A STUDY OF THE VARIATION IN SOME STRUCTURAL FEATURES AND SOME WOOD PROPERTIES OF PINUS CARIBAEA

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A thesis submitted to the University of Oxford for the degree of Doctor of Philosophy

- by -

S. H. ONG

Trinity Term 1978

Wolfson College Oxford

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To my father and mother

A STUDY OF THE VARIATION IN SOME STRUCTURAL FEATURES AND SOME WOOD PROPERTIES OF *PINUS CARIBAEA*

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A thesis submitted to the University of Oxford for the degree of Doctor of Philosophy

Hilary Term 1978 Wolfson College

Wood density and fibre morphology of *Pinus caribaea* var. *hondurensis* Barrett and Golfari from Fiji were studied in relation to pulp properties.

Densitometry and anatomical measurement were examined using billets taken from a sub-sample of 20 12-13 year old trees, chosen as representative of the density range observed in a first sample of 120 trees. Pulping properties were examined at the Tropical Products Institute, London.

Considerable differences between trees were found in all characteristics examined and all characteristics showed fairly marked tree to tree variation in development patterns in a radial direction though differences along the stem were small. Between ring differences for ring width, density, cell wall thickness and cell wall percentage were considerable but cell lumen width and cell diameter were fairly constant between rings.

Tree morphological characteristics cannot be used for estimation of whole tree values for any of the features studied. Whole tree values for wood characteristics can be accurately predicted from samples taken at 5% height level.

Characteristic patterns of wood density distribution classes and tracheid cross sectional dimension classes were found, resembling chi-squared, binomial and bimodal curves.

Wood properties could be used to predict pulp yield percentage and tear factor accurately by simple regression, less precise estimates could be obtained in this way, for burst factor and breaking length, which were best indicated by cell wall thickness.

The best indicators of variation in pulp total yield percentage were chemical properties. Density was the best indicator of tear factor whilst cell wall thickness was the most important factor in explaining burst factor and breaking length. Growth rate showed negative correlation with wood density; trees of lower density produce paper of a strength generally at least equal to that obtained with higher density trees, though tear factor was lower. Thus the selection of trees for fast growth rate is suggested as the most profitable course. The most desirable selection criteria are listed.

ABSTRACT

In many tropical countries Pinus caribaea Morelet is one of the most important exotic forest plantation species. The study now reported is part of a continuing programme of investigation of the wood properties of P.caribaea var. hondurensis Barrett and Golfari from Fiji.

The main project was initially designed to investigate the variation in structural features and specific gravity of P. caribaea in relation to variation in rate of growth. The purpose of the present investigation is to study wood density and fibre morphology in relation to pulp properties.

In 1971 one hundred and twenty 10-11 year old trees were selected at random from plantations at three locations (Drasa, Nausori Highlands and Seaqaqa) in Fiji. Increment cores taken at breast height were examined by X-ray densitometry and the trees were ranked by weighted core density. A sub-sample of 20 trees (12-13 year old) was then selected to cover the range of density observed. The sub-sample trees were felled (1973) and eight billets were taken at 10% intervals (5,15 ... 65, 75% of total tree height) along the stem for densitometry and anatomical measurements at Oxford and for evaluation of pulp properties on an individual tree basis at the Tropical Products Institute, London.

The results of this study are based on the examination of these twenty trees. It was decided to measure density at all eight height levels but to limit the measurement of tracheid cross-sectional dimensions to 5%, 15%, 35% and 65% height levels. In each disc (level), two random radii were selected for measurement, and measurement of wood features was carried out on a series of growth rings from the pith outwards.

The features investigated were ring width, density, latewood percentage, compression wood percentage and cross-sectional dimensions. The choice of measurement characters and techniques was mainly guided by the works of Hughes (1970), Brown (1969), Lantican (1972) and Paraskevopoulou (1973).

With tracheid cross-sectional dimensions, it was difficult to distinguish earlywood and latewood in the samples. To simplify measurement, it was decided to measure tracheids along radii from pith outward to the bark at intervals of 1mm. This sampling strategy yielded adequate precision for estimates of tree, level and ring means.

To investigate the effects of variation and the patterns of distribution of density and tracheid cross-sectional dimensions, it was decided to separate density, into eight classes (with intervals of 0.15 g/cc), cell wall thickness, lumen width and cell diameter into five classes and cell wall percentage into seven classes.

For all features examined, differences along the stem were found to be small. Changes in the axial direction were either linear or quadratic.

For the data of the 20 trees pooled, no significant differences associated with levels were found in ring width, compression wood, cell lumen width and cell diameter. Levels were significantly and negatively related to mean density, cell wall thickness and cell wall percentage. These effects, however, as shown by the R^2 value of simple regressions, were found to be generally weak, and the range of values between levels were small.

Analyses of variance of data representing the breast height measurements of ring width and ring density from the original sample of 120 trees, disclosed very highly significant differences between ring positions for the mean values of ring width and ring density and the effect of rings

accounted for the largest part of the total variation (VC% = 81.6, 29.4, variance components expressed as percent of total variation).

For the sub-sample (20 trees), there were very considerable between ring differences in ring width, density, cell wall thickness and cell wall percentage. These features showed marked quadratic patterns of changes in the radial direction at all heights. The differences between rings in cell lumen width and cell diameter, however, were found to be small. Cell lumen width and cell diameter increased up to ring number 2 and then showed very little change with further increase in ring numbers. In general, changes in any of the features which showed variations with increasing age (ring number) from the pith were more pronounced in the first few rings than in the outer rings sampled.

All features examined showed fairly marked tree to tree variation in their patterns of development in the radial direction. Some trees showed little change with age from the pith, but in the others there were considerable changes with age from the pith.

The radial patterns of variation of the different features varied from level to level within some trees, but showed little variation with height in others.

For the sample of 120 trees, there were no significant differences between sites in the mean values for ring width (VC% = 0.84). There were highly significant differences between plots but the variance component was very small (VC% = 0.64). It seems therefore that there were no major differences in conditions at the tree sites influencing rate of tree growth.

There were, however, highly significant differences between sites in the mean values for density with a considerable component of variance

(VC% = 12.3) but no significant differences between plots (VC% = 0). This indicated that the relationship between ring density and ring width was weak (R = -0.48).

For the three sites separately (20 trees sample), simple regression showed that there were considerable differences in cell lumen width and cell diameter associated with ring number, year number, ring width, % height level and distance from pith, but small differences in cell wall thickness and cell wall percentage.

Ring width and mean ring density showed statistically significant between tree differences with large variance components for density (VC% = 1.3 and 27.6). For the tracheid cross-sectional dimensions, between tree differences were also considerable. The between tree differences in these features, although phenotypic, are of such magnitude as to indicate that it may be possible to select trees for breeding in order to improve wood quality.

In this investigation, results showed that tree height, tree volume, diameter at breast height, crown width and crown length cannot be used for estimation of whole tree values of any of the features studied, and consequently are of no value in stratifying a stand in terms of wood quality.

Whole tree values, for wood density and tracheid cross-sectional dimensions can be validly predicted from samples taken at the 5% height level (normally close to breast height).

Characteristic patterns of wood density distribution classes and tracheid cross-sectional dimensions classes, resembling chi-squared bi-nomial and bi-modal curves were found in the sub-sample (20 trees).

The most obvious differences between trees occurred because of differences in the amount of the highest and lowest distribution classes. Wood uniformity appeared to be controlled by the relative amounts of very high and low density wood, with high densities exercising the greatest influence.

There is general agreement between the results of this study and those available in the literature regarding the correlations between density and tracheid cross-sectional dimensions. All of the tracheid cross-sectional dimensions show highly significant correlations with density and latewood percentage, which are in turn rather strongly correlated with each other.

Good prediction equations resulted from the simple regressions of pulp yield percentage and tear factor on features of tracheid cross-sectional dimensions and their distribution, wood density and its distribution and chemical composition of wood on P. caribaea. It seems that simple regression analysis can be used to predict these pulp properties from wood properties.

There were less precise estimations of burst factor and breaking length from simple regressions on wood properties. Some multiple regressions had high values of R^2 but they had a large number of terms in relation to the number of observations of pulp properties (20) and therefore cannot be used with confidence to predict pulp properties.

Chemical properties rather than wood physical and structural characteristics were predominant for explaining variation in pulp total yield percentage. Cell wall thickness was the most important indicator of burst factor and breaking length. Density was the most important factor in explaining variation in tear factor.

From this study it seems that trees of lower density produce paper strength at least as good as those from the higher density trees. Only tear factor was lower and this was still within the range acceptable for linerboards.

A more serious aspect of a reduction in density is its effect on pulp yield, which is directly related to wood density. Selection of trees for fast rate of growth may be the most profitable action to take, because although mean tree density will be lower, the total amount of wood substance produced per hectare per annum may be greater.

In this study, growth rate showed weak negative correlation with wood density ($R = -0.42$). However, the fastest tree growth rate was about four times greater than the slowest tree growth rate ($0.606m^3$ - $0.149m^3$). This was a far greater difference than the disparity between the density values (0.44 g/cc - 0.72 g/cc). Some trees of faster than average growth rate also had higher than average density (e.g. 52-84 = 0.58 g/cc, 0.606 m^3).

From this study it seems that in selecting and breeding P. caribaea in Fiji for the pulp and paper industry, primary emphasis should be placed on improving growth rate, tree form and wood uniformity, followed by further selection for the desirable wood properties as determined by the final product.

To improve wood uniformity and paper strength, it is suggested that the most desirable trees for growing and pulping are those with the following characteristics:

a. Fast growth rate

b. Mean density about 0.58 g/cc

c. Latewood percentage about 25%

d. Large percentage of wood in ED-4 (0.51-0.65 g/cc)

e. Above average pulp fibre length.

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CHAPTER 1

Introduction

Pinus caribaea Morelet is one of the most important exotic plantation trees in many tropical countries, because it is a long fibred species capable of growing at sea level in the tropics on poor infertile sites. Over 350 field trials with this species have been set up in more than 40 countries largely as an international cooperative research programme coordinated by the CFI, Oxford. Commercial plantations of *P. caribaea* have been successfully established in West Indies, Australia and in several countries in Africa and the Far East.

Luckhoff (1964) and Barrett and Golfari (1962, see Lamb, 1973) made a thorough and detailed study of the variation within the natural range of the pines now included in the species *P. caribaea*. As a result of the investigations this species is classified into three varieties:

(a) *Pinus caribaea* Mor. - var. *caribaea*, natural distribution in Cuba and Isle of Pines.

(b) *Pinus caribaea* Mor. var. *hondurensis* Barr. and Golf. nov. var., natural distribution in Central America.

(c) *Pinus caribaea* Mor. var *bahamensis* Barr. and Golf. nov. var. natural distribution in Bahamas and Caicos Islands.

An attempt has been made to compare the performance of *P. caribaea* with other tropical pines that occur naturally under similar conditions and also with *P. elliottii* Engelm, the most extensively planted sub-tropical pine. From these comparisons it would appear that there is no other pine as suitable as *P. caribaea* var. *hondurensis* for the hot

lowland coastal plains of the equatorial zone up to 18 degrees from the equator, provided its form can be improved by selection (Lamb, 1973).

The three different varieties of P. caribaea were slightly different with respect to soil and climate requirements. Generally, trials have indicated that P. caribaea var. hondurensis is the most productive variety, and shows much greater variation in form than either of the other varieties. The variety hondurensis has been used very extensively for afforestation purposes in many counties, primarily because it adapts very well to a range of climate conditions and seeds are more easily procured from Belize (formerly British Honduras) than from the other sources.

The wood of P. caribaea is suitable for a wide variety of uses. According to Hughes (1967) and Gray (1972) the wood is suitable for light and heavy construction, sleepers and piles, particle boards and furniture making. The species also promises to be a valuable source of raw material for pulp and paper making, and its wood quality for this purpose is the main concern of the study reported here.

Some previous reports have described the variation of many structural features and wood properties of P. caribaea. Inchbald-Stevens (1959), Bayne (1960), Murray (1961) worked on the variation of tracheid length of P. caribaea from the pith outwards. These were preliminary small scale studies without any planned sampling technique. Schmidt and Smith (1961) made a more advanced study with a large number of samples, using a sampling technique and design which allowed a statistical assessment of the results. They worked on tracheid length, density, longitudinal shrinkage and spiral grain of plantation material of P. caribaea grown in Queensland, Australia.

The P. caribaea research programme of the Commonwealth Forestry Institute in Oxford, includes a series of investigations designed to demonstrate the extent and pattern of variation of the most important structural features, and it is based on appropriate sampling techniques. It includes studies by Brown (1969), Hughes (1970), Burley et. al. (1971), Lantican (1972) and Paraskevopoulon (1973).

The properties investigated by Brown (1969) and Burley et. al. (1971) included tracheid length and density on trees grown in Jamaica. These were also covered in the work of Hughes (1970) in addition to spiral grain, latewood percentage and compression strength parallel to the grain. In the study of Hughes (1970), emphasis was placed on developing an efficient sampling scheme for further investigation of this species. The material was taken from five different site types in British Honduras.

The work of Lantican (1972) has presented a detailed investigation of ten trees obtained from one of the sites in the natural range (Belize) described by Hughes (1970). This included on examination of the variation of density and tracheid length, and also the cross-sectional dimensions of tracheid.

More recently, Paraskevopoulon (1973) worked on twenty trees selected from plantation and natural forest material of P. caribaea var. caribaea from Cuba. This investigation included an examination, not only of the variation of tracheid length and cross-sectional dimensions of tracheids, but also of the variation of density measured by X-ray densitometry method to provide more detailed data. Further reference to these researchers' results will be made in the literature review (Chapter two).

Growth of P. caribaea var. hondurensis in Fiji is promising. The

first trial planting over 3 ha was made in 1955 using P.caribaea var. hondurensis, further trials from 1958 to 1960 were followed by steady expansion from 1961 onwards to a programme of 1,000 ha a year by 1969 (Shepherd, 1969, see Lamb, 1973). There will be a local supply working circle to supply the local market for sawn pine and chips and pulp export working circle which together may cover about 81,000 ha (Lamb, 1973).

The study now reported is part of a continuing programme of investigation of the wood properties of P. caribaea from Fiji. In 1971 one hundred and twenty 10 - 11 year old trees were selected at random by Mr.A.S.Alston* from plantations at three locations in Fiji. Increment cores taken at breast height were examined by X-ray densitometry and the trees were ranked by weighted core density. A sub-sample of 20 trees (12-13 year old, 1973) was then selected to cover the range of density. The sub-sample trees were then felled and billets were taken at 10% intervals along the stem for densitometry and anatomical measurements at Oxford and for evaluation of pulp properties on an individual tree basis at the Tropical Products Institute, London.

The purpose of this detailed investigation is the study of wood density and fibre morphology in relation to pulp properties. The principal objectives of the study are as follows:

1. To obtain basic data for this species on various parameters of wood structure used as indices of wood quality, such as growth rate, density and fibre dimensions, and to demonstrate the extent in this sample of between tree and within tree variation in these parameters.

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1. Principal Utilisation Officer, Department of Forestry, Suva, Fiji.

2. To establish the relationships of these parameters to pulping quality by:-

   a) investigation of the interrelationship between physical properties and fibre morphology.

   b) Ascertaining which wood properties have the greatest influence and best predictor value for pulp yield and strength of paper.

3. To consider the practical application of these investigations, and particularly if they give any indication for this species:-

   a) of the possibility of predicting whole tree values for density and fibre dimensions from small samples, taken from cores in the lower bole.

   b) of the possibilities for selecting and breeding from trees with superior structural features, and consequently superior wood quality.

   c) of the possibilities for the silvicultural control of wood structure, and consequently of wood properties.

CHAPTER 2

Review of Literature

The review of literature will be concerned mainly with the wood characters (density and tracheid dimensions) considered in this research, which are chosen because of their generally accepted usefulness as indices of wood quality, particularly for paper-making requirements. The review is divided into two parts, one concerned with the genus Pinus and the other one with particular reference to the species Pinus caribaea.

1 Literature review of genus Pinus

1.1 Tracheid length

Tracheid length is an important characteristic because it is related to many properties of wood and wood products. This wood property has been of interest to tree breeders, since there is evidence that fibre length is heritable although it can also be influenced by environmental conditions.

1.1.1 Variation of tracheid length within the tree

A. Tracheid length in the axial direction

In 1872, Sanio described the relationship between tracheid length and height in a growth sheath of P. sylvestris. Since 1915, this relationship has been reported as Sanio's second "law" by Bailey and Shepard, which according to the translation given by Spurr and Hyvarinen (1954) was as follows:

> The final size of the tracheid in the stem increases from the bottom toward the top; at a definite height it reaches a maximum and then decreases toward the crown.

This general pattern of variation has been subsequently confirmed with a wide range of species including several tropical pines. These include the work of Burley (1969), Burley, Pattinson and Geary (1972) on P. merkusii Jungh. and de Vries. Some workers, however, have found that tracheid length increases with increasing height up to some point in the stem, after which it remains more or less constant. Species where this type of pattern have been recorded include P. patula (Burley, Pattinson and Morgan, 1970), and other work confirming this general trend has been reviewed by Dinwoodie (1961) and Panshin and de Zeeuw (1970).

Different tree species exhibit different patterns of variation in fibre lengths with respect to height. In softwoods the average tracheid length for slash pine increased from the stem towards the upper trunk 2/3 h (height of the stem). But for Luchu Pine and Japanese Black Pine the length of tracheids were found to be greater at the mid-trunk ($1/_3$ h) than in the lower and the upper trunks (Wang and Chu, 1967).

b. Tracheid length in the radial direction

Sanio's (1872) results with P. sylvestris, concerning the variation in tracheid length from the pith outwards, has been quoted as Sanio's first "law", and according to the translation of Spurr and Hyverinen (1954) it was as follows:

> Tracheids in the stem and branches generally increase in size from the inside toward the outside through a number of annual rings until a definite size is reached, and then remain constant for the following annual rings.

This statement has been subsequently confirmed by several workers (see Spurr and Hyverinen, 1954; Goggans, 1961).

There is, however, some doubt about the general validity of Sanio's

first "law". Some authors report a decrease in tracheid length after attainment of a maximum value for a number of coniferous species including P. kesiya Royle ex Gordon (Burley, 1969; Burley, Geary and Pattinson, 1972), P. roxburghii Sarg., Picea smithiana Boiss and Abies pindrow Spach. (Ahmad, 1968, 1969, 1970; see Lantican 1972). It has been postulated that decrease in cell length after attainment of a maximum value may be due to the onset of senescence (Dinwoodie, 1961). It is also evident that the increase in tracheid length after 15-30 annual rings is slight when compared to the increase that occurs in the first few annual rings.

Similar results were found by Erickson and Harrison (1974) working with Douglas - Fir (Pseudotsuga menzesii) that tracheid length was highly correlated with age, the age relationship is much less after age 12 when the length begins to level off rapidly. At age 30 there is still some increase in tracheid length.

1.1.2 Variation of tracheid length between trees

Large differences between trees in average tracheid length have been reported for many species of pine (see Goggans, 1961; Panshin and de Zeeuw 1970; Elliott, 1970). Differences in trees grown in the same stand or site have been described for P. patula (Burley, Pattinson and Morgan, 1970). P. kesiya (Burley, Geary and Pattinson, 1972; Burley and Andrew, 1970; Burley, Adlard and Waters, 1970), P. merkusii (Burley, Adlard and Waters, 1970; Andrew and Burley, 1971).

Cole et. al. (1966) could find no significant differences in average fibre length between different species (Slash, loblolly and long-leaf pine) growing in single natural stands. On the other hand, it is generally known that mean tree values fibre length varies greatly

from tree to tree within one species. (Burley, Pattinson and Morgan, 1970; Burley, Geary and Pattinson, 1972; Burley and Andrew, 1970).

Tracheid length has been shown to be an inherited feature in P. radiata D. Don, the southern hard pines , and Picea sitchensis (Bong) Carr. On the whole, length of fibrous elements appears to be under stronger heritable control than diameter.

1.1.3 The Effect of compression wood, latewood, earlywood, growth rate and age on tracheid length

Compression wood fibres are invariably shorter than those of normal wood. This has been demonstrated for many species (see Spurr and Hyvarinen, 1954).

Several investigators have shown that latewood tracheids are usually somewhat longer than those in the early wood (see Spurr and Hyvarinen, 1954; Dinwoodie, 1961; Goggans, 1961; Panshion and de Zeeuw, 1970).

In the survey of previous work on fibre length, a matter that has not been resolved is the relation of growth to cell size. Much has been done on this subject but the findings are contradictory and inconclusive. Several investigators have been unable to find any close correlation between width of growth ring and fibre length. In contrast, a number of workers have found some relationship between tracheid or fibre size and growth rate. Some authors have reported a negative correlation within trees between growth rate and tracheid length.

For the most part maximum tracheid lengths are associated with ring widths, usually of 0.5 to 2mm wide, depending on the species (Bannen, 1967; Larson, 1957; see Panshin and de Zeeuw, 1970). Ring widths either lesser or greater than this "optimum" are associated with shorter tracheid lengths.

Sudo (1973) investigated the within tree variation in tracheid length and ring width with fifty-five years old Pinus densiflora. In regard to the first ring, it appears that the wider the rings, the longer are their tracheids. For a few rings, from the second ring outwards, ring width does not seem to have much influence on tracheid length unless there is an extremely large change in the width of successive rings. From about the fifth ring, tracheid length seem to be influenced noticeably by the change of ring width. However, in the outer part of the tree, ring width influences variation in length in such a way that a maximum length is associated with the ring width between 1 - 2 mm, from which tracheid length decreases both with increase or decrease in ring width.

As a consequence of the general increase in the length of tracheids with age, there is greater variability between growth increments than there is within a growth increment. The longest tracheids in outer rings are generally at least twice as long as the shorter ones found near the pith and usually they are three to five times longer (Dinwoodie, 1961, Panshin and de Zeeuw, 1970).

Goggans (1961), in his brief summary, states that age (number of rings from the pith) is the factor most strongly correlated with tracheid length. Rate of growth and environmental factors have less effect than age and they account for very little of the between tree variation that is found in tracheid length.

Sado (1973) working on P.densiflora, described three main factors that contribute to variation in tracheid length. They are stem thickening (ring width), elongation (length of internode) and ring number from the pith, which influence variation in tracheid length in combination with each othe r throughout a whole stem of a

tree. The influence of two of these factors, extent of elongation of internodes and ring number from pith is dominant in the first few rings so that the influence of thickening (ring width) is not generally discernible, although there are some indications of this effect when rings are extremely wide or narrow. With increasing ring number from the pith the influence of elongation becomes gradually obscured and that of thickening gradually is more apparent. Moreover, the influence of thickening close to the bark becomes more significant and seems to be the only important factor influencing variation in tracheid length in adult wood.

1.2 Tracheid cross-sectional dimensions

It is well known that the cross-sectional dimensions of coniferous tracheids vary within any single annual ring of a tree. The earlywood cells have a large lumen and thin walls, while latewood cells are thick-walled with a small lumen. Since cell wall material very largely determines extracted wood density, it follows that low density trees have cross-sectional tracheid dimensions that differ from those of high density trees. There are large differences between the average cross-sectional cell dimensions of different species and often considerable differences between trees of the same species. Trees of high density tend to produce progenies with high density and it therefore seems that cross-sectional cell dimensions are under genetical control.

1.2.1 Variation of tracheid cross-sectional dimensions within tree

A Tracheid cross- sectional dimensions in the axial direction

Larsen (1966), working on radial double cell wall thickness at 6 ft (1.83 m) and 18 ft (5.49 m) height levels of a single tree of Pinus resinosa Ait, found very little difference.

Similar results were reported by Wheeler, Zobel and Weeks (1966), sampling at 6 height levels, starting from 5 ft (1.52 m) up to 50 ft (9.14 m) for tangential cell width of loblolly pine in juvenile and mature wood.

Nylinder (1973) reported that fibre width slowly decreases with increasing height in the stem in a cross-section of stems of pine and spruce.

B. Tracheid cross-sectional dimensions in the radial direction

In many conifers, radial wall thickness has been shown to increase with age from the pith, accerding to the investigations quoted by Goggans (1968) and Panshin and de Zeeuw (1970). Examples of these are Larix decidua Mill, P.sylvestris L, P. mugo Turra (Schultz-Dewitz, 1958, see Goggans , 1965) P. echinata Mill. (McGinnes, 1963, see Panshin and de Zeeuw 1970), and P.resinosa Ait. (red pine, Larson , 1966). In some species, however, like loblolly pine (P.taeda L.) (Taras, 1965, Goggans , 1965, McMillin, 1968), Norway spruce (Picea excelsa Link) and Douglas fir (Pseudotsuga menziesii (Mirb.) Franco) (Schultz-Dewitz, 1958), this feature has been reported to be unaffected by age from the pith.

McMillin (1968) working on loblolly pine, found that in earlywood radial cell width increased by about 3 per cent from the pith outwards while in latewood it increased only slightly. Schultz-Dewitz (1965) found that the radial cell width increased with age from the pith in the earlywood samples of Scots pine, mountain pine and common larch, while in latewood it was very highly variable.

Taras (see Goggans, 1965) found that in three slash pine trees (Pinus elliottii) earlywood tangential lumen and cell widths both increased for the first 8 to 12 years, and then increased slowly until an approximate age of 20, after which no further important increases occurred. Latewood tangential cell width increased until the age of 30 years, while lumen width decreased slightly for 8 to 20 years and then increased slightly thereafter.

Nylinder (1973) reported that fibre width of pine and spruce increased from the pith, at first rapidly, then increasingly slower towards the cambium.

1.2.2 Variation of tracheid cross-sectional dimensions between tree

A few investigations have worked on the variation in cross-sectional dimensions between trees of the same species. Smith (1967), studying the variation of radial cell width in both P.elliottii and P.taeda, found considerable between trees variation. Similar results were reported by Goggans (1962) for earlywood radial double wall thickness and lumen, earlywood and latewood cell widths and tangential cell width in young (5 to 6 years old) loblobby pine trees grown in Louisiana, and for latewood tangential cell widths radial lumen width and double wall thickness in trees grown in Georgia.

Wheeler, Zobel and Weeks (1966) detected significant between trees differences in tangential cell width of P.taeda. Posey (1964), with the same species, found significant differences between trees in both tangential cell width and wall thickness. Zobel et al. (1961) found a great deal of variation between trees in cell width and wall thickness of P.taeda.

Conifers grwon under tropical or semitropical conditions do not exhibit the marked differences between early and latewood that are found in the temperate zones. They are reported to show only about 50 per cent reduction in radial diameter from early to latewood and have walls which are thick and almost uniform in width across the increment. The thickness of these walls is about equal to that found in Larix and hard pine late wood (Panshin and de Zeeuw, 1970).

1.3 Density

Basically all the physical properties of wood are affected by the amount of cell wall substance present in a given volume of wood. Cell wall substance is measured by the density of the wood and density therefore provides the most useful index to the predicted physical behaviour of wood.

There are three primary reasons for giving priority to the study of density:

1. There is a close correlation between density and mechanical strength, with yield and some strength properties in pulping and papermaking, and usually with wood shrinkage. Density gives a good indication of machining and working qualities.

2. Variability in wood density is under moderate to strong genetic control as shown in the review by Zobel (1964) and by Harris (1965), Stonecypher et al. (1973) and Matziris and Zobel (1973).

3. Density is easily determined from increment cores taken nondestructively from living trees.

The variation of density within and between trees has been studied by many investigations in the past. Contributions in this regard have been made by silviculturists, forest geneticists, wood anatomists and technologists, and timber engineers. For this study the reviews of Spurr and Hsiung (1954), Carson (1957), Goggans (1961), Pual (1963), Elliot (1970) and Panshin and de Zeeuw (1970) have been used, with particular reference to softwood.

1.3.1 Variation of density within the tree

A. Density in the axial direction

According to Panshin and de Zeeuw (1970) three trends of variation of density with height level in the tree have been reported. They are:

1. Decreasing uniformly with increasing height.
2. Decreasing in the lower trunk and then increasing in the upper trunk.
3. Increasing in the trunk from base to top in a nonuniform pattern.

The first trend appears to be typical of many conifers, according to Panshin and de Zeeuw (1970), Goggans (1961) and Elliot (1970). This general trend has been reported in Libocedrus decurrens, Torr., Pseudotsuga menziesii, Tsuga heterophylla (Raf.) Sarg. (Panshin and de Zeeuw, 1970) and Japanese Larch (Isebrands and Hunt, 1975).

The second trend has been noticed in P. contorta Dougl., P. strobus L. (Panshin and de Zeeuw, 1970) and P. merkusii (Andrew and Burley, 1971). It has been suggested that this pattern occur

mainly as a result of the incusion of greater proportions of high density knots in the crown wood (Larson, 1962).

The third trend described has been noticed in Picea sitchensis (Bong.) Carr. (Jeffers, 1959) and Thuja plicata Don. (Wellwood, 1962) (see Panshin and de Zeeuw 1970).

Lack of significant differences in density among height levels is uncommon in pines, but has been reported quite often in Picea species. Burley, Pattinson and Morgan (1970) working on two trees of Pinus patula found no significant differences of density between height levels. In Picea species Elliott (1966) working especially with Picea sitchensis also found that in ten out of the twelve trees studied, there was no significant differences in density at various height levels.

B. Density in the radial direction

A general classification of the pattern of variation of density from the pith outwards has been described in the literature and is briefly as follows:

1. Density increases from the pith outwards.
2. Density decreases from the pith for the first few years and then increases with increasing age from the pith.
3. Density increases near the pith and then remains more or less constant or sometimes decreases again near the bark.
4. Density generally decreases from the pith outwards.

Examples of each type are given by Panshin and de Zeeuw (1970). According to Panshin and de Zeeuw (1970), conifers usually belong to the first type, and show a trend of increasing density from pith to bark. Many investigators have confirmed this pattern by their results.

These include Plumptre (1972), Burley, Pattinson and Morgan (1970) for Pinus patula, Burley (1970), Burley and Andrew (1970) for P.kesiga and many other references mentioned in the review of Spurr and Hsiung (1954) and Panshin and de Zeeuw (1970).

Burley et al (1973) working of P.occidentalis and Burley et al. (1973) working on P.Keisya indicated that important differences in density occurred between annual rings and between individual trees. The effects of height of discs above ground and of quadrants (radial differences) were relatively unimportant.

1.3.2 Variation of density between trees

A. Site or environmental effect

References quoted by Goggans (1961) indicate that in most species large tree to tree variation in density occurs within stands. In managed plantation-grown conifers the largest or dominant stems usually have the lowest average density values, while the smallest stems usually have the highest. A significant negative linear regression of density on diameter at breast height in even crops has been reported. In contrast, there are other reports which show no significant relationship between average density values of individual trees and their dominance. The apparent divergence of findings has been attributed to: 1) the sampling pattern adopted for individual tree assessment, (2) the age of the tree sampled in association with the degree of between tree competition, 3) the availability of water, again with particular reference to between tree competition, and (4) the influence of crown characteristics at the time of sampling (see Elliott 1970).

The general conclusion of most review authors, is that site quality is not highly correlated with density value (Goggans, 1961; Elliott, 1970) and within a defined geographical region has better effect on the density of whole tree.

Kleen (1957) however, reported that Norway spruce grown on good sites had lower density than those grown on poor sites. Similar results were reported by Wellwood (1952) for Douglas fir. Jayne (1958) found that the best sites produced larger volumes of lower density wood. Larson (1957), working on slash pine, found that most of the plot to plot variation in density could be accounted for by the amount of June and July rainfall and the depth of the fine-textured soil. Paul and Marts (1954) found a close correlation between soil water supply and the formation of summerwood. Irrigation during the summer months increased greatly the proportion of summerwood. The effect of rainfall on density has also been reported by Paul and Smith (1950), for Southern pines and by Wheeler and Mitchell (1959) for loblolly pine, (See Goggins 1961).

The references quoted by Elliott (1970) indicate that geographic variation of wood density within an entire species range, is that in the northern hemisphere average density values for a given species increase from north to south. For exotic conifers planted in the southern hemisphere density values for a given species increase from south to north. The general contention might be that wood density values within a species tend to increase towards the tropics. Regional variation for average density values does not, however, have unequivcoal support and a number of authors stress that the magnitude of individual tree variation is such that variation due both to soil

and geographical region may be obscured (see Elliott, 1970).

B. Heritability of density

Several reviews (Goggans, 1961, Zobel, 1959, Elliott, 1970, Panshin and de Zeeuw, 1970) have demonstrated the existence of heritability of wood density in conifers, from consideration of geographic and provenance variation. An observed difference in density between trees growing in different localities or in different soil types, however, may be due in part to differences in environmental conditions and in part to basic differences in the genotypic constitution of the crops. There are very few reported investigations in which the extent of the effects of heredity and environment have been separated.

Knudson (1958) studied eight provenances of Norway spruce, from widely separated regions of Europe, and could not find marked influence of seed origin on the wood density. But Rees and Brown (1954), working on red pine (P. resinosa) showed that although 18 of their 19 sources exhibited no differences in wood density, the 19th source from Bay City, Michigan, was significantly more dense than the other sources.

Kramer and Smith (1956), in sampling wood properties of slash pine plantations, suggested that a portion of the variation they observed was attributable to seed source. In Norway spruce, Kleen (1957) found higher density in spruce of German origin than that of Norwegian origin. Larson (1957) reported that the lowest wood densities were found in the northern and western portions of the slash pine range. He attributed these differences to moisture and soil charactistics. Zobel and McElwee (1958) showed a similar northerly

and westerly trend for loblolly pine. Of particular interest is the work of Zobel et al. (1960) who found highly significant differences in density of loblolly pine between geographic locations. Echols (1958) showed a very highly significant variation in the wood density of several geographic races of Scots pine when grown on the same site type in New Hampshire, showing clearly the effects of heritable factors.

Progress toward genetic control of wood morphology in the southern pines has been summarized by Zobel. He noted that tracheid length, wood specific gravity, and bark thickness can be modified through genetic selection.

Goggans (1964) and Zobel (1971) (see Koch 1972) rank characteristics according to the ease with which they can be altered in a selection programme as follows:

Ease of change by genetic selection and characteristics

Easiest

- Tracheid length, latewood
- Percent of latewood in tree
- Specific gravity of tree
- Tracheid diameter, earlywood
- Tracheid length, earlywood
- Bark thickness

Intermediate

- Specific gravity of latewood
- Double wall thickness, latewood
- Tracheid diameter, latewood
- Ratio of wall thickness to radial diameter, earlywood

Most difficult

- Ratio of wall thickness to radial diameter, latewood
- Double wall thickness, earlywood
- Specific gravity, earlywood

1.3.3 The effect of growth ring width, latewood, earlywood and age on wood density

The radial width of an increment in a tree stem varies with the height above ground. Minimum width is found near the base of the tree, the width increases with increasing height in the stem to a maximum in the general vicinity of the base of the live crown and then decreases to the top of the tree (Panshin and de Zeeuw, 1970).

For conifers, reports of ring width relationship to the various wood properties are not in agreement. A considerable number of investigations have shown that there is a decrease in density with increasing ring width. However, many studies, which appear to be equally valid and as carefully analyzed, claim no relationship between density and ring width, or at most a very limited correlation.

Maximum width in the early wood occurs in the upper part of the live crown and decreases down the trunk to the minimum width 5 to 10 ft (1.52 to 3.05 m) above the growth. The late-wood zones are reported to be of maximum width in the basal portion of the stem below the live crown. Within anyone increment the latewood percentage is greatest at the base of the tree and decreases upward to a minimum value near the pith at the top of the tree (Larson, 1957, 1962 , see Panshin and de Zeeuw, 1970).

In conifers there is a definite relationship between density of the wood and late wood percentage. In many conifers, the density of the latewood zone is more than twice that of the earlywood zone , thus any increase in the proportion of the latewood inevitably leads to an increase in whole ring density. It has been shown that the difference between values for earlywood and latewood is more pronounced in species where there is a clear distinction between the two zones. Conversely, for species that do not show a clearly defined

transition to the latewood zone the correlation between whole-ring density and percent latewood is often obscure (Elliott, 1970).

The general statement that in plantation grown conifers there is an increase in whole ring density value with increasing age from the pith has received considerable support. It has, however, long been recognized that in overmature trees this relationship may be reversed in the outermost annual rings. The outermost rings of over mature trees have been designated as senescent wood, where decreasing density values are paralleled by decreasing percent latewood and ringwidth. The characteristics of senescent wood have been attributed to the limits imposed by crown development, particularly the remoteness of the crown from the site of wood formation (see Elliott, 1970).

1.4 Relationship between density, tracheid cross-sectional dimensions and some other factors

Variations in the density of wood, are due to differences in the amounts of cell wall substance and of extraneous materials present per unit of volume. The amount of cell wall substance is largely determined by the structural characteristics of the wood, i.e., by the sizes and proportional amounts of the different cell types present and by the thickness of the cell walls. Of these, cell wall thickness has the greatest effect on density.

Several investigations have studied the relationship between density and tracheid cross-sectional dimensions. Hiett et al. (1960) found that between-tree variation in wood density was related to differences of cross-sectional dimensions in earlywood and latewood. For Picea abies Fry (1958) and Jones (1958) found that high density was associated with small cell width. McMillin (1968) working with loblolly

pine found a close negative relationship between density and radial cell width (earlywood and latewood). With the same species Pew et al. (1939) found a considerable variation in density which was attributed to differences in tracheid wall thickness and tracheid widths. Similar results were reported by Zobel et al. (1961) Van Buijtenen (1964), in an investigation of the anatomical factors influencing density in slash pine, found that double tracheid wall thickness in latewood was strongly related to density. Tracheid width also had a considerable influence.

Einspahr (1976) reviewed the influence of short-rotation forestry on wood quality and summarized the inter-relationships in the following table:

Summary of Interrelated Factors Influencing Wood Quality[a] of Short Rotation Conifers

Wood or paper property	Juvenile wood vs mature wood	Reaction wood vs normal wood	Rapid vs normal wood
Density	Lower	Higher	Equal or lower
Fibre length	Shorter	Shorter	Equal
Cell wall thickness	Thinner	Thicker	Thinner
Lignin	Higher	Higher	Lower
Cellulose	Lower	Lower	Higher
Extractive	Higher	Higher	Equal

[a] Based upon rotation ages 8 - 20 years

1.5 Wood density distribution

A radiological approach to recording variations in wood (see Fletcher and Hughes, 1970) density has been tried by Phillips et al. (1962), Polge (1965, 1966) and others. The use of x-rays for determining intra-incremental density distributions in wood provides a useful technique for wood research.

Interest in wood density distribution within individual growth rings has coincided with development of techniques for evaluating their characteristics. The patterns of density distribution basically influence mean density as well as percentage of latewood. If a problem can be shown as characteristic of a tree or stand, it can be interpreted in terms of the wood quality of that tree or stand. Density distribution and mean density provide a measure of wood uniformity and may given an indication of its degree of suitability for various end uses.

Echols (1972, 1973), working on ponderosa pine (P. ponderosa) with a mean density about 0.4% used X-ray method and the density distribution was measured with an integrator that divided the range of density into 14 classes (0.20 to 0.90 g/cc) recording the amounts of wood in each 0.05 class. A uniformity number (density distribution index) for each wood sample was derived from the relative distribution of wood in the 14 density classes. By using the mean density as a base, the per cent of wood in each 0.05 density class above and below the mean were multiplied by weighting factors 1, 2, 3 ... n, then added to the percent of wood in the class containing the mean. The result is a combined number derived from the relative distribution of wood in all of the density classes. A score of 100 indicates uniform, virtually homogeneous wood, and is the lowest number that can be derived. Higher numbers represent less uniform wood.

These uniformity numbers can be used to compare wood samples and could be extended to represent trees and stands with suitable correlations.

A characteristic pattern of wood density distribution obtained by Echols resembles a chi-square curve, with between tree variations occurring most frequently at the highest and lowest density levels. Wood uniformity appeared to be controlled by the relative amounts of very high- and low-density wood, with high densities exercising the greatest influence.

1.6 The relationship between physical properties, fibre morphology, and chemical composition of wood and paper properties

A great number of investigations have been made into the influence of the physical properties, fibre morphology and chemical composition of wood on the properties of paper. Early reviews (Holzer, 1950, Wangaard, 1958, Besley, 1960, Tappi Forest Biology Sub-Committe, 1960, Swanson and Jones, 1962, Gallay, 1962, Tamolang and Wangaard, 1961, Dadswell and Watson, 1962, Emerton, 1957, Tappi Monograph series - No.24, 1962) deal with some of the literature published prior to 1962. More recent reviews (Dinwoodie, 1965 Wardrop, 1969, van Buijtenen, 1969, Wangaard, 1973) are concerned with some of the literature published prior to 1973. The influence of anatomical structure and chemical composition of wood fibres on the properties of paper has been mentioned in some textbooks (Casey, 1952, Panshim, 1952, Libby, 1962, Higham, 1969, Macdonald, 1969). In the following review, emphasis will be placed on the literature of the last decade.

The most important considerations in paper manaufacture are the percentage yield of usable pulp obtainable from the raw material and the quality of the paper that can be made from it. The characteristic which determine the quality of the paper are: 1) Opacity, 2) Surface smoothness, 3) porosity, 4) strength. Strength properties of paper include a) burst factor, b) breaking length, c) tear factor. All these properties depend on the kind of fibres from which the paper is made.

1.6.1 Pulp yield

A The influence of chemical composition of wood on pulp yield

The main chemical constituents of the cell walls in wood are cellulose, non-cellulosic polysaccharides (hemi-cellulose), lignin and extractives. Yield of pulp obtainable from wood has been related to the cellulose and hemi-cellulose content and particularly to the former. In the Kraft process, for example, Sjostrom (1977) reported that more than 20% of the wood polysaccharides are lost during pulping. The yield loss is especially high for glucomannan (hemi-cellulose) but cellulose losses occur as well. During the removal of the initial 5% of the lignin, more than 15% of the non-lignin material is also lost, where the non-lignin material is here defined as consisting of carbohydrates and minor amounts of pitch and other non-carbohydrate components. After the high loss of carbohydrate material with the lignin during the early part of the cook, selective delignification is improved but again becomes poorer towards the end of the cook.

Most of the lost carbohydrates are degraded during the Kraft pulping process, and pulp yield is highly dependent on the cooking condition and on the amount and degree of polymerisation of alpha-cellulose in the wood.

There is little doubt that in general proportion of lignin, 1% NaOH Soluble, alcohol-benzene soluble and hot water soluble materials are negatively correlated with pulp yield.

B. The influence of fibre morphology on pulp yield

Several researchers (e.g. Gonin and Taylor, 1973) have reported that fibre length and cell wall thickness are related to pulp yield, probably because of relationships between these parameters and cellulose content. On the other hand, Barefoot, Hitchings, and Ellwood (1966) who worked on four selected Loblolly pines, have shown that the percentage of total and screened yield of pulp obtained could not be statistically correlated to the morphology of the fibres. This may be due to the limited sample.

C. The influence of physical properties of wood on pulp yield

A number of workers have found positive correlations between pulp yield and wood density, and wood density is determined largely by the thickness of the fibre walls. Mean fibre wall thickness, in turn, is determined largely by the ratio of latewood to earlywood. Consequently this ca uses a high correlation between the density of the wood and the proportion of latewood. The percentage of latewood then becomes a dominant factor (positively correlated) in determing pulp yield and it also influences pulp quality. Gladstone's

dissertation (1969) showed that Loblolly pine latewood, depending upon the time of cooking, yields up 4-6% more pulp on an oven-dry O.D. weight basis than the earlywood. This difference may arise because latewood has a thicker secondary wall in which the proportion of cellulose is higher, which gives a higher cellulose content for the fibre wall as a whole.

Ellwood, Barefoot and Hitchings (1969) working on Loblolly pine have suggested that the total yield of high Kappa number (No.68) pulp is a non-linear function of percent latewood. Their results showed that the total yield percentage of high Kappa pulp from Loblolly pine changes with the percentage of latewood, and with a greater effect in the corewood (low percentage latewood) than in the outerwood (high percentage latewood). A rapid rise in total yield percentage (slope = 0.48) occurred with increasing latewood percentage in the cores and there was a smaller rise in yield (slope = 0.19) which increasing latewood percentage in the outerwood, van Buijtenen et al. (1961), however,using a multiple regression analysis, showed that yield is strongly influenced by the percentage alcohol-benzene extractives and the percentage lignin, but that the influence of the percentage latewood was negligible. Haught (1957) showed there is a tendency for pulp yield percentage to decrease with increasing occurrence of compression wood, because of its higher lignin content.

1.6.2 Paper strength

Paper is a bonded network of natural cellulose fibre and its strength is a function of individual fibre strengths and of the bonding between fibres. The surfaces of cellulose fibres have a strong mutual affinity during the drying of a paper sheet, the fibres mat together and adhere at regions where they cross because of the formation of intermolecular hydrogen bonds between adjacent

fibre surfaces.

A. The influence of chemical composition of wood on paper strength

In 1933 Jonas and Rieth (see Cottrall, 1950) reported that hemicellulose played a predominant part in the effects of beating on the strength of paper. They found that the only apparent difference between two pulps was in the content of the hemicellulose mannan, which was 3% greater in the pulp with the faster beating time and possessed a higher strength.

Later Cottrall (1944, see Cottrall 1950) showed that there was no obvious relationship between bursting strength and alpha- or beta-cellulose content of the pulp. On the other hand, there did seem in general some relationship between bursting strength and gamma-cellulose. When the pulp had a low gamma-celluose content and at the same time a high alpha-cellulose, showingthat the natural hemi-cellulose had been removed with minimum deterioration of the cellulose, such pulps had a low bursting strength. The same occurred for tear, when the comparison was made on an equal freeness basis, showing that the fibres in the extracted pulp have been shortened more than in the unextracted pulp. In the pulp with higher hemicellulose, fibres are well fibrillated and shortened, due to the fibrillation of the pulp. On the other hand, the fibres of the pulp with less hemi-cellulose, show considerably less fibrillation. This would account for the reduction in bonding and, consequently reducing in strength.

Since swelling can be assumed to be a measure of the degree of plasticity which a fibre attains on soaking in water, fibres with low swelling capacity, will be relatively nonplastic. In the beating process, the pressure of the beater bars will thus be restricted to a

small area when they strike non-plastic fibre and the impact will not be distributed by the plastic flow of the material. Consequently, the fibre will tend to break at the point where it is hit by the bar instead of being shredded or fibrillated.

Jayme and Lochmuller-Kerler (1944) and Rothomel (1948) (see Cottrall 1950) demonstrated that the greater the hemicellulose content, the greater was the swelling capacity of fibres. In their later work, Jayme and Lochmuller-Kerler have shown that the strength of paper reaches a maximum at a certain hemicellulose content of the pulp and then begins to fall. Jayme gives two explanations for the phenomenon of an optimum hemicellulose content at which maximum strength is attained.

1. The strength of paper depends not only on the extent of the fibre bonded area but also on the intrinsic strength of the bonding. Bonding with short chain hemicellulose is intrinsically weaker than with cellulose. As the yield of pulp from the wood is increased, as occurs with less severe treatments, it contains increasing amounts of shorter chain hemicelluloses which are the most hydrolyzable, and are therefore removed when a more drastic isolation treatment giving lower yields is applied. The increasing proportion of such short-chain hemicelluloses will progressively decrease the strength of the pulp. At the same time, however, the presence of increasing amounts of hemicellulose in the pulp has an opposing effect on strength because it causes increased plasticity of the fibres which increases the bonding area. At low pulp yields, the intrinsic bonding strength is higher but the bonding area is lower, whereas the reverse is the condition at high pulp yields. Somewhere in between there is an optimum pulp yield and hemi-cellulose content for maximum strength.

2. Another possible explanation is that, as the amount of hemicellulose in the fibre increases, the proportion of cellulose, the long chain constitutent which confers strength to the fibre itself, must decrease. Increasing amounts of hemi-celluloses in the fibre therefore progressively reduce the intrinsic strength of the fibre, and thus weaken the structure as a whole. At a certain pulp yield point, a maximum strength is attained, when the sum of bond strength and fibre strength is at a maximum. The work of Jayme and Lochmuller-Kerler has also received confirmation by March (1948, see Cottrall, 1950).

Ross (1950, see Cottrall 1950) analysed the results of a series of Kraft cookings of spruce, balsam and Douglas-fir and concluded that pulps with widely different pentosans or hemi-cellulose content can be beaten at the same rate, but give entirely different sheet properties. Pulps with more pentosans can be beaten more rapidly to give sheets with better strength, with other pulps the order can be reversed. It is probable that the actual hemicellulose content in pulp is not the only factor and that the distribution of hemi-cellulose in the fibre is also important. When pulps are composed on the basis of equal lignin content, differences in papermaking qualities appear to be affected more by cooking liquor composition than by the composition of the pulps. Cottrall (1950) considered that, at the same hemi-cellulose content, the fibrous material with the highest degree of polymerization should give the strongest paper.

From the work reviewed above, it could appear that paper strength could be a compromise between degree of polymerization, which determines intrinsic fibre strength as well as bonding strength, and hemicellulose content, which determines plasticity and, consequently, fibre-bonding area.

Since the largest quantities of lignin in the wood are found in the compound middle lamella, which is destroyed in pulping, a considerable amount of the lignin is removed in the process. Further amounts of lignin, remaining in the secondary cell wall of the fibres, are removed in the bleaching operation. The amount of lignin remaining in the pulp after bleaching affects the papermaking properties of the pulp by making the fibres stiff and by decreasing the interfibre surface bonding activities of the hemicellulose, resulting in paper of low strength and high opacity. (Jayme, 1958). On the other hand, lignin-rich fibres do not shrink much when dried, and therefore papers made of such fibres has good dimensional stability.

Many kinds of extraneous materials are destroyed in pulping. The most vexing problem is that of the extraneous materials retained in the pulp, which, because they affect the colour or brightness of pulp, require expensive bleaching for their removal. The precise effect on the properties of paper of the residual extraneous materials, in the pulp after bleaching is difficult to evaluate, because of the variety of such materials that might be present. However, it is believed that the amounts of such residual products are small and that their effect is insignificant in relation to other factors that influence the characteristics of finished paper.

There is little doubt that in general: 1. lignin is negatively correlated with fibre strength, 2. alpha-cellulose is positively correlated with fibre strength and, 3. hemi-cellulose is important as a bonding, swelling and plasticizing agent.

B. The influence of fibre morphology on paper strength

It has been shown in previous studies, that each of the anatomical elements may have a different potential contribution to pulp quality. In a broad evaluation of this same relationship for slash pine, Wangaard (1966) noted that up to 80% of the pulp quality could be accounted for by fibre characteristics. Barefoot, Hitchings and Ellwood (1964, 1970) noted that from 60 to 95% of the total variation in the beating time, apparent density, burst ratio, breaking length and tear factor of loblolly pulp could be accounted for by correlating these variables to the dimensional qualiti es of the summerwood cells. The thickness of the summerwood cell walls (or density) was the most important of these, but sometimes tracheid length was a positive secondary factor. More recently Wang and McKimmy (1977) using multiple regression analysis, found wood and fibre morphological factors to be responsible for 54-97% of the variation in hand sheet paper properties in single-species pulping.

a. Fibre length

As pointed out by several researchers (Dinwoodie, 1965; Barefoot 1966; Wangaard, 1973), fibre length as a factor contributing to pulp strength is not considered as important today as it was at the beginning of this century. However, more recent investigations, which have allowed for the fact that pulp strength is the result of the interaction of various fibre dimensions, showed that fibre length does contribute to overall strength. It unquestionably influences the tear factor and is a major factor in sheet formation.

Long fibres have an adverse effect, giving an open paper structure , which leads to low sheet density, low air resistance and a rough surface. Longer than average fibre length is generally accompanied by higher tear resistance, and to a lesser extent, by an increase in burst, tensile and folding strength. The longer fibres provide a larger area over which applied stress is distributed and, therefore, greater stress can be tolerated. From an analytical or explanatory point of view, the apparent effect of increased fibre length is more likely the result of increased fibre strength than of fibre length per se (Emerton, 1958; Giertz, 1962; Wangaard, 1973).

A number of workers have found that fibre length and density or cell wall thickness are of approximately equal importance. Annergren et al. (1963) in reporting the results of a large number of cooking trials on both softwood and hardwood in Sweden, reported that within the softwoods, fibre length was of secondary importance and cell wall thickness was the principal factor controlling the tear resistance of paper. This confirmed the work of Watson et al. (1952) who found that though fibre length was of some importance, the principal factor influencing tear is density or cell wall thickness.

However, Wang and McKimmy (1977), Dinwoodie (1966) and Dadswell and Watson (1962, 1964) showed that fibre length was the most significant characteristic for tear. It may be that the tear factor is affected more by differences in intrinsic fibre strength than either breaking length or burst factor.

Recently, Wangaard in collaboration with others (1964, 1968, 1970, 1973) used multiple-regression equations involving fibre strength, fibre length and sheet desnity to predict the properties of Kraft pulps of hardwood and slash pine P.elliottii. Their results showed that

breaking length and burst factor increase with increasing sheet density and increasing fibre length. The separate effect of fibre length also increases with increasing sheet density. With hardwood pulps fibre strength had negligible effect on breaking length and burst factor at low sheet densities of the order of 0.30 g/cm^3. There is increasing positive effect of fibre strength on these properties with increased sheet densities at least up to 0.80 g/cm^3. Tear factor shows a similar negligible relationship with fibre length and fibre strength at the lowest sheet density. As sheet density increases, however, increasing fibre length exerts a strong positive effect until maximum tear factor values are attained with sheet densities at or beyond 0.50 g/cm^3 (for hardwood pulps), and 0.40 g/cm^3 (for P.elliottii). Beyond this point there is a decreasing trend in tear factor with increasing sheet density. Thoughout the entire range of declining tear factor the rate of decrease for the longer fibre pulps. The adverse effect of increased fibre length in P.elliottii is evident at much lower sheet densities than with the hardwoods.

It must be noted that in these studies hardwood fibre length was measured from the original whole fibre length and not the length in the pulp as affected by Valley-beater processing. Watson and Dadswell (1964) postulated that tearing strength of a pulp sample will increase with an increase in fibre length up to an optimum length of about 4 mm, after which an increase in fibre length has no additional beneficial effect.

It was expected that after cooking and beating the fibres their length should be shorter. In England at the Kraft mill of Wiggins Teape Co., an average pulp fibre length of 2.5 mm is recorded and, it is considered that lengths over 3 mm are difficult to use.

As the fibre length increases, the tendency of suspensions of fibres in water to c lot becomes greater, resulting in very uneven paper.

Fibres longer than about 5 mm require special techniques for the preparation of sheets which are neither very thick nor very lumpy. The production of the very uniform thin papers which are used for printing and for many other purposes requires a high proportion of fibres of about 1 mm or less.

b. Cell wall thickness

Cell wall thickness of fibres is a very important factor in determining the papermaking characteristics of wood pulps. In general increased fibre wall thickness tends to give:

a. Higher tear strength, b. Lower tensile strength

c. Lower bursting strength

Early researchers recognized that thin-walled fibres from wood with low density collapse to form flattened ribbons in the process of papermaking and consequently form a compact dense sheet with highly effective fibre to fibre contact areas and resultant strong bonds. Such papers are high in burst and tensile strength. On the contrary, thick-walled fibres resist collapse and retain their tubular shape to form a bulky low-density sheet. Because of the reduced area of contact between such fibres, bonding is poorly developed and the sheet is relatively low in tensile strength and burst. These observations based on fibre collapse provide an insight into paper structure and properties that is still useful today.

Smith and Byrd (1972) in their investigation of loblolly pine (Pinus taeda showed that when wood is pulped, the thinner walled earlywood fibres collapse into ribbon-like forms 40μ to 65μ wide and 10μ to 12μ thick, twice the cell wall thickness (5μ to 6μ). The latewood fibres retain their tubular form and are 25u to 35u in diameter with a wall thickness of 10u to 15u.

It is interesting that Barefoot et al. (1964) found that the most useful single predictor of the properties of paper made from four loblolly pines was latewood cell wall thickness.

c. Fibre diameter

According to the report of the TAPPI Forest Biology Committee (1960), fibre diameter, at a given wall thickness, influences the behaviour of the pulps in washing, screening and refining operations, and has an important effect on sheet formations, fibre bonding, fibre rigidity, and mobility. At present there does not appear to be a quantitative understanding of the relationship."

In general, however, it is felt that small diameter, thin walled fibres are desirable for good sheet formation and strength, compared to fibres with large diameter. The effect of fibre diameter independent of wall thickness is perhaps most readily apparent from the influence it has on increasing fibre coarseness (Britt, 1966). With southern pines this will tend to give poor sheet formation, a loss of bursting strength (Wangaard, et al., 1967) and a reduced tear factor (Einspahr et al., 1969). With spruce, Ladell (1968) found a positive relation between fibre diameter and tensile strength.

d. The ratio of fibre dimensions

A number of complex expressions of fibre morphology have been widely used. Some of the most commonly accepted coefficients are the following:

1. Runkel ratio: The ratio between the double cell wall thickness and the lumen diameter. It is positiv ely correlated with wood density and tearing strength of pulp and negatively correlated with bonding strength. Of fibre ratios, the Runkel ratio was found by Barefoot et al. (1964) to be the most useful predictor of paper properties in Pinus taeda.

2. Mulsteph ratio: The ratio between the transverse area of the cell wall and the transverse area of the whole fibre. A low ratio is associated with low density wood and paper with good formation and high bonding strength whereas a high ratio, resulting in coarse sheets with a high tearing strength (Gonin and Taylor, 1973), is obtained from stiff and thick-walled fibres associated with high density wood.

3. Rigidity co-efficient: The ratio between the double cell wall thickness and the fibre diameter. It is negatively correlated with bonding strength and positively with tearing and fibre strength.

4. Felting power (or fibre slenderness or felting coefficient): The ratio between fibre length and fibre diameter. It is negatively correlated with fibre flexibility. From the results of studies in which felting power was used, it is difficult to decide whether or not it is an important indicator of pulp properties. Some investigations (Wangaard and Mckimmy, 1977) claimed that felting power is positively correlated with tearing as well as

bonding strength while others could not find any correlation. Some consider felting power to be more important than fibre length in providing information on the variation of tearing strength. Watson and Dadswell (1964) in their review state that the felting power cannot be expected to provide basic information on strength properties associated with fibre bonding, there may be cases where a correlation can be established with felting power but this is clearly due to a combination of other factors.

5. Fibre coarseness: The number of meters of fibre per gram of fibre. Casey (1960), discussing the importance of different fibre properties, has stated that "fibre coarseness", or a relationship of fibre width to length, is at least as important as fibre length". Fibre coarseness was inversely related to tensile and bursting strength and, in general, had an adverse effect on tearing strength (Clark, 1962).

6. Fibre flexibility: The ratio of lumen diameter to fibre diameter. This varies between 0.05 and 0.9 for various species. Fibre flexibility is positively correlated with bursting and tensile strength, folding endurance and sheet density and negatively correlated with fibre strength. Dinwoodie (1966) found that fibre flexibility had a greater influence than fibre length in explaining the properties of softwood pulp. In general, the effect of fibre flexibility has been found to be the most useful of the complex expressions of fibre morphology.

Matolesy (1975), examining the correlation of fibre dimensions and wood properties with the physical properties of Kraft pulp of Abies balsamea L.(Mill), noted that it was not possible to predict accurately the physical properties of paper from the fibre dimension ratios (flexibility ratio, rigidity coefficient, Runkel ratio and

felting power), and this is in disagreement with the findings of many researchers.

C. The influence of wood physical properties on paper strength

The relationships between wood density and latewood percentage and paper strength have been known for a long time. Effects of wood density on pulp and papermaking quality are indirect, and due to the individual factors contributing to wood density. These include such features as differences in latewood content in conifers and differences in the ratio of wall thickness to lumen diameter, with resulting change in fibre flexibility (Mottet, 1965).

As a consequence of increased wood density and latewood content, pulps possessing the following properties are obtained:

a. High tear factor

b. Low tensile strength

c. Low bursting strength

These effects are smilar to those obtained with increasing cell wall thickness. The importance of latewood percentage obviously depends upon the extent of differences between early- and late-wood, it is therefore of significance mainly for certain coniferous species, where such differences are marked.

Rys (1955) who studied some Brazilian tropical and subtropical hardwoods, showed that all of the strong pulps worthy of commercial investigation came from species having wood density less than a 75g/cc This supports the long held view that thick-walled fibres of species having very high density do not collapse appreciably and yield very bulky papers of inadequate strength for most uses.

Differences between juvenile and mature are a reflection of their anatomical structure. Juvenile wood in conifers, when compared to mature wood, has been found to have: (1) low density, (2) low levels of latewood and a greater proportion of thin-walled fibre elements, (3) shorter fibre length, (4) higher levels of compression wood, and (5) higher levels of lignin, extractives, and moisture.

Reaction wood (compression wood) in conifers, when compared to normal wood, has been found to have: (1) higher lignin content, (2) shorter fibre length, (3) thicker cell wall, (4) higher density, (5) faster growth rate. It is less desirable than juvenile wood for papermaking (Keays, 1971) because the consumption of chemicals during pulping of compression wood is exceptionally high while the pulp yield is low. Compression wood fibres have a lower strength per unit cross-section area than normal softwood fibres and result in paper with a low tearing strength but there is no major effect on bonding strength. Although the presence of compression wood is undesirable, it would not seriously reduce the yield or quality of sulphate pulp provided the proportion is not excessive (Venter, 1967).

In conifers the influence of growth rate on wood and fibre quality has been investigated by a number of research workers. Growth rate is a function of the genetic potential of a tree and of its age, and is influenced by many environmental conditions, such as length of growing season, amount and distribution of rainfall, nutrient status of the soil and spacing. Each one of these factors also has an influence on wood quality (Posey[1], 1967, Smith[2], 1968, Klem[3], 1968). Einspahr (1976) reviewed the influence of short-rotation forestry on pulp and paper quality and summarized the pulp quality interrelationships in the following table:

1, 2 = See van Buijtenen, J. P. (1970)
3 = See Einspahr, D. W. (1976)

Summary of interrelated factors influencing paper quality of short rotation conifer

Wood or paper property	Juvenile wood vs mature wood	Reaction wood vs normal wood	Rapid vs normal growth
Pulp yield	lower	lower	equal or lower
Tear factor	lower	lower	lower
Burst factor	higher	lower	higher
Tensile strength	higher	lower	higher
Fold endurance	higher	lower	higher
Beating energy	lower	higher	lower
Cooking time	shorter	longer	equal
Chemical requirement	higher	higher	equal

Based upon rotation age 8-20 years.

2. Literature review of *Pinus caribaea*

In this study, the works of Brown (1969), Hughes (1970). Burley et al. (1971), Lantican (1972), Paraskevopoulou (1973), Schmidt and Smith (1961), Smith (1973), and Palmer and Gibbs (several serial works) have been used with general reference to the species of P.caribaea. It is noted that most of the published work has used P.caribaea var hondurensis, and unless another variety is specifically named the following review refers to this variety.

2.1 Tracheid length

2.1.1 Variation of tracheid length within the tree

A. Axial pattern of variation

Investigations have been carried out by Brown (1969), Burley et al. (1973) based on average disc mean tracheid length for all trees. Lantican (1972) and Paraskevopoulou (1975) based their analyses on fixed numbers of rings from the pith (ring of the same physiological age), in order to determine the axial pattern of variation of tracheid length in P.caribaea.

The general pattern of axial variation is an increase in tracheid length from the base upward in the bole to a definite height where, it reaches a maximum and then decreases towards the crown. This pattern does not conform to the results of Paraskevopoulou (1973), who found tracheid length attained a more or less constant value after a certain height. She pointed out that perhaps the younger material (12 years old) used in her study does not show the full development of the pattern.

B. Radial pattern of variation

Schmidt and Smith (1961), Burley et al. (1971) have shown that tracheids in the stem generally increase in length from the inside toward the outside through a number of annual rings until a definite size is reached, and then remain constant for the following annual rings.

Brown (1969) and Paraskevopoulou (1973) found a linear relationship between tracheid length and age. Lantican (1972), who has worked with older material (30 years old) of P.caribaea, has described an increase with age until at a particular age a peak value is attained after which length starts to decrease.

Burley, et al. (1973), working on 12 year old P.caribaea var. caribaea, found that mean tracheid length increased from 1.8 mm, in the second ring, to 3.43 mm in the tenth ring of the lowest discs.

Palmer and Gibbs (1972, 1975, 1976) found that average fibre length increase with age in pulped P.caribaea from various sites.

2.1.2 Variation of tracheid length between trees

Lantican (1972), working on ten trees of P.caribaea var. hondurensis, found large differences between mean values for trees, accounting for 18 per cent of the variation. Large differences between trees were also found by Brown (1969) in his study of 10 years old trees of P.caribaea var, hondurensis grown in Jamaica.

Burley et al. (1971) also found large differences between tree of the same variety (P.caribaea var, hondurensis) but grown in a different location of Jamaica.

Hughes (1970) working on P.caribaea var hondurensis, taken from five different sites, found that differences in mean tree values for tracheid length between trees on the same site were greater than differences in the mean values between sites. He suggested that genetic reasons could be considered to explain this big variation.

Schmidt and Smith (1961) have also mentioned large differences between trees. Similar results have been reported lately by Andrew and Hughes (1973), working on material from two plantation sites in Trinidad.

Paraskevopoulou (1973) in her study of P.caribaea var caribaea from Cuba, mentioned that the variation of tracheid length between the trees of each plot in both plantation and natural forest material was small compared with the results of other investigators with

this species.

2.2 Tracheid cross-sectional dimensions

2.2.1 Variation of tracheid cross-sectional dimentions within the tree

A. Axial pattern of variation

Very little work has been done on the variation of the cross-sectional dimensions of P.caribaea. Lantican (1972) and Paraskevopoulou (1973) found that there was not much variation with height for any of the cross sectional dimensions features either in earlywood or in latewood samples of P.caribaea.

B. Radial pattern of variation

Paraskevopoulou (1973) found that the trends of variation of both radial and tangential double cell wall thickness is to increase from the pith outwards. Lantican (1972), who worked on older material of P.caribaea var. hondurensis, found that radial double cell wall thickness of the earlywood samples increased with increasing age. while in latewood samples it increased up to a certain age after which it started to decrease.

Lantican (1972) also found that with 30 year old trees, earlywood radial cell width increased with age to about 40 per cent from the pith outwards, while latewood radial cell width remained more or less unaffected by changes in ring number.

Paraskevopoulou (1973) found that in 12 year old trees radial cell width increased by about 20 per cent from the pith outwards to the eighth ring in plantation trees. In naturally grown trees radial cell width increased by about 6 per cent up to the tenth ring.

After this it decreased about 10 percent in the plantation material but only very slightly in the natural material.

Lantican (1972) found that, in both earlywood and latewood samples, tangential cell width increased from the pith outwards. Paraskevopoulou (1973 P.caribaea var caribaea) generally agreed with Lantican. With plantation material, after the eighth ring, a slight decrease was apparent to the tenth ring but after this width increased again.

Palmer and Gibbs (1972, 1975, 1976) found that average cell wall thickness increased with age.

2.2.2 Variation of tracheid cross-sectional dimensions between trees

Lantican (1972) and Paraskevopoulou (1973) found significant differences between trees, accounting for a considerable amount of variation for all cross-sectional dimensional features.

2.3 Density

2.3.1 Variation of density within the tree

A. Axial pattern of variation

Concerning the work done on P.caribaea, the findings of Brown (1969) and Burley et al. (1971), working on P.caribaea var. hondurensis, showed that density decreases from the base upwards. Their sampling system was based on measurements taken at fixed distances from the pith expressed as percentages of total pith to bark distances. Similar results were found by Lantican (1972, P.caribaea var. hondurensis) on the basis of a fixed number of rings from the pith. Paraskevopoulou (1973) showed that a decrease occurred from the base upward in natural

forest material. In plantation material, no significant differences were detected due to the effect of levels, while in one plot there was a general trend in which a slight decrease with height was followed by an increase.

Palmer and Gibbs (1972) found that with P.caribaea from Fiji, the density of the upper parts of trees is generally about 10 per cent less than the average of the whole trees.

B. Radial pattern of variation

Except for Schmidt and Smith (1961) who found no significant pith to bark trend of density for P.caribaea, and Paraskevopoulou (1973), who found that density decreased in the first one or two rings from the pith and then increased slightly with increasing ring number, all other investigators have reported an increase of density from the pith outwards. These include Lantican (1972), Burley et al. (1971), Brown (1969), Shand (1966), Hughes and Andeena (1972) and Burley et al.(1973).

Palmer and Gibbs (1972, 1975, 1976) found that the average density increases with age.

2.3.2 Variation of density between trees

Andrew and Hughes (1973) found with P.caribaea from Trinidad that 24 per cent of the total variation in density was due to the differences between trees and 26 per cent due to sites. Lantican (1972), reported 14 per cent of the total variation due to differences between the ten trees studied. Hughes (1970) found 34.6 per cent of the total variation was due to differences between trees in a sample of 50 trees

representing 5 different sites in British Honduras, where the between site variance component accounted for only 18 per cent of the variation. Similarly, considerable between these trees differences for density in P.caribaea have been found by Shand (1966), Brown (1969), Burley et al.(1971) and Schmidt and Smith (1961).

Paraskevopoulou (1973) found differences in mean density between trees in each of four plots of P.caribaea var caribaea, but variance components for the effect of trees accounted for only 3.5% to 7.0% of total variation. The between plots component of variance, however, was greater than the variation between trees of each plot. In plantation material the variation between plots accounted for 33.3 per cent of total variation using sample from four heights within trees and 24.9 per cent using one level only. In natural forest material it was 11.4 per cent in the four levels height analysis and 9.4 per cent in the one level height analysis.

2.3.3 Variation of density between plots and between sites

The wood density of P.caribaea var. hondurensis has been investigated with samples from different locations in the natural range and also with samples from plantation crops from several conditions representing a considerable range of sites.

Variation of density in trees from five different sites in the natural range has been described by Hughes (1970), who found that between site differences accounted for 18 per cent of the total variation. Material of one site in the natural range has been studied by Lantican (1972). Brown (1969) working on two plantation plots in Jamaica did not detect any significant differences between them, but Hughes and Andrew (1971) found that differences between the average values of density of samples from two plantation sites in Trinidad accounted for 26 per cent of the total variation.

Paraskevopoulou (1973) reported that very highly significant differences were found between the mean values for density in plantation and natural forest material, accounting for 53 per cent of the total variation. The differences in density can be explained by the greater occurrence of latewood in the natural material. In the plantation area, rainfall was about double that of the natural forest area.

The differences in density between varieties of this species have been well described by several authors, particularly Smith (1973) and are not reported in this review.

2.4 Interrelationships between tracheid dimensions, density and other wood properties

Lantican (1972) in his study of ten trees from British Honduras showed that ring width is not significantly correlated with earlywood radial and tangential double wall thicknesses, radial cell width, latewood tangential cell width, double wall thickness tracheid length, further, was only weakly correlated with earlywood tangential cell width, latewood radial cell width and double wall thickness. No significant correlation was found between wood density and ring width.

Tracheid length is positively correlated with earlywood radial and tangential cell widths and latewood tangential cell width, and negatively correlated wi th latewood radial cell width. Tracheid length is also positively correlated with earlywood and latewood radial and tangential double wall thickness. Tracheid length and wood density are not significantly associated with each other.

There is general agreement between Lantican's results and those available in the literature regarding the correlations between wood density and tracheid cross-sectional dimensions. Significant negative correlations are reported between wood density and earlywood cell widths and latewood tangential cell width. Tracheid diameter and wall thickness have been found to be positively associated with the variation of wood density. Most of the earlywood and latewood tracheid cross-sectional dimensions examined were found to have a highly significant correlation with age from the pith.

A high degree of correlation was found between density and latewood percentage, as would be expected. Similarly, a high degree of correlation was found between density and cell wall percentage computed on the basis of measurements of tracheid cross-sectional dimensions.

Paraskevopoulou (1973) found that the closest relationship existed between density and cell wall thickness (radial and tangential) but the amount of variation accounted for was not very high (radial cell wall thickness r^2* = 52 per cent, tangential cell wall thickness r^2 = 57 per cent). The relationship between density and cell width was very poor (radial cell width r^2 = 0), and suggests that variation in cell wall thickness, rather than cell size, was the more important factor influencing variation in density.

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* r^2 = Coefficient of determination.

2.5 The relationship between wood properties and paper proporties of P.caribaea

2.5.1 General review of pulping properties

A number of samples of P. caribaea have been examined to determine the value of this species as a raw material for paper making.

Almost all of the available information on the pulping characteristics of P.caribaea is based on work done using the sulphate process. The information in this section is taken mostly from work at Tropical Products Institute, London. Published information shows that different workers have had widely different experiences in comparing P.caribaea pulps with those of other species.

South African experience is that pulp from P. caribaea wood between 9 and 14 years old and grown in Natal are 20% weaker than pulp from P. elliottii of the same age growing in the same environment. Australian experience shows little difference between pulps from P. elliottii and P.caribaea grown in Queensland. (see the reviews of Palmer and Tabb, 1971).

Palmer and Tabb (1971) and F.A.O. (1975) reported in their reviews that with different samples of P.caribaea the alkali consumption in the sulphate process varies from normal to high for softwoods. As regards the strength properties, the general impression is that the P. caribaea yields a pulp similar to North American Southern pine. But inferior in bonding strength and superior in tearing strength to pines from northern temperate pines (Scandinavian pine).

With proper attention to seed selection, and to selection of soil and climate as well as other considerations, a pulp resembling southern pine sulphate pulp is perhaps the best that can be obtained

from this species. However, the yield tends to be slightly lower than average for pine sulphate pulp.

Palmer and Gibbs (1972, 1975) state that wood from P.caribaea trees of different densities could be cooked satisfactorily together and without difficulty by the sulphate process, there being no significant difference in the digestion conditions need for any of the samples.

2.5.2 Effect of age on pulping properties

Several researchers had indicated that old, naturally grown samples yield pulps with very high tearing strengths and relatively low bonding strength (Schafer and Chidester, 1961, Chittenden and Palmer, 1959, Blok, 1958). Pulp from young plantation grown samples had better bonding strengths but poorer tearing strengths (Palmer and Gibbs, 1967, 1968, 1972). Since then a number of reports have been issued where age is variable but the samples, came from sites close together. Fairest (1967) and Sanchez (1967) working in Venezuela, on samples from Trinidad, showed that pulp from 14 year old trees was better than that from 5, 10 or 17 year old trees.

Palmer and Peh (1967) indicated that 6 year old samples from Malaysia had the best bonding and the poorest tearing strength, 12 year old samples had the best tearing and the poorest bonding strengths, 10 year old samples were intermediate in both respects.

Palmer and Gibbs (1971) compared a sample of 9 year old material from Sabah with pulp from 5 year old material from the identical site examinated earlier. Pulp from the older samples had poorer bonding strength and equal tear.

Palmer and Gibbs (1976) compared P. caribaea pulp from the Belize samples and other samples of P. caribaea, the Belize samples tended to be weaker than the pulps from very young samples grown in other countries. There were some exceptions to this trend especially with tearing strength.

2.5.3 Effect of wood density pulping properties

Wood with a high density may be expected to have more thick walled fibres than wood with a low density. From this it was expected that high density wood would give higher yield pulps with better tearing and poorer bonding strength, whilst low density wood would give pulp with better bonding but poorer tearing strength. This relationship was found in examining three trees of 12 year old material from the same plantation in Jamaica (Palmer and Gibbs, 1973). When the trees of highest and lowest density of six 9 year old trees from Sabah were compared, there were no clear relationship of pulp properties to between mean tree density (Palmer and Gibbs, 1971).

2.5.4 Effect of rate of growth on pulping properties

Palmer and Gibbs (1969) examined 12 year old trees from two sites planted in the same year in Trinidad and found no correlation between density and growth rate on either site. The pulps obtained from three samples of different growth rates from the same site showed no significant difference in bonding strength, but tearing strength was significantly different, the faster grown samples having a lower tearing strength. The samples from the second site gave pulps with different characteristics, but these correlated neither with density nor growth rate.

Recently, Palmer and Gibbs (1977) reporting on the effect of rate of growth on P.caribaea from Fiji, found that the volume of wood produced by trees selected as fast grown was approximately twice that produced by the slow grown trees. There were no significant differences in wood density or chemical composition. When compared as weight of pulp per volume of wood, the slow grown samples yield more pulp than the fast grown one (3-8%).

2.5.5 Effect of growing conditions on pulping properties

Growing conditions can have an appreciable effect on pulp quality as was demonstrated by Palmer and Gibbs (1968) from examination of samples of 9/10 year old samples of P. caribaea var. hondurensis from three sites in Fiji, cooked under identical conditions.

The sites were not very far apart but there is a difference in rainfall and soil type. Since the trees used in this examination had been planted in the same year and the seed source was the same, it is apparent that differences in growing conditions, sufficient to have a significant effect on the quality of pulp can occur in a limited area.

2.5.6 Effect of variety on pulping properties

Palmer and Gibbs (1970) compared the characteristics of a pulp from old natural samples of P.caribaea var. bahamensis grows on Great Abaco Island and several pulps from old, natural grown P. caribaea var. hondurensis from Belize. In bonding strength the pulp from one var. bahemensis sample was comparable with that from

some var. hondurensis woods, but the tearing strength did not reach the same high values.

In South Africa, samples of the Cuban variety (P. caribaea var. caribaea) have been examined. One sample was seven years old and came from a plantation at 3000 ft. altitude in Eastern Transvaal. The second was nine years old and grew on the Western Natal Coast. In each case the pulps obtained were equal in strength properties to those of P. patula and 25% weaker than those from P. elliotti of the same age and from the same site.

Other work in South Africa gave a different conclusion:- "It was found that P. Oocarpa, P.caribaea (Grand Bahamas) and the P. caribaea mixture (a mixture of five strains) yield pulp of lower quality than P. elliottii and P. caribaea (Cuba). The latter two samples were about equal in strength but the yield of P.caribaea (Cuba) was significantly lower than that of P. elliotti".

Palmer and Gibbs (1975) investigated two samples of Pinus caribaea var. caribaea from Cuba pulped by the sulphate process. The first sample came from natural forest, and was about 20 years old. The second came from a plantation, and was 12 years old. These samples compared with established coniferous pulps (including Southern pines) yielded less pulp with lower strength characteristics. Results were also compared with previously published information about the pulping of P. caribaea var. hondurensis and P.caribaea var. bahamensis from samples with a wide range of physical, chemical and fibre characteristics, the P.caribaea var. caribaea material tended towards lower yields of weaker pulps.

Palmer and Gibbs (1972, 1976), working on P. caribaea var. hondurensis from Fiji and from Belize, found that samples from Belize and the ten years old samples from Fiji were more like pulps obtained from the Southern Pines of the U.S.A. than pulps from northern coniferous species.

Chapter 3

MATERIALS AND METHODS

1. Origin of the material for this investigation

The main archipelago of Fiji lies between 15° and 22°S latitude and between 175°E and 177°W longitude. Viti Levu and Vanua Levu, the largest islands, are the areas of major interest for forest plantation development. In these two islands the main geological formations are ancient volcanic and andesite rocks but there are also Cretaceous and Tertiary sediments. Generally the terrain is rugged, with sharp peaks and crags running up to about 4,500 feet (1371.6 m) above sea level, but there are extensive areas of flat land arising from the drainage pattern of the major rivers.

The prevailing winds are the east to southeast trades, but wind direction becomes more variable in the 'wet' or 'hurricane' season between November and April. In comparison with the tropical rain forest on the windward sides, the vegetation to the leeward is grassland, with an interspersion of reed, fern and scattered trees. The grassland is in various stages of deterioration from repeated burning and uncontrolled grazing.

Mean annual temperatures, over most of the area, are around 80°F (26.7°C) and annual rainfall is 80 -100 in (2032-2540 mm) with three dry months, one of which may be very dry. On Viti Levu, the coastal belt has a dry season of five months, of which three months may be very dry, and a broader spread of annual rainfall of 55-100 in (1397-2540 mm). The rain falls mostly in the hotter

months of November to April, that is in the period when the prevailing wind direction is less predictable and often replaced by variable northerlies.

P. caribaea var. hondurensis has been planted on trial plots since 1955, further trials from 1958 to 1960 were followed by steady expansion from 1961 onwards to a programme of 1,000 ha a year by 1969. According to Clarke and Shepherd (1973), P.caribaea var. hondurensis in Fiji is being planted in open grasslands, mostly degraded agricultural land or burnt-over hill-sides, on the drier sides (rainshadow areas) of West Viti Levu and the north of Vanua Leuv. Planting is at 2.4 x 3 m, at 6 - 8 years, the first thinning is to 720 trees per ha, at 9 - 11 years, a second thinnings is to 430 trees per ha and the final crop is estimated to be 300 trees per ha.

The major existing plantations of P. caribaea var. hondurensis are:

Viti Levu (Drasa/Lololo in the northwest corner in lowland elevations less than 1,000 ft (304.8 m) above aea level. Nausori Highland in the wet windward side of Viti Levu, 1200 - 1500 ft (365.8 - 457.2 m) above sea level.)

Vanua Levu (Seaqaqa in the north centre, elevation less than 1,000 ft (304.8 m) above sea level.)

The material for this investig ation was planted in 1960/1961, and the seed source for all of these plots was Mountain Pine Ridge, Belize. Samples were collected by Mr. A.S.Alston (Principal Utilisation Officer, Forest Department, Suva, Fiji), during 1973

from plantations at the three main planting locations:-

(a) Drasa, (b) Nausori Highland, and (c) Seaqaqa.

The growing conditions and history of plantations at these three sites are described in Appendix I (A), from information provided by the Forest Department in Fiji.

2. Field sampling

The project was initially designed to investigate the structural features of P. caribaea in relation to growth conditions as reflected in specific gravity variation. Twenty sample trees were selected at random from each of two plots in 10-11 year old (1971) plantations at Drasa, Nausori Highlands and Seaqaqa. Increment cores taken at breast height were examined by x-ray densitometry at Oxford and the trees were ranked by weighted core density. From the results obtained, sample trees were classified according to weighted core density into one of five classes within the range of 0.45 g/cc to over 0.65 g/cc as follows:-

1. Over 0.65 g/cc
2. 0.61 - 0.65 g/cc
3. 0.55 - 0.60 g/cc
4. 0.50 - 0.55 g/cc
5. 0.45 - 0.50 g/cc

A sub sample of 20 trees 12-13 year old (1973) was then selected to cover the range of density (four sample trees from each density class). These trees were felled and billets were taken, at 10% intervals along the stem from 5% of total height upward, for densitometry and anatomical measurements at Oxford and for tests at the Tropical Products Institute London, to evaluate pulp properties on an individual tree basis.

The results of this study are based on the examination of these twenty trees. Measurements of the sample trees are presented in Table 3.1 and more details are given in Appendix I (B).

