in Appendix II and Appendix III

The First equation, relating ln Ht and ln Den to ln Mvol has a co-efficient of determination (r^2) of 96 6%

$$\widehat{\ln Mvol} = -3\ 95248 + 2\ 23424 \ln Ht - 0\ 46716 \ln Den \quad \text{(Eq 1)}$$

The second equation, relating ln Mvol and ln Den to ln Dq has a co-efficient of determination (r^2) of 99.2%

$$\widehat{\ln Dq} = 3.57525 + 0\ 34435 \ln Mvol - 0\ 06108 \ln Den \quad \text{(Eq 2)}$$

Both equations were examined for residuals and their bias with respect to independent variables were also tested (Fig. 10 and Fig 11) It is found that the Eq 1 is slightly biased in the lower density range (Fig 10a) and the higher height range (Fig 10b) Fig 11 indicates that the Eq 2 is also slightly biased in the lower density (Fig 11a) and Mvol (Fig 11b) ranges Nevertheless, they gave a very high r^2 values and the regression co-efficients were also highly significant (Appendix II and III) Further, the various other combinations of dependent and independent variables that we have examined yielded relatively lesser r^2 values (Table 11) More work would be required to fit a better regression model linking Mvol with Dq, Den and Ht

5.5.2. Density management diagram (DMD) format: According to Long (1985), format of DMD is a matter of personal preference We followed the Mc Carter and Long (1986)

Table 11. Models for data set.

SL. No.	Dependent variable	Independent Variable	Co-efficients	Intercept	Co-efficient of determination (r^2)	Standard Error (SE)
1	Dq	Mvol Den	5.52971 -0.01713	23.99261	0.97699	1.79916
2	* ln Dq	ln Mvol ln Den	0.34435 0 06108	3.57525	0 99232	0.03738
3	Ht	Den Dq	-0 00429853 0.29517	11.07178	0 75987	2.42178
4	ln Ht	ln Den ln Dq	0.15944 0 97327	-1 14000	0 85709	0.11453
5	Vol	Den Ht	0.37324 24.95943	-352.71644	0.54822	71.60329
6	Vol	Den Dq	0 22839 6.54284	-42 47407	0 18272	96 30641
7	Vol	Ht Dq	23.28197 -5.32909	-70.76887	0 40940	81 86859
8	ln Vol	ln Den ln Ht	0 53284 2.23424	-3.95248	0 84541	0 19835
9	ln Vol	ln Den ln Dq	1.12644 2.77512	-9.69643	0 95575	0.10612
10	ln Vol	ln Ht ln Dq	2.35327 -1.08720	2 00953	0 50256	0 35580
11	Mvol	Den Ht	-0.00119575 0.22239	-2.06407	0.67494	0.90980
12	Mvol	Den Dq	0 00249074 0.16726	-3 78030	0 96155	0 31290
13	Mvol	Ht Dq	-0.02310 0.13786	-1.86191	2809	0.42791
14	ln Mvol	ln Den ln Dq	0 12644 2 77512	-9 69643	0 99030	0.10612
15	* ln Mvol	ln Den ln Ht	-0 46716 2.23424	3.95248	0.96610	0 19835

* Models used in construction of density management diagram

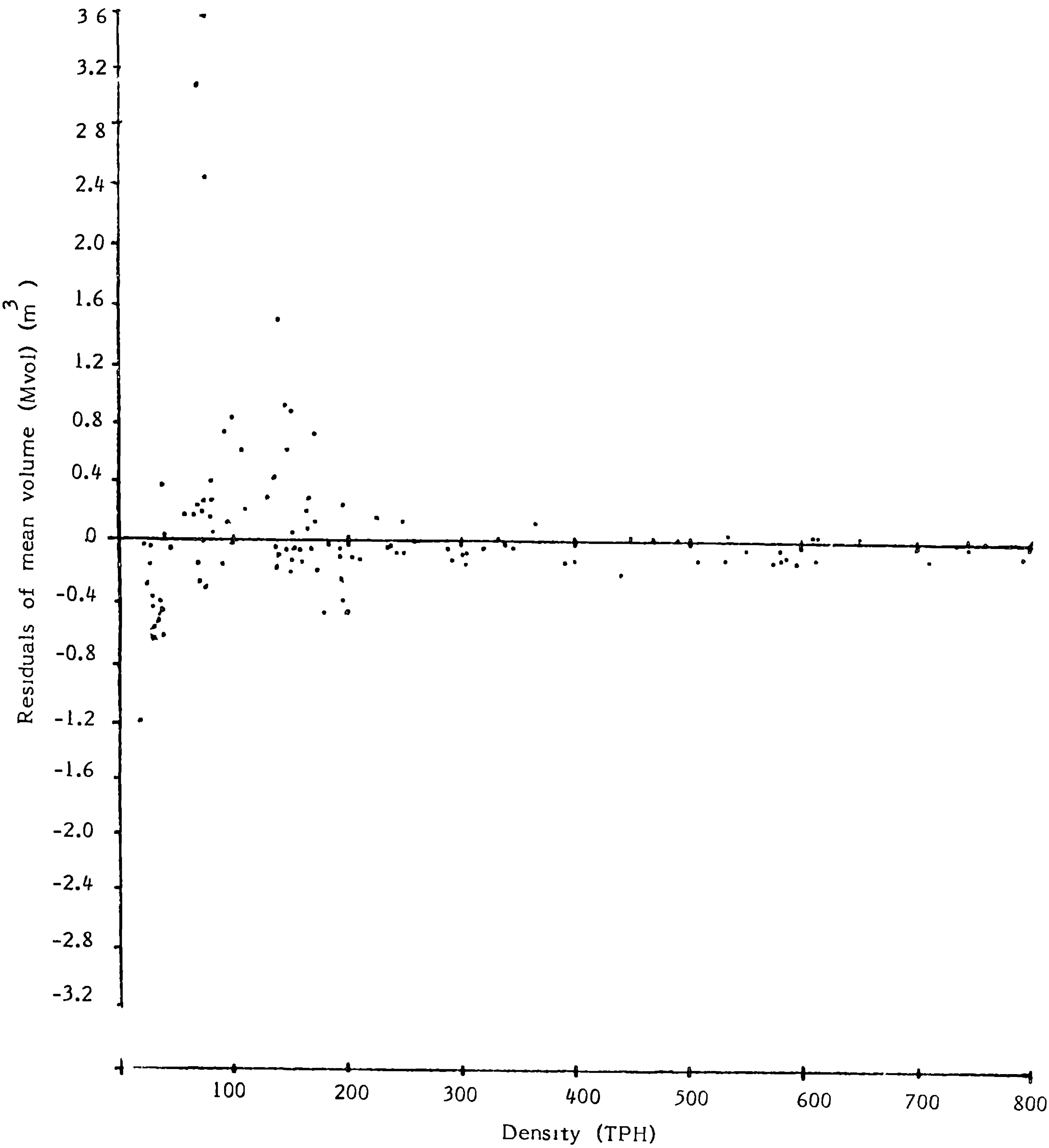

Fig.10(a) Back transformed residuals of mean volume per tree versus density (equation I)

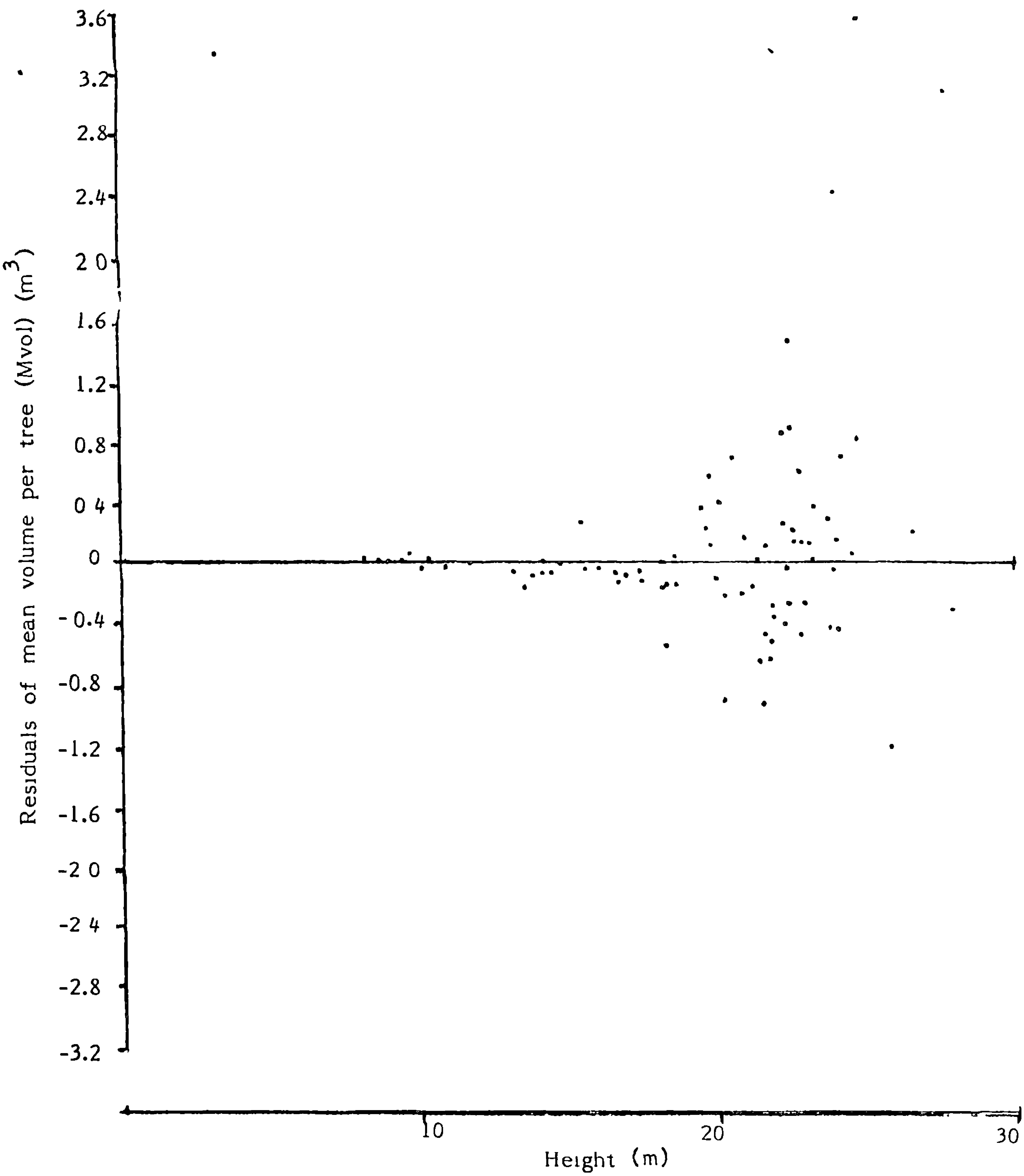

Fig 10(b) Back transformed residuals of mean volume per tree against height (equation I)