3. Laboratory techniques and sampling procedures

For this study it was decided to measure density at the 5%, 15%, 25%, 35%, 45%, 55%, 65% and 75% height levels but to limit the measurement of tracheid dimensions to 5%, 15%, 35% and 65% height levels. The choice of four levels was guided by the work of Hughes (1970) and Brown (1969), who found that the pattern of variation in tracheid length and density with increasing height could be described satisfactorily from these sampling levels.

Lantican (1972), on the other hand, has pointed out that sampling three levels per tree would be adequate, and that there seems little advantage in increasing the number of levels to more than four per tree, because the between-level component of variance was never of considerable magnitude for the features of tracheid length, density and earlywood and latewood tracheid cross-sectional dimensions.

When levels were decided, the next task was to determine the scheme of sampling at each level. In a preliminary examination, several discs were chosen and sanded on the top side to establish annual ring boundaries.

In each disc, two random radii were selected for measurement. The choice of two radii within each disc as a sampling strategy was guided by the results of Brown (1970), who found little variation between radii within discs in tracheid length and specific gravity of P. caribaea, and by Lantican (1972) and Paraskevopoulou

Table 3.1 Records of measurements of twenty sampled trees selected from the various sites.

Sites	Fiji Tree code No.	Oxford Tree No.	Height (m)	Girth (cm)
Drasa	D1-6	1	19.81	91.44
	D1-57	2	18.72	74.93
	D1-71	3	19.51	68.58
	D2-11	4	18.59	72.39
Nausori highlands	NH1-24	5	20.57	99.70
	NH1-40	6	23.77	113.03
	NH1-44	7	24.69	87.63
	NH1-50	8	20.35	86.36
Seaqaqa	S1-8	9	24.48	99.70
	S1-31	10	24.25	83.82
	S1-36	11	22.61	86.36
	S1-45	12	24.82	91.44
	S1-55	13	20.29	71.12
	S1-64	14	24.59	101.60
	S2-1	15	24.43	92.71
	S2-6	16	21.79	101.60
	S2-37	17	25.78	101.60
	S2-51	18	22.50	93.98
	S2-79	19	24.79	89.54
	S2-84	20	25.10	114.94

(1973), who have shown that two radial samples per level would be adequate for sampling any of the features to be measured.

Radii were selected using a table of random numbers and following a clockwise direction starting always from the longest radius. These radial positions were marked on all discs of each level, by superimposing the matched specimens, and lines were then drawn from the bark to pith.

From these discs, and along each of the radii, two strips of about 1 cm wide were cut. One of these pairs, about 5 mm thick, was used for determination of wood density and tracheid cross-sectional dimensions, and the other one about 13 mm thick was kept as a reserve sample.

Examination of the discs revealed the frequent occurrence of false rings, which made it difficult to ascertain the boundaries of the annual growth zones. The technique used by Lantican (1972) was followed for annual ring demarcation, in which each annual ring is examined carefully around the disc by cross-matching with corresponding growth zones in discs from different heights of the same tree and from other trees representing the same height level, it was found that false rings could be identified and the true annual ring boundaries distinguished.

In this study, it was decided to examine every ring from each of the radii to determine the within-ring and between-ring variability of density and tracheid cross-sectional dimensions (Table 3.2).

Table 3.2: Annual rings sampled within the trees studied

Disc height level	Drasa and Naursori Highland, plantation annual rings sampled	Seaqaqa plantation annual ring sampled
5%	1, 2, 3 ....., 10	1, 2, 3, ... 11
15%	1 9	1 10
25%	1 9	1 10
35%	1 8	1 9
45%	1 7	1 8
55%	1 5	1 6
65%	1 4	1 5
75%	1 3	1 4

4. Measurement of wood properties

In this study the following growth characteristics and wood properties were measured:-

1. Age
2. Ring width
3. Density
   a. Average density
   b. Maximum and minimum density
   c. Density class
   d. Latewood percentage
4. Compression wood percentage
5. Tracheid cross-sectional dimensions
   a. Cell wall thickness
   b. Lumen width
   c. Cell diameter
   d. Cell wall percentage
6. Tracheid length
7. Chemical content
8. Unbleached pulp evaluation.

9. Other derived determinations were
   a. Runkel ratio
   b. Flexibility ratio
   c. Slenderness ratio
   d. Fibre stiffness ratio
   e. Fibre index

Table 3.3 lists the wood characteristics and pulp properties determined or calculated in this study.

The procedures adopted and the equipment used for measuring each of these properties are described below.

4.1 Age determination

The first stage was to determine the correct number of annual rings in each disc, because subsequent measurements an analysis were dependent upon the assignment of a correct age and year of origin to each ring. It was found that false rings could be identified and the true annual ring boundaries distinguished.

4.2 Density and ring width

In recent years the application of non-gravimetric methods (Beta-ray, Gamma-ray and X-ray) for measuring density have become prominent, because they allow rapid and accurate measurement of variation in intra-ring specific gravity as well as ring width. Among non-gravimetric methods, the X-ray densitometric technique is considered to be superior for detailed work (Mackinnell, 1970).

The procedures for the measurement of wood density, now used at the Department of Forestry of the University of Oxford, were derived from techniques first demonstrated by Polge (1966), who recognized that variation could be recorded by X-radiography and measured by scanning the radiographs with an optical densitometer.

Table 3.3 Wood characteristics and pulp properties

Wood characteristics	
Ring width	
Wood mean density (extracted)	ED
Density classes 1-8	ED-X
Latewood percentage	L%
Compression wood percentage	Co%
Growth rate	
Mean cell wall thickness	CW
Cell wall thickness classes 1-5	CW-X
Mean cell lumen width	CL
Cell lumen width classes 1-5	CL-X
Mean cell diameter	CD
Cell diameter classes 1-5	CD-X
Mean cell wall percentage	CW%
Cell wall percentage 1-7	CW%-X
Tracheid length	FL
Runkel ratio	2CW/CL
Flexibility ratio	CL/CD
Slenderness ratio	FL/CD
Fibre stiffness	FL/2CW
Fibre index	2CW$\dot{x}$FL
Holocellulose	
Alpha cellulose	
Hemicellulose	
Lignin	
Total extractive	

Pulp properties	
Total pulp yield %	TY%
Burst factor	BF
Breaking length	BL
Tear factor	TF

At Oxford, this technique has been developed by Hughes, Franklin and Sardinha (1972) following the work of Fletcher and Hughes (1970) and Polge (1969). Important innovations in the development of this method were the construction of special optical wedges to deal with problems of non-linearity of attenuation of the X-ray beam, the use of plastic standards for calibration and checking, the setting up of system for recording the output of the densitometer on Computer tape, the sorting and presentation of data and the mathematical analysis and interpretation of results.

4.2.1 Preparation of the samples

From the air dried discs which had been selected for the study of density, 8 to 9 mm wide radial strips were cut to uniform 5 mm thickness by machining on a spindle moulder, fitted with a pair of tungsten carbide tipped saws, separated by spacing collars of the appropriate size.

To obtain standard conditions for comparison the machined wooden strips were conditioned to 12 per cent moisture content. The density of the conditioned wood strips was then measured by radiography and densitometry as described below.

4.2.2 Measurement of wood density by the X-ray densitometry method

A. Principles of the X-ray densitometry techniques

The main principle of the X-ray technique, according to Polge (1963, 1966), is that if in wood specimens the thickness and moisture content are constant, soft X-rays are absorbed according to an exponential law that depends only on sample density. The equation which describes this behaviour is:

$$I = Io^{-mtd} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

I = intensity of radiation after passing through a sample of thickness t.

I_o = the initial intensity of radiation

m = the characteristic absorption coefficient of the sample material

t = thickness of the specimen

d = physical density of the specimen

The optical density (D) according to Silberstein's law is given by

$$D \cong \log I_o/I \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

Substituting (1) in (2) gives

$$D = mtd$$

which shows that the relative optical density is directly proportional to the physical density of the wood.

If the exposures are made at high accelerating voltages, the relationship between the optical density and physical density is virtually linear, but because of the increased scatter introduced by shorter wave length X-rays, the contrast is poor (Polge, 1966, Fletcher and Hughes, 1970). To obtain satisfactory contrast in blackening, soft X-rays (procured by low peak accelerating voltage) have to be used. Low frequency radiation, however, produces a non-linear relationship between optical and physical density, but this is subsequently transformed by modification of the optical wedge system of the densitometer, as will be explained later.

B. The technique

The standard procedure used in this study was as follows:-

(1) Production of a negative image of the transverse cross section of a wood sample by projecting a beam of X-radiation onto a sheet of X-ray film through the wood.

(2) Development of the film under standard conditions,

(3) Scanning the radiograph on an optical densitometer

(4) Estimation of the mean and variation of physical density of the specimens, from transformation of the optical density of the photographic images of the specimens.

a. X-radiography

Many factors related to X-ray exposure conditions and to film processing can affect the quality of the radiographs. To achieve suitable definition and contrast the following procedures were adopted:-

1. All samples were exposed at a distance of 2.6 m from the source, using Kodak X-ray film (8" x 10")

2. The direction of the radiation on the wood specimens was axial,

3. The exposure time was 4 min 40 sec,

4. The voltage was 17 kv,

5. The current was 25 milliamps,

6. The development of the films was done in a specially constructed developing tank using a Kodak liquid DX 80 developer with a development time of 4 min at $68^{\circ}F.$ $(20^{\circ}C)$.

These exposure and development conditions give a film with a background density of about 2.7 D.

b. Densitometry

1. Principles of optical densitometry

The X-ray films were scanned with a Joyce-Loebl Double-Beam Automatic Recording Microdensitometer (Joyce Loebl Mark III CS microdensitometer). This machine has been fitted with an Auto-densidater (type P) data acquisition system, a tape punch output, and a Bryans Model 28000 Chart Recorder.

The densitometry operation is based on a double-beam system in which two beams of equal intensities, derived from a single light source, are switched alternately to a single photomultiplier. One of these beams, with appropriate collimation and focussing, passes through the radiograph, which is fixed on a table that can be moved at a controlled rate. This beam is attenuated to an extent corresponding to the optical density of the specimen images. It is then matched with the unattenuated beam by inserting in its path an optically black wedge which has a fixed graduation and gradient of density. The traverse of this wedge corresponds to changes in the degree of attenuation produced by the film, that is to changes in the optical density of the specimen images. This movement is recorded by a double potentiometer, which is connected to give a chart recording of the pattern of density variation and also a recording, on punch tape, of the wedge movement on a 999 scale at pre-set intervals of the movement of the specimen table.

Because the relationship between the attenuation of the soft X-rays used in the procedures described here and the physical density of the wood specimen is not linear, the photographic response similarly is not linear, and the microdensitometer records of the optical density cannot be shown directly in terms of specimen density. To deal with this situation, the standard linear optical wedge of the instrument, supplied by the manufacturer, has been replaced with a non-linear wedge with a gradation of optical density similar to that of the radiograph of the wood specimens.

These non-linear optical wedges are made from radiographs of accurately machined and ground wedges of plastic (Kemetal), which has similar action to that of wood in the attenuation of X-ray. The machined thickness of these wedges is from 0.5 mm to 4.00 mm over a distance of 20 cm, which is the length of the standard wedge in the instrument.

With a non-linear wedge of this type the instrument can be adjusted to give a recording of optical density which has a linear relationship with the physical density of the wood specimens.

2. Instrumental settings and scanning

The densitometer is provided with stepper motors and leadscrews which can move the specimen scanning stage in X and Y directions. There are programme controls by which can be set (1) the size of step, in either direction, from 5 μm upward in multiples of 5 μm, (2) the length of a scan, (3) the number of scans. The value for optical density at each step is recorded separately on a 999 scale

and then produced on paper tape. Recording formats can be arranged in various ways so that the output can be processed by a computer. The common step intervals for wood specimens are between 50 μm and 200 μm, and the maximum measuring rate is 20 points per second.

Other instrument settings, including the magnification of the objective, the dimensions of the primary slit of the light beam, and of the final slit, are determined for each application separately.

In this study the readings were made at the following settings:

1. Step interval = 200 μm
2. Magnification (Objective) = x 10
3. Primary slit height = 227μm
4. Primary slit width = 45 μm
5. Final slit height = 5 mm
6. Final slit width =-1 mm
7. Standard condensor = 2.2 mm

The length of the strip and the step of reading are set on the machine before the scanning is started. The setting of the machine is also checked for linearity in each film by scanning the images of the three standards which are strips of kematal very accurately finished to 1 mm, 2 mm and 3 mm thickness and of densities 0.137 gr/cm^3, 0.277 gr/cm^3 and 0.417 gr/cm^3 respectively.

C. Computing of density, sorting and presentation of data

The data produced on paper tape by scanning were analysed by a computer program. The program first compares the three standards and it rejects any input data in which there is deviation of more than 0.5% from a straight line relationship of the 1 mm, 2 mm and 3 mm kematal strips. A deviation indicates that the instrument has not been correctly adjusted to give a linear response or that some fault has occurred during exposure or development (Paraskevopoulou, 1973, Sardinha, 1974, Hughes and Sardinha, 1974.) If the scans of the standards are satisfactory, the program then proceeds to transform the variation in relative optical density of the wood specimens into terms of the physical density, according to a regression equation previously calculated. The print-out of the computer program developed for this purpose includes the following parameters:-

1. Mean, maximum and minimum density for each ring separately.

2. Percentage in various density class for each radius and for the whole tree.

3. Ring width and ring area for each annual ring separately.

4. Overall mean density and overall length of each radius.

C. The relationship between measuring X-ray density and gravimetric density

To determine a convenient and accurate method of measuring X-ray density which gave a close correlation with gravimetric density. 40 radial sample strips were taken at random for 5% height discs, and were carefully machined to a thickness of 5 mm in the axial and in the tangential directions and cut to about 6 cm in length. They

were conditioned at 12% MC and at this stage the length, width and thickness and weight of the specimens were carefully measured. The gravimetric density from these measurements was calculated at 12% MC .

With the same specimens and conditions density was then computed by the X-ray method, taken in the axial direction.

The regression of best fit was given by a linear model as follows:

$Y = 0.05368 + 0.8898\ x \quad R^2 = 0.978$

where $Y \doteq$ X-ray density

X = Gravimetric density.

It is obvious that values of density obtained by the two methods are very similar.

In this study, it was decided to use the axial direction of the specimen for radiography because of the high R^2 between X-ray axial direction density and gravimetric density, and because of the greater difficulty in preparing accurately the tangential specimens. (Also see Paraskevopoulou, 1973.).

4.2.3 Density class

P.caribaea has a large range of within-tree and between-tree variation in density, and the density recorded in this study ranged from 0.05 g/cc (lowest) to 1.30 g/cc (highest). To investigate the effects of variation in this characteristic, it was decided to separate density into eight classes, with intervals of 0.15 g/cc as follows:

Density class	1:	0.05 - 0.20	g/cc
	2:	0.21 - 0.35	g/cc
	3:	0.36 - 0.50	g/cc
	4:	0.51 - 0.65	g/cc
	5:	0.66 - 0.80	g/cc
	6:	0.81 - 0.95	g/cc
	7:	0.96 - 1.10	g/cc
	8:	Greater than 1.10	g/cc

Using the X-ray densitometry method, this range of densities was automatically recorded, classified and then converted to percentage figures of wood density distribution for each radius in the sample.

Individual trees were classified into three density groups, on the basis of weighted mean tree density:

1. Medium density tree: 0.4 - 0.499 g/cc
2. Medium high density tree: 0.5 - 0.599 g/cc
3. High density tree: Greater than 0.6 g/cc

4.2.4 Latewood percentage

Latewood within each radius was measured and expressed as a percentage of the total area of each growth ring. Little or no latewood was present conforming to Mork's (1928) definition (2 cw > 2CL). Therefore, for this study the latewood boundary was defined from the abrupt transition of density and of cell size and wall thickness in each annual ring.

Before defining the latewood boundary, a check was made of the chart record of density and of the record of cell wall percentage taken at intervals of 1 mm along each radius. It was found that the abrupt transition of wood density often appeared at above 0.66 g/cc, and that the abrupt transition of cell wall percentage often occurred at above 40%. Fortunately, the latewood percentage values based on

density and cell wall percentage were very close. Therefore for this study, it was decided that latewood percentage would be based on wood percentage in the density class from 0.66 g/cc upwards.

4.2.5 Extracted density

It is known that wood resin may cause troubles, such as pitch deposition, in the manufacture of pulp and paper from certain species of wood. It may also adversely affect the quality of finished pulp. Wood resin, however, is a source of valuable chemicals. The terpenes are the basis of the turpentine industry, and the resin and fatty acids of many species cooked by the Kraft process are recovered in the tall oil and separated into pure fractions (Cohen, in Hillis, 1962).

Soft woods generally contain considerably more resin than the hardwoods. Among the softwoods, the pines stand out as having by far the highest resin content (Mutton, in Hillis, 1962). For this reason, a study was conducted to determine the extent to which resin affected the density of the samples being investigated.

Resins are insoluble in water but soluble in neutral organic solvents, such as alcohol, benzene, dry diethyl ether and petroleum ether, etc. After unextracted density was determined, resin was removed from all samples in a Soxhlet extractor using a solvent solution of one-third ethyl alcohol and two-thirds benzene by refluxing for 32 hours. Samples were then dried in a vacuum oven under vacuum, reconditioned to 12% MC and their density determined using the X-ray method.

The results of this experiment with unextracted and extracted density are shown in Appendix IV, the best fit was given by the linear model as follows:

$$Y = 0.00009536 + 1.019\ X \qquad R^2 = 0.950$$

where Y = unextracted density

X = extracted density

The constant of the above regression (0.00009536) is very small and may be ignored, which means extracted density was an average only 2% lower than unextracted density. Some specimens may have had much greater resin contents than others, a factor which may adversely affect pulping and account for some of the differences between trees. As a consequence, only extracted density was determined in the main study.

4.2.6 Effect of Moisture content in wood on its density

The density of wood is influenced by its moisture content and standardization of moisture content is necessary for purposes of comparison. For pulping studies it is generally agreed that specific gravity should be based on the ovendry weight of the sample.

In this study, the density of wood was measured at 12% MC because this is close to the equilibrium moisture content of wood in the laboratory. To convert 12% MC density to ovendry density, it is necessary to find its transformative regression.

Forty radial sample strips were taken at random from 5% height discs and were carefully machined to a thickness of 5mm in the axial and in the tangential directions, cut to about 6 cm long. They were extracted with alcohol and benzene, and after conditioning at 12% MC, density was determined by the X-ray method. The same specimens were then used to determine oven dry density.

Twelve different regression models (see later section) were tested to regress ovendry density on 12% MC density. The best fit was given by the quadratic but the linear regression was close.

$$Y = -0.05672 + 1.114X - 0.1278X^2 \qquad R^2 = 0.999$$

or $$Y = -0.01038 + 0.9572X \qquad R^2 = 0.998$$

where Y = Ovendry density

X = 12% MC density

It seems that oven dry density is about 6% lower than 12% MC density.

4.3 Compression wood percentage

Compression wood percentage is an important factor in the utilization of juvenile wood because it lowers the quality and the yield of pulps. It can be identified by examining over a light source cross sections, of wood cut to about 1/8" inch (3 mm) thick. This method is very useful for the determination of intermediate stages that are difficult to detect otherwise and for marking the full extent of compression wood in a given piece. For accurate determination of compression wood microscopic examination is necessary, especially when the wood is only slightly affected.

In this study, discs were sanded on the top side until rings and compression wood were visible to the naked eye. The area of compression wood and the disc cross-sectional areas were measured by planimeter to produce a weighted compression wood percentage. The identification of compression wood area, was based on, (1) darker colour ("Rotholz") than normal wood, (2) growth rings which appear to contain a abnormally large proportion of latewood in the region of fastest growth, (3) gradual transition from early to latewood and

(4) a change in the distinctness of the latewood zone, if normal wood shows a distinct and sharp latewood band, this becomes indistinct in compression wood, on the other hand, if latewood is usually indistinct, the latewood band in compression wood is more evident (Panshin and de Zeeuw, 1970).

It was expected that this method would be less accurate than the use of a light source but it still provided a useful indication of the extent of compression wood.

4.4 Tracheid cross-sectional dimensions

4.4.1 System of measurement

The measurements of cell wall thickness and lumen size of tracheids were made on cross-sectional surfaces. The arguments which led to this decision are contained in a report of the TAPPI Forest Biology Subcommittee No.2 (1966).

4.4.2 Preparation of specimens for microscopic examination

The method employed in this study was the same as that described by Lantican (1972). Cross-sectional measurements were done on the same 5 mm thick pieces used for X-ray density determination. The sample was glued to a piece of wood and then polished with a sanding machine using a fine textured (No.400) TRI-M-MITE silicon carbide belt.

Sanding the wedges for few minutes produced smooth and evenly polished surfaces suitable for microscopic examination without requiring any further treatment, except that the application of a very small amount of paraffin wax on the polished surface just before the microscopic examination greatly enhanced the images produced.

4.4.3 Equipment used for measurements

Measurements of radial and tangential transverse dimensions of the tracheids were made on a LEITZ LABORLUX microscope fitted with an ULTROPAK incident light illuminator, a 22x Uo objective, and a LEITZ 12.5 X screw micrometer eyepiece. The objective and the eyepiece, used in combination with the 1.25 x combined binocular phototube of the microscope produced a total magnification of 343.75 x. Lighting was reduced somewhat by using a green and yellow filter, which also produced better contrast between cell wall and lumen.

4.4.4 Procedure for sampling within radii and sample size

Earlywood and latewood bands within an annual increment in the materials under study were sometimes difficult to identify by visual inspection. According to Mork's definition (1928) latewood is wood in which the radial common wall between two cell lumina multiplied by two is greater than or equal to the radial width of the lumen. Lantican (1972) found that this definition excluded some bands of narrow-diameter and thick-walled cells indicative of latewood in some annual rings of P.caribaea. Because the transition from earlywood to latewood was abrupt in most cases, he decided to distinguish latewood by visual inspection by microscope and on the basis of cell wall thickness changes.

In this study, to simplify measurement and to avoid the problems described above, it was decided to measure radii from pith outward to bark at very small intervals. Although this sampling system does not separate earlywood and latewood exactly, it does provide a measure of the variability of cell dimensions in each annual ring and useful data for comparison with densitometry data.

A sampling strategy was required to give an unbiassed and reasonably precise estimate of the means of the parameters to be studied. A preliminary investigation was therefore conducted to indicate an appropriate interval distance in radii, and how many rows of cells and how many cells per row should be measured at each position.

In this preliminary study, a radius (112 mm) was randomly selected from a sample disc. After polishing, a line was drawn along the radius of the wedge. It was decided to measure at 1 mm intervals from the pith outward to the bark. The location of sampling positions (1 mm interval) was determined by using a swift automatic point counter equipped with a mechanical stage geared to take linear steps of 200 μ. This counter was fastened to the lateral movement of the microscope (each mm interval was equivalent to five steps). At each position five rows were selected at random from the 10 rows at each side of the line. In each row two cells were measured.

For each of the selected cells, the radial and tangential dimensions of double walls and lumen were measured with the eyepiece micrometer. Four sets of data were obtained: radial double wall thickness, radial lumen width, tangential double wall thickness and tangential lumen width. The variances of the measurements of these features were analysed, using a multistage sampling design of the following mathematical model:

$$X_{ijk} = U + Si + Rij + Cijk$$

where U = True mean effect

Si = Effect of the ith sample

Rij = Effect of the jth row in the ith sample

Cijk = Effect of the Kth cell in the jth row in the ith sample.

and i = 1, 2, ... 112 (number of position)

j = 1, 2,..... 5 (number of rows)

K = 1, 2, (number of cells)

The general form of this analysis of variance tabulated below:

Source of variation	D.F.	M.S.	Expected mean squares
Samples (positions)	S-1	MSS	Vc + cVr + crVs
Rows in samples	S(r-1)	MSR	Vc + cVr
Cells in rows in samples	Sr(c-1)	MSC	Vc

where: Vc = the variance due to differences among cells

Vr = " " " " " " rows

Vc = " " " " " " samples

c = number of cells per row

r = number of rows per sample

s = number of samples

For each of these analyses, variance components for samples, rows and cells were compared according to the following formulas:

Vs = (MSS-MSR)/rc

Vr = (MSR-MSC)/c

Vc = MSC

The results of the analysis are presented in Tables 3.4, 3.5, 3.6 and 3.7. These tables show that sample position as well as rows, vary significantly in all features examined, and that the variance component for sample positions accounted for the largest percentage of variance.

To determine the precision with which the experimental mean was estimated, the variance of means and standard errors (SE) were calculated as

$$V_{mean} = V_c/crp + V_r/rp + V_p/p$$

$$SE_{mean} = \sqrt{V_{mean}}$$

The coefficient of variability was computed by dividing the standard error by the mean and multiplying by 100.

To determine the relative efficiency of the sampling strategy used with respect to alternative sampling plans, varying values of p, r and c were substituted in the formula for calculation of the variance of the mean. The relative expected precision or efficiency of alternative sampling strategies according to variable values of p, r, and c was computed by

$$\text{Efficiency \%} = \frac{\text{Variance of original design}}{\text{Variance of proposed design}} \times 100$$

The result of the above calculations are presented in Appendix III which show that increasing the number of sampling positions is more effective in reducing the variance than increasing the number of rows and cells. In these tables, the original sampling scheme is shown as having an efficiency of 100 %. Values greater than 100 % represent greater efficiency and consequently greater precision.

In this study, it was decided to adopt the combination of p = 112 (1 mm interval), r =1 and c = 1 for the main study. This sampling plan represents a loss in efficiency of 33.6%, 26.8%, 22.4% and 57% from that of the original design for radial wall thickness

Table 3.4 Analysis of variance of tracheid radial cell wall thickness data.

Source of variation	DF	MS	F	VC	VC (%)
Positions	111	37.17	11.5 ***	3.39	60.66
Rows	448	3.233	2.77 ***	1.03	18.44
Cells	560	1.169		1.17	20.89

Overall mean = 5.3399 μ

V_{mean} = 0.033152 μ

SE = 0.18208 μ

PI = 3.41 %

Table 3.5 Analysis of variance of tracheid radial lumen width data .

Source of variation	DF	MS	F	VC	VC (%)
Positions	111	84.20	14.71 ***	78.5	68.28
Rows	448	57.25	3.65 ***	20.8	18.08
Cells	560	15.68		15.7	13.64

Overall mean = 34.0219 μ

V_{mean} = 0.7521 μ

SE = 0.8672 μ

PI = 2.55 %

Table 3.6 Analysis of variance of tracheid tangential cell wall thickness data.

Source of variation	DF	MS	F	VC	VC (%)
Positions	111	120.6	17.07 ***	11.4	72.96
Rows	448	7.066	5.23 ***	2.86	18.36
Cells	560	1.351		1.35	8.68

Overall mean = 5.7782 μ

SE = 0.3288 μ

V_{mean} = 0.1081 μ

PI = 5.67 %

Table 3.7 Analysis of variance of tracheid tangential lumen width data.

Source of variation	DF	MS	F	VC	VC (%)
Positions	111	282.0	3.36 ***	19.8	30.26
Rows	448	83.84	11.15 ***	38.2	58.26
Cells	560	7.52		7.52	11.48

Overall mean = 31.7485 μ

SE = 0.5017 μ

V_{mean} = 0.2517 μ

PI = 1.58 %

radial lumen width, tangential wall thickness and tangential lumen width respectively, but the precision indices for all features at this level, are 4.18%, 2.98%, 6.46% and 2.41%, which is considered to be satisfactory.

4.4.5 Data recording system and data sorting

Each measurement was recorded on computer tape, using an automatic recording system connected to a digitiser fitted to a filar traversing screw micrometer eyepiece.

The data representing each sample were transformed into a common unit of measurement (micrometers, μm) and sorted by computer, using a program developed for the purpose.

For the purpose of calculation of all derived anatomical variables considered in this study, certain basis assumptions were made in terms of the shape of the cells and their lumina. The fibre and lumen cross-sections were assumed to be rectangular. In each case cell wall thickness was conventionally measured as half the width of the double cell wall between adjacent lumina at its narrowest point.

So, if fibre radial double wall thickness is 2 RCW, tangential double wall thickness is 2TCW, fibre lumen in radial direction is RCL and TCL is the lumen width in the tangential directions, the derived variables of an assumed rectangular shape for tracheid cross-sectional dimensions were:-

Average cell wall thickness $CW = (2RCW + 2TCW)/2$

Average lumen width $CL = (RCL + TCL)/2$

Average tracheid diameter $CD = (RCW + RCL + TCW + TCL)/2$

Cell wall percentage: $CW\% = \frac{(RCW + RCL)(TCW + TCL) - (RCL \times TCL)}{(RCW + RCL)(TCW + TCL)}$

To facilitate comparison with other characteristics and to describe their variation within and between trees, it was decided to separate these characteristics into several classes, as follows:-

Cell wall thickness classes

0.00 - 4.00 μ

4.01 - 8.00 μ

8.01 - 12.00 μ

12.01 - 16.00 μ

Greater than 16.01μ

Lumen width classes

0.00 - 20.00 μ

20.01 - 30.00 μ

30.01 - 40.00 μ

40.01 - 50.00 μ

Greater than 50.01 μ

Cell diameter classes

0.00 - 20.00 μ

20.01 - 30.00 μ

30.01 - 40.00 μ

40.01 - 50.00 μ

Greater than 50.01 μ

Cell wall percentage

0.00 - 20.00 %

20.01 - 30.00 %

30.01 - 40.00 %

40.01 - 50.00 %

50.01 - 60.00 %

60.01 - 70.00 %

Greater than 70.01 %

Recently Lantican (1972) and Paraskevopoulou (1973) have worked on tracheid cross-sectional dimensions of P.caribaea. In their work, the main studies were concentrated on the variation of radial and tangential direction of cell wall thickness and cell lumen separately. It is assumed that average values have a close relationship to both radial and tangential values. Therefore, in this study, the attention was concentrated only on the average variation of these features (average cell wall thickness, average lumen width, average tracheid diameter and cell wall percentage) and in comparison with others factors and its influence on the pulp properties.

4.5 Fibre length, Chemical contents and unbleached pulp evaluation (pulp yield %, burst factor, breaking length and tear factor)

A sub-sample of 20 trees was selected to cover the range of density. Information on fibre length, chemical contents, unbleached pulp evaluation data were provided by the Tropical Products Institute, London Evaluation data and experimental methods in pulping tests and are given in Appendix V.

Each tree was chipped separately and subjected to four sulphate (Kraft) cooking conditions. Common cooking temperature was 170°C and this was attained after 1 hour. Common sulphidity was 25% Active alkali was varied:- Cook 1, 16.25% and 3 hours cooking, Cook 2, 16-25 and 4 hours, Cook 3, 17.5 and 4 hours, Cook 4, 20.0 and 4 hours. Two duplicate samples for each cook. Each duplicate sample was then beaten for 1, 3, 5 and 7 minutes, with two replicate samples of each beat. Pulps were fabricated into handsheets and strength and other properties evaluated. For burst factor, breaking length and tear factors these values were then adjusted to 500 Canadian Standard Freeness and 35 kappa by the standard technique of interpolation from regressions.

Fibre lengths were estimated in the pulps by Bauer-McNett fractionation (8 classes). It is expected that fibre lengths measured in this way are much shorter on average and more uniform than in the original wood.

4.6 Fibre dimension ratios

From the measurements of cell dimensions a number of ratios were calculated, as follows:

1. Runkel ratio = 2 x cell wall thickness/lumen width
2. Flexibility ratio = cell lumen/cell diameter

   (Rigidity coefficent = 2 x cell wall thickness/cell diameter: this parameter is the complement of fibre flexibility, rigidity coefficient therefore omitted from the analysis).
3. Slenderness ratio = fibre length/cell diameter.
4. Fibre stiffness ratio = fibere length/2 x cell wall thickness.
5. Fibre index = 2 x cell wall thickness x fibre length.

In these various ratios, it should be noted that fibre length was measured from pulp and fibre cross-sectional dimensions were measured from wood.

5. Methods of statistical analysis

5.1 Analysis of variance and variance components

It is not possible to compare the difference (or effect) of sites and plots by analysis of variance of wood properties from the subsample of twenty trees, because the sites and plots have a different number of trees. To examine differences between sites and plots, the breast height density and ring width of the original material (120 trees) was examined by orthogonal analyses of variance using a computer programme developed by Andrew in 1974. The data comprised:

3. sites

2 plots per site at random

20 trees per plot at random

2 radii from breast height at random

6 rings per radius.

The mathematical model used is as follows:-

$$Y_{ijklm} = U + Si + Pij + Tijk + Wijl + Rm + (SR)im + (PR)ijm + TRijkm + Eijklm$$

where

Y_{ijklm} = the observed response

U = the effect of the overall mean

S_i = the effect of the ith site

P_{ij} = the effect of the jth plot in the ith site

T_{ijk} = the effect of the kth tree in the jth plot in the ith site

W_{ijkl} = the effect of the lth radius in the kth tree in the jth plot in the ith site

R_m = the effect of the mth ring

E_{ijklm} = residual random error.

i = number of sites

j = " " plots

k = " " trees

l = " " radii

m = " " rings

The analysis of variance format for this model is tabulated below:

Entry number	Source of variance	DF	Expected mean squares
1	Sites (S)	(S-1)	V_E+ptwrVs+trwVp+wrV_T+rVw
2	Plots (P)	S(p-1)	V_E+twrVp+wrV_T+rVw
3	Tress (T)	Sp(t-1)	V_E+wrV_T+rVw
4	Radii (W)	Spt(w-1)	V_E+rVw
5	Ring (R)	(r-1)	V_E+sptwV_R+twV_{PR}+wV_{TR}
6	S x R	(S-1)(r-1)	V_E+ptwV_{SR}+twV_{PR}+wV_{TR}
7	P x R	S(P-1)(r-1)	V_E+twV_{PR}+wV_{TR}
8	T x R	SP(t-1)(r-1)	V_E+wV_{TR}
9	Residential	Spt(w-1)(r-1)	V_E

Appropriate variance comparison: 1:2, 2:3, 3:4, 4:9, 5:7, 6:7, 7:8, 8:9.

For these features analysed, appropriate variance comparisons were made and evaluated. At the same time, variance components were calculated for each source of variation and expressed as percentages of total effects.

In the interpretation of analysis of variance, the estimated components of variance are often more useful than significance levels for assessment of the relative importance of the various sources of variation. Differences between levels of factors when estimated with very large numbers of degrees of freedom, particularly in the case of interactions, may be very small but detected as statistically significant.

5.2 Regression analysis

The most common applications of regression methods have one or both of the following objectives.

(1) To find a mathematical function that can be used to describe the relationship between a dependent variable and one or more independent variables.

(2) To test some hypothesis about the relationship between a dependent variable and one or more independent variables.

Simple regression analysis was used to determine the form of the relationship which gives the best fit between dependent and independent variable. The computer program which was developed by Andrew (1974), tests 12 models

The 12 models were:

1. $y = a + bx$ (simple linear)
2. $y = a + b/x$ (reciprocal)
3. $y = a + bx + cx^2$ (quadratic)
4. $y = a + be^{-cx}$
5. $y = a(1-e^{-bx})$

6. $y = a + bx^c$

7. $y = ax^b$

8. $y = 1/(a + bx)$

9. $y = X/(a + bx)$

10. $y = 1/(a + be^{-cx})$

11. $y = a(1-e^{-bx})^c$

12. $y = X/(a + bx + cx^2)$

where y is the dependent or explained variable, a is the regression constant and b, c are regression coefficients. The goodness of fit of alternative models may be compared by means of the R squared statistic which is a measure of the proportion of variation in the y variable explained by the regression.

Multiple regression analyses were developed for each of the main features to achieve a better understanding of the response of wood characteristics to several independent variables likely to be relevant and also to assess the possibilities for accurate prediction.

The computer programme for multiple regression analyses developed by Andrew (1975), which has been used in this study, included a procedure for successive elimination of non-significant independent variables. The final model included only variables with regression coefficients which were statistically significant at a probability of P = 0.95.

For the regression of dependent and independent variables the following basic model was used:

$$Y = a + b_1X_1 + b_2X^2_1 + b_3X_2 + b_4X^2_2 + b_5X^2_3 + b_6X^2_3$$

where Y is the dependent or explained variable, a is the regression constant and b_1, b_2 ... are regression coefficients, X_1, X_2 ... are the independent variables.

It was considered impractical to record all the relationships tested in the investigation, since many were of little interest and were not statistically significant. For the purposes of this study, only the relationships which were significant from a statistical or practical standpoint were considered. It is also emphasised that a regression description may not be reliable beyond the range of the sample observations used in fitting the equation.

In this study, to describe the relationship between dependent and independent variables, correlation coefficient (R) and coefficient of determination (R^2) was used. It is noted that in this study normally correlation coefficient (R) was used to explain simple linear correlation, and coefficient of determination (R^2) were used to describe the best fit model of simple regression and multiple regression.

To indicate whether the correlation coefficient (R) are significant or not, the following symbols are made:

n.s.	:	not statistically significant
*	:	statistically significant at a probability of P = 0.95
**	:	" " " " " " P = 0.99
***	:	" " " " " " P = 0.999

Chapter 4

VARIATION IN RING WIDTH, LATEWOOD PERCENTAGE AND COMPRESSION WOOD PERCENTAGE

1. Variation in ring width

1.1 Variation as explained by the analysis of variation

The analysis of variance was used to examine the main sources of variations and interactions of ring width for the original data (120 trees). The results of orthogonal analysis of variance with F test and variance components are set out in Table 4.1

Table 4.1: Results of the orthogonal analysis of variances and components of ring width in original data (120 trees)

Source	DF	MS	F. sig.	VC(%)
Sites (S)	2	1753	n.s.	0.84
Plots (P)	3	534.4	***	0.64
Trees (T)	114	69.83	***	1.31
Radii	120	22.34	***	0.79
Rings (R)	5	59480	***	81.57
S x R	10	1527	**	4.80
P x R	15	368	***	2.75
T x R	570	36.07	***	4.63
Residual	600	8.079		2.68

Table 4.1 showed that the differences of mean ring width between the sites were not significant, The variation between the plots in sites was significant, but the variance component was very small (0.64%).

The differences between the mean values for trees within plots were highly significant but only accounted for 1.31% of the total variation. The effect of height levels is not indicated inthis analysis of variance but will be explained in another section in this chapter.

There were significant differences in the mean values for ring width between radii, but in terms of variance component this source of variation is very small (0.79%).

A large amount (81.57%) of the variation was attributed to the effect of ring number. The interactions trees in plots by ring number, plots in sites by ring number and sites by ring number are also very highly significant but accounted for only 4.63%, 2.75% and 4.80% of the total variation respectively. Thus although the relationship of ring width to ring number varies statistically in different trees, plots and sites, these sources are small in relation to the mean ring variation.

1.1.1 Variation of ring width within tree

The variation in ring width within trees can be summarised as below:

1. There were highly significant differences in ring width between radii and between rings within trees and within plots (Table 1).

2. For the sub-sample of 20 trees (pooled data), the general trend of ring width was to decrease rapidly with increasing ring number from the pith to ring number 4, and then gradually to decrease from ring 4 to ring 10. (Table 4.2, Figure 4.1).

3. The changes of ring width with increasing ring number at eight levels were similar. At all levels ring width decreased more rapidly at the first 2 or 3 rings than afterwards (Figures 4.1 and 4.2).

4. Ring width for same ring number but at different height level generally decreased from the base to the top in a non-uniform pattern (Table 4.2, Figure 4.1).

5. Ring width for the same calendar year number but at different height levels, increased with increasing height level from the bottom to top (excepted the 5% height at 1971). (Table 4.3, Figure 4.2).

6. The range of ring width based on year number (calendar year) at different level height was larger than ring width based on ring number (physiological age). (Figures 4.1 and 4.2).

1.1.2 Variation of ring width between trees, between plots and between sites

Differences between the sites were not significant in the analysis of original data (120 trees). There were highly significant differences between trees and between plots, but they accounted for only a small part of the total variation (Table 4.1).

Figure 4.1
PATTERNS OF VARIATION OF RING WIDTH TO RING NUMBER

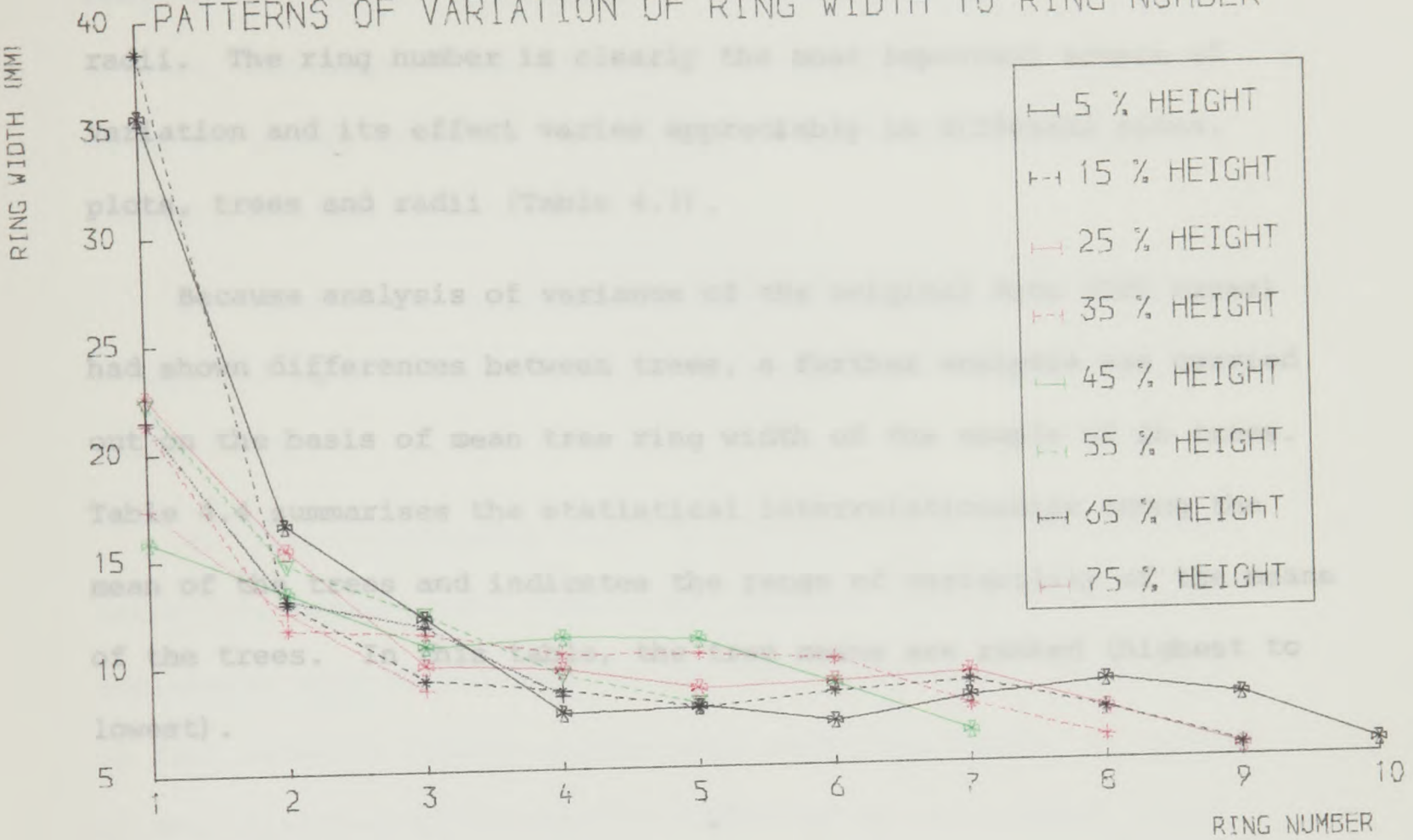
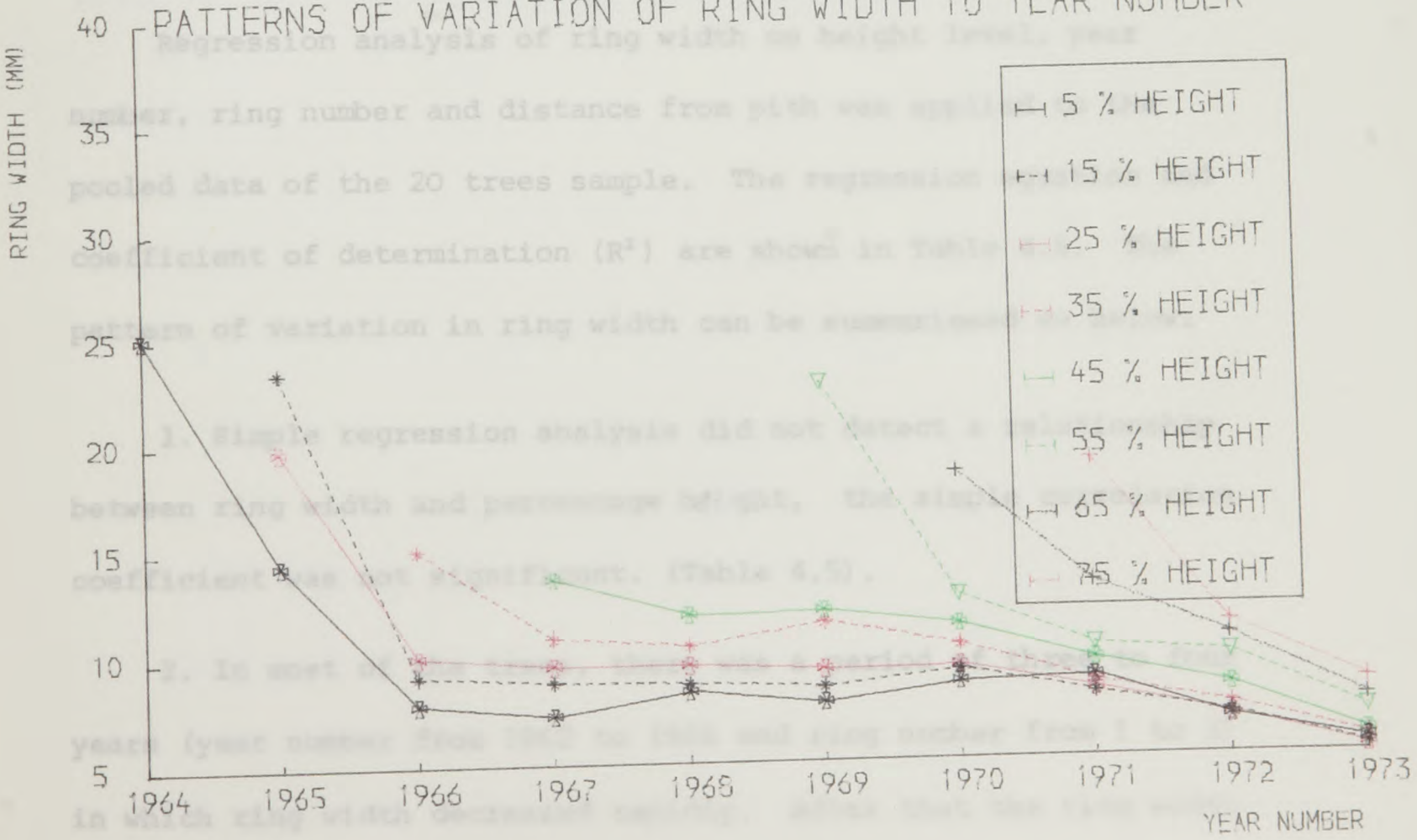


Figure 4.2
PATTERNS OF VARIATION OF RING WIDTH TO YEAR NUMBER



The effects of the interaction tree X ring (T x R), plot X ring (P X R) and site X ring (S X R) were larger than the main effect sources of variation, such as sites, plots, trees and radii. The ring number is clearly the most important source of variation and its effect varies appreciably in different sites, plots, trees and radii (Table 4.1).

Because analysis of variance of the original data (120 trees) had shown differences between trees, a further analysis was carried out on the basis of mean tree ring width of the sample of 2o trees. Table 4.4 summarises the statistical interrelationships among the mean of the trees and indicates the range of variability of the means of the trees. In this table, the tree means are ranked (highest to lowest).

1.2 Variation as explained by regression analysis

Regression analysis of ring width on height level, year number, ring number and distance from pith was applied to the pooled data of the 20 trees sample. The regression equation and coefficient of determination (R^2) are shown in Table 4.5. The pattern of variation in ring width can be summariesed as below:

1. Simple regression analysis did not detect a relationship between ring width and percentage height, the simple correlation coefficient was not significant. (Table 4.5).

2. In most of the trees, there was a period of three to four years (year number from 1962 to 1966 and ring number from 1 to 3) in which ring width decreased rapidly. After that the ring width decreased much less rapidly. This pattern of growth has been reported for many pines and would be expected where during the first

few years each tree is free from competition and the crown extends to the bottom of the tree, giving larger ring widths. At a later stage in growth, when the stand is closing, competition becomes greater, the base of the crown becomes progressively higher and the width of growth rings in the lower bole decreases gradually. (Figures 4.3 and 4.4).

3. Ring width decreased rapidly from the pith outwards to about 41 mm, and then remained more or less the same outward to the bark (Figure 4.5).

4. The relationship shown by multiple regression analysis using year number, ring number and distance from pith was poor, explaining only 40 per cent of the total variation. Ring width in fact showed a closer relationship with ring number, 67 percent of the total variation could be explained by ring number using model 12 (decrease exponential) (Table 4.5).

Table 4.2 Ring width and ring number at different % heights

% height										
75	17.445	12.565	8.815							
65	21.505	13.080	11.735	8.440						
55	22.335	14.755	12.375	9.465	8.005					
45	15.945	13.465	10.930	11.260	11.045	8.835	6.535			
35	21.405	11.765	11.455	10.420	10.320	9.975	7.720	6.130		
25	22.640	15.470	9.960	9.695	8.720	8.935	9.270	7.455	5.555	
15	38.540	12.950	9.250	8.665	7.775	8.435	8.820	7.390	5.630	
5	35.590	16.565	12.155	7.625	7.830	7.025	8.115	8.715	7.925	5.605
Ring No.	1	2	3	4	5	6	7	8	9	10
Mean	24.426	13.827	10.834	9.367	8.949	8.641	8.092	7.423	6.370	5.605

Table 4.3 Ring width and year number at different % heights.

% height										
75								18.855	11.195	8.485
65							18.330	13.090	10.560	7.610
55						22.665	12.630	10.240	9.790	7.095
45				13.700	11.960	12.050	11.305	9.590	8.320	6.040
35			15.105	10.930	10.500	11.495	10.335	8.550	7.375	5.820
25		19.795	10.105	9.630	9.590	9.290	9.360	8.200	6.880	5.310
15		23.420	9.175	8.810	8.695	8.435	9.120	7.940	6.910	5.335
5	25.155	14.420	7.850	7.285	8.310	7.710	8.535	8.705	6.730	5.600
Year No.	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973
Mean	25.155	19.212	10.559	10.071	9.811	11.941	11.374	10.646	8.470	6.412

Table 4.4 Ranking order of trees ring width , tree statistical interrelationship and ranges of between tree-variation (mean tree ring width)

Studentized range test P.05

Rank	Tree number	Ring width (mm)
1	6	15.52
2	5	14.11
3	20	13.93
4	7	12.55
5	15	12.44
6	8	12.31
7	1	12.28
8	17	11.92
9	14	11.54
10	2	11.23
11	16	11.19
12	9	10.73
13	18	10.66
14	10	10.58
15	11	10.43
16	3	10.04
17	4	9.84
18	19	9.81
19	13	9.75
20	12	9.47

$SE_{\bar{x}}$ = 0.3053 mm

Mean covered by the same vertical line are not significantly different ($P < 0.05$)

Table 4.5

Regression of ring width on year number, ring number and distance from pith in pooled data.

Independent variable	Regression of best fit model	R^2
Year number	$y = x/(5502406-5625.24x+1.437702x^2)$	0.422
Ring number	$y = x/(-0.06978+0.09832x+0.006319x^2)$	0.668
Distance from pith	$y = 5.389+26.37e^{-0.02931\ x}$	0.412

Simple correlations of ring width with % height, year number, ring number and distance from pith.

Variable	R	Sig
% height	0.0493	n.s
Year number	-0.5969	***
Ring number	-0.5473	***
Distance from pith	-0.5610	***

Coefficients of determination (R^2) for multiple regressions of ring width.

Independent variables	R^2	Sig
Year number , ring number , distance from pith	0.395	***
Ring number , distance from pith	0.394	***

Figure 4.3

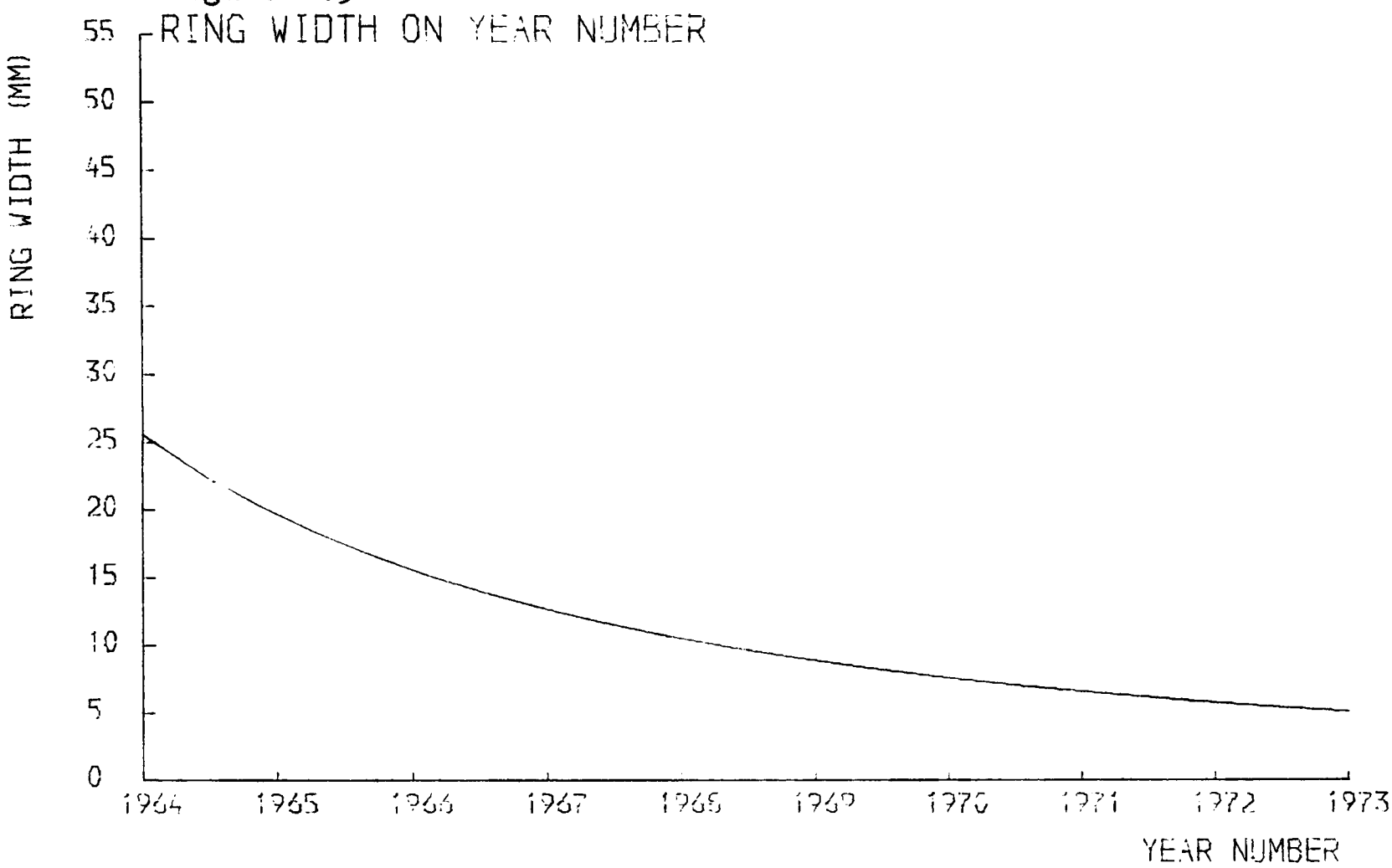


Figure 4.4

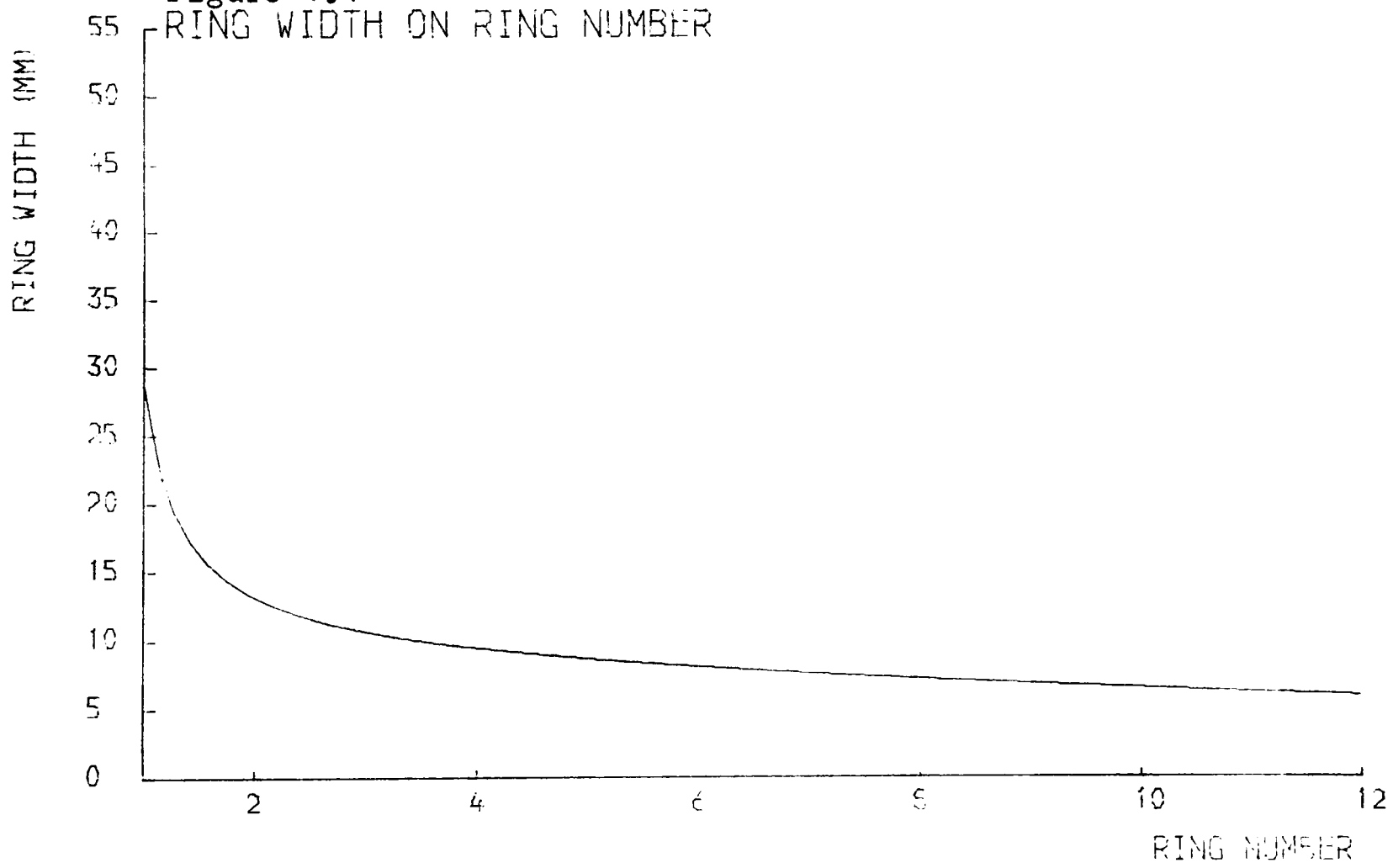
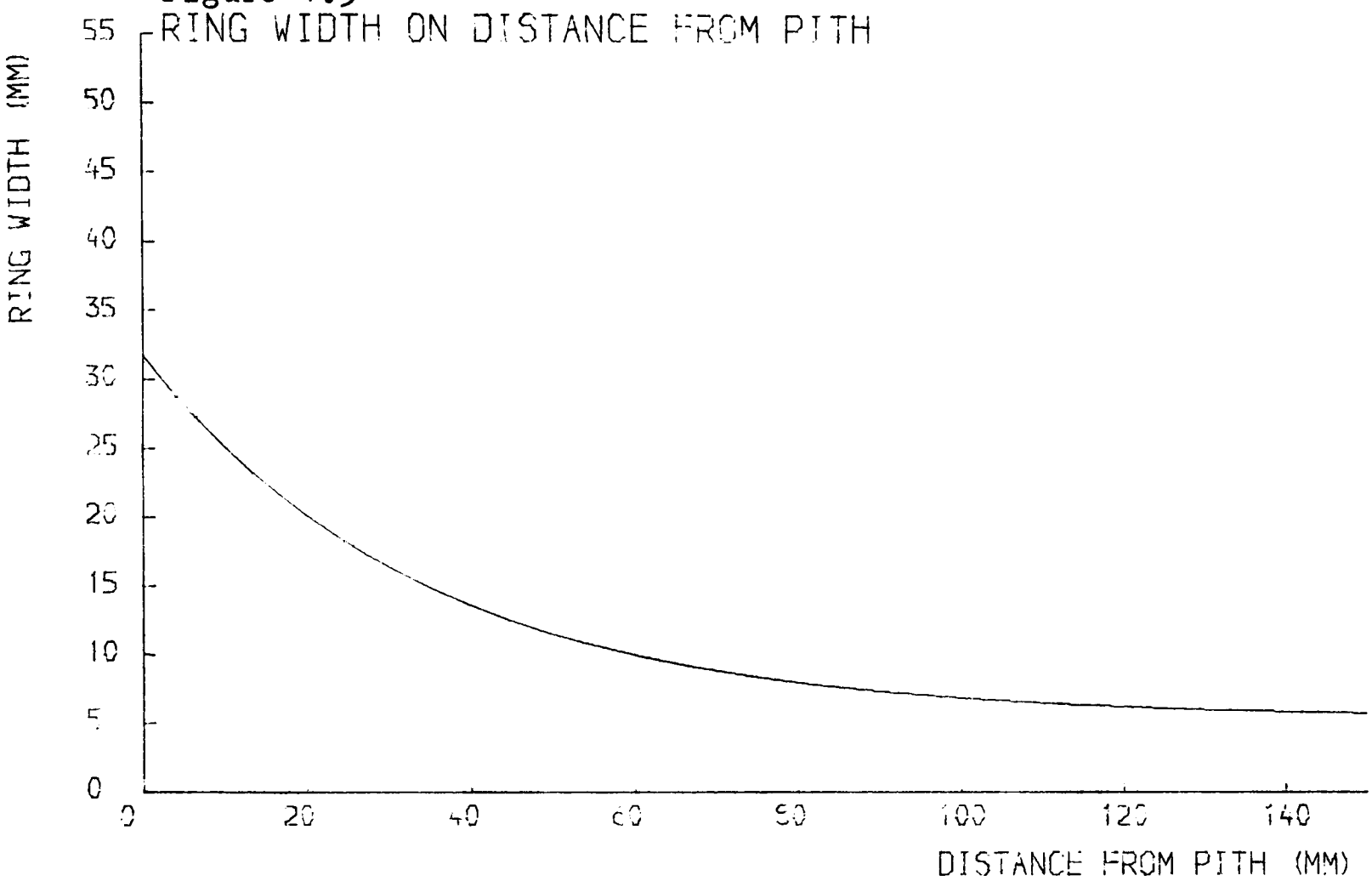


Figure 4.5


RING WIDTH ON DISTANCE FROM PITH
RING WIDTH (MM)
55
50
45
40
35
30
25
20
15
10
5
0
0
20
40
60
80
100
120
140
DISTANCE FROM PITH (MM)

2. Latewood percentage

In this study, variation in latewood percentage was examined only by regression analysis, and the results are presented in Table 4.6. The measurements of latewood percentage in each level in each tree and values for whole tree means are presented in Appendix IV .

Table 4.6

SUMMARY OF CORRELATION COEFFICIENTS (R) AND SIGNIFICANCE TEST OF LATEWOOD PERCENTAGE AND INDIVIDUAL VARIABLES (linear relationships)

1. Weighted disc % latewood

Variable	R	Sig.
% height of total tree (160 discs)	-0.416	***

2. Weighted whole tree % latewood

Variables	R	Sig.
D.B.H (20 trees)	-0.4012	ns
Tree height (20 trees)	0.0457	ns
Crown width (20 trees)	-0.0859	ns
Crown length (20 trees)	-0.2039	ns

3. Multiple correlation coefficient of D.B.H., tree height, crown width and length = $R^2 = 0.35, R = 0.59$, n.s.

Latewood percentage was not significantly correlated with tree size (D.B.H., tree height, crown width and length) or a combination of these parameters. However, it was negatively correlated with tree % height sampling from 5% height at the base to 75% height at the top.

To consider the effect of size and certain morphological factors on latewood %, it is interesting to note that crown length explained more of the variation in latewood per cent than crown width. Furthermore the partial correlation between the two was negative. This was contradictory to the result of Brown (1969) who found that latewood percentage was positively correlated to both crown length and crown width, although these correlations were not statistically significant. It is impossible to explain this occurrence from the information available for this study. However, this is a point that could be of importance in pruning practice (depending whether a high or low proportion of latewood is desirable for a particular end use) and should be investigated.

3. Compression wood percentage

In this section the weighted disc and whole tree compression wood percentage are examined in relation to diameter at breast height, tree height, crown width, crown length and percentage height of tree. The results are presented in Table 4.7 and in Table Appendix IV.

Table 4.7: SUMMARY OF CORRELATION COEFFICIENTS (R) AND SIGNIFICANCES TEST OF COMPRESSIONS WOOD PERCENTAGE WITH INDIVIDUAL VARIABLES (linear relationships).

1. Weighted disc % compression wood		
Variable	R	Sig.
% height of tree (160 discs)	0	ns
2. Weighted whole tree % compression wood		
Variables		
D.B.H.	0.30	ns
Tree height	0.049	ns
Crown width	0.216	ns
Crown length	0.437	*

3. Multiple regression of D.B.H., tree height, crown length and crown width

R^2 = 0.31 R = 0.556 Sig = ns

From the results of this study it appears that compression wood percentage is positively correlated, but weakly, with parameters of tree size. Non-significant differences were observed for between disc comparisons, indicating that compression wood percentage was not specifically related to different height levels in trees.

In general, the results indicated that crown length and diameter at breast height were the most important factors explaining the variation in compression wood percentage. Previous studies have also suggested that the high incidence of compression wood found in slash pine is positively correlated to the rapid growth rate in the juvenile period (Zobel et al, 1971, Zobel and Kellison 1972, Barger et al., 1976).

Chapter 5

VARIATION IN DENSITY

1. Variation as explained by the analysis of variance

In this study an analysis of variance was made for mean ring density from the original data (120 trees, see Chapter 3). The results, with F test (significance) and variance components are summarised in Table 5.1.

TABLE 5.1: RESULTS OF THE ANALYSIS OF VARIANCE AND VARIANCE COMPONENTS OF MEAN DENSITY FROM ORIGINAL DATA (120 trees)

Source	DF	MS	F significance	VC %
Sites	2	1.349	**	12.25
Plots	3	0.02968	ns	0.00
Trees	114	0.08042	***	27.62
Radii	120	0.008836	***	4.35
Rings	5	1.532	***	29.35
S X R	10	0.0956	***	4.98
P X R	15	0.009554	ns	0.42
T X R	570	0.005887	***	6.24
Residual	600	0.003193		14.79

By using the above results a general indication can be obtained of the changes in the radial direction over a wide range of rings, but only at breast height. By using regression analysis, it was

possible to explain variation in both axial and radial direction, as explained in other sections of this chapter.

Table 5.1 showed that there were significant differences between the mean values for density of each of the sites, and the between sites percentage of the variance component was relatively high (12.24%). However, the differences between plots was not significant and the variance component was zero.

The effect of trees in plots in sites was very highly significant, and the variance components of mean tree density was one of the largest sources of variance (27.62%).

The difference between the mean values for radii at the same level (breast height) was very highly significant for all trees, but accounted for only a small part of the total variation (4.35%)

The effect of rings, that is the age or the ring number from the pith outwards, was highly significant for all trees and was a most important source of variation as shown by a variance component of 29.35%.

Of the interactions, sites X rings (S X R) and trees Xrings (T X R) were very highly significant, but plots X rings (P X R) was not significant. All these effects, however, accounted for only a small part of the total variation.

The significance of S * R and T * R indicates that the differences in density at each of the ring positions at breast height (that is differences in the overall within tree pattern of development of density from the pith outwards) varied from tree to tree (6.24%) and site to site (4.98%).

1.1 Variation of density within trees

The principal features of variation in density in the radial and axial direction are summarised below, on the basis of the results of analysis of variance of the original data (120 trees) sampled at breat height and a sub-sample of 20 trees sampled at 10% intervals of total height. For the pooled data of the 20 trees, mean values of density for each ring and each level, are presented in Table 5.2 and Figure 5.1, and similar values for year number in Table 5.3 and Figure 5.2.

1.1.1 Radial variation

The variation in density in the radial direction can be summarised as below:

1. For the original sample of 120 trees, differences in mean ring density within trees were highly significant, and accounted for a large part of the total variation (VC% = 29.35). Ring density was also highly significant difference between trees (VC% = 6.24) and between sites (VC% = 4.98) (Table 5.1).

2. For the 20 trees using pooled data, the general trend was for density to increase progressively and rapidly from the pith outwards to the bark, the mean tree increase in this feature was from 0.43 g/cc in ring number 1 to 0.67 g/cc in ring number 10. (Table 5.2, Figures 5.1 and 5.3).

3. For chronological age, the average patterns of mean year density with increasing year number were similar at eight different height levels. At most of the levels, density increased more rapidly during the first few years than later. Level 5 was the exception. From 1968 to 1970, the rate of increase of

increase of density was reduced and it then increased rapidly again from 1971 onwards. At the 5% and 15% height levels in 1972 to 1973, density slightly decreased, but at level 3 (25% height) to level 8 (75% height) an increase in density was maintained. It should be noted that in this study, some trees only had a half ring in 1973. (Table 5.3, Figure 5.2)

1.1.2 Axial variation

The variation in density in the axial direction can be summarized as below:

1. For most of the 20 trees the maximum weighted density (mean disc density) occurred at the 5% height level, and mean disc density also decreased with increasing height. The rate of decrease in this feature changed quite rapidly between the 5% to 15% and 15% to 25% height levels, and then gradually from the 25% to 75% height level. Mean weighted density at different height levels, for 20 trees pooled, decreased by about 18% from the 5% height (0.6 g/cc) to the 75% height level (0.49 g/cc) (Table 5.4, Figure 5.4).

2. On the basis of fixed year number (Chronological age), mean ring density decreased with increasing height level (Table 5.3, Figure 5.2).

3. On the basis of fixed number of rings (ring number) from the pith, mean ring density generally decreased in the trunk from base to top in a nonuniform way. It is noted that the pattern variation of mean ring density in the axial direction was different

from ring number to ring number. For example, in ring number 1, a slight increase of density occurred from the base upward. For ring number 2, 3, 4, 5 and 6 there was a slight decrease with height and followed by an increase. With ring number 7, 8 and 9 density decreased from the base upward (Table 5.2, Figure 5.1).

4. Within rings, the range of density based on year number (calendar year) at different level height was larger than density based on ring number (physiological age) at different level height. (Tables 5.2 and 5.3, Figures 5.1 and 5.2).

1.2 Variation of density between trees, between plots and between sites

As pointed out in the foregoing results (Table 5.1), differences between sites may be of practical importance, because of the relatively high percentage of this variance component (12.25%), but differences between plots within sites was not significant (0.0%). Differences between trees in plots in the mean values for density at breast height was very significant and was one of the main source of variation (27.62%).

The effects of the interaction trees x rings (T * R) (VC% = 6.24) was larger than plots X ring (P * R) (VC% = 0.42) and sites x rings (S * R) (VC% = 4.98). Both T * R, S * R were very highly significant and accounted for fourth and fifth largest of the total variation. This interaction indicates that ring effects, average at breast height, varied from tree to tree, site to site with it seems, tree effects more influential than site effect.