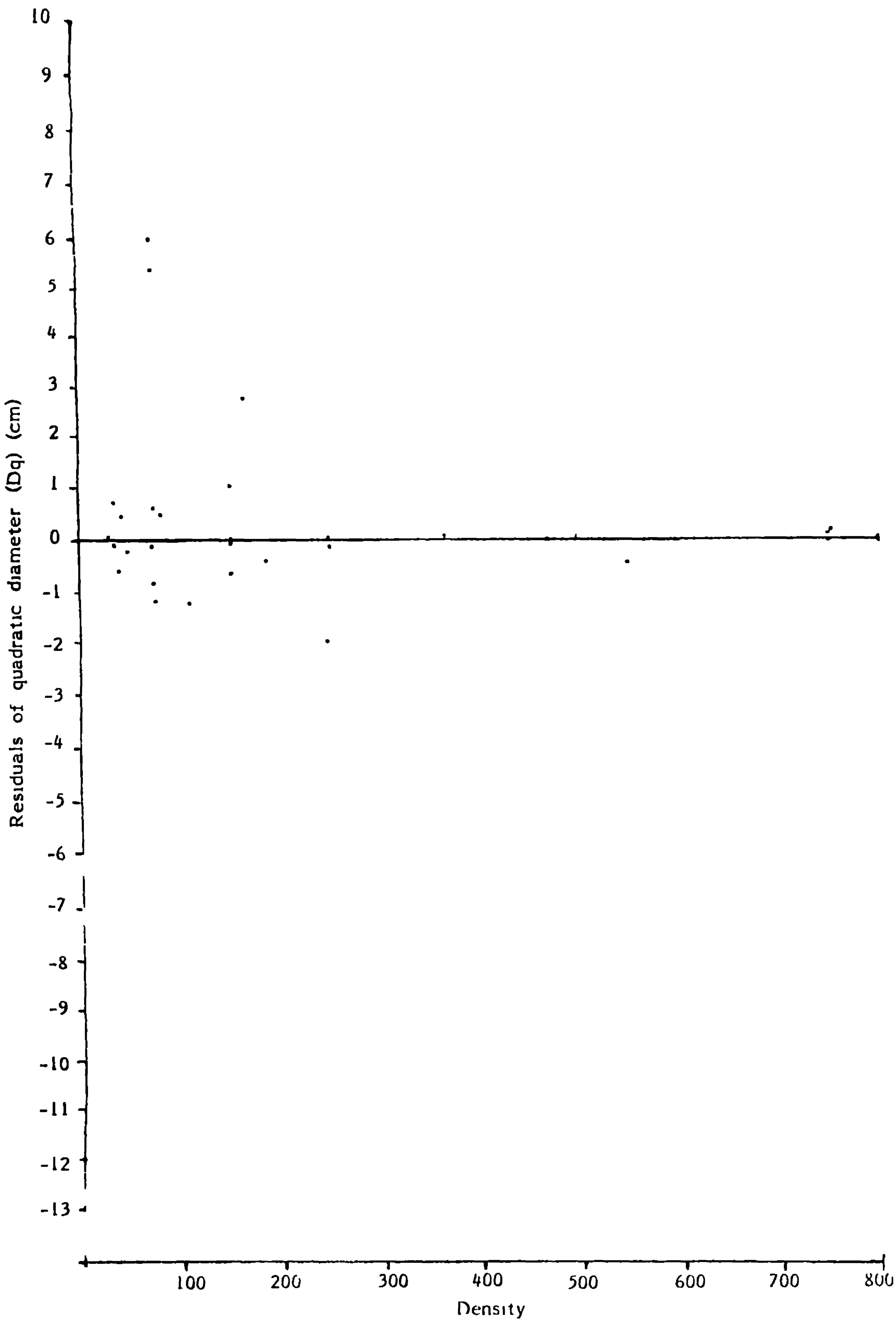

Fig 11(a) Back transform l residuals of quadratic di imeter versu density (equation II)

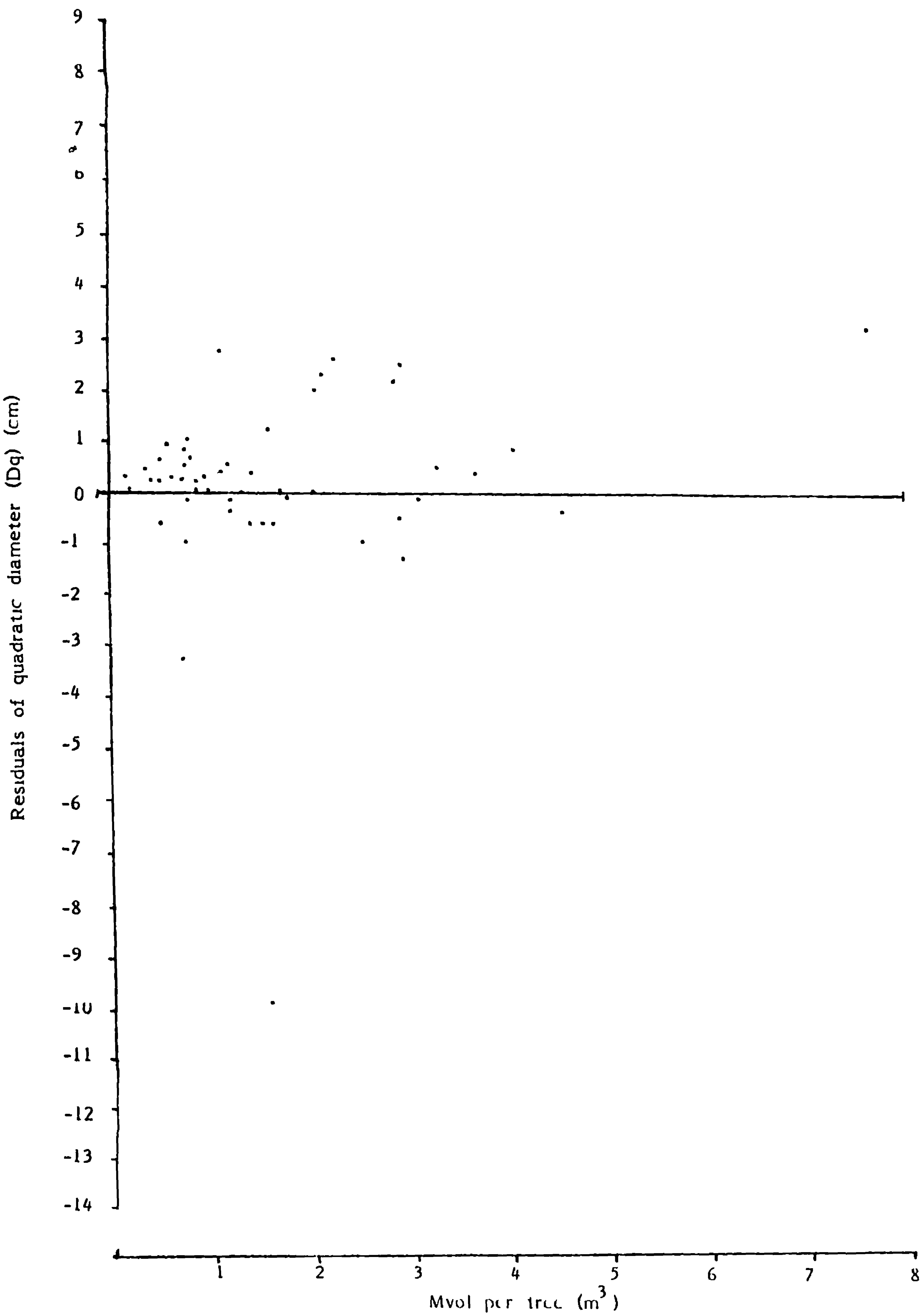

Fig 11(b) Back transformed residuals of quadratic diameter versus Mvol per tree (equation II) pattern and chose to display Dq and density on the ordinate and abscissa respectively

The density taken on x-axis ranges from 50 to 5000 TPH and Dq on y-axis ranges from 1 to 100 cm (Fig 12) These two parameters were chosen because, of the variables included, they are the most commonly used and easiest to estimate in the field.

The solid diagonal lines in Fig. 12 represent SDIs. For the construction of the DMD, Dqs were calculated for all possible combinations of SDI (50 - 600) and densities (50 - 5000 TPH) using Reineke's formula (Table 4) SDI lines were put on the diagram using the parameters Dq and Den (Appendix IV). The upper most SDI line corresponds to the maximum SDI for teak found from the maximum size - density relationships for the species (Fig 7)

The shorter broken lines represent site heights (the height of the dominants). For plotting height lines, first the Mvol were calculated for all the combination of heights ranging from 5 to 60 meters and densities ranging from 50 to 5000 TPH with an interval of 5 m and 50 TPH respectively using Eq.1 (Appendix V) Then, using Eq 2, Dqs were generated for these Mvols and the respective densities (Appendix VI)

The longer broken lines represent volume (Fig 12)

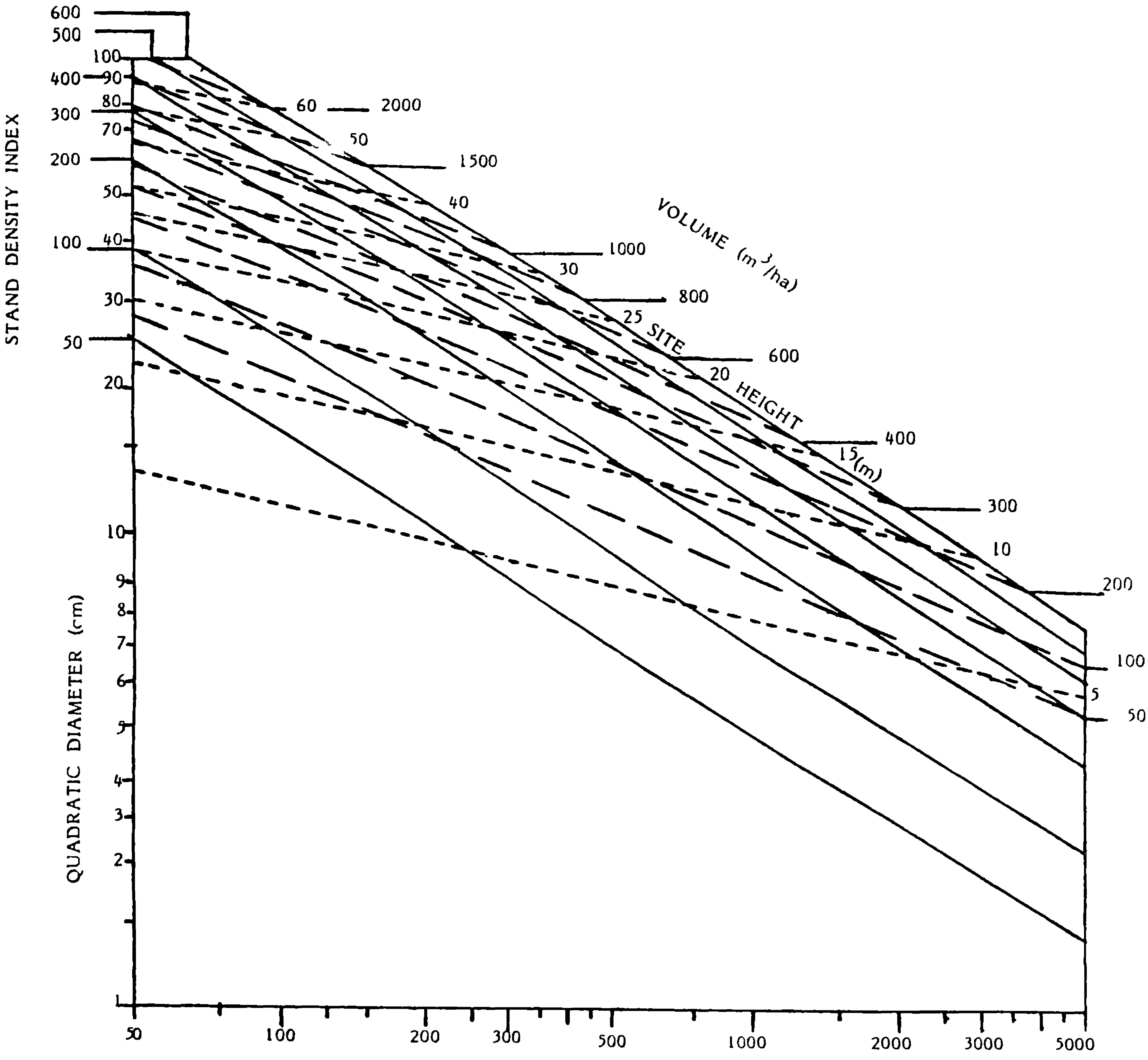

Fig 12 Density management diagram for teak (Tectona grandis Linn f)

Using Eq. 2, Dqs were calculated for different combinations of volumes and densities (Appendix VII) The volume ranged from 50 to 2000 $m^3 ha^{-1}$ and density range was from 50 to 5000 TPH were used For convenience and to avoid over crowding all lines representing SDI Ht and volume are not plotted on the graph. Instead only few selected lines are shown

5.6. Designing Density Management Regimes

Use of density management diagram to design density management regimes is illustrated here with two alternate hypothetical density management situations The first logical step in designing density management regimes is to translate the stand management objectives into desirable levels of growing stock, compatible with these objectives This can be achieved by using any of the relative density indexes After choosing an appropriate size-density related index, suitable upper and lower limits are fixed.