Table 5.2 Ring density and ring number at different % heights

% height										
75	0.4518	0.4798	0.5088							
65	0.4413	0.4727	0.4988	0.5259						
55	0.4387	0.4718	0.5035	0.5217	0.5367					
45	0.4372	0.4722	0.4886	0.4943	0.5266	0.5530	0.5687			
35	0.4457	0.4683	0.4994	0.5282	0.5150	0.5503	0.5641	0.5802		
25	0.4232	0.4356	0.4789	0.5191	0.5504	0.5486	0.5701	0.6004	0.6124	
15	0.4175	0.4813	0.5124	0.5635	0.6096	0.5906	0.6023	0.6567	0.6349	
5	0.3936	0.4932	0.5506	0.5662	0.6206	0.6761	0.6558	0.6555	0.6801	0.6747
Ring number	1	2	3	4	5	6	7	8	9	10
Mean	0.4311	0.4719	0.5051	0.5313	0.5608	0.5837	0.5922	0.6232	0.6425	0.6747

Table 5.3 Ring density and year number at different % height

% height										
75								0.4681	0.4972	0.5242
65							0.4649	0.4819	0.5184	0.5404
55						0.4504	0.4867	0.5141	0.5311	0.5791
45			0.4701	0.4709	0.4953	0.5077	0.5382	0.5571	0.5943	
35		0.4632	0.4995	0.5106	0.5165	0.5256	0.5556	0.5696	0.6218	
25			0.4367	0.4632	0.5205	0.5356	0.5456	0.5497	0.5954	0.6109	0.6495
15			0.4560	0.5060	0.5557	0.5784	0.5858	0.5925	0.6399	0.6573	0.6429
5		0.4352	0.5427	0.5625	0.6055	0.6515	0.6510	0.6507	0.6811	0.6977	0.6904
Year number		1964	1965	1966	1967	1968	1969	1970	1971	1972	1973
Mean		0.4352	0.4785	0.4988	0.5303	0.5494	0.5408	0.5397	0.5593	0.5800	0.6054

Figure 5.1

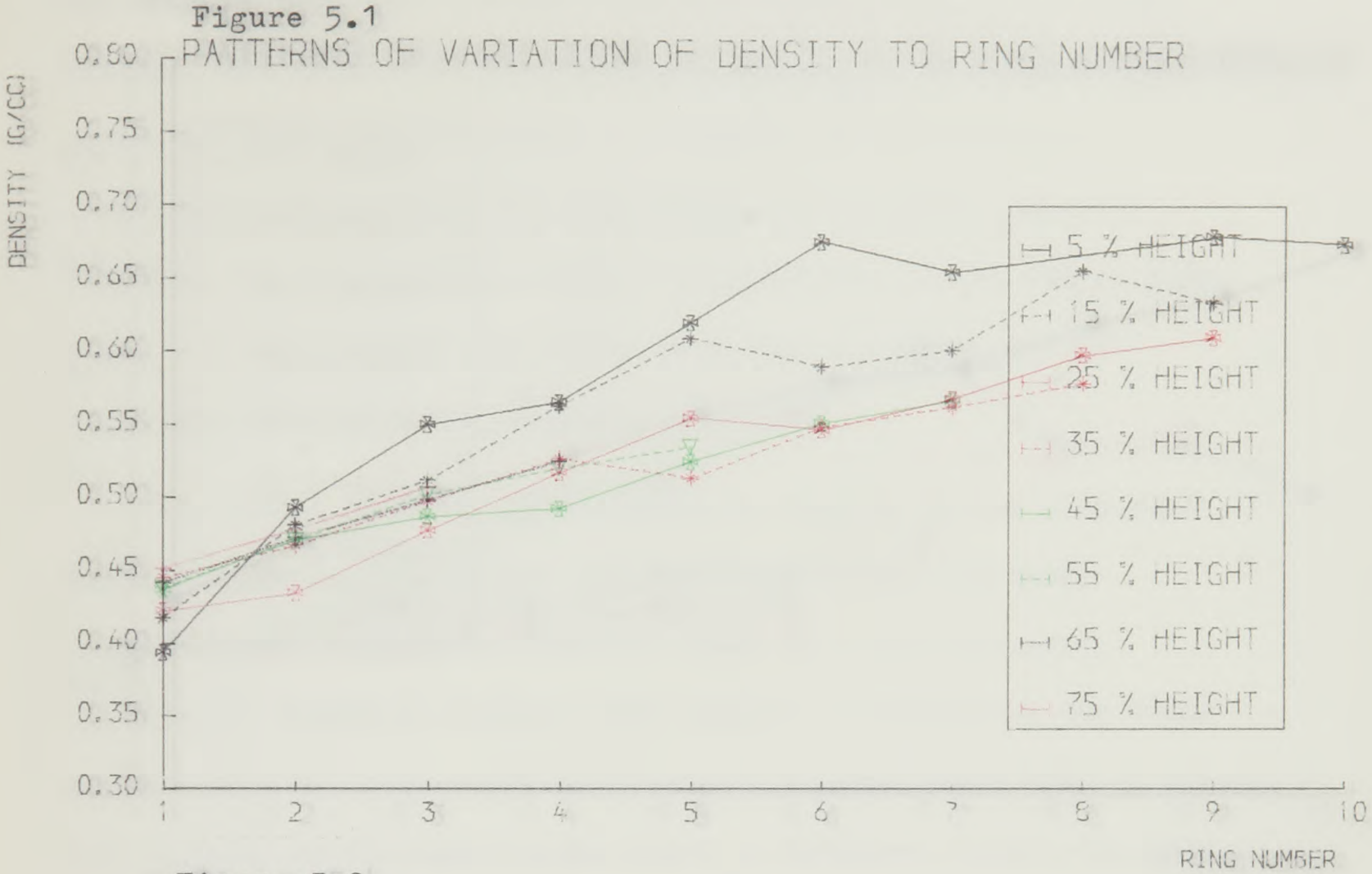


Figure 5.2

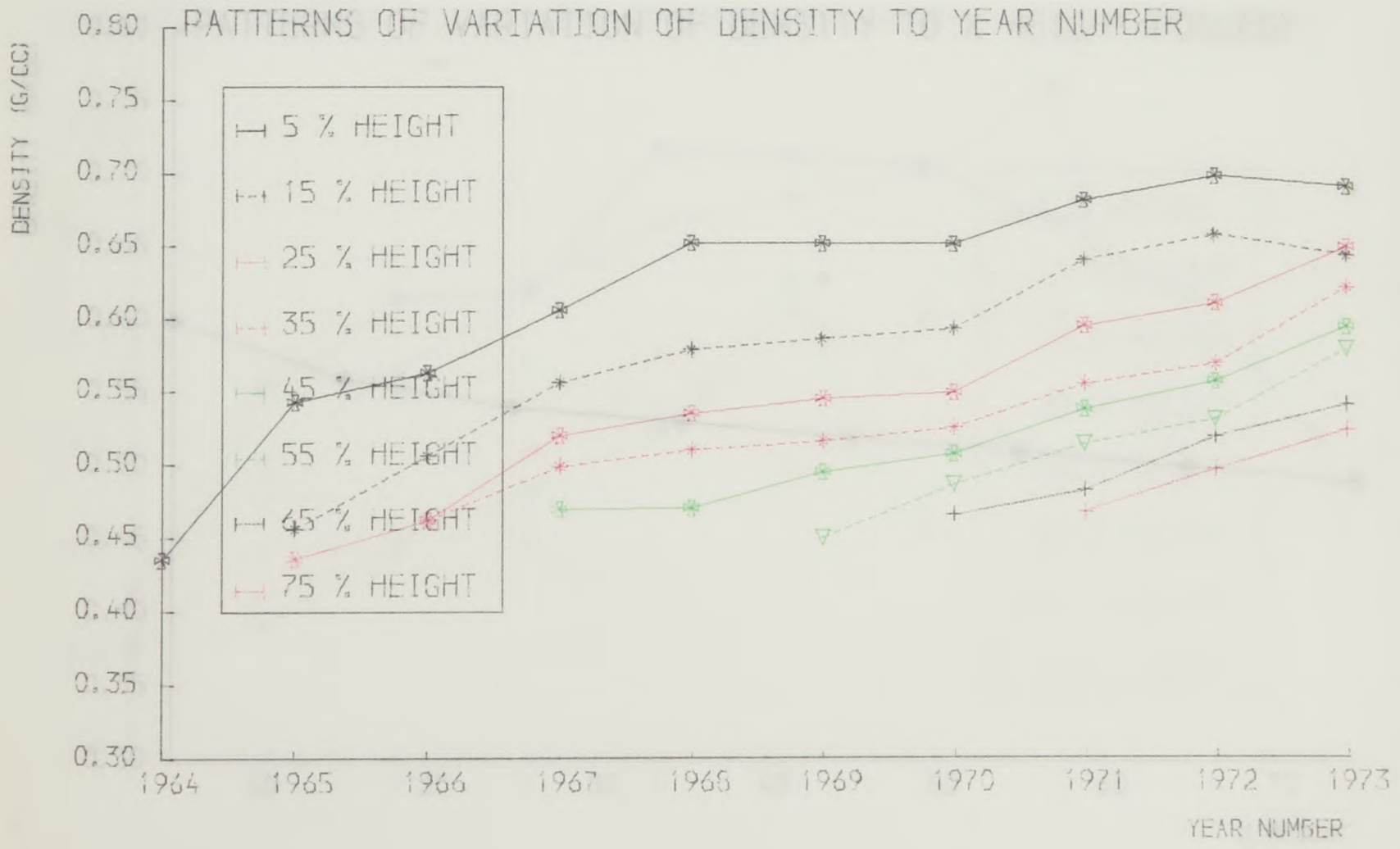


Figure 5.3

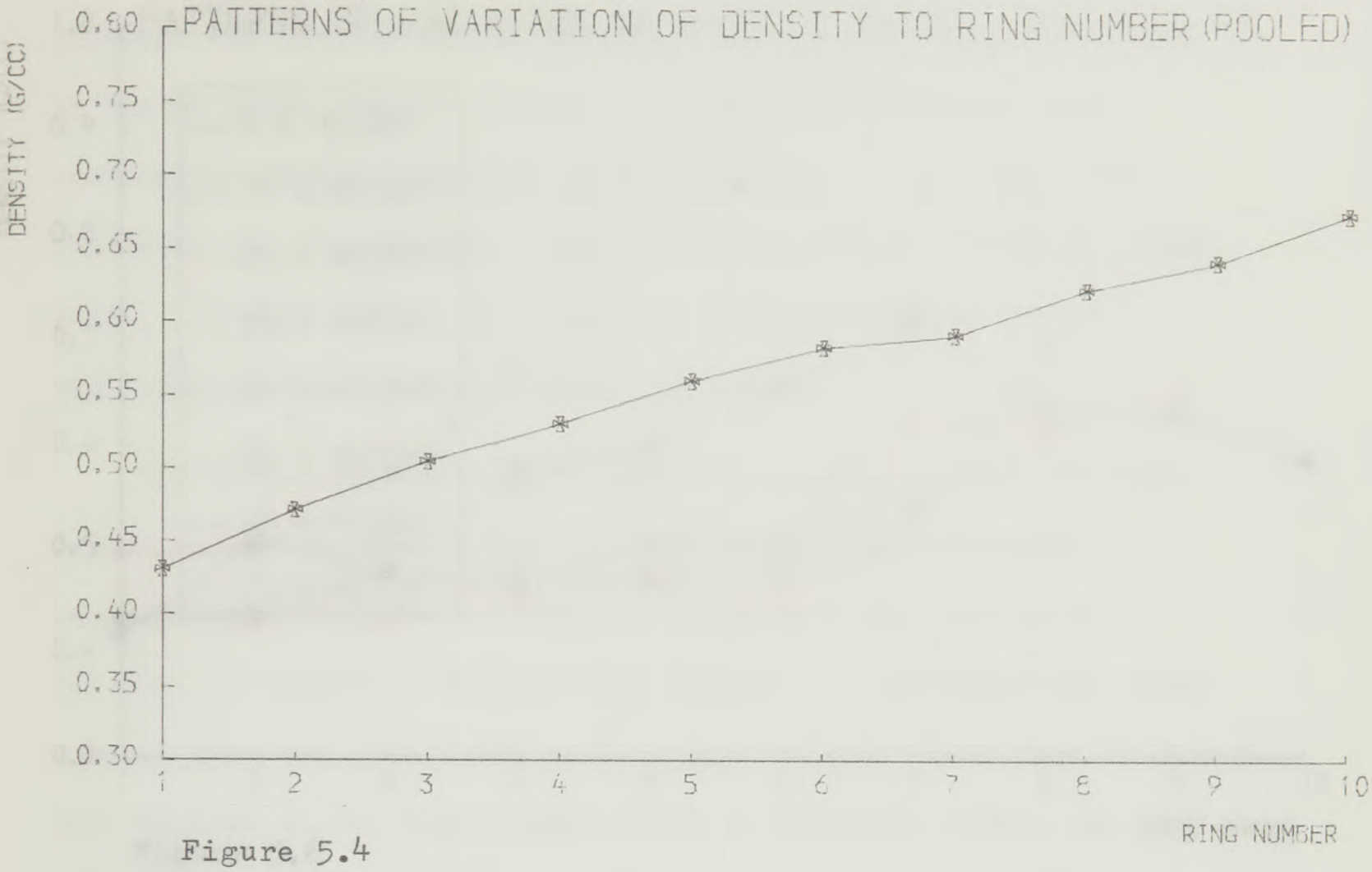


Figure 5.4

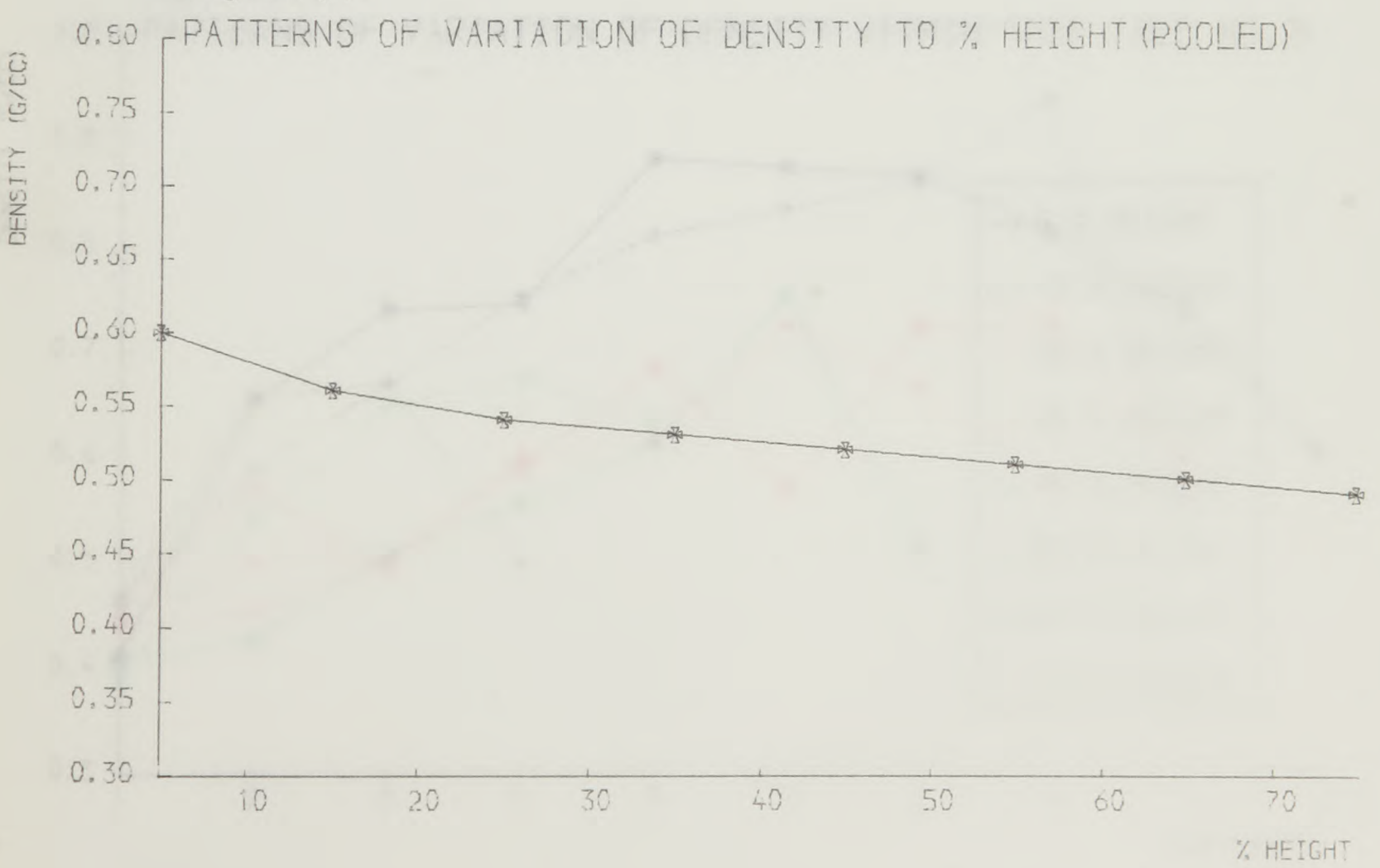


Figure 5.5

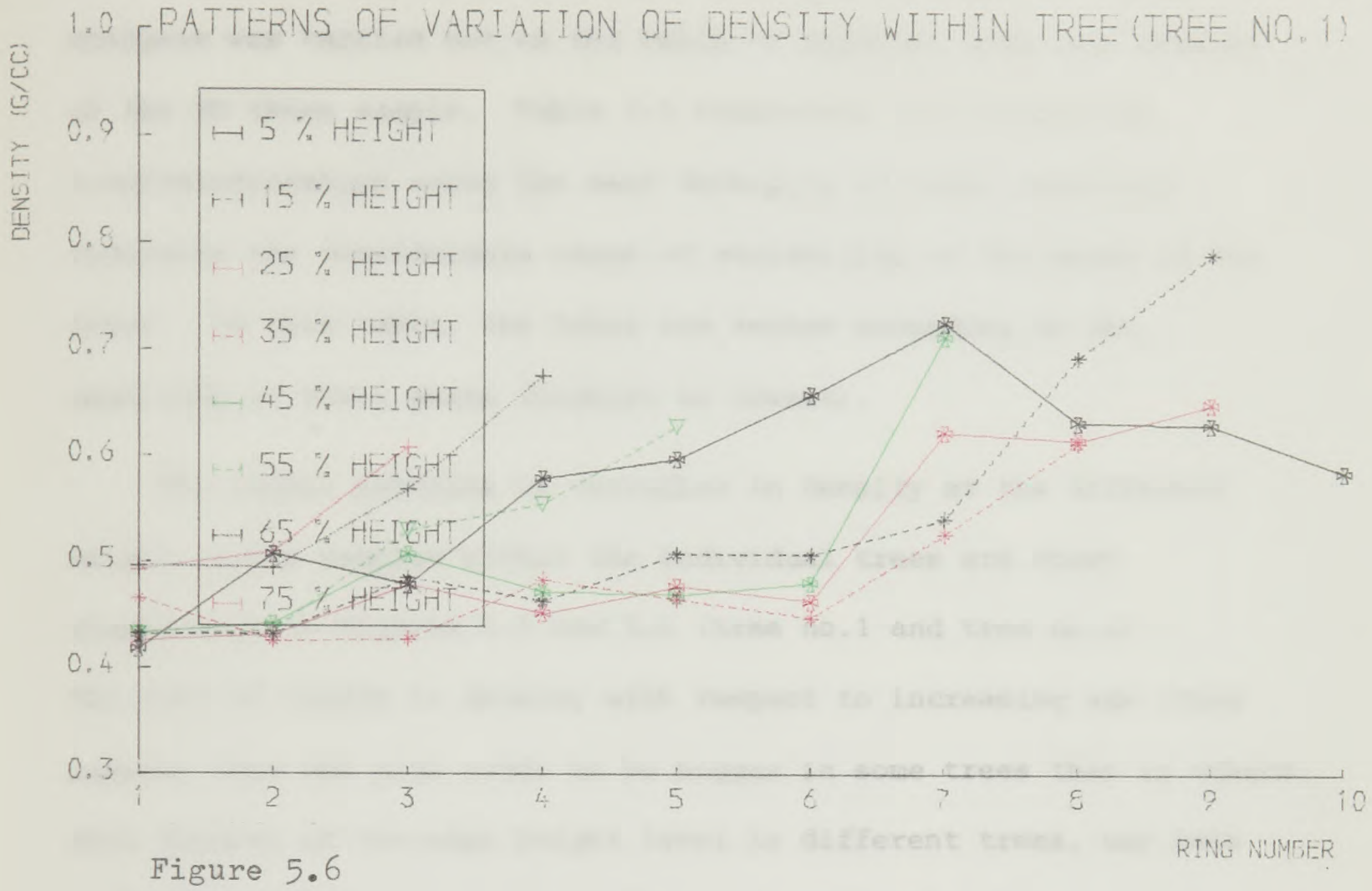
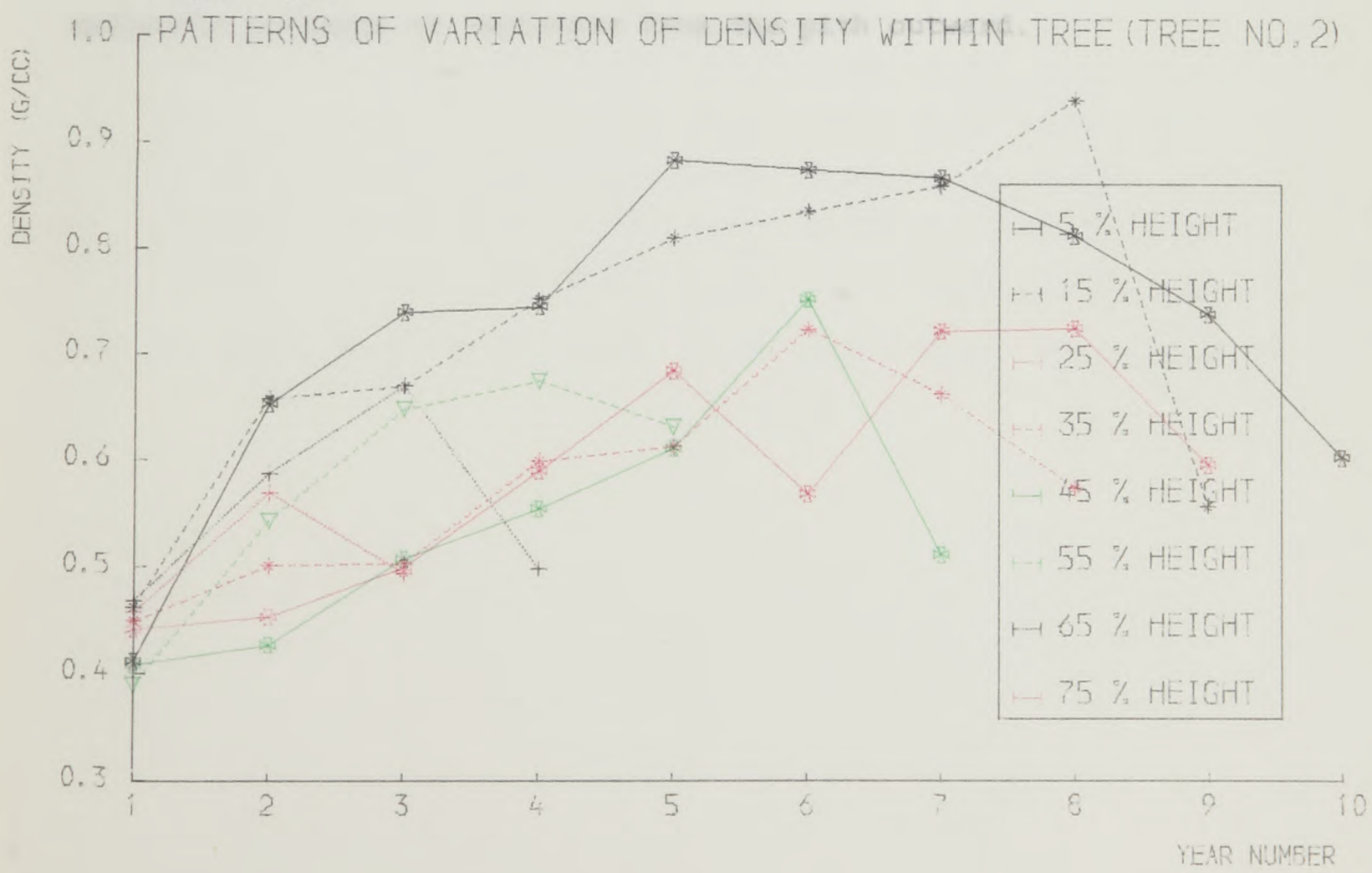


Figure 5.6



Because analysis of variance of the original data (120 trees) had shown differences between sites and between trees, a further analysis was carried out on the basis of weighted tree mean density of the 20 trees sample. Table 5.5 summarises the statistical interrelationships among the mean densities of these trees and indicates the considerable range of variability of the means of the trees. In this table, the trees are ranked according to the magnitude of their means (highest to lowest).

The radial patterns of variation in density at the different height levels sampled within the individual trees are shown graphically in Figures 5.5 and 5.6 (tree no.1 and tree no.2). The rate of change in density with respect to increasing age (ring number) from the pith tends to be bigger in some trees than in others. Ring density at the same height level in different trees, may have different patterns of variation from the pith outward.

Table 5.4 Mean weighted density at different % heights

% height		5	15	25	35	45	55	65	75	Tree mean
Tree	number									
1	D1-6	0.56	0.51	0.51	0.49	0.50	0.52	0.57	0.53	0.52
2	D1-57	0.73	0.73	0.59	0.59	0.55	0.55	0.56	0.50	0.63
3	D1-71	0.68	0.62	0.55	0.52	0.54	0.49	0.49	0.47	0.57
4	D2-11	0.70	0.66	0.63	0.62	0.55	0.59	0.55	0.53	0.63
5	NH1-24	0.51	0.45	0.43	0.46	0.42	0.38	0.38	0.37	0.44
6	NH1-40	0.48	0.48	0.42	0.43	0.43	0.37	0.38	0.45	0.44
7	NH1-44	0.63	0.60	0.52	0.54	0.49	0.52	0.48	0.49	0.55
8	NH1-51	0.57	0.52	0.50	0.48	0.48	0.46	0.44	0.45	0.51
9	S1-8	0.65	0.56	0.58	0.51	0.50	0.52	0.44	0.48	0.56
10	S1-31	0.62	0.55	0.52	0.59	0.58	0.58	0.44	0.48	0.56
11	S1-36	0.62	0.58	0.57	0.56	0.51	0.52	0.47	0.50	0.56
12	S1-45	0.78	0.77	0.72	0.69	0.68	0.62	0.64	0.64	0.72
13	S1-55	0.49	0.48	0.51	0.48	0.47	0.45	0.43	0.42	0.48
14	S1-64	0.49	0.47	0.49	0.51	0.52	0.52	0.50	0.45	0.49
15	S2-1	0.48	0.46	0.46	0.44	0.39	0.36	0.40	0.42	0.44
16	S2-6	0.53	0.54	0.52	0.56	0.59	0.58	0.65	0.61	0.55
17	S2-37	0.61	0.55	0.53	0.50	0.51	0.48	0.46	0.48	0.54
18	S2-51	0.58	0.55	0.59	0.55	0.52	0.55	0.49	0.52	0.55
19	S2-79	0.67	0.61	0.67	0.61	0.64	0.61	0.67	0.59	0.64
20	S2-84	0.65	0.57	0.57	0.53	0.56	0.54	0.52	0.51	0.58
Average mean		0.60	0.56	0.54	0.53	0.52	0.51	0.50	0.49	0.55

Table 5.5 Ranking order of trees ,tree statistical interrelationships and ranges of between tree variation (weighted density)

Studentized range test P.05

Rank	Tree number	Density(g/cc)
1	12	0.7212
2	19	0.6405
3	4	0.6339
4	2	0.6258
5	20	0.5755
6	3	0.5684
7	11	0.5649
8	10	0.5643
9	9	0.5576
10	18	0.5543
11	7	0.5539
12	16	0.5536
13	17	0.5350
14	1	0.5221
15	8	0.5070
16	14	0.4921
17	13	0.4796
18	5	0.4416
19	6	0.4413
20	15	0.4383

Highest mean value : 0.72 g/cc

Lowest mean value : 0.44 g/cc

Range : 0.28 g/cc

Standard error of a mean = 0.0089

Numbers subtended by the same vertical line refer to the trees whose mean are not significantly different from each other.

2. Variation as explained by simple regression analysis

In order to describe the pattern of variation of mean ring density from the bottom to the top of the tree, and from the pith outwards, simple regression analysis of mean density on height level, distance from pith, ring number (physiological age), year number (calendar year in which the wood was form or chronological age) and ring width were applied, with pooled data from all 20 trees and with pooled data from each site separately (Drasa : 4 trees, Nausori Highland:4 trees, Seaqaqa12). The regression and coefficients of determination (r^2) obtained for pooled data and sites are shown in Table 5.6 and the patterns of variation illustrated in Figures 5.7 - 5.11. The results may be summarised as follows:

1. Considering the variation of density with height level in the tree, with pooled data from 20 trees the regression line showed that density decreased slightly from 5% to 35% height, with very little further decrease to the 75% height. In some trees, however, (S1-64) density decreased to a certain level in the stem and increased afterwards. Tree S2-6 showed a density increase from the bottom to top. There was no general well marked trend of variation with height, as it is apparent from the low values of the coefficient of determination for these regressions (Figure 7).

2. With pooled data for each site separately, for Drasa and Seaqaqa there was a steady increase in density with increasing year number, but with the Highland site, there was little increase in density from 1964 to 1968 and after 1968 density increased rapidly. (Figure 8).

3. The regression of density on ring number with pooled data from 20 trees showed that density increased uniformity from ring 1 to ring 12. At Drasa site, where the trees had the highest

density, the regression line showed an increase from ring 1 to ring 9. then density remained more or less the same to ring 12. Seaqaqa. data showed that density increased steadily from ring 1 to ring 12. Nausori Highland showed a density trend with little increase from ring 1 to ring 12. It is obvious that density increased more rapidly for the first few rings than afterwards in all sites. (Figure 9).

4. The regression of density on ring width showed that density decreased with increasing ring width to a width of 20 mm (except Drasa to 30 mm), and then remained steady. In the 20 to 30 mm range data, however represented only a few points, normally from the first few rings in the tree. (Figure 10).

5. The regression of density on distance from the pith showed, for all data pooled that density increased from the pith outwards to the 110 mm position, and then there was very little increase outwards. Nausori Highland and Seaqaqa (the two less dense sites) showed that density increased constantly from pith outwards to the bark (note here that this is the regression line, not the actual data). Of the trees in Drasa site, the maximum distance from pith (one tree) was only about 115 mm. It seems likely that the trend showing a decrease in density after a maximum had been reached is caused by the inadequacy of this simple regression and in particular the cubic model to describe the variation in density for the pith outwards in this species. (Figure 11).

Figure 5.7

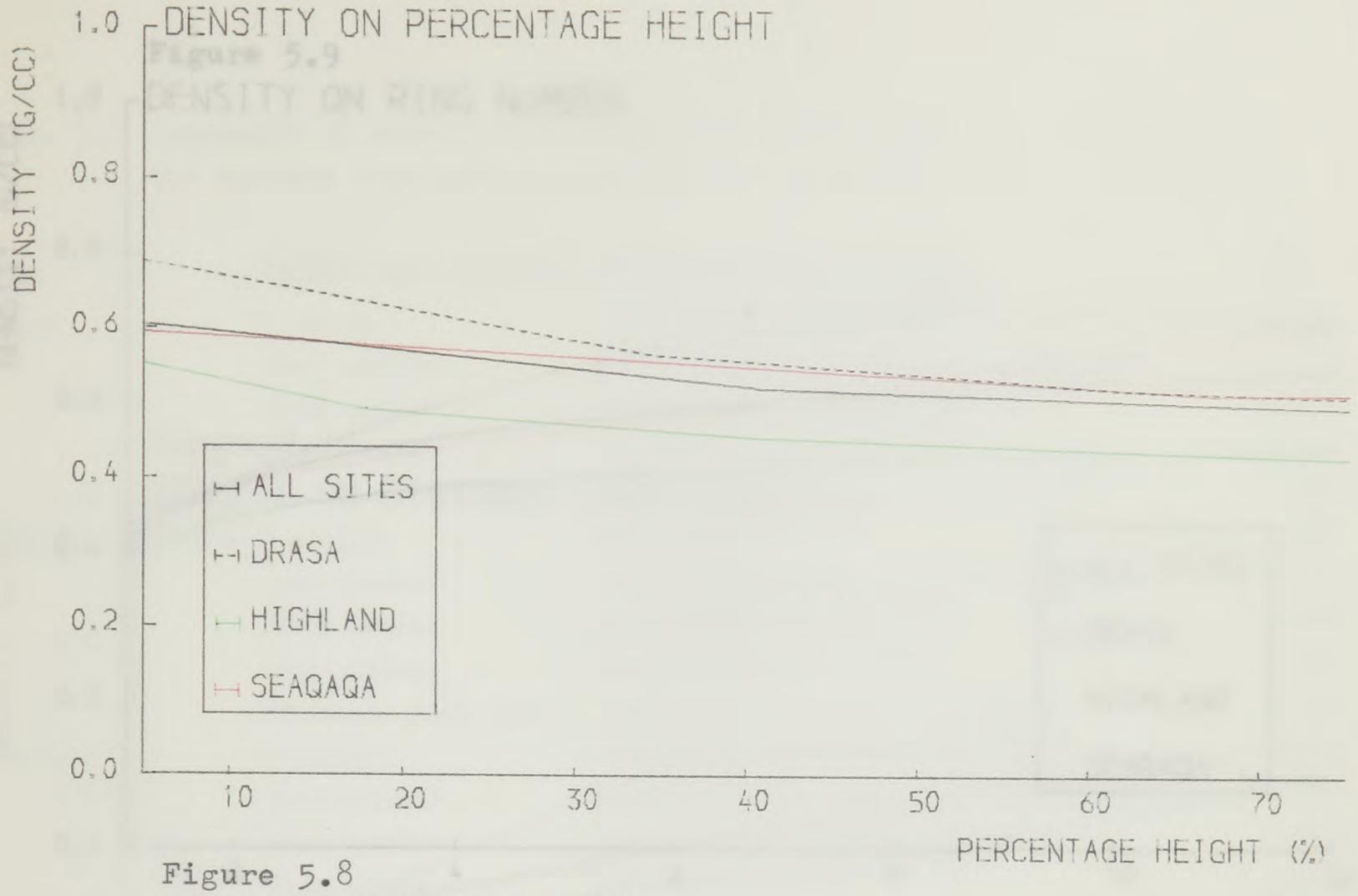


Figure 5.8

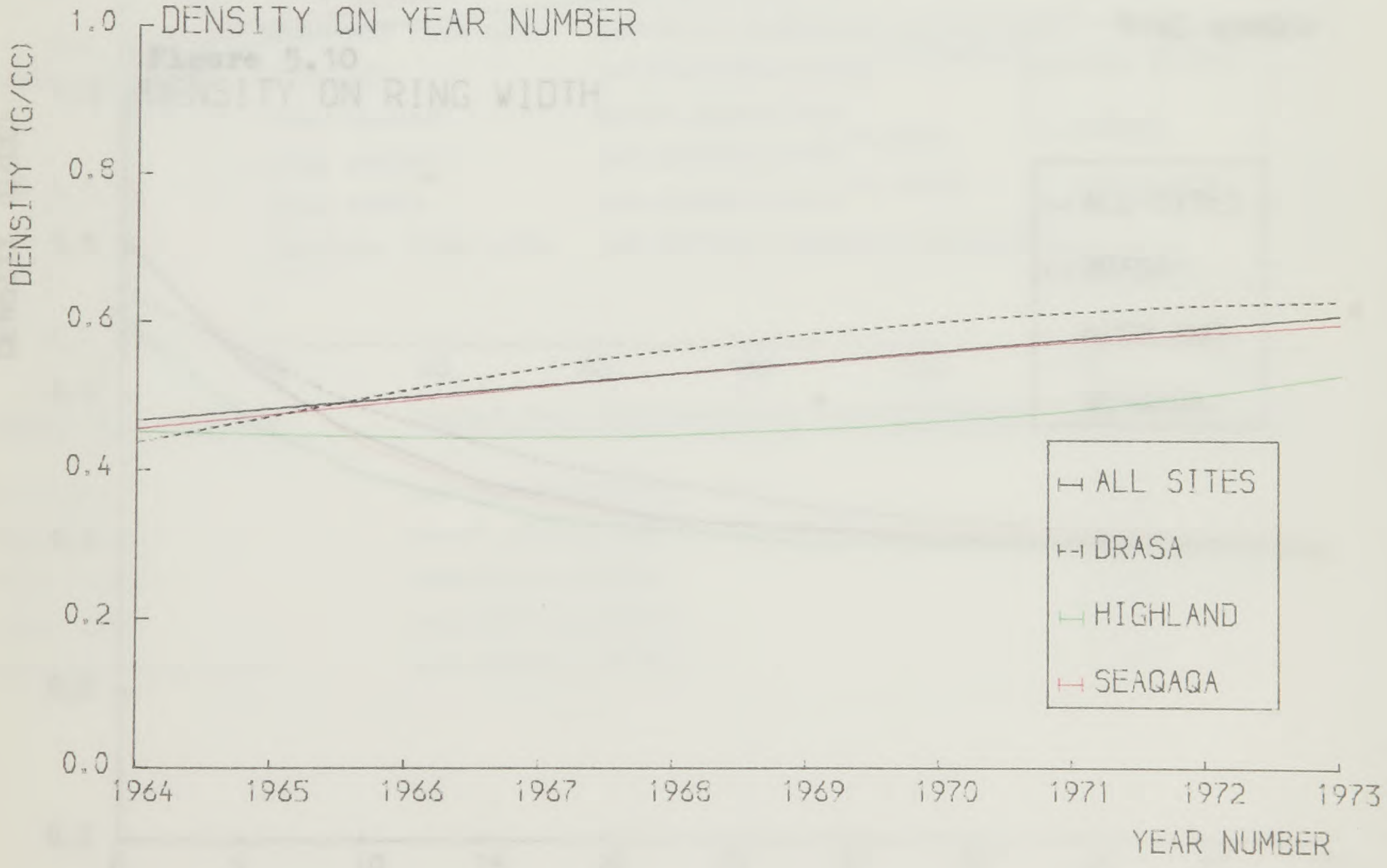


Figure 5.9

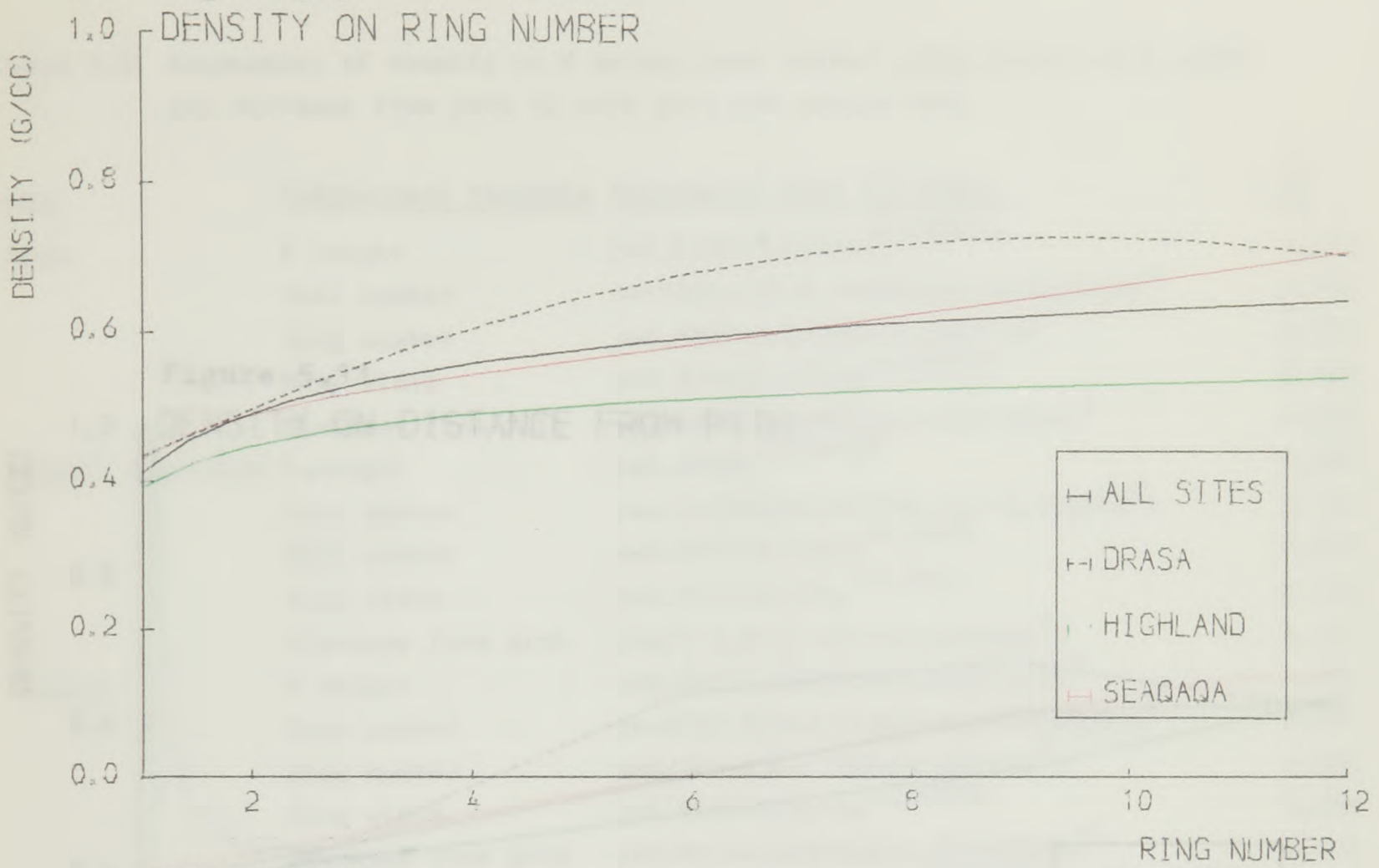


Figure 5.10

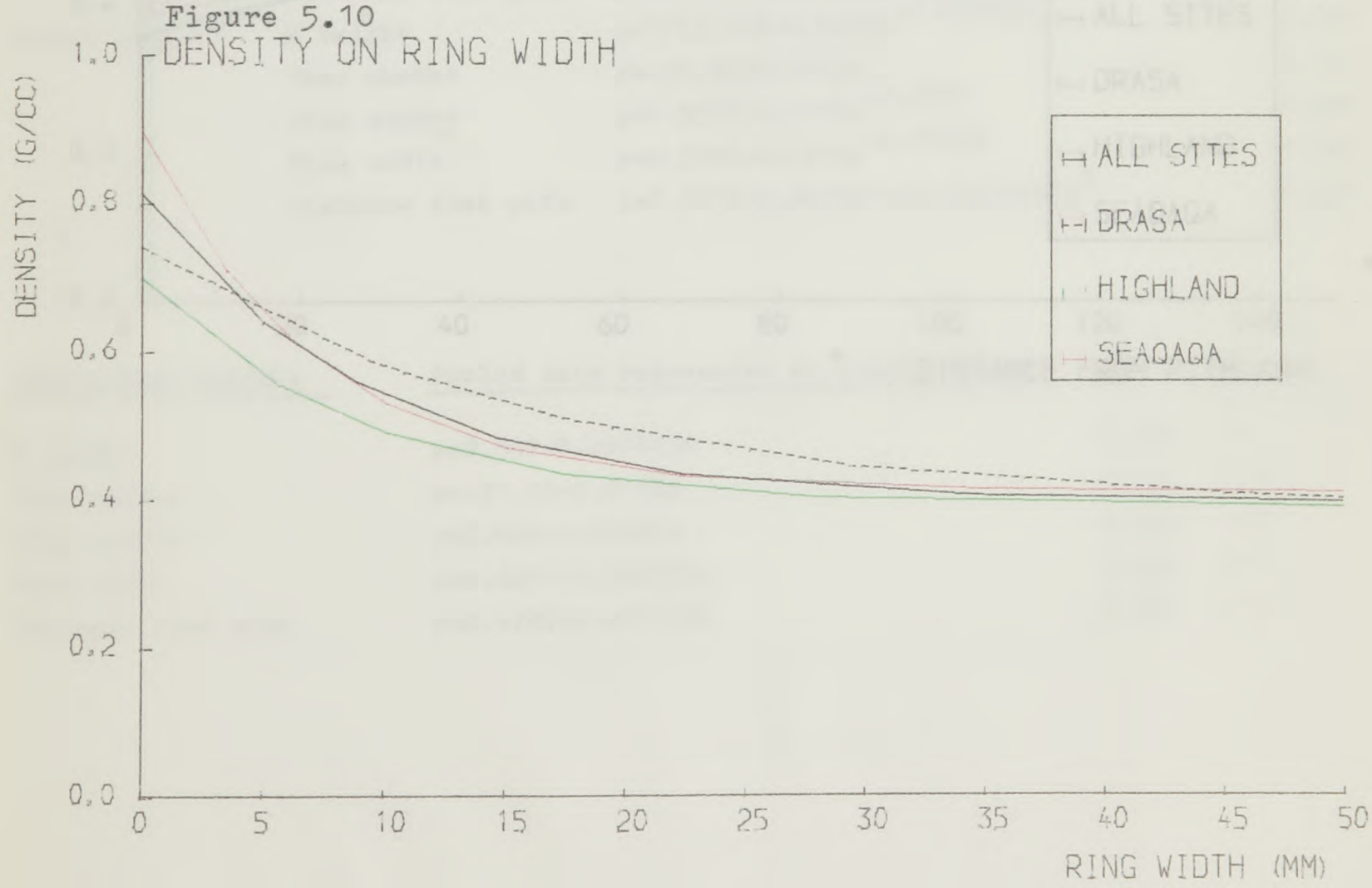


Figure 5.11

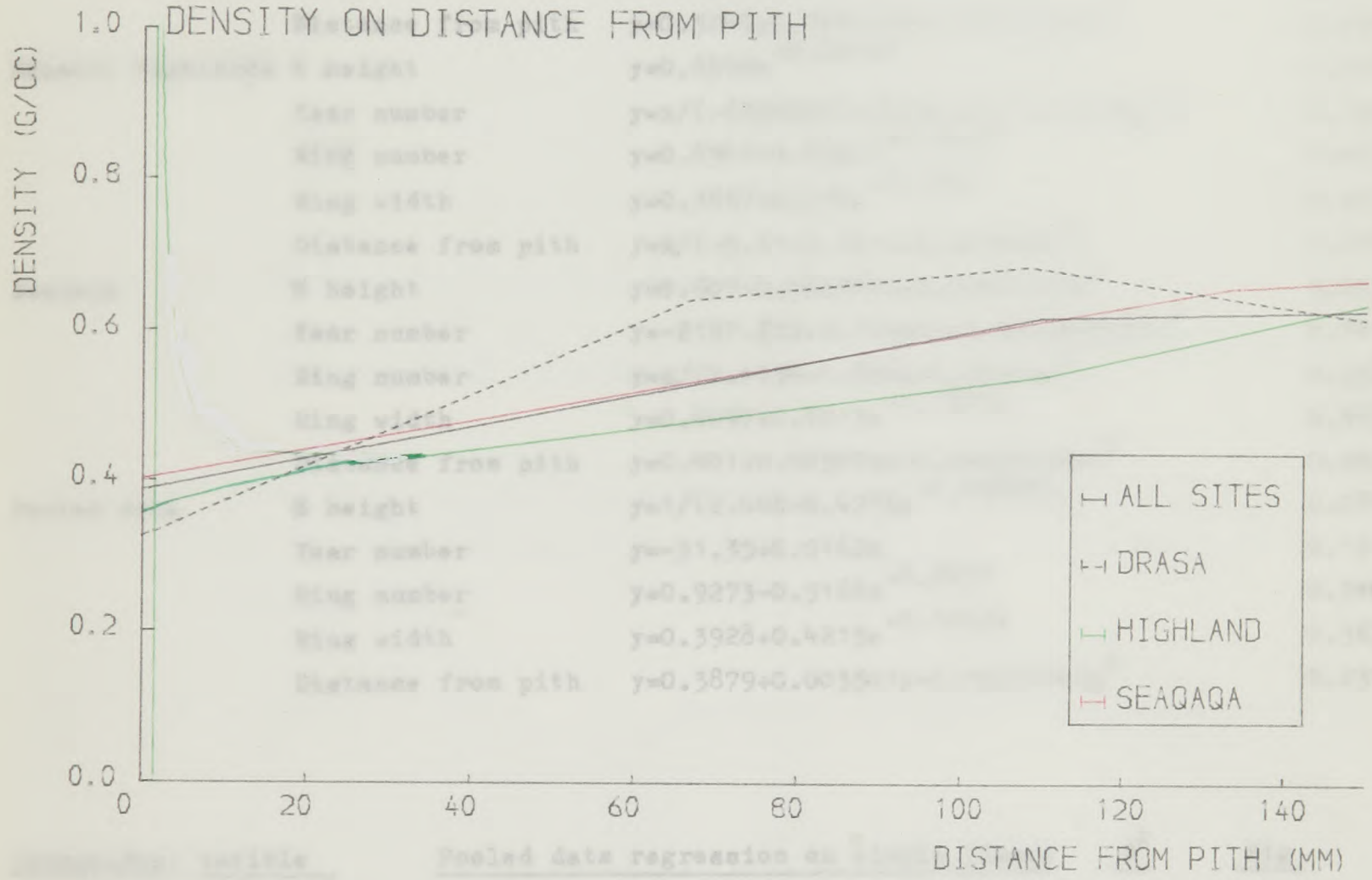

DENSITY ON DISTANCE FROM PITH
DENSITY (G/CC)
1.0
0.8
0.6
0.4
0.2
0.0
0
20
40
60
80
100
120
140
DISTANCE FROM PITH (MM)
ALL SITES
DRASA
HIGHLAND
SEAQAQA

Table 5.6 Regression of density on % height, year number, ring number, ring width and distance from pith in each site and pooled data.

Site	Independent variable	Regression best fit model	R^2
Drasa	% height	$y=0.4928+0.2319e^{-0.03344x}$	0.215
	Year number	$y=-7999.237+8.106143x-0.002053457x^2$	0.150
	Ring number	$y=0.3587+0.07834x-0.004118x^2$	0.565
	Ring width	$y=0.3799+0.3616e^{-0.05891x}$	0.327
	Distance from pith	$y=0.3246+0.007016x-0.00003362x^2$	0.453
Nausori Highlands	% height	$y=0.6399x^{-0.09128}$	0.207
	Year number	$y=x/(-63069510+64154.4x-16.31334x^2)$	0.126
	Ring number	$y=0.6542-0.2597x^{-0.3463}$	0.402
	Ring width	$y=0.3897+0.314e^{-0.1096}$	0.337
	Distance from pith	$y=x/(-3.61+2.661x-0.007205x^2)$	0.276
Seaqaqa	% height	$y=0.607-0.002547x+0.00001772x^2$	0.053
	Year number	$y=-2127.272+2.145561-0.0005408337x^2$	0.141
	Ring number	$y=x/(0.4634+1.894x-0.04409x^2)$	0.332
	Ring width	$y=0.4097+0.4913e^{-0.1377x}$	0.365
	Distance from pith	$y=0.401+0.003072x-0.000008329x^2$	0.266
Pooled data	% height	$y=1/(2.068-0.4773e^{-0.02802x})$	0.087
	Year number	$y=-31.35+0.0162x$	0.131
	Ring number	$y=0.9273-0.5168x^{-0.2437}$	0.340
	Ring width	$y=0.3928+0.4215e^{-0.1052x}$	0.363
	Distance from pith	$y=0.3879+0.003501x-0.0000124x^2$	0.237

Independent varible	Pooled data regression on simple linear	R^2	Sig
% height	$y=0.597-0.001603x$	0.079	**
Year number	$y=-31.35+0.0162x$	0.131	***
Ring number	$y=0.426+0.02625x$	0.332	***
Ring width	$y=0.6231-0.006509x$	0.233	***
Distance from pith	$y=0.4289+0.001882x$	0.225	***

able 5.7 Simple correlations of ring density with positional variables

ariable	R	Sig
alendar year (x_1)	0.3618	***
eight level in percentage (x_2)	-0.3027	***
ing number (x_3)	0.5766	***
ing width (x_4)	-0.5144	***
istance from pith (x_5)	0.4956	***

able 5.8 Regression coefficients and coefficients of determination (R^2) for multiple regressions of ring density and residual standard deviation.

1) $y = 4430 - 4.513x_1 - 0.004782x_1^2 + 0.03179x_2 - 0.01265x_2^2 - 0.001428x_3 + 0.001146x_3^2 + 0.00004104x_4 - 0.0006797x_4^2 + 0.0001856x_5 - 0.000003019x_5^2$

$R^2 = 0.406$ * ** Residual standard deviation = 0.0934

2) $y = 0.6237 + 0.006923x_3 - 0.01649x_3^2 + 0.0007226x_4 + 0.0002884x_4^2$

$R^2 = 0.416$ *** Residual standard deviation = 0.0924

3) $y = 0.6448 - 0.01699x_3^2 + 0.001295x_4 + 0.0002905x_4^2$

$R^2 = 0.415$ *** Residual standard deviation = 0.0924

3. Variation as explained by multiple regression analysis

The simple regression analysis suggested that changes in mean ring density would accompany changes in the age of rings, distance from the pith, its calendar year of formation, per cent height of tree and ring width. A multiple regression model was therefore fitted to the data as follows:

$$y = b_o - b_1X_1 - b_2X_2 + b_3X_3 - b_4X_4 - b_5X_5 + b_6X_1^2 + b_7X_2^2$$

$$-b_8X_3^2 + b_9X_4^2 - b_{10}X_5^2$$

where b's = partial regression coefficients

X_1 = calendar year in which the wood was form (year numbered)

X_2 = height level (percentage)

X_3 = cambial age for the ring (ring number)

X_4 = ring width (mm)

X_5 = distance from the pith (mm)

y = predicted mean ring density (g/cc)

This gave a determination coefficient (r^2) = 0.406, with residual standard deviation (g/cc) = 0.0934, % of residual standard deviation to population mean = 17.28 and F = 81.10, *** .

As shown in Table 5.7, ring number (age) had the largest simple correlation with ring density (r = 0.5766), followed by ring width (r = -0.5144) and distance from pith (r = 0.4956). Using X_3^2, X_4, X_4^2 or X_3, X_3^2, X_4, X_4^2 the coefficients of determination(r^2), for the multiple regression of density are larger than with the above model (Table 5.8) and the residual standard deviation was reduced from 0.0934 g/cc to 0.0924 g/cc. It seems that ring number and ring width had the greatest effect on ring density.

The proportion of the variation explained by these models, as indicated by the values of R^2 (0.416), was very low. In practical terms these euqations cannot be used to predict ring or tree density reliably from these independent variables. Although the low r^2 values of the multiple regression preclude their use for prediction, they do indicate that ring number and ring width are the most important features associated with variability in density. The extent of variability between trees is clearly shown both by the analysis of variance, and by deviation from the pooled data of the simple regressions for sites separately and also by individual tree density contours.

4. Variation as explained by morphological characteristics

In an even aged stand of conifers there may be wide variation in wood density from tree to tree. Many investigators have attempted to establish the influence of such factors as growth rate, crown class and crown size and proportion of clear bole. Zobel and Rhodes (1955) and Fielding and Brown (1960) concluded that such factors accounted for little of the variation between trees, and that genetical factors must be of primary importance. However, progeny test are required to resolve this unequivocally.

In this study, linear regressions were calculated to relate weighted whole tree (20 trees) density to each of the following characteristics for which the correlated coefficients were shown below:

1. Tree height (m)	R = 0.068	ns
2. Tree volume (m^3)	- 0.4207	ns
3. Diameter at breast height	- 0.4137	ns
4. Crown width	- 0.1172	ns
5. Crown length	- 0.1854	ns
6. Age	0.1544	ns

Since the size and distribution of the living crown are the principal intrinsic factors governing the patterns of growth and cell characteristics, and therefore wood density (Larson, 1962), correlations with crown attributes are to be expected. In this study, however, the correlations were not high, perhaps due to the use of crude measures of crown size or because trees were selected from three different sites.

The insignificantly negative correlation of wood density with tree volume and diameter at breast height means that these characterists cannot be used as a basis for stratifying a stand in terms of whole tree density.

5. Possibility of predicting whole tree density

The practical application of these investigations to the possibility of predicting whole tree values for density from small samples was considered. Simple regressions were calculated to relate whole tree weighted mean value for density to weighted density at various levels as follows:

where y = whole tree weighted density, and

X = weighted density at various percentages of height

% height	Model	R^2	A	B
5%	1	0.788	- 0.007486	1.122
15%	1	0.906	- 0.03961	1.114
25%	1	0.905	0.008636	0.9817
35%	1	0.875	0.0791	0.8279
45%	1	0.817	- 0.006944	0.9279
55%	1	0.729	0.01512	0.8911
65%	1	0.582	0.04035	0.8173
75%	1	0.653	0.06714	0.758

% height	Best fit model	R^2	A	B	C
5%	12	0.790	1.174	-0.9275	0.7769
15%	3	0.916	0.3197	-0.1627	1.116
25%	12	0.914	0.4556	1.889	-1.603
35%	12	0.876	0.678	0.982	-0.6215
45%	4	0.825	0.9716	-1.448	2.071
55%	4	0.798	0.6617	-5.107	6.506
65%	3	0.585	-0.1539	1.507	-0.6032
75%	12	0.656	0.534	1.856	-1.369

The results of this study indicate that the value for r^2 of simple linear regression and the r^2 of best fit model were almost the same. For trees of this age (12/13 years), an investigation of the variation in wood density can validly be based on 5% height level (normally close to breast height) data alone, but the 15% and 25% height levels were in fact better for predicting tree weighted density.

In this study a multiple regression analysis was also carried out to see whether the addition of characteristics expressing tree size made a significant improvement on the simple regression relationships of tree weighted density. The independent variables considered in the multiple regression analysis were:

X_1 = 5% height level weighted density

X_2 = Age (12/13)

X_3 = Tree height

X_4 = Diameter of 5% height level

X_5 = Crown width

X_6 = Crown length

The equation of multiple regression for estimation of whole weighted tree density before step elimination was:

$$Y = 0.4177 + 0.7667X_1 + 0.04441X_2 - 0.002421X_3 + 0.00005593X_4 + 0.004686X_5 - 0.003175X_6$$

This gave $r^2 = 0.886$, $F = 16.9^{***}$ and residual standard deviation = 0.0302 (g/cc)

The significant variables after step wise elimination were:

$$Y = -0.3774 + 0.755X_1 + 0.03755X_2$$

$r^2 = 0.872$, $F = 57.66^{***}$ and residual standard deviation = 0.028 (g/cc).

As indicated, there was a substantial improvement in the predictive ability of the model. Whole tree density can be predicted confidently from the weighted values for density at the 5% height level, together with the age of the tree, tree height, diameter of 5% height level, crown width and crown length. However, in spite of the improvement in the coefficient of determination by including other parameters, they did

not reach a value as high as coefficients of determination using weighted density at 15% and 25% height levels alone.

6. Density distribution

The main purpose of this part of the study was to examine relationships between pulp properties and the density distribution within trees and between trees. Because P.caribaea has a large range of within tree and between tree variation in this characteristic, it was decided to separate density into eight density classes as shown in chapter 3. The following results list the simple correlations of whole tree weighted density with the percentage of wood they contain of each of eight different density classes:

		R	sig
Weighted tree density	ED-1 (0.05 - 0.20 g/cc)	-0.2393	ns.
	ED-2 (0.21 - 0.35 g/cc)	-0.7132	***
	ED-3 (0.36 - 0.50 g/cc)	-0.5986	**
	ED-4 (0.51 - 0.65 g/cc)	0.5183	*
	ED-5 (0.66 - 0.80 g/cc)	0.8029	***
	ED-6 (0.81 - 0.95 g/cc)	0.8006	***
	ED-7 (0.96 - 1.10 g/cc)	0.9219	***
	ED-8 (Greater than 1.11 g/cc)	0.6862	***

As indicated, whole tree density was negatively correlated with the first three classes, and positively correlated with the last five classes. There was no significant correlation with ED-1, perhaps because all the trees have less than 1% of their wood in this class.

Trees were divided into three classes based upon the mean whole tree density as follows:

1. Medium density tree: 0.4 - 0.499 g/cc
2. Medium high density tree: 0.5 - 0.599 g/cc
3. High density tree : Greater than 0.6 g/cc

The distribution of density classes within trees is illustrated in Figures5.12-15. The distribution of the various classes is as follows:

1. Density class 1 (0.05 - 0.20 g/cc), all the trees have less than 1% of their wood in this class ; the percentage decreases from medium density trees to high density tree. (0.0% — 0.8%)
2. Density class 2 (0.21 - 0.35 g/cc); the percentage decreases from medium density to high density trees. (1.4 - 43.0%).
3. Density class 3 (0.36 - 0.50 g/cc); present as a very high percentage in all trees, the percentage decreases from medium density to high density trees. (22.3 - 57.3%)
4. Density class 4 (0.51 - 0.65); (9.9 - 29.6%)
5. Density class 5 (0.66 - 0.80 g/cc) ; (4.9 - 14.5%)
6. Density class 6 (0.81 = 0.95 g/cc) ; (3.0 - 17.7%)
7. Density class 7 (0.96 - 1.10 g/cc) ; (1.1 - 22.8%)

4-7, percentage increases from medium to high density trees.

Some of the higher density trees have a second maximum at class 6 or class 7, most apparent the case of tree 51-45 where there is an equally pronounced maximum at density class 7.

8. Density class 8 (>1.11 g/cc) ; the percentage increases from medium to high density trees, but was low in all trees (0.08 - 4.1%).

Four characteristic patterns of wood density distribution were found in this species (Figures 5.16, 5.17).

1. A pattern resembling a chi-squared curve appears in data from all discs with mean desnity below 0.399 g/cc.

2. A pattern resembling a binomial distribution occurs in data from discs and from whole trees with a mean density between 0.4 and 0.59 g/cc.

3. A pattern resembling a bi-modal distribution, (second peak lower than the first peak) appears in discs and trees with a mean density between 0.6 and 0.69 g/cc.

4. A pattern resembling a bi-modal distribution, this time with the second peak similar to or higher than the first peak, occurs in discs and tree with a mean density higher than 0.7 g/cc. (Because in all the trees mean density is higher than 0.48/cc, no whole tree density distribution has a pattern resembling a chi-squared curve.)

The following characteristics were found to emerge from a study of the graphs on density distribution variations in three cases as follows:

1. Between groups of trees from different sites (Figure 5.20)

Three site groups were found to contain different percentages of the different density classes, but had similar patterns to each other, resembling a binomial distribution. The percentage of density classes in all sites rises to a sharp maximum from density class 2 to density class 3. The percentage then drops steeply at density class 4 and gradually decreases with higher density classes. There are thus three regions of different slope for all sites.

2. Between trees (Figures 5.12 - 5.15)

When the density variations between trees within the groups of trees from different sites were considered, considerable differences were found to occur. Most trees showed a rise to a sharp maximum at density class 3. In the case of S2-1, the lowest mean density tree, however, the maximum occurred in density class 2. In most trees there was a sudden reduction in the percentage of density class 4 and then a fall-off at three different rates. Some of the higher mean density trees however, exhibited a secondary maximum at density class 6 or 7, most striking in the case of the tree S1-45 where there is an equally pronounced maximum at density class 7.

3. Within trees (Figures 5.18, 5.19)

Finally, considering variation of density distribution within the tree, it was found that the pattern of density class distribution was related to mean tree density and wood uniformity. The lower the mean density, the greater was uniformity. Figures 5.18 and 5.19 showed that the pattern of density distribution at each height level was different within each tree from the bottom upwards and to trends also varied from tree to tree.

Figure 5.12

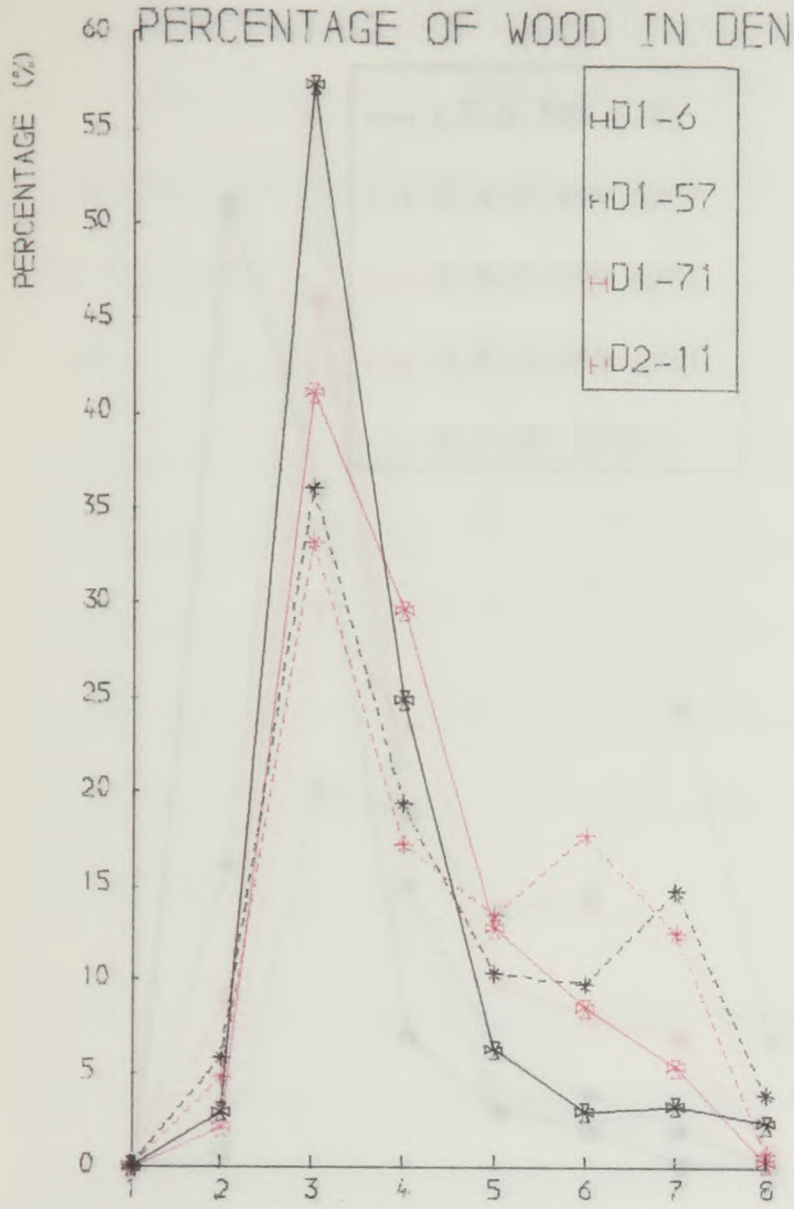


Figure 5.13

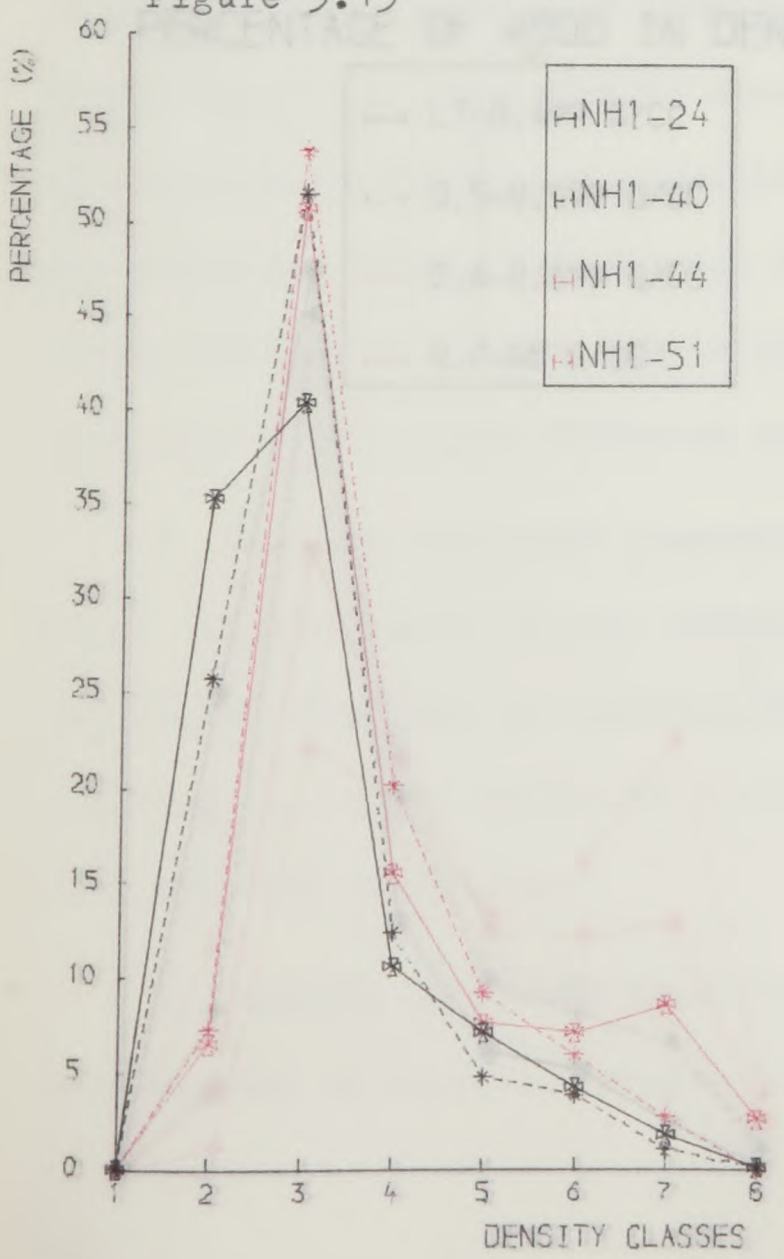


Figure 5.14

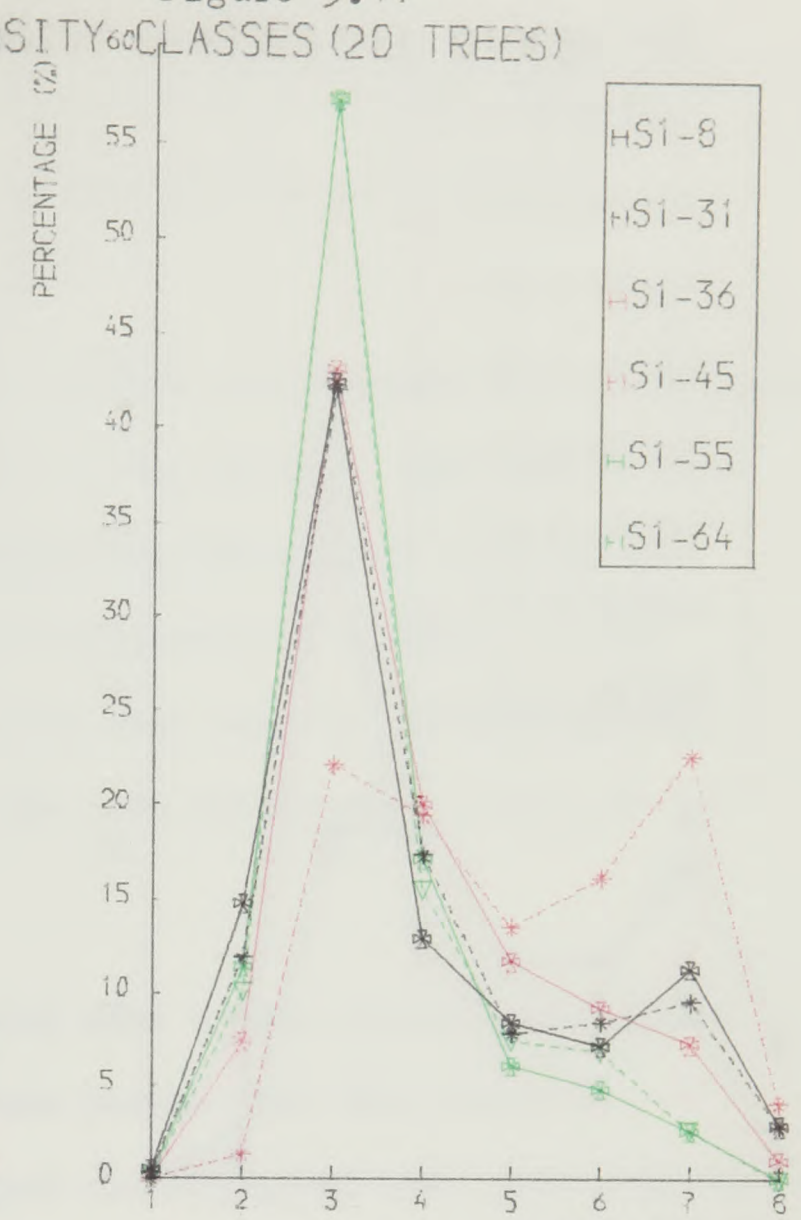


Figure 5.15

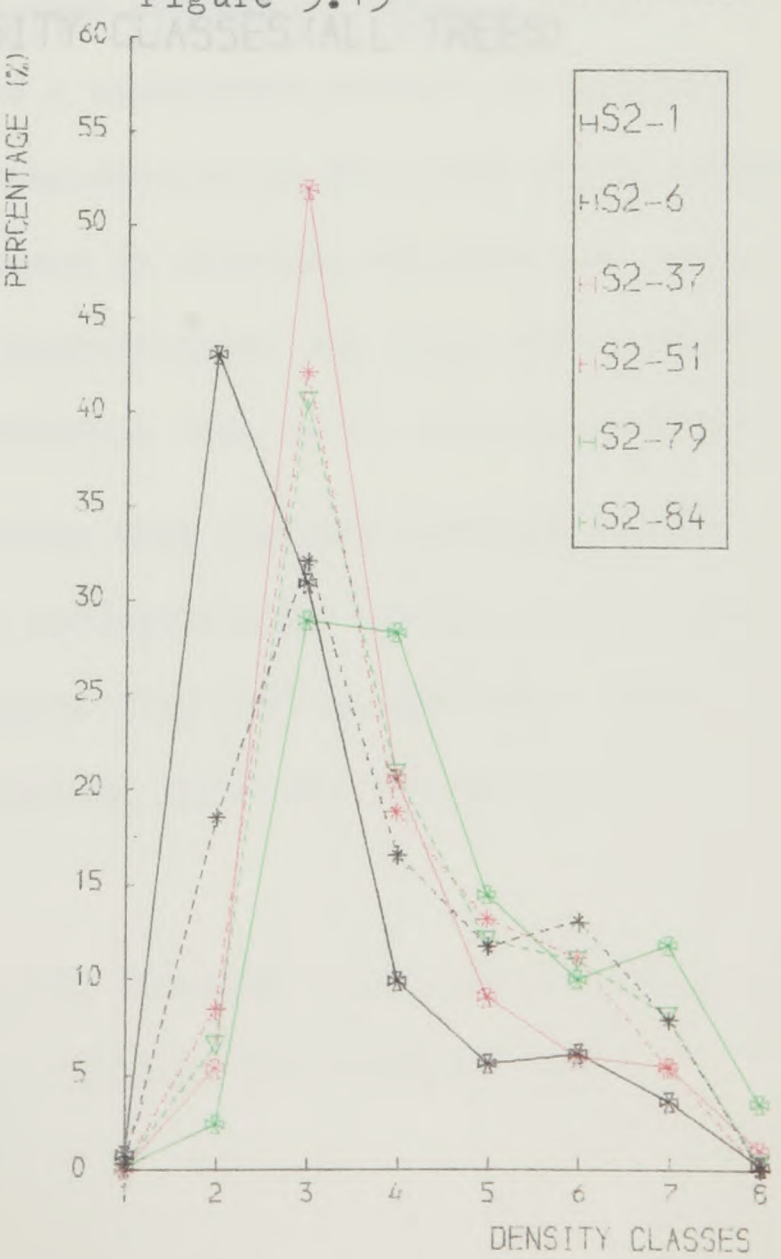


Figure 5.16

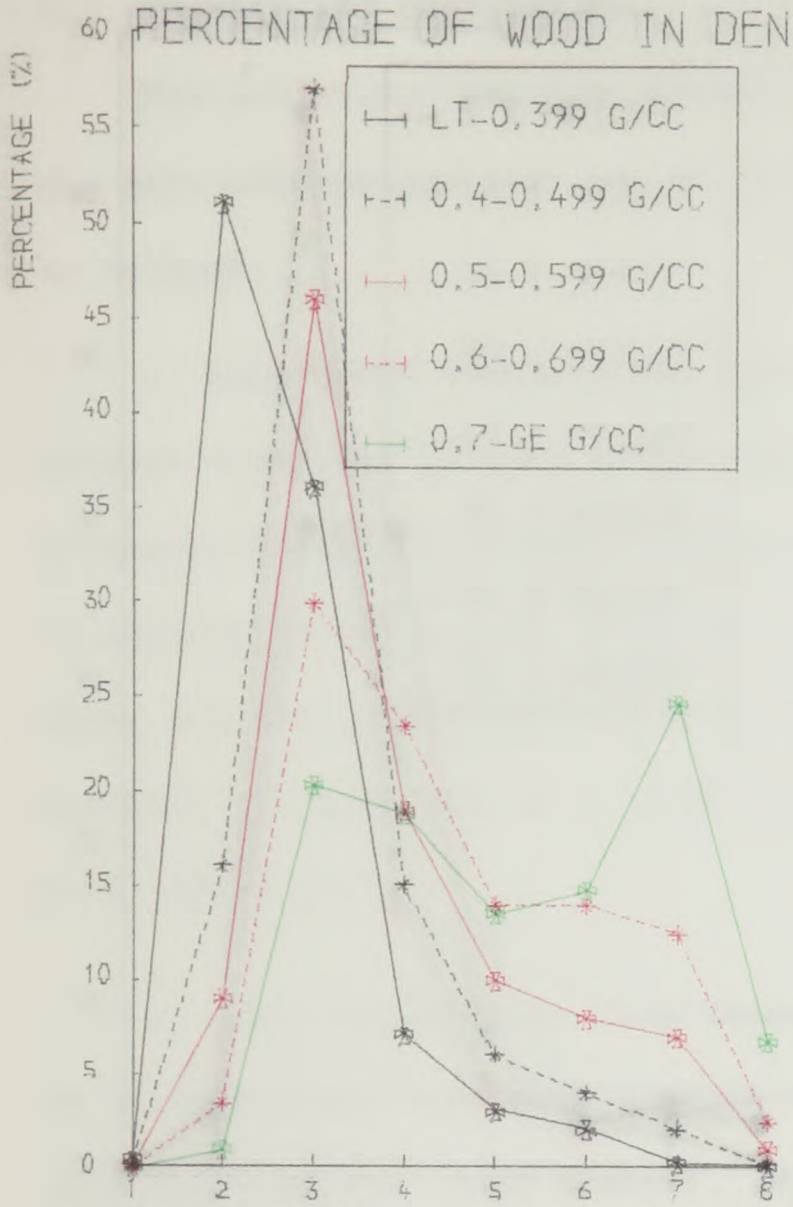


Figure 5.17 DENSITY CLASSES

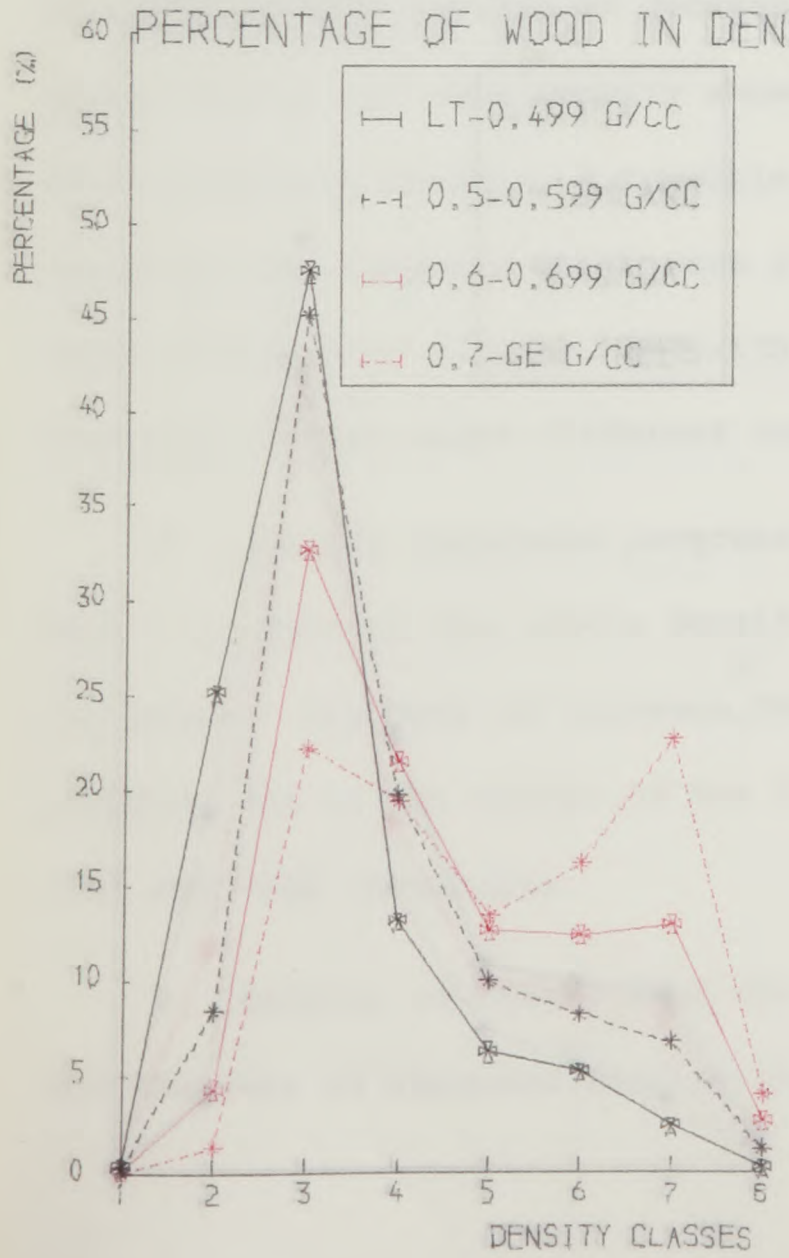


Figure 5.18

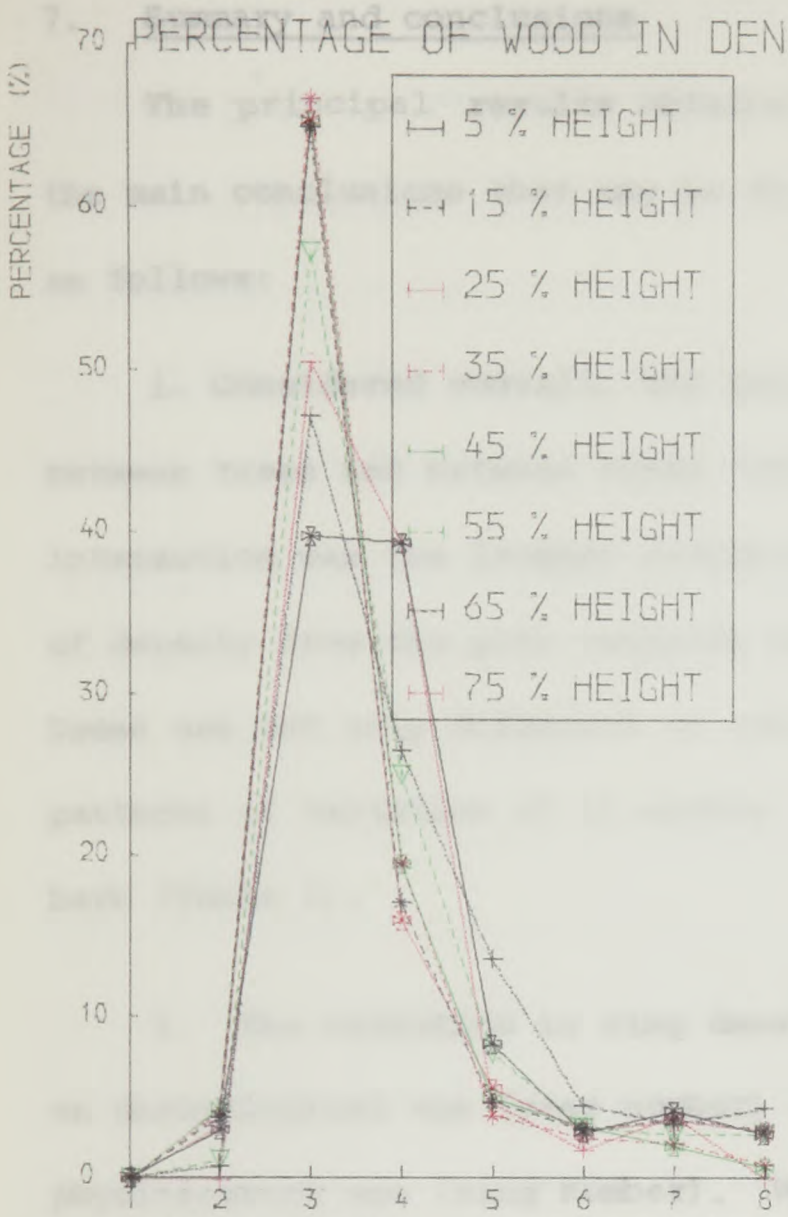


Figure 5.19

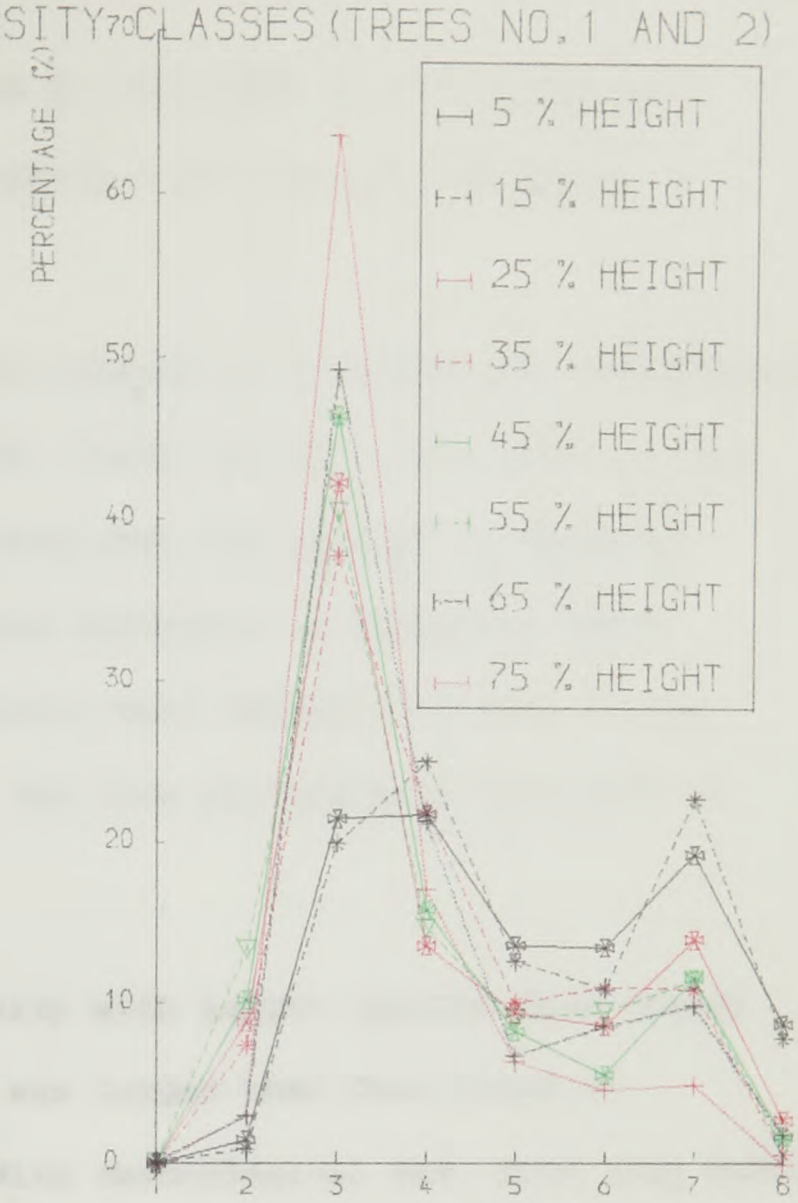
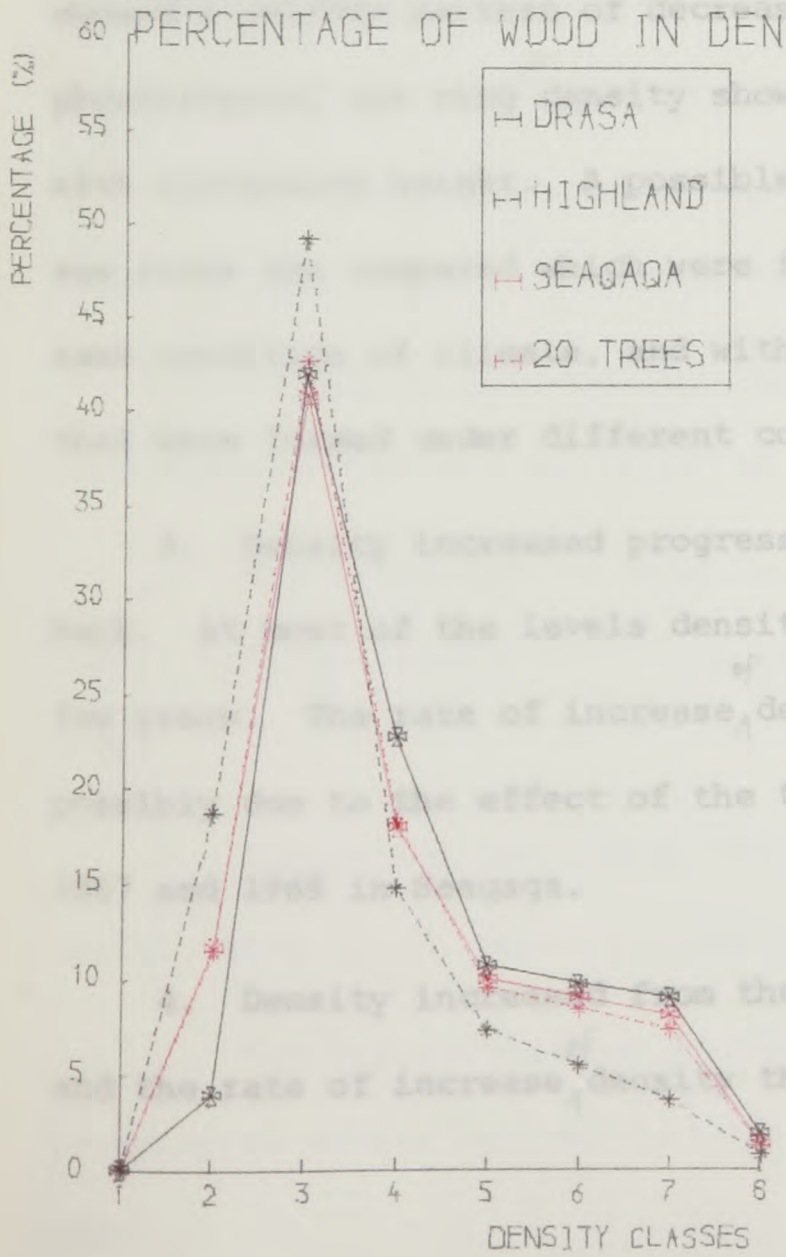


Figure 5.20



7. Summary and conclusions

The principal results obtained in this part of the study and the main conclusions that may be derived from them are summarized as follows:

1. Considered overall, the main sources of variation were differences between trees and between rings (VC%: 27.62, 29.35). The tree by ring interaction was the largest indicating that the pattern of increase of density from the pith outwards was different in different trees. Trees are not only different in overall mean density but also in the patterns of variation of it within the tree particularly from pith to bark (Table 1).

2. The variation in ring density with height (pooled data) based on chronological age (year number) was larger than that based on physiological age (ring number). With chronological age, mean ring density showed a uniform pattern of decrease with increasing height. With physiological age ring density showed a nonuniform pattern of decrease with increasing height. A possible explanation is that with chronological age rings are compared which were formed in the same calendar year under the same condition of climate, and with physiological age rings were compared that were formed under different conditions that is in different years.

3. Density increased progressively from the pith outwards to the bark. At most of the levels density increased more rapidly in the first few years. The rate of increase of density from 1968 to 1970 was reduced, possibly due to the effect of the thinning which was carried out in 1967 and 1969 in Seaqaqa.

4. Density increased from the pith outwards to the 110 mm position, and the rate of increase of density then declined and levelled out.

5. Density decreased with increasing ring width to a width of 20 mm, and then remained steady.

6. Ring number (physiological age) had the largest simple correlation with ring density (r = 0.5766), followed by ring width (r = -0.5144), distance from pith (r = 0.4956), year number (calendar year, r = 0.3618) and % height (r = -0.3207).

7. Tree weighted density was not significantly correlated with tree height, tree volume, diameter at breast height, crown width, crown length or tree age.

8. Whole tree weighted density can be predicted confidently from the weighted values at the 5% height and parameters of the tree growth (age, tree height, D.B.H., crown width and length). Normally tree weighted density is close to the weighted density between the 15% and 25% height level (Table 5.4), and the 15% and 25% height levels had the highest coefficients of determination in regressions predicting the whole tree weighted density.