The choice of the upper and lower limits represent a typical silvicultural trade-off between maximization of stand growth on the one hand and maximization of individual tree growth and vigour on the other This is because, maximization of individual tree growth and total volume production are in perpetual conflict with each other As a result, one has to compromise one for the other Thus, the choice of appropriate levels of growing stock becomes a direct consequence of the stand management objectives i e , whether to maximise total volume production without regard to tree vigour or to maximize individual tree growth For maximization of volume growth, ideally the upper and lower limits of growing stock should be chosen in such a way that the stand would be in zone III of Fig 9 Alternatively, if the manager desires to maximise individual tree growth and sizes, without regard to total stand volume on an area basis, the stand could be maintained in zone I (Fig 9) itself Similarly, if the management objective is to get quick returns at shorter time intervals, then ideally the upper and lower limits must be kept closer to one another

Defining the management objectives and constraints such as maximization of individual tree growth vs stand growth, minimum acceptable tree vigour, end-of-rotation tree dimensions, thinning constraints such as minimum size and volume removed etc forms an essential pre requisite in the process of designing density management regimes In fact, the upper and lower limits of the growing stock will be a function of all these parameters and thus represent a compromise between the two silvicultural extremes (individual tree vs stand growth) The stand is then allowed to grow up to the targeted upper limit of growing stock and is thinned down to the lower limit This process is repeated as many times as necessary

To illustrate the process, two simple density management regimes are developed for a hypothetical even aged stand with 2500 TPH

5.6.1. Situation I : Log regime : The stand management objective here is to pr duce large sized logs This situation assumes to produce logs with a quadratic diameter (Dq) of 50 cm (ie Class I teak logs). The minimum commercially utilizable Dq is assumed to be 10 cm (Class IV poles) The management objective in the instant case can be interpreted as maximization of individual tree growth (ie "sudden sawlog"). According to Daniel et al (1979) to enhance merchantable yield, it is desirable to maintain stocking level in the lower part of the optimal range because this results in larger material with perhaps some sacrifice in total volume

The first logical step in this approach is to translate the management objective of bigger log production into desirable levels of growing stock. The following upper and lower limits of growing stock were selected in this context

1 Lower limit of growing stock SDI of 120
(20% of SDI max)

2. Upper limit of growing stock SDI of 210
(35% of SDI max)

These limits were selected because the management objective here was to maximize individual tree growth and size, without regard to volume production on an area basis Therefore, an appropriate strategy would be to maintain the level of growing stock within zone I of Fig 9, a direct consequence of which will be instant response to release Incidentally tree growth and vigour are greater when the level of growing stock is in this zone Hence a lower limit of growing stock corresponding to 20% of the maximum SDI was chosen, which incidentally represents a level of growing stock much below the onset of competitive interactions in the stand (Table 10) and thus ensures tree growth at its maximum potential If we keep the stand above the threshold for competitive interaction (ie, transition between zone I and II, fig. 9), the individual tree growth falls below the potential for open grown trees of he species, site quality and age One possible fall out of the low level of growing stock is the manifestation of large number of lateral branches, and its possible negative influence on log quality This, however, can be prevented by resorting to pruning of the lateral branches

Regarding the upper limit of growing stock, 35% SDI was selected becasue it ensures full site utilization (complete utilization of all the site resources) for atleast some part of the rotation Thus, much of the volume production is not sacrificed, although the total volume production is certainly less than that of a density management regime with higher levels of growing stock

The trees under such a density management regime are growing reasonably fast with great vigour and the volume production sacrificed by means of retaining the level of growing stock lower also is not quite substantial

The target end-of-rotation Dq chosen here was 50 cm This target end-of-rotation Dq and the growing stock upper limit (SDI = 120) together define a stand with approximately 70 TPH and 400 $m^3 ha^{-1}$ volume (Table 12 and Fig 13) It is then easy to work backward through the rotation as indicated in Fig 13

For this, a line parallel to Y-axis was drawn from the point indicating 50 cm Dq and 210 SDI till it hits the lower SDI of 120 and the Dq at that point was read Then the density before thinning was calculated using the Dq thus found and upper SDI limit with the help of Reineke's SDI formula given in Table 4 A line joining these two points was drawn This process was repeated till the Dq before thinning reached the minimum commercial Dq of 10 cm Further, a single precommercial thinning (PCT, ie thinning which does not give merchantable materials) was used to set up the first commercial thinning (CT) This precommercial thinning is desirable to avoid early overcrowding of the stand It is

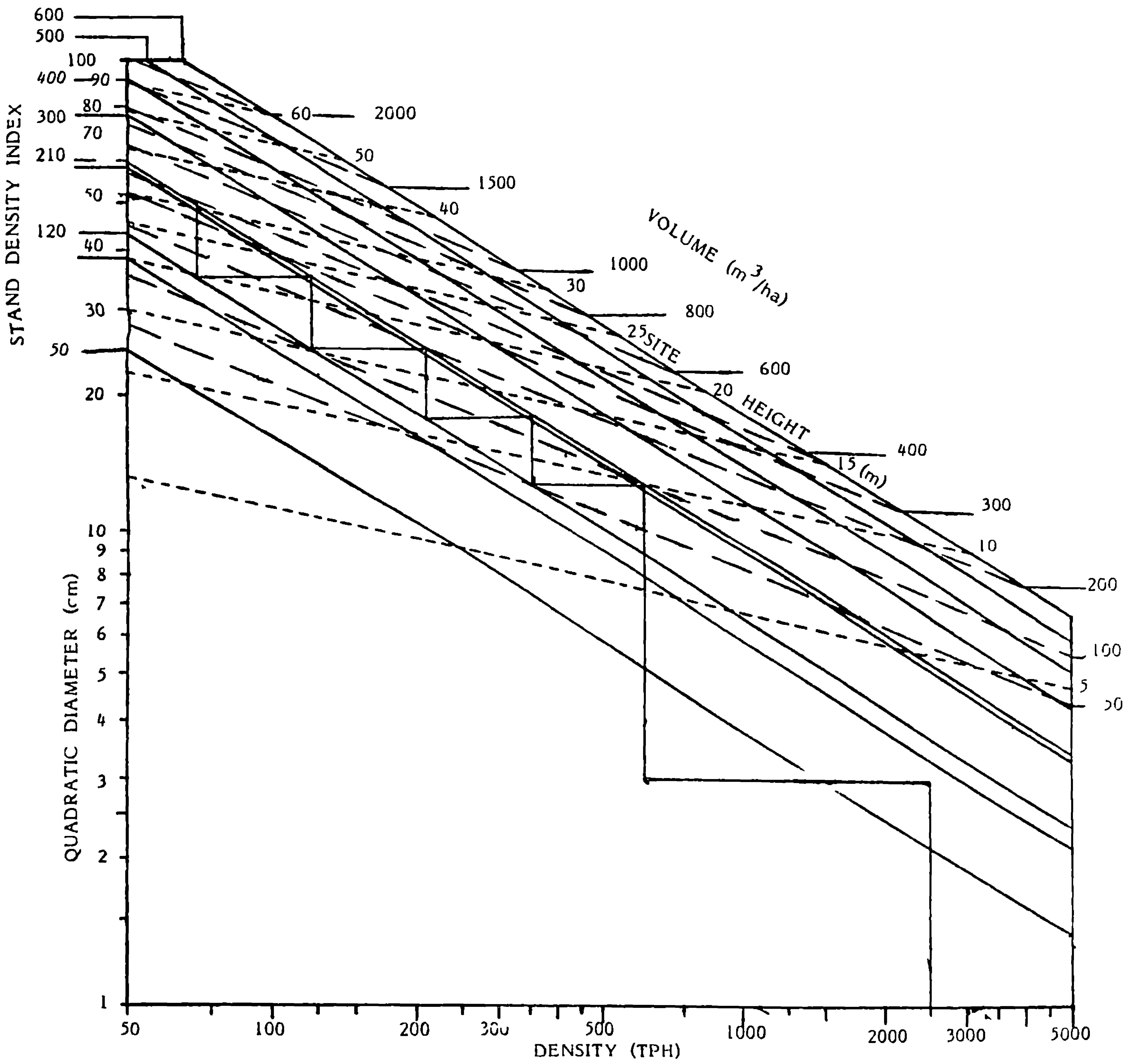

Fig 13 Density management diagram for log regime

Table 12. yield table for log regime.

Thinning	Site ht(m)	SDI Before	SDI After	Den (TPH) Before	Den (TPH) After	Dq (cm)	Age (year)	Volume ($m^3 ha^{-1}$)	Removed volume ($m^3 ha^{-1}$)	Cumulative Volume ($m^3 ha^{-1}$)	Mean annual increment ($m^3 ha^{-1} yr^{-1}$)	PAI ($m^3 ha^{-1} yr^{-1}$)
PCT	--	210	120	2500	617	30	--	--	--	--	--	--
CT1	10	210	120	617	355	12.75	12.9	100.0	50 0	100.0	7.8	--
CT2	13.8	210	120	355	210	18.25	21.5	168.8	77.5	218.8	10.2	13.8
CT3	17.9	210	120	210	122	25.0	31.9	200.0	100.0	327.5	10.3	10.5
CT4	23.6	210	120	122	70	35.0	47.5	276.9	155.0	504.4	10.6	11.3
FH	31.4	210	120	70	--	50.0	70.8	400.0	--	782.5	11.1	11 9

Abbreviation used:

PCT - Precommercial thinning
CT - Commercial thinning
FH - Final harvest
SDI - Stand Density Index
TPH - Tree per hectare
cm - Centimeter
m - Meter
ha - Hectare
PAI - Periodic annual increment

similar to the first mechanical thinning in the sense that the thinned materials have no commercial value The volume before each thinning, the volume removed in thinning and site height (height of dominant trees, similar to crop height) were read from the diagram (Fig 13 and Table 12) The age, mean annual increment and periodic annual increment were also calculated (Table 12, Fig 15) Age w estimated using the equation $\hat{Age} = -6\ 8852 + 1\ 5532\ Dq$

5.6.2. Situation II : Pole production : The stand management objective here is to produce teak poles (preferably Class I) rather quickly This management objective can b interpreted as maximization of volume production per unit area This situation assumes to produce poles of quadratic diameter of 20 cm (I class teak poles) Thinning constraints include commercially utilizable poles with minimum Dq of 8 cm, ie V class poles

The following upper and lower limits of growing stock which commensurate with the land management objectives were selected

1 Lower limit of growing stock SDI of 210 (35% of SDI max)

2 Upper limit of growing stock SDI of 300 (50% of SDI max)

In order to maximize total volume production, without regard to individual tree size, upper and lower limits of growing stock should be chosen in such a way that the stand remains within zone III of Fig 9 for most part of the rotation. The volume increment of the stand will be higher, if it can be maintained in the zone III of Fig 9 The 60% of SDI max actually represents the commencement of self-thinning No prudent land manager would allow stagnation in the stand and loss of volume production on account of competition related mortality To avoid competition related mortality and to ensure reasonable amount of vigour, an upper level of growing stock corresponding to an SDI of 50% of the maximum was chosen To ensure full site utilization, the lower limit of 35% of maximum SDI was selected. Again, the closer upper and lower limits shortens the period between successive thinnings

The target end-of-rotation Dq was 20 cm (Class I poles) The combination of the target end-of-rotation Dq and the growing stock upper limit (SDI=300) together results in a stand with approximately 420 TPH and a volume of 233 $3m^3 ha^{-1}$ (Table 13 and Fig 14) This stand can also be worked backward as in the previous case The first commercial thinning (CT) has been set up with a precommercial thinning (PCT) that reduced the level of growing stock to approximately 1718 TPH (Table 13 and Fig 14) Mean annual increment and periodic annual increment are shown in Fig 15

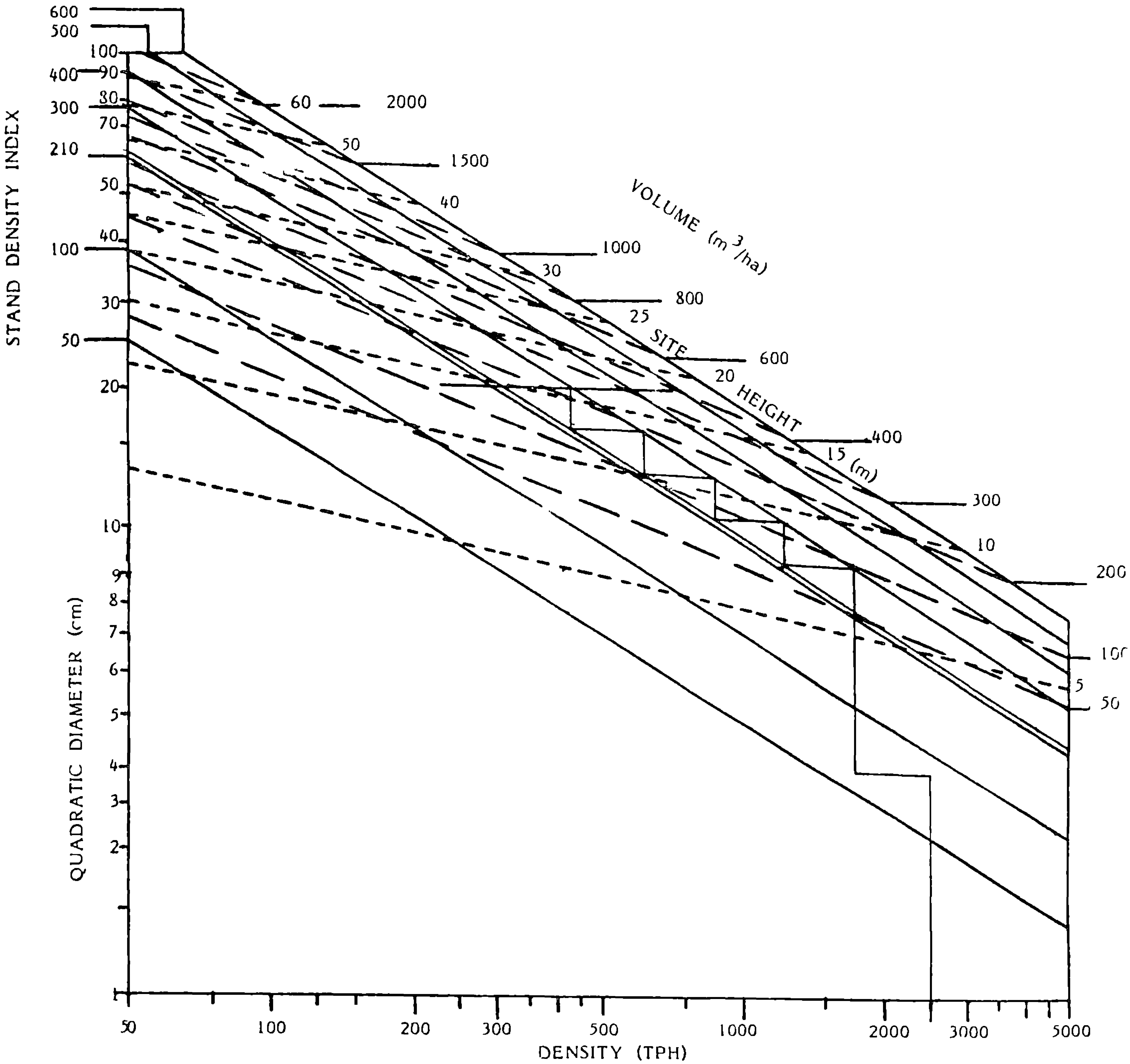

Fig 14 Density management diagram for pole regime

Table 13 yield table for pole regime

Thinning	Site height (m)	SDI Before	SDI After	TPH Before	TPH After	Dq (cm)	Age (years)	Volume ($m^3 ha^{-1}$)	Removed volume ($m^3 ha^{-1}$)	Cumulative Volume ($m^3 ha^{-1}$)	Mean Annual increment ($m^3 ha^{-1} yr^{-1}$)	PAI ($m^3 ha^{-1} yr^{-1}$)
PCT		--	-	2500	1718	3 0		-		--		-
								-			-	
CT1	8.2	300	210	1718	1202	8.4	6 2	96 3	70 0	96 3	15.5	-
CT2	9 4	300	210	1202	854	10.5	9 4	128.9	85 0	198 9	21 2	13 8
CT3	11.1	300	210	854	597	13.0	13 3	142 1	100 0	297.1	22 3	25 2
CT4	13 6	300	210	597	420	16 25	18.4	194 7	134 2	449 7	24 4	29 9
FH	16.3	300	210	420	--	20 0	24 2	233 3		622.5	25.7	29.8

Abbreviation used:

PCT - Precommercial thinning
CT - Commercial thinning
FH - Final harvest
SDI - Stand Density Index
TPH - Tree per hectare
cm - Centimeter
m - Meter
ha - Hectare
PAI - Periodic annual increment

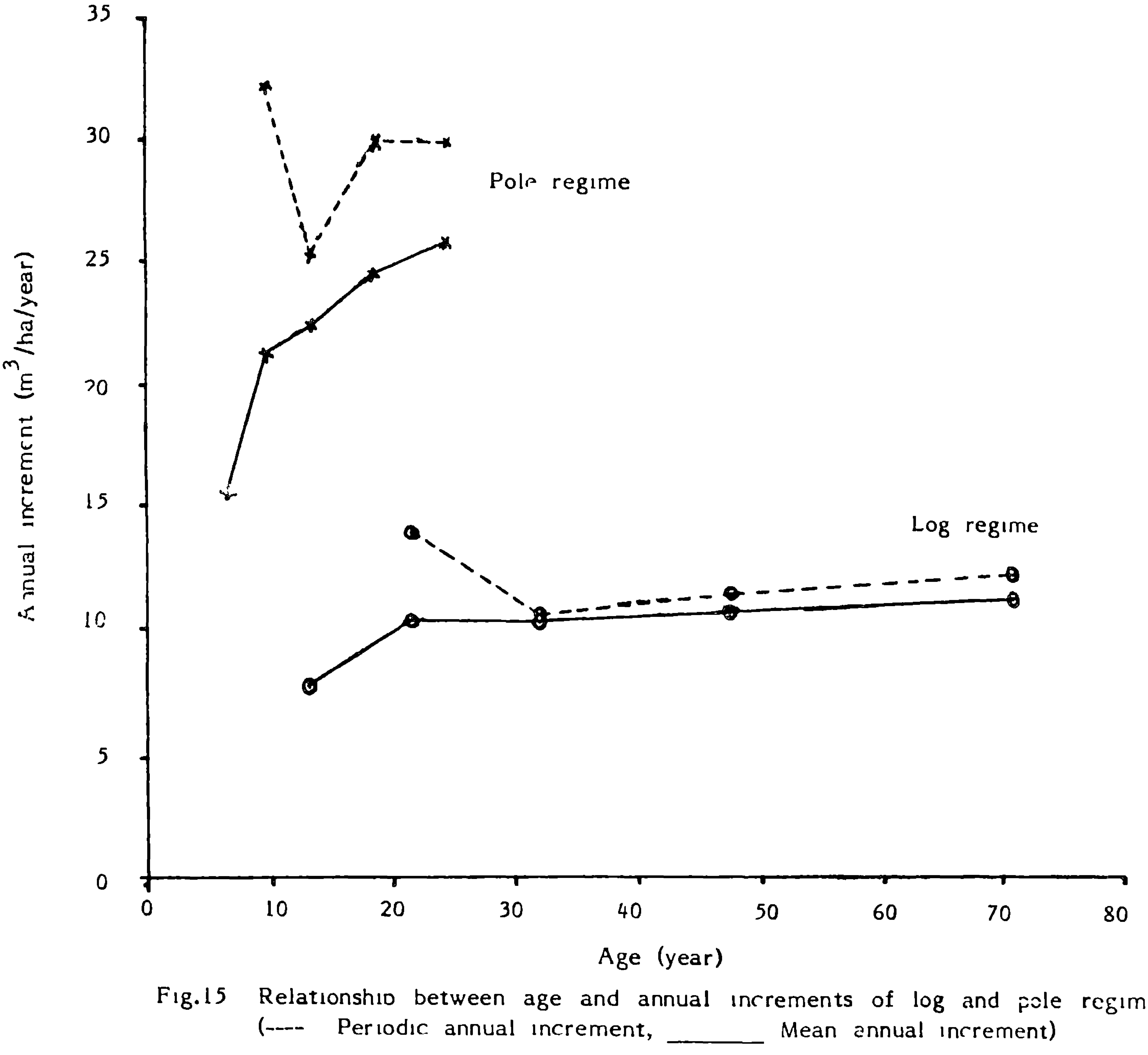

Fig.15 Relationship between age and annual increments of log and pole regime (---- Periodic annual increment, ________ Mean annual increment)

It is seen in both cases that only one PCT has been suggested because the cost of thinning in case of PCT is more when cost/benefit analysis is done, because the materials removed in a PCT or for that matter in the first mechanical thinning do not have any commercial value It is obvious from Table 12 and 13 that the volume obtained from the pole production regime is substantially larger than the sudden sawlog regime For example, the former gave a volume of about 622 5 m^3 ha^{-1} at the age of 24 2 years (Table 13) while the latter gave only a total volume of 400 m^3 ha^{-1} at an age of 31 4 years (Table 12) Both mean annual increment (MAI) and periodic annual increment (PAI) were higher in case of pole regime than the log regime (Fig 15) In both cases, however, the rotation ended before the culmination of the PAI One can formulate or design any number of alternate density management regime depending upon the management situations After examining all those options one of the better options can be selected and the stand could be managed accordingly

5.7. Potentials and Limitations of Density Management Diagram

The most outstanding feature of the density management diagram is that it is a simple, inexpensive, easy to use, graphical tool to simulate stand growth and yield for any given set of management situations The use of density management diagram does not require any sophisticated computer hardware or software, as in the case of the newer generation stand growth and yield simulation models, eg prognosis (Stage, 1973, Wykoff et al 1982, Farrar, 1985) The mathemetical programming approaches have the criticism that the results are specific to the stands included in the analysis and are also not amenable to current optimization procedures (Riitters and Brodie, 1984) Despite its simplicity, density management diagrams can be used for predicting the likely consequences of a very large number of alternate silvicultural decisions on stand growth and yield

Density management diagrams delimit stand conditions likely to result in a particular pattern of growth and development This type of diagram can easily be used by non-biometricians and can be extrapolated to untested management regimes easily

Stand density manipulation has a potential to make a major impact on individual tree size and stand yield The density management diagrams repl[illegible]e the voluminous tables of stand yield It can be used for comparing, checking and implementing the results of optimization analysis apart from designing alternate management regimes

The regression models used in the construction of the density management diagrams are generally characterised by very high r^2 values which means that a substantially high proportion of the variations in the data-set are explained by these regression equations

Limitations: The important short-comings of the density management diagrams are discussed below

1) Lack of "memory" The density management diagram can not remember the influence of a heavy or light thinning especially late in the rotation

2) Another discomforting feature of the model is the convergence to the same rotation age irrespective of the path taken by the stand for a predetermined quadratic diameter (Dq) and stand density index (SDI) combination

3) In many cases the rotation ends before the culmination of the periodic annual increment

4) The growth-growing stock relationship in this case, portray only three initial phases of the Langsaeter's curve as against five in the original Langsaeter curve (Langsaeter, 1941) It may be because, Langsaeter may have developed the set of curves for a hypothetical stand or alternately the relative insufficiency of the data-set used in this investigation also might be responsible for this situation The data-set in the

instant case covers only three out of the 20 territorial forest divisions of Kerala State

5) The assumption of a single maximum size-density relation or stocking rate for a species is also questionable There may be potential differences in this respect in the case of species with wide ecological amplitude

6) The density management diagram is applicable only for an even aged stand and is not suitable for complex unevenaged and mixed species stands However, recent works of Kikuzawa (1983) suggested that density management diagrams can be constructed for stands with more structural complexity

7) The residual plots (Fig 10 and 11) against the independent variables depicts a divergent pattern of distribution indicating lesser dependability of the model for higher and lower values of height and mean volume The residual plots thus indicate a slight possibility of under-predicting at lower values and over predicting at higher values of mean volume and vice versa in the case of height