9. Tree weighted density was negatively correlated with the first three density classes and positively correlated with last five classes.

10. Relationships between mean tree densities and density class distributions can be summarized as follows:

a. The percentage of wood in density classes 1 to 3 decreased and in density classes 4 to 8 increased from medium to high density trees.

b. Except for two trees, the lowest density tree S2-1 and the highest density tree S1-45, density class 3 was presented in the highest proportion.

c. The distribution of density class percentages change more abruptly in medium and medium high density trees than in high density trees.

d. There were greater differences between trees within sites in the distribution of density classes than the differences between sites based on pooled data.

e. The pattern of density distribution at increasing height within tree varied considerably from height to height and from tree to tree.

11. Wood uniformity appears to be controlled by the relative amounts of very high and low density wood, with high density wood exercising the greates influence.

12. Contour diagrams of mean wood density for each tree are shown in Appendix VI . This contour plotting program was designed by H.L. Wright* to plot contours of density and ring width within the tree stem using mean whole ring density and ring width measured in successive rings at different heights, (See R.A. Plumptre*).

* H.L. Wright

* R.A. Plumptre: Some techniques used in the study of wood density, 1977.

Department of Forestry, Commonwealth Forestry Institute, Research Officers.

Chapter 6

VARIATIONS IN TRACHEID CROSS-SECTIONAL DIMENSIONS

In this chapter, the principal features of variations in tracheid cross-sectional dimensions are explained on the basis of the sub-sample of 20 trees. The methods of statistical analysis were the same as those used in the examination of the variation in density.

1. Variation in cell wall thickness

1.1. Variation as explained by the data shown in tables and graphs

1.1.1 Variation of cell wall thickness within trees

For the data of the 20 tree sample pooled, mean values of cell wall thickness for each ring number at each level, and ring means, are presented in Table 6.1 and illustrated in Figure 6.2. Similar information for each year number is given in Table 6.2 and Figure 6.1

1.1.1.1 Radial variation

The variation in cell wall thickness in the radial direction can be summarised as below:

1. On the basis of fixed year number (chronological age), using pooled data, the pattern of development of mean ring cell wall thickness at four different height levels was similar. Cell wall thickness increased more rapidly during the first few years than afterwards. From 1968 to 1970, the rate of increase of cell wall thickness was reduced and it then increased rapidly again from 1971 onwards.

At the 5% and 15% height levels, in 1972 to 1973, cell wall thickness decreased slightly, but at the 35% and 65% height levels an increase in cell wall thickness was maintained. (Table 6.2, Figure 6.1).

2. Again, using pooled data, the general trend was for cell wall thickness to increase with ring numbers from the pith outwards to the bark. The mean overall value for this feature was 4.39μ in ring number 1 to 9.54 μ in ring number 10.

It is noted that at the 5% height level, cell wall thickness of ring number 6 was slightly greater than ring number 7 and 8. One possible explanation of this occurrence is that pruning was carried out during that time. At the 5%, 15% and 35% height levels, in ring number 9 to ring number 10, cell wall thickness decreased slightly. This is perhaps because some trees had only a few months to develop the last ring (3 trees felled April, 1973, 6 trees felled on June 1973, and 11 trees felled November, 1973). (Table 6.1 and Figure 6.2).

1.1.1.2 Axial variation

The variation in cell wall thickness in the axial direction can be summarised as below:

1. On the basis of a fixed year number (chronological age), mean ring cell wall thickness decreased with increasing height level. (Table 6.2 and Figure 6.1).

2. On the basis of a fixed number of rings (ring number or physiological age) from the pith, mean ring cell wall thickness generally decreased in the trunk from the base to the top of the tree, but in a non-uniform pattern (Table 6.1 and Figure 6.2).

3. The change of cell wall thickness on the basis of year number (calendar year) at different height levels was larger than on

the basis of ring number (physiological age) at different heights (Figures 6.1 and 6.2).

4. For most of the 20 trees, the maximum weighted cell wall thickness (mean disc value) occurred at the 5% height, and mean disc cell wall thickness decreased with increasing height level. Some trees did not conform to this pattern and axial trends were not uniform. Mean weighted cell wall thickness at different height levels, for the data from 20 trees pooled, decreased by about 24% from the 5% height (8.27 μ) to the 65% height level (6.30 μ) (Table 6.3).

1.1.2 Variation in cell wall thickness between trees

Table 6.4 summarises the statistical interrelationships between the mean values for cell wall thickness of the 20 trees (based on weighted disc values) and demonstrates the considerable range of variability of these tree means.

The rate of change in cell wall thickness with respect to increasing age from the pith was bigger in some trees than in others (Table 6.5). The pattern of cell wall thickness at the different height levels in different trees also varied from tree to tree. Generally, cell wall thickness decreased with increasing height level, but in some trees (D1-6, S2-6, S2-79) cell wall thickness decreased to a certain level in the stem and increased afterwards. Trees NH1-4 and S1-45 showed an increase in cell wall thickness from the 5% to the 15% height level, then cell wall thickness decreased afterward. (Table 6.3)

1.2 Variation as explained by simple regression analysis

The relationship of cell wall thickness with % height, year number, ring number, ring width and distance from the pith were examined by simple regression analysis, using pooled data, for the twenty trees sample and for the data from each site separately. The regressions and coefficients of determination (R^2) are given in Table 6.6 and the patterns of variation illustrated in Figure 6.3 - 6.7. The results may be summarised as follows:

1. The pooled data regression lines shows that cell wall thickness decreased from the bottom to the top of the tree, with a slightly larger rate of decrease at the lower height levels than at the higher height levels.

2. There was an increase in cell wall thickness with increasing year number, and the regression line shows that cell wall thickness increased more rapidly in the early years than afterwards.

3. Cell wall thickness increased from ring 1 to ring 12, and more rapidly in the first few rings than afterwards. At Drasa site, the regression line shows an increase from ring 1 to ring 9, then cell wall thicknessdecreased slightly or remained more or less the same to ring number 12. Data from the Nausori Highland and Seagaga sites showed that cell wall thickness increases steadily from ring 1 to ring 12.

4. The regression of cell wall thickness on ring width indicated that cell wall thickness decreased with increasing ring width to a width of 20 to 30 mm, and then remained steady. In the 20 to 30 mm range, the data, however, represented only a few points, normally from the first few rings in some of the trees.

5. Cell wall thickness increased from the pith outwards to about the 110 mm position, with very little further increase outwards to the bark. It is noted that in Drasa site the maximum distance from the pith (one tree) was only about 115 mm. It is likely that the trend showing a decrease in cell wall thickness after a maximum had been reached is caused by the inadequacy of this simple regression.

6. Values for R^2 were low although statistically highly significant. In general these were poor relationships between cell wall thickness and age, growth rate, or position in the tree. Cell wall thickness was more closely associated with ring number (model 3, R^2 = 0.46), ring width (model 4, R^2 = 0.38) and distance from pith (model 3, R^2 = 0.40) than with height level (model 12, R^2 = 0.25) and year number (model 3, R^2 = 0.21), as is apparent from the lower values of the coefficients of determination and narrower range for these regression lines.

7. There was little improvement in the value of R^2 of simple regression when the data from the 3 sites were considered separately.

1.3 Variation as explained by multiple regression analysis

The multiple regression models were the same as those employed in the examination of the variation in ring density. A summary of the main results of multiple regression analysis for cell wall thickness as the dependent variable is presented in Table 6.7.

The coefficient of determination for the first model of the multiple regression of cell wall thickness (R^2 = 0.51) was only slightly higher than for the second model (R^2 = 0.506), which indicated that the trend of variation in cell wall thickness was correlated in a linear way with five independent variables.

Ring number had the largest simple linear correlation with cell wall thickness, but was eliminated from the second model multiple regression and the third model multiple regression, and the coefficients of determination for these two multiple regressions changed very little. Perhaps this is because of the interrelation between these five independent variables.

Although the coefficients of determination of multiple regressions were larger than simple regressions, they were low and these equations are not very useful to explain the factors associated with variation in cell wall thickness.

1.4 Variation as explained by morphological characteristics and age

Simple linear regressions were calculated to examine the association of whole tree mean cell wall thickness with each of the following characteristics, for which the correlation coefficients are shown below:

Variables	R	Sig.
Age	0.1148	n.s.
Tree height (m)	0.1649	n.s.
Diameter of breast height (mm)	-0.3814	n.s.
Crown width	-0.0778	n.s.
Crown length	-0.1502	n.s.

Multiple regression analysis was not carried out because of few observations (20 trees) in this study and because of the poor values for R, which were also statistically insignificant in simple linear regressions.

Although, these characteristics cannot be used as a basis for stratifying a stand in terms of whole tree cell wall thickness, It was apparent that diameter at breast height has greater effects

than other morphological features on cell wall thickness.

1.5 Possibility of predicting tree cell wall thickness

To examine the possibility of predicting whole tree values for cell wall thickness from small samples, simple regressions were calculated to relate whole tree weighted values to weighted cell wall thickness at various levels as follows:

% height level	Model	R^2	A	B
5	1	0.917	0.7182688	0.816034
15	1	0.835	1.387216	0.7961089
35	1	0.892	0.5058819	0.9891269
65	1	0.527	3.195104	0.678189

% height level	Best fit model	R^2	A	B	C
5	12	0.925	0.2982453	0.1812306	-0.009873468
15	10	0.854	0.08694864	0.6331095	0.3446316
35	10	0.893	0.07362207	0.5089543	0.3040478
65	12	0.563	0.9749292	-0.08484378	0.009675364

The results indicated that the whole tree mean values for cell wall thickness can be estimated with confidence from the 5% height values. The coefficient of determination of a simple linear regression was close to that of the best fit model (model 12).

Although the 5% level is the best prediction, Table 6.3 shows that for most of the trees the actual weighted mean tree value of cell wall thickness was close to that between the 15% and 35% height levels.

1.6 Cell Wall thickness distribution

Cell wall thickness was separated into five classes as shown in Chapter 3. The following results list the simple correlations of whole tree weighted cell wall thickness with the percentage content of wood in each of the five different cell wall thickness classes:

	Cell wall thickness classes	R	Sig.
Cell wall thickness (tree)	CW-1 (0.00 - 4.00 μ)	-0.702	***
"	CW-2 (4.01 - 8.00 μ)	-0.771	***
"	CW-3 (8.01 - 12.00 μ)	0.733	***
"	CW-4 (12.01-16.00 μ)	0.904	***
"	CW-5 (Greater than 16.01 μ)	0.795	***

Mean tree cell wall thickness was negatively correlated with the first two classes, and positively correlated with the last three classes, and class CW-4 had the closest correlation.

The patterns of distribution of cell wall thickness within trees and between trees are illustrated in Figures 6.8 and 6.14. The percentage distribution of the various cell wall thickness classes was very different in different trees, with a range as follows:

CW-1 = 2.315 % to 24.258%
CW-2 = 34.873 % to 73.615%
CW-3 = 11.286 % to 27.608%
CW-4 = 3.023 % to 24.348%
CW-5 = 0.0 % to 12.523%

Patterns of cell wall thickness distribution in discs (levels) were found in two forms, resembling either a binomial distribution or a bi-modal distribution occurred in most trees.

The following characteristics are apparent from a study of the graphs of cell wall thickness distribution:

1. Between trees (Figures 6.8-6.11)

There were considerable differences between trees in cell wall thickness distribution. Generally, the percentage of the first two cell wall thickness classes decreased and the last three cell wall thickness classes increased with increasing whole tree mean values of cell wall thickness. But there were some exceptions, for example, tree NH1-40 had a lower cell wall thickness value (6.32μ) than tree S1-8 (8.34 μ), but the percentage of wood in CW-1 of NH1-40 (9.6%) was lower than CW-1 of S1-8 (12.4%). Mean cell wall thickness of D2-11 (8.7 μ) was higher than S1-8 (8.3μ) but the percentage in CW-5 of D2-11 (3.4%) was lower than in CW-5 of S1-8 (12.2%). However, all trees showed a rise to a sharp maximum of class 2 (CW-2). Most trees (except S1-45) then showed a sudden reduction in the amount of class 3 (CW-3), and subsequently a fall off at different rates.

2. Within trees (Figures 6.12 and 6.13)

There were considerable differences in the within tree pattern of distribution of cell wall thickness at different heights, and these trends also varied from tree to tree.

TABLE 6.1 MEAN CELL WALL THICKNESS AND RING NUMBER AT DIFFERENT % HEIGHTS

% HEIGHT										
65	4.556	5.691	6.263	6.463						
35	4.226	5.483	6.083	6.752	6.738	7.520	7.877	7.717		
15	4.524	5.939	6.463	7.245	8.041	8.100	8.311	9.374	9.171	
5	4.239	6.091	7.166	7.210	8.410	9.263	9.181	9.151	9.788	9.537
RING NO.	1	2	3	4	5	6	7	8	9	10
MEAN	4.385	5.801	6.494	6.918	7.746	8.294	8.456	8.747	9.479	9.537

TABLE 6.2 MEAN CELL WALL THICKNESS AND YEAR NUMBER AT DIFFERENT % HEIGHTS

% HEIGHT										
65							5.315	6.042	6.617	6.787
35			5.038	5.920	6.431	6.782	7.103	7.721	7.947	7.852
15		5.391	6.282	7.153	7.504	8.027	8.118	8.931	9.544	9.052
5	5.184	6.895	7.320	7.992	8.879	9.052	9.053	9.678	10.237	9.191
YEAR NO.	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973
MEAN	5.184	6.143	6.213	7.022	7.605	7.954	7.397	8.093	8.587	8.221

TABLE 6.3 MEAN WEIGHTED CELL WALL THICKNESS AT DIFFERENT % HEIGHTS

% HEIGHT	D1-6	D1-57	D1-71	D2-11	NH1-24	NH1-40	NH1-44	NH1-51	S1-8	S1-31
5	7.335	9.171	8.598	9.752	6.710	6.841	9.227	8.270	10.085	8.932
15	6.684	9.042	7.590	8.659	6.249	7.109	7.966	7.628	8.541	8.276
35	5.765	7.373	6.839	8.755	5.811	5.737	7.836	6.411	7.305	7.910
65	6.291	6.788	5.300	6.618	4.648	5.260	6.070	6.200	6.191	6.316
MEAN	6.607	8.254	7.275	8.721	6.008	6.323	8.015	7.321	8.342	8.078

% HEIGHT	S1-36	S1-45	S1-55	S1-64	S2-1	S2-6	S2-37	S2-51	S2-79	S2-84
5	7.915	10.494	6.624	6.450	6.667	7.845	8.131	7.412	10.690	8.346
15	6.395	11.471	6.225	6.051	5.961	7.220	7.942	7.445	8.469	7.910
35	6.659	8.921	6.166	6.489	5.722	7.420	6.812	6.546	9.384	6.971
65	4.756	7.859	5.705	6.079	5.469	8.880	5.558	6.125	9.376	6.602
MEAN	6.683	9.993	6.249	6.297	6.036	7.707	7.333	7.016	9.544	7.613

Figure 6.1

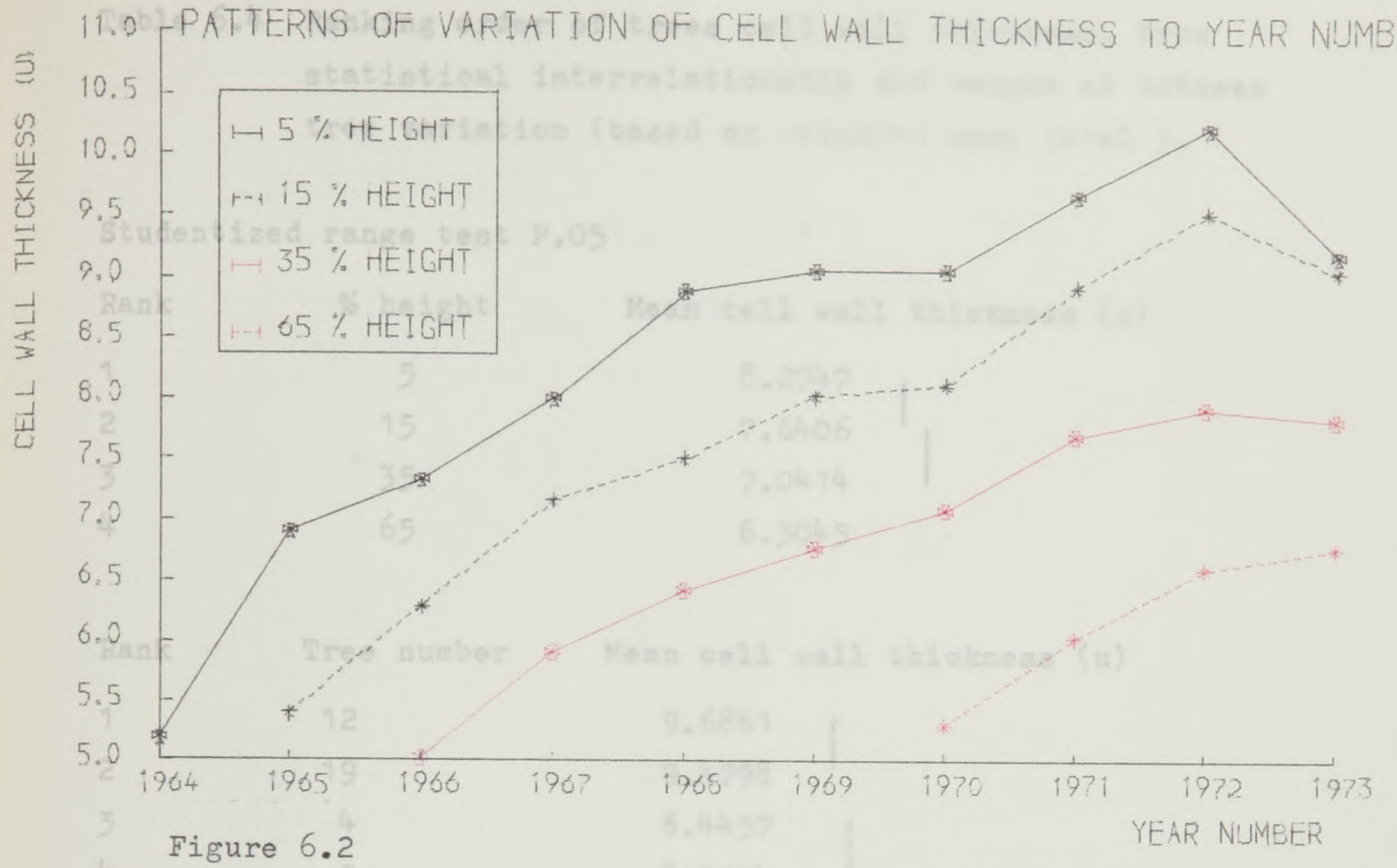


Figure 6.2

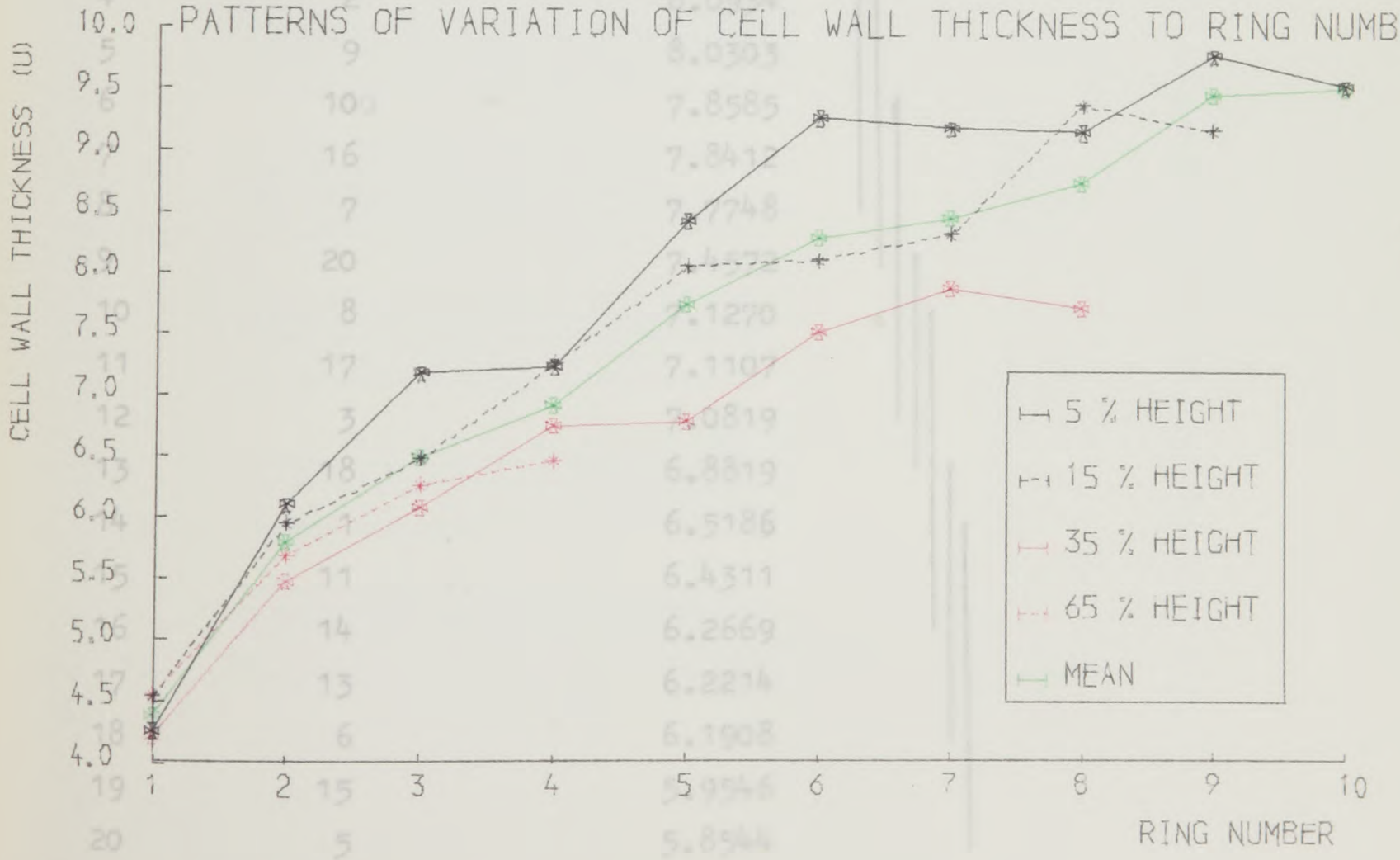


Table 6.4 Ranking order of trees cell wall thickness, tree statistical interrelationship and ranges of between tree variation (based on weighted mean level).

Studentized range test P.05

Rank	% height	Mean cell wall thickness (u)
1	5	8.2747
2	15	7.6406
3	35	7.0414
4	65	6.3045

Rank	Tree number	Mean cell wall thickness (u)
1	12	9.6861
2	19	9.4798
3	4	8.4457
4	2	8.0934
5	9	8.0303
6	10	7.8585
7	16	7.8412
8	7	7.7748
9	20	7.4572
10	8	7.1270
11	17	7.1107
12	3	7.0819
13	18	6.8819
14	1	6.5186
15	11	6.4311
16	14	6.2669
17	13	6.2214
18	6	6.1908
19	15	5.9546
20	5	5.8544

Standard error of a mean = 0.2052 u

Mean value = 7.3153 u

Numbers subtended by the same vertical line refer to the trees whose mean are not significantly different from each other.

TABLE 6.5 MEAN CELL WALL THICKNESS AT DIFFERENT RING NUMBERS

RING NØ.	1	2	3	4	5	6	7	8	9	10
TREE NØ.										
1	4.355	5.058	5.756	6.591	7.068	6.978	8.162	9.046	10.298	9.428
2	4.288	6.938	7.960	7.599	9.486	10.435	10.254	10.012	9.496	5.607
3	4.301	5.800	6.566	6.344	8.097	8.933	9.760	8.327	10.509	6.031
4	4.202	6.053	7.309	8.434	8.900	10.222	11.070	11.914	11.876	11.860
5	3.991	5.073	5.052	4.945	5.248	6.046	6.498	7.584	8.732	8.257
6	4.790	5.810	5.650	5.578	6.317	6.831	6.875	7.531	7.275	7.964
7	5.154	6.519	6.856	6.775	8.025	8.810	9.148	9.521	7.852	8.808
8	5.102	6.310	6.599	6.231	7.674	8.386	8.052	7.948	9.420	7.654
9	4.427	6.063	6.501	7.633	8.467	8.724	9.025	10.419	14.152	14.367
10	4.522	5.383	6.148	6.635	8.983	10.606	9.320	9.488	9.589	13.919
11	3.451	4.676	5.160	5.554	6.715	7.268	7.982	9.144	8.218	8.589
12	5.003	7.205	9.206	9.721	10.820	12.174	12.382	12.175	14.307	12.420
13	3.894	5.107	5.614	4.955	6.459	6.063	6.803	6.284	7.609	8.376
14	4.049	5.074	5.850	6.376	6.585	6.999	6.052	6.809	7.188	7.049
15	3.503	4.596	5.025	5.688	6.055	6.455	6.468	6.619	6.791	9.219
16	4.622	6.362	7.717	8.751	7.190	7.833	8.102	7.753	7.986	9.712
17	4.645	6.210	6.426	7.471	7.349	7.688	7.416	8.055	8.278	9.710
18	3.996	5.661	6.230	7.138	7.669	7.246	7.102	6.724	7.634	7.972
19	4.966	6.522	7.795	8.741	9.828	10.160	9.943	10.888	12.040	13.128
20	4.441	5.598	6.458	7.194	7.996	8.025	8.706	8.698	10.338	10.680

Table 6.6 Regression of cell wall thickness on % height, year number, ring number, ring width and distance from pith in each site and pooled data

Site	Independent variable	Regression best fit model	R^2	sig.
Drasa	% height	$y = 8.843939 - 0.04936372X$	0.158	
	year number	$y = -298425.9 + 302.7118X - 0.07676255X^2$	0.257	
	Ring number	$y = 2.842356 + 1.59495X - 0.09137421X^2$	0.585	
	Ring width	$y = 2.230011 + 8.360857e^{-0.04690038X}$	0.412	
	Distance from pith	$y = 2.334861 + 0.1359582X - 0.0006381561X^2$	0.489	
Nausori Highland	% height	$y = 7.634804 - 0.05455704X + 0.00029294X^2$	0.204	
	Year number	$y = X/(5355005 - 5427.685X + 1.375407X^2)$	0.175	
	Ring number	$y = 4.396917 + 0.5696746X - 0.01533619X^2$	0.504	
	Ring width	$y = 4.073146 + 5.05196e^{-0.05845053X}$	0.293	
	Distance from pith	$y = 4.118136 + 0.04721075X - 0.0001202787X^2$	0.436	
Seaqaqa	% height	$y = 8.452952 - 0.06216374X + 0.0004109767X^2$	0.092	
	Year number	$y = -130597.5 + 132.321X - 0.0335146X^2$	0.228	
	Ring number	$y = X/(0.1144694 + 0.1227481 - 0.002908011X^2$	0.452	
	Ring width	$y = 4.089634 + 9.25448e^{-0.1143306X}$	0.391	
	Distance from pith	$y = 3.199415 + 0.09244507X - 0.0003490314X^2$	0.420	
Pooled data	% height	$y = X/(-0.03458 + 0.1252X + 0.0005191X^2)$	0.247	
	Year number	$y = -141376.9 + 143.2808X - 0.03630044X^2$	0.211	
	Ring number	$y = 3.665 + 1.028X - 0.04612X^2$	0.458	
	Ring width	$y = 3.762143 + 7.817335e^{-0.08354845X}$	0.379	
	Distance from pith	$y = 3.184 + 0.09454X - 0.0003854X^2$	0.402	
Pooled data simple linear	% height	$y = 8.253 - 0.03124X$	0.239	***
	Year number	$y = -696.7679 + 0.3575691X$	0.197	***
	Ring number	$y = 4.63 + 0.5312X$	0.435	***
	Ring width	$y = 8.988 - 0.1503X$	0.294	***
	Distance from pith	$y = 4.466 + 0.04397X$	0.366	***

Table 6.7 Matrix of simple correlations and multiple regression of ring cell wall thickness.

where		R	Sig
y =	cell wall thickness		
x_1 =	% height (weighted mean)	-0.3285	***
x_2 =	year number	0.4438	***
x_3 =	ring number	0.6593	***
x_4 =	ring width	-0.5423	***
x_5 =	distance from pith	0.6047	***

Model 1 : $y = -73140-0.07933x_1+74.19x_2+0.4969x_3-0.1843x_4 +0.009673x_5+0.0008219x_1^2-0.01885x_2^2-0.004585x_3^2 +0.002853x_4^2-0.0001819x_5^2$

with $R^2 = 0.51$, F test = 68.29 *** and residual standard deviation = 1.603 μ

Model 2 : $y = -631.7-0.0536x_1+0.3257x_2+0.1825x_3-0.07936x_4 -0.01606x_5$

with $R^2 = 0.506$, F test = 135.5 *** , and residual standard deviation = 1.6033 μ.

Model 2 after step elimination was :

$y = -929.4-0.06741x_1+0.4775x_2-0.08179x_4-0.0138x_5$

with $R^2 = 0.503$, F test = 168.06 *** , and residual standard deviation = 1.6058 μ

Figure 6.3

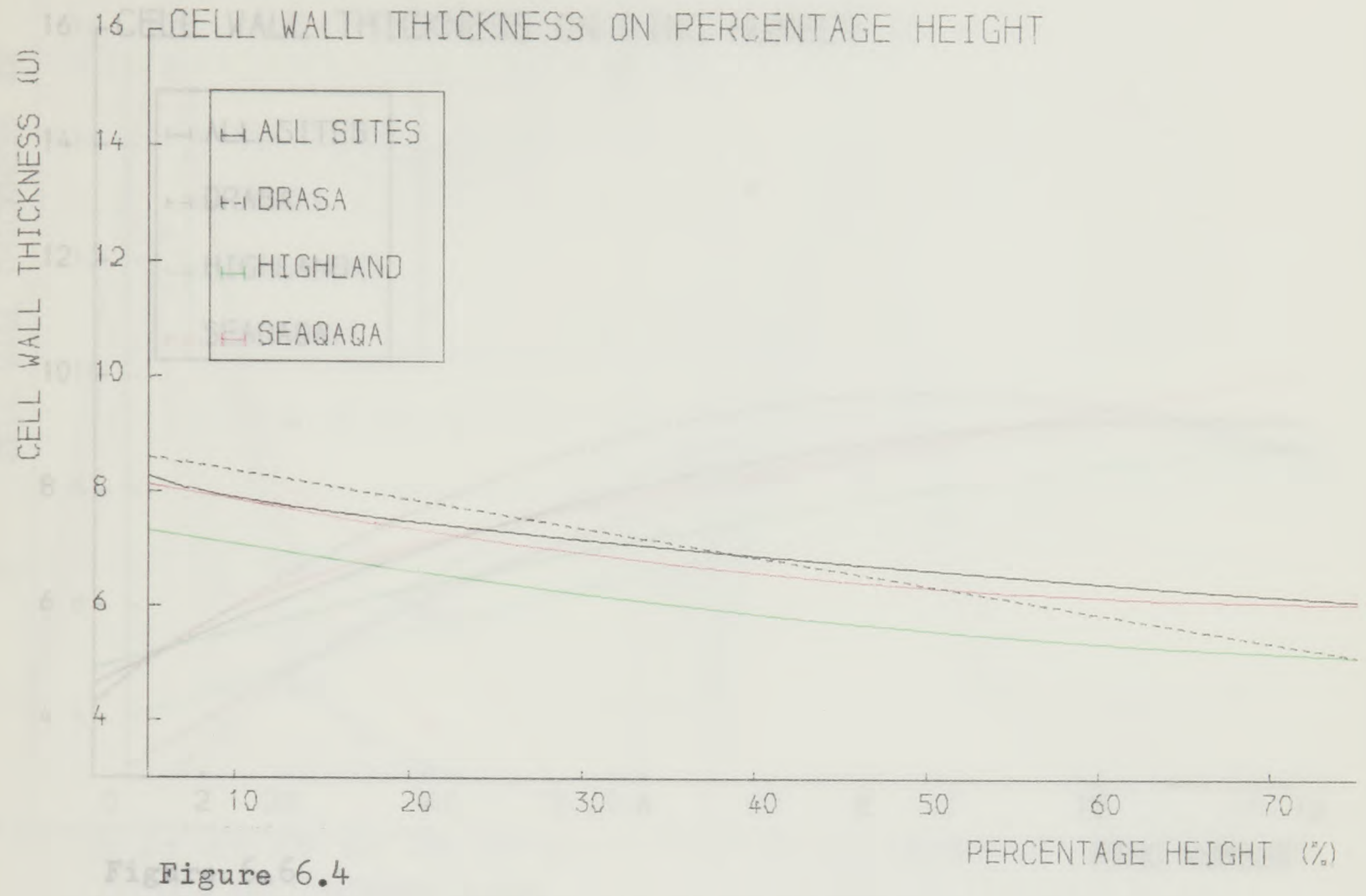


Figure 6.4

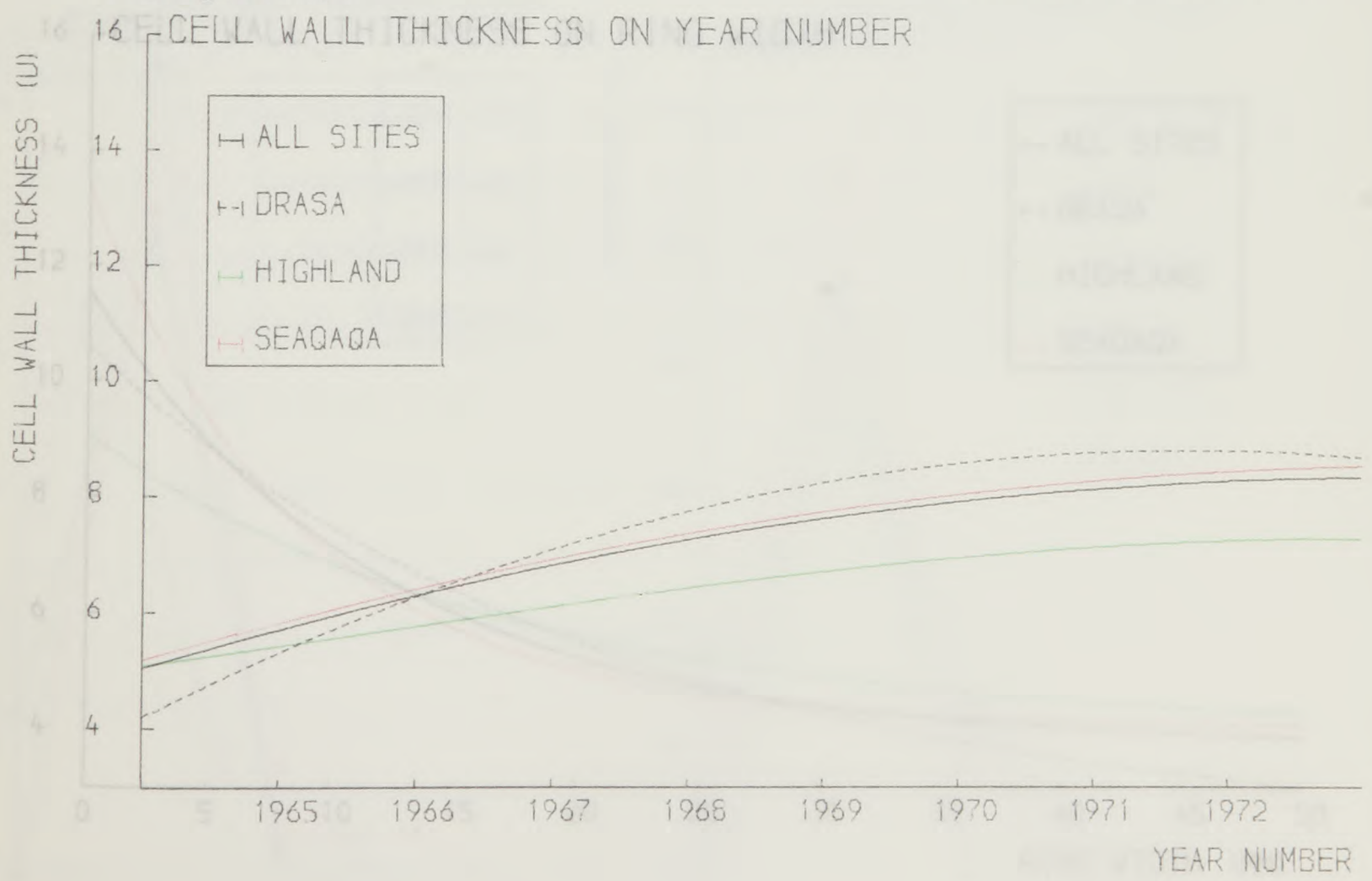


Figure 6.5

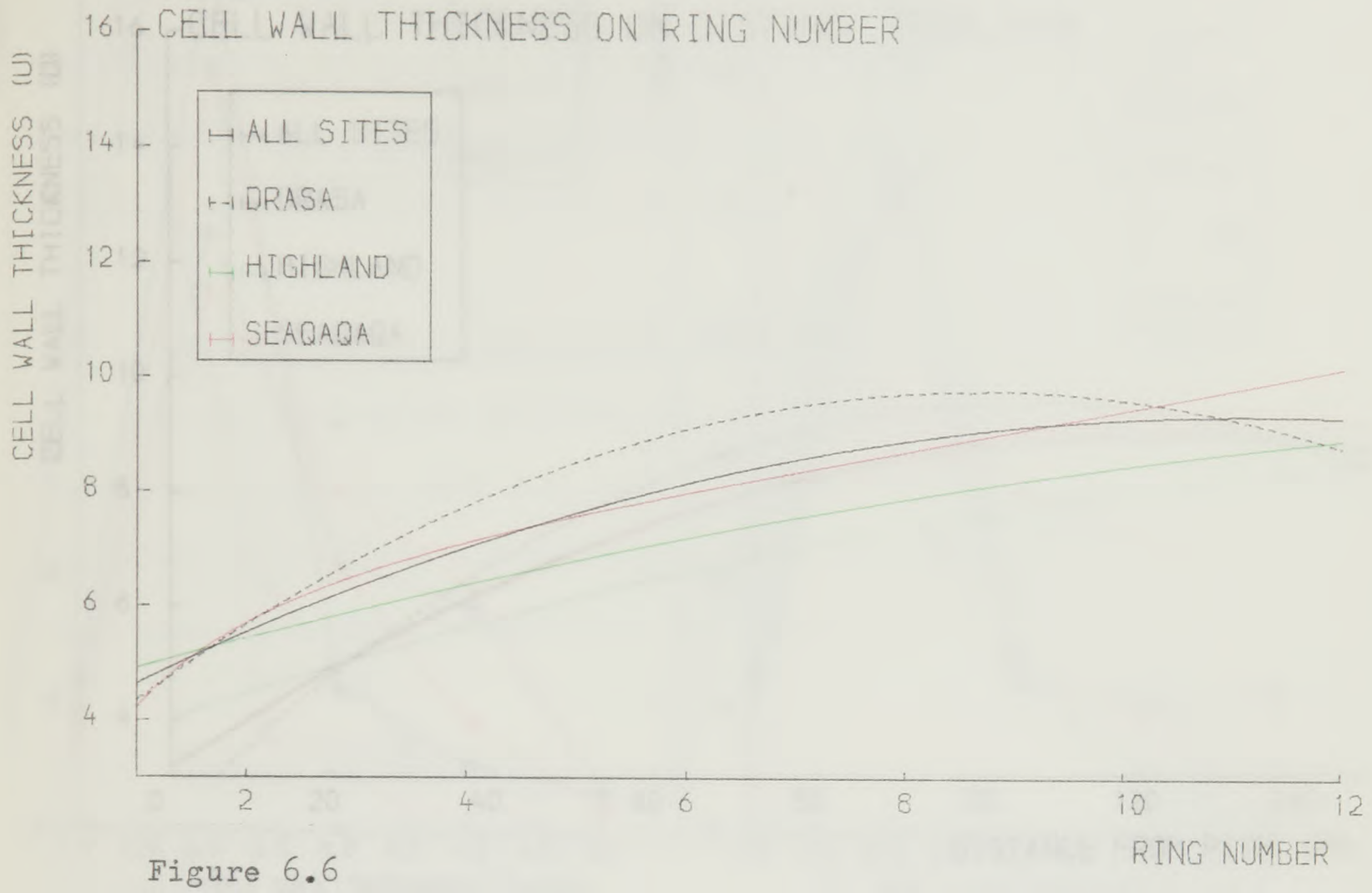


Figure 6.6

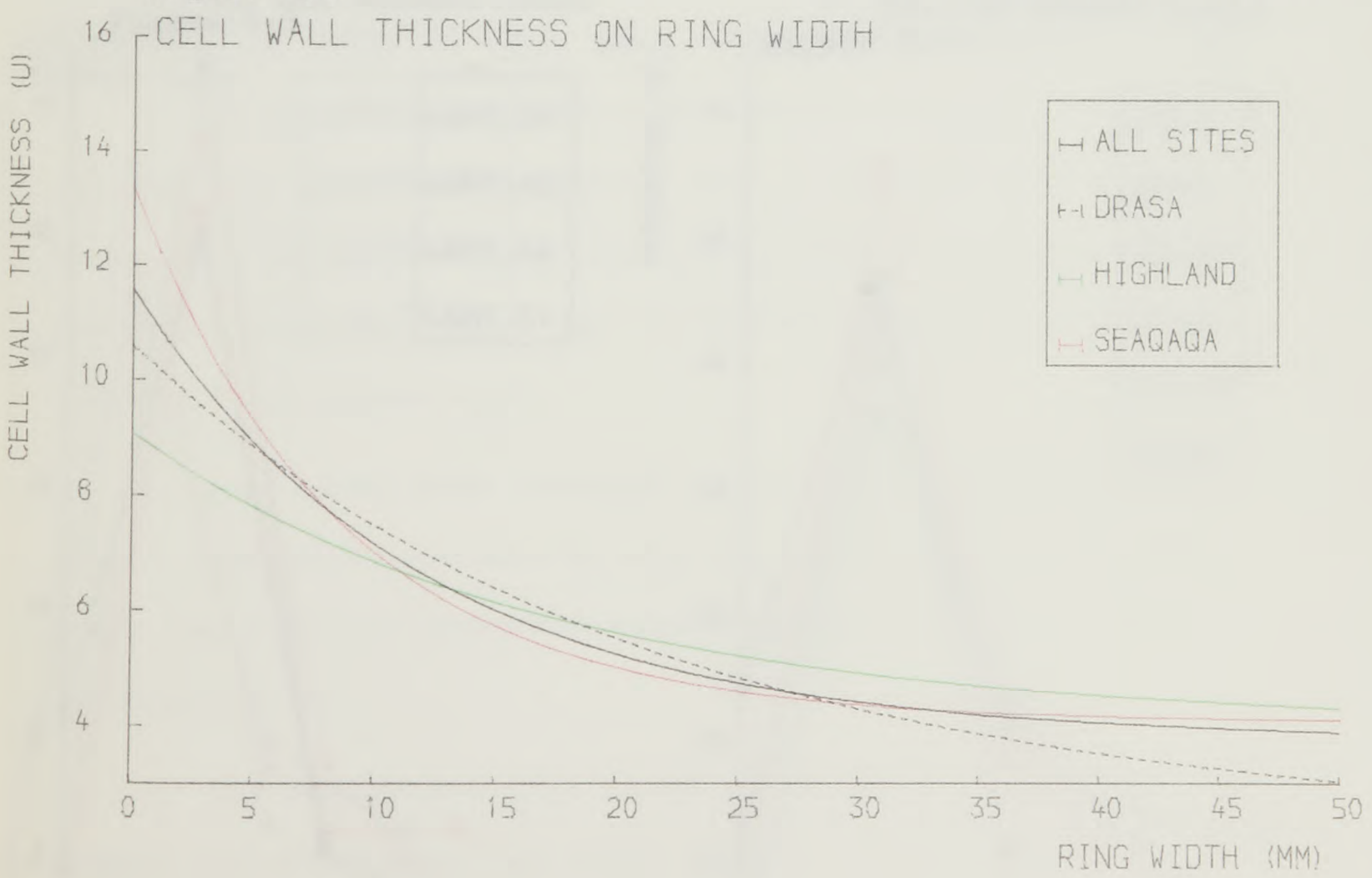


Figure 6.7

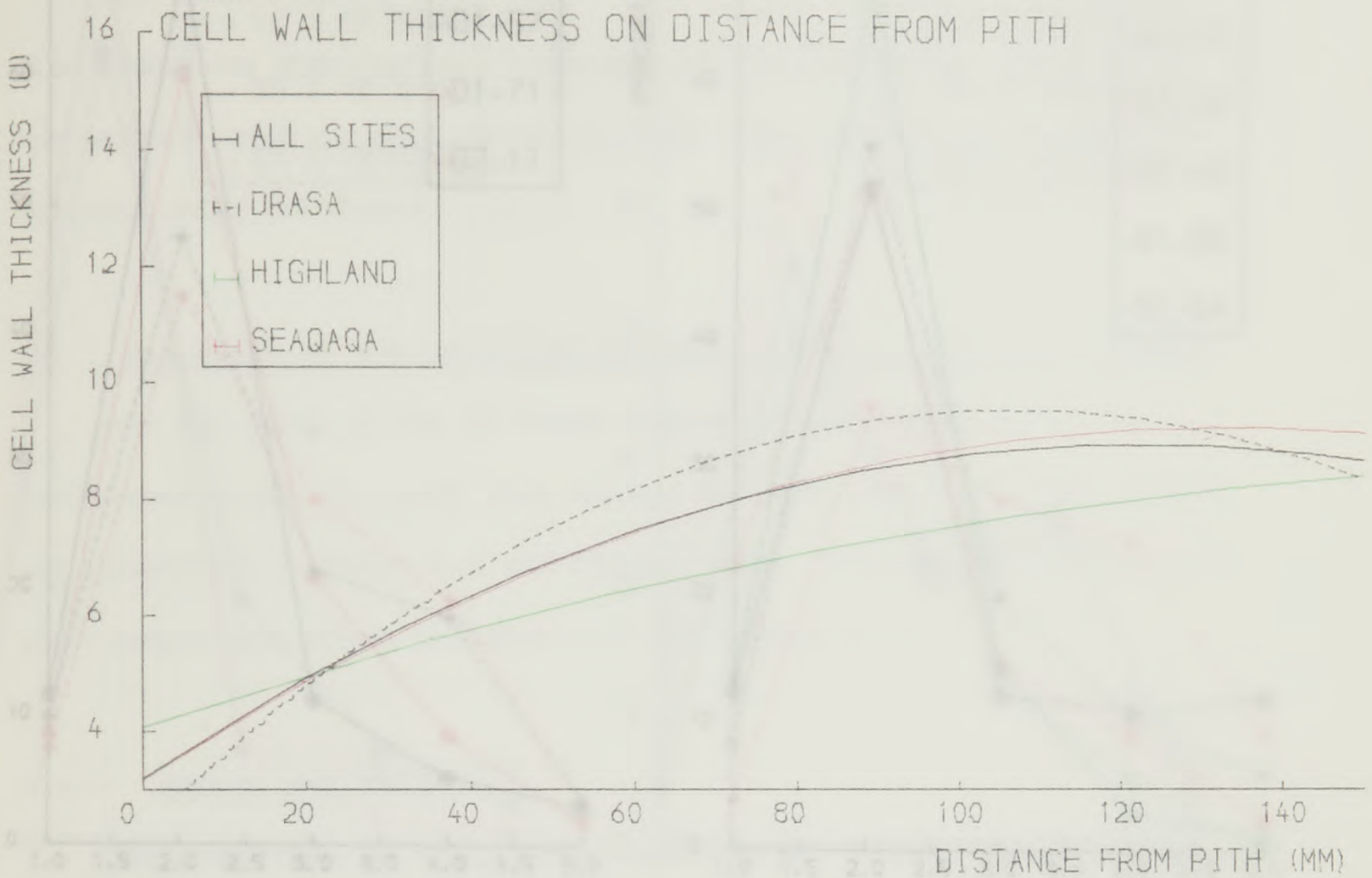

CELL WALL THICKNESS ON DISTANCE FROM PITH
CELL WALL THICKNESS (U)
16
14
12
10
8
6
4
ALL SITES
DRASA
HIGHLAND
SEAQAQA
0
20
40
60
80
100
120
140
DISTANCE FROM PITH (MM)

Figure 6.8

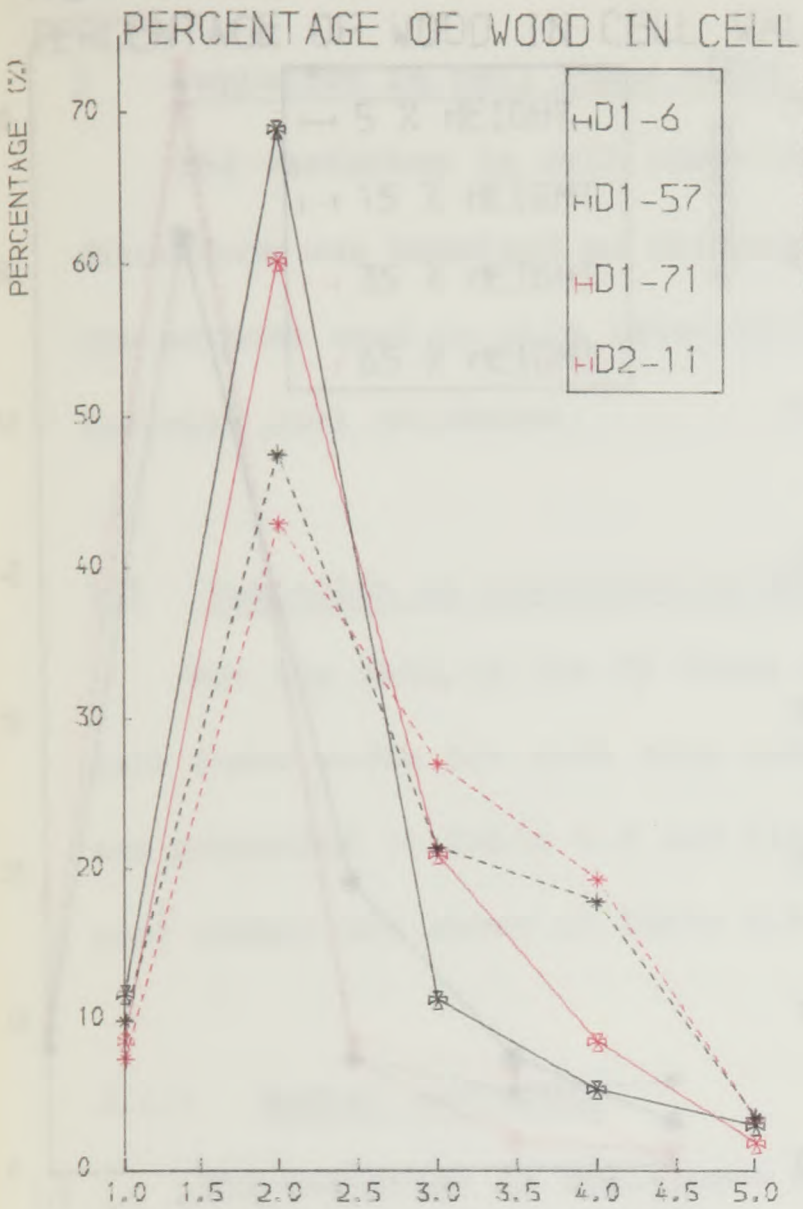


Figure 6.9

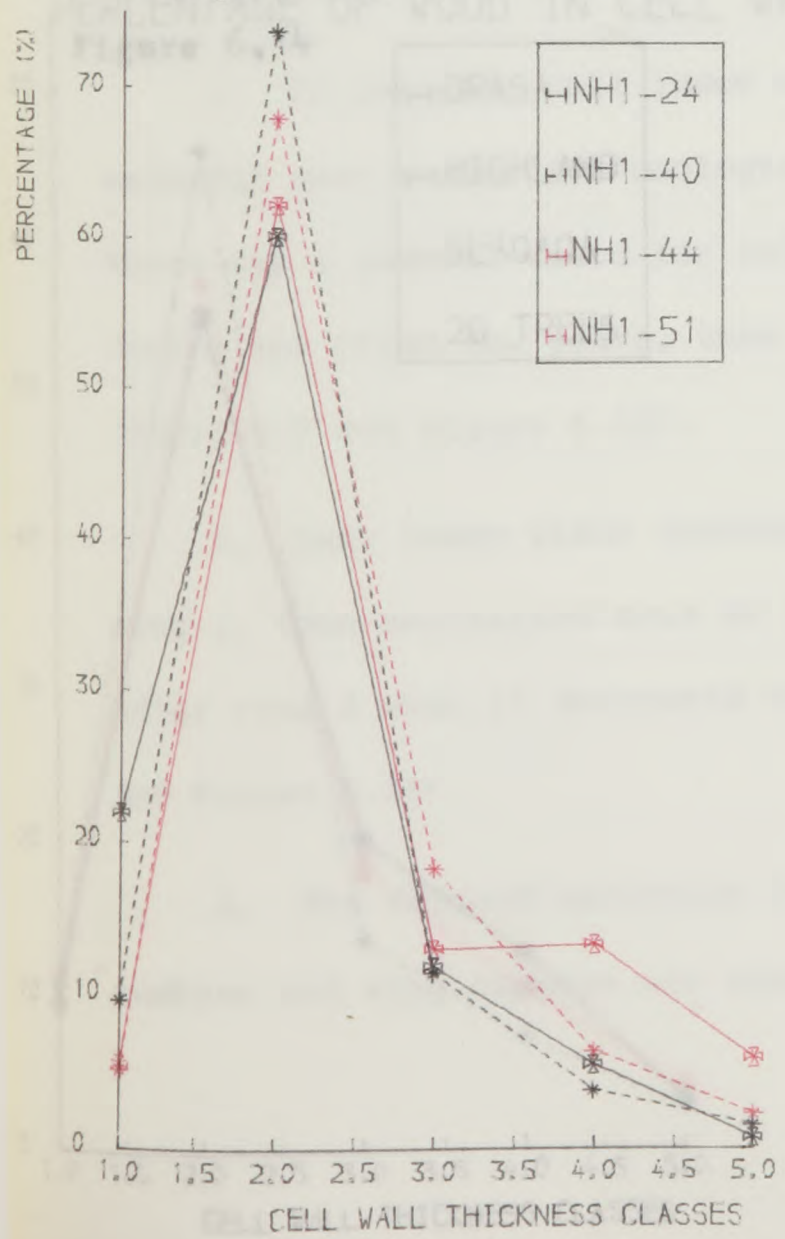


Figure 6.10

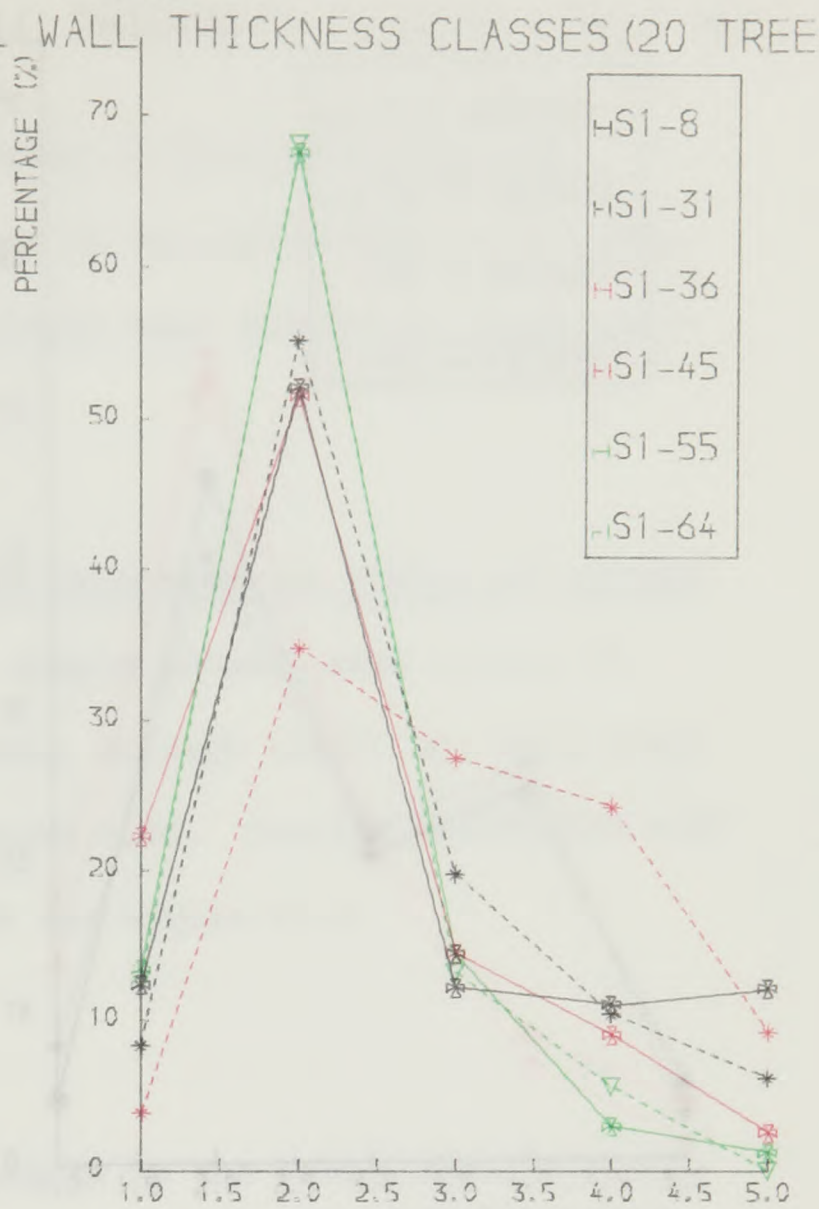


Figure 6.11

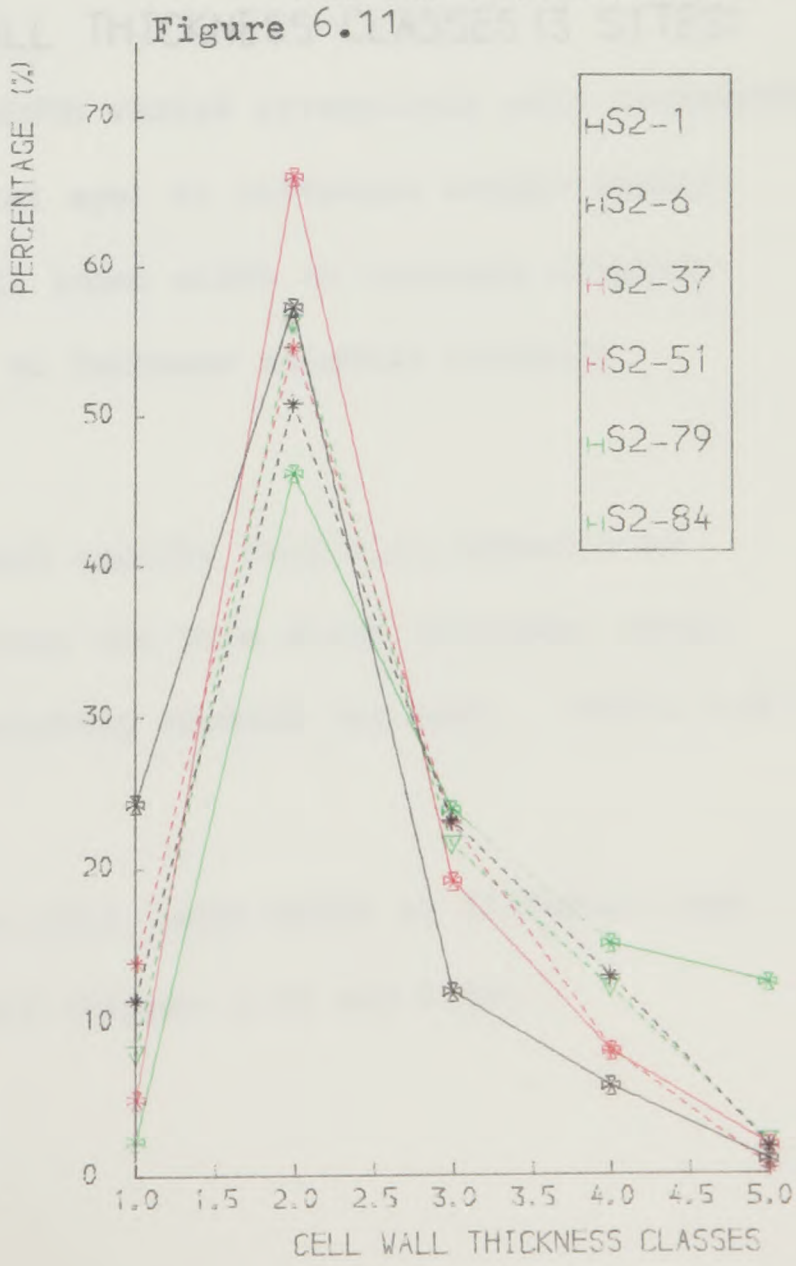


Figure 6.12

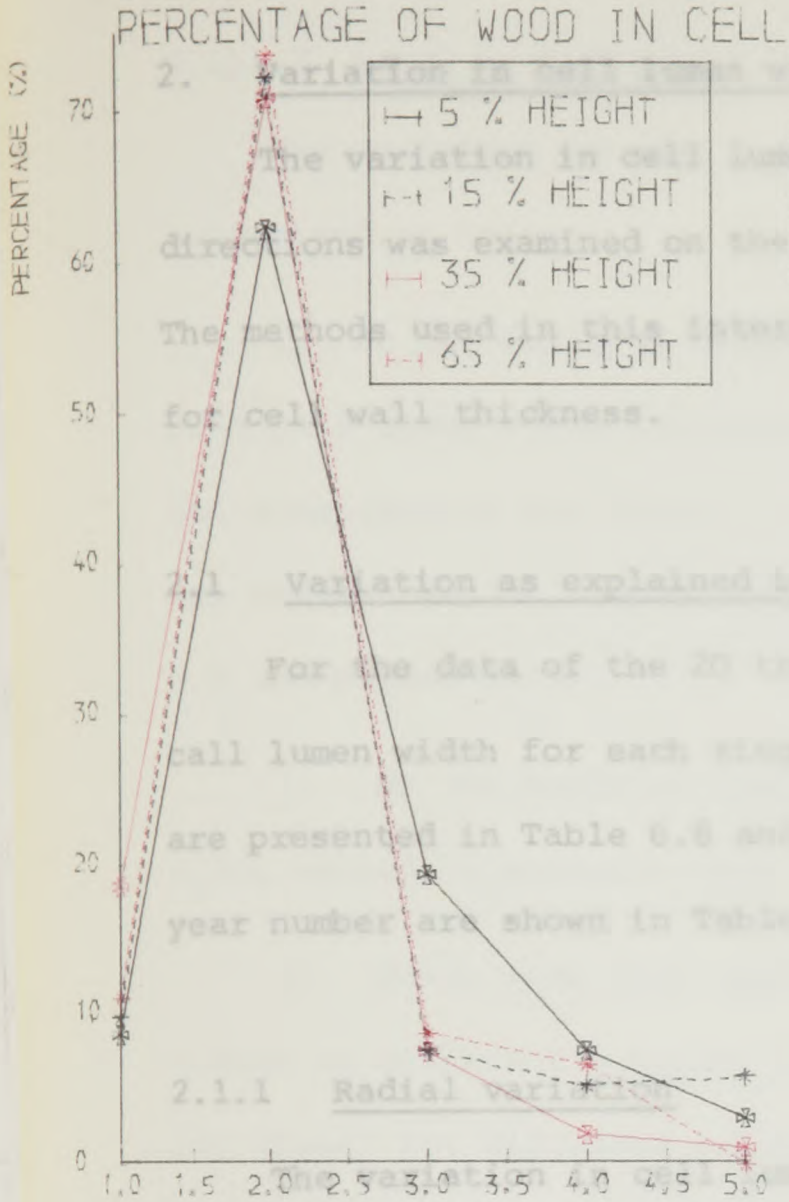


Figure 6.13

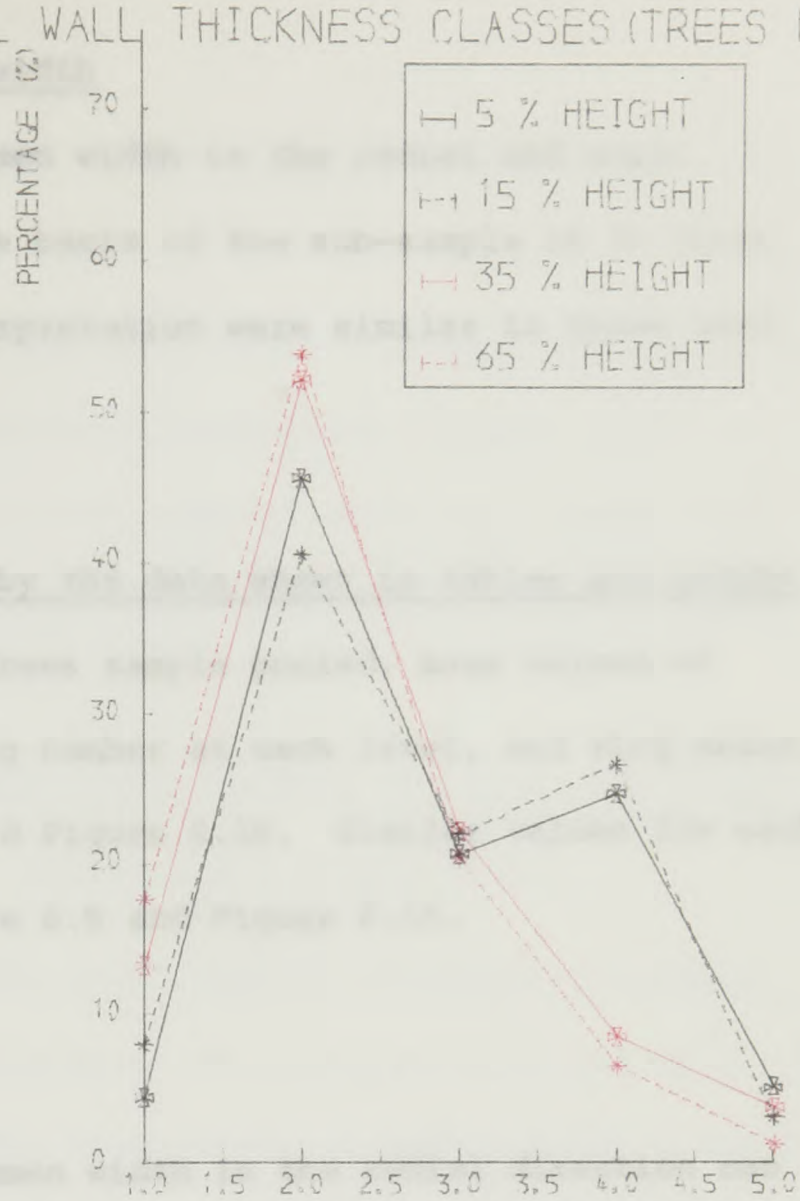
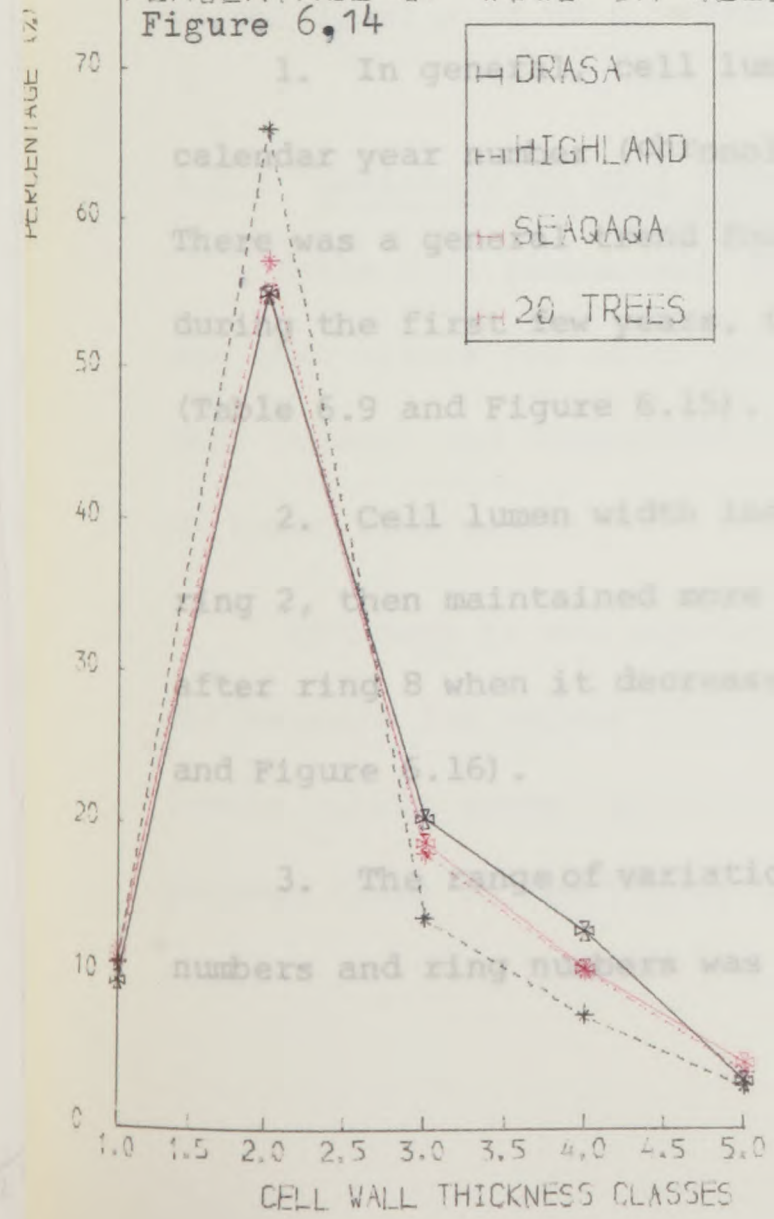


Figure 6.14



2. Variation in cell lumen width

The variation in cell lumen width in the radial and axial directions was examined on the basis of the sub-sample of 20 trees. The methods used in this interpretation were similar to those used for cell wall thickness.

2.1 Variation as explained by the data shown in tables and graphs

For the data of the 20 trees sample pooled, mean values of call lumen width for each ring number at each level, and ring means, are presented in Table 6.8 and Figure 6.16. Similar values for each year number are shown in Table 6.9 and Figure 6.15.

2.1.1 Radial variation

The variation in cell lumen width in the radial direction can be summarised as below:

1. In general, cell lumen width varied irregularly with increasing calendar year number (chronological age) at different height levels. There was a general trend for cell lumen width to increase slightly during the first few years, then to decrease slightly outwards (Table 6.9 and Figure 6.15).

2. Cell lumen width increased rapidly from ring number 1 to ring 2, then maintained more or less the same value outwards, until after ring 8 when it decreased slightly towards the bark. (Table 6.8 and Figure 6.16).

3. The range of variation in cell lumen width at different year numbers and ring numbers was small (Figure 6.15 and 6.16).

2.1.1.2 Axial variation

The variation in cell lumen width in the axial variation can be summarised as below:

1. On the basis of calendar year number (chonological age), mean ring cell lumen width increased with increasing % height level with the exception of the first two year numbers where cell lumen width was smaller at 35% and 65% height levels than at 5% and 15%. (Table 6.9 and Figure 6.15).

2. On the basis of number of rings from the pith, cell lumen width varied irregularly with increasing % height level.

3. There were very small and irregular differences between trends at different % height levels. The average of pooled data (20 trees) for different height level were: 5% height level = 33.15 μ, 15% height level = 34.93 μ, 35% height level = 55.68 μ and 65% height level = 34.64 μ. (Table 6.10)

2.1.2 Variation in cell lumen width between trees

Table 6.11 summarises the statistical interrelationships between the mean values for cell lumen width of the 20 trees (based on weighted disc values) and demonstrates the considerable range of variability of these tree means.

Although in the previous section it was shown that there were small differences for values of cell lumen width between rings and between levels within trees (pooled data), but there were considerable differences between trees in the values at the various levels as is shown in Table 6.10.

2.2 Variation as explained by simple regression analysis

From the study of variation in cell lumen width with % height level, year number, ring number, ring width and distance from pith, the regression and coefficient of determination obtained for pooled data and for sites separately are shown in Table 6.12 and the patterns of variation are illustrated in Figures 16.17 - 16.21. The results can be summarised as below:

1. For pooled data, the coefficients of determination of simple linear regressions between cell lumen width and % height level year number, ring number, ring width and distance from pith were not significant.

2. For the best fit regression lines, cell lumen width increased rapidly with ring number, ring width and distance from pith increase, at the beginning and then maintained a peak value or decreased slightly.

3. For the 3 sites separately, regression lines showed that there were considerable differences in cell lumen width at % height level, year, number, ring number, ring width and distance from pith

2.3 Variation as explained by multiple regression analysis

The models used in this section were the same as those employed in the examination of the variation in density. A multiple regression model was fitted to the data as follows:

$$y = b_o - b_1X_1 + b_2X_2 - b_3X_3 + b_4X_4 + b_5X_5 + b_6X_1^2 - b_7X_2^2$$

$$- b_8X_3^2 - b_9X_4^2 - b_{10}X_5^2$$

where b's = partial regression coefficients

X_1 = year number

X_2 = height level

X_3 = ring number

X_4 = ring width

X_5 = distance from the pith

y = cell lumen width

This gave a coefficient of determination (R^3) = 0.274, with residual standard deviation = 4.5756 μ and F value = 24.83 ***

The second model was

$$y = b_o - b_1X_1 + b_2X_2 - b_3X_3 + b_4X_4 + b_5X_5$$

This gave a coefficient of determination (r^2) = 0.17, with residual standard deviation = 4.8752 μ and F value = 27.09 ***. The proportion of the variation explained by these two models, as indicated by the values of R^2, was very low. In practical terms these equations cannot be used to predict cell lumen width reliably even within a single ring sample.

2.4 Variation as explained by morphological characteristics and age

In this part of the study, simple linear regressions were calculated to examine the association of whole tree mean cell lumen width with each of the following characteristics, for which the correlation coefficients are shown below:

Variables	R	sig
Tree age	-0.0276	n.s.
Tree height (m)	0.2266	n.s.
Diameter of breast height (mm)	0.5621	**
Crown width	0.136	n.s.
Crown length	0.1782	n.s.

Cell lumen width was positively correlatated with D.B.H. indicating that cell lumen width positively affected by the trees growth rate,

but the positive correlations with tree height, crown width and crown length were not significant.

Multiple regression analysis was not carried out because of few observations (20 trees) in this study.

2.5 Possibility of predicting whole tree cell lumen width

To examine the possibility of predicting whole tree values of cell lumen width from small samples, simple regressions were calculated to relate whole tree weighted value to weighted cell lumen width at four levels as follows:

			Coefficients	
% height level	Model	R^2	A	B
5	1	0.938	4.768488	0.8980404
15	1	0.953	3.479473	0.889187
35	1	0.925	1.713901	0.9199391
65	1	0.734	2.719165	0.9184982

The results indicate that the mean value of cell lumen width of cell lumen width of whole trees can be validly predicted from the 5% height level alone (best from 15% but most practical at 5%).

2.6 Cell lumen width distribution

Cell lumen width was separated into five classes as shown in Chapter 3. The following results list the simple correlations of whole tree weighted cell lumen width with the percentage of wood in the tree of each of these five different cell lumen width classes:

	Cell lumen width classes	R	sig.
Cell lumen width (20 trees)	CL-1(0.00-20.00 μ)	-0.8758	***
"	CL-2(20.01 - 30.00 μ)	-0.9291	***
"	CL-3(30.01 - 40.00 μ)	-0.3242	n.s.
"	CL-4(40.01 - 50.00 μ)	0.9493	***
"	CL-5 (Greater than 50.01 μ)	0.9168	***

Tree mean cell lumen width was strongly and negatively correlated with the first two classes, and strongly and positively correlated with the last two classes, but there was an insignificant negative correlation with class 3 (CL-3).

The percentage of the wood in the five cell lumen width classes varied considerably in different trees, as shown by the following range

CL-1: 1.9 % to 23.8 %

CL-2: 10.8 % to 39.6 %

CL-3: 27.5 % to 49.0 %

CL-4: 6.8 % to 39.8 %

CL-5: 0.0 % to 21.8 %

Distributions of cell lumen width within trees and between trees are illustrated in Figures 6.22 - 6.28. The pattern of cell lumen width distribution in all discs and all trees resembled a binomial function.

The following characteristics were found to emerge from the study of the graphs of cell lumen width distribution:

1. Between trees (Figures 6.22 -6.28)

There were considerable differences between trees in cell lumen width distribution. Although most trees showed a pattern resembling

Table 6.8 Mean cell lumen width and ring number at different % heights

% height										
65	30.8210	34.6380	35.5398	35.2435						
35	30.5750	35.6434	36.0709	35.1375	38.3847	36.0670	35.9962	35.2310		
15	33.8642	36.9360	37.6950	36.0406	34.0514	35.5074	35.3505	33.3149	32.7414	
5	33.5506	34.9996	34.7462	36.1435	34.0169	32.3217	32.8524	33.1608	31.6175	32.1702
Ring No.	1	2	3	4	5	6	7	8	9	10
Mean	32.2027	35.5543	36.0130	35.6413	35.4843	34.6320	34.7337	33.9022	32.1795	32.1702

Table 6.9 Mean cell lumen width and year number at different % heights

% height										
65							32.9669	35.7301	35.6827	34.4458
35			33.8751	35.3627	35.6024	37.4761	37.4323	36.2404	35.2891	34.0590
15		35.5216	37.3558	36.0114	35.6039	35.2241	35.8128	33.9575	33.0558	31.9367
5	35.2879	34.2938	34.9366	34.6467	33.3576	33.1450	33.2599	31.9055	30.9761	30.9289
Year No.	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973

Table 6.10 Mean weighted cell lumen width at different % heights

% height	D1-6	D1-57	D1-71	D2-11	NH1-24	NH1-40	NH1-44	NH1-51	S1-8	S1-31
5	32.5236	27.8763	26.4499	26.6967	39.9944	41.3674	34.2339	35.9282	30.6860	35.7355
15	34.2890	27.1631	28.8681	29.3028	42.3189	39.9432	36.0076	39.2272	35.7530	38.3270
35	36.3534	30.7899	30.9668	27.3883	41.9110	41.7067	35.8124	42.8205	37.3725	37.1286
65	30.9129	31.8555	32.3508	29.6968	42.2833	40.7396	37.5250	38.8184	38.0298	36.5453
Mean	33.7364	29.1309	29.3432	28.0908	41.5222	40.9501	35.6586	38.9636	34.9086	36.9693

% height	S1-36	S1-45	S1-55	S1-64	S2-1	S2-6	S2-37	S2-52	S2-79	S2-84	Pooled
5	29.7174	25.6788	36.6257	36.1133	38.3891	34.1874	32.6308	32.3444	32.8382	33.0126	33.1515
15	32.5050	25.8468	37.6985	37.4716	40.6335	36.0333	35.4463	32.9156	34.9088	33.9652	34.9312
35	32.0974	29.4197	38.7135	35.6747	40.9026	34.1634	36.9563	34.4416	33.2230	35.8126	35.6828
65	34.2255	29.7499	36.6762	33.6178	38.4573	30.5067	34.7002	33.2458	29.8876	33.0538	34.6443
Mean	31.7984	27.2564	37.4256	36.1132	39.6402	34.1949	34.8389	33.1281	33.1344	33.9933	34.5400

Figure 6.15

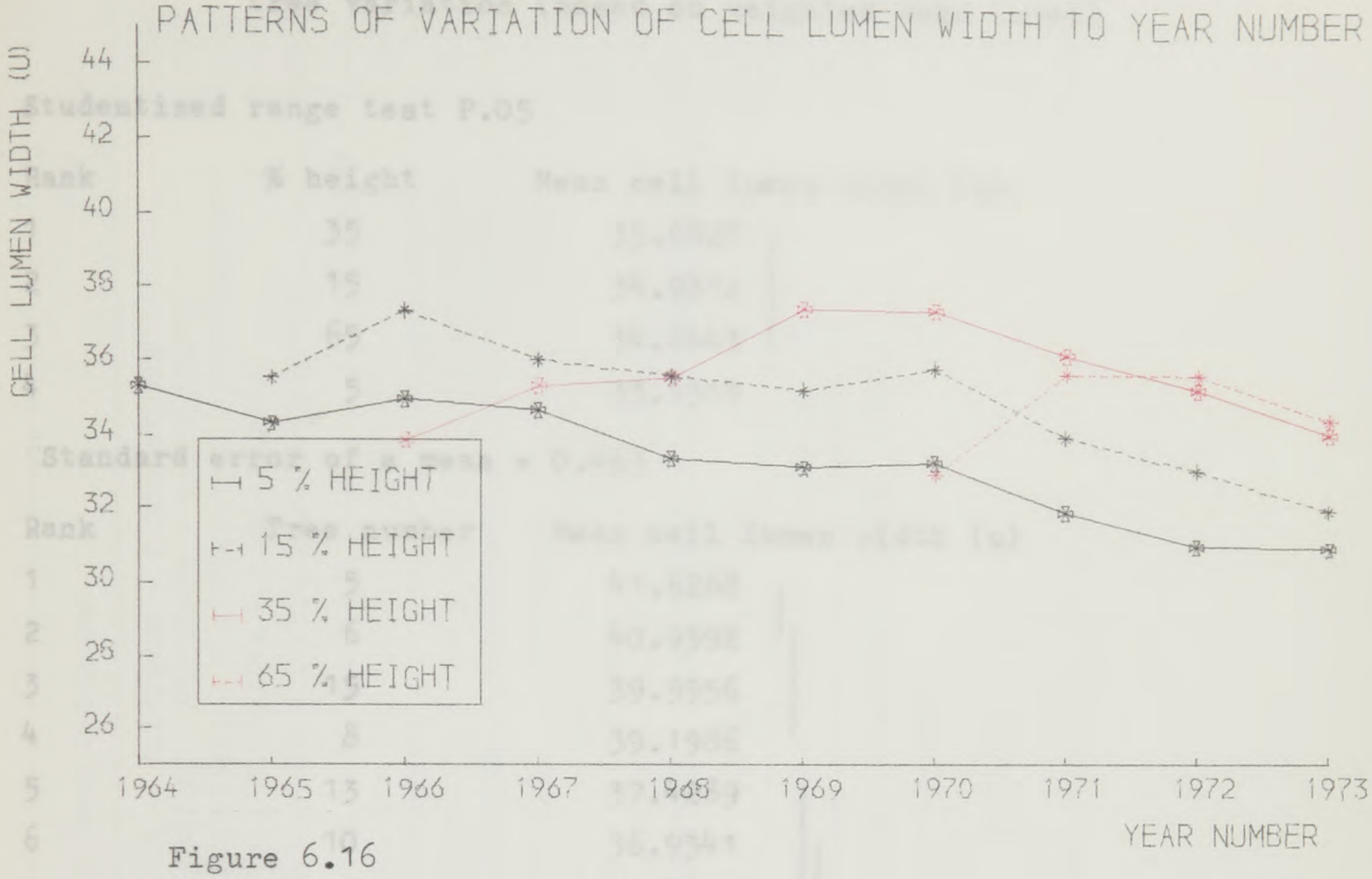


Figure 6.16

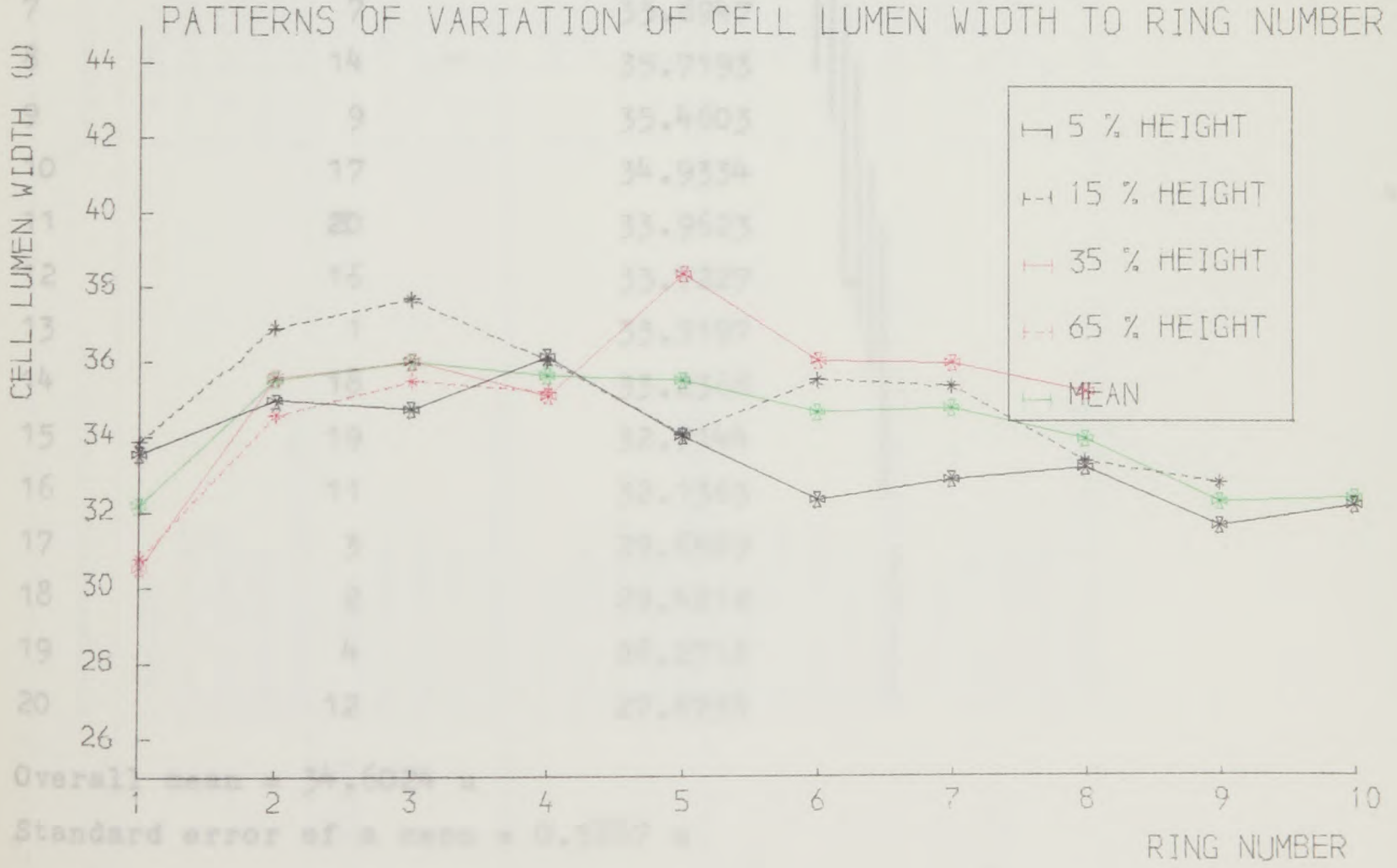


Table 6.11 Ranking order of trees cell lumen width ,tree statistical interrelationship and ranges of between tree variation (based on weighted mean level)

Studentized range test P.05

Rank	% height	Mean cell lumen width (u)
1	35	35.6828
2	15	34.9312
3	65	34.6443
4	5	33.1515

"Standard error of a mean = 0.463

Rank	Tree number	Mean cell lumen width (u)
1	5	41.6268
2	6	40.9392
3	15	39.5956
4	8	39.1986
5	13	37.4289
6	10	36.9341
7	7	35.8947
8	14	35.7193
9	9	35.4603
10	17	34.9334
11	20	33.9623
12	16	33.7227
13	1	33.5197
14	18	33.2368
15	19	32.7144
16	11	32.1363
17	3	29.6589
18	2	29.4212
19	4	28.2712
20	12	27.6738

Overall mean = 34.6024 u

Standard error of a mean = 0.5867 u

Numbers subtended by the same vertical line refer to the trees whose mean are not significantly different from each other.