Nevertheless, it could be safely assumed that the model could give reasonably good predictions in the range of the data-set However, extrapolation beyond the range of data set (for density, volume, age etc) may produce dubious results

Despite these short-comings, with more work, the present density management diagram can be improved to overcome many of the pitfalls mentioned herein

6. SUMMARY

6. SUMMARY

Forest plantation management in India, in general and Kerala, in particular, has not received much attention in the past The old practices are still being followed even now without much changes Proper management of the plantations is required especially in veiw of the rising demand for timber and other forest products The question is not only to utilize maximum land area but also how properly and economically the land can be utilized In short, forest management has to be geared to meet these new challenges The use of density management diagram would help forest manager to design stand density regimes to meet the ends of the multiple objective forest resource management

Density management diagram is a simple graphical representation of the stand growth through time in terms of stand characteristics, which enables the land manager to predict the likely consequences of various silvicultural operations on stand growth and yield A teak density management diagram to facilitate the management of teak plantations for various objectives such as traditional timber production, wild life habitat management etc was constructed (Fig 12) using the stand inventory data collected from the teak plantations of Parambikulam, Thrissur and Chalakudy divisions The format shows density (TPH) on x-axis and quadratic mean diameter (Dq) in centimeter on y-axis Volume per hectare, site height (ie height of dominant trees) and stand density index (SDI) are also given in the diagram

The stand inventory data clearly indicate that Parambikulam was a better site for teak But in the light of the recent policy shift, the area cannot any longer be used for establishing large scale teak plantations

The first step in designing a density management regime is to choose a suitable size-density relationship, which should be independent of site, age and species In the present study Reineke's stand density index (SDI) which represents the number of trees having an average stand diameter of 25 cm at breast height, on a hectare basis was chosen for the purpose This index is indepedent of site quality and age and can be made independent of species too by using the percentage or proportion of the maximum SDI for the species. For teak (Tectona grandis Linn f) the maximum SDI was estimated to be 600 It is assumed that there will not be any real combination of density and diameter which will correspond to more than the maximum SDI

The translation of the management objectives such as maximization of volume production per unit area or maximization of individual tree growth, thinning intensity and interval between two successive thinnings, etc, into appropriate lower and upper limit of growing stock is another crucial step in the design of density management regimes The upper and lower limits of growing stock are dependent on the management objectives For example, if the management objective is to maximise the volume per unit area without regard to individual tree vigour, the stand should always be above 35% of the SDI maximum (the zone where full site occupancy occurs) On the other hand, if it suits the land manager to maximise the individual tree growth without regard to volume per unit area the level of growing stock should always correspond to less than 35% of maximum SDI because the tree growth will fall below its potential for open grown trees of that species if the level of growing stock is greater than 35% of the max SDI Another consideration in this context would be quick response to release

In the present study a density management diagram was constructed for teak and its utility in designing alternate density management regimes is described for two hypothetical management situations, namely, log regime and pole regime In the former case the density management regime aims at maximization of tree vigour and in the latter, it is designed for maximization of volume per unit area without regard to tree vigour

The most dramatic feature of the density management diagram is that it can be used for designing alternate management regimes and for predicting the likely consequences of different silvicultural operations on stand growth and yield processes It can also be used to check, implement and to compare the results of optimisation analysis and can replace the voluminous stand yield tables However, it suffers from weaknesses such as lack of "memory", prediction of same rotation age for a predetermined Dq and SDI combination, rotation ends before the culmination of periodic annual increment, assumption of a single maximum size-density relation etc

7. REFERENCES

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Adiyodi, P N 1973 The seventh working plan for Wynad forest division (1974-75 to 1983-84) State Forest Department, Government of Kerala, Trivandrum, 150p

Akkara, K 1984 Working Plan for the Chalakudy forest division for the period 1984-85 to 1993-94 State Forest Department, Trivandrum, 315p

Ando, T 1968 Ecological studies on the stand density control in even aged pure stand Bull Govt For Exp Sta , Tokyo 210 1-153

Arnold, L E 1978 Gross yields of rough wood products from a 25 - year-old loblloly and short leaf pine spacing study Urbana, IL Illinois Agril Centre 6 230-236

Assamann, E. 1970. The priciples of forest yield study studies in the organic production, structure, increment and yield of forest stands Pergamon Press, Oxford 506p

Baker, F S 1934 Theory and practice of silivicuture Mc Grow Hill Book Co , N Y 502p

Ballard, L A and Long, J N 1988 Influence of stand density on log quality of lodgepole pine Can J For Res , 18(7) 911-916

Barrett, J W 1981 Twenty year growth of thinned and unthinned ponderosa pine in the Methow valley of northern Washington Res Pap Pacific Northwest For and Range Exp Sta , USDA, For Ser , Pacific Northwest 286 13p

Bazzaz, F A and Harper, J L 1976 Relationship between plant weight and number in mixed populations of _Sinapsis alba_ (L) Rabenh and _Lepidium sativum_ (L) J Appl Ecol , 13 211-216

Bendtsen, B A 1978 Properties of wood from improved and intensively managed trees For Prod J ,28 61-72

Bennett, F A 1963 Growth and yi... of slash pine plantations Res Pap Southeastern-1 Asheville, USDA, For Ser Southeastern For Exp Sta

23p

Bennett, F A 1969 Spacing and slash pine quality timber production Res Pap Southeastern-53 Asheville, USDA, For Ser Southeastern For Exp Sta 9p

Bennett, F A 1971 The role of thinning and some other problems in management of slash pine plantations Res Pap Southeastern - 86 Asheville, USDA, For Ser Southeastern For Exp Sta 14p

Beumee, G B Jr 1922 Results of remeasuring of 40 permanent sample plots reserved for the investigation regarding thinning and yield of teak plantation Tectona 15 1-76

Black, J.N 1958 Competition between plants of different initial seed sizes in swards of subterranean clover (Trifolium subterraneum L) with particular reference of leaf area and light microclimate Australian Agric Res , 9 299-318

Black, J N and Wilkinson, G N 1963 The role of time of emergence in determining the growth of individual plants in swards of subterranean clover Australian Agric Res , 14 628-638

Blackbury, P and Petty, J A 1988 Theoretical calculation of the influence of spacing on stand density Forestry 61(3) 235-244

Blandford, H R 1923 Thinning in teak plantation Burma For Bull , 9 1-8

Blume, B M. 1961 Age-size relationships in all aged northern hardwoods Res Note 125 Broomall, PA USDA, For Ser Exp Sta 3p

Box, B H , Linnartz, N E and Applequist, M B 1964 Comparative growth and volume of loblolly pine planted at various spacings LSU For Note 60 Baton Rouge, LA Louisiana State Univ 2p

Brazier, J D 1977 The effect of forest practices on quality of the harvested crop Forestry SO 49-

66

Brender, E V 1965 Thinning loblolly pine Pages 99 - 110 In W G Wahlenberg (Ed) A guide to loblolly and slash pine plantation management in Southeastern USA Rep No 14 Macon, GA Georgia Forestry Res Council

Bryndum, H 1987 Danish thinning experiments with beech Allgemeine Forst-uad Jagdzeitung Danish Forest Exp Sta 2930 Klampenborg Denmark, 158(7/8) 115-121

Burton, J D. 1982 Sawtimber by prescription - The Sudden sawlog story through age 33 Res Pap SO-179 New Orleans USDA, For Ser , Southern For Exp Sta 9p

Carleton, T J and Wannamaker, B A 1987 Mortality and self-thinning in postfire black spruce Ann Bot , 59 621-628

Curtis, R O. 1970. Stand density measures an interpretation Forest Sci , 16 403-414

Curtis, R O 1971 A tree area power function and related stand density measures for Douglas-fir Forest Sci , 17 146-159

Curtis, R O 1982 A simple index of stand density for Douglas-fir Forest Sci , 28 92-94

Daniel, T W , Helms, J A and Baker, F S 1979 Principles of Silviculture (2nded) Mc Grow Hill Book Co N Y 500p

Davis, K P 1966 Forest management Regulation and Valuation (2nded) Mc Grow Hill Book Co N Y 519p

Day, M W and Rudolph, V J 1971 Thinning red pine by precent of height Mich Agr Exp Sta Res Rep , 125 8p

Day, M W and Rudolph, V J 1972 Thinning plantation red pine Mich Agr Exp Sta Res Rep , 151.12p.

Drew, T J and Flewelling, J W 1977 Some recent Japanese theories of yield-density relationship and their application to Monterey pine plantations Forest Sci ,23 517-534

Drew, T J and Flewelling, J W 1979 Stand density management an alternative approach and its application to Douglas-fir plantations Forest Sci , 25(3) 518-532

Dzedzyuyla, A A 1985 Model and basic principles of density regulation in scots pine stand for the rapid production of large diameter timber Lesovodstion i Agrolesomelioratsiya, USSR, 70 30-33

Edie, A G 1916 Thinning of teak coppice in the poles areas of Kanara Indian Forester, 43(3) 157-159

Ek, A.R and Dawson, D H 1976 Actual and projected growth and yields of populus 'Tristis #1' under intensive culture Can J For Res , 6 132-144

Farrar, R M Jr 1968 Thinning longleaf pine on average sites J For , 66(12) 906-908

Farrar, R M Jr 1985 Predicted stand and stock tables from a spacing study in naturally regenerated longleaf pine USDA, For Ser Res Pap SO-219 Southern For Exp Sta New Orleans, LA Louisaina 28p

Feduccia, D P and Mosier, J 1977 The wood worth spacing and thinning study-an oblituary Forests and people, 27(1) 18-21

Fender, D E. 1968 Short rotation up to 33 years Pages 11-12 In G A Cordele G A (ed) Proc Symp on planted pines 1968 October 22-23 Atlanta USDA, For Ser Southeastern Area State and Private Forestry

Flewelling, J W 1981 A comparision of three stand density indices for predicting gross volume growth in plantation of loblolly pine Diss Univ of Georgia, Athens 83p

Ford, E D 1975 Competition and stand structure in some even-aged plant monocultures J Ecol , 63 311-333

FRI (Forest Research Institute) 1955 Teak plantation- Wynad-best intensity of thinning For Res India Part III 1954-55 Forest Research Institute Dehradun, India, 78-79

George, M P 1954 Working plan for Trichur forest division (1955-56 to 1969-70) State Forest Department, Government of Kerala, Trivandrum, 121p

Gingrich, S F 1967 Measuring and evaluating stocking and stand density in upland hardwood forest in the Centrel State For Sci , 13 38-53

Gorham, E 1979 Shoot height, weight and standing crop in relation to density of monspecific plant stands Nature, 279 148-150

Grime, J P. 1973 Competition and diversity in herbaceours vegetation- a reply Nature, 244 310-311

Guilkey, P C and Westing, A H 1956 Effects of initial spacing on the development of young jack pine in north lower Michigan papers Michigan Acad Science, Arts, and Letter, 41 45-50

GSI (Geological Survey of India) 1964 After Uniyal V K See Uniyal (1988)

Handler, M M 1984 Relative distance of trees- applicability as a measure of density Dansk Skovforenings Tidsskrift, 69(4) 361-374

Hara, K.L , and Oliver, C D 1988 Three Dimensional representation of Douglas-fir volume growth Comparison of growth and yield models with stand data Forest Sci , 34(3) 724-743

Harper, J L 1977 Population biology of plants Acad Press, New York 829p

Hellinga, G 1939 The natural thinning in unthinned _Tectona grandis_ Plantation Tectona, 32(4/5)

Hibbs, D E 1987 The self-thinning rule and red alder management For Ecol Manage , 18 273-281

Hibbs, D E , Emmingham, W H and Bondi, M C 1989

Thinning red alder Effects of method and spacing Forest Sci , 35(1) 16-29

Hungerford, R D 1987 Estimation of foliage area in dense Montana lodgepole pine stands Can J For Res , 17 320-324

Hutchings, M J and Budd, C S J 1981 Plant competition and its course through time Bioscience, 31(9) 640-645

Iyer, M K C 1982 Third working plan for the Punalur Forest Division State Fo est Department, Government of Kerala, Triv ndrum, 96p