Table 6.12 Regression of cell lumen width on % height, year number, ring number, ring width and distance from pith in each site and pooled data

Site	Independence variable	Regression best fit model	R^2	Sig.
Drasa	% height	$y = 28.01176 + 0.142442X - 0.001542969X^2$	0.048	
	Year number	$y = X/(464107.8 - 472.2367X + 0.1201434X^2)$	0.053	
	Ring number	$y = X/(0.004573944 + 0.02704038X + 0.001050807X^2)$	0.128	
	Ring width	$y = 26.8 + 0.456259X - 0.009018865X^2$	0.088	
	Distance from pith	$y = 32.91211 - 0.09745793X + 0.0006560037X^2$	0.029	
Nausori Highland	% height	$y = X/(0.008010805 + 0.02452988X + 0.000009769268X^2$	0.029	
	Year number	$y = -709294.2 + 720.4187X - 0.182919X^2$	0.084	
	Ring number	$y = X/(0.009519091 + 0.01862042X + 0.0007904933X^2)$	o.279	
	Ring width	$y = X/(0.01412751 + 0.02234653X + 0.0001318568X^2)$	0.081	
	Distance from pith	$y = X/(0.08536722 + 0.02150365X + 0.0000306958X^2)$	0.193	
Seaqaqa	% height	$y = X/0.01666223 + 0.02663624X + 0.00004377661X^2)$	0.039	
	Year number	$y = -207207.6 + 210.7316X - 0.05356986X^2$	0.020	
	Ring number	$y = 31.32977 + 1.737885X - 0.1724712X^2$	0.099	
	Ring width	$y = X/(0.02252088 + 0.0255218X + 0.00008939501X^2)$	0.047	
	Distance from pith	$y = X/(0.08056194 + 0.02427251X + 0.00004652033X^2)$	0.103	
Pooled data	% height	$y = 32.54 + 0.1686X - 0.002106X^2$	0.041	
	Year number	$y = -264793.5 + 269.2028X - 0.06841235X^2$	0.016	
	Ring number	$y = X/(0.007203 + 0.02312X + 0.0007387X^2)$	0.078	
	Ring width	$y = X/(0.02408 + 0.02517X + 0.00008831X^2)$	0.07	
	Distance from pith	$y = X/(0.0607 + 0.02586X + 0.00002802X^2)$	0.043	
Pooled data simple linear	% height	$y = 34.06 + 0.01819X$	0.009	ns.
	Year number	$y = a + bx$	0.0	ns
	Ring number	$y = 35.4 - 0.2069X$	0.012	ns
	Ring width	$y = a + bx$	0.0	ns
	Distance from pith	$y = a + bx$	0.0	ns

Figure 6.17

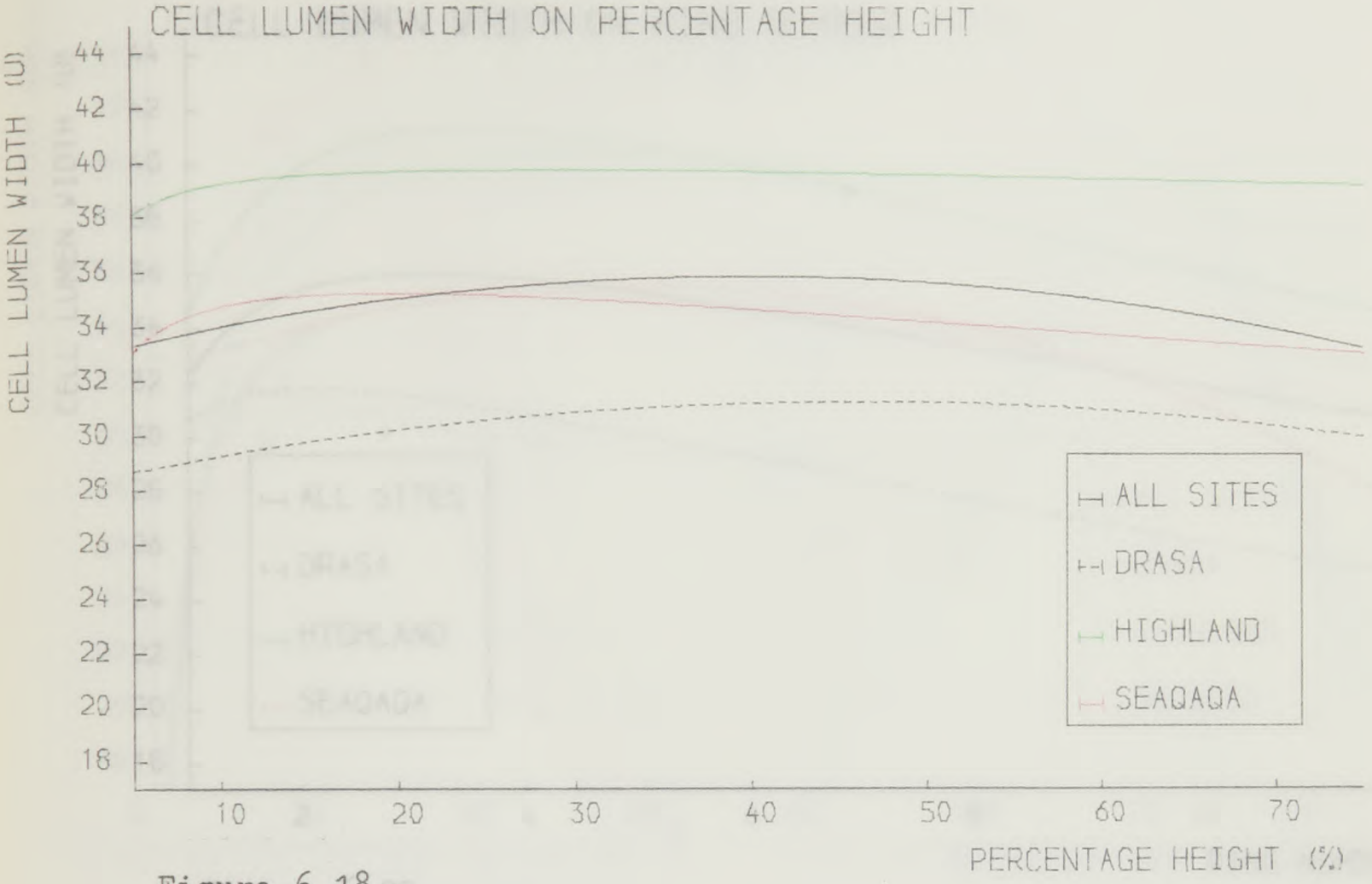


Figure 6.18

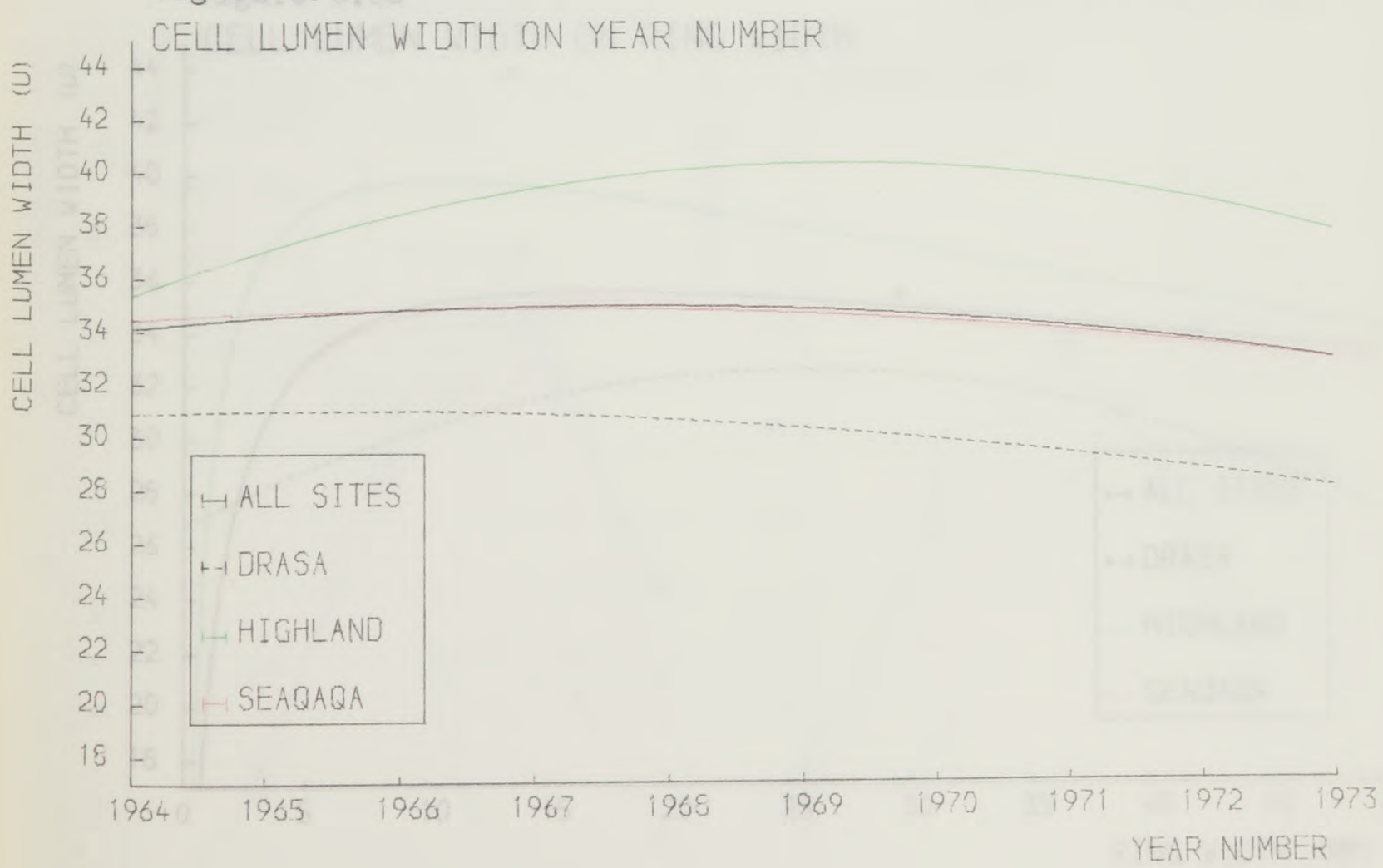


Figure 6.19

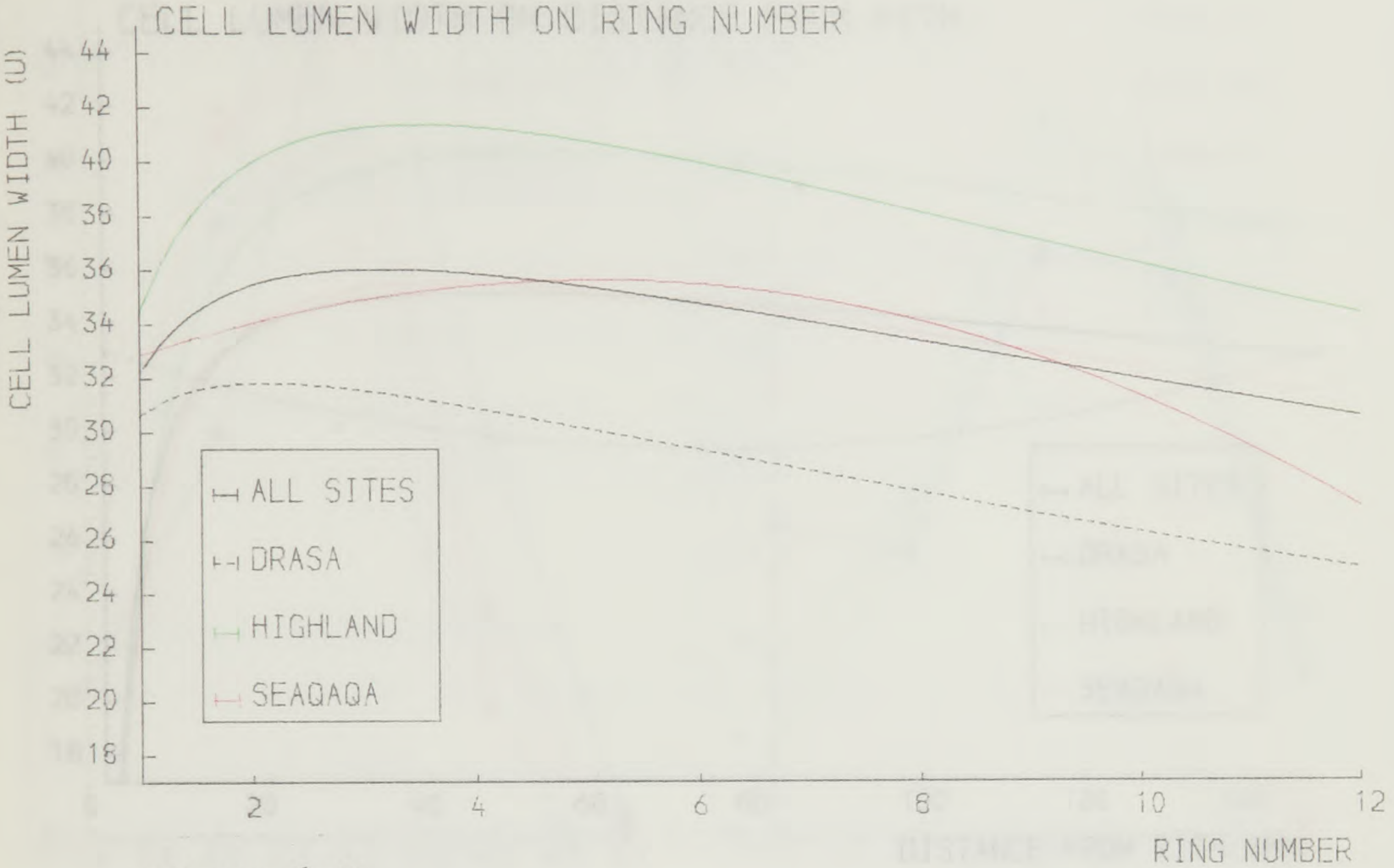


Figure 6.20

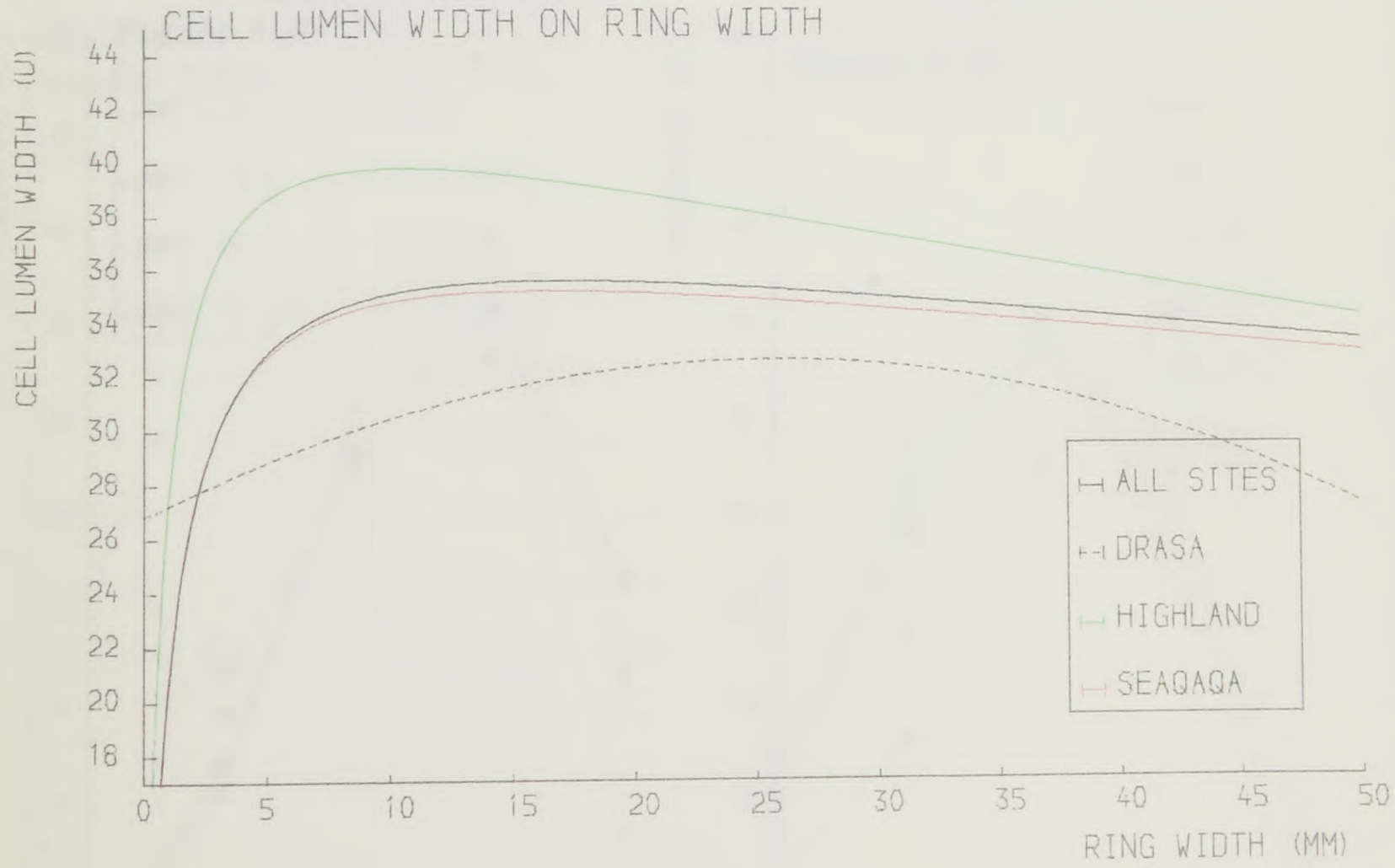


Figure 6.21

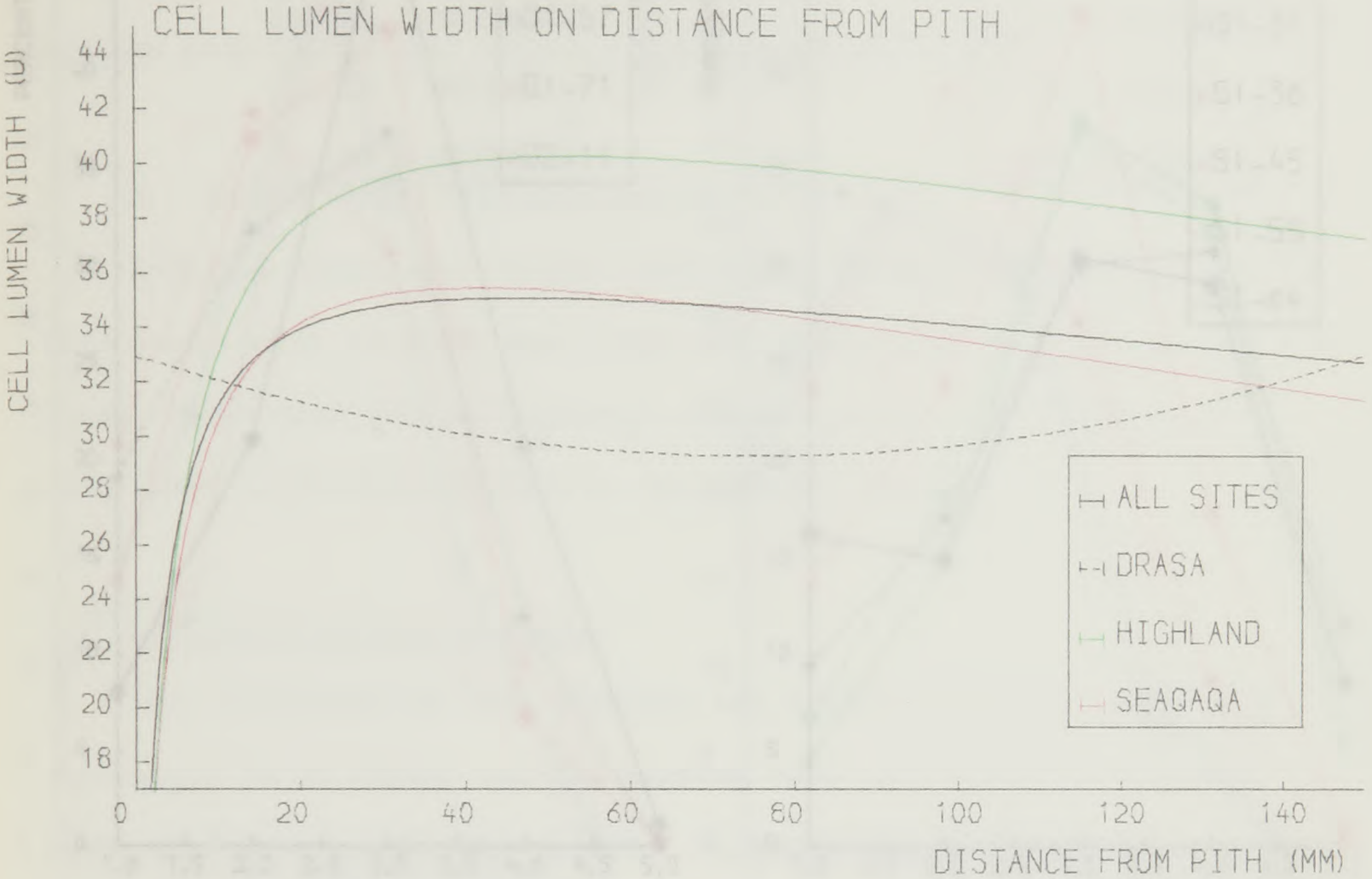

CELL LUMEN WIDTH ON DISTANCE FROM PITH
CELL LUMEN WIDTH (U)
44
42
40
38
36
34
32
30
28
26
24
22
20
18
0
20
40
60
80
100
120
140
DISTANCE FROM PITH (MM)
ALL SITES
DRASA
HIGHLAND
SEAQAQA

Figure 6.22

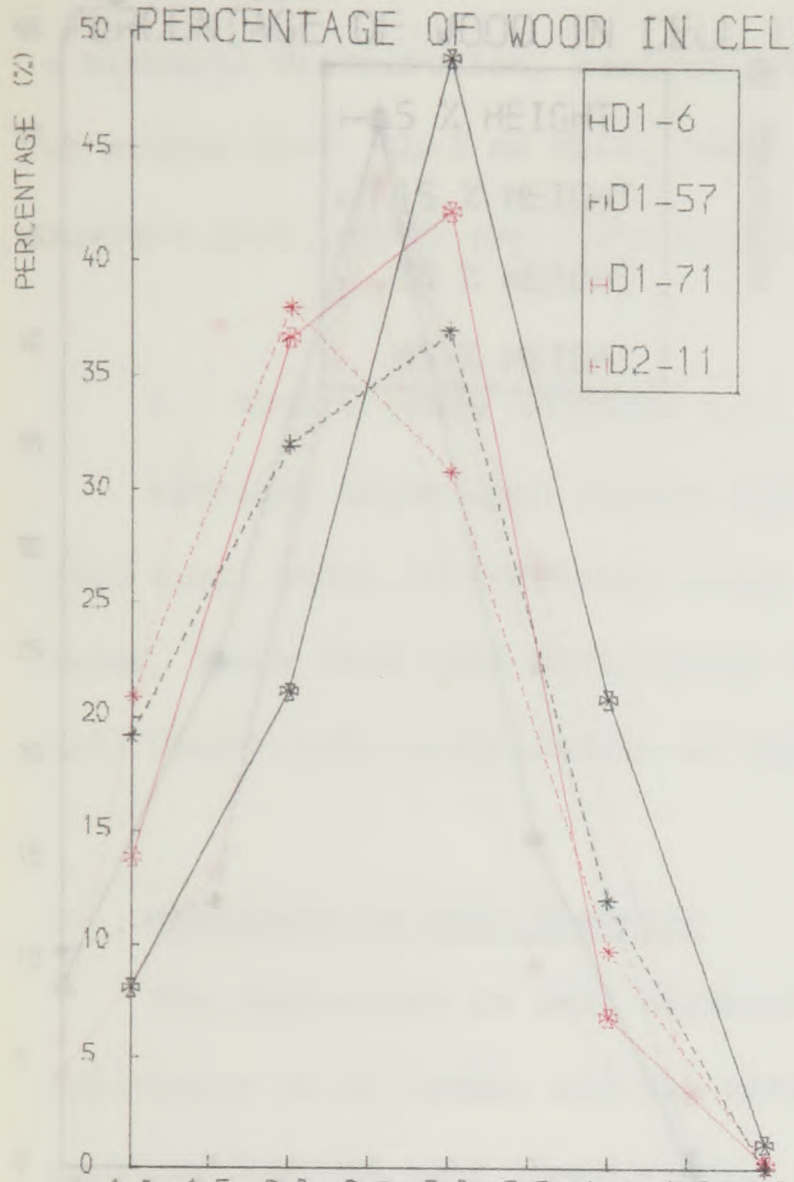


Figure 6.23

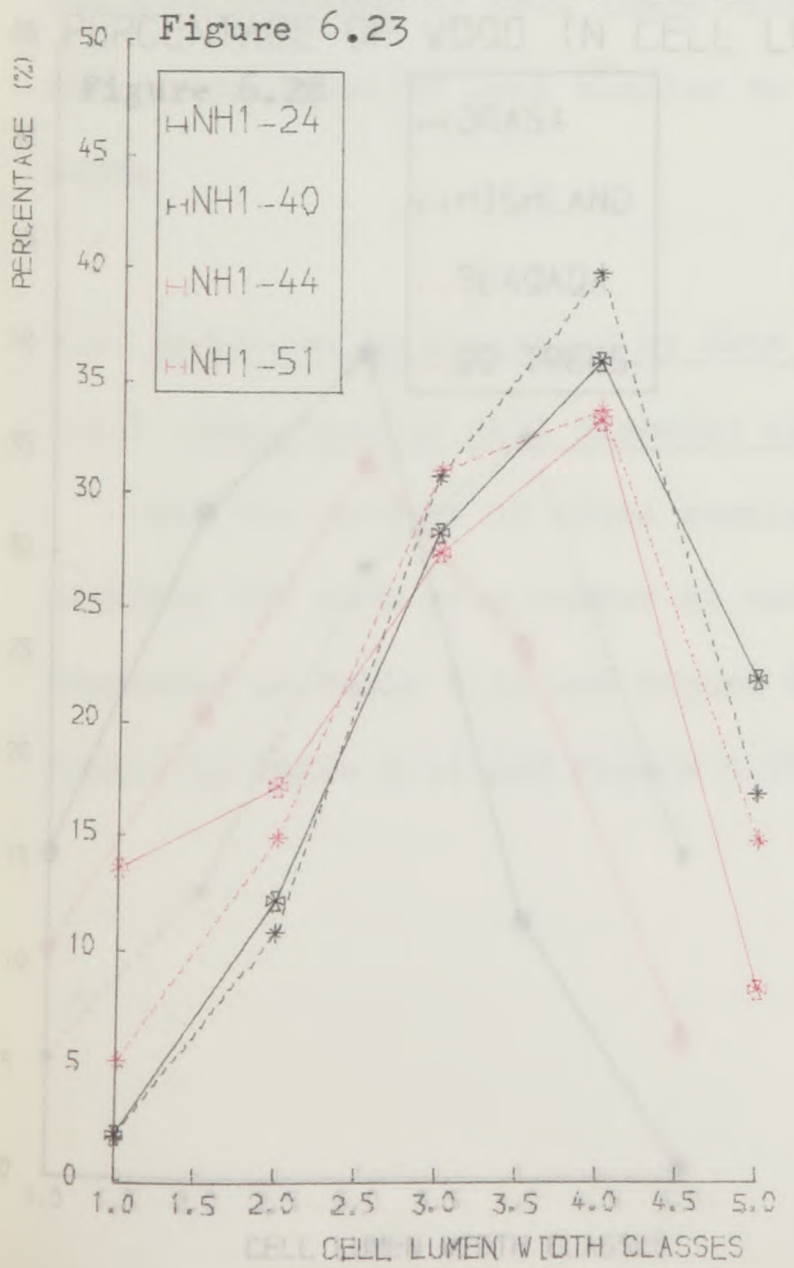


Figure 6.24

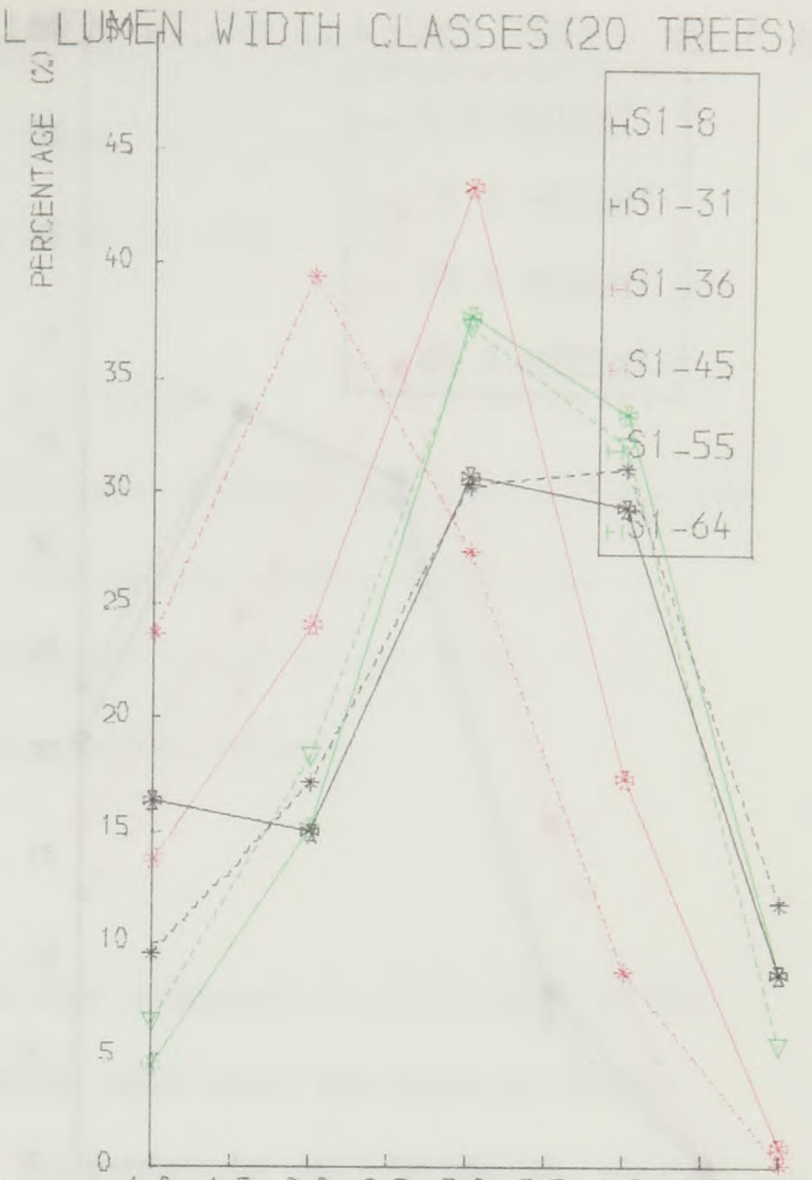


Figure 6.25

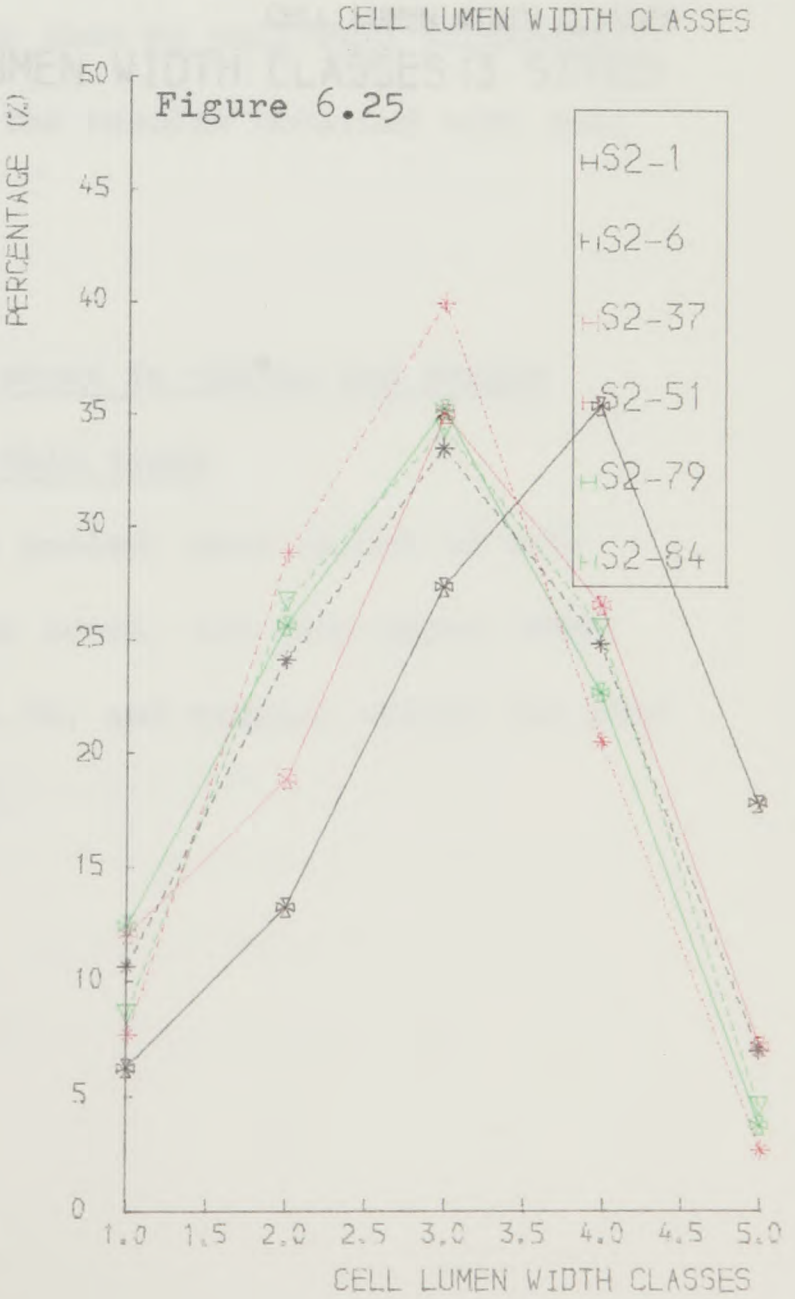


Figure 6.26

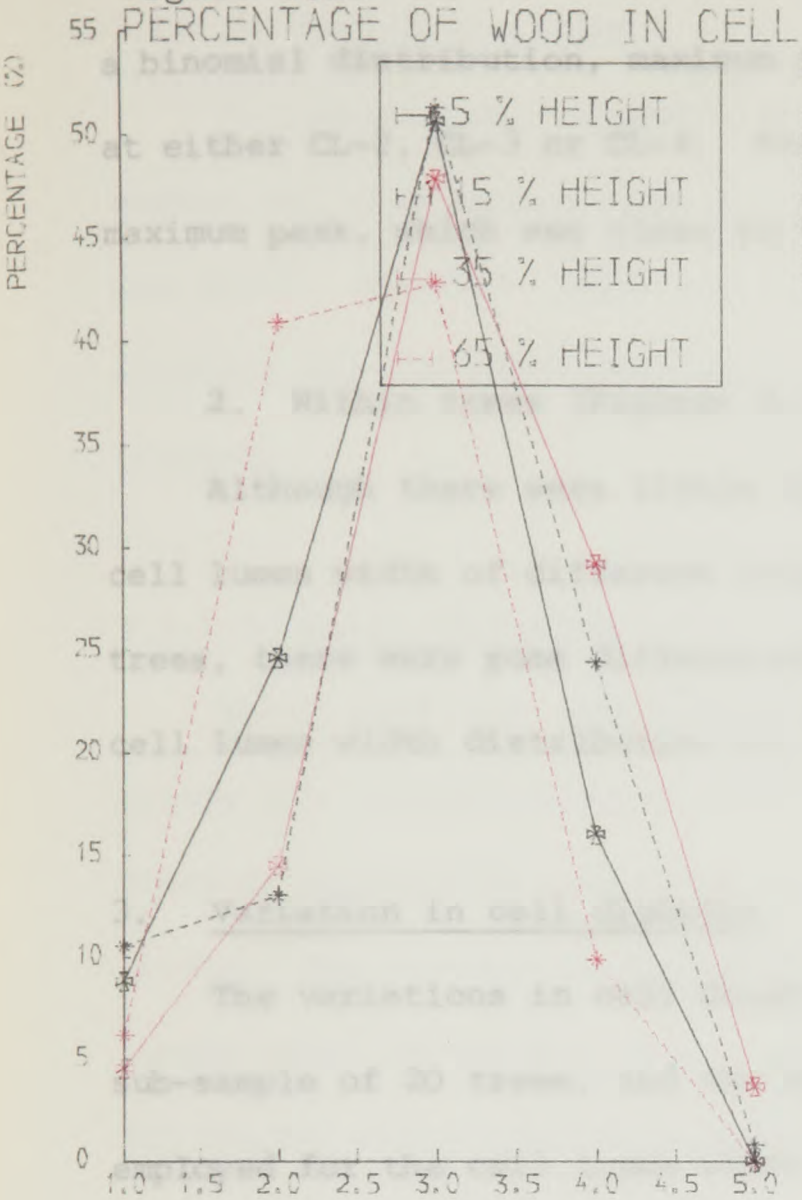


Figure 6.27

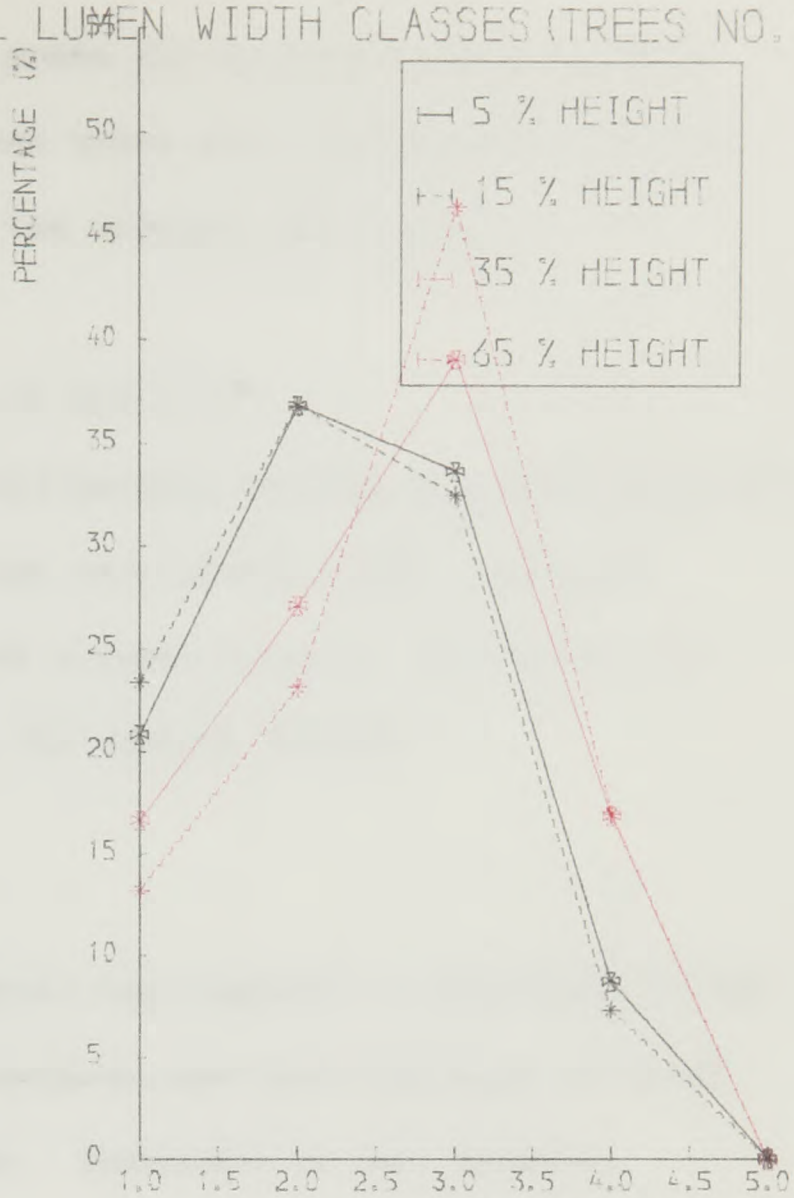
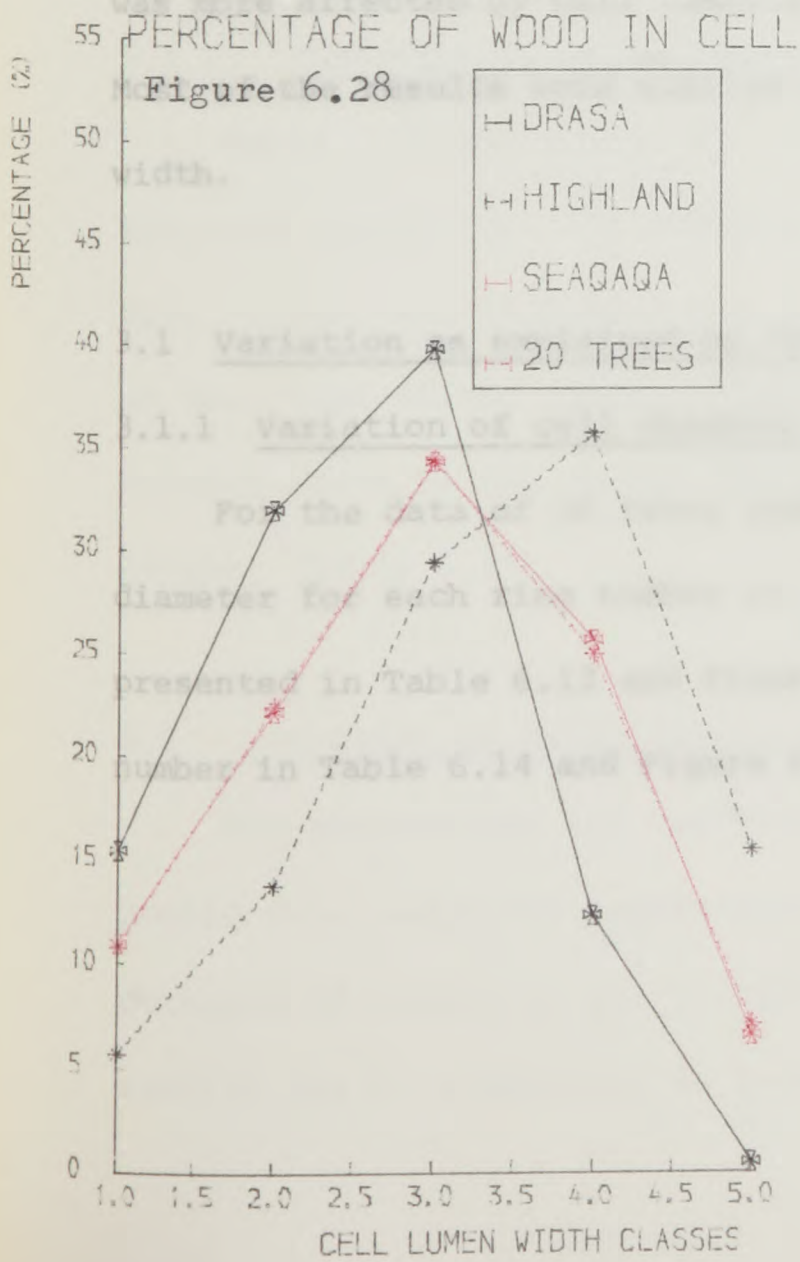


Figure 6.28



a binomial distribution, maximum peaks for different trees occurred at either CL-2, CL-3 or CL-4. Some trees also exhibited a secondary maximum peak, which was close to the maximum peak value.

2. Within trees (Figures 6.26 and 6.27)

Although there were little differences between the mean values for cell lumen width of different rings and levels within individual trees, there were some differences between trees in the pattern of cell lumen width distribution at the various levels.

3. Variation in cell diameter

The variations in cell diameter was examined on the basis of the sub-sample of 20 trees, and the methods used were the same as those employed for the cell lumen width. Variation in cell diameter was more affected by cell lumen width than by cell wall thickness. Most of the results were similar to the results obtained with cell width.

3.1 Variation as explained by data shown in tables and graphs

3.1.1 Variation of cell diameter within trees

For the data of 20 trees sample pooled, mean values of cell diameter for each ring number at each level, and ring means, were presented in Table 6.13 and Figure 6.30, and similar values for year number in Table 6.14 and Figure 6.29.

3.1.1.1 Radial variation

In general, cell diameter varied irregularly with increasing year number and ring number from the pith outward to the bark, but the range was small. However, there was a trend for cell diameter to increase slightly for the first few years (or rings), then to decrease slightly outwards.

3.1.1.2 Axial variation

There were very small and irregular differences between mean values for cell diameter at different % height levels, and for cell diameter within the same year number or ring number at different levels. The average of pooled data (20 trees) at different height levels were: 5% height level = 41.42 μ, 15% height level = 42.56 μ, 35% height level = 42.72 μ and 65% height level = 40.95 μ.

3.1.2 Variation of cell diameter between trees

Table 6.16 summarises the statistical interrelationships between the mean values for cell diameter of the 20 trees (based on weighted disc values) and indicates the considerable range of variability of the means of the trees. There was also considerable differences between trees in the values for cell diameter at the various height levels. (Table 6.15)

3.2 Variation as explained by simple regression analysis

The regressions and coefficients of determination obtained for pooled data and sites separately are shown in Table 6.17 and the patterns of variation are illustrated in Figures 6.31-6.35. The results can be summarised as below:

1. For pooled data, using simple linear regression, cell diameter was positively correlated with distance from pith, but correlation with % height level, year number, ring number and ring width was not significant. Values of the coefficient of determination (R^2) were small.

2. For the best fit regression lines, cell diameter increased rapidly with ring number, ring width and distance from pith at the very beginning and then flattened off or decreased slightly.

The coefficients of determination (R^2) were again small, indicating a poor relationship between cell diameter and these tree growth parameters.

3. For the data of the 3 sites separately, regression lines showed that there were considerable differences between them at the various % height level, year number, ring number, ring width, and distance from pith.

3.3 Variation as explained by multiple regression analysis

The models used in this section were the same as those employed in the examination of the variation in cell lumen width. A multiple regression model was fitted to the data as follows:

$$y = b_o - b_1X_1 + b_2X_2 + b_3X_3 + b_4X_4 + b_5X_5 + b_6X_1^2 - b_7X_2^2 - b_8X_3^2 - b_9X_4^2 - b_{10}X_5^2$$

where b's = partial regression coefficients

X_1 = year number

X_2 = % height level (%)

X_3 = ring number

X_4 = ring width (mm)

X_5 = distance from pith (mm)

y = cell diameter (μ)

This gave a coefficient of determination (R^2) = 0.31, with residual standard deviation = 3.86 μ and F test = 29.87 ***.

Although the results given by this model was highly significant, the proportion of the variation explained by the values of R^2 was low. This indicated that these equations cannot be used to predict ring or tree cell diameter reliably from these tree growth parameters.

3.4 Variation as explained by morphological characteristics

The values for weighted tree mean cell diameter were regressed against each of the following characteristics, for which the correlation coefficients (R) of simple linear regressions are shown below:

Variables	R	Sig.
Tree height	0.323	n.s.
Tree age	0.005	n.s.
Diameter at breast height	0.541	**
Crown width	0.136	n.s.
Crown length	0.162	n.s.

Cell diameter was positively correlated with D.B.H, indicating that cell diameter was positively effected by the tree's growth rate, but positive correlations with tree height, crown width and crown length were not significant.

Multiple regression analysis was not carried out because of the few observations (20 trees) in this study and because of the poor value R in simple linear regressions.

3.5 Possibility of predicting whole tree cell diameter

For the possibility of predicting whole tree values for cell diameter from small samples, simple regressions were calculated to relate whole tree weighted values to weighted cell diameters at four different levels as follows:

% height level	Model	R^2	A	B
5	1	0.946	3.831678	0.9216127
15	1	0.971	3.12235	0.9136505
35	1	0.941	2.516496	0.9243973
65	1	0.832	1.11838	0.9986199

Again, although the best prediction is the 15% height sample, the mean value of cell diameter of whole trees can adequately predicted from a sample taken at 5% height level alone.

3.6 Cell diameter distribution

Cell diameter was separated into five classes as shown in chapter 3. The following results list the simple correlations of whole tree weighted cell diameter with the percentage of wood in the tree of each of the five different cell diameter classes:

	Cell diameter classes	R	Sig.
Cell diameter (20 trees)	CD-1 (0.00-20.00 μ)	0	n.s.
"	CD-2 (20.00-30.00 μ)	-0.9371	***
"	CD-3 (30.01-40.00 μ)	-0.9781	***
"	CD-4 (40.01-50.00 μ)	0.6729	***
"	CD-5 (Greater than 50.01μ)	0.9818	***

Tree mean cell diameter was not related to the CD-1, but was strongly and negatively correlated with CD-2 and CD-3, and positively correlated with CD-4 and CD-5.

The wood percentage of the five cell diameter classes varied considerably in different trees, as shown by the following range as follows:

CD-1: 0.0% to 0.23%

CD-2: 1.10% to 16.16%

CD-3: 17.41% to 56.44%

CD-4: 27.48% to 47.69%

CD-5: 1.24% to 39.42%

The following characteristics were found to emerge from the study of the graphs of cell diameter distribution:

1. Between trees (Figures 6.36-6.39)

There were differences between trees in cell diameter distribution. Maximum peak of wood percentage for different trees occurred at CD-3, CD-4 and CD-5. Some trees were found to have equal values at CD-3 and CD-4 or CD-4 and CD-5. However, most trees showed a pattern resembling a binomial distribution.

2. Within trees (Figures 6.40-6.41)

There were little differences between the mean values for cell diameter of different rings and levels within individual trees. Differences in the pattern of cell diameter distribution within trees at various levels were small, (see Figures 6.40 and 6.41) but there were considerable between trees differences in actual values at various levels.

% height										
65	35.3770	40.3294	41.8029	41.7071						
35	34.7956	41.1264	42.1542	41.8891	45.1724	43.5868	43.8750	42.9475		
15	38.3835	42.8746	44.1577	43.2657	42.0927	43.6074	43.6612	42.6886	41.9124	
5	37.7900	41.0902	41.9126	43.3538	42.4271	41.5842	42.0329	42.3112	41.4052	41.7076
Ring No.	1	2	3	4	5	6	7	8	9	10
Mean	36.5877	41.3552	42.5069	42.5589	43.2307	42.9261	43.1897	42.6491	41.6588	41.7076

Table 6.14 Mean cell diameter and year number at different % heights

% height										
65							38.2816	41.7718	42.3000	41.2333
35			38.9132	41.2830	42.0334	44.2582	44.5354	43.9611	43.2365	41.9114
15		40.9127	43.6373	43.1643	43.1083	43.2509	43.9310	42.8879	42.6000	40.9889
5	40.4720	41.1886	42.2561	42.6385	42.2361	42.1971	42.3133	41.5838	41.2134	40.1196
Year No.	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973

Table 6.15 Mean weighted cell diameter at different % heights

% height	D1-6	D1-57	D1-71	D2-11	NH1-24	NH1-40	NH1-44	NH1-51	S1-8	S1-31
5	39.8587	37.0474	35.0481	36.4484	46.7041	48.2087	43.4609	44.1978	40.7710	44.6676
15	40.9726	36.2050	36.4584	37.9612	48.5674	46.8682	43.9740	46.8552	44.2938	46.6034
35	42.1185	38.1626	37.8063	36.1432	47.7220	47.4434	43.6482	49.2310	44.6771	45.0384
65	37.2035	38.6431	37.6505	36.3145	46.9314	45.9999	43.5947	45.0183	44.2207	42.8611
Mean	40.3438	37.3851	36.6177	36.8120	47.5307	47.2734	43.6732	46.2843	43.2504	45.0471

% height	S1-36	S1-45	S1-55	S1-64	S2-1	S2-6	S2-37	S2-51	S2-79	S2-84	Pooled
5	37.6320	36.1726	43.2501	42.5632	45.0557	42.0321	40.7617	39.7566	43.5286	41.3588	41.4200
15	38.6995	37.3174	43.9238	43.9223	46.5947	43.2535	43.3879	40.3607	43.3776	41.8752	42.5600
35	38.7563	38.3404	44.8793	42.1633	46.6242	41.5829	43.7686	40.9871	42.6073	42.7831	42.7400
65	38.9618	37.6093	42.3833	39.6962	43.9266	39.3869	40.2581	39.3708	39.2631	39.6608	41.0000
Mean	38.4812	37.2492	43.6749	42.4100	45.6757	41.9021	42.1720	40.1442	42.6781	41.6068	42.5100

Figure 6.29

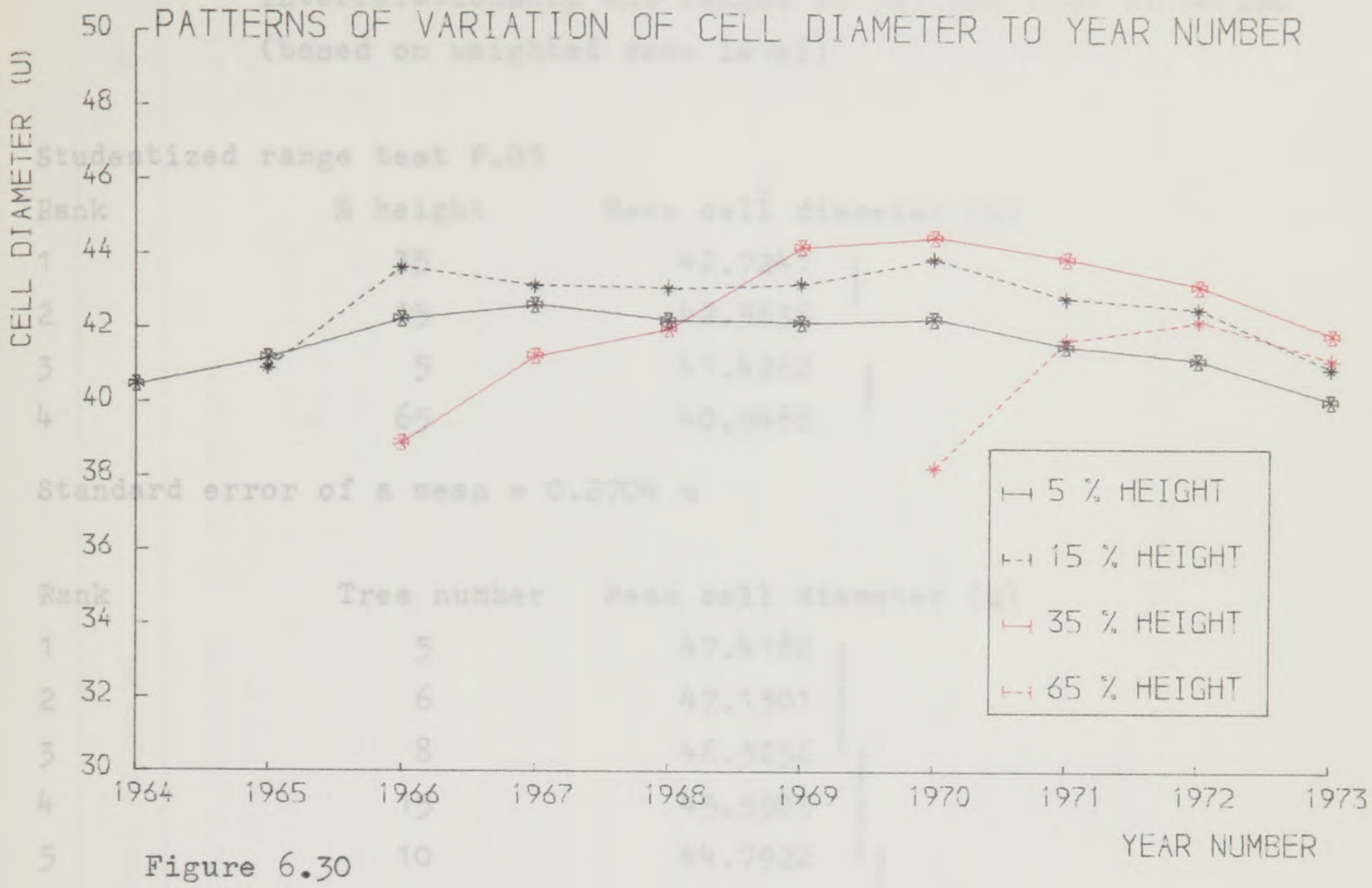


Figure 6.30

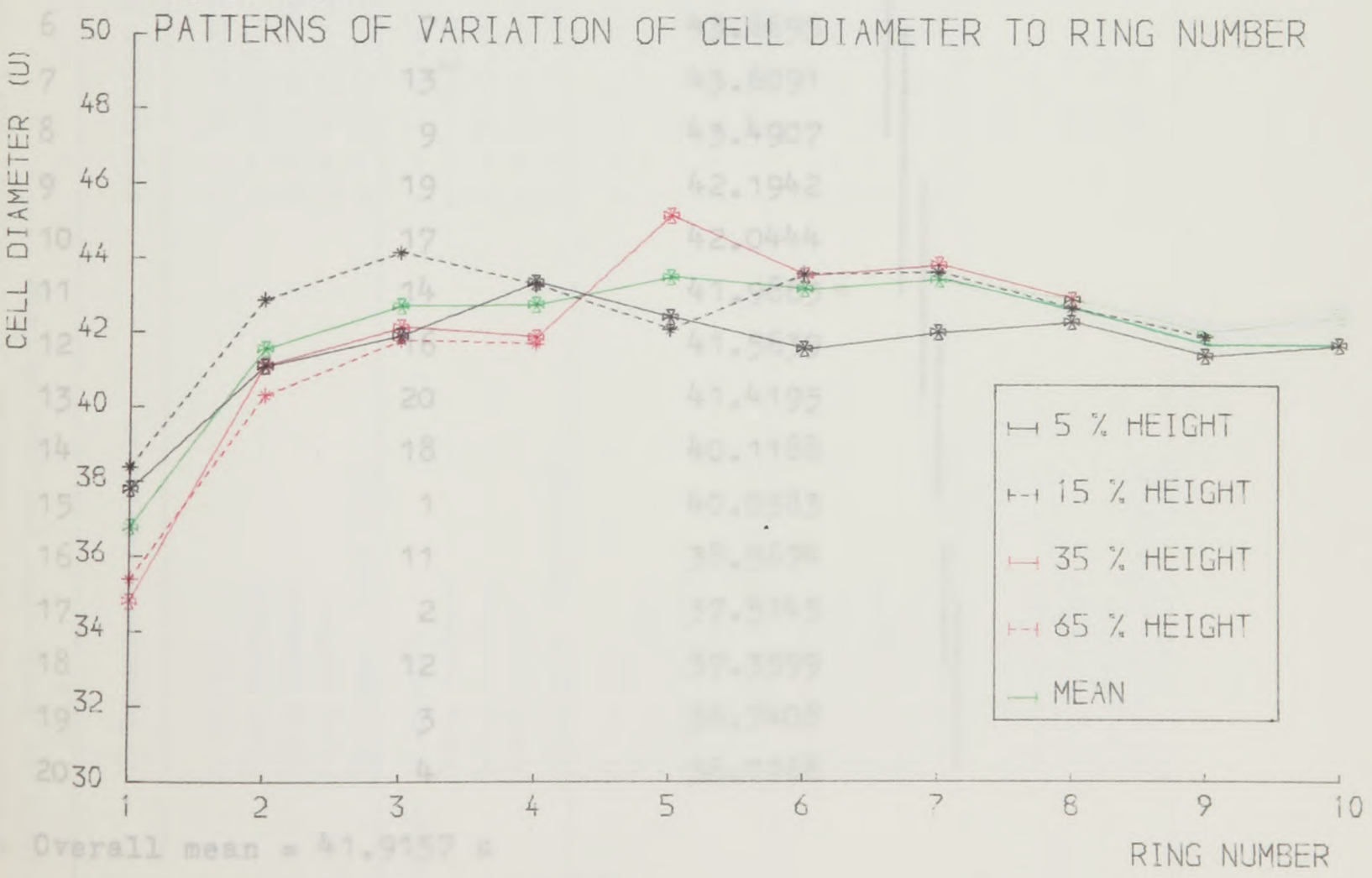


Table 6.16 Ranking order of trees cell diameter, tree statistical interrelationship and ranges of between tree variation (based on weighted mean level)

Studentized range test P.05

Rank	% height	Mean cell diameter (u)
1	35	42.7241
2	15	42.5636
3	5	41.4262
4	65	40.9488

Standard error of a mean = 0.2704 u

Rank	Tree number	Mean cell diameter (u)
1	5	47.4182
2	6	47.1301
3	8	46.3256
4	15	45.5503
5	10	44.7922
6	7	43.6695
7	13	43.6091
8	9	43.4907
9	19	42.1942
10	17	42.0444
11	14	41.9863
12	16	41.5639
13	20	41.4195
14	18	40.1188
15	1	40.0383
16	11	38.5674
17	2	37.5145
18	12	37.3599
19	3	36.7408
20	4	36.7168

Overall mean = 41.9157 u

Standard error of mean = 0.4560 u

Numbers subtended by the same vertical line refer to the trees whose mean are not significantly different from each other.

Table 6.17 Regression of cell diameter on % height, year number, ring number, ring width and distance from pith in each site and pooled data

Site	Independent variable	Regression best fit model	R^2	sig.
Drasa	% height	$y = 37.13327 + 0.06311583X - 0.00109025X^2$	0.017	
	Year number	$y = -452477 + 459.5956X - 0.1166966X^2$	0.053	
	Ring number	$y = X/(0.004903091 + 0.02341111X + 0.0003283556X^2)$	0.114	
	Ring width	$y = X/(0.003025582 + 0.02527992X + 0.0000802213X^2)$	0.057	
	Distance from pith	$y = X/(0.02404907 + 0.02690314X - 0.00001461316X^2)$	0.116	
Nausori Highland	% height	$y = X/(0.004833584 + 0.0208685X + 0.00002105671X^2)$	0.019	
	Year number	$y = -789379.9 + 801.5352X - 0.2034572X^2$	0.173	
	Ring number	$y = X/(0.007583459 + 0.01731717X + 0.0004218958X^2)$	0.453	
	Ring width	$y = X/(0.00900504 + 0.01905137X + 0.000142547X^2)$	0.206	
	Distance from pith	$y = X/(0.06964906 + 0.01954544X + 0.00001061844X^2)$	0.404	
Seaqaqa	% height	$y = X/(0.009547319 + 0.02207616X + 0.000045401X^2)$	0.057	
	Year number	$y = -337803.3 + 343.0507X - 0.08708398X^2$	0.052	
	Ring number	$y = X/(0.006952688 + 0.02040833X + 0.000288655X^2)$	0.265	
	Ring width	$y = X/(0.004472222 + 0.0223712X + 0.0001030088X^2)$	0.064	
	Distance from pith	$y = X(0.07336002 + 0.0214778X + 0.00001299196X^2)$	0.310	
Pooled data	% height	$y = 41.02 + 0.1149X - 0.00179X^2$	0.041	
	Year number	$y = -406172.4 + 412.4857X - 0.1047133X^2$	0.045	
	Ring number	$y = X/0.006677 + 0.02033X + 0.0003136X^2)$	0.182	
	Ring width	$y = X/(0.009555 + 0.02152X + 0.0001163X^2$	0.069	
	Distance from pith	$y = X/(0.05958 + 0.02251X + 0.0000001937X^2)$	0.205	
Pooled data simple linear	% height	$y = 42.31 - 0.01299X$	0.007	n.s.
	Year number	$y = -362.4 + 0.2052X$	0.016	n.s.
	Ring number	$y = 40.03 + 0.3244X$	0.039	n.s.
	Ring width	$y = 42.68 - 0.09106X$	0.026	n.s.
	Distance from pith	$y = 38.42 + 0.05047X$	0.117	***