Karunakaran, C K 1970 Second working plan for the Kottayam Forest Division (1970-71 to 1984-85) State Forest Department, Government of Kerala, Trivandrum, 115p

Khalil, M A K 1943. Advance thinning for teak plantation Indian Forester, 69(1) 15-19

Khanna, L S 1984 Tending Principles and practice of silviculture (3rded) Khanna Bandhu Publication, Dehradun, India 414-457

Kikuzawa, K 1983 Yield-density diagram Compactness index for stand and stand components For Ecol Manage , 7(1) 1-10

Kisilev, A F and Atroshchenko, O A 1985 Modelling the growth and productivity of Belorussian Norway spruce stands Lesovedenic i Lesnoe Khozyaistvo Belorns, Technol Inst im S M Kirova, Minsk, Belorussian SSR No 20 70-75

KSFD (Kerala State Forest Department) 1988 Kerala state forest department social forestry guide State Forest Department, Government of Kerala, Trivandrum, 1-6

Kumar, B M , Bhardwaj, S D. and Long, J N 1989 Relationships between size and density in mixed-species population Indian J Ecology (in press)

Langsaeter, A 1941 Om tynning enaldret gran-ogfuruskog (About thinning in even-aged stands of spruce, fir and pine) Meddel f d Norske

Skogforsoksvesen, 8 131-216

Lanner, R M 1985 On the insensitivity of height growth to spacing For Ecol Manage , 13 143-148

Leak, W B 1975 Age distribution in virgin red spruce and northern hardwoods Ecology, 56 1451-1454

Leak, W B 1985 Relationships of tree age to diameter in old growth northern hardwoods and spruce - fir Res Note Northeastern - 329 USDA, For Ser Northeastern For Exp Sta 4p

Leduc, D J and Zeide, B 1987 Development of loblolly pine stand at various levels of density and prunning Arkansas For Res Dep For Resour , Agric Exp Sta Univ Arkansas, Fayetteville, U S A , 36(3) 2p

Liu, J.R 1984 Preliminary study on relationship between mean diameter and stand density For Sci , Technol , 3 17-21

Lloyd, F T. and Harms, W R 1986 An individual stand growth model for mean plant size based on the rule of self-thinning Ann Bot , 57(5) 681-688

Long, J N 1985 A practical approach to density management For Chron , 61 23-27

Long, J N , McCarter, J B and Jack, S B 1988 A modified density management diagram for coastal Douglas-fir Western J Appl Forestry, 3(3) 2p

Long, J N and Smith, F W 1984 Relation between size and density in developing stands a desciption and possible mechanisms For Ecol Manage , 7(3) 191-206

Lonsdale, W M 1990 The self-thinning rule dead or alive? Ecology, 71(4) 1373-1388

Lonsdale, W M and Watkinson, A R 1982 Light and self-thinning New Phytol , 90 431-445

Lonsdale, W M and Watkinson, A R 1983 Plant geometry and self-thinning J Ecol , 71 285-297

Malende, Y H and Dingo, W N 1987 Effect of thinning intensities on wood basic density in Cupressus lusitanica Indian J For , 10(1) 24-26

Mathauda, G S 1954 Relationship between the average diameters of the main and subsidiary crops in the case of plantation teak (Tectona grandis Linn f) Indian Forester, 80(11) 707-708

Mc Carter, J B and Long, J N 1986 A lodgepole pine density management diagram Western J Appl Forestry, 1(1) 6-11

Merzlenko, M D 1983 A differential approach to plantation density Lesnoe Khozyaistvo, No(3) 29-31

Nebeker, T E , Hodges, J D , Karr, B K and Moehring, D M 1985 Thinning practices in Southern Pines-with pest management recommendations USDA, For Ser Tech Bull , 1703 1-36

Nigi, T 1986 Development structure of selection cutting systems Analysis of the management of Thujopsis dolabrata forest in Shimonta national forest Res Bull the college experimental forest Hokkaido Univ , 43(2) 177-316

Ohn Maung, 1968 Control of thinning of teak plantation in Burma Union Burma J Life Sci , 1(2) 194-199

Outcalt, K W 1986 Stand density affects growth of choctawhatche stand pine Southern J Appl Forestry, 10(3) 128-131

Pearson, J A , Fahey, T J and Knight, D H 1984 Biomass and leaf area in contasting lodgepole pine forests Can J For Res , 14 259-265

Pongsopha, Ch 1962 Comparison of teak growth resulting from different degree of thinning Thesis of Faculty of Forestry (1961-62) Kasetsart Univ Bangkok, Thailand 80p

Ram Prasad,1973 Limitation of formula thinning in teak forest of M P paper no 81 in the Forestry conference (Silviculture conference) from 6 to

10th December 1973 at Forest Rsearch Institute, Dehradun (U P) India

Reineke, L H 1933 Perfecting a stand density index for even aged forest J Agric Res , 46 627-638

Rennolls, K and Peace, A 1986 Flow models of mortality and yield for unthinned forest stands Forestry, 59(1) 47-58

Riitters, K , Brodie, J D and Hann, D W 1982 Dyanamic programming for optimizing of timber production and grazing in ponderosa pine Forest Sci , 28(3) 517-526

Riitters, K and Brodie, J D 1984 Implementing optimal thinning strategies Forest Sci , 30(1) 82-85

Rudolf, P O 1951 Stand density and the development of young jack pine J For , 49 254-255

Sagreiya, K P 1963 Single stem silviculture (height/ spacing relationship) Indian Forester, 89(10) 652-656

Sagreiya, K P and Chacko, V S 1962 A statistical approach to models for yield tables in even aged teak forests and some application Indian Forester, 88(12) 896-906

Sagwal, S S and Gupta, N K 1987 A study on density of stem and percentage in natural forests of Ohi (Albizzia chinensis Osbeck Merr) Indian J For , 10(2) 153-154

Sakai, K I , Runibino, A , Iyama, S and Gadrinab, L V 1987 Studies on interference among trees in a plantation of Altingia excelsa Biotropia, 1(1) 26-40

Saramaki, J and Sekeli,P M 1984 The effect of spacing and thinning on the growth and yield of Eucalyptus cloziana Res Note, Division of For Res , For Dept , Zambia, 34(1) 8p

Sarlin, P 1966 The first thinning in teak plantations Bios For Trop , 108 5-20

Senft, J F , Bendtsen, B A and Galligan, W.L 1985 Weak wood fast grown trees make problem timber J For , 83 476-484

Shelton, M G and Switzer, G L 1980 The development of unthinned loblolly pine plantations at various spacings Pages 53-54 In Proc Symp on thinning southern pine plantations March 3-5 Long Beach MS Southern For Econ Workshop

Shepard, R K Jr 1973. The effect of various initial spacings on the development of loblolly pine For Res Rep Cathonn, LA North Louisiana Hill Farm Exp Sta , 15-35

Shirley, G S 1928 Effect of neglect of thinning in teak plantations Indian Forester, 54(3) 170-172

Shirley, G S 1929 Note on the natural thinning in young teak plantations Indian Forester, 55(4) 225-227

Smith, N J and Hann, D W 1986 A growth model based on the self-thinning rule Can J For Res , 16(2) 330-334

Smith, F W and Long, J N 1987 Elk hiding and thermal cover guidelines in the context of lodgepole pine stand density Western J Appl Forestry, 2 5p

Stage, A R 1973 Prognosis model for stand development USDA, For Ser Res Pap INT-137 32p

Sterba, H 1987 Estimating potential density from thinning experiment an inventory data Forest Sci , 33(4) 1022-1031

Tubbs, C H. 1977 Age and structure of a northern hardwood selection forest , 1929-1976 J Forestry, 75 22-24

Uniyal, V K 1988 The first working plan for Parambikulam Wildlife Sanctuary Kerala Forest Department, Trivandrum, 250p

Vasudevan, K G 1966 Working plan for Nilambur Forest Division (1967-68 to 1976 77) State Forest Department, Govt of Kerala, Trivandrum, 247p

Ware, L M and Stahelin, R. 1948 Growth of southern pine plantation at various spacings J For , 46 267-274

Weller, D E 1987 A re-evaluation of the -3/2 power rule of plant self-thinning Ecological Monagraphs, 57(1) 23-43

Westoby, M 1984 The Self-thinning rule Advances in Ecol Res , 14 167-225

White, J and Harper, J L 1970 Corrected changes in plant size and number in plant populations J Ecol , 58 467-485

Wilde, S A Giordano,A , Shaw, B H , Fedkenheuer, A W and Seip, W T 1968 Tree spacing in forest plantations as related to soils and revenue Univ Wisconsin College Agric and Life Sci Bull , 589p

Wilson, F G 1946 Numerical expression of stocking in temrs of height J For ,44 756-761

Wilson, F G 1979 Thinning as an orderly discipline A graphic spacing schedule for red pine J For , 77 483-486

Wykoff, W R , Crookston, N L and Stage, A R 1982 User's guide to the stand prognosis model Gen Tech Rep INT-133 Ogden, Utah USDA, For Ser , 112p

Yang, Y C and Lin, F P 1981 Bertalanfly's generalized growth function applied to stands of varying CCF J Jap Forestry Soc , 63(8) 294-297

Yoda, K , Kira, T., Ogawa, H and Hozumi, K. 1963 Self-thinning in over crowed pure stands under cultivated and natural conditions J Biol Osaka City Univ , 14 107-129

Zavitkovski, J and Dawson, D H 1978 Structure and Biomass production of 1- to 7- year old intensively cultured jack pine plantations in Wisconsin USDA For Ser Res Paper, North Central For Exp Sta For Ser USDA NC-197 15p

Zeide, B 1985 Tolerance and self-tolerance of trees

For Ecol Manage , 13 149-166

APPENDICES

APPENDIX I

Data for stand characteristics for teak plantations.