Figure 6.31

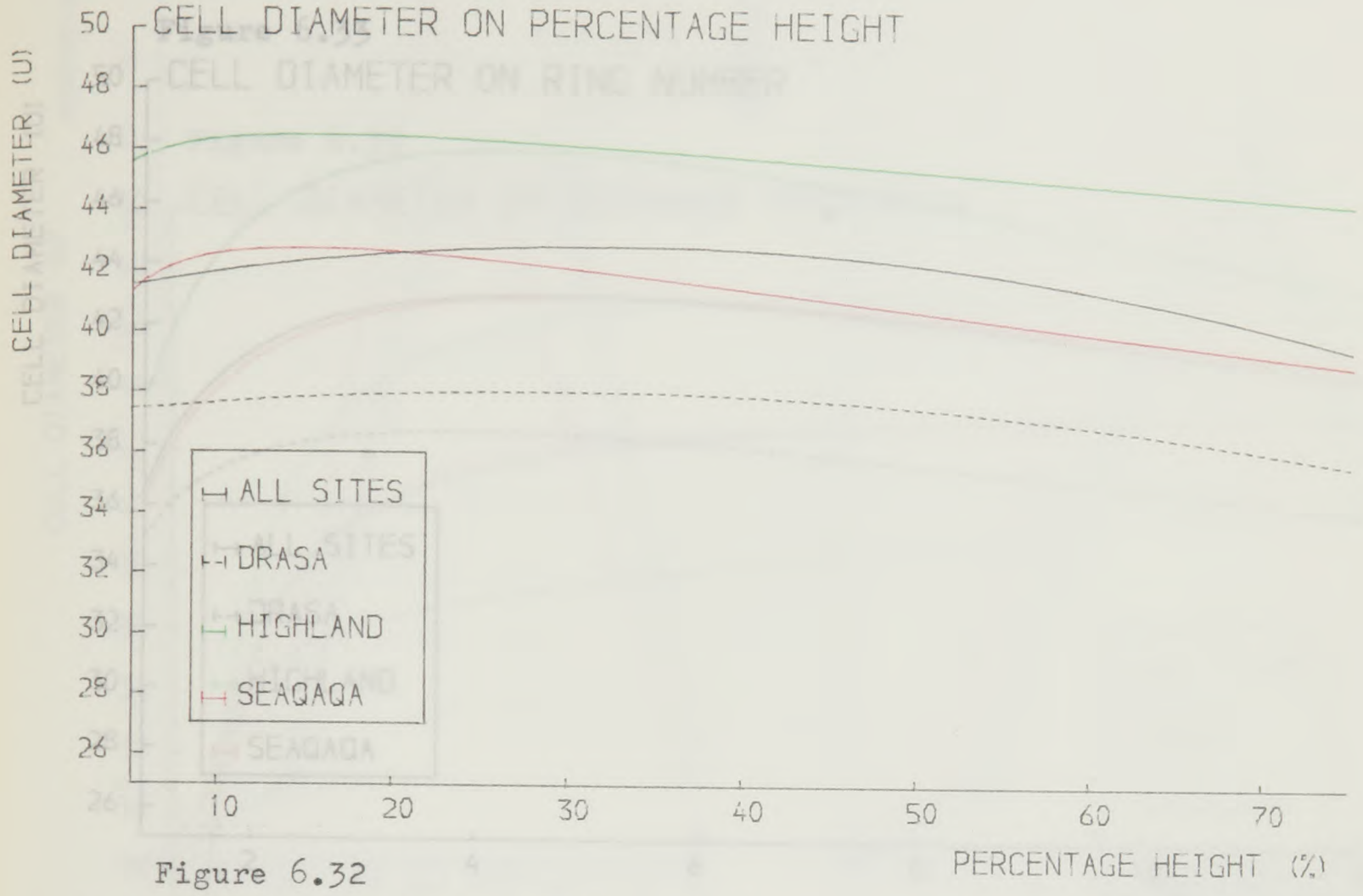


Figure 6.32

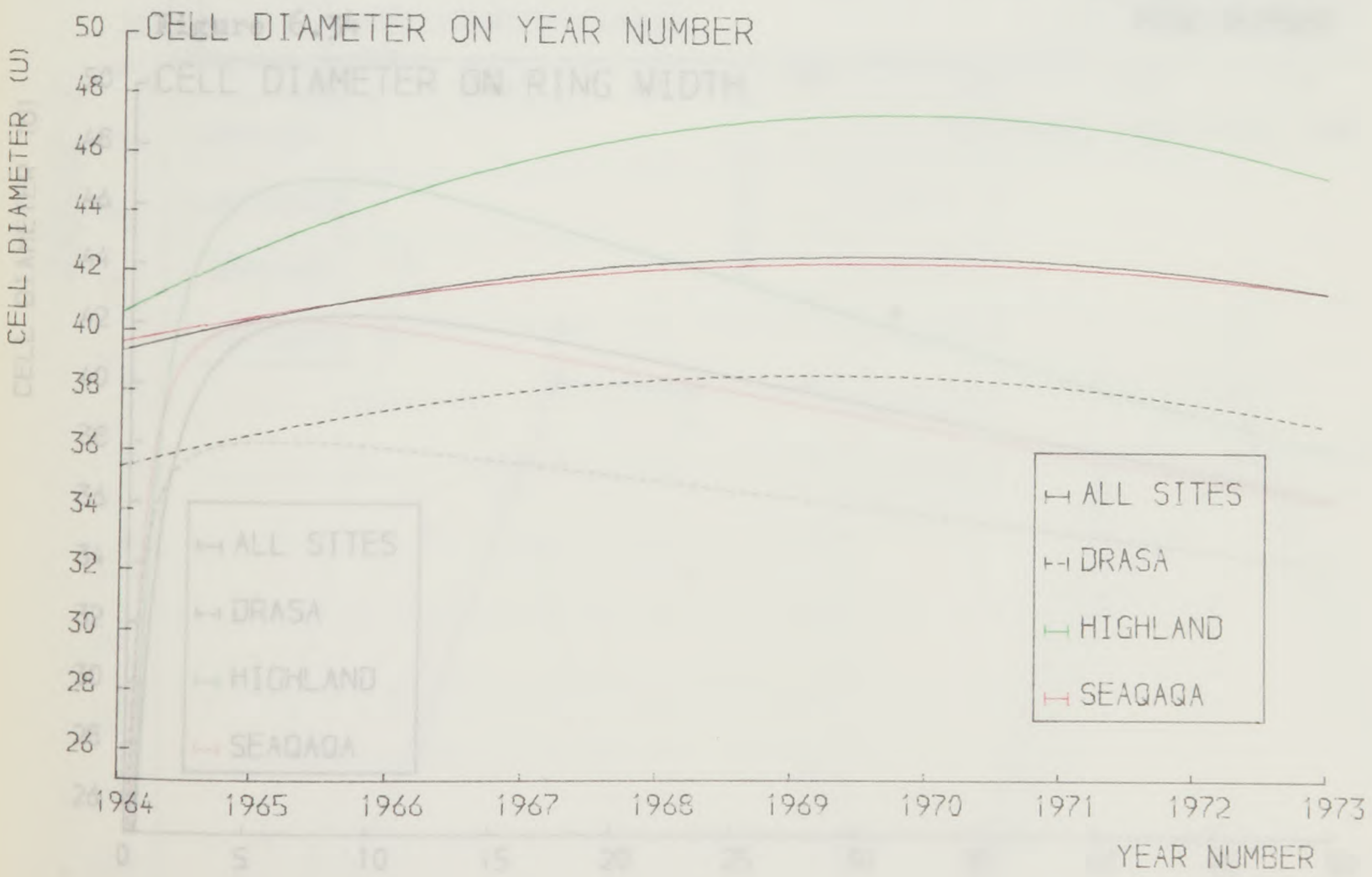


Figure 6.33

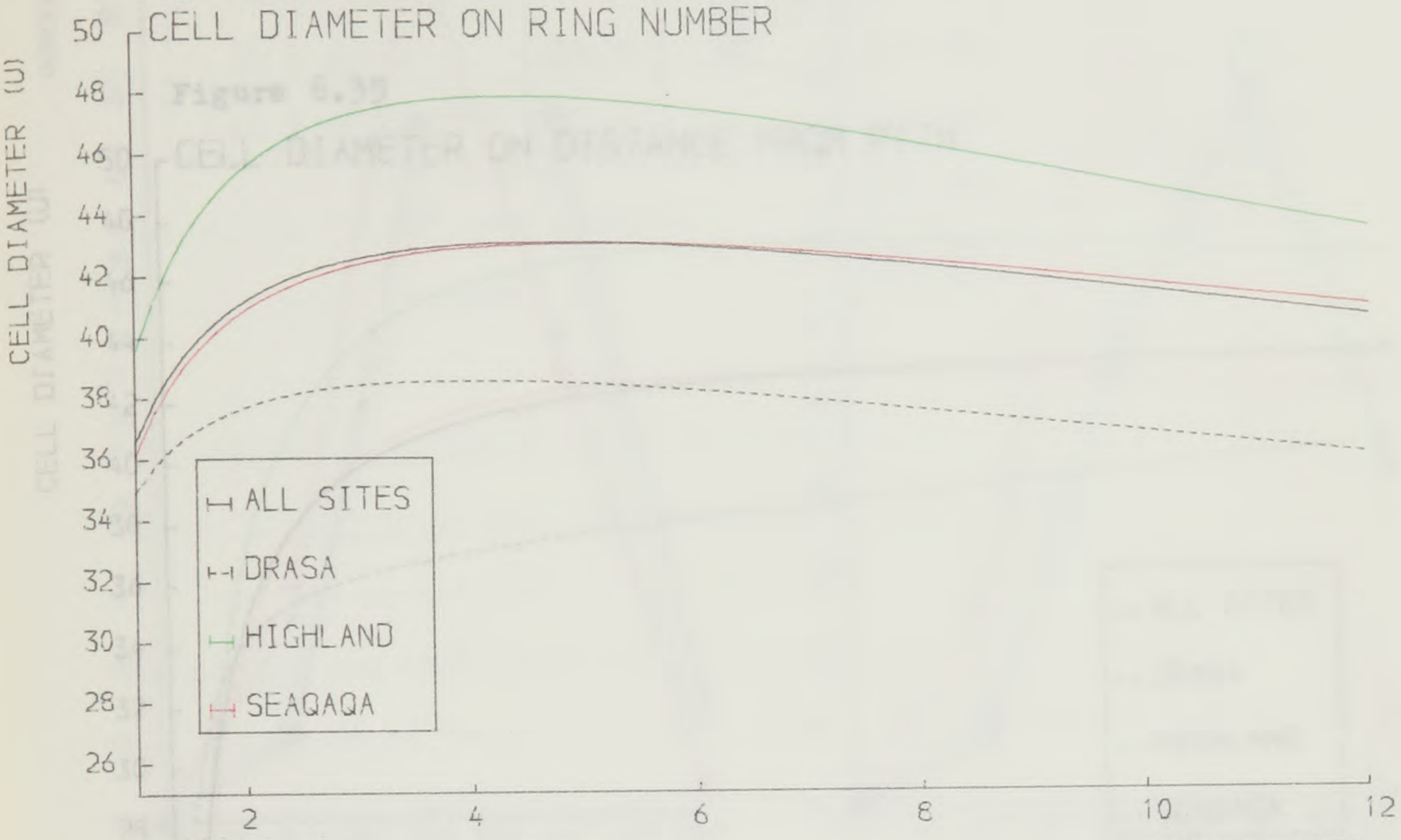


Figure 6.34

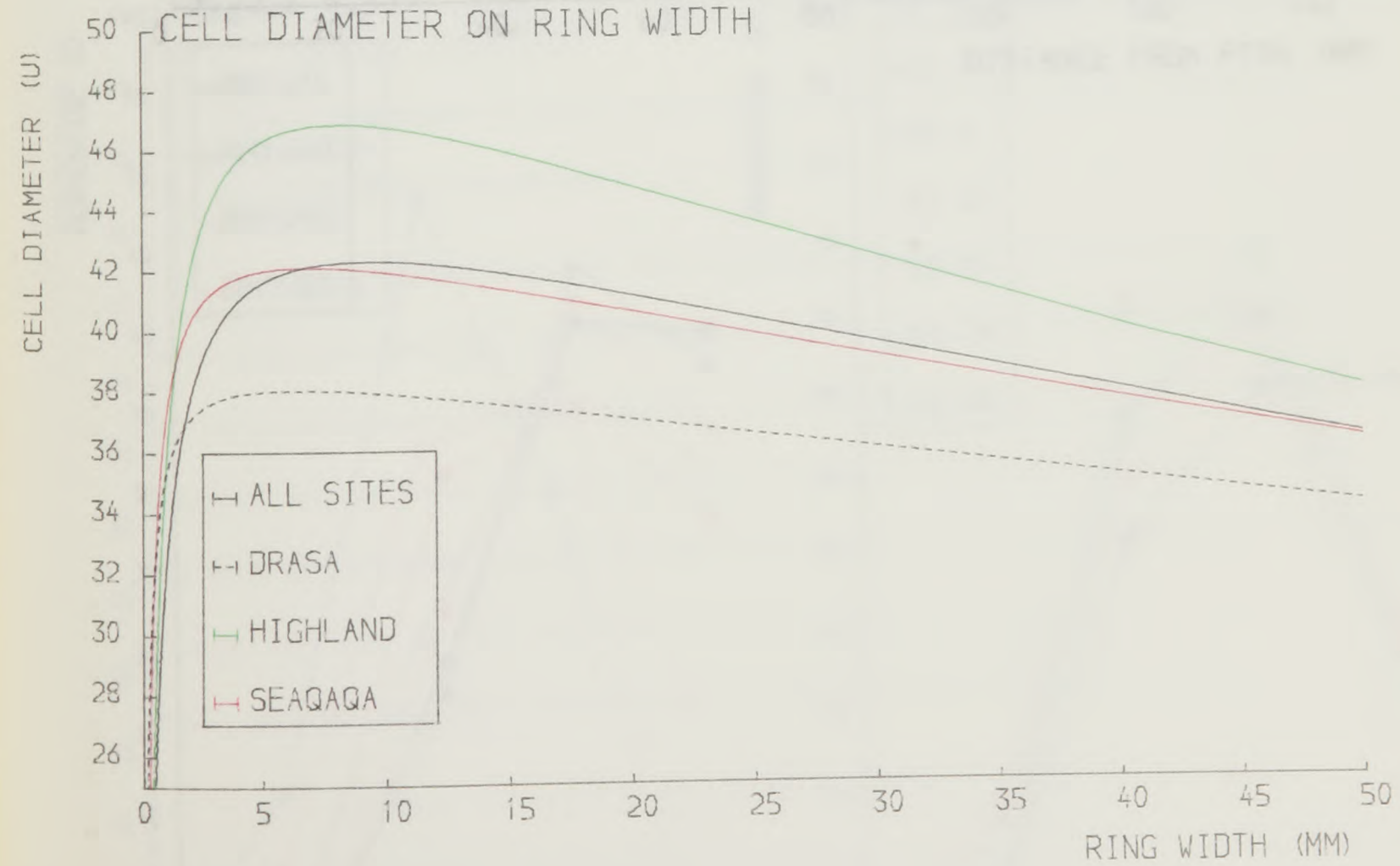


Figure 6.35

CELL DIAMETER ON DISTANCE FROM PITH

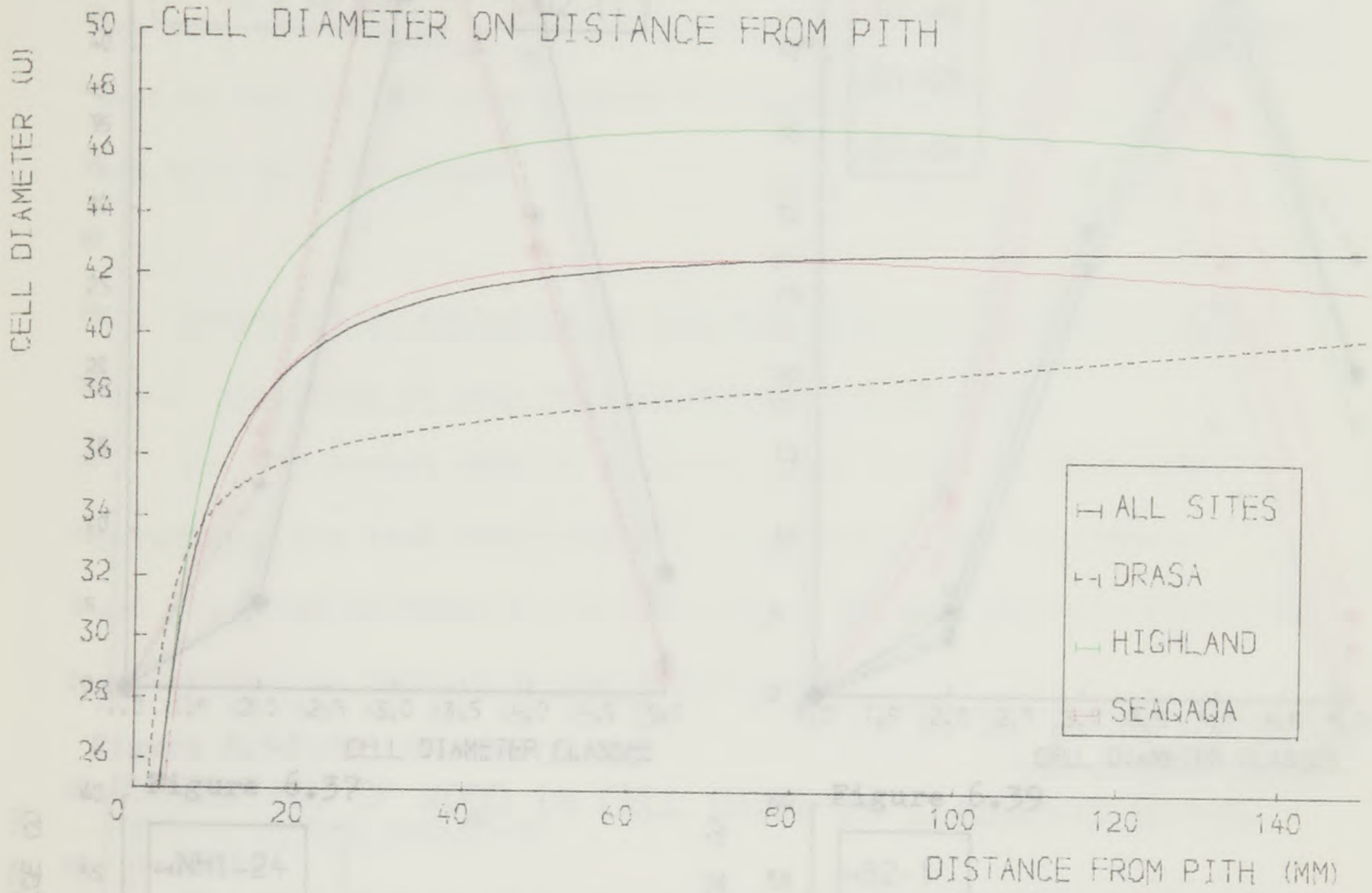


Figure 6.36

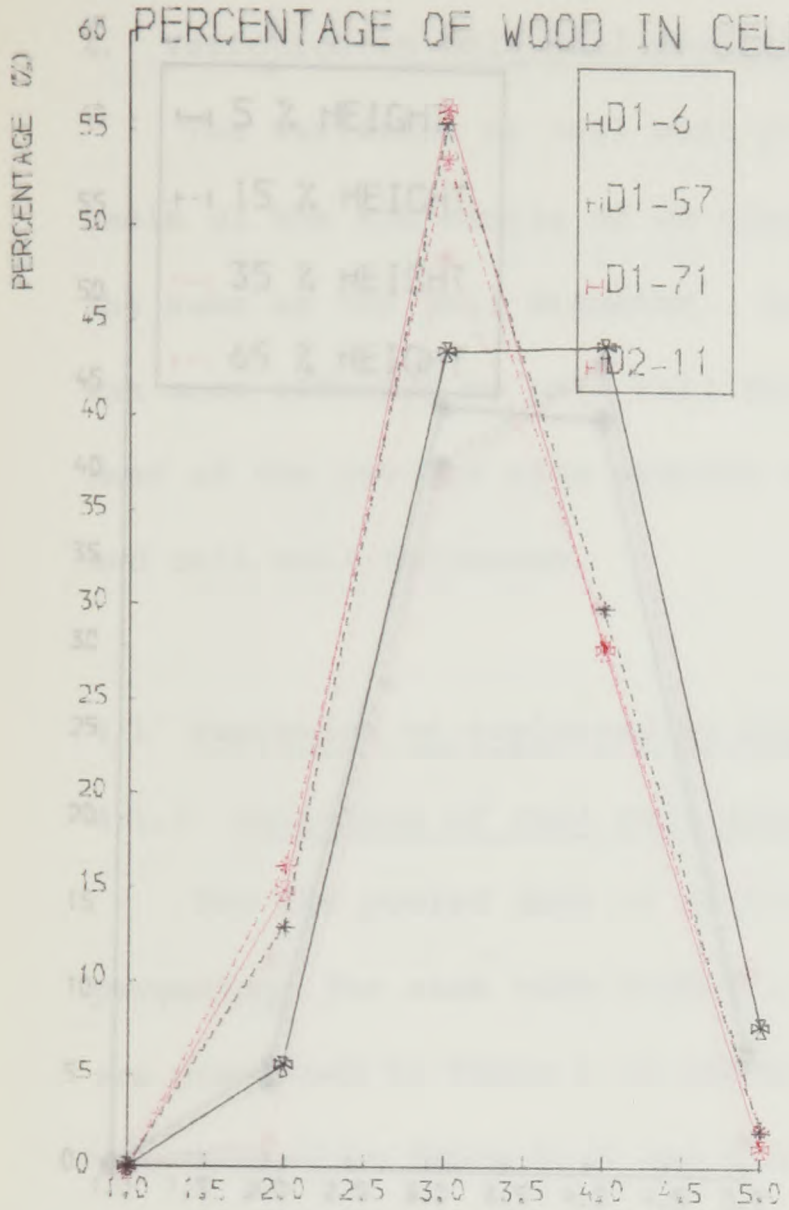


Figure 6.37

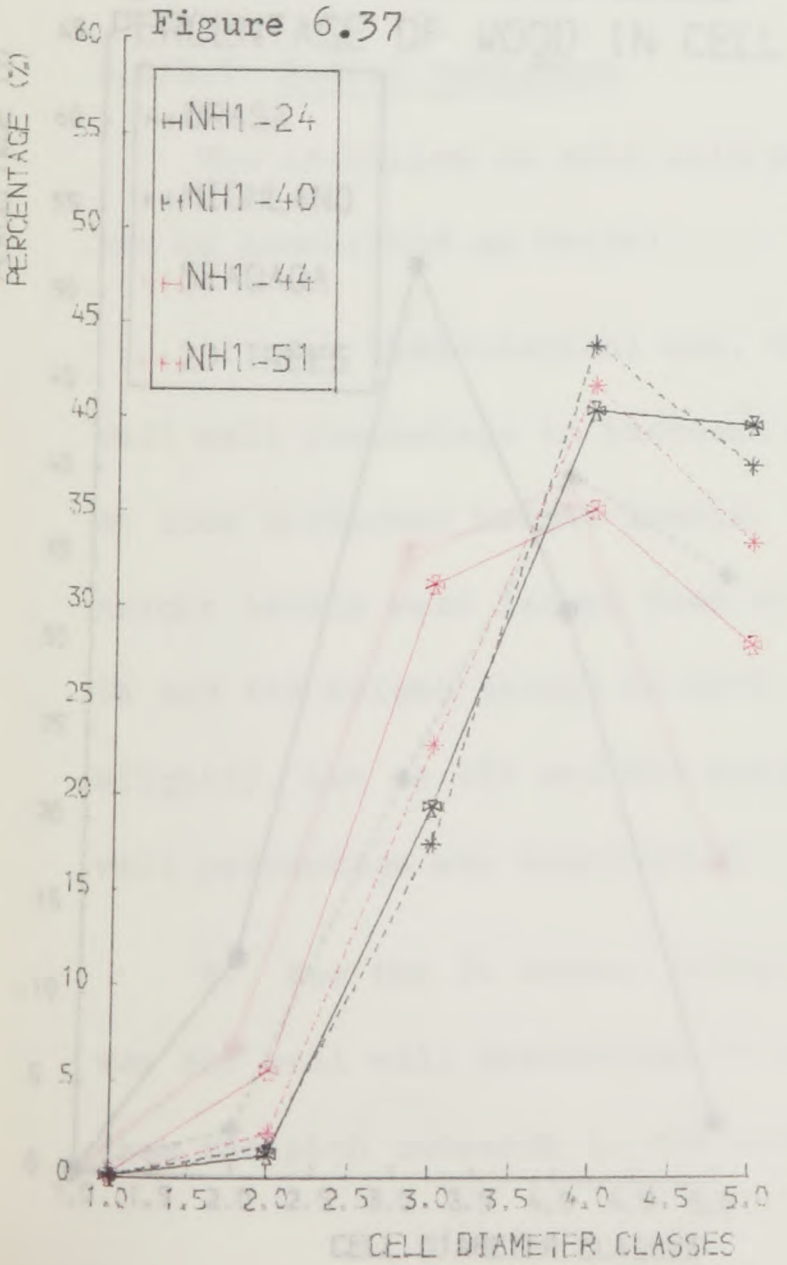


Figure 6.38

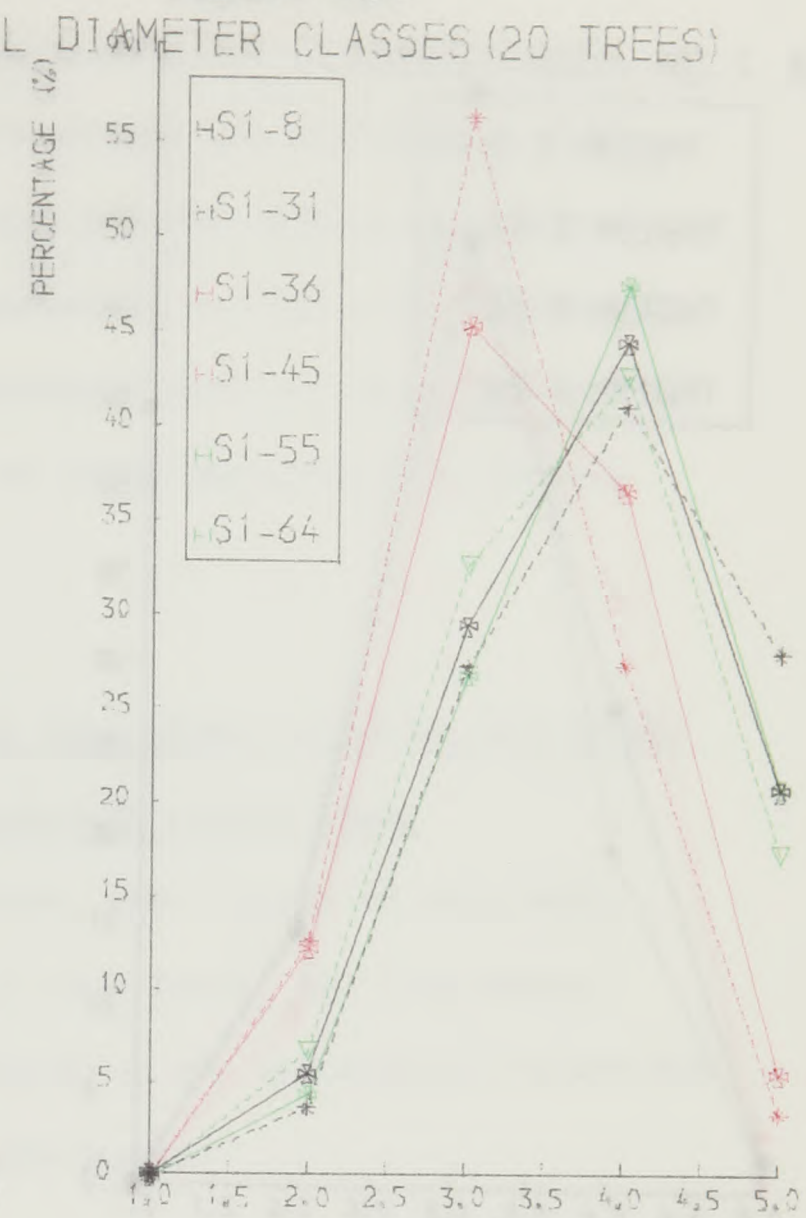


Figure 6.39

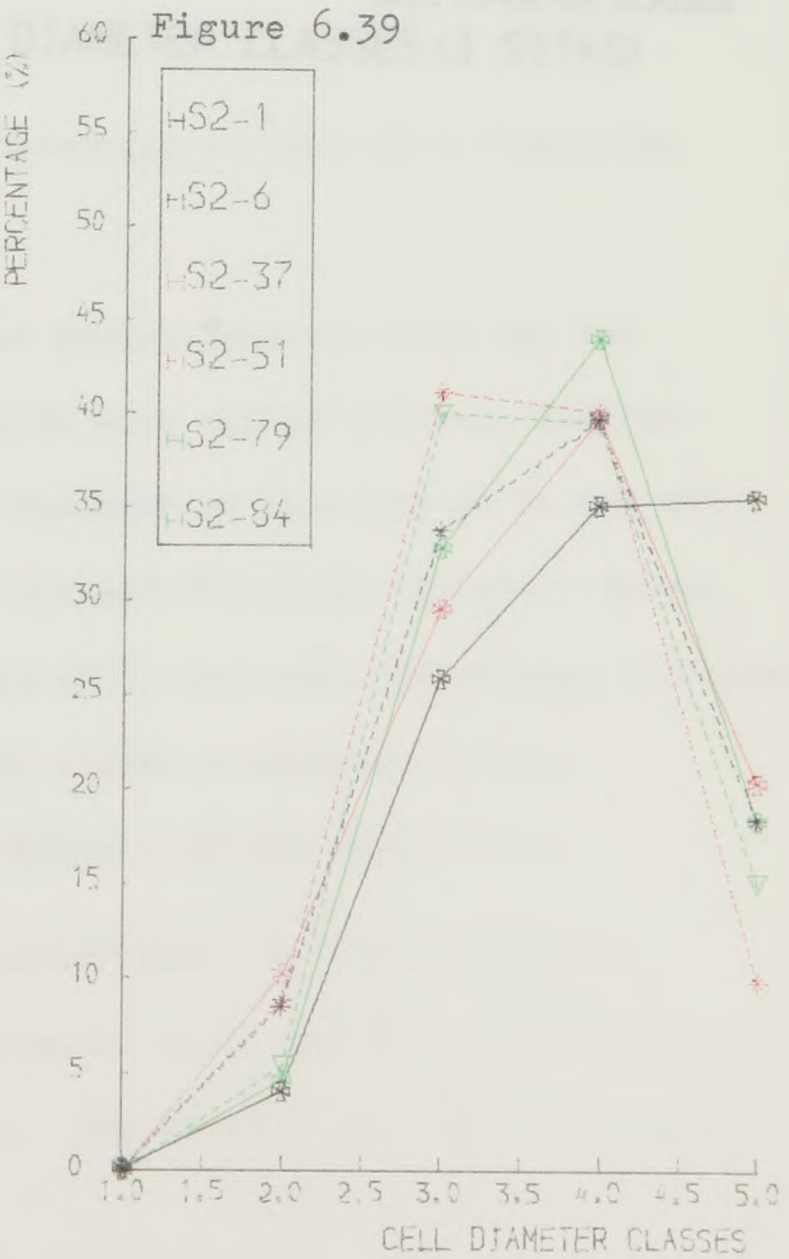


Figure 6.40

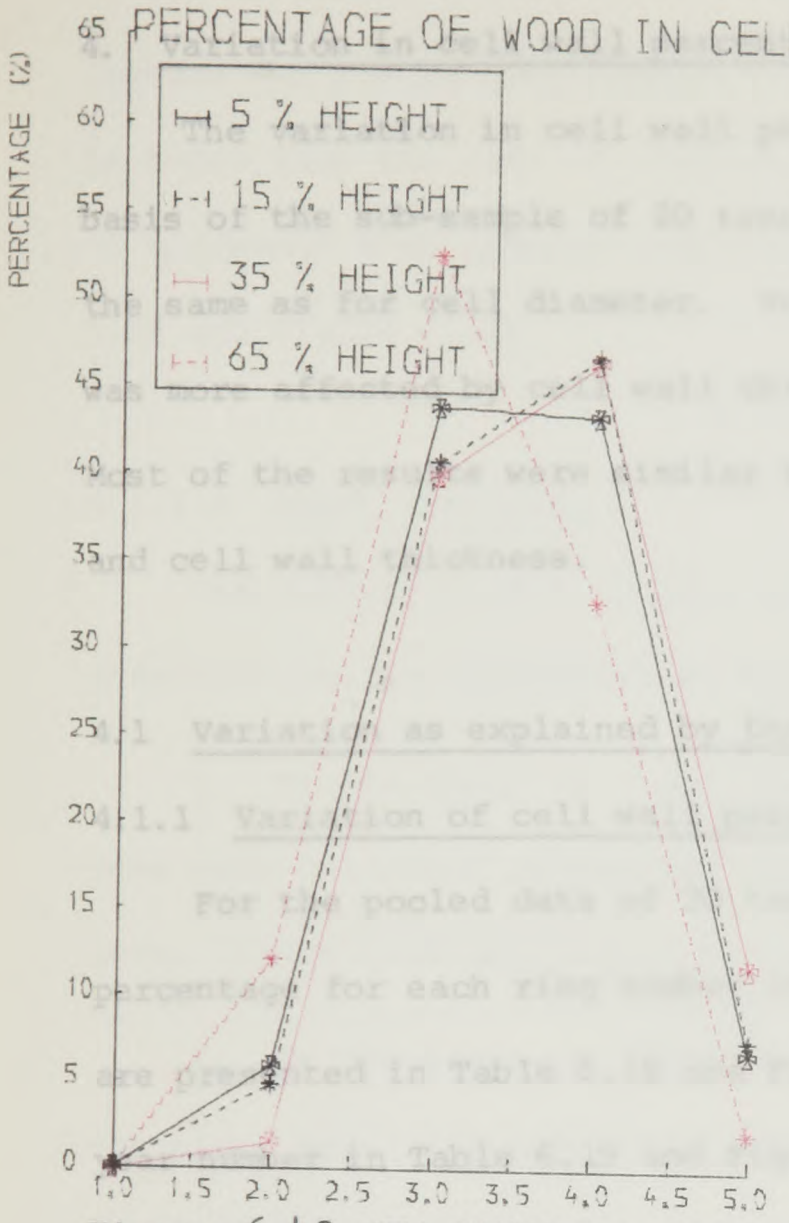


Figure 6.41

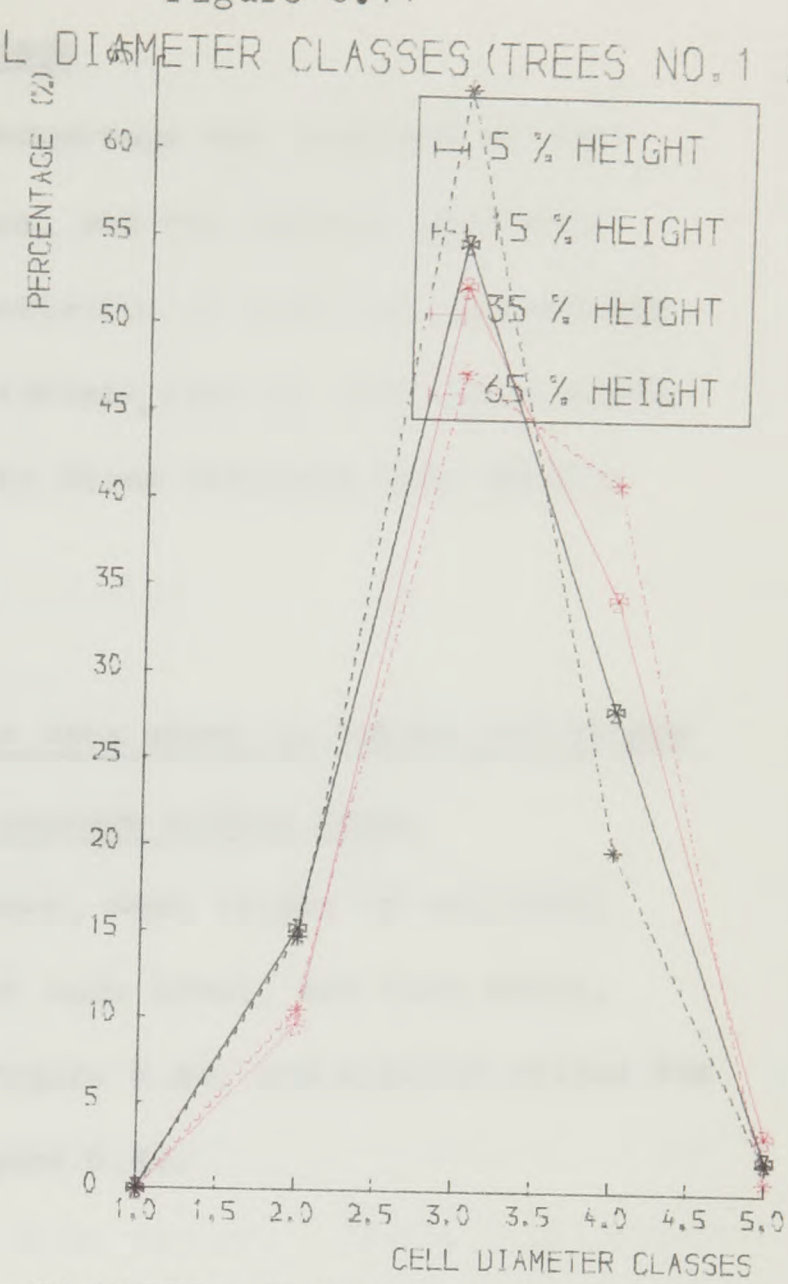
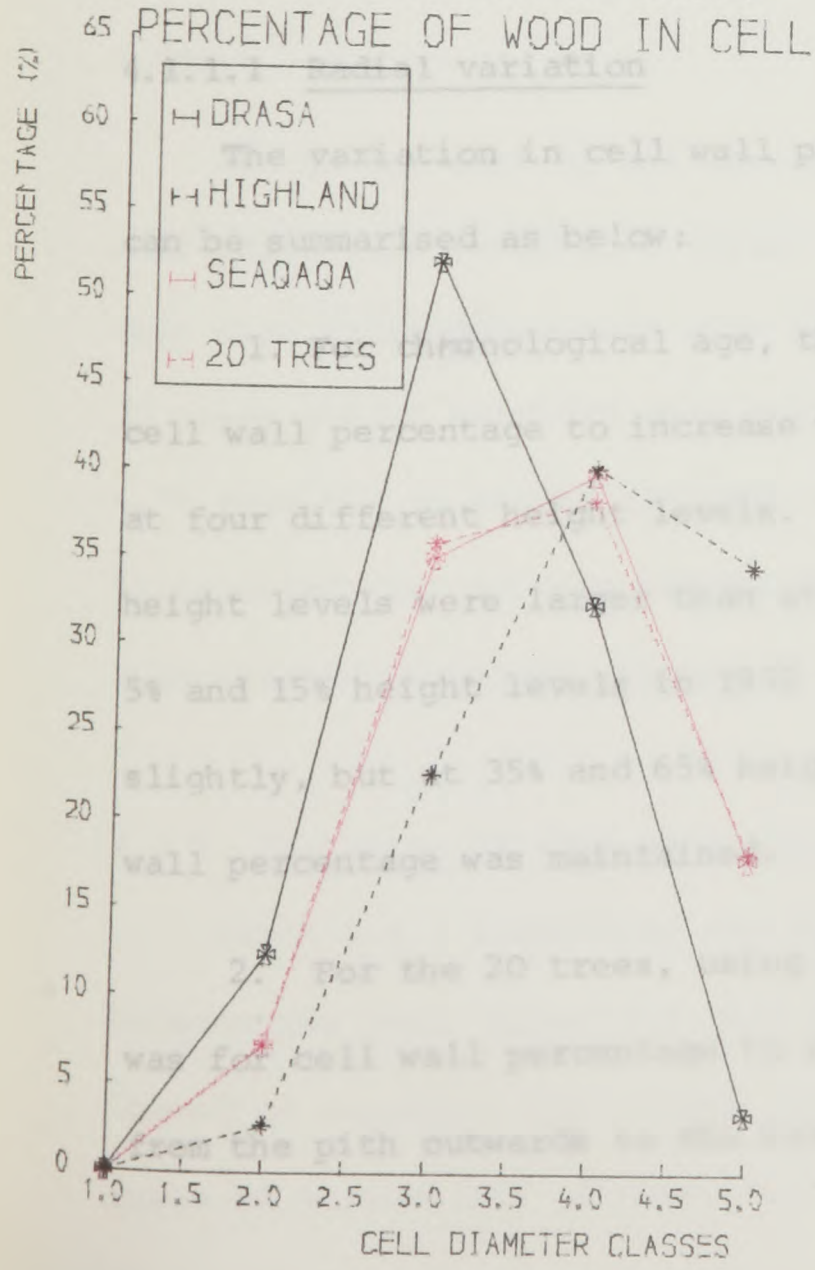


Figure 6.42 CELL DIAMETER CLASSES



4. Variation in cell wall percentage

The variation in cell wall percentage was examined on the basis of the sub-sample of 20 trees, and the methods used were the same as for cell diameter. Variation in cell wall percentage was more affected by cell wall thickness than by cell lumen width. Most of the results were similar to those obtained with density and cell wall thickness.

4.1 Variation as explained by the data shown in tables and graphs

4.1.1 Variation of cell wall percentage within trees

For the pooled data of 20 trees, mean values of cell wall percentage for each ring number at each level, and ring means, are presented in Table 6.18 and Figure 6.44, and similar values for year number in Table 6.19 and Figure 6.43.

4.1.1.1 Radial variation

The variation in cell wall percentage in the radial direction can be summarised as below:

1. For chronological age, the general pattern ring was for cell wall percentage to increase with year number and were similar at four different height levels. The rate of increase at 5% and 15% height levels were larger than at 35% and 65% height levels. At the 5% and 15% height levels in 1972 to 1973, cell wall percentage decreased slightly, but at 35% and 65% height levels a increase in cell wall percentage was maintained. (Table 6.19 and Figure 6.43).

2. For the 20 trees, using pooled data, the general trend was for cell wall percentage to increase with ring number progressing from the pith outwards to the bark. The overall mean value for this

feature was 23% in ring number 1 and 43% in ring number 10. It is noted that the rate of increase of cell wall percentage varied at different ring numbers and at different height levels. (Table 6.18 and Figure 6.44).

4.1.1.2 Axial variation

The variation in cell wall percentage in the axial direction can be summarised as below:

1. On the basis of fixed year number (chronological age), mean ring cell wall percentage decreased with increasing height level (Table 6.19 and Figure 6.43).

2. On the basis of fixed number of rings (ring number) from the pith, mean ring cell wall percentage generally decreased in the trunk from base to top in a nonuniform pattern. (Table 6.18, Figure 6.44).

3. As for most of the 20 trees the maximum weighted cell wall percentage (mean disc value) occurred at the 5% height level, and mean disc values decreased with increasing height level. For 20 trees pooled weighted mean cell wall percentage decreased by about 6.7% from the 5% height (36.06%) to the 65% height level (29.36%). It is noted that in some trees, the change of cell wall percentage with increasing height levels was nonuniform. (Table 6.20).

4.1.2 Variation of cell wall percentage between trees

Table 6.2.1 summarises the statistical interrelationships between the mean values for cell wall percentage of the 20 trees (based on weighted disc value) and demonstrates the considerable range of variability of these tree means. The pattern (and values) of cell wall percentage at the different height levels in different

trees also varied from tree to tree. (Table 6.20).

4.2 Variation as explained by simple regression analysis

The relationship of cell wall percentage with % height, year number, ring number, ring width and distance from the pith were examined by simple regression analysis, using pooled data for the 20 trees sample and for the data from each site separately. The regressions and coefficients of determination (R^2) are given in Table 6.22 and the patterns of variation illustrated in Figures 6.45 - 6.49. The results may summarised as follows:

1. For the pooled data the regression line showed that cell wall percentage decreased slightly from the bottom to the top.

2. There was a steady increase in mean cell wall percentage with increasing year number.

3. For the pooled data, cell wall percentage increased steadily from ring number 1 to ring number 12. At Drasa site, the regression line showed an increase from ring number 1 to ring number 9, then cell wall percentage decreased slightly towards ring number 12. The rate of increase of cell wall percentage at the Highland site was lower than at Drasa and Seaqaqa sites.

4. The regression line of cell wall percentage on ring width showed that cell wall percentage decreased with increasing ring width to a width of 20 to 30 mm, and then remained steady.

5. For pooled data the regression line showed that cell wall percentage increased steadily from the pith outwards to the bark, with a larger rate of increase near the pith than near the bark. At the Drasa site, the cell wall percentage began to decrease after reaching the 100 mm position. It is noted that for trees in the Drasa site,

the maximum distance from the pith (one tree) was about 115 mm.

6. For the data of the 3 sites separately, regression lines showed that there were some differences between them in cell wall percentage at the various % height levels, year numbers, ring numbers, ring widths and distances from pith.

4.3 Variation as explained by multiple regression analysis

The models used in this section were the same as those employed in the examination of the variation in cell wall thickness. A multiple regression was fitted to the data as follows:

where b's = partial regression coefficients

X_1 = year number

X_2 = % height level

X_3 = ring number

X_4 = ring width

X_5 = distance from pith

Y = cell wall percentage

First model $y = -276400 + 280X_1 - 0.4049X_2 + 1.441X_3$

$-1.056X_4 - 0.08544X_5 - 0.07105X_1^2 + 0.003798X_2^2$

$+ 0.03669X_3^2 + 0.01618X_4^2 - 0.0004005X_5^2$

this gives a value of $R^2 = 0.427$, F value = 48.9***, and residual standard deviation = 7.5782%.

The second model was

$y = -3773 + 1.941X_1 - 0.2963X_2 + 0.7923X_3 - 0.3642X_4$

$- 0.1569X_5$

with $R^2 = 0.42$, F value = 95.99 *** and residual standard deviation = 7.5918 %.

The second model after step elimination was

$$y = -5065 + 2.6X_1 - 0.3562X_2 - 0.3747X_4 - 0.1471X_5$$

with R^2 = 0.418, F value = 119.04 *** and residual standard deviation = 7.6011%.

Ring number had the largest correlation coefficient (simple linear) with cell wall percentage (r = 0.5718), followed by ring width (r = -0.4889), distance from pith (r = 0.4837), year number (r = 0.3912) and % height level (r = -0.3872). It seems that ring number had the greatest effect on ring cell wall percentage, but ring number was eliminated from the second regression after step wise elimination, and the R^2 value of the revised regression changed very little. This indicates a close interaction between some of these five variables.

Although these multiple regressions had high significance, as shown by the F test, the proportions of the variation explained by them, as indicated by the values of R^2, were low. The R^2 value for the first model of cell wall percentage was not improved in the second model, and this indicated that the trend of cell wall percentage was linearly correlated with these five variables.

4.4 Variation as explained by morphological characteristics

In this part of the study, simple linear regressions were calculated to examine the association of whole tree mean cell wall percentage with each of the following characteristics, for which the correlation coefficients are shown below:

Variables	R	sig
Tree age	0.069	n.s.
Tree height	-0.0098	n.s.
Diameter at breast height	-0.506	*
Crown width	-0.112	n.s.
Crown length	-0.1767	n.s.

Cell wall percentage was negatively correlated with tree size, but D.B.H. was the only parameter that was statistically significant.

Multiple regression analysis was not carried out because of few observations (20 trees) in this study.

4.5 Possibility of predicting tree cell wall percentage

To examine the possibility of predicting whole tree values for cell wall percentage from small samples, simple linear regressions were calculated to correlate whole tree weighted values with weighted cell wall percentage at four different levels as follows:

% height level	Model	R^2	A	B
5	1	0.916	2.9137	0.8256526
15	1	0.890	5.4418	0.8289651
35	1	0.891	3.29301	0.9606161
65	1	0.528	13.21628	0.6898616

The results indicated that the whole tree value for wall percentage can be estimated with confidence from the 5% height values. Table 6.20 shows that for most of the trees the weighted mean tree value of cell wall percentage was in fact closer to the value for the 15% height level.

4.6 Cell Wall percentage distribution

Cell wall percentage was separated into seven classes as shown in Chapter 3. The following results list the simple correlations of whole tree weighted cell wall percentage with the percentage content of wood in each of seven different cell wall percentage classes:

Cell wall percentage (tree)	Cell wall percentage classes	R	Sig.
"	CW%-1 (0.00-20.00%)	-0.8633	***
"	CW%-2(20.01-30.00%)	-0.5187	*
"	CW%-3(30.01-40.00%)	0.6163	**
"	CW%-4(40.01-50.01%)	0.6703	***
"	CW%-5(50.01-60.00%)	0.7823	***
"	CW%-6(60.01-70.00%)	0.9087	***
"	CW%-7(Above 70.01%)	0.8062	

Whole tree weighted cell wall percentage was negatively correlated with the first two classes, and positively correlated with the last five classes. CW%-6 had the closest correlation.

The distribution of cell wall percentage within trees and between trees are illustrated in Figures 6.50-6.56 The amounts of the various cell wall percentage classes was very different in different trees, with a range as follows:

CW%-1: 9.8183% to 50.7273%
CW%-2: 19.0847% to 49.1086%
CW%-3: 8.1984% to 20.9883%
CW%-4: 3.6139% to 11.4610%
CW%-5: 1.8371% to 14.3947%
CW%-6: 1.0133% to 15.7936%
CW%-7: 0.8892% to 14.3008%

Patterns of cell wall percentage distribution in discs and in trees were found in three forms; resembling a chi-square distribution, resembling a binomial distribution and resembling a bi-modal distribution.

The following characteristics were found to emerge from a study of the graphs on cell wall perentage distribution variation in two cases as follows:

Between trees (Figures 6.50-6.53)

There were considerable differences between trees. Most trees had a maximum of the CW%-2 class, a reduction in the amounts of CW%-3 and then a fall off at different rates for the higher classes. In the case of NH1-24 and S2-1, the two trees with the lowest mean cell wall percentage, however, the maximum occurred in CW%-1. Another low mean cell wall percentage tree S1-55, had an equal amount of wood of the CW%-1 and CW%-2 classes. For the highest mean cell wall percentage tree S1-45, amounts in each class were more uniform and a second maximum peak occurred at CW%-3 (17.7%)

Table 6.18 Mean cell wall percentage and ring number at different % heights

% height										
65	24.5678	27.2240	28.5857	29.5863						
35	23.3090	25.7758	28.1494	30.5535	28.8578	33.0029	33.9750	34.2227		
15	22.6410	26.9418	28.7201	32.3413	35.6201	35.0967	35.6912	40.7024	40.5860	
5	21.5099	28.6465	32.4494	32.0365	37.5660	40.8883	40.3018	40.0283	42.6010	41.6197
Ring No.	1	2	3	4	5	6	7	8	9	10
Mean	23.0069	27.1470	29.4762	31.1294	34.0146	36.3293	36.6560	38.3178	41.3527	41.6197

Table 6.19 Mean cell wall percentage and year number at different % heights

% height										
65							26.5812	27.6148	29.8963	31.2520
35			24.8729	27.8560	29.1543	29.2080	30.8544	33.4091	34.3525	35.6389
15		25.5100	28.0294	32.0200	33.1841	34.8689	34.7847	38.7479	41.2778	40.9791
5	24.6289	32.0529	32.7891	35.9909	38.9768	39.5096	39.3075	42.1332	44.6691	41.7692
Year No.	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973

Table 6.20 Mean weighted cell wall percentage at different % heights

% height	D1-6	D1-57	D1-71	D2-11	NH1-24	NH1-40	NH1-44	NH1-51	S1-8	S1-31	
5	33.4740	43.6767	43.6450	46.9182	27.6860	27.2555	38.9891	34.9200	43.5063	37.2002	
15	30.3042	43.9812	37.6184	41.1064	25.1690	27.9845	34.8306	30.9983	35.5566	33.1914	
35	26.0201	35.5319	33.1575	43.1105	23.8852	23.6119	33.7031	25.4927	31.1515	33.1982	
65	31.5965	32.7526	26.3859	34.3206	19.3232	22.1258	27.3514	26.7904	26.8970	28.0882	
Mean	30.4520	39.7439	36.1782	42.3964	24.6182	25.6873	34.6186	30.2837	35.5822	33.6057	
% height	S1-36	S1-45	S1-55	S1-64	S2-1	S2-6	S2-37	S2-51	S2-79	S2-84	Pooled
5	38.3281	49.6308	28.8357	29.1770	29.1303	34.7102	37.9275	34.7939	43.4595	36.8692	37.0067
15	30.8430	51.7308	27.3273	26.9839	25.9110	31.9613	35.1825	34.5565	35.9221	35.4205	33.8091
35	32.7206	41.4089	26.6268	29.4589	24.1704	34.0935	30.0325	30.3660	39.3171	31.1813	31.4124
65	23.2722	37.8778	25.9856	29.2689	24.3219	40.6890	26.5320	29.4458	42.8703	31.2410	29.3567
Mean	32.4768	46.4496	27.4123	28.6070	26.0958	34.6099	33.3436	32.8948	40.1697	34.1812	33.4683

Figure 6.43

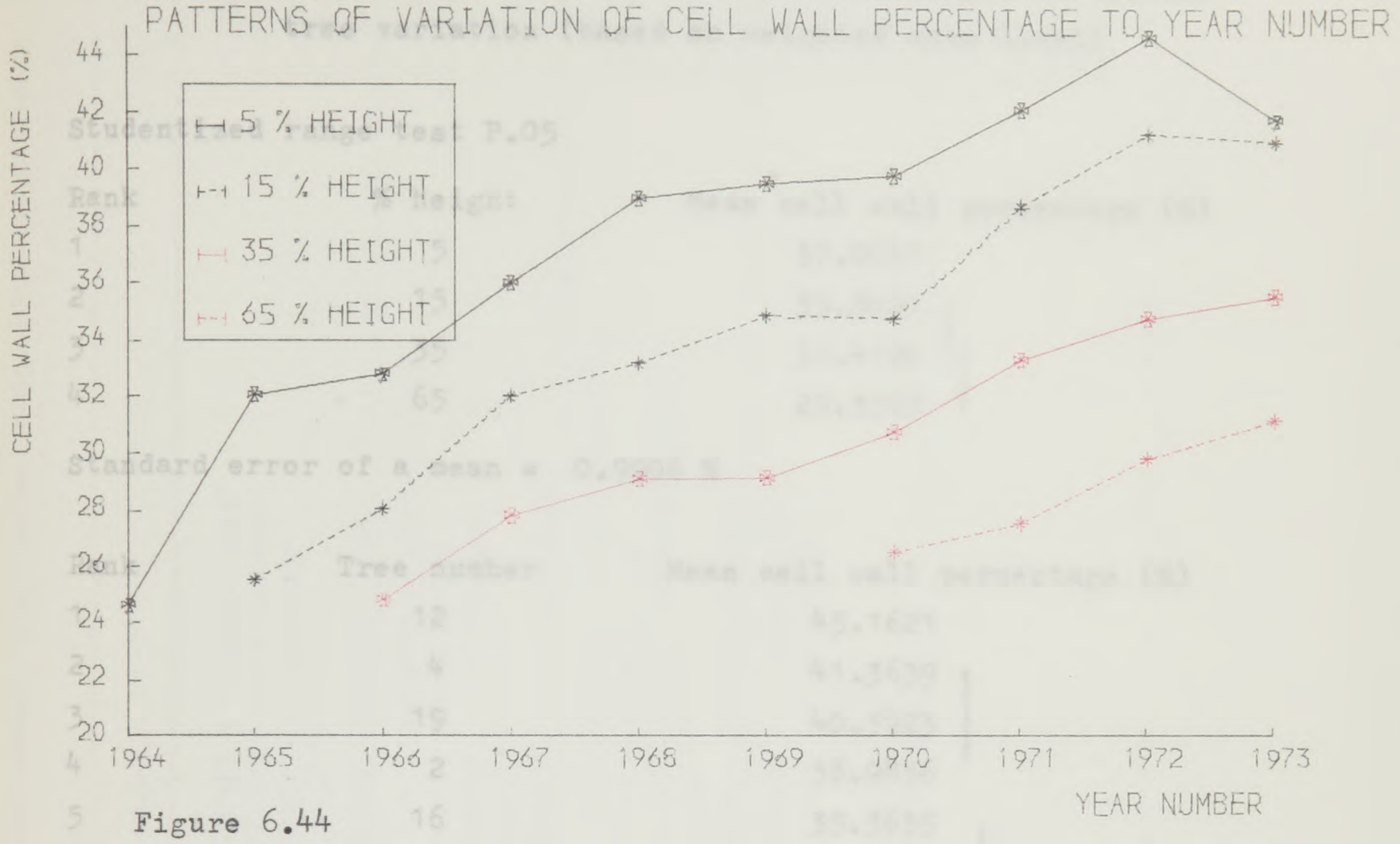


Figure 6.44

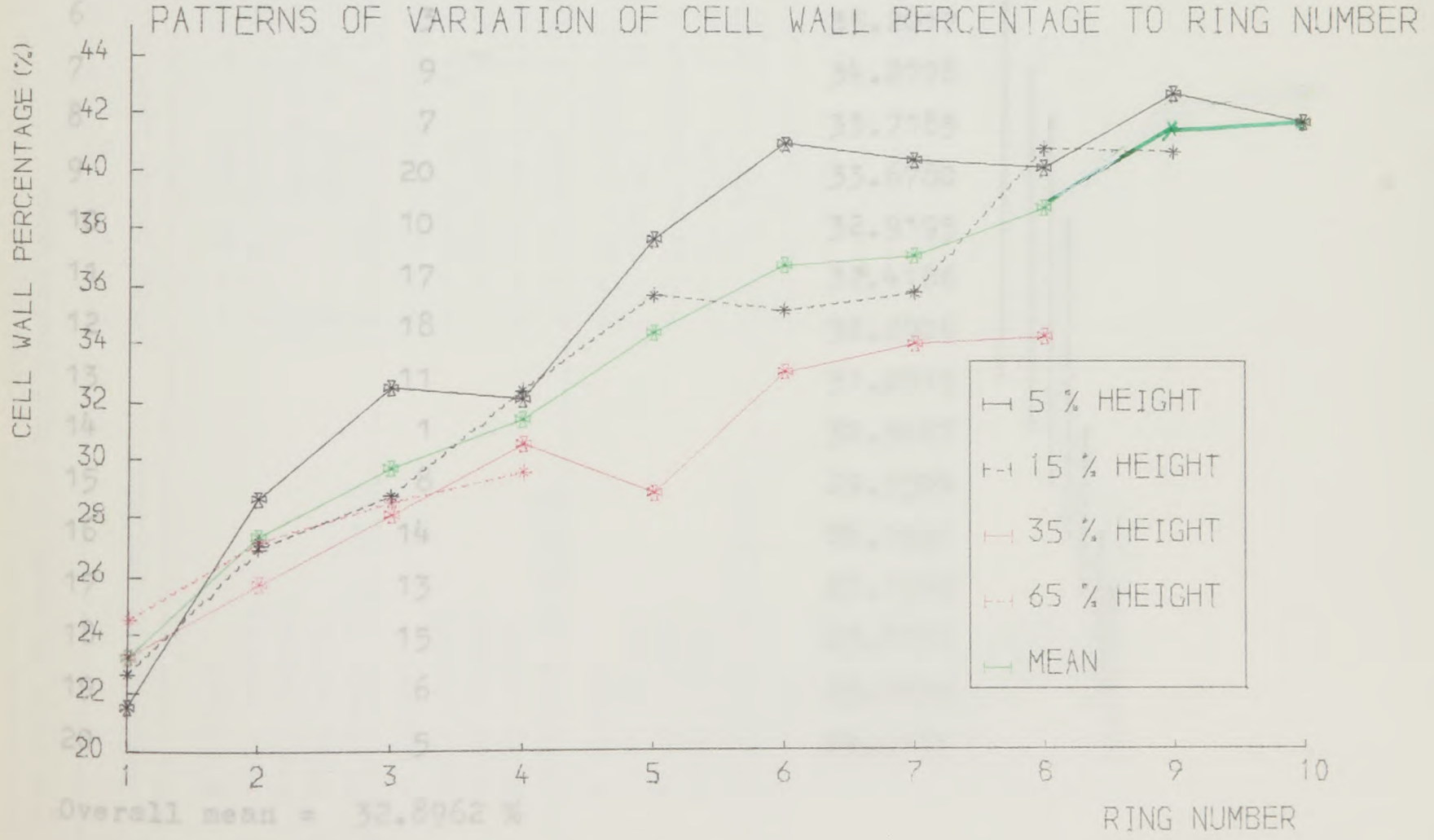


Table 6.21 Ranking order of trees cell wall percentage, tree statistical interrelationship and ranges of between tree variation (based on weighted mean level)

Studentized range test P.05

Rank	% height	Mean cell wall percentage (%)
1	5	37.0067
2	15	33.8091
3	35	31.4124
4	65	29.3567

Standard error of a mean = 0.9906 %

Rank	Tree number	Mean cell wall percentage (%)
1	12	45.1621
2	4	41.3639
3	19	40.3923
4	2	38.9856
5	16	35.3635
6	3	35.2017
7	9	34.2778
8	7	33.7185
9	20	33.6780
10	10	32.9195
11	17	32.4186
12	18	32.2906
13	11	31.2915
14	1	30.3487
15	8	29.5504
16	14	28.7221
17	13	27.1939
18	15	25.7859
19	6	25.2439
20	5	24.0159

Overall mean = 32.8962 %

Standard erroe of a mean = 1.0086 %

Numbers subtended by the same vertical line refer to the trees whose means are not significantly different from each other.

Table 6.22 Regression of cell wall percentage on % height, year number, ring number, ring width and distance from pith in each site and pooled data

Site	Independent variable	Regression best fit model	R^2	Sig.
Drasa	% height	$y = 43.50805 - 0.3732042X + 0.002531619X^2$	0.136	
	Year number	$y = X/(2452701 - 2488.189X + 0.6310596X^2)$	0.210	
	Ring number	$y = 17.40135 + 6.351841X - 0.3487616X^2$	0.480	
	Ring width	$y = 16.48293 + 33.83879e^{-0.0553870 1X}$	0.351	
	Distance from pith	$y = 14.3154 + 0.6185866X - 0.003271248X^2$	0.366	
Nausori Highland	% Height	$y = X/(-0.009304048 + 0.03358527X + 0.0001512187X^2)$	0.162	
	Year number	$y = 95837.1 - 98.12765X + 0.02512372X^2$	0.110	
	Ring number	$y = 22.87616 + 0.4345442X + 0.09994404X^2$	0.361	
	Ring width	$y = 21.54272 + 17.97265e^{-0.09499401X}$	0.206	
	Distance from pith	$y = 21.76549 + 0.07489826X + 0.0001783169X^2$	0.252	
Seaqaqa	% height	$y = X/(-0.01444621 + 0.02990268X + 0.00007656632X^2)$	0.077	
	Year number	$y = -370142.1 + 374.6774X - 0.09480715X^2$	0.189	
	Ring number	$y = X/(0.01284065 + 0.03217613X - 0.000962834X^2)$	0.356	
	Ring width	$y = 21.35196 + 37.25984e^{-0.1288625X}$	0.347	
	Distance from pith	$y = 19.586 + 0.2732488X - 0.0008002479X^2$	0.311	
Pooled data	% height	$y = X/(0.01423 + 0.02948X + 0.00007487X^2)$	0.166	
	Year number	$y = -377492.7 + 382.1687X - 0.09671592X^2)$	0.158	
	Ring number	$y = 20.78 + 3.055X - 0.09676X^2$	0.332	
	Ring width	$y = 20.38684 + 33.1289e^{-0.105438X}$	0.341	
	Distance from pith	$y = 18.94 + 0.3139X - 0.001219X^2$	0.253	
Pooled data	% height	$y = 36.44 - 0.118X$	0.15	***
	Year number	$y = -2676.48 + 1.376X$	0.153	***
simple linear	Ring number	$y = 22.8 + 2.013X$	0.327	***
	Ring width	$y = 39.58 - 0.5926X$	0.239	***
	Distance from pith	$y = 22.99 + 0.154X$	0.234	***

Figure 6.45

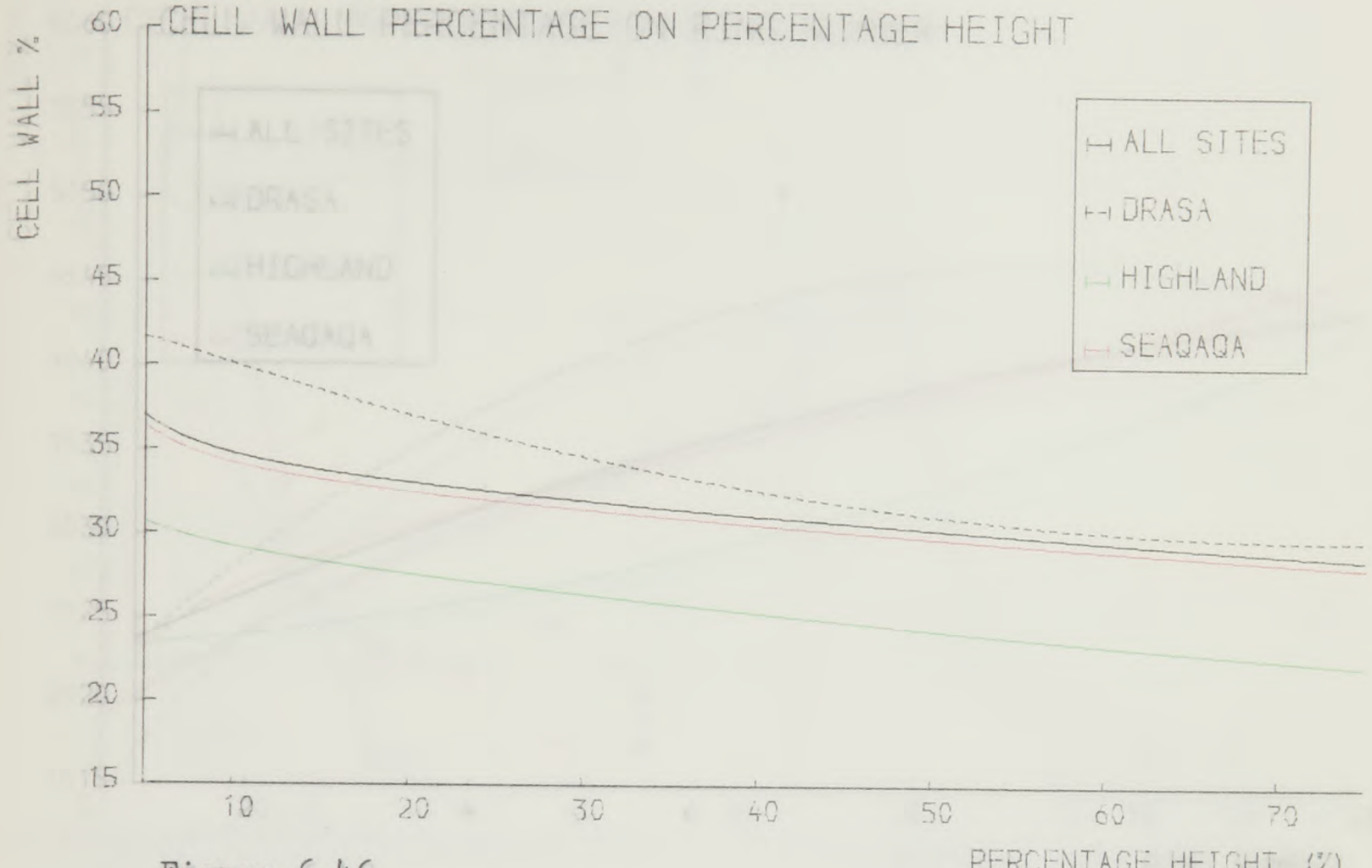


Figure 6.46

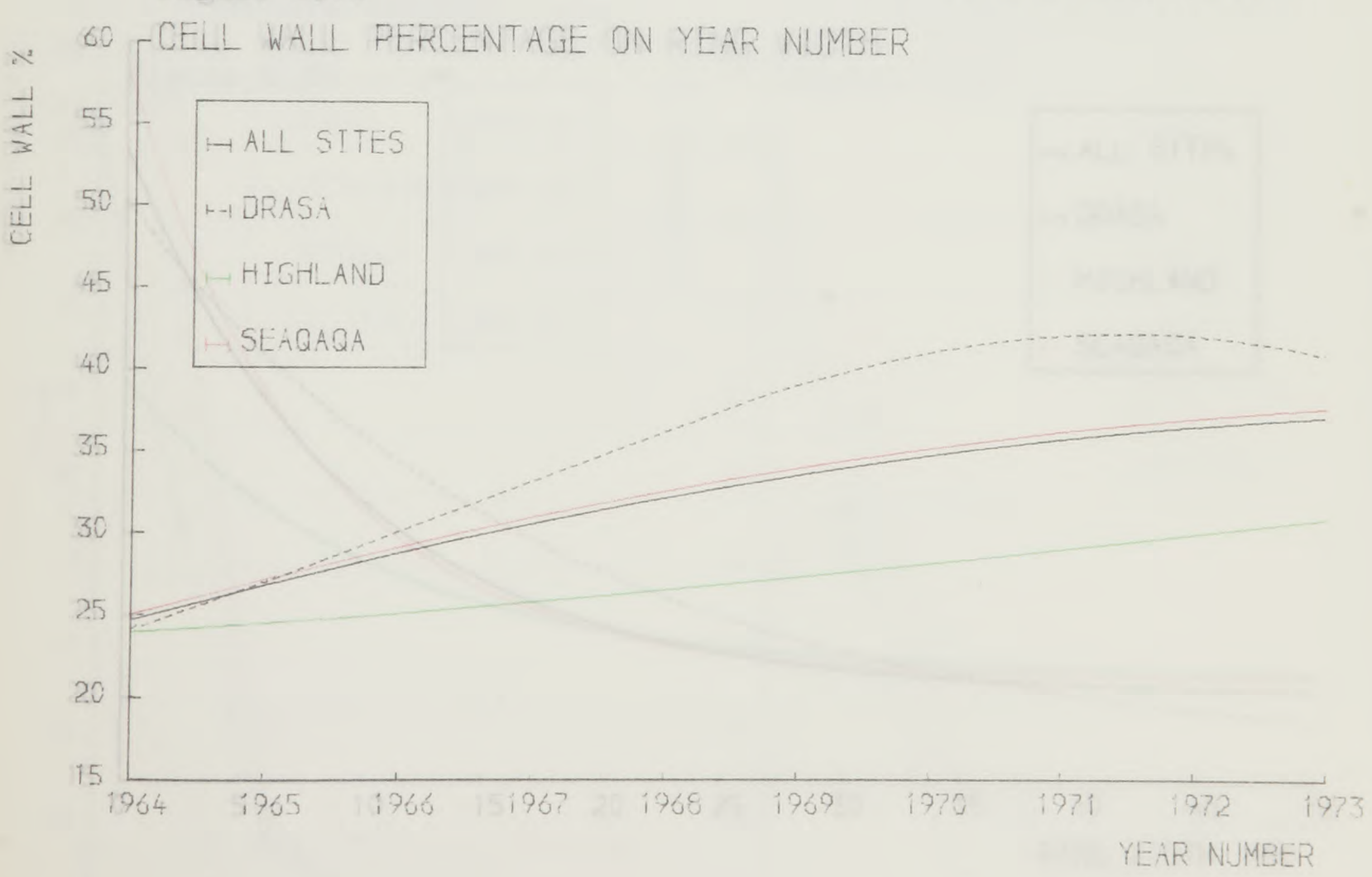


Figure 6.47

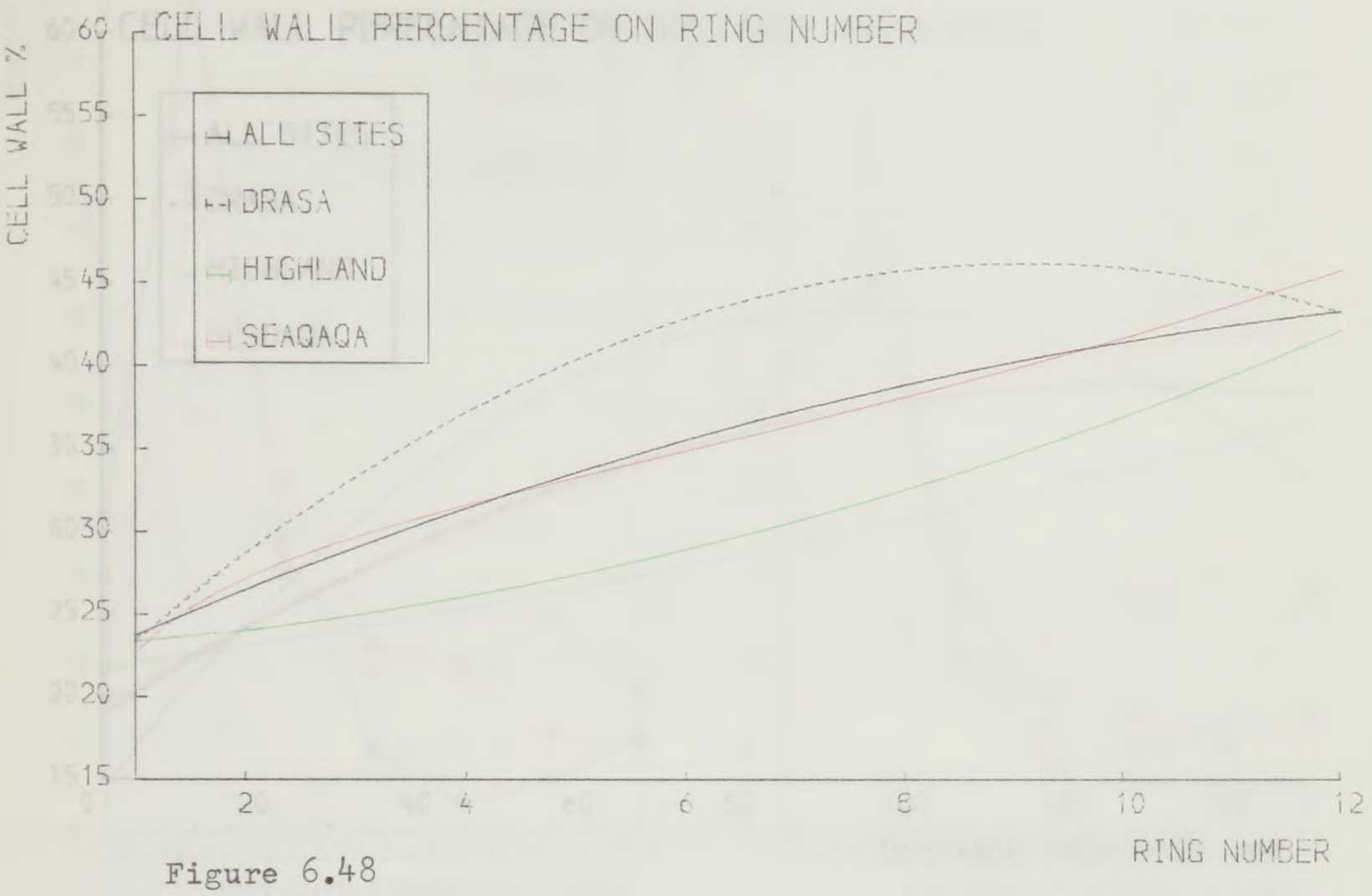


Figure 6.48

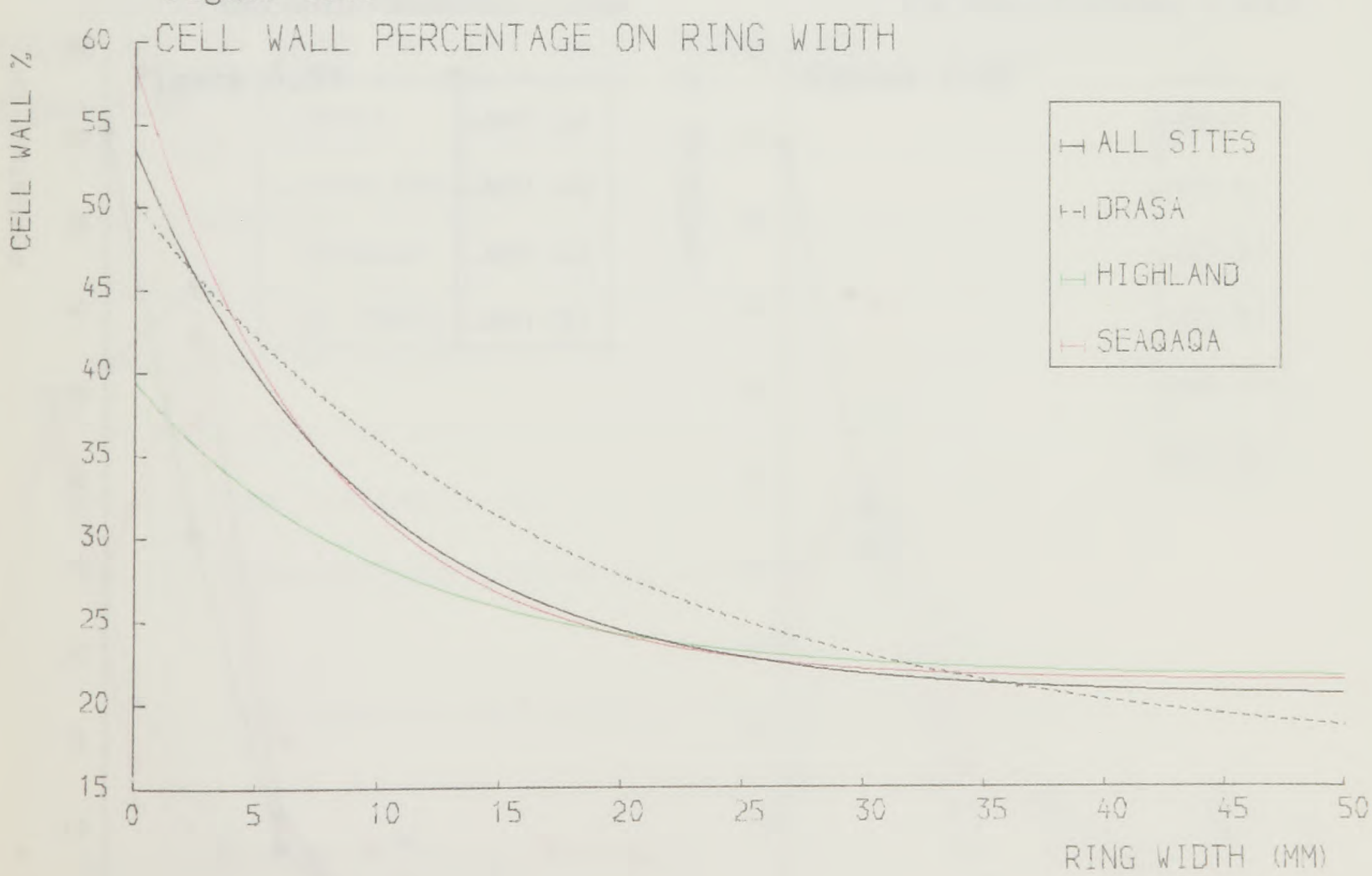


Figure 6.49

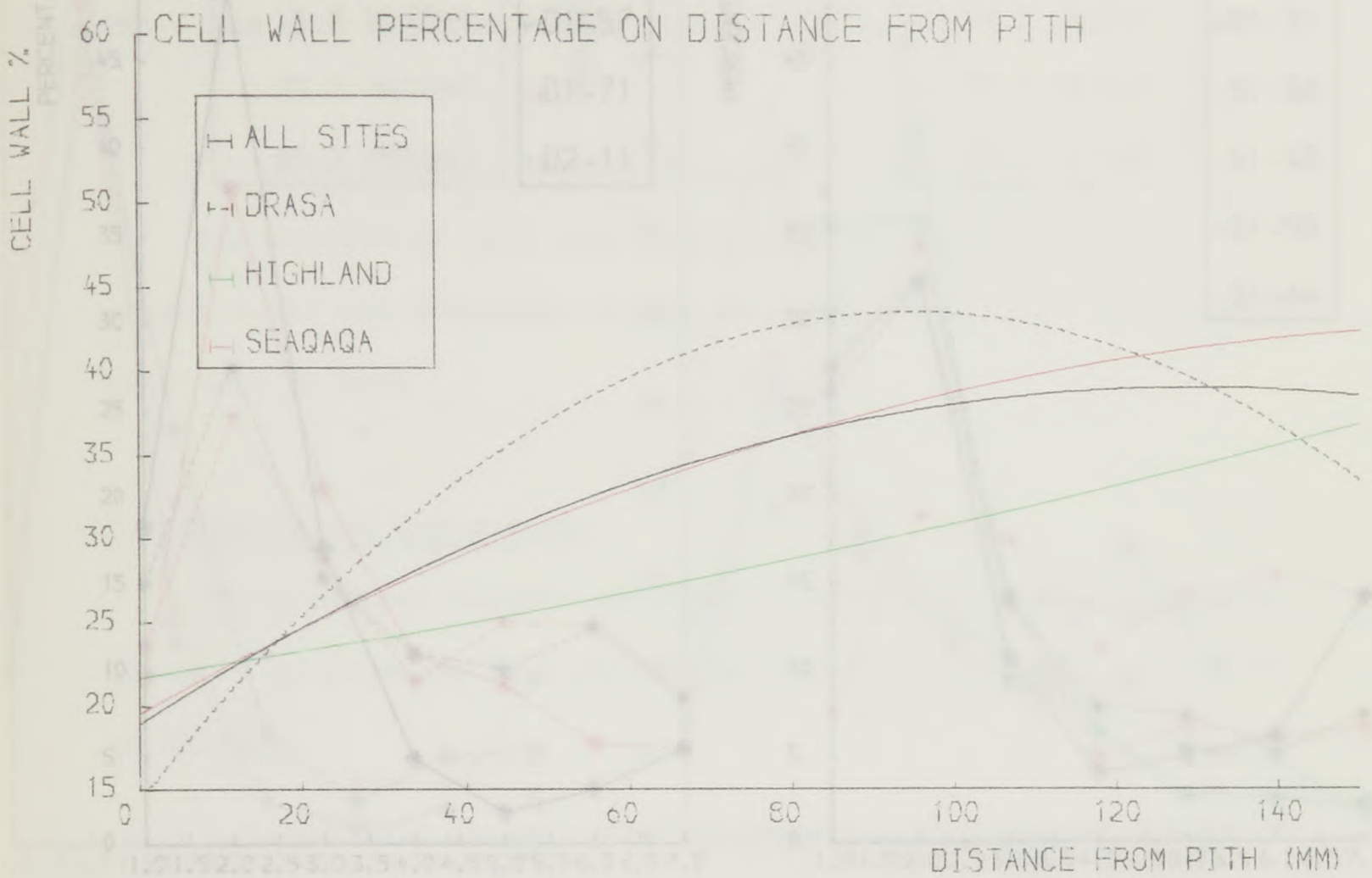


Figure 6.51

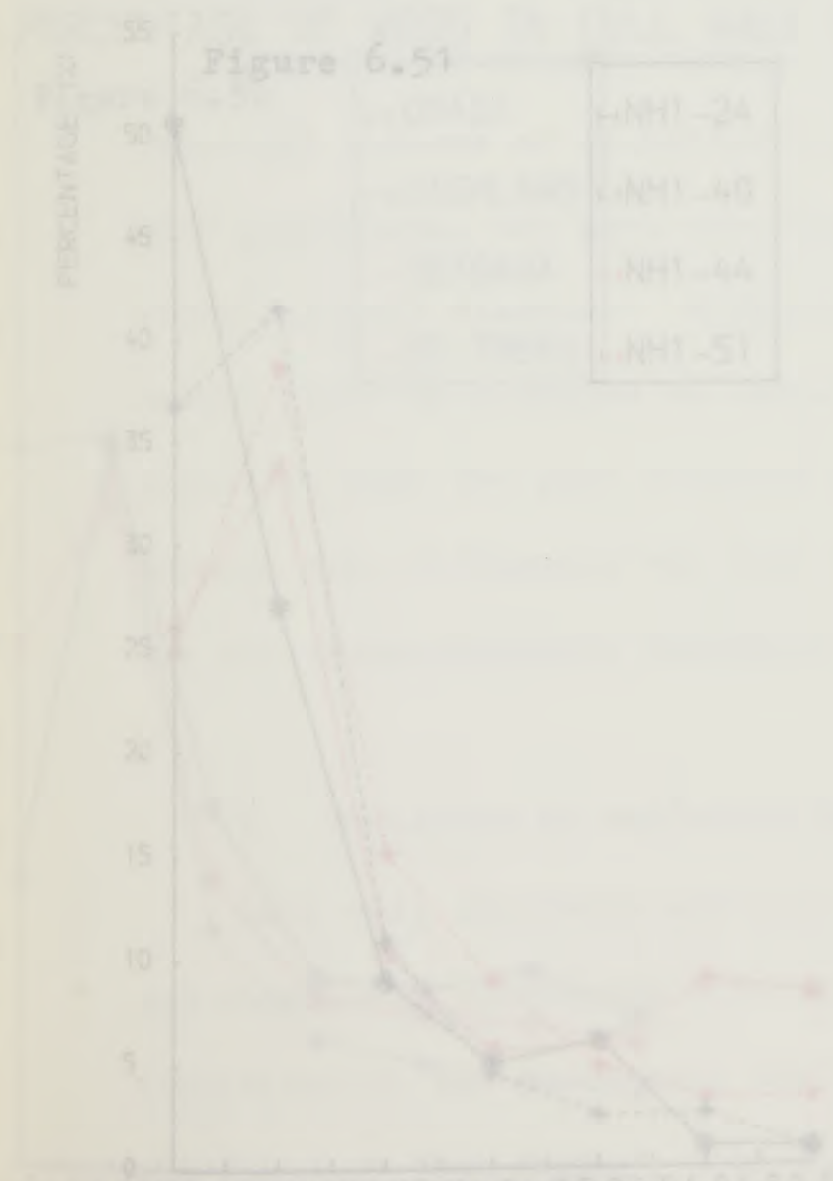


Figure 6.53

Figure 6.50

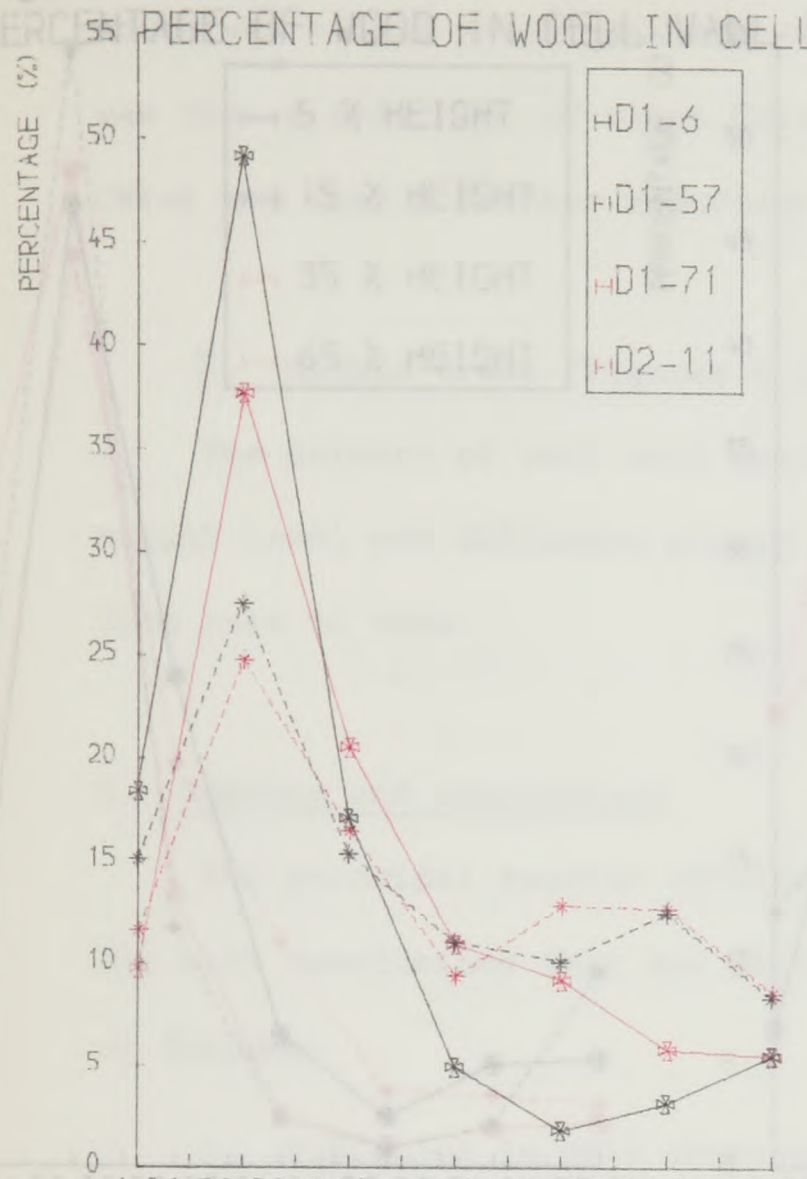


Figure 6.51

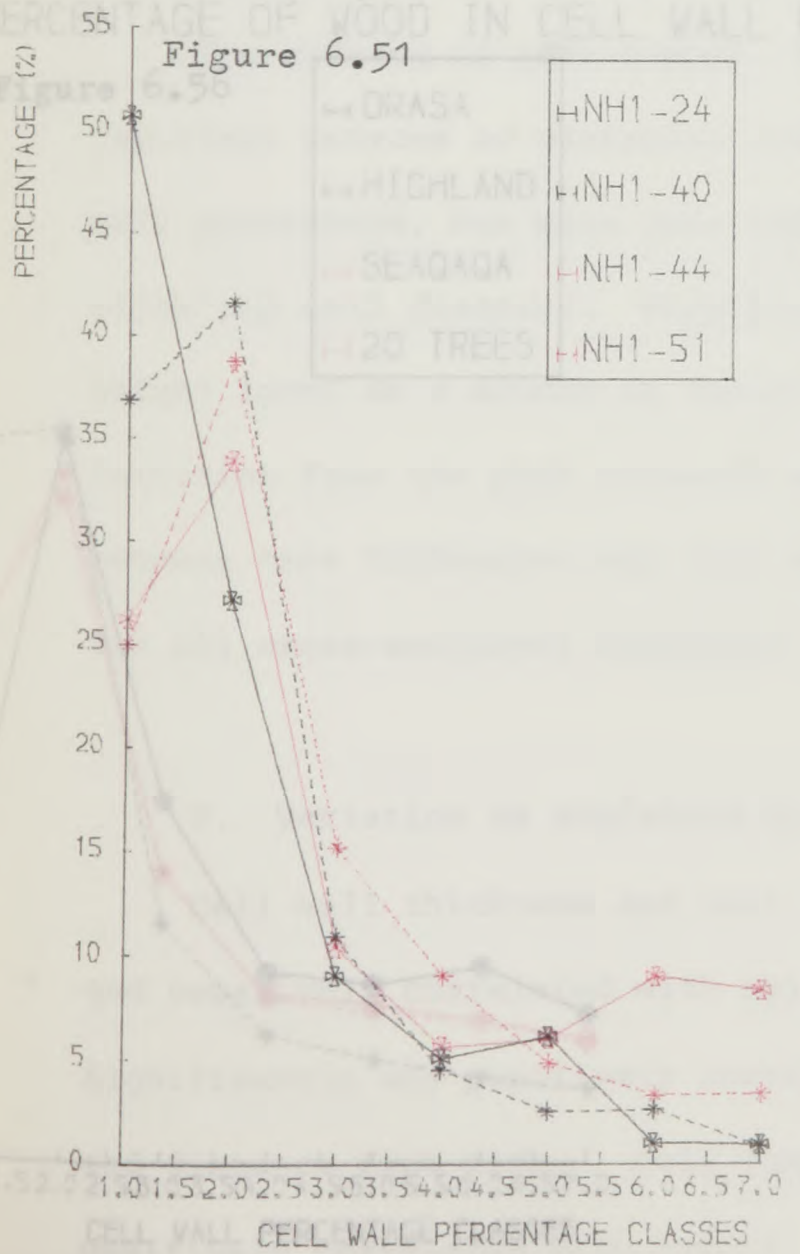


Figure 6.52

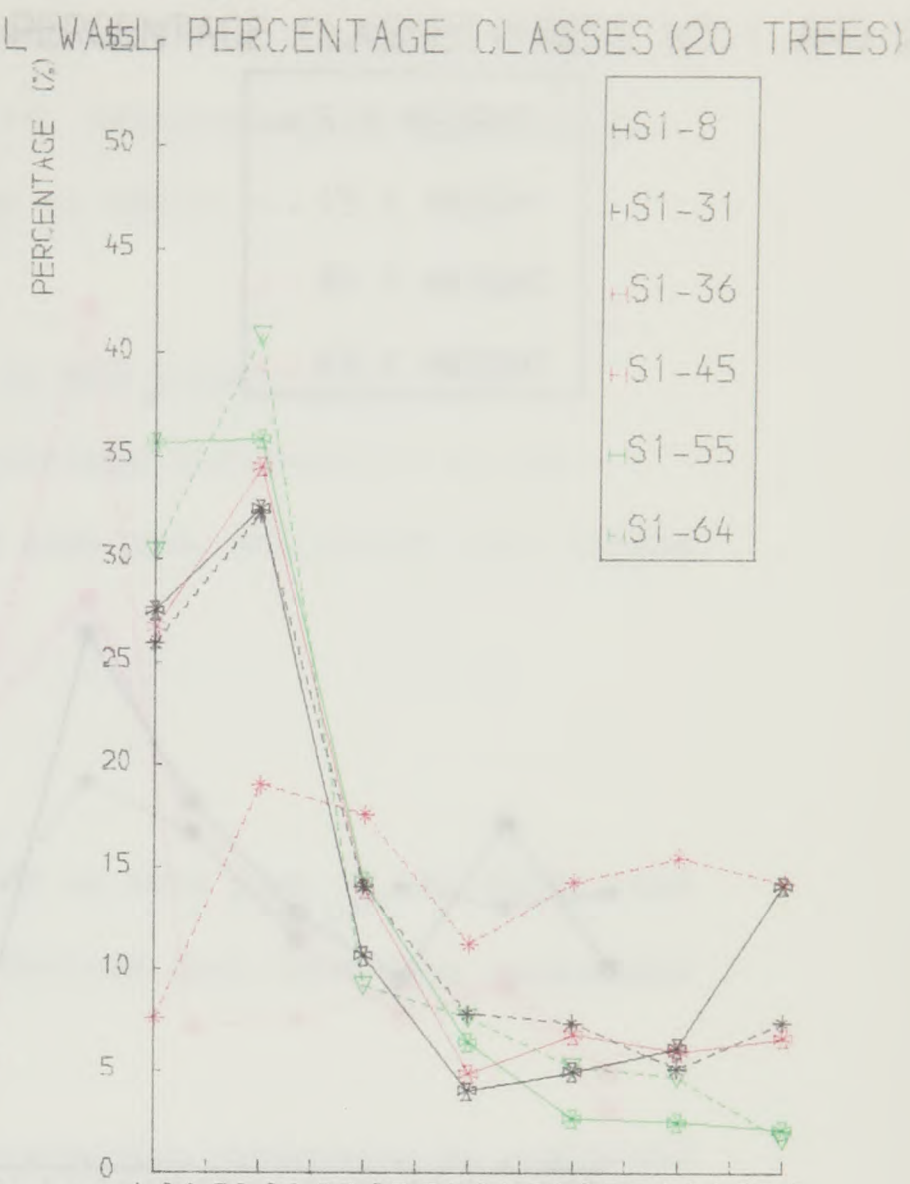


Figure 6.53

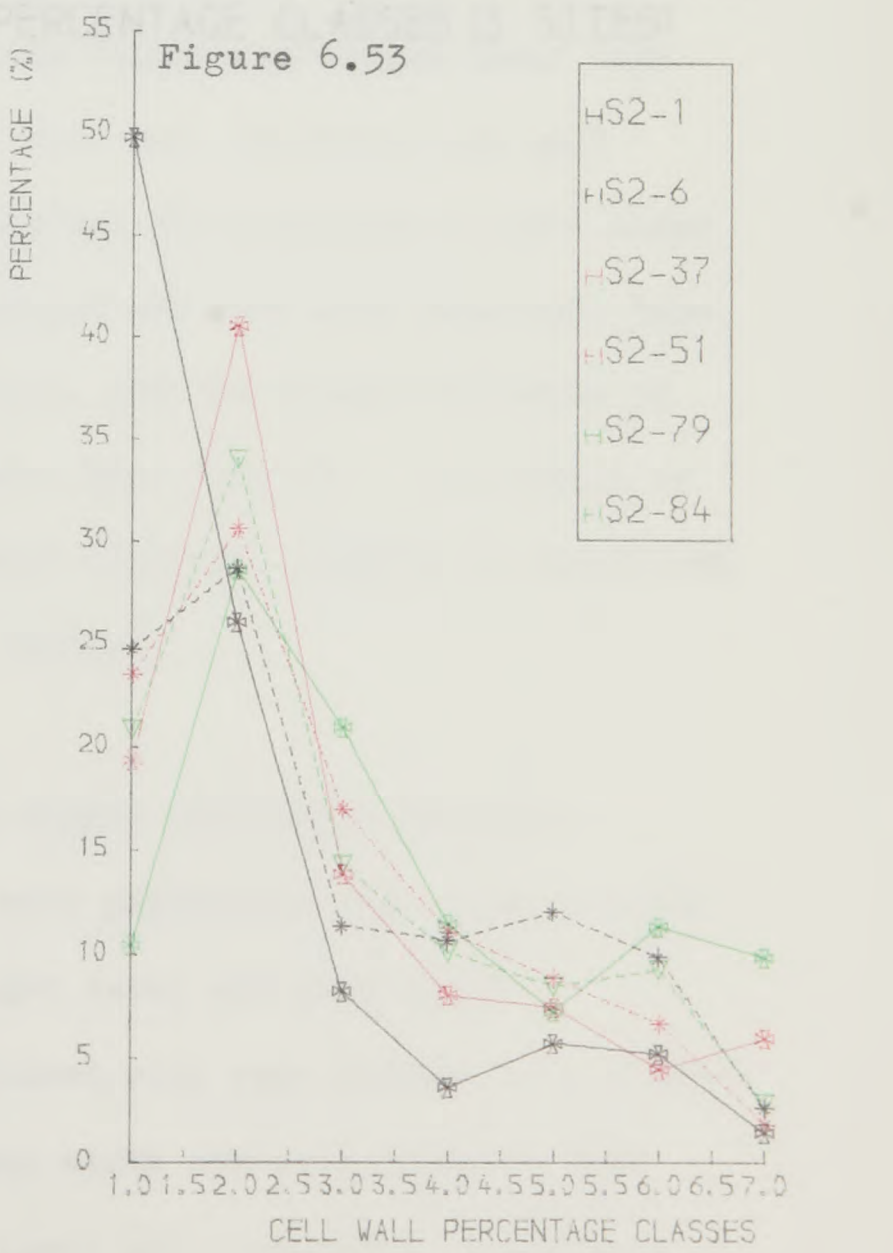


Figure 6.54

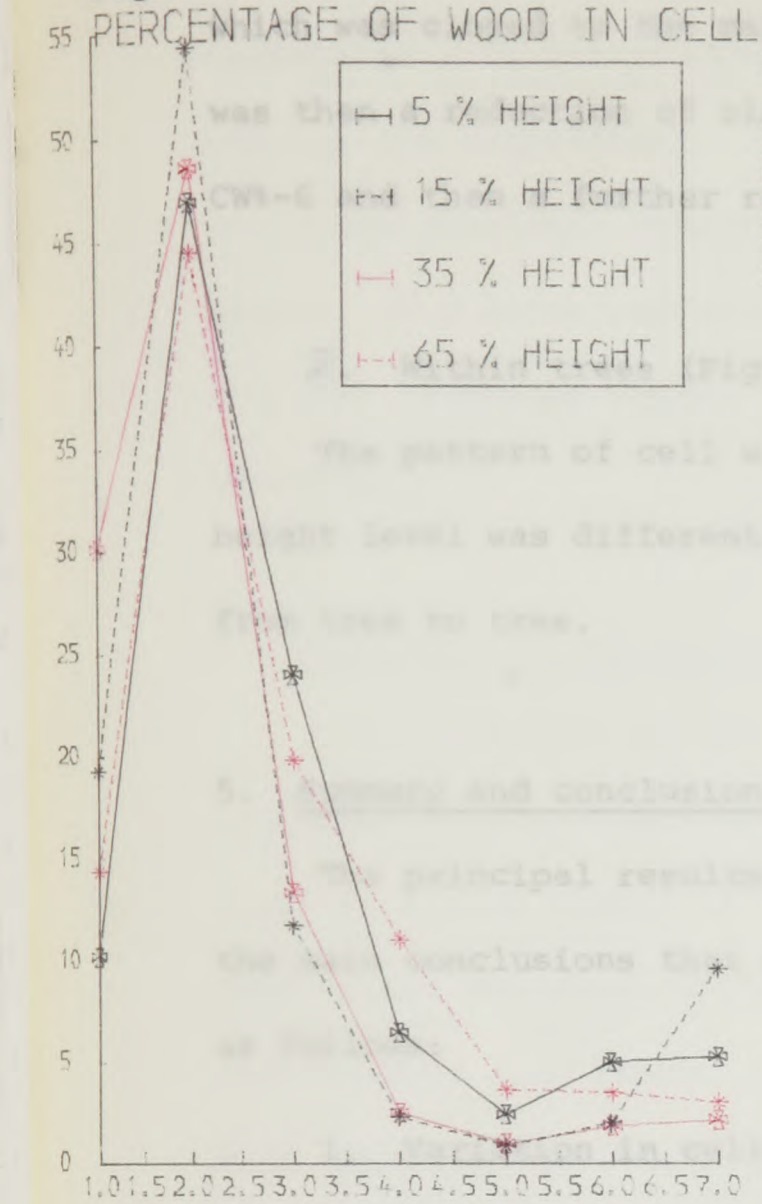


Figure 6.55

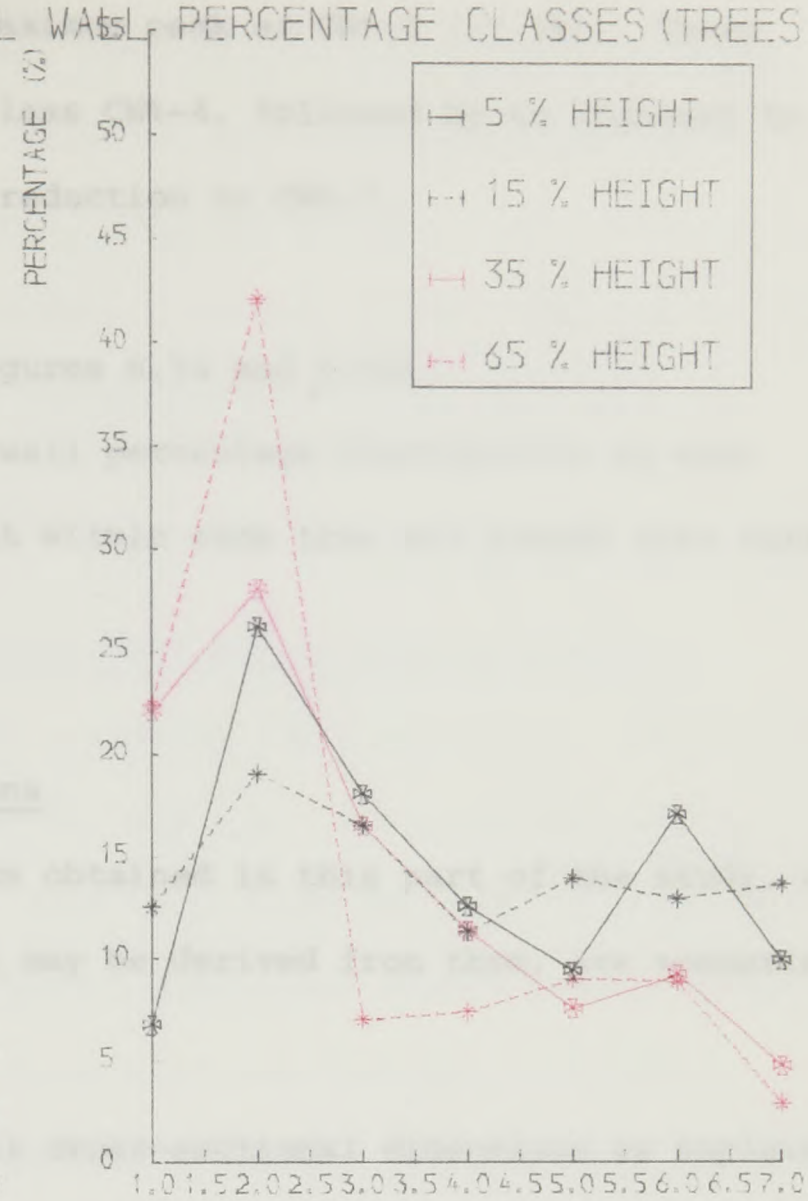
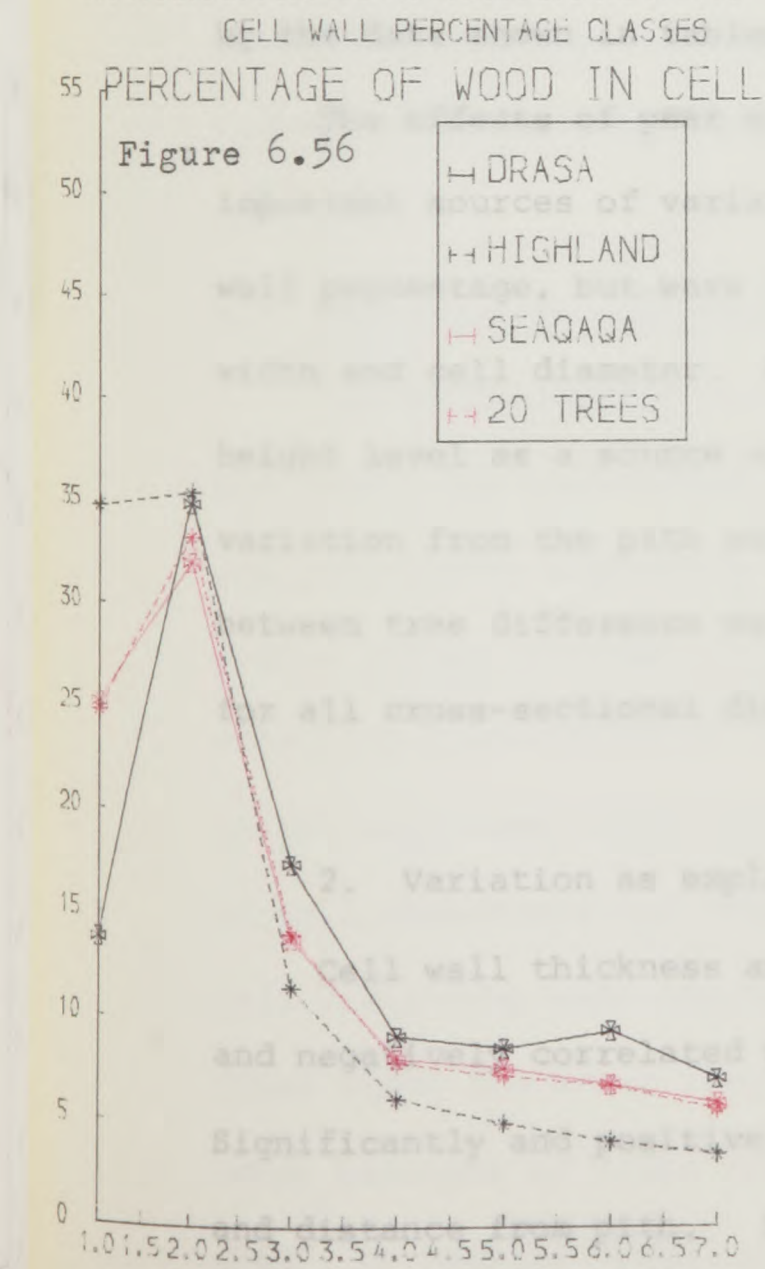


Figure 6.56



which was closed to the maximum peak at CW%-2 (19.1%). There was then a reduction of class CW%-4, followed by an increase to CW%-6 and then a further reduction to CW%-7.

2. Within trees (Figures 6.54 and 6.55)

The pattern of cell wall percentage distribution at each height level was different within each tree and trends also varied from tree to tree.

5. Summary and conclusions

The principal results obtained in this part of the study, and the main conclusions that may be derived from them, are summarised as follows:

1. Variation in cell cross-sectional dimensions as explained by the data shown in tables and graphs.

The effects of year number, ring number and height level were important sources of variation for cell wall thickness and cell wall percentage, but were less important for variation of cell lumen width and cell diameter. Ring position was much more important than height level as a source of variation, and the general patterns of variation from the pith outwards were more definite. The effect of between tree difference was also most important source of variations for all cross-sectional dimension features.

2. Variation as explained by simple regression analysis.

Cell wall thickness and cell wall percentage were significantly and negatively correlated with height level and ring width. Significantly and positively correlated with year number, ring number, and distance from pith. Cell lumen width and cell diameter were positively correlated with height level and ring width, negatively

correlated with year number, ring number and distance from pith, but was not significant. With the best fit regression lines, all cross-sectional dimension features increased rapidly with ring number, ring width and distance from pith at the very beginning and then flattened gradually decreased outwards.

3. Variation as explained by multiple regression analysis

The proportion of the variation explained by all models, as indicated by the values of R^2, was low. In practical terms, these equations cannot be used to predict reliably ring or mean tree values for cross-sectional dimensions from % height level, year number, ring number, ring width and distance from pith. Both simple and multiple regression showed that the most important variable affecting all cross-sectional dimension features was ring number, with distance from pith or ring width ranked next.

4. Variation as explained by morphological characteristics

For morphological characteristics, only D.B.H. was significantly and negatively correlated with cell wall percentage and significantly and positively correlated with cell lumen width and cell diameter. Simple linear correlation showed that the most important variable affecting cross-sectional dimension features was D.B.H., with tree height and crown length ranked next. However, the correlations of cell dimensions and tree morphological characteristics were poor. Cell dimensions were insignificantly correlated with tree height, crown width and crown length. This was perhaps due to the use of crude measures of crown size (pruning was carried out in 1964 and 1968), or because trees were selected from three different sites.

5. Possibility of predicting whole tree value

The prediction of mean weighted values for cross-sectional dimensions of whole tree can be validly based on values from a 5% height sample, using simple linear regressions.

6. The distribution of cross-sectional dimensions

a. The differences between trees in the percentage of wood in the various cross-sectional dimension classes was very large.

b. There were great differences between trees in the distribution of all the cross-sectional dimensions.

c. There were considerable differences within trees in the pattern of distribution at different height levels and these patterns also varied from tree to tree.

d. The distribution of cell wall thickness and cell wall percentage classes, showed more abrupt changes in the tree with low mean values than in the trees with large mean values.

e. The distribution of cell lumen width and cell diameter classes, wood percentage changed more abruptly in those trees with large mean values than in the trees with small mean values.

f. The distribution of wood percentage in all cross-sectional dimension classes, in general appeared to be related to the tree mean values, but some trees with similar mean values, showed some different percentages in the various classes.

7. Variation in cell diameter was more affected by cell lumen width than by cell wall thickness. Most of the results with cell diameter were similar to the results obtained with cell lumen width.

8. Variation in cell wall percentage was more affected by cell wall thickness than by cell lumen width. This is perhaps because the differences of cell lumen width with increasing ring number, ring width, height level and distance from pith was small, but the corresponding differences of cell wall thickness were large.

Chapter 7

EFFECT OF WOOD CHARACTERISTICS ON PULP PROPERTIES

The objects of this part of the study were (a) to ascertain the relationship between paper properties and wood characteristics, and to define some of the correlation of physical properties, fibre morphology and chemical composition of wood with pulp yield and paper strength, (b) to develop a mathematical model for predicting paper properties by measuring some wood characteristics.

In the following sections attention will be concentrated on the wood characteristics influencing pulp yield percentage, burst factor, breaking length and tear factor, since these are considered the most important pulp properties, technically and economically.

1. Pulp yield percentage

1.1 The influence of the chemical composition of the wood on pulp yield percentage (TY%)

A. Alpha cellulose content

After chemical pulping, cellulose is the principal constituent remaining in the wood fibres. In combination with the residual hemicellulose, the amounts left account for the variations in pulp yield obtained with different wood samples or with different cooking conditions.

Figure 7.1 shows that alpha cellulose was positively correlated with TY% (Total yield %), and the curve may be a non-linear function; TY% rises at a faster rate with increasing alpha cellulose content

when the percentage of alpha cellulose is low than when it is high. This may be because it is combined with variable amounts of residual hemi-cellulose. Alternatively, it may be because a small part of the alpha cellulose is lost when Kraft cooking takes place, and the loss with a high alpha cellulose percentage is slightly higher than the loss which occurs when the alpha cellulose percentage is low. However, alpha cellulose is a good single predictor for TY %, as is shown by the high values for the coefficient of determination in the regression equation (model 1 R^2 = 0.81, model 6, R = 0.881 (R^2 = 0.78) Table 7.1).

B. Hemicellulose content

Table 7.1 shows that hemicellulose was not significantly correlated with TY%. In the Kraft process the chemical action of delignification also causes the elimination of a great part of the hemicellulose, so that TY% is greatly dependent on alpha cellulose content but not on hemicellulose content.

C. Holocellulose content

Since holocellulose is essentially alpha cellulose plus hemicelluloses, the relationship of TY% with holocellulose should be similar to that with alpha cellulose.

The curve function is shown in Figure 7.2, and the R value indicates a highly significant positive correlation (Table 7.1, model 1, R = 0.67, model 4 R = 0.71).

D. Lignin content

Of the three principle cell wall constituents, lignin is considered undesirable in the chemically produced pulp, and is largely eliminated. Wood with a lower lignin content therefore produces a higher yield of pulp. Wood with low lignin content also requires less pulping and bleaching chemicals.

As shown in Table 7.1, lignin was negatively correlated with TY% (model 1, R =-0.56, model 12, R = 0.57).

E. Total Extractives content

The total extractive (1% NaOH Solubility, alcohol, Benzene and hot water solubility) percentage, as expected, had a highly significant negative correlation with TY% (model 1, R =-0.73, model 12, R = 0.77, Table 7.1).

1.2 The influence of fibre dimensions on pulp yield percentage (TY%)

A. Fibre length

Fibre length did not show a significant correlation with TY%, and the value of R was only 0.35 (Table 7.1).

B. Mean cell wall thickness (CW) and percentages of wood in cell wall thickness classes (CW-X)

Table 7.1 shows that relationships between TY% with mean cell wall thickness (CW) and the proportions of cells in a number of defined classes of wall thickness (CW-X) from CW-1 to CW-5 were; TY% positively correlated with CW, CW-3 and CW-4, and negatively correlated with CW-2. However the correlation of TY% with CW-1 (negative) and CW-5 (positive) were not statistically significant. The best correlation was with CW-2 where the value of R (linear) was only -0.66. The R value of linear regressions showed very small differences compared with the best fit of

non-linear regressions.

Table 7.2 (2-1) shows that when the data for the five various classes of cell wall thickness were used in combination in a multiple regression, the value of R^2 (0.53) obtained was low. This indicated that cell wall thickness data alone could not provide a good prediction of TY%.

C. Mean cell lumen width (CL) and percentage of wood in cell lumen width classes (CL-X)

Table 7.1 shows that TY% was positively correlated with CL-1 (R = 0.670), CL-2 (R = 0.64)and CL-3 (R = 0.29), and negatively correlated with CL-4 (R = -0.66), CL-5 (R = -0.74) and CL (R = -0.79). Excepted for CL-3 (which in fact contains a mixture latewood and earlywood and had a higher percentage of wood compared to other classes), the value of R (simple linear) of other variables were highly significant.

Table 7.1 also shows that, excepted for CL-3 and CL-5, the R values of other classes were greatly improved when using a nonlinear model. Figures 7.3 - 7.6 show that CL-1 and CL-2 were related to TY% by a non linear function where TY% rises rapidly at the low percentage levels and rises less rapidly at the high percentage levels. With CL-4, TY% increased to about 15% level and then decreased rapidly. The CL-5 curve was a negative slope linear function, indicating that an increasing proportion of cells with a wider lumen is associated with a lower cell wall percentage and a smaller amount of cell wall substance giving a lower yield. It is possible that wood with wider cell lumina contains more hemicellulose, lignin and extractives than wood with narrow cell lumina.

As apparent from Table 7.1, cell lumen data could be good single predictors for TY%. The best single predictor for TY% in this study was weighted mean cell lumen (CL) (model 6, R^2 = 0.71).

Combining all the cell lumen width data by multiple regression, did slightly improve the R^2 value (Table 7.2, 2.2). When choosing the regression for predicting the TY%, the simple regression of CL (model 6, R^2 = 0.71) may be much more satisfactory than multiple regression, because it has fewer variables and it is the simplest for calculation (Total of observation of call regressions was only 20).

D. Mean cell diameter (CD) and percentage of wood in cell diameter classes (CD-X)

Table 7.1 showed that TY% was positively correlated with CD-1 (R = 0.17), CD-2 (R = 0.59) and CD-3 (R = 0.71), and was negatively correlated with CD-4 (R = -0.41), CD-5 (R = -0.72) and CD (R = - 0.72). Except for CD-1 and CD-4, all other variables were highly significant. CD-1 and CD-4 had a low R value. This is because the class CD-1 formed less than 1% of the wood, and although CD-4 had the highest percentage compared with other classes, this class contained a mixture of earlywood and latewood, which possibly prevents a clear indication of its relationship with TY%.

Table 7.1 shows that the R values of CD-2, CD-3 and C.D. was highly improved when using a nonlinear model. Figures 7.7 - 7.9 show that CD-2 and CD-3 were similarly related with TY%; a rapid rise in TY% at low percentage levels and a lesser rise at high percentage levels. With increasing CD, TY% increases slightly at first and then decreased rapidly afterwards. Comparing the above curve functions, it can be assumed that TY% decreased more rapidly when the cell diameter increased or the percentage of large cells increased, which means large cells (with

a low percentage of cell wall) have more effect in reducing yield % than the small cells (with a high cell wall percentage).

The best single predictor of TY% in this study was CD-3 (model 6, R^2 = 0.76) with CD (model 3, R^2 = 0.64) ranking next. When some cell diameter data are combined together by multiple regression, the value of R is greatly improved, but it would not be advisable to use such expressions for prediction because of the small number of observations of TY% on which they are based (20 trees only).

E. Mean cell wall percentage (CW%) and percentages of wood in cell wall percentage classes (CW%-X)

Table 7.1 shows that TY% was negatively correlated with CW%-1 and CW%-2 classes and, positively correlated with all other classes and CW., The R value of classes CW%-2, CW%-3 and CW%-4 were not statistically significant, the others were statistically significant. The best single predictor for TY% was CW%-7 (model 6, R^2 = 0.52), with CW%-6 (model 3, R^2 = 0.49) ranking next. Figures 7.10 - 7.11 show that at the low percentage levels of CW%-6 and CW%-7 increase in the amount of these class had a greater effect in yield than at the high percentage levels.

The value of R^2 was greatly improved when all the cell wall percentage classes (CW%-X) were combined in a multiple regression. Table 7.2(2-4) showed that 84 per cent of the variability in TY% can be accounted for by variation in CW%-X, which provided a good prediction of TY%. Although the value of R^2 for this multiple regression is high, this regression must be used with caution because it is calculated from only 20 tree values and has a considerable number of terms on the independent variable side.

1.3 The influence of the physical properties of wood on pulp yield percentage (TY%)

A. Mean density (ED), latewood percentage (L%) and percentage of wood in density classes (ED-X)

Table 7.1 shows that TY% was negatively correlated with the low density classes (0.20 g/cc - 0.50 g/cc), positively correlated with highdensity classes (greater than 0.51 g/cc), latewood percentage (L%) and mean weighted density (ED). Excepted for the ED-1 and ED-4 classes, all other variables were significantly correlated with TY%. ED-1 and ED-4 had low values of R. A possible explanation is that class ED-1 formed less than 1% of the wood in all trees. Class ED-4 occurred as a high percentage (10% - 30%) of wood in all trees. Wood in this class, however, contained a mixture of earlywood and latewood, which possibly prevents a clear indication of its relationship with TY%. The value of R (R = 0.33) although showing a positive correlation with TY%, was not statistically significant.

The R values of some variables were improved when using a nonlinear model (Table 7.1). Figures 7.12 - 7.16 show that TY% decreased rapidly with low percentage levels of the ED-2 class, and decreased less with high percentage level of this class. ED-7, ED-8, L% and ED gave a similar result, low levels of these variables had a greater effect on the TY% than the high level.

A rapid rise in TY% occurred at low L% levels and a lesser rise at the high L% levels. This is in accordance with the results of Barefoot et al (1970) who suggested that the total yield from loblolly pine is a non-linear function of percentage latewood (see literature review).

The best single predictor for TY% from density data was ED-7 (model 12, R^2 = 0.64), with L% (model 6, R^2 =0.51) and ED (model 3, R^2 = 0.46) ranking next. Table 7.2 (2-5) shows that when all the factors based on density data were combined together in a multiple regression, the value of R^2 did not improve in comparison with the simple regression of ED-7 model 12.

B. Compression wood percentage

A review of the literature (Chapter 2) indicates that a high compression wood percentage occurs frequently in very fast grown trees. Although in compression wood the density and cell wall thickness is higher than in normal wood, trees with a high percent of compression wood often have lower mean desnity than normal trees. It is also known that compression wood contains more lignin and extractives but less alpha cellulose than normal wood, this causing the compression wood percentage to be negatively correlated with TY%. As Table 7.1 shows the R value of compression wood percentage and TY % had a highly significant negative correlation (model 1, R = - 0.69).

C. Growth rate

Growth rate here was based on wood volume divided by tree age. Table 7.1 shows it is negatively correlated with TY% (R = - 0.50).

The fastest growing tree had more than four times the volume of wood of the slowest growing tree. When compared as percent weight of pulp per volume of wood, the slow grown tree yielded more pulp (47%) than the fast growing tree (42%).

1.4 Pulp yield percentage conclusions

The principal results obtained in this part of the study and the main conclusions that may be derived from them are summarised as follows:

Compared with cell wall thickness and cell wall percentage data, cell lumen and cell diameter data were better single predictors of TY%. This may be due to the methods adopted for classification of the data or because cell lumen width data had a larger value than cell wall thickness data, and therefore could be measured much more accurately. It seems that pulp yield is mainly a function of the cell size and alpha cellulose content of the wood.

In all the various data classes showing distribution of density and cell dimensions, the classes which had a low percentage of the wood (such as ED-1, ED-8, CW-1, CW-5, CD-1), and the classes containing a high percentage of the wood but also a mixture of earlywood and latewood (such as ED-4, CL-3, CD=4 and CW%-4) had poorer correlations and lower R^2 values for prediction of TY%.

As previous results showed, the relationship between TY% and some variables (alpha cellulose, holocellulose, cell lumen, cell diameter, cell wall percentage and density) of the wood were non-linear functions. A possible reason for the above is high density wood with a large percentage of latewood and thick cell walls (large cell wall percentage) also had a higher alpha cellulose content. Because of cooking conditions, part of the alpha cellulose and hemicellulose may be lost during the Kraft process, and high density wood (with large latewood percentage, thick cell walls and large cell wall percentage) requiring more severe cooking may lose more of its alpha cellulose content than low density wood (with low latewood percentage and thin cell walls).

Table 7.1 show that out of ten of the best single predictors of TY% (based on best fit model), four were from cell lumen width data, three from cell diameter data, two from chemical data and only one from density data (ED-7). The most important single variable was alpha cellulose content, which explained 78 per cent (model 6) of the variability in pulp yield percentage (TY%), with CD-3 (model 6, R^2 = 0.75), CL (model 6, R^2 = 0.71) and CD (model 3, R^2 = 0.64) ranking next. Except for alpha cellulose content, cell diameter and cell lumen width data were the best single predictors of TY%, a finding which has not been recorded previously.

Some different variables were combined in a multiple regression to explain their joint relationships with TY% and to improve the R^2 value of predictors of TY%. Table 8.2 lists some of the regressions chosen for this study.

Compression wood and wood chemical data greatly improved the R^2 value when considered with density data (Table 8.2 (2-6, 2-7). Fibre dimensions and mean denisty (ED) provided a high significance of R^2 value when combined in multiple regression. Considered overall, cell wall percentage classes were the best predictors of TY% (R^2 = 0.84), but these regressions must be used with caution because they are calculated from only 20 tree values and have a considerable number of terms on the independent variable side.

It is noted that wood volume and mean density (ED) provided very good predictors of total pulp yield (TY% x dry matter (kg)), accounting for 97% of the variability (R^2 = 0.97), but not so good for pulp yield percentage (TY%), only accounting for 47% (R^2 = 0.47)

Table 7.1: Correlation between pulp yield % and wood characteristics

	Simple linear R	Sig.	Best fit nonlinear model Model	R	R^2
Alpha cellulose content	0.810	***	6	0.881	0.78
Hemicellulose content	0.0		3	0.114	0.01
Holocellulose content	0.673	***	4	0.709	0.50
Lignin content	-0.557	**	12	0.572	0.33
Total extractives content	-0.725	***	12	0.768	0.59
Fibre length	0.351		12	0.351	0.12
CW-1	-0.055		12	0.158	0.03
CW-2	-0.657	***	6	0.684	0.47
CW-3	0.442	*	3	0.467	0.22
CW-4	0.592	**	3	0.611	0.37
CW-5	0.315		3	0.359	0.13
Mean cell wall thickness (CW)	0.477	*	3	0.479	0.23
CL-1	0.665	***	12	0.777	0.60
CL-2	0.641	**	6	0.781	0.61
CL-3	0.285		12	0.303	0.09
CL-4	-0.656	***	3	0.760	0.58
CL-5	-0.742	***	3	0.744	0.55
Mean cell lumen width (CL)	-0.787	***	6	0.840	0.71
CD-1	0.167		3	0.226	0.05
CD-2	0.592	**	10	0.784	0.61
CD-3	0.712	***	6	0.867	0.75
CD-4	-0.408		3	0.442	0.20
CD-5	-0.723	***	3	0.750	0.56
Mean cell diameter (CD)	-0.719	***	3	0.799	0.64
CW%-1	-0.503	*	3	0.521	0.27
CW%-2	-0.420		3	0.453	0.21
CW%-3	0.402		12	0.406	0.16
CW%-4	0.369		3	0.443	0.20
CW%-5	0.480	*	12	0.508	0.26
CW%-6	0.668	***	3	0.704	0.50
CW%-7	0.485	*	6	0.720	0.52
Mean cell wall percentage (CW%)	0.634	**	12	0.653	0.43
ED-1	0.105		3	0.185	0.02
ED-2	-0.442	*	4	0.506	0.26
ED-3	-0.435	*	3	0.457	0.21
ED-4	0.332		3	0.387	0.15
ED-5	0.513	*	6	0.529	0.28
ED-6	0.559	**	3	0.575	0.33
ED-7	0.600	**	12	0.796	0.63
ED-8	0.491	**	4	0.515	0.27
Mean wood density (ED)	0.653	**	3	0.676	0.46
Latewood percentage (L%)	0.643	**	6	0.708	0.50
Compression wood percentage (CO%)	-0.685	***	3	0.704	0.50
Growth rate	-0.500	**	12	0.513	0.26

Regression equation

$y = 47.49 - 1227 \times 10^{25}(X^{-17.15})$
$y = 27.44 + 1.872 \times -0.04689\ x^2$
$y = 47.69 - 808400e^{-0.2070X}$
$y = X/(1.896 - 0.1244X + 0.002798X^2$
$y = X/(0.1305 + 0.00184X + 0.0007358X^2)$
$y = X/(-0.02084 + 0.04118X - 0.004134X^2)$
$y = X/(-0.001586 + 0.02209X - 0.00001265X^2)$
$y = 47.7 - 0.00000144\ X^{3.428}$
$y = 46.80 - 0.2177X + 0.008796X^2$
$y = 43.81 + 0.2831X - 0.005502X^2$
$y = 45.19 + 0.3556X - 0.01944X^2$
$y = 40.66 + 0.848X - 0.01792X^2$
$y = X/(0.002988 + 0.02155X - 0.0000211X^2)$
$y = 47.12 - 1568X^{-2.539}$
$y = X/(-0.07786 + 0.02722X - 0.00009128X^2)$
$y = 45.73 + 0.1798X - 0.005912X^2$
$y = 47.13 - 0.1793X + 0.001404X^2$
$y = 47.45 - 0.0000000009915X^{5.895}$
$y = 45.76 + 41.29X - 157.4X^2$
$y = 1/(0.0214 + 0.003218e^{-0.4891X})$
$y = 47.25 - 5442X^{-2.47}$
$y = 57.98 - 0.5718X + 0.006595X^2$
$y = 46.96 - 0.001587X - 0.001988X^2$
$y = -13.93 + 3.17X - 0.04124X^2$
$y = 48.10 - 0.1170X + 0.001044X^2$
$y = 52.55 - 0.3206X + 0.003541X^2$
$y = X/(-0.006103 + 0.02367X - 0.0001032X^2)$
$y = 47.92 - 0.8099X + 0.06377X^2$
$y = X/(-0.001599 + 0.0230X - 0.0001344X^2)$
$y = 43.59 + 0.4954X - 0.01653\ X^2$
$y = 46.28 - 0.8402X^{-13.08}$
$y = X/(0.1081 + 0.01759X + 0.00002524X^2)$
$y = 45.68 + 2.712X - 2.841X^2$
$y = 44.55 + 2.692e^{-0.07277X}$
$y = 51.4 - 0.2073X + 0.001786X^2$
$y = 41.62 + 0.3897X - 0.007733X^2$
$y = 46.56 - 682.9X^{-3.516}$
$y = 43.47 + 0.3955X - 0.009971X^2$
$y = X/(0.002329 + 0.02128X - 0.000008492X^2)$
$y = 46.61 - 1.924e^{-3.142X}$
$y = 28.86 + 49.94X - 33.59X^2$
$y = 46.98 - 371.7X^{-1.966}$
$y = 46.59 - 0.08598X - 0.01417X^2$
$y = X/(0.00001219 + 0.01981X + 0.05352X^2)$

Table 7.2: Coefficient for multiple regressions of pulp yield percentage

	Constant term						
2-1		CW-1	CW-2	CW-3	CW-4	$(CW-2)^2$	$(CW-3)^2$
	20.49	-0.02062	1.081	-0.2866	-0.3016	-0.009795	0.007688
	48.71***					-0.000812**	
2-2		CL	CL-1	CL-2	CL-4	CL-5	$(CL)^2$
	290.6	-11.78	0.2819	-0.6178	0.9897	0.2447	0.129
	60.57***	- 0.5108**			0.125*		
		CL-1	CL-2	CL-3	CL-4	CL-5	
	-7464	74.8	74.47	74.55	74.59	74.42	
2-3		CD	CD-2	CD-3	CD-4	CD-5	$(CD)^2$
	384.8	1.35	-3.033	-2.608	-5.889	-415	-0.001269
	129.1***		-0.7913***		-2.017**	-0.6798***	
		CD-1	CD-2	CD-3	CD-4	CD-5	
	94.45	6.994	-0.5545	-0.4502	-0.4714	-0.5611	
2-4		CW%-1	CW%-2	CW%-3	CW%-4	CW%-5	CW%-6
	-50450*	504.8*	504.8*	505*	504.9*	504.7*	505*
2-5		ED-1	ED-3	ED-4	ED-6	ED-7	ED-8
	40.5***	2.327	0.02828	0.05348	0.3867	0.2152	0.8621
2-6		ED-2	ED-3	ED-4	ED-5	ED-6	ED-7
	29.66	0.1676	0.1473	0.1753	0.02834	0.5446	-0.05649
	45.49***					0.1571**	
		ED	CO%				
	41.96***	8.64**	- 0.2085**				
		L%	CO%				
	45.26***	0.05489**	-0.2236**				
2-7		ED-5	ED-6	ED-7	ED-8	FL	alpha
2-8		ED	CW	CL	CD	CW%	FL
	69.78**	-8.269	1.681	-0.702*	0.1825	-0.5138	1.686
2-9		ED	Volume				
	41.03***	10.48**	-2.361				
Pulp yield (kg)		183.9***	25.8***				
	-100.6 ***						

				R^2	R	Sig
$(CW-4)^2$				0.530	0.728	
0.0179				0.453	-0.673	**
$(CL-1)^2$	$(CL-2)^2$	$(CL-4)^2$				
0.0.038	0.006733	-0.01127		0.774	0.880	*
				0.703	0.838	***
				0.641	0.80	**
$(CD)^2$	$(CD-3)^2$	$(CD-4)^2$	$(CD-5)^2$			
0.001269	-0.01298	0.02775*	0.007311	0.860	0.927	**
	-0.008255***	0.01619*		0.810	0.900	***
				0.616	0.785	*
CW%-7						
504.9				0.842	0.918	***
				0.590	0.768	*
ED-8	CO%					
0.8604	-0.2395			0.764	0.874	*
	-0.249**			0.670	0.818	***
				0.654	0.809	***
				0.685	0.828	***
Holo				0.792	0.890	***
				0.742	0.861	**
				0.468	0.684	**
				0.973	0.987	***

Figure 7.1

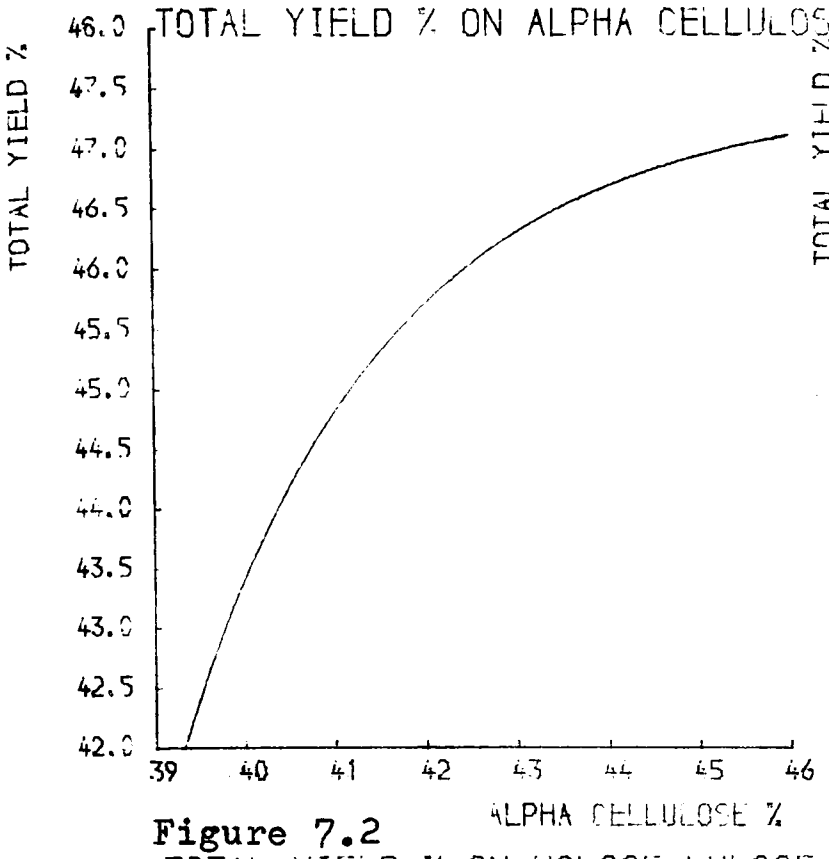


Figure 7.2

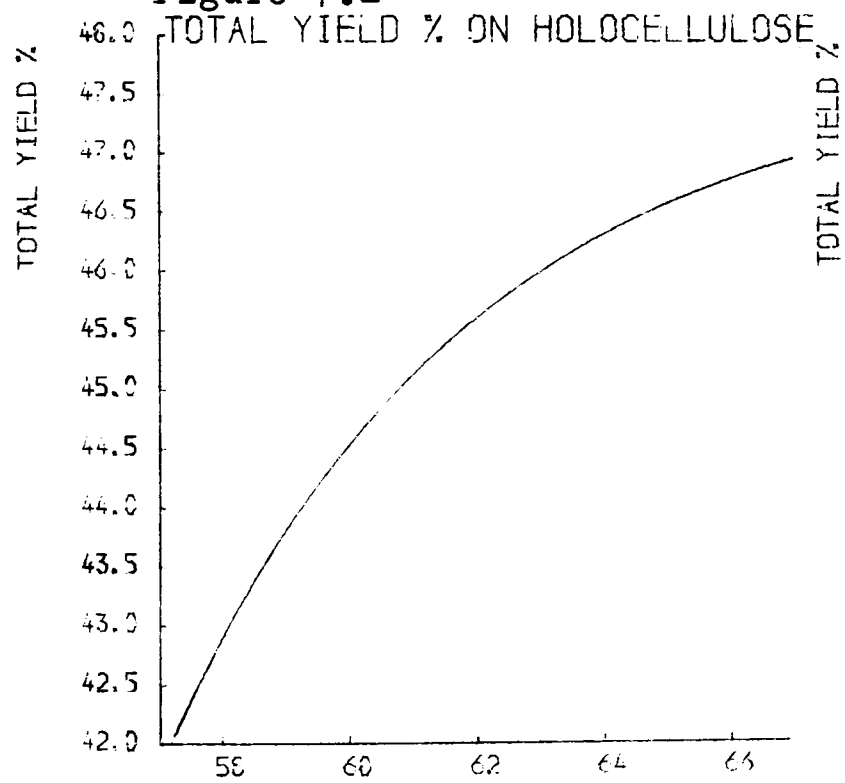


Figure 7.3

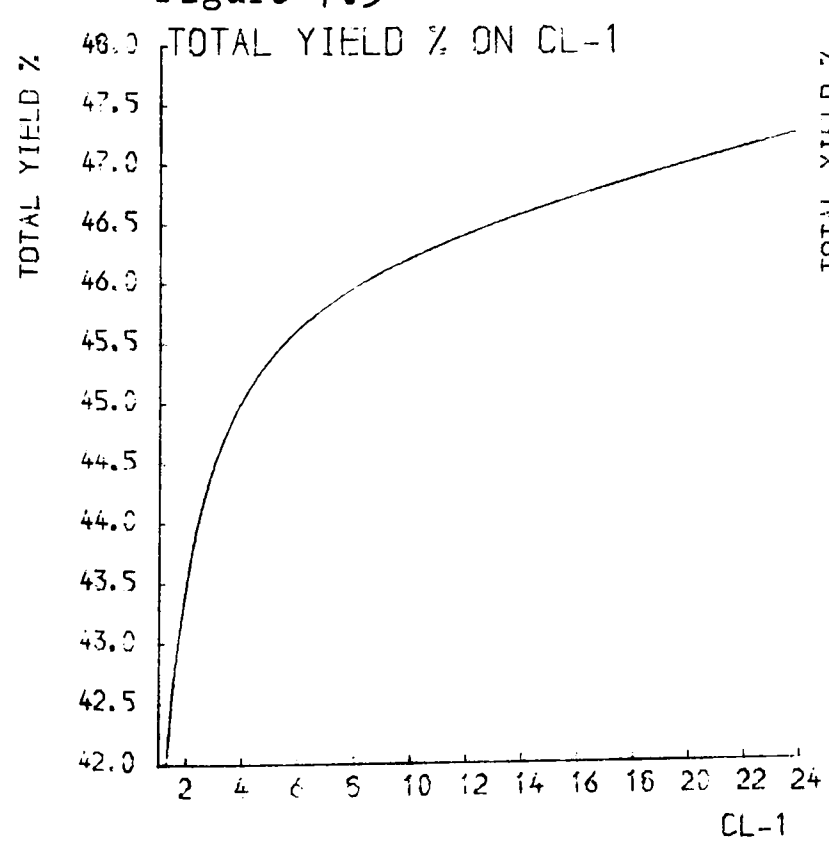


Figure 7.4

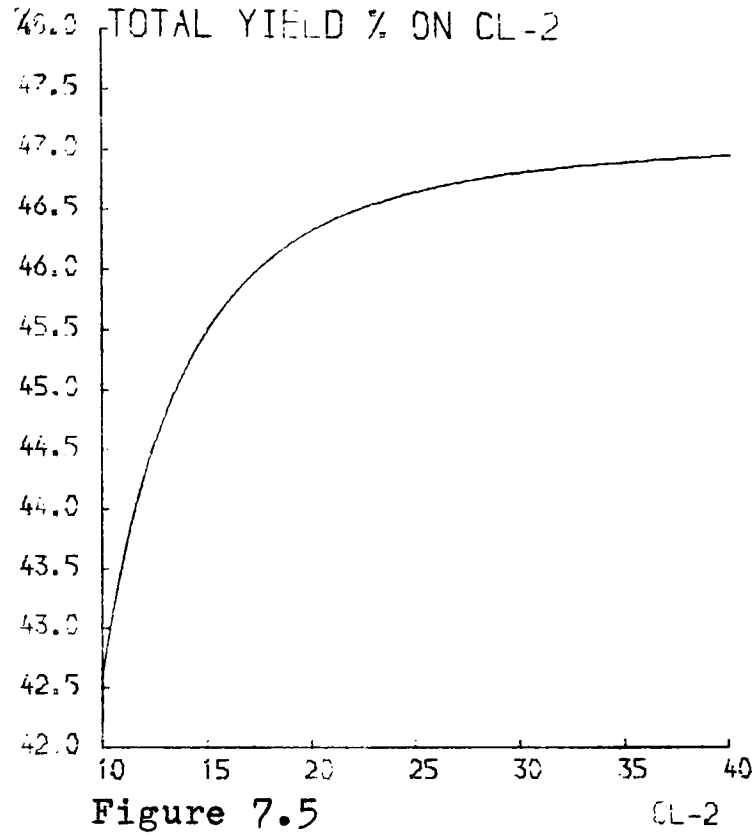


Figure 7.5

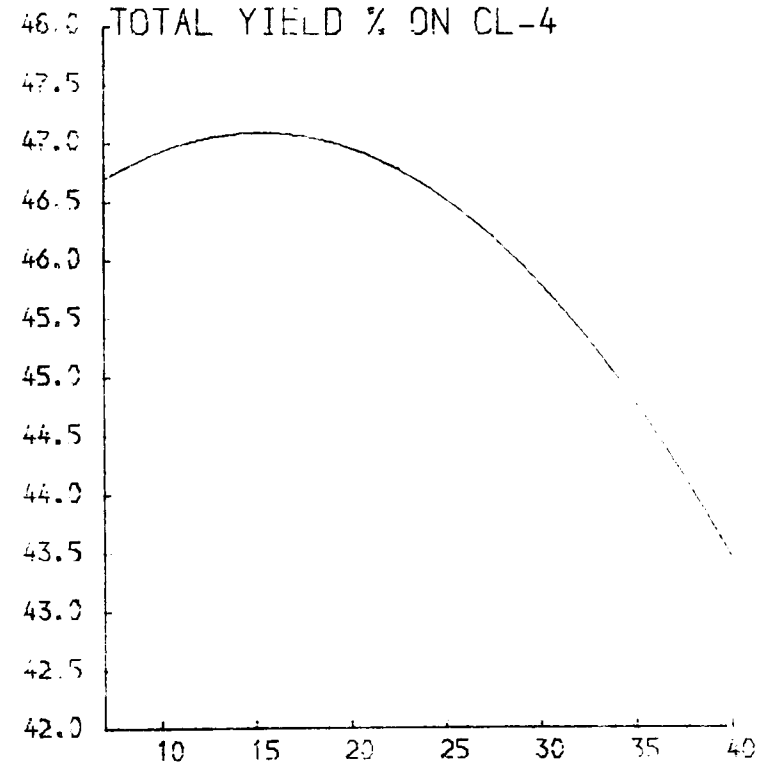


Figure 7.6

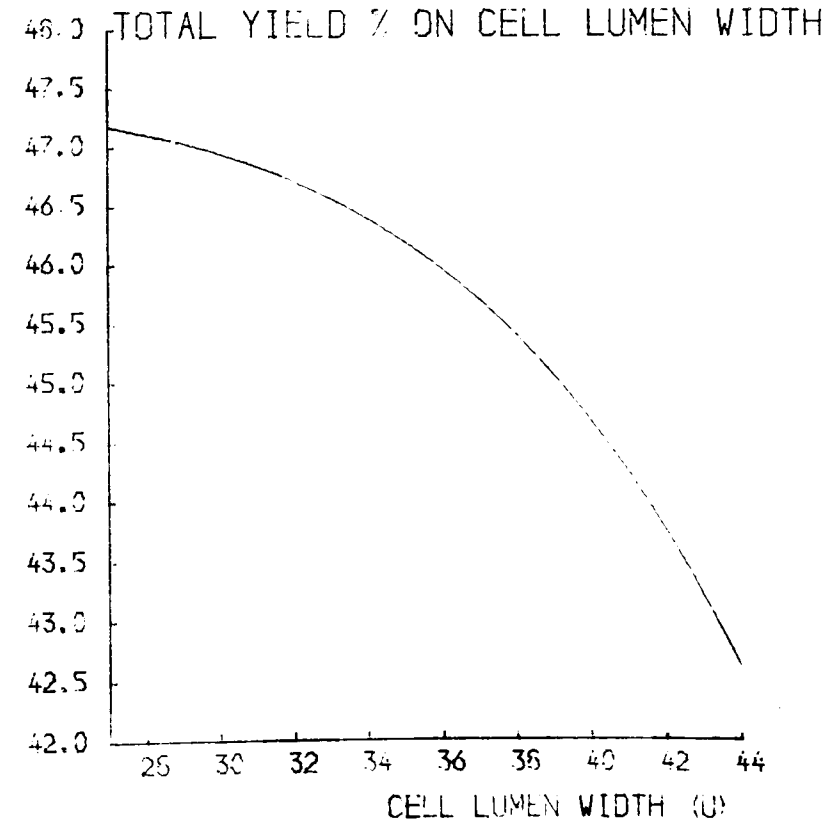


Figure 7.7

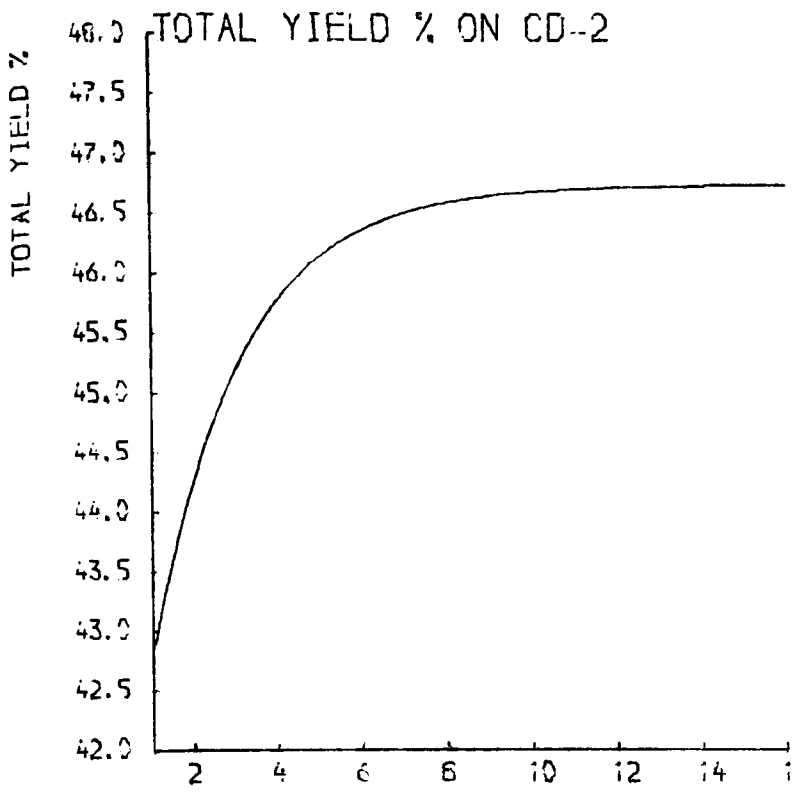


Figure 7.8

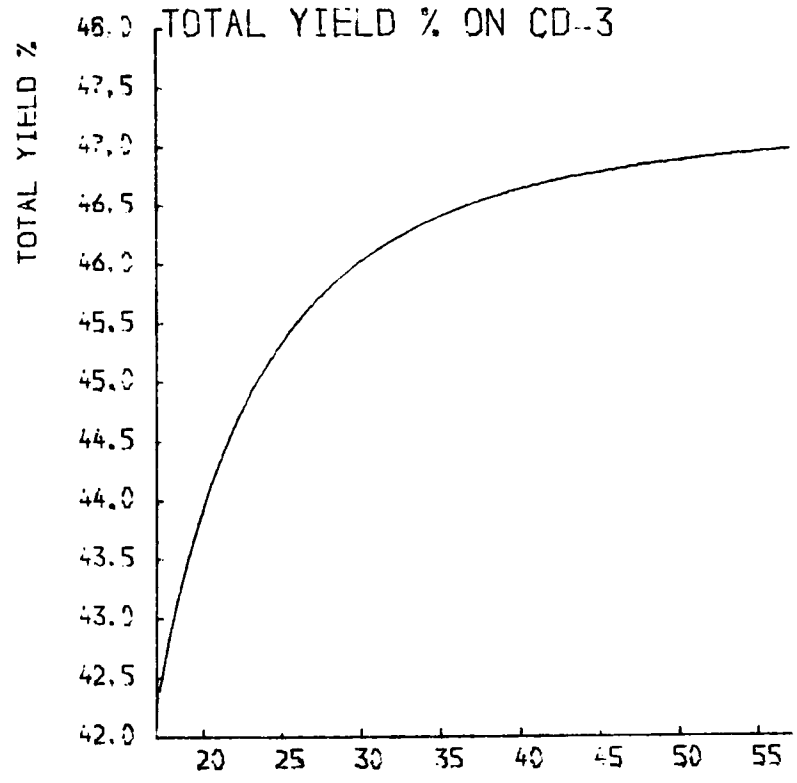


Figure 7.9

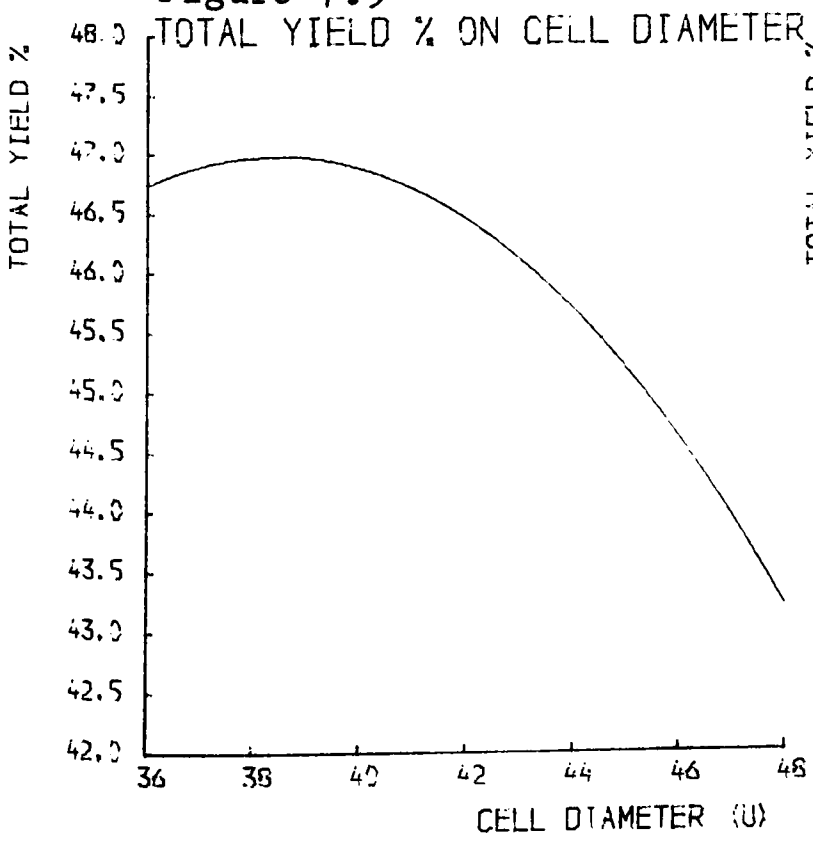


Figure 7.10

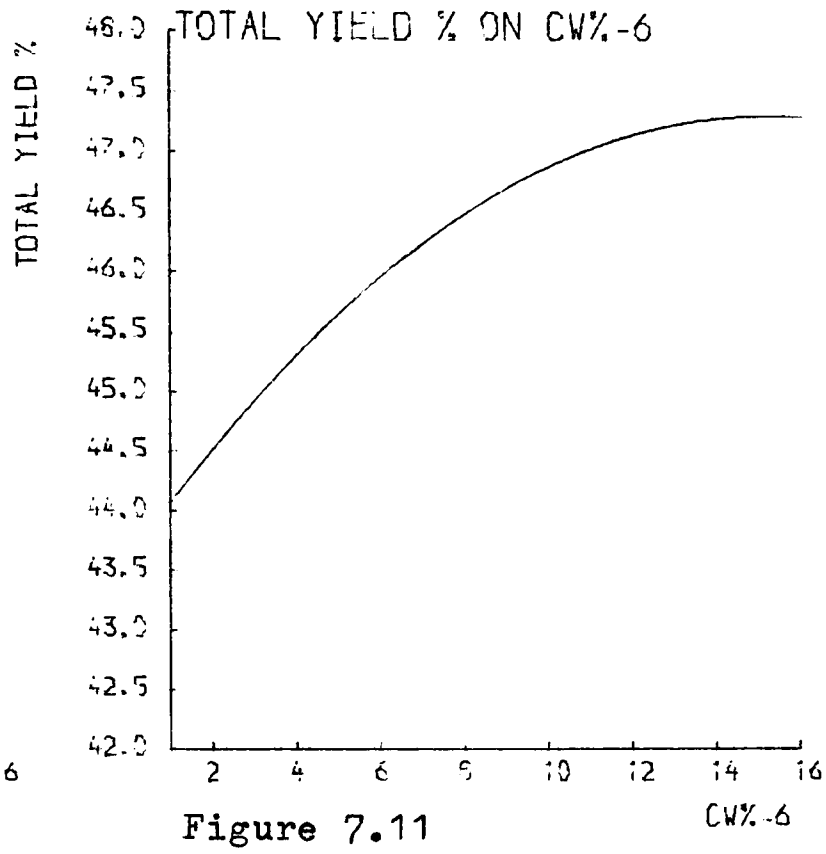


Figure 7.11

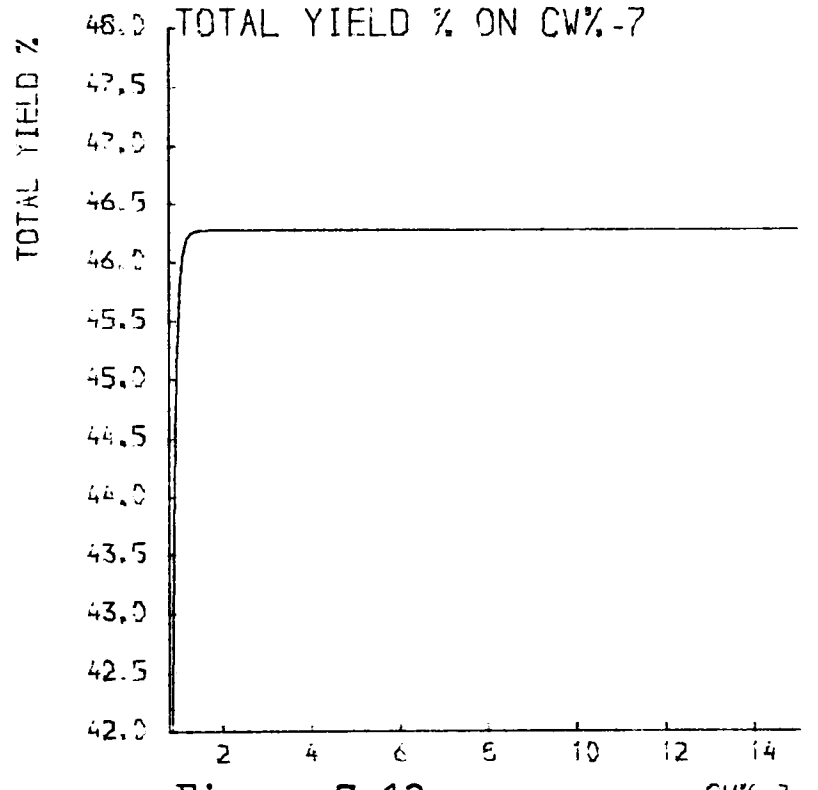
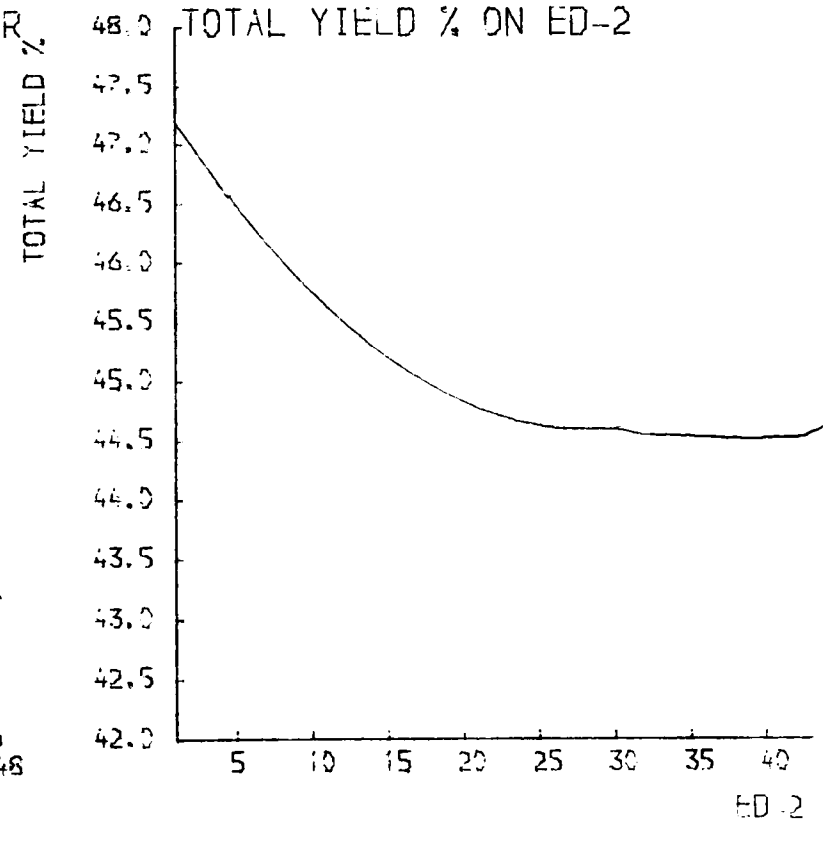


Figure 7.12



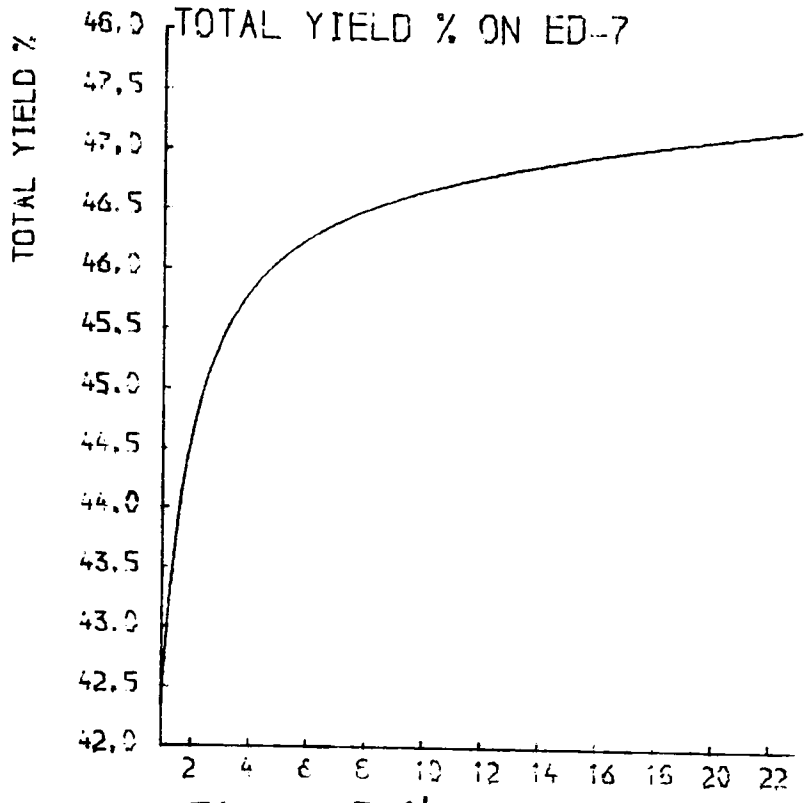


Figure 7.14

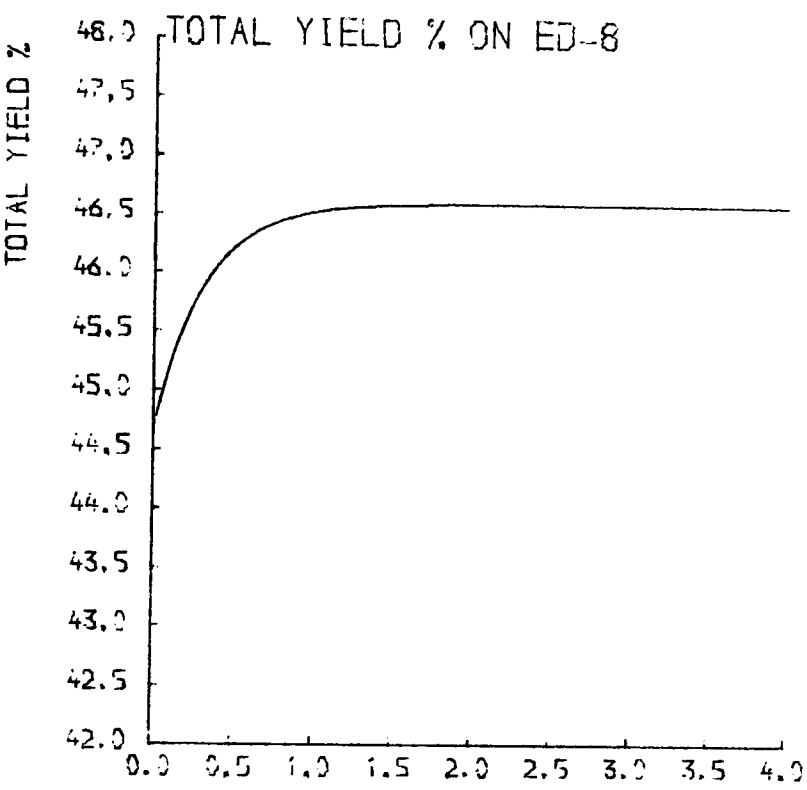


Figure 7.15

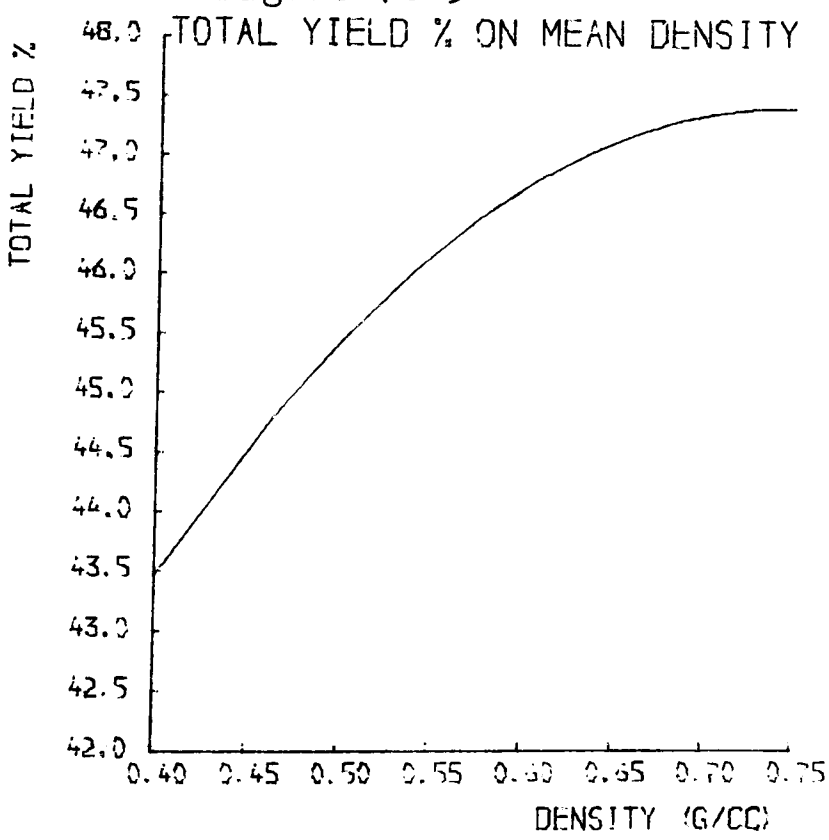
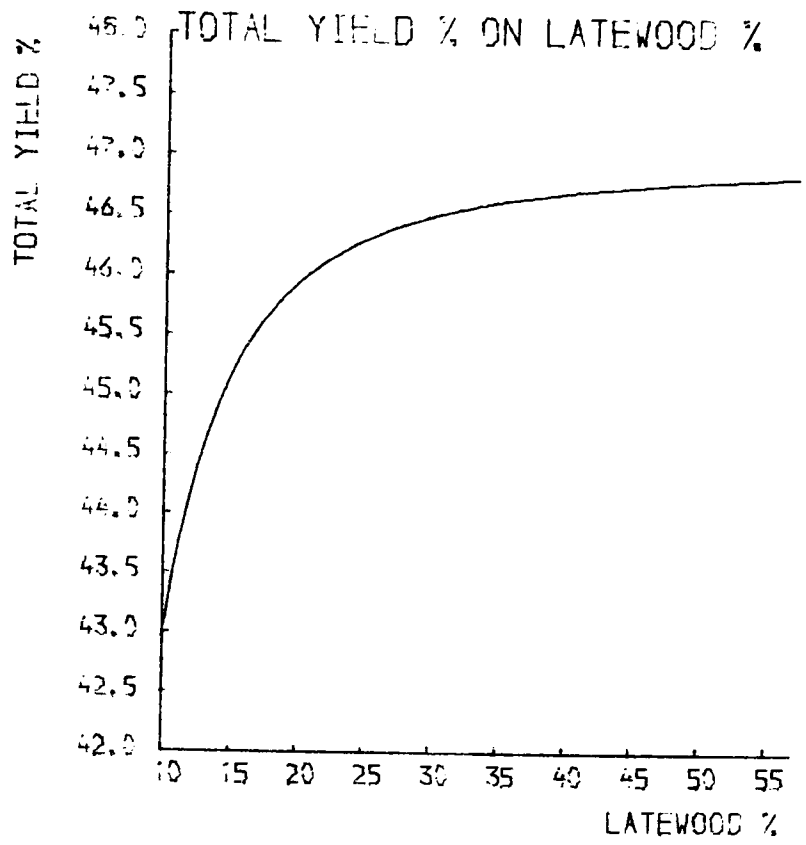


Figure 7.16



2. Burst factor

2.1 The influence of chemical composition of the wood on burst factor (BF)

Table 7.3 shows that alpha cellulose, holocellulose and lignin content were not significantly correlated with burst factor (BF), but hemi-cellulose was positively correlated with BF (linear, R = 0.50). In spite of the insignificant linear correlation between BF and alphacellulose content. Figure 8.17 shows that a non-linear relationship between BF and alpha cellulose with R^2 = 0.35 (model 3, R = 0.59). BF increases with an increase of alphacellulose content at first, then decreases after the alpha cellulose content reaches 42%. It should be noted that alphacellulose content of between 39.9% to 41.9% occurred in only three trees. If three trees of the lowest alpha cellulose content are eliminated, the regression line is linear and negatively related.

It is known that the effects on BF mainly depend on the fibre bond area and on individual intrinsinc fibre strength. In this study, alpha cellulose was known to be positively correlated with cell wall thickness (linear, R = 0.76). A review of literature showed that before cell wall thickness reaches a certain level, cell walls could collapse completely. Within this range, the intrinsic fibre strength increase with increase in cell wall thickness, while fibre bond area remains the same, resulting in an increase in BF. After cell wall thickness has reached a certain level, increasing cell wall thickness, will cause the cell wall to resist collapse. Although fibre intrinsic strength increases, the fibre bond area begins to decrease, and also BF begin to decrease.

2.2 The influence of fibre dimension on burst factor (BF)

A. Fibre length (Tracheid length)

Assuming that cell wall thickness and lumen width are constant, it would be expected that the longer the fibre the larger the fibre bond area,

because longer fibres could overlay more fibres than the shorter fibres. This should increase the burst factor and breaking length.

Table 7.3 shows that fibre length was not significantly correlated with BF. In Figure 7.18 the non-linear function (model 3, R = 0.48, R^2 = 0.25) shows that BF decreased at first when fibre length increased from 2.78 mm to about 3.0 mm, then BF increases after fibre length reached about 3mm. This could be explained by the fact that fibres of the same length could have a different cell wall thickness; if BF were affected by both cell wall thickness and fibre length, but if cell wall thickness affected BF more than fibre length, then the significance of the effect of fibre length on BF would be reduced.

B. Tracheid cross-sectional dimensions and various classes

Table 7.3 shows that of the tracheid cross-sectional dimensions, only cell wall thickness and cell wall percentage were significantly correlated with BF. From Figures 7.19 - 7.20 it is apparent that BF gradually increased with increase in the percentage of cell wall classes (such as the thin walled CW-1 and CW-2), rising faster at the lower percentage levels than at the higher percentage levels.

Thick cell wall classes (CW-3, CW-4 and CW-5) are negatively correlated with BF. For CW-3 the non-linear regression graph (Figure 7.21) shows that BF increased at first with increasing percentage of CW-3 to a certain level (about 16%), and then decreased. BF gradually decreased as mean cell wall thickness (CW) increased.

The behaviour of CW-3 in relation to BF may interpreted in the same way as alpha cellulose content effects BF (see previous section). Before cell wall thickness reaches a certain level, cell walls could collapse completely. Within this range, fibre bond changes vary little,

but the intrinsic fibre strength increases with increase in cell wall thickness increase, resulting in an increase in BF. After cell wall thickness has reached a certain level, increasing cell wall thickness will cause the cell wall to resist collapse. Although fibre intrinsic strength increases the fibre bond area begins to decrease, and BF also begin to decrease.

Mean cell wall percentage (CW%) and the higher part of the range of cell wall percentage classes (CW%-5 and CW%-6) are negatively correlated with BF. The results of these relationships, illustrated in the non-linear graphs show in Figures 7.22 - 7.24, were similar to those of CW-3 with BF. This may be because cell wall percentage is determined to a considerable extent by the cell wall thickness.

It seems that the proportion of thick walled cells and of cells with a high cell wall percentage has greater influence on BF than the proportion of thin walled cells and cells with a low cell wall percentage.

Table 7.4 shows that multiple regression based on fibre cross-sectional dimensions alone could not improve the R^2 value of BF.

C. Fibre dimension ratios

Table 7.3 shows that the various ratios based on tracheid dimensions, with the exception of fibre slenderness ratio (FL/CD), were significantly related to BF; the Runkel ratio (2CW/CL) and fibre index (2CW x FL) were negatively correlated with BF, the flexibility ratio (CL/CD) and fibre stiffness (FL/2CW) were positively correlated with BF. Among these ratios, fibre stiffness (FL/2CW) has a higher correlation with BF (R = 0.64) than the other ratios.

2.3 The influence of wood physical properties on burst factor (BF)

A. Mean density (ED), latewood percentage (L%) and percentage of wood in density classes (ED-X)

Table 7.3 shows that ED-3 (R = 0.49) was positively correlated with BF, ED-6 (R = -0.51), ED-7 (R = -0.44), L% (R = -0.50) and ED (R = -0.44) were negatively correlated with BF.

When BF was plotted as a function of density (Figures 7.25 - 7.29) these non-linear graphs show that BF increased a little with increase in ED-6, ED-7, L% and ED, and then gradually decreased. Earlywood class (ED-3) had a reverse relationship to that described above.

Table 7.4 shows that multiple regressions based on density data did not improve the value of R^2 compared with simple regression in relation to BF.

B. Compression wood percentage

Table 7.3 shows that BF was not significantly correlated with compression wood percentage.

C. Growth rate

Table 7.3 shows that BF was not significantly correlated with growth rate.

2.4 Burst factor conclusions

All factors examined had a low or very low correlation with BF. Cell lumen width and cell diameter data were not significantly related to BF. CW-3 (model 12, R^2 = 0.42) is the best single indicator of BF, with fibre stiffness (model 12, R^2 = 0.40) and alpha cellulose (model 3, R^2 = 0.35) ranking next.

It is clear that cell wall thickness data are the most important indicators of BF since they comprise five of the variables in the ten best indicators of BF. These parameters which are concerned with latewood have the most important effect on BF.

Alpha cellulose percentage, latewood percentage, ED-6, ED-7, CW-3, CW%-5 and CW%-6 all have a similar relationships with BF, in which BF increased slightly with increases in these variables, and then gradually decreased. The behaviour of the above may be explained by the fibre bond area and fibre intrinsic strength contributing to the paper strength as explained in the previous sections.

Burst factor (BF) is clearly a function of several different factors, Table 7.4 lists some of the different variables combined together by multiple regression, in which the value of R^2 was greatly improved. It was noted that fibre length was the most important single factor in the multiple regressions. Regressions 4-4, 4-5, 4-6 and 4-7 showed that when fibre length was eliminated from equations, the value of R^2 dropped very abruptly.

Multiple regression 4-4 had the higher value of R^2, but included too many variables and was signfiicant only at the 5% level. Considered overall, multiple regression 4-71 and 4-9 may be the two most reliable predictors of BF. However, these multiple regressions must be used with caution because they are calculated from only 20 tree values.

Table 7.3 Correlation between burst factor and wood characteristics

	Simple linear		Best fit non-linear model		
	R	Sig.	Model	R	R^2
Alpha cellulose content	-0.295		3	0.592	0.35
Hemi-cellulose content	0.499	*	3	0.526	0.28
Holocellulose content	0.155		3	0.253	0.06
Lignin content	0.152		3	0.173	0.03
Fibre length	0.253		3	0.482	0.23
CW-1	0.453	*	12	0.528	0.28
CW-2	0.424		3	0.534	0.29
CW-3	-0.431	*	12	0.651	0.42
CW-4	-0.572	**	12	0.589	0.35
CW-5	-0.391		10	0.394	0.16
Mean cell wall thickness (CW)	-0.577	**	3	0.589	0.35
CL-1	-0.318		12	0.396	0.16
CL-2	-0.279		12	0.292	0.09
CL-3	0.326		12	0.329	0.11
CL-4	0.167		12	0.219	0.05
CL-5	0.118		3	0.126	0.02
Mean cell lumen width (CL)	0.187		3	0.300	0.09
CD-1	-0.100		3	0.485	0.24
CD-2	-0.077		12	0.114	0.01
CD-3	-0.105		12	0.134	0.02
CD-4	0.176		3	0.239	0.06
CD-5	0.045		12	0.152	0.02
Mean cell diamter (CD)	0.077		3	0.084	0.01
CW%-1	0.370		12	0.406	0.16
CW%-2	0.292		3	0.435	0.19
CW%-3	0.089		3	0.173	0.03
CW%-4	-0.345		3	0.395	0.16
CW%-5	-0.464	*	3	0.517	0.27
CW%-6	-0.565	**	12	0.591	0.35
CW%-7	-0.292		12	0.382	0.12
Mean cell wall percentage (CW%)	-0.474	*	12	0.515	0.27
Runkel ration (2CW/CL)	-0.481	*	12	0.498	0.25
Flexibility ration (CL/CD)	0.473	*	12	0.494	0.24
Slenderness (FL/CD)	0.032		3	0.114	0.01
Fibre Stiffness (FL/2CW)	0.633	**	12	0.635	0.40
Fibre Index (2CW*FL)	-0.471	*	12	0.542	0.29
ED-1	0.095		3	0.190	0.04
ED-2	0.118		6	0.324	0.10
ED-3	0.489	*	10	0.535	0.29
ED-4	-0.077		12	0.095	0.01
ED-5	-0.415		12	0.455	0.21
ED-6	-0.507	*	12	0.574	0.33
ED-7	-0.436	*	12	0.513	0.26
ED-8	-0.261		3	0.326	0.11
Mean desnity (ED)	-0.440	*	12	0.498	0.25
L%	-0.498	*	12	0.568	0.32
Compression wood %	-0.255		3	0.277	0.08
Growth rate	-0.148		12	0.158	0.02

$y = -1047 + 52.63X - 0.6219X^2$

$y = 127.6 - 7.651 + 0.2212X^2$

$y = -437.4 + 15.73X - 0.1231X^2$

$y = -209.8 + 18.84X - 0.3229X^2$

$y = 959.9 - 606.7X + 102.5X^2$

$y = X/(0.005348 + 0.01510X - 0.00001642X^2)$

$y = 18.58 + 1.492X - 0.01182X^2$

$y = X/(0.1366 - 0.002444X + 0.000543X^2)$

$y = X/(-0.0033 + 0.01533X + 0.00006932X^2)$

$y = 1/(0.01786 - 0.002721e^{-0.0578X})$

$y = 59.48 + 3.274X - 0.3476X^2$

$y = X/(0.002611 + 0.01413X + 0.0001006X^2)$

$y = X/(0.01284 + 0.0136X + 0.00005991X^2)$

$y = 49.41 + 0.6085X - 0.005138X^2$

$y = X/C-0.01034 + 0.01735X - 0.00004872X^2)$

$y = 63.38 + 0.1581X - 0.00422X^2$

$y = 6.723 + 3.14X - 0.04219X^2$

$y = 65.69 - 366.8X + 1528X^2$

$y = X/(0.0006038 + 0.01518X + 0.00003828X^2)$

$y = X/(0.02076 + 0.01399X + 0.00002671X^2)$

$y = 85.48 - 1.348X + 0.02015X^2$

$y = X/(-0.001052 + 0.01605X - 0.00001626X^2)$

$y = 45.22 + 0.8103X - 0.008527X^2$

$y = X/(0.01205 + 0.01515X - 0.000006732X^2)$

$y = 35.33 + 1.588X - 0.02082X^2$

$y = 57.2 + 1.14 - 0.04332$

$y = 60.09 + 1.883X - 0.1553X^2$

$y = 64.63 + 0.5564X - 0.07163X^2$

$y = X/(0.001212 + 0.01406X + 0.0001836X^2)$

$y = X/(0.001013 + 0.01449X + 0.0001357X^2)$

$y = X/(0.2238 - 0.0009272X + 0.000289X^2)$

$y = X/(0.000949 + 0.009277X + 0.00978X^2)$

$y = X/(0.05316 - 0.1049X + 0.06779X^2)$

$y = 14.95 + 1.337X - 0.009011X^2$

$y = X/(0.5538 + 0.01453X - 0.000008144X^2)$

$y = X/(0.4674 - 0.007996X + 0.0002874X^2)$

$y = 64.47 - 6.793X + 12.78X^2$

$y = 64.79 - 10.96X^{-2.041}$

$y = 1/(0.01496 + 0.01553e^{-0.08186X})$

$y = X/(-0.009757 + 0.01647X - 0.00001627X^2)$

$y = X(0.01747 + 0.01012X + 0.0003601X^2)$

$y = X(0.008396 + 0.01209X + 0.0002725X^2)$

$y = X/(0.001847 + 0.01411X + 0.0001441X^2)$

$y = 64.45 + 1.495X - 0.6046X^2$

$y = X/(0.00663 - 0.0124X + 0.02867X^2)$

$y = X/(0.03121 + 0.0116X + 0.00009659X^2)$

$y = 66.03 - 0.7503X + 0.03065X^2$

Table 7.4 Coefficient for multiple regressions of burst factor.