Plot no.	No.of trees	Age (yr)	DBH (cm)	D_q (cm)	Ht (m)	Den (TPH)	BA (sq cm)	Volume (cu m)	DPAI (cm/ ac/yr)	HPAI (m/ ac/yr)	GVPAI (cu m/ ac/yr)	SDI	f_r
1	12	75	42.3365	42.6530	21.6567	30.0	4.2864	94.2160	0.5645	0.2888	0.0419	70.5239	0.0776
2	9	75	53.1239	53.3976	24.0889	22.5	5.0385	122.3596	0.7083	0.3212	0.0725	75.7727	0.0840
3	11	75	48.1820	48.5695	22.4918	27.5	5.0949	116.4645	0.6424	0.2999	0.0565	79.5812	0.0869
4	11	75	48.6160	48.8548	24.0745	27.5	5.1549	125.4874	0.6482	0.3210	0.0608	80.3304	0.0913
5	11	75	45.5486	45.9287	21.3236	27.5	4.5559	100.3926	0.6073	0.2843	0.0487	72.7719	0.0787
6	8	75	51.5279	52.0234	25.7775	20.0	4.2511	111.2202	0.6870	0.3437	0.0741	64.6017	0.0757
7	9	75	41.4876	42.0924	20.3878	22.5	3.1309	65.2083	0.5532	0.2718	0.0386	51.7851	0.0552
8	12	75	36.8985	37.2578	18.4508	30.0	3.2706	62.0076	0.4920	0.2460	0.0276	56.8020	0.0587
9	10	75	46.6656	47.4400	22.0440	25.0	4.4188	99.8744	0.6222	0.2939	0.0533	69.6736	0.0759
10	11	75	45.1435	45.9618	22.1891	27.5	4.5625	104.3529	0.6019	0.2959	0.0506	72.8558	0.0807
11	27	74	57.5686	58.8325	27.9419	67.5	18.3491	516.7011	0.7780	0.3776	0.1034	265.4531	0.3163
12	30	65	59.0588	59.3662	25.0520	75.0	20.7595	519.7161	0.9086	0.3854	0.1066	299.2400	0.3289
13	30	65	53.1699	54.0692	24.2717	75.0	17.2202	420.9463	0.8180	0.3734	0.0863	257.6776	0.2858
14	15	65	44.9255	45.3665	24.2167	37.5	6.0615	147.1206	0.6912	0.3726	0.0604	97.2981	0.1125
15	14	65	41.9272	42.3823	21.9600	35.0	4.9376	108.9138	0.6450	0.3378	0.0479	81.4439	0.0900
16	16	65	43.6893	44.1323	22.1956	40.0	6.1186	141.2039	0.6721	0.3415	0.0543	99.3039	0.1119
17	23	65	40.4127	40.8228	21.2570	57.5	7.5257	164.7345	0.6217	0.3270	0.0441	126.0107	0.1399
18	18	65	40.3028	40.4827	21.9650	45.0	5.7920	129.1670	0.6200	0.3379	0.0442	97.3060	0.1097
19	15	65	40.5751	40.7283	21.9180	37.5	4.8854	108.2845	0.6242	0.3372	0.0444	81.8768	0.0917
20	16	65	45.3207	46.3063	22.5075	40.0	6.7362	159.3917	0.6972	0.3463	0.0613	107.2457	0.1213
21	14	65	42.3592	43.3860	22.5921	35.0	5.1742	121.7146	0.6517	0.3476	0.0535	84.5520	0.0969
22	32	56	41.3417	41.6397	23.5350	80.0	10.8939	262.5551	0.7382	0.4203	0.0586	180.9666	0.2132
23	30	56	43.2171	43.5375	28.8507	75.0	11.1652	327.9212	0.7717	0.5152	0.0781	182.1962	0.2420
24	29	56	43.1378	43.6019	26.2517	72.5	10.8250	293.1365	0.7703	0.4688	0.0722	176.5400	0.2220
25	32	56	39.7103	40.1374	23.0919	80.0	10.1220	241.6939	0.7091	0.4124	0.0539	170.6339	0.2017
26	28	56	36.4589	36.8968	22.6496	70.0	7.4843	177.0423	0.6511	0.4045	0.0452	130.4899	0.1568
27	28	56	38.3006	38.8807	23.8457	70.0	8.3108	209.3399	0.6839	0.4258	0.0534	141.8956	0.1753
28	32	56	39.4716	40.0381	24.1028	80.0	10.0720	255.8664	0.7048	0.4304	0.0571	169.9590	0.2095
29	33	56	39.8188	40.1421	24.7264	82.5	10.4407	266.6863	0.7111	0.4415	0.0577	175.9986	0.2176
30	28	56	40.3129	40.7107	22.7454	70.0	9.1116	215.9309	0.7199	0.4062	0.0551	152.7315	0.1790
31	29	56	37.0677	37.4664	21.5145	72.5	7.9928	180.2464	0.6619	0.3842	0.0444	138.5038	0.1605
32	54	50	35.3806	35.9008	20.2828	135.0	13.6653	276.3345	0.7076	0.4057	0.0409	240.8774	0.2626
33	68	50	36.5740	37.0963	20.6681	170.0	18.3733	381.6245	0.7315	0.4134	0.0449	319.6498	0.3517
34	30	50	36.6067	38.0125	23.4217	75.0	8.5112	219.6003	0.7321	0.4684	0.0586	146.6358	0.1852
35	44	50	37.7787	39.1648	26.9664	110.0	13.2514	394.3340	0.7556	0.5393	0.0717	225.5911	0.3109
36	37	50	33.8537	35.6992	23.1192	92.5	9.2584	250.7930	0.6771	0.4624	0.0542	163.5651	0.2170
37	43	50	36.2366	37.7970	22.8674	107.5	12.0615	319.4783	0.7247	0.4573	0.0594	208.2749	0.2681
38	30	50	37.4556	38.5027	22.3923	75.0	8.7321	219.2740	0.7491	0.4478	0.0585	149.6728	0.1850
39	40	50	41.0075	41.9752	24.7873	100.0	13.8376	376.0778	0.8201	0.4957	0.0752	229.1311	0.2918
40	37	50	41.0804	41.9178	24.4159	92.5	12.7648	338.7822	0.8216	0.4883	0.0733	211.4825	0.2652

APPENDIX I

Data for stand characteristics for teak plantations.

Plot no.	No.of trees	Age (yr)	DBH (cm)	Dq (cm)	Ht (m)	Den (TPH)	BA (sq m)	Volume (cu.m)	DPAI (cm/ac/yr)	HPAI (m/ac/yr)	GVPAI (cu.m/ac/yr)	SDI	ρ_r
41	30	50	41.0950	42.0326	26.1143	75.0	10.4066	299.1344	0.8219	0.5223	0.0798	172.2244	0.2276
42	55	45	39.4484	39.9262	22.6613	137.5	17.2146	388.5583	0.8766	0.5036	0.0628	290.8114	0.3316
43	58	45	40.1137	40.6388	22.6200	145.0	18.8074	425.1893	0.8914	0.5027	0.0652	315.4788	0.3584
44	52	45	37.1270	37.4951	24.0650	130.0	14.3539	351.8459	0.8250	0.5348	0.0601	248.6562	0.3046
45	60	45	39.0843	39.4513	22.4252	150.0	18.3354	423.4539	0.8665	0.4983	0.0627	311.2325	0.3615
46	60	45	29.6037	30.0640	19.6920	150.0	10.6479	213.4027	0.6579	0.4376	0.0316	201.4941	0.2289
47	69	45	30.4249	30.8329	19.9609	172.5	12.8794	264.7871	0.6761	0.4436	0.0341	241.2726	0.2770
48	65	45	29.9024	30.2497	19.5355	162.5	11.6781	234.0011	0.6645	0.4341	0.0320	220.4469	0.2500
49	69	45	27.9429	28.4009	20.9954	172.5	10.9278	236.3427	0.6210	0.4666	0.0304	211.5520	0.2567
50	65	45	30.9161	31.5115	19.6346	162.5	12.6727	257.1061	0.6870	0.4363	0.0352	235.3426	0.2662
51	60	45	29.5347	29.8742	18.8612	150.0	10.5138	204.3938	0.6563	0.4191	0.0303	199.4625	0.2224
52	59	40	35.3604	36.3097	19.9517	147.5	15.2727	310.8536	0.8840	0.4988	0.0527	267.9939	0.2925
53	78	40	30.6525	31.2740	19.8482	195.0	14.9789	301.9818	0.7663	0.4962	0.0387	279.0133	0.3149
54	63	40	27.1835	27.4445	18.0692	157.5	9.3168	172.5252	0.6796	0.4517	0.0274	182.8539	0.2019
55	60	40	26.7070	27.0199	18.5920	150.0	8.6007	162.6373	0.6677	0.4648	0.0271	169.8562	0.1910
56	65	40	27.6595	27.9568	18.3226	162.5	9.9749	186.4488	0.6915	0.4581	0.0287	194.3257	0.2149
57	68	40	27.0712	27.5004	18.6556	170.0	10.0973	192.9783	0.6768	0.4664	0.0284	198.0106	0.2232
58	60	40	27.3330	27.6528	18.7693	150.0	9.0084	172.4578	0.6833	0.4692	0.0287	176.2668	0.1986
59	55	40	27.8385	28.1165	18.7140	137.5	8.5369	162.5840	0.6960	0.4678	0.0296	165.9343	0.1855
60	63	40	26.4660	26.7990	18.3194	157.5	8.8837	165.9126	0.6616	0.4580	0.0263	176.0220	0.1967
61	60	40	26.6858	27.0145	18.5682	150.0	8.5973	162.1903	0.6671	0.4642	0.0270	169.8015	0.1907
62	99	35	30.4397	30.9596	23.1606	247.5	18.6313	437.4484	0.8697	0.6617	0.0505	348.4531	0.4365
63	100	35	30.2149	30.7545	22.7344	250.0	18.5709	430.3113	0.8633	0.6496	0.0492	348.2482	0.4332
64	77	35	20.9223	21.7487	14.3340	192.5	7.1511	111.7747	0.5978	0.4095	0.0166	154.0355	0.1617
65	93	35	22.2584	22.8047	15.8360	232.5	9.4962	160.7889	0.6360	0.4525	0.0198	200.7046	0.2194
66	66	35	28.3063	29.5655	15.4858	165.0	11.3275	177.4688	0.8088	0.4425	0.0307	215.7928	0.2090
67	54	35	31.7199	32.5457	22.3546	135.0	11.2305	267.4435	0.9063	0.6387	0.0566	205.8827	0.2569
68	55	35	27.1034	27.7362	18.4764	137.5	8.3076	165.4167	0.7744	0.5279	0.0344	162.3579	0.1877
69	73	35	25.2780	25.7145	17.1016	182.5	9.4776	172.0748	0.7226	0.4886	0.0269	190.9171	0.2117
70	60	35	23.3540	24.5779	14.9845	150.0	7.1163	115.6216	0.6673	0.4281	0.0220	145.9682	0.1521
71	56	35	26.3637	27.2495	17.5334	140.0	8.1643	157.2577	0.7532	0.5010	0.0321	160.6928	0.1825
72	146	30	26.7475	27.3709	21.8436	365.0	21.4758	481.1997	0.8916	0.7281	0.0439	421.9411	0.5295
73	103	30	24.0254	24.7706	18.2266	257.5	12.4087	240.7718	0.8008	0.6076	0.0312	253.7298	0.2971
74	100	30	23.5620	24.0646	18.1271	250.0	11.3704	211.4189	0.7854	0.6042	0.0282	235.2031	0.2697
75	97	30	24.5598	25.0669	18.5044	242.5	11.9863	226.3710	0.8187	0.6168	0.0311	243.8507	0.2795
76	80	30	22.9986	23.5394	16.8507	200.0	8.7036	155.1739	0.7666	0.5617	0.0259	181.6350	0.2037
77	56	30	20.0996	20.8088	13.5923	140.0	4.7610	68.3520	0.6700	0.4531	0.0163	104.3807	0.1047
78	115	30	21.6319	21.9754	16.2410	287.5	10.9041	184.6459	0.7211	0.5414	0.0214	233.9016	0.2582
79	64	30	24.4061	24.9982	15.5867	160.0	7.8526	129.1662	0.8135	0.5196	0.0269	159.9812	0.1674
80	60	30	24.6804	25.1506	14.8345	150.0	7.4519	116.7159	0.8227	0.4945	0.0259	151.4488	0.1531

APPENDIX I

Data for stand characteristics for teak plantations.

Plot no.	No of trees	Age (yr)	DBH (cm)	Dq (cm)	Ht (m)	Den (TPH)	BA (sq.cm)	Volume (cu m)	DPAI (cm/ac/yr)	HPAI (m/ac/yr)	GVPAI (cu m/ac/yr)	SDI	ϑr
81	60	30	24.0013	24.5969	14.8483	150.0	7.1274	112.3356	0.8000	0.4949	0.0250	146.1490	0.1493
82	138	25	17.5168	17.9660	13.2256	345.0	8.7458	123.9638	0.7007	0.5290	0.0144	203.3467	0.2104
83	133	25	20.8008	21.3612	14.9941	332.5	11.9157	184.7189	0.8320	0.5998	0.0222	258.5173	0.2711
84	120	25	18.4227	18.8753	14.0266	300.0	8.3943	124.4637	0.7369	0.5611	0.0166	191.3577	0.2013
85	135	25	19.4882	20.0184	14.2588	337.5	10.6221	161.5427	0.7795	0.5704	0.0191	236.5142	0.2492
86	127	25	18.5302	19.0608	14.2421	317.5	9.0595	138.4070	0.7412	0.5697	0.0174	205.7153	0.2202
87	78	25	27.4775	28.1886	22.6541	195.0	12.1691	287.9020	1.0991	0.9062	0.0591	236.2918	0.3051
88	75	25	19.2477	19.7728	21.6655	187.5	5.7572	132.6891	0.7699	0.8666	0.0283	128.8264	0.1797
89	80	25	25.5053	26.1736	22.9389	200.0	10.7605	261.6630	1.0202	0.9176	0.0523	215.2325	0.2887
90	71	25	24.5285	25.5017	21.7893	177.5	9.0660	212.6410	0.9811	0.8716	0.0479	183.2334	0.2416
91	78	25	25.3472	26.2315	22.3527	195.0	10.5380	251.1547	1.0139	0.8941	0.0515	210.5945	0.2785
92	233	20	17.7453	18.3845	17.9862	582.5	15.4624	302.1463	0.8873	0.8993	0.0259	356.2177	0.4537
93	232	20	17.8176	18.3858	17.1286	580.0	15.3982	286.1837	0.8909	0.8564	0.0247	354.7286	0.4370
94	229	20	17.3088	17.8162	17.6880	572.5	14.2720	275.2627	0.8654	0.8844	0.0240	332.9480	0.4239
95	232	20	18.1771	18.8279	17.2947	580.0	16.1476	303.1533	0.9089	0.8647	0.0261	368.4740	0.4541
96	220	20	17.8042	18.4677	16.7156	550.0	14.7322	267.0663	0.8902	0.8358	0.0243	338.7817	0.4100
97	233	20	17.9201	18.5905	17.5150	582.5	15.8108	300.1187	0.8960	0.8758	0.0258	362.6245	0.4517
98	203	20	17.9529	18.5709	17.6335	507.5	13.7461	264.0853	0.8976	0.8817	0.0260	315.4022	0.3961
99	213	20	17.8752	18.4815	18.0020	532.5	14.2847	280.3003	0.8938	0.9001	0.0263	328.3942	0.4189
100	176	17	20.5895	21.1610	20.3474	440.0	15.4740	322.2316	1.2111	1.1969	0.0431	336.9824	0.4313
101	196	15	11.8200	12.9203	10.3133	490.0	6.4242	89.1816	0.7880	0.6876	0.0121	170.4224	0.1899
102	260	15	12.1023	13.2420	9.1001	650.0	8.9516	109.8689	0.8068	0.6067	0.0113	235.1450	0.2398
103	214	15	12.9990	13.8661	9.4464	535.0	8.0787	96.2685	0.8666	0.6298	0.0120	208.3424	0.2057
104	196	15	12.7799	13.6085	9.3813	490.0	7.1268	85.1890	0.8520	0.6254	0.0116	185.1777	0.1842
105	187	15	12.5540	13.6096	9.4511	467.5	6.8006	84.4919	0.8369	0.6301	0.0120	176.6974	0.1803
106	245	15	11.0307	12.2192	8.1667	612.5	7.1824	84.0947	0.7354	0.5446	0.0092	194.8368	0.1967
107	243	15	11.5250	12.6154	8.6602	607.5	7.5931	90.0792	0.7683	0.5773	0.0099	203.3673	0.2053
108	180	15	12.2854	13.3474	9.0097	450.0	6.2963	75.1814	0.8190	0.6006	0.0111	164.8712	0.1647
109	298	10	13.5414	14.0557	11.7053	745.0	11.5594	151.0473	1.3541	1.1705	0.0203	296.4931	0.3102
110	303	10	12.3651	12.9478	10.4367	757.5	9.9736	119.9723	1.2365	1.0437	0.0158	264.3575	0.2675
111	300	10	12.3253	12.9231	10.8820	750.0	9.8371	126.4366	1.2325	1.0882	0.0169	260.9406	0.2761
112	300	10	12.4495	13.0950	10.5842	750.0	10.1007	129.7552	1.2449	1.0584	0.0173	266.5184	0.2810
113	304	10	12.4375	13.0182	10.1544	760.0	10.1156	123.5655	1.2437	1.0154	0.0163	267.5416	0.2732
114	294	10	12.4448	13.0104	10.1283	735.0	9.7712	118.8211	1.2445	1.0128	0.0162	258.4939	0.2632
115	298	10	12.5811	13.1277	10.3427	745.0	10.0835	125.5163	1.2581	1.0343	0.0168	265.8002	0.2742
116	296	10	12.3005	12.9175	9.6568	740.0	9.6976	114.6324	1.2300	0.9657	0.0155	257.2835	0.2575

APPENDIX II

Analysis of variance for Equation I

Dependent variable ln Mvol

Independent variables (1) ln Den
(2) ln Ht

Multiple R	0 98290
R Square	0 96610
Adjusted R Square	0 96550
Standard error	0 19835

<u>Analysis of variance</u>

	DF	Sum of Squares	Mean Square
Regression	2	126 70001	63 35000
Residual	113	4 44563	0 03934

F = 1610 24546 Signif F = 0 0

Variables in the equation

Variable	B	SEB	Data	T	Sig T
ln Den	-0 46716	0 02780	-0 42558	-16 805	0000
ln Ht	2 23424	0 09005	-0 62833	24 810	0000
Constant(a)	-3 95248	0 37676		-10 491	0000

APPENDIX III

Analysis of variance for the Equation II

Dependent variable	ln Dq
Independent variables	(1) ln Den
	(2) ln Mvol
Multiple R	0 99615
R Square	0 99232
Adjusted R Square	0 99218
Standard Error	0 03738

<u>Analysis of Variance</u>

	DF	Sum of squares	Mean square
Regression	2	20 39976	10 19988
Residual	113	0 15789	0 00140

F = 7299 98918 Signif F = 0 0

Variables in the Equation

Variable	B	SEB	Beta	T	Sig T
ln Den	-0 06108	0 00766405	-0 14055	-7 970	0000
ln Mvol	0 34435	0 006982	0 86974	49 319	0000
Constant(a)	3 57525	0 03993		89 530	0000

APPENDIX IV

Predicted quadratic diameter (D_q) values (cm) for different combinations of density and stand density index (SDI) values

SDI \ Density(TPH)	50	100	300	500	1000	3000	5000
50	25.0000	16.2105	8.1582	5.9284	3.8441	1.9346	1.4059
100	38.5553	25.0000	12.5817	9.1429	5.9284	2 9836	2.1681
150	49.6753	32.2105	16.2105	11 7799	7.6383	3.8441	2.7934
200	59.4604	38.5553	19.4036	14.1003	9.1429	4.6013	3.3437
250	68.3591	44.3254	22.3075	16.2105	10.5112	5.2900	3.8441
300	76.6098	49.6753	25.0000	18.1671	11 7799	5.9284	4.3081
350	84.3580	54.6994	27.5284	20.0044	12.9713	6 5280	4.7438
400	91.7004	59.4604	29.9245	21.4753	14.1003	7 0962	5.1567
450	98.7056	64.0026	32.2105	23.4068	15.1774	7.6383	5.5506
500	105.4242	68 3591	34.4029	25.0000	16.2105	8 1582	5 9284
550	111.8949	72.5549	36.5145	26.5345	17.2055	8.6590	6.2923
600	118.1485	76.6098	38.5553	28.0174	18.1671	9.1429	6.6440

APPENDIX V

Predicted Mvol (m^3 $tree^{-1}$) values for different combinations of density (DEN) and height (Ht) values.

DEN(TPH) / Ht (m)	50	100	300	500	1000	3000	5000
5	0.1126	0.0814	0.0487	0.0384	0.0278	0.0166	0.0131
10	0.5297	0.3832	0.2293	0.1807	0.1307	0.0782	0.0616
15	1.3105	0.9480	0.5674	0.4470	0.3233	0.1935	0.1524
20	2.4922	1.8028	1.0791	0.8500	0.6149	0.3680	0.2899
25	4.1030	2.9681	1.7760	1.3994	1.0123	0.6059	0.4773
30	6.1661	4.4605	2.6699	2.1031	1.5213	0.9106	0.7173
35	8.7014	6.2945	3.7676	2.9678	2.1468	1.2850	1.0122
40	11.7261	8.4825	5.0773	3.9994	2.8931	1.7317	1.3641
45	15.2561	11.0360	6.6057	5.2033	3.7640	2.2530	1.7747
50	19.3053	13.9652	8.3590	6.5844	4.7631	2.8510	2.2457
55	23.8867	17.2794	10.3427	8.1470	5.8934	3.5276	2.7787
60	29.0125	20.9873	12.5622	9.8952	7.1581	4.2845	3.3749

APPENDIX VI

Predicted quadratic diameter (Dq)(cm) values for different combinations of density (DEN) and height (Ht) values

DEN (TPH) / Ht (m)	50	100	300	500	1000	3000	5000
5	13.2526	11 3629	8.9041	7.9498	6.8162	5.3412	4.7688
10	22.5892	19 [illegible]	15.1772	13.5505	11 6183	9.1043	8.1284
15	30.8583	26.4585	20.7334	18.5111	15.8715	12.4372	11 1041
20	38.5036	33.0133	25.8698	23.0970	19.8035	15.5184	13.8551
25	45.7151	39.1965	30.7151	27.4229	23.5126	18.4249	16 4500
30	52.5992	45.0989	35.3404	31.5524	27.0533	21.1994	18.9272
35	59.2224	50.7778	39 7903	35.5256	30 4596	23.8687	21.3104
40	65.6299	56.2716	44.0955	39.3691	33.7554	26.4513	23 6161
45	71.8550	61.6089	48 2778	43.1031	36 9570	28.9602	25 8562
50	77.9221	66.8110	52 3543	46.7427	40.0776	31.4055	28.0393
55	83.8506	71.8943	56.3376	50.2991	43.1268	33.7951	30.1728
60	89.6560	76.8718	60.2381	53.7815	46.1127	36.1348	32.2616

APPENDIX VII

Predicted quadratic diameter (cm) values for different combinations of density (DEN) and volume (Vol) values

DEN(TPH) / Vol (m^3 ha^{-1})	50	100	300	500	1000	3000	5000
50	28.1150	21.2276	13 5973	11.0541	8 3453	5 3459	4 3459
100	35.6946	26 9505	17.2628	14.0342	10 5952	6 7869	5 5174
200	45.3178	34.2162	21 9165	17.8161	13 4516	8 6167	7 0048
300	52.1070	39 3423	25 2005	20.4872	15.4669	9 9078	8 0544
400	57.5354	43 4365	27 8248	22.6192	17.0782	10 9396	8.8932
500	62 1281	46 9074	30 0471	24 4263	18 4422	11.8133	9 6035
600	66.1550	49 9489	31.9940	26.0079	19 6367	12.5788	10 2257
700	69.7602	52 6697	33.7382	27 4269	20 7077	13 2645	10 7832
800	73.0395	55 1469	35.3257	28 7173	21 6824	13 8887	11 2906
900	76 0661	57 4308	36 7879	29.9062	22 5795	14 4636	11 7579
1000	78.8778	59.5550	38.1471	31.0097	23 4132	14.9980	12.1924
1500	90 6948	68 4771	43.8631	35 6589	26.9208	17 2452	14 0193
2000	100.1431	75.6033	48.4308	39.3698	29 7253	19 0411	15.4792

Stand Density Regulation in Even Aged Teak Plantations

BY

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ABSTRACT OF A

THESIS

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ABSTRACT

A teak density management diagram was constructed using the stand inventory data on teak collected from Parambikulam, Thrissur and Chalakudy areas Density management diagram is a graphical representation of the stand growth through time, in terms of density and quadratic diameter, volume, height and Reineke's stand density index A size-density based index such as Reineke's stand density index incidentally provides a good biological basis for the translation of management objectives into levels of growing stock Stand density index (SDI) incidentally is also independent of site quality and age The data-set also revealed that Parambikulam is a better site for teak followed by Thrissur and Chalakudy The maximum SDI for teak was found to be 600 which probably covers all possible combinations of size and density included in the data-set

The use of diagram for designing two alternate density management regimes for a hypothetical stand is illustrated Designing a density management regime requires the translation of management objectives into appropriate levels of growing stock Maximization of volume production and maximization of individual tree growth are the two alternate but contrasting silvicultural strategies in this context For maximization of volume per unit area the level of the growing stock should fall in the zone II of the Langsaeter's

curve. On the other hand, if the land management objective is to maximize individual tree growth, then trees should not experiance much competition (preferably in zone I of the Langsaeter's curve) So, in the former case the levels of growing stock will be naturally higher than that of latter

After fixing the appropriate upper and lower levels of size - density relations the stand is allowed to grow till it reaches upper limit and then thinned down to the lower limit This process is repeated as many times as necessary The diagram has diverse utility from designing alternate density management regimes to comparing the results of optimization analyses However, it suffers from some shortcomings such as lack of memory, prediction of same rotation age irrespective to the path taken by stand, rotation ending before culmination of periodic annual increment, the assumption of single maximum size-density relationship and slight bias of the model with respect to the independent variables outside the range of the data base However, with more work many of these defects could be over come