	Constant term							
4-1		CW-1	CW-3	$(CW-1)^2$	$(CW-3)^2$			
	37.81**	0.651	2.701	-0.01471	-0.07706*			
	67.6				-0.009901*			
4-2		CW%	CW%-1	CW%-5	CW%-6	CW%-7		
	-6.481	2.522	0.412	-0.8744	-1.675	-1.047		
	68.08				-0.5633**			
4-3		ED-2	ED-3	ED-4	ED-5	ED-6	ED-7	ED-8
	592.8	-5.358	-5.167	-5.266	-5.158	-6.488	-4.366	-783
	68.81***					-0.5479*		
4-4		CW	CL	CD	L%	ED	FL	$(CO)^2$
	371.4	-10.99	-41.07	46.39	0.8046	-116.8.	-371.9	0.477
	691.1*	-5.621*	-10.24*	2.911			-351.7	0.105
	154.4*	-6.172*	-9.834*	3.021				0.098
	62.94***		-0.5441*					
4-5		CW	CL	CD	ED	FL	$(CL)^2$	$(CD)^2$
	1189	-0.5814	16.22	-30.34	-113.7	-496.9	-0.2078	0.337
	424.5	-0.7146	19.11	-29.1	-236.3		-0.2495	0.322
4-6		CW	CO	CD	CW%	ED	FL	
	81.38	-1.135	-1.34	0.5756	-0.7423	-9.503	14.36*	
	87.2**		-0.9263**		-1.05***		14.56*	
	125.2	-0.427	-1.791	0.9354	-1.052	0.2636		
4-7		CW	CL	CD	CW%	L%	FL	
	14.81	-5.281	-1.476	1.442	1.044	-0.4335	18.5**	
4-71	48.2*		-0.8116**			-0.4911***	18.9**	
	104.8	-1.855	-1.935	1.33	-0.3002	-0.2026		
4-8		L%	$(L\%)^2$	FL/2CW				
	45.47***	0.2205	-0.004126	0.07932*				
4-9		L%	ED	FL/2CW				
	-21.79	-0.6833**	133.6**	0.518**				
4-10		CL	CD	FL	$(CL)^2$	$(CD)^2$	$(FL)^2$	
	1250**	15.21**	-30.49**	-548.3*	-0.1893**	0.3365*	93.72*	
4-11					ED	$(ED)^2$	FL/2CW	
				-18.76	200.1	-166.3	0.1169*	

				R^2	R	Sig.
				0.473	0.687	*
				0.228	-0.478	*
				0.376	0.614	
				0.319	-0.565	**
				0.393	0.627	
				0.257	-0.507	*
$(CD)^2$	$(L\%)^2$	$(ED)^2$	$(FL)^2$			
-0.458	-0.0303	245.2	65.42	0.864	0.929	*
	-0.01051*	88.10	61.73	0.823	0.907	**
	-0.01079*	96.49	3.211**	0.773	0.879	**
	-0.006156***		2.752**	0.602	0.776	**
$(ED)^2$	$(FL)^2$					
101.9	85.01			0.724	0.851	
214.9				0.478	0.692	
				0.610	0.781	*
				0.605	0.778	**
				0.456	0.675	
				0.706	0.840	**
				0.679	0.824	***
				0.480	0.693	
				0.436	0.661	*
				0.649	0.806	***
				0.708	0.841	**
				0.487	0.698	*

Figure 7.17

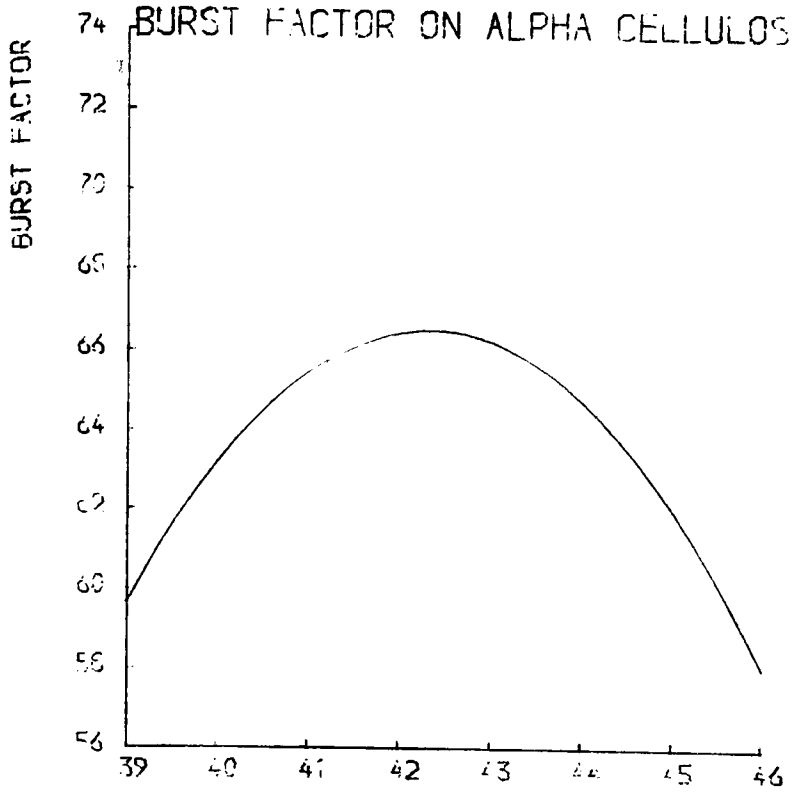
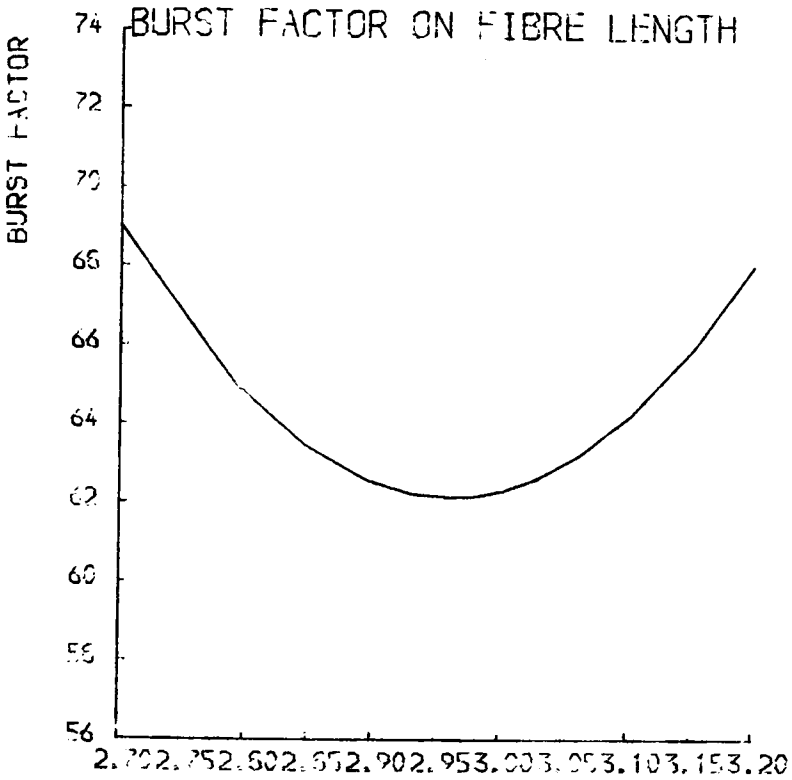


Figure 7.18



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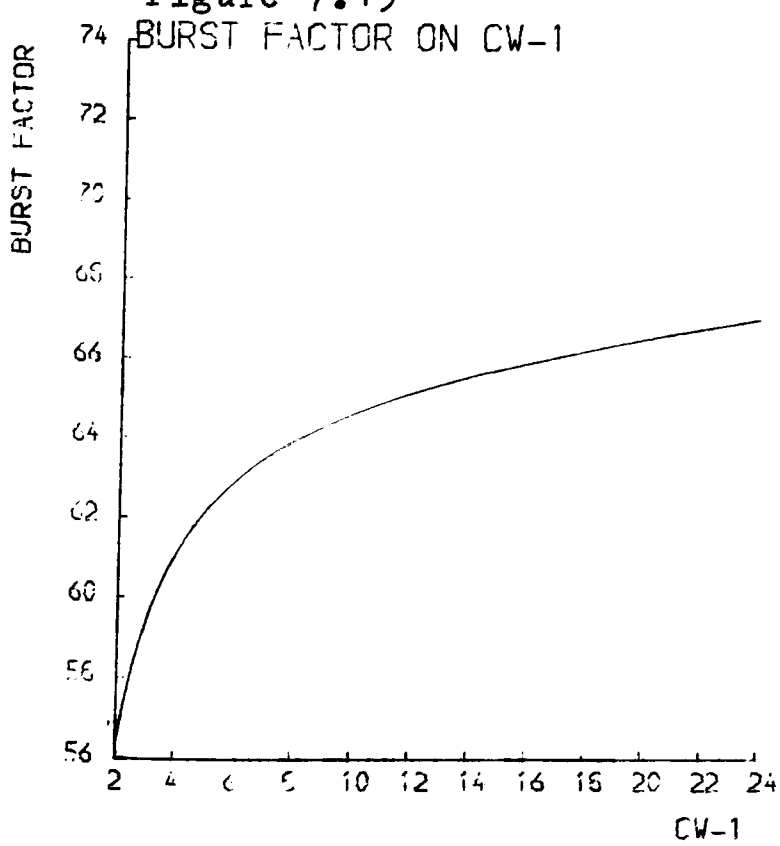

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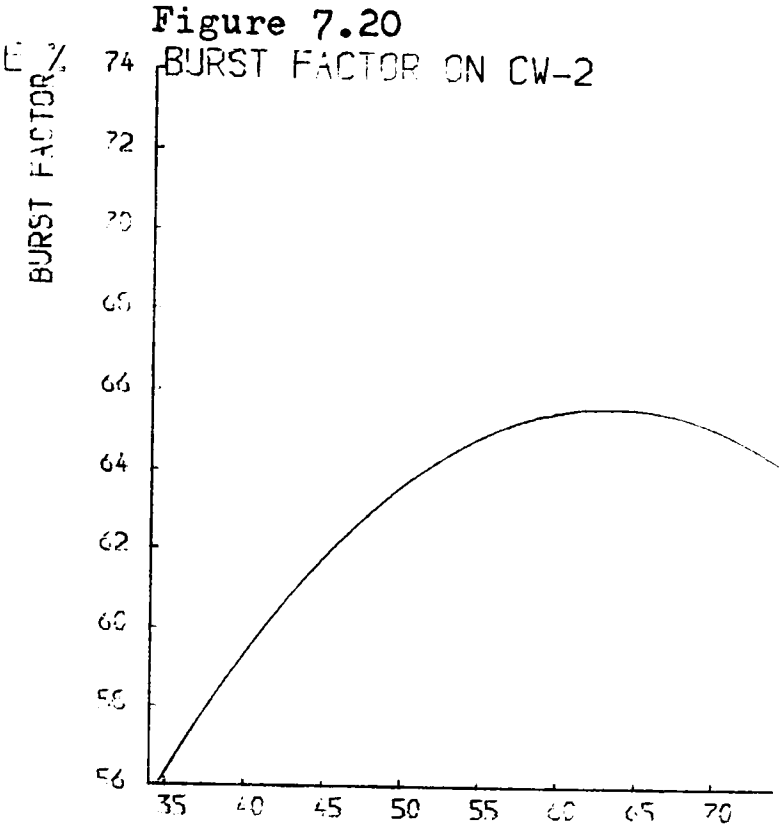


Figure 7.21

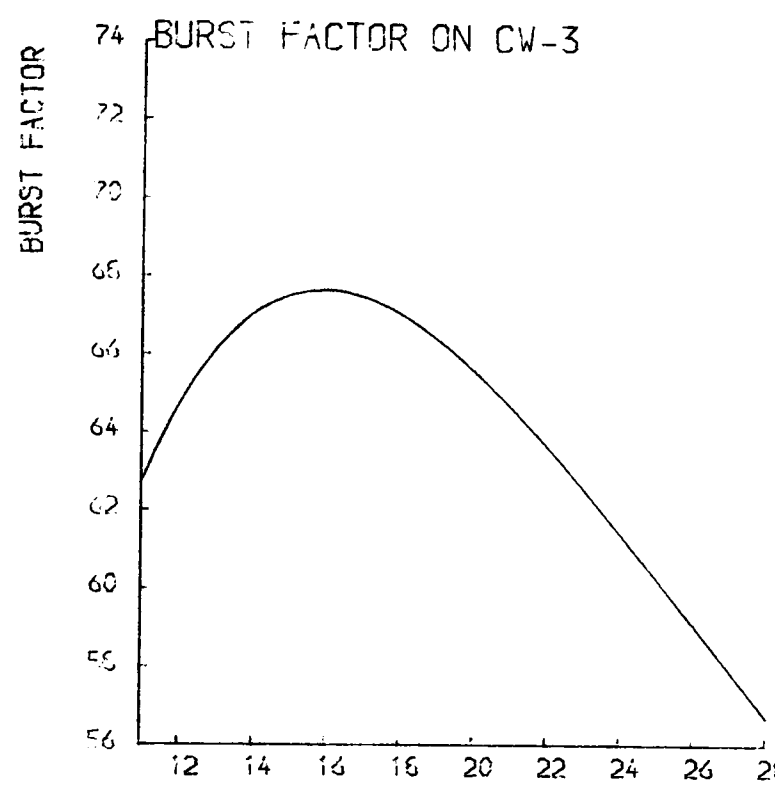
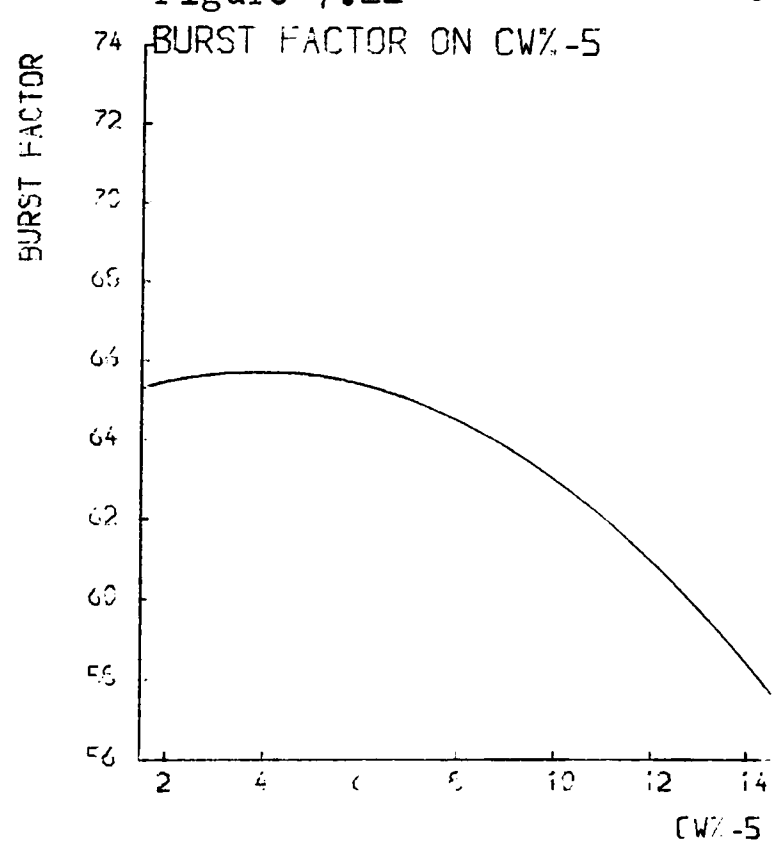


Figure 7.22



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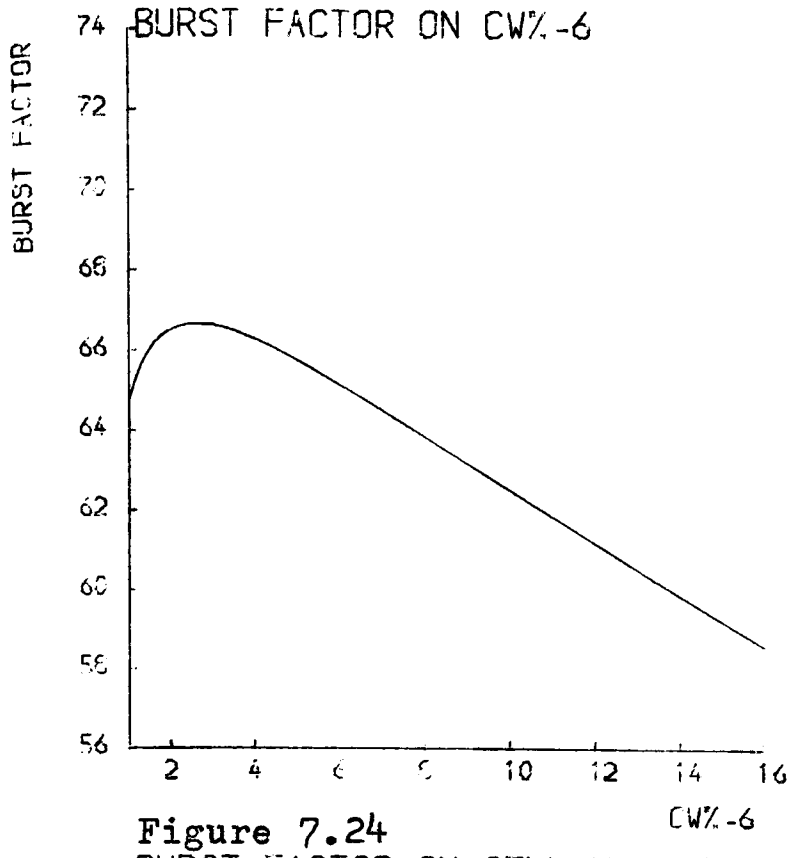
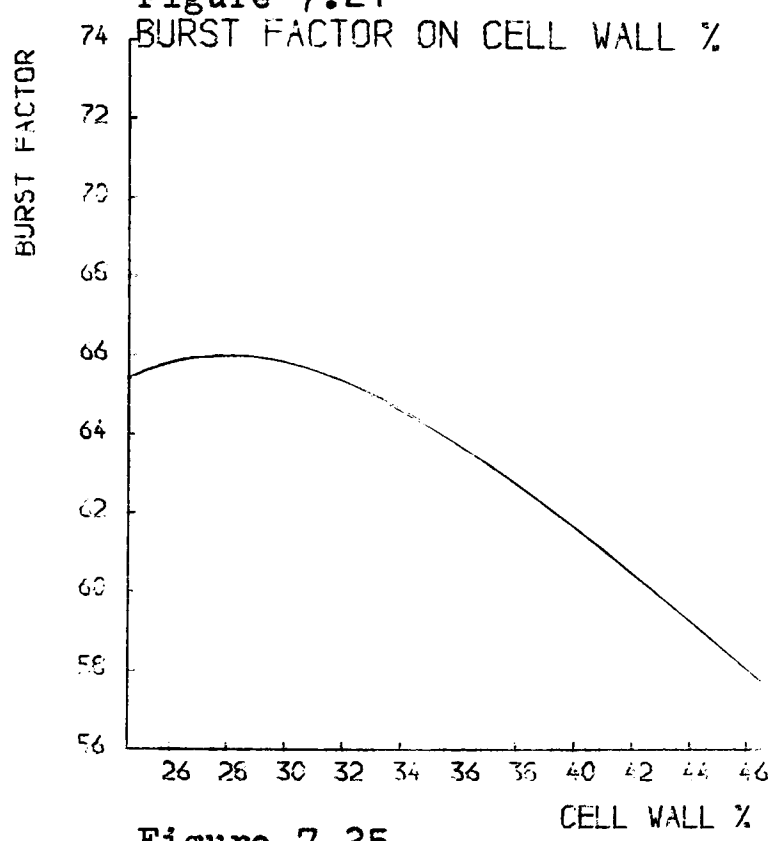


Figure 7.24



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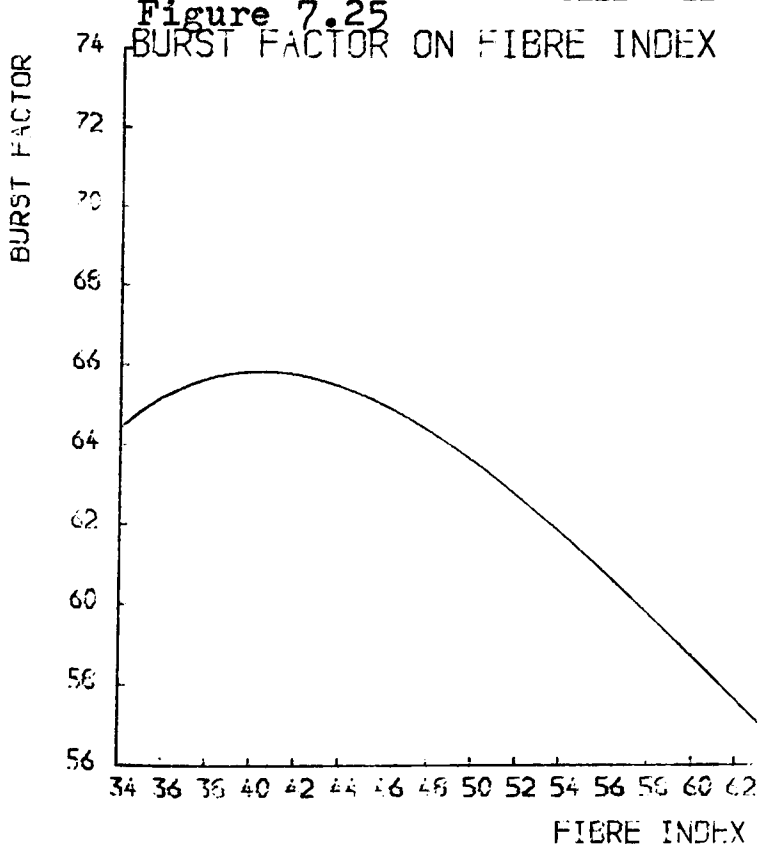


Figure 7.26

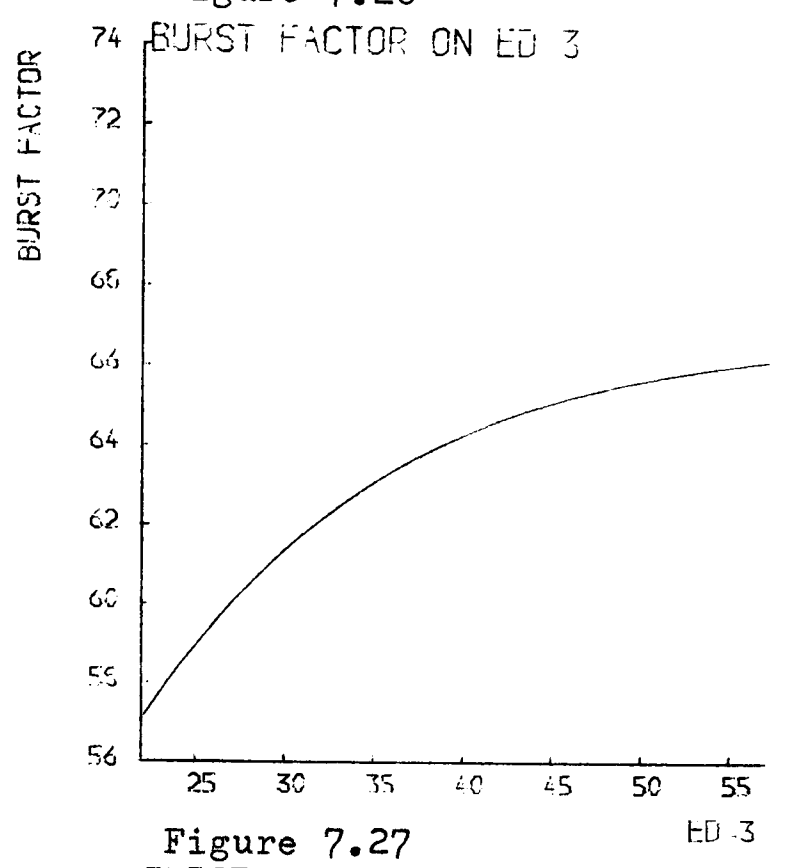


Figure 7.27

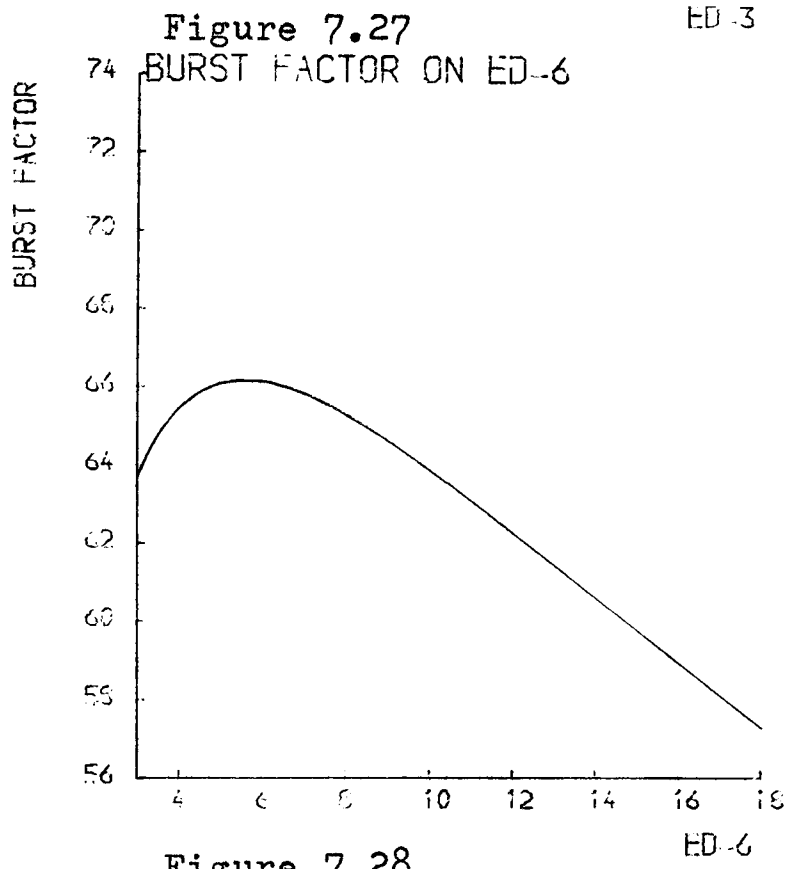


Figure 7.28

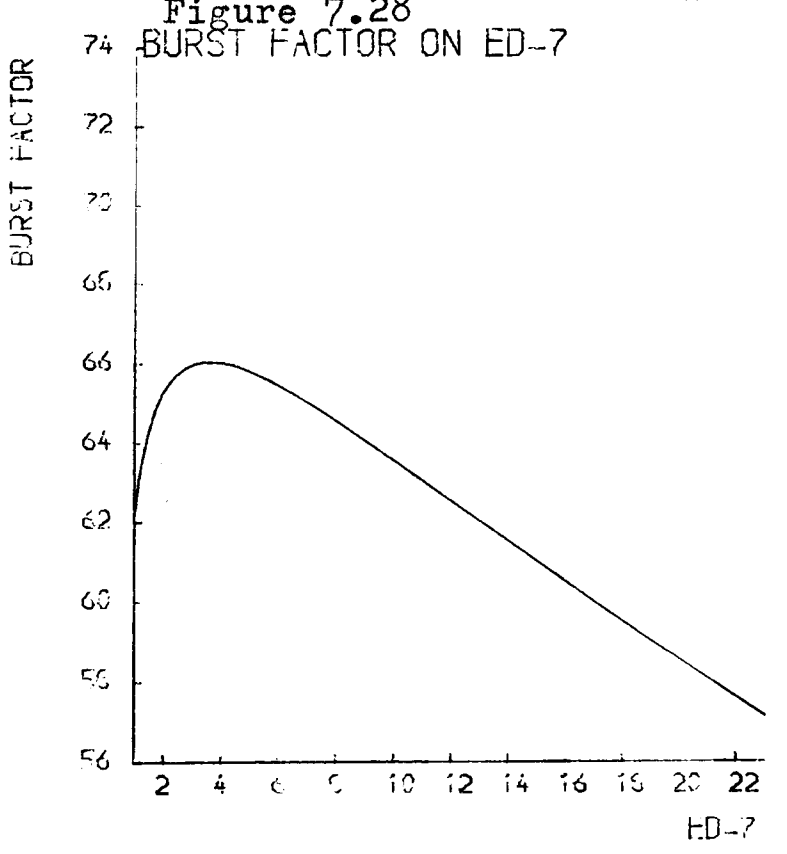


Figure 7.29

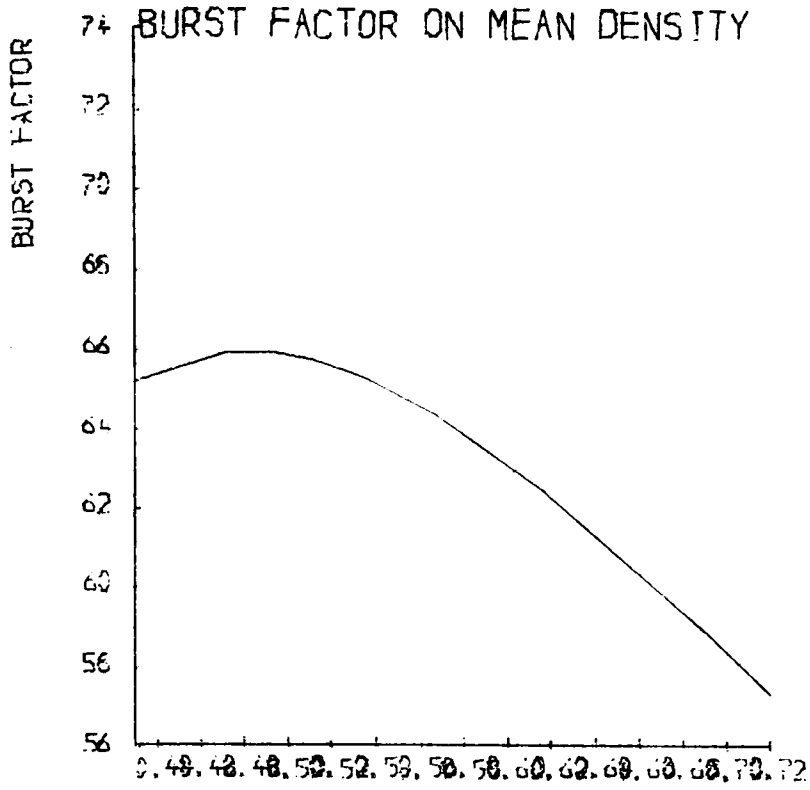
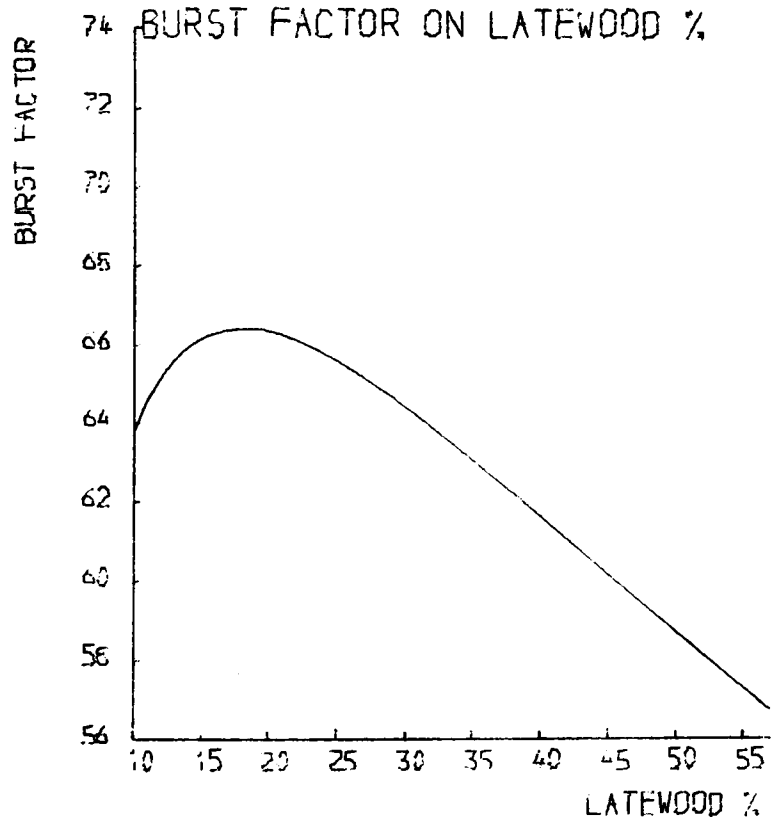


Figure 7.30



3. Breaking length

3.1 The influence of wood chemical composition on breaking length (BL)

The relationships of the chemical content of wood with BL, were similar to those with BF. Table 7.5 shows that holo-cellulose, alpha cellulose and lignin content were not significantly correlated with BL, but hemicellulose was significantly and positively correlated.

Figure 7.31 illustrates the non-linear rleationship of alpha cellulose content with BL (model 12, $R = 0.50$, $R^2 = 0.25$) which is similar to the curve of alpha cellulose content with BF. BL increased initially with an increase alpha cellulose content, and after alpha cellulose content reached a certain percentage, BL began to decrease.

The non-linear curve of BL with hemicellulose (model 3, $R = 0.68$, $R^2 = 0.47$) is shown in the Figure 7.32. There is no obvious explanation why BL decreased initially with an increase of hemicellulose content to about 20%. After hemicellulose content reached about 20%, BL began to increase with increase of hemicellulose content.

3.2 The influence of fibre dimensions on breaking length (BL)

The relationships between fibre dimensions and BL are similar to those between fibre dimensions and BF.

A. Fibre length

Table 7.5 shows that BL was insignificantly correlated with fibre length. The non-linear function illustrated in Figure 7.33 (model 3, $R = 0.49$, $R^2 = 0.24$) shows that BL decreased initially with an increase of fibre length. After fibre length reached a certain length (about 3 mm), BL increased with increase in fibre length (for reasons see previous section on BF).

B. Tracheid (fibre) cross-sectional dimensions and various classes

Table 7.5 shows that except for CW-4, CW and CW%-6 which were significantly and negatively correlated with BL, most of the cross-sectional dimension factors were not significantly correlated with BL.

From Figure 7.34 - 7.36 it is apparent that the nonlinear function of CW-1, CW-2 and CW-3 with BL were similar to the variation of those variables with BF; with an increasing proportion of CW-1 class there was a greater increase in BL at the low percentage levels of CW-1 than at higher percentage levels. BL increases slightly with an increase in CW-3, then decreased after CW-3 reached about 15% (reason see previous BF section).

Table 7.6 shows that when cell wall thickness data are combined in the multiple regression with BL, somewhat improved values of R^2 were obtained (Table 7.6 (6-1)).

C. Fibre dimension ratios

Table 7.5 shows that only fibre stiffness (FL/2CW) is significantly and positively correlated with BL (model 1, R = 0.500) and fibre index (2CWXFL) (model 1, R = -0.49) was significantly and negatively correlated.

3.3 The influence of wood physical properties on breaking length (BL)

A. Mean density (ED), latewood percentage (L%) and percentage of wood in density classes (ED-X)

The results of correlation of BL with density data were more or less similar to those of BF with density data. Table 7.5 shows that only ED-3 was positively correlated and ED-6 and L% were negatively correlated with BL. Table 7.6 (6-2) shows that density data alone, even when combined

together in multiple regression, could not improve the value of R^2.

B. Compression wood percentage (CO%)

Compression wood percentage was not significantly correlated with BL (Table 7.5).

C. Growth rate

Growth rate was not significantly correlated with BL (Table 7.5).

3.4 Breaking length conclusions

The results of relationships of BL with various parameters of wood structure and tree growth were similar to those with BF, except that the R values for BL were slightly lower than that of BF.

After hemicellulose content, cell wall thickness data were the best indicators, of BL (model 12, R = 0.55).

Fibre length is an important factor affecting BL, as shown by the multiple regression (Table 7.6 (6-3 to 6-6)). When fibre length was eliminated from the equation, the value of R^2 dropped abruptly.

Table 7.6 shows that whilst multiple regressions 6-1, 6-5 and 6-10 had highest values of R^2, it must be noted that there regressions consisted of many variables and had low significance. Considered overall, regressions 6-31 and 6-51 may be better indicators of BL.

Table 7.5 Correlation between breaking Length and Wood Characteristics

	Simple linear		Best fit non-linear model		
	R	Sig.	Model	R	R^2
Alpha cellulose content	-0.355		12	0.499	0.25
Hemicellulose content	0.494	*	3	0.683	0.47
Holocellulose content	0.100		3	0.122	0.01
Lignin content	0.241		3	0.243	0.06
Fibre length	0.0		3	o.492	0.24
CW-1	0.366		6	0.467	0.22
CW-2	0.418		3	0.436	0.19
CW-3	-0.400		12	0.470	0.22
CW-4	-0.483	*	6	0.581	0.34
CW-5	-0.412		8	0.421	0.18
Mean cell wall thickness (CW)	-0.537	**	12	0.545	0.30
CL-1	0.195		4	0.210	0.04
CL-2	0.164		3	0.207	0.04
CL-3	0.349		12	0.349	0.12
CL-4	0.032		12	0.224	o.05
CL-5	0.045		3	0.126	0.02
Mean cell lumen width (CL)	0.089		5	0.095	0.01
CD-1	0.045		3	0.274	0.08
CD-2	0.095		12	0.170	0.03
CD-3	0.0		3	0.155	o.02
CD-4	0.063		3	0.318	0.10
CD-5	0.055		11	0.292	0.09
Mean cell diameter (CD)	-0.055		3	0.122	0.01
CW%-1	0.266		12	0.274	0.08
CW%-2	0.307		3	0.342	0.12
CW%-3	-0.045		3	0.145	0.02
CW%-4	-0.335		12	0.354	0.13
CW%-5	-0.386		6	0.391	0.15
CW%-6	-0.455	*	3	0.475	0.23
CW%-7	-0.243		12	0.257	0.07
Mean cell wall percentage (CW%)	-0.381		3	0.385	0.15
Runkel ratio (2CW/CL)	-0.376		3	0.377	0.14
Flexibility ratio (CL/CD)	0.374		6	0.377	0.14
Slenderness (FL/CD)	0.055		12	0.122	0.01
Fibre Stiffness (FL/2CW)	0.502	*	12	0.504	0.25
Fibre index (2CW * FL)	-0.487	*	12	0.512	0.26
ED-1	-0.105		4	0.321	0.10
ED-2	0.084		12	0.192	0.04
ED-3	0.465	*	10	0.483	0.23
ED-4	-0.045		4	0.114	0.01
ED-5	-0.333		3	o.351	0.12
ED-6	-0.451	*	3	0.467	0.22
ED-7	-0.416		12	0.431	0.19
ED-8	-0.322		12	0.355	0.13
Mean density (ED)	-0.405		12	0.427	0.18
L%	-0.457	*	12	0.464	0.22
Compression wood %	0.032		12	0.100	0.01
Growth rate	0.o			0.o	0.0

$y = X/(0.0612 - 0.002818X + 0.00003495X^2)$

$y = 41470 - 3428X + 89.65X^2$

$y = -16500 + 788.2X - 6.063X^2$

$y = -11160 + 1286X - 20.1X^2$

$y = 168200 - 106300X + 17720X^2$

$y = 9441 - 3299X^{-1.094}$

$y = 5702 + 97.17X - 0.6466X^2$

$y = X/(0.0004985 + 0.00003986X + 0.000002226X^2)$

$y = 9664 - 66.32X + 0.9346X^2$

$y = 9404 - 117.1X + 3.998X^2$

$y = X/(0.0002798 + 0.000008961X + 0.00000844X^2)$

$y = 8946 + 624.3\ e^{-0.1839X}$

$y = 9939 - 66.4X + 1.099X^2$

$y = X/(-0.0001836 + 0.0001351X - 0.0000005654X^2)$

$y = X/(-0.0001162 + 0.0001286X - 0.0000003794X^2)$

$y = 9134 - 29.66X + 1.743X^2$

$y = 9181\ (1-e^{-0.1353X})$

$y = 9209 - 29850X + 125100X^2$

$y = X/(-0.000007086 + 0.0001146X - 0.0000003984X^2)$

$y = 9994 - 52.4X + 0.6772X^2$

$y = 16100 - 403.6X + 5.616X^2$

$y = 9034\ (1-e^{-2.235X})^{-1.288}$

$y = 19800 - 506.3X + 5.94X^2$

$y = X/(0.00003296 + 0.0001108X - 0.000000009516X^2)$

$y = 6630 + 123.2X - 1.425X^2$

$y = 8061 + 159.6X - 5.81X^2$

$y = X/(0.00005012 + 0.00008762X + 0.000001926X^2)$

$y = 10150 - 452.9X^{0.4474}$

$y = 9794 - 145.7X + 4.701X^2$

$y = X/(0.000003054 + 0.0001055X + 0.0000006269X^2)$

$y = 9584 + 10.08X - 0.7285X^2$

$y = 9788 - 1196X - 837.1X^2$

$y = 10530 - 742.6X^{-3.283}$

$y = X/(-0.005403 + 0.0002641X - 0.000001087X^2)$

$y = X/(0.003165 + 0.0001039X - 0.00000004584X^2)$

$y = X/(0.002064 - 0.000002805X + 0.000001462X^2)$

$y = 9003 + 832.8\ e^{-63.08X}$

$y = X/(0.000009241 + 0.000108X + 0.00000003412X^2)$

$y = 1/(0.0001044 + 0.00006197e^{-0.05958X})$

$y = 9053 + 65370e^{-0.5559X}$

$y = 8901 + 119.6X - 9.53X^2$

$y = 10030 - 153X + 4.083X^2$

$y = X/(0.000005129 + 0.0001033X + 0.0000007607X^2)$

$y = 9185 + 120.1X - 68.07X^2$

$y = X/(0.0000277 - 0.00001519X + 0.000135X^2)$

$y = X/(0.00005747 + 0.00009718X + 0.000000386X^2)$

$y = X/(-0.0000067463 + 0.0001108X - 0.00000004309X^2)$

Table 7.6 Coefficient for multiple regressions of breaking length

	Constant term						
6-1		CW	CW-2	CW-3	CW-5	$(CW)^2$	$(CW-1)^2$
	-51430**	5144*	1030**	731.6**	1343***	-750.1**	8.329*
6-2		ED-2	ED-3	ED-4	ED-5	ED-6	ED17
	36.48	89	106.7	104.6	109.6	-130.3	296.8
	9683***					-70.14*	
6-3		CW	CL	CD	ED	FL	$(CL)^2$
	185600	47.52	-530.6	-774.4	5776	-99460*	5.33
	136600*		-130.9**			-81020*	
6-4	18850	-136.5	-939.5	630.5	-1609		9.353
6-5		CW	CL	CD	L%	FL	$(CL)^2$
	107500	-806.3	-6035	6615	77.07	-86740*	71
	166500**		-1086**			-92050*	13.71**
6-6	-16480	-692.7	-4366	5106	5.851		49.7
6-7		CL	CW%	FL	$(CL)^2$	$(CW\%)^2$	$(FL)^2$
	171000*	-1030	186.6	-96340*	12.85	-4.545	16210*
	15180***	-119.4*				-1.701**	
6-8		CW%	FL	$(CW)^2$	$(FL)^2$		
	141000*	97.39*	-89340*	-46.66**	15020*		
6-9		CL	CD	CW%	FL	$(CL)^2$	(CW%)
	181300*	-1373	149.1	191.8	-100500*	15.27	-3.184
	167100**	-699.6*		29.74	- 95000 *	7.898	
	163600**	-704.2*			- 92270 *	7.896	
	136600*	-130.9**			- 81020 *		
6-10		CL		FL	$(CL)^2$		$(FL)^2$
	166500	-1086		-92050*	13.71**		15580*

$(CW-2)^2$	$(CW-4)^2$		R^2	R	Sig.
-5.424*	36.01***		0.786	0.887	**
ED-8					
-470.7			0.418	0.647	
			0.203	-0.451	*
$(CD)^2$	$(ED)^2$	$(FL)^2$			
9.369	-15790	16740*	0.693	0.832	
	- 8992 **	13630*	0.601	0.775	**
-5.861	-9077		0.471	0.681	
$(CD)^2$	(L%)	$(FL)^2$			
-67.53	2.93	14740	0.791	0.889	*
	1.046***	15580*	0.714	0.845	**
-51.71	-1.556		0.559	0.748	
			0.610	0.781	*
			0.350	0.592	*
			0.597	0.773	**
$(FL)^2$	$(ED)^2$				
16920*	-10780		0.695	0.834	*
16000*	- 12070		0.685	0.827	**
15550*	- 10250 ***		0.682	0.826	**
13630*	- 8992 **		0.601	0.775	**
$(L\%)^2$					
-1.046***			0.714	0.845	**

Figure 7.31

BREAKING LENGTH ON ALPHA CELLULOSE %

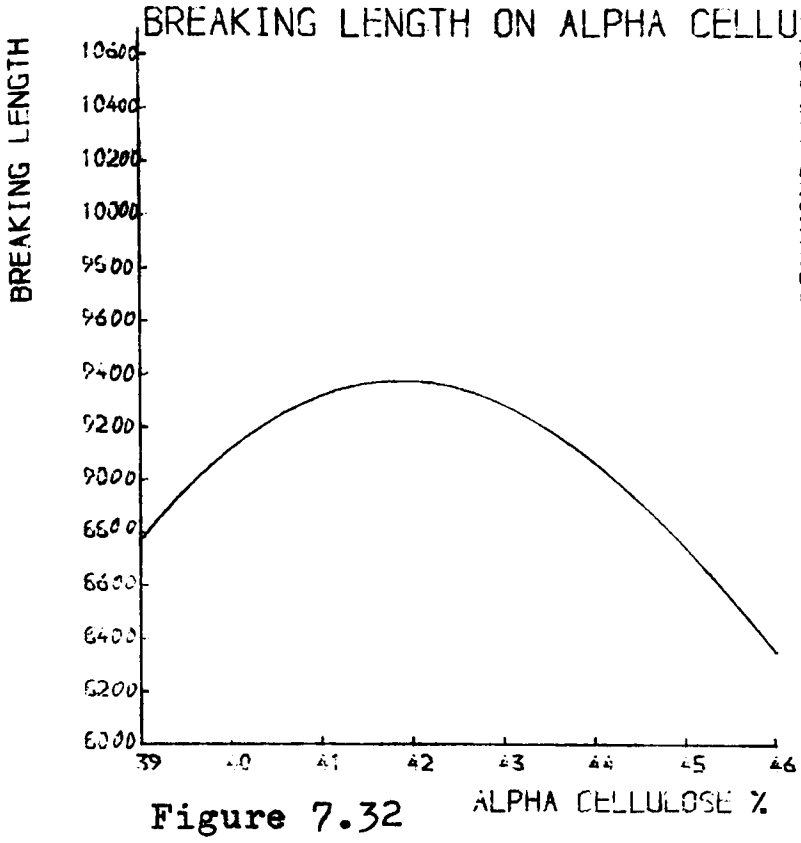


Figure 7.32

BREAKING LENGTH ON HEMICELLULOSE %

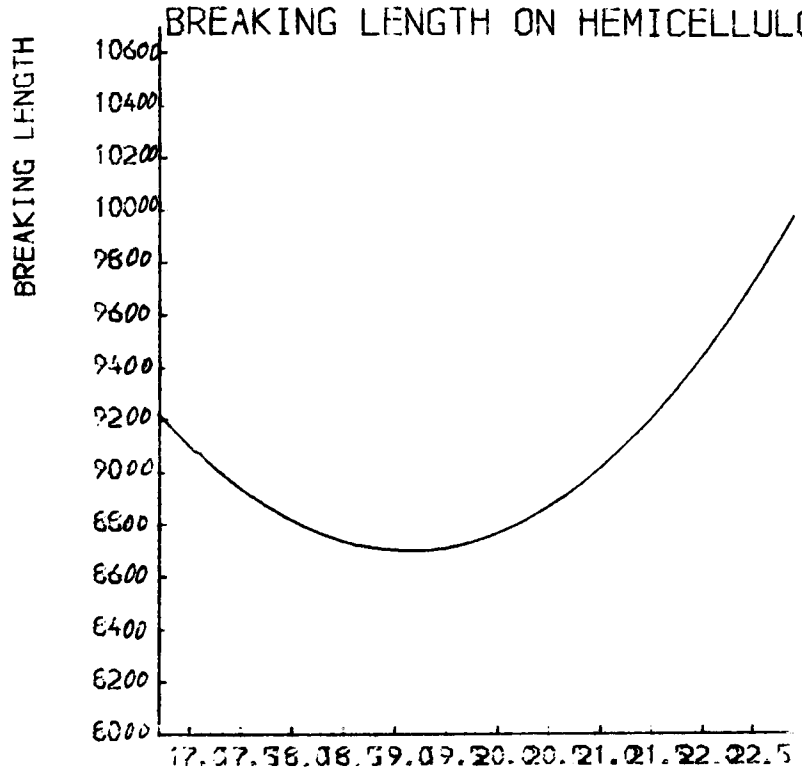


Figure 7.33

BREAKING LENGTH ON FIBRE LENGTH

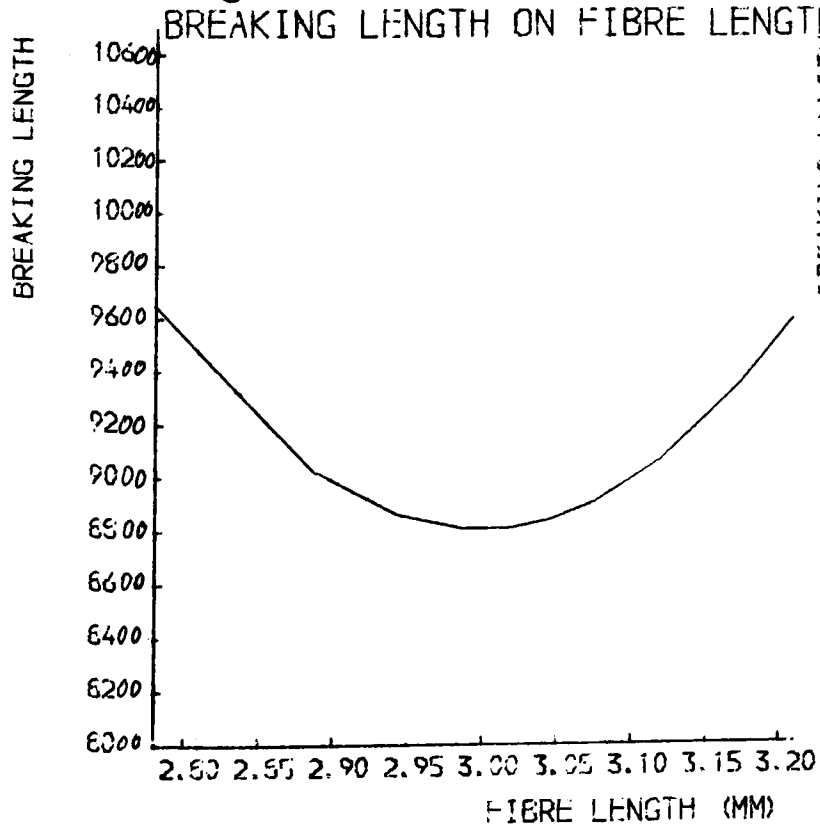


Figure 7.34

BREAKING LENGTH ON CW-1

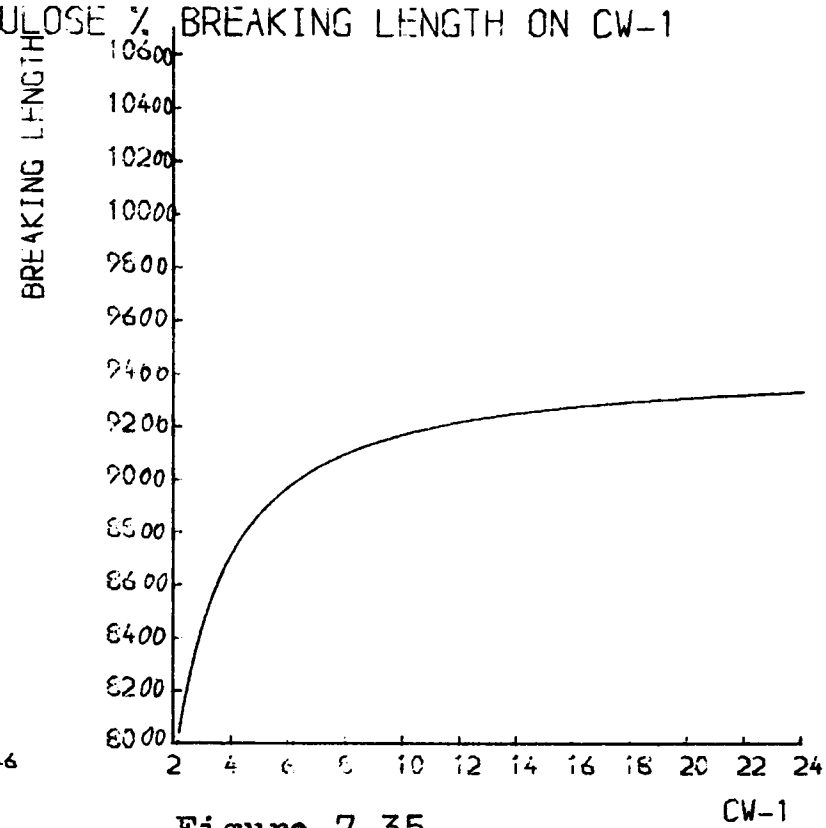


Figure 7.35

BREAKING LENGTH ON CW-2

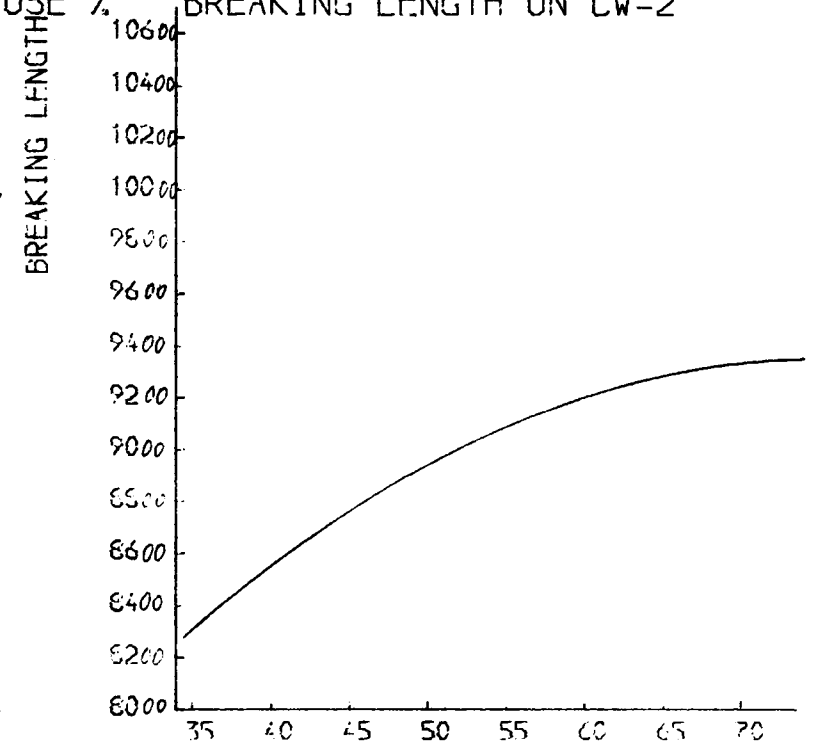


Figure 7.36

BREAKING LENGTH ON CW-3

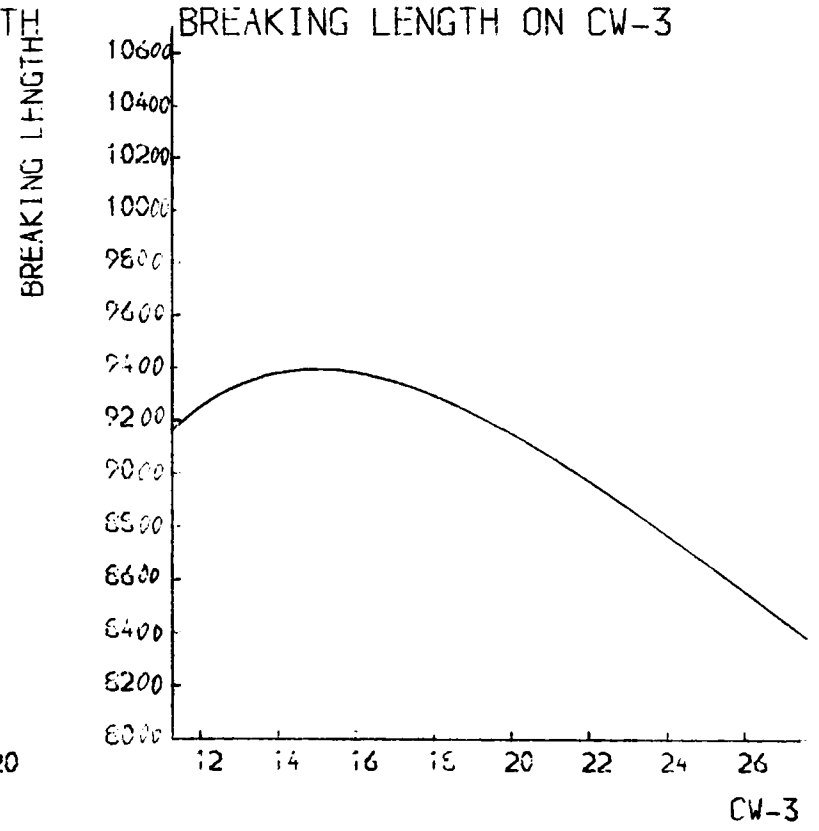


Figure 7.37

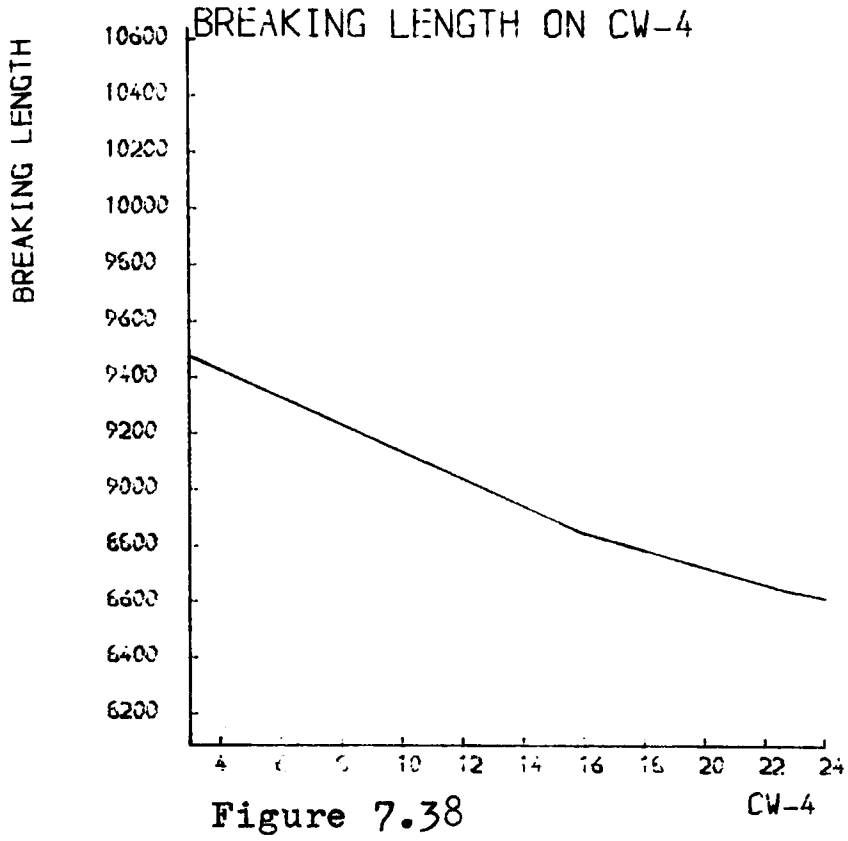


Figure 7.38

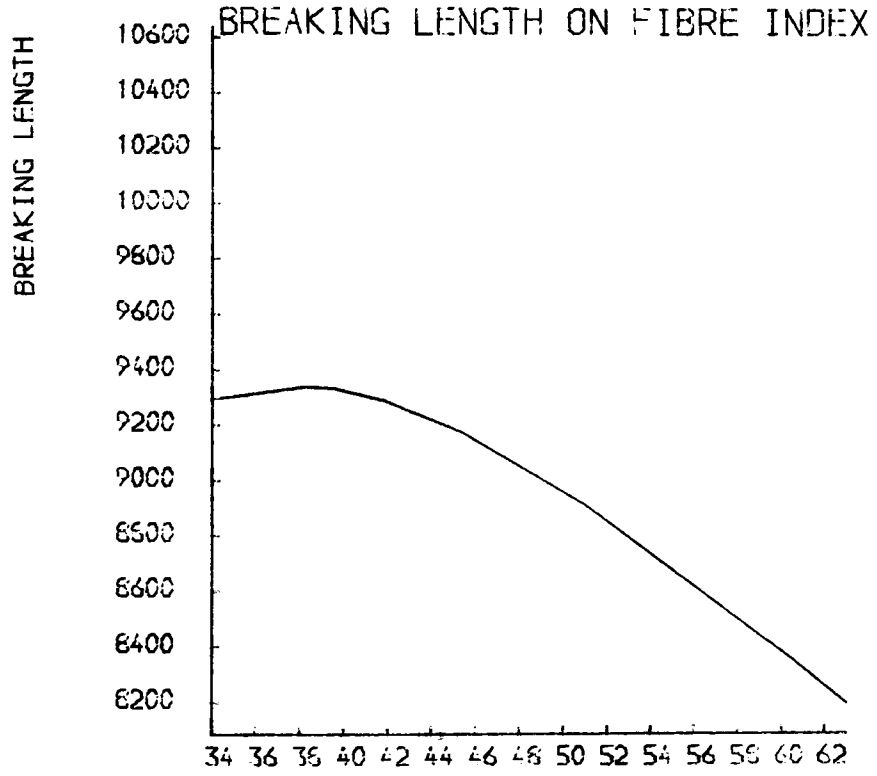


Figure 7.39

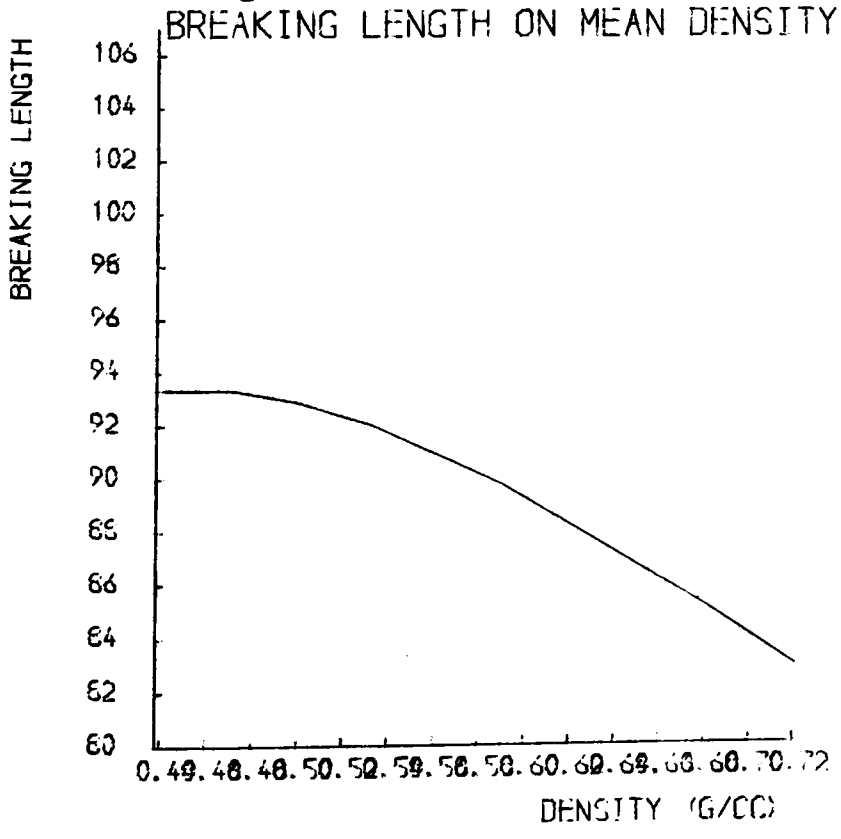
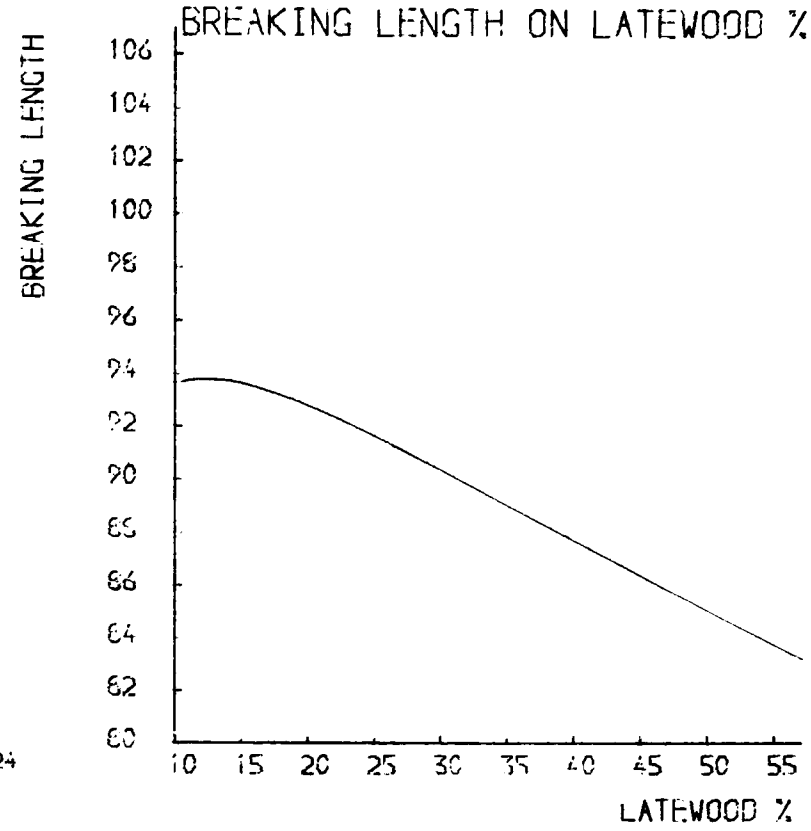


Figure 7.40



4. Tear factor

4.1 The influence of wood chemical composition on tear factor (TF)

Table 7.7 shows that holo cellulose was positively but insignificantly (R= 0.38) correlated with TF and hemicelulose (R = -0.515) was negatively and insignificantly correlated with TF. Lignin (R = -0.57) was significantly and negatively correlated and alpha cellulose (R = 0.75) was significantly and positively correlated with TF.

Figure 7.41 shows that TF increased with an increase of hemicellulose content from 16.7% to about 20%, after which it decreased with increasing hemicellulose content. It is noted that this graph indicates a linear negatively correlated relationship with TF if the two trees with the lowest hemicellulose content are eliminated (D2-11: 16.7% and NH1-40:17.7%).

4.2 The influence of fibre dimensions on tear factor (TF)

A. Fibre length

As expected, TF was affected by fibre length to a greater extent than BF and BL. Table 7.7 shows a significant and positive correlation between TF and fibre length(R = 0.56). Figure 7.42 shows that TF increased initially with fibre length. After the fibre length reached about 3mm, TF remained more or less constant.

B. Fibre cross-sectional dimensions and various classes

Table 7.7 shows that except for cell diameter all other fibre cross-sectional dimensions were significantly related to TF. For cell wall thcikness data, only CW-1 was not significantly related to TF: mean cell wall thickness (CW) (R = 0.62), CW-3 (R = 0.50), CW-4 (R = 0.64) and CW-5(R=0.50) were positively correlated, and CW-2 (R = -0.71) was negatively correlated.

As expected the relationships of cell wall percentage data to TF were similar to those of cell wall thickness and were significantly correlated except for CW%-1 and CW%-3. The low cell wall percentage class (CW%-2) was negatively correlated with TF (R = -0.59), and the high cell wall percentage classes (CW%-4; R = 0.45, CW% -5; R = 0.55, CW%-6; R = 0.63 and CW% -7; R = 0.50) and CW% (R = 0.6) were positively correlated. It is difficult to explain the non-linear relationship of TF to CW%-4 (Figure 7.47), TF increased with an increase in CW%-4 at first then decreased after CW%-4 reached about 6%.

The non-linear graphs of TF with the high cell wall thickness class (CW-4) (Figure 7.43), and the high cell wall percentage classes (CW% -5 and CW%-6) (Figures 7.48 and 7.49) shows that TF increased at a faster rate when the proportion of these classes were small than when they were large. The relationships between TF and CW-5 (Figure 7.44) and CW% - 7 (Figure 7.50) were different, and seemed to be more or less constant, linear and positive.

For cell lumen width data, as expected, TF was significantly and negatively related to mean cell lumen width (CL) (R = -0.49) and significantly and positively correlated with small lumen width classes (CL-1; R = 0.55 and CL-2; R = 0.45). Figures 7.45 and 7.46 show that TF increased at a faster rate at low levels that at high level of CL-1 and CL-2.

Latewood classes had a higher significance in correlation with TF than earlywood classes (similar, see TY%, BF and BL sections).

Using multiple regression a combination of cell wall percentage data, gave a highly improved value for R^2 for predicting TF (Table 7.8

(8-31)). This regression however has a large number of terms in relation to the number of observations of TF and in therefore of limited value for predicting TF.

C. Fibre dimension ratios

Table 7.8 shows that except for fibre stiffness (FL/2CW) all fibre dimension ratios were significantly related to TF. Flexibility ratio (CL/CD) (R= - 0.59) was negatively correlated with TF, Runkel ratio (2CW/CL) (R = 0.60) fibre slenderness (FL/CD) (R = 0.52) and fibre index (2CW * FL) (R = 0.69) were positively correlated. Among these, fibre index had a higher correlation coefficient than the other fibre dimension ratios.

4.3 The infuence of wood physical properties on tear factor (TF)

A. Mean density (ED), latewood percentage (L%) and percentage of wood in density classes (ED-X)

Table 7.7 shows that ED-1, ED-2 and ED-4 were not significantly related to TF. ED-3 (R = -0.63) was significantly and negatively correlated with TF, and the high density classes (ED-5 to ED-8, R = 0.54, 0.60, 0.70, 0.48), L% (R = 0.70) and mean density (ED) (R = 0.64) were significantly and positively correlated with TF.

Figures 7.52 - 7.55 show that the non-linear regressions of ED-5 to ED-8 had a different pattern of relationship. There is no obvious explanation why TF rose at a very fast rate initially with an increasing proportion of ED-6, and then flattened off after Ed-6 reaches about 6%, but for increasing proporition of ED-5 and ED-7 TF increased uniformly. Since there was very little wood in any tree of the ED-8 class, the curve showing the relationship of TF

to ED-8 has limited applications. However, it seems that L% and the percentage density classes ED-5 to ED-8 (i.e. the latewood data) were the main factors associated with and positively correlated with TF.

B. Compression wood percentage

Compression wood percentage was negatively correlated with TF (R = 0.51) (Table 7.7), This may be expected since compression wood has a shorter fibre length than normal wood. Also compression wood % had a negative correlation with mean tree density and a positive correlation with growth rate. Consequently compression wood tracheids do not collapse as easily as normal wood in the pulping process, and therefore do not form strong fibre to fibre bonds, which reduces tear strength.

C. Growth rate

Table 7.7 shows that TF was not significantly correlated with growth rate.

4.4 Tear factor conclusions

Density data were the most important indicators of TF, with alpha cellulose content and cell wall thickness ranking next. The higher ranges of density classes and cell wall thickness clases had a closer relationship with TF, as indicated by the value of R than the lower ranges of density classes and cell wall thickness classes.

Multiple regressions using combined cell wall thickness data alone, or cell wall percentage data lone, or density data alone, improved the R^2 value with TF (Table 7.8 (8-1, 8-2 and 8-3). Some different types of variables combined together in a multiple regression, gave improved values for R^2, but contained a large number of terms and cannot

7.7 Correlation between tear factor and wood characteristics

	Simple linear		Best fit non-linear model		
	R	Sig.	Model	R	R^2
Alpha cellulose content	0.746	***	12	0.760	0.58
Hemicellulose content	-0.315		12	0.675	0.46
Holocellulose content	0.379		6	0.402	0.16
Lignin content	-0.573	**	12	0.576	0.33
Fibre length	0.560	**	12	0.678	0.46
CW-1	-0.170		12	0.377	0.14
CW-2	-0.712	***	3	0.713	o.51
CW-3	0.495	*	12	0.498	0.25
CW-4	0.644	**	12	0.685	0.47
CW-5	0.499	*	3	0.502	0.25
Mean cell wall thickness (CW)	0.617	**	12	0.637	0.41
CL-1	0.545	**	12	0.603	0.36
CL-2	0.446	*	6	0.500	0.25
CL-3	-0.232		3	0.311	0.10
CL-4	-0.351		3	0.410	0.17
CL-5	-0.362		3	0.371	0.14
Mean cell lumen width (CL)	-0.489	*	6	0.504	0.25
CD-1	-0.077		3	0.170	0.03
CD-2	0.276		10	0.483	0.23
CD-3	0.394		4	0.522	0.27
CD-4	-0.339		3	0.352	0.12
CD-5	-0.324		3	0.378	0.14
Mean cell diameter (CD)	0.342		3	0.396	0.16
CW%-1	-0.362		10	0.471	0.22
CW%-2	-0.592	**	3	0.592	0.35
CW%-3	0.167		12	0.247	0.06
CW%-4	0.452	*	12	0.594	0.35
CW%-5	0.550	**	10	0.646	0.42
CW%-6	0.632	**	10	0.725	o.53
CW%-7	0.501	*	3	0.531	0.28
Mean cell wall percentage (CW%)	0.600	**	12	0.602	0.36
Runkel ration (2CW/CL)	0.595	**	12	0.597	0.36
Flexibility ratio (CL/CD)	-0.593	**	12	0.596	0.36
Slenderness (FL/CD)	0.517	*	4	0.559	0.31
Fibre stiffness (FL/2CW)	-0.307		12	0.377	0.14
Fibre index (2CW x FL)	0.690	***	12	0.693	0.48
ED-1	0.286		3	0.315	0.10
ED-2	-0.230		6	0.456	0.21
ED-3	-0.628	**	12	0.648	0.42
ED-4	0.105		3	0.173	0.03
ED-5	0.536	**	12	0.544	0.30
ED-6	0.596	**	10	0.767	0.59
ED-7	0.703	***	12	0.734	0.54
ED-8	0.476	*	3	0.599	0.36
Mean density (ED)	0.640	**	3	0.653	0.43
L%	0.704	***	12	0.725	0.53
Compression wood %	-0.510	*	6	0.512	0.26
Growth rate					

$y = X/(-1.061 + 0.0706X - 0.000925X^2)$
$y = X/(1.323 - 0.1301X + 0.003473X^2)$
$y = 189.6 - 1705 \cdot 10^{15} X^{-9.365}$
$y = X/(-0.115 + 0.000007166X + 0.0003633X^2)$
$y = X/(0.6171 - 0.3921X + 0.0641X^2)$
$y = X/(-0.004009 + 0.006847X - 0.00002576X^2)$
$y = 229.2 - 0.5601X - 0.009363X^2$
$y = X/(0.00246 + 0.007104X - 0.00006614X^2)$
$y = X/(0.006001 + 0.005609X - 0.00002876X^2)$
$y = 156.8 + 1.597X + 0.1138X^2$
$y = X/(-0.02535 + 0.01588X - 0.0008487X^2)$
$y = X/(0.002936 + 0.005972X - 0.00002971X^2)$
$y = 177.8 - 18370X^{-2.545}$
$y = 43.05 + 7.699X - 0.1169X^2$
$y = 162.7 + 1.681X - 0.05442X^2$
$y = 172.6 - 0.4121X - 0.0433X^2$
$y = 187.4 - 0.00001001X^{4.085}$
$y = 168.7 - 647.3X + 2615X^2$
$y = 1/(0.005868 + 0.005839e^{-1.035X})$
$y = 172.4 - 1313e^{-0.1938X}$
$y = 135.2 + 3.187X - 0.06089X^2$
$y = 169.1 + 0.6441X - 0.03183X^2$
$y = -428.2 + 30.85X - 0.3954X^2$
$y = 1/(0.006169 - 0.09911e^{-0.5572X})$
$y = 220.7 - 1.41X - 0.007093X^2$
$y = X/(-0.02552 + 0.01047X - 0.0001768X^2)$
$y = X/(-0.02008 + 0.01326X - 0.0005384X^2)$
$y = 1/(0.0057 + 0.006912e^{-0.5759X})$
$y = 1(0.005426 + 0.003767e^{-0.3418X})$
$y = 157.4 - 0.4631X + 0.2272X^2$
$y = X/(0.02252 + 0.007514X - 0.00006369X^2)$
$y = X/(0.0002215 + 0.00689X - 0.003034X^2)$
$y = X/(-0.002606 + 0.002308X + 0.008472X^2)$
$y = 45.87 + 1.646X.$
$y = X/(-1.611 + 0.02041X - 0.00003092X^2)$
$y = X/(0.02683 + 0.008119X - 0.0000581X^2)$
$y = 156.6 + 71.47X - 55.34X^2$
$y = 178.3 - 4.014X^{0.5059}$
$y = X/(-0.03992 + 0.006144X + 0.00002171X^2)$
$y = 125.7 + 3.915X - 0.08808X^2$
$y = X/(0.009538 + 0.005269X - 0.00003007X^2)$
$y = 1/(0.00549 + 0.01094e^{-0.4427X})$
$y = X/(0.001587 + 0.00618X - 0.00006131X^2)$
$y = 162.7 - 15.17X + 6.045X^2$
$y = 184.7 - 264.9X + 413X^2$
$y = X/(0.01958 + 0.005688X - 0.00001756X^2)$
$y = 175.5 - 2.089X^{1.192}$

Table 7.8 Coefficient for multiple regressions of tear factor

	Constant term						
8-1		CW-1	CW-2	CW-3	CW-4	$(CW)^2$	$(CW-1)^2$
	-2492	28.88	22.47	36.37	18.46	6.925	-0.07767
	126***	0.9158			2.518**		
	139***				2.586**		
8-2		CL	CL-2	$(CL)^2$	$(CL-1)^2$		
	-1588*	81.97*	4.509	-1.001*	0.2044*		
8-3		CW%	CW%-2	CW%-3	CW%-4	CW%-5	CW%-6
	993.2*	-76.19*	7.754*	18.41*	68.78	28.65*	58.38**
8.31	1361**	-75.44*	5.686*	12.07*	28.03**	25.62*	40.14**
8-4		ED-1	ED-2	ED-3	ED-4	ED-6	ED-7
	676.2	46.6	-5.813	-5.348	-6.869	-7.946	-2.77
	261***	45.42	-1.562*	-1.328**	-1.552		
	224.5			-1.376**			
8-5		CW	CL	CD	CW%	FL	ED
	-6263	-8.101	-186.9	242.9	54.28	3228*	-4163
	-105.1					74.38*	
8-6		CW	CL	CD	CW%	L%	ED
	489.3	33.41	-6.323	0.8685	-13.41	3.201*	-51.6
8-7		ED-3	ED-5	ED-6	ED-7	ED-8	FL
	-146.2	-0.4813	2.406	-3.313	2.078	-3.828	56
	-242.3						
8-8		FL	alpha	Holo	$(FL)^2$	$(alpha)^2$	$(Holo)^2$
	-3879	2243	-173.4	132	-362.8	2.094	-1.046
	-40.33					0.1108***	
8-9		ED	CO%	L%	FL		
	138.4	-264.9	-2.473*	2.544*	37		
	279.8**	-340.4	-3.04*	3.073**			
	142.6***		-2.291*	1.146**			
	-150.5	162.7**			74.74*		
	- 62.11			1.093	65.29*		

					R^2	R	sig
$(CW-3)^2$	$(CW-5)^2$						
-0.5331*	0.7079						
	0.1435				0.712	0.844	*
					0.514	0.717	**
					0.415	0.644	**
					0.489	0.699	*
CW%-7	$(CW\%-1)^2$	$(CW\%-4)^2$	$(CW\%-6)^2$	$(CW\%-7)^2$			
40.64*	0.03921	-2.821*	-0.8053*	0.7308*	0.885	0.941	*
49.75**					0.766	0.875	***
ED-8							
-5.707							
					0.679	0.824	*
					0.633	0.796	**
					0.394	-0.628	**
$(CL)^2$	$(CD)^2$	$(CW\%)^2$	$(FL)^2$	$(ED)^2$			
2.09	-2.457	-0.9579	-527.1*	3979	0.851	0.922	*
				147**	0.575	0.758	***
					0.639	0.799	*
Alpha	Holo						
6.99	-2.271				0.698	0.835	*
9.47***					0.557	0.746	***
					0.782	0.884	**
					0.561	0.749	***
					0.704	0.839	***
					0.674	0.821	***
					0.599	0.774	***
					0.565	0.752	**
					0.610	0.781	***

Figure 7.41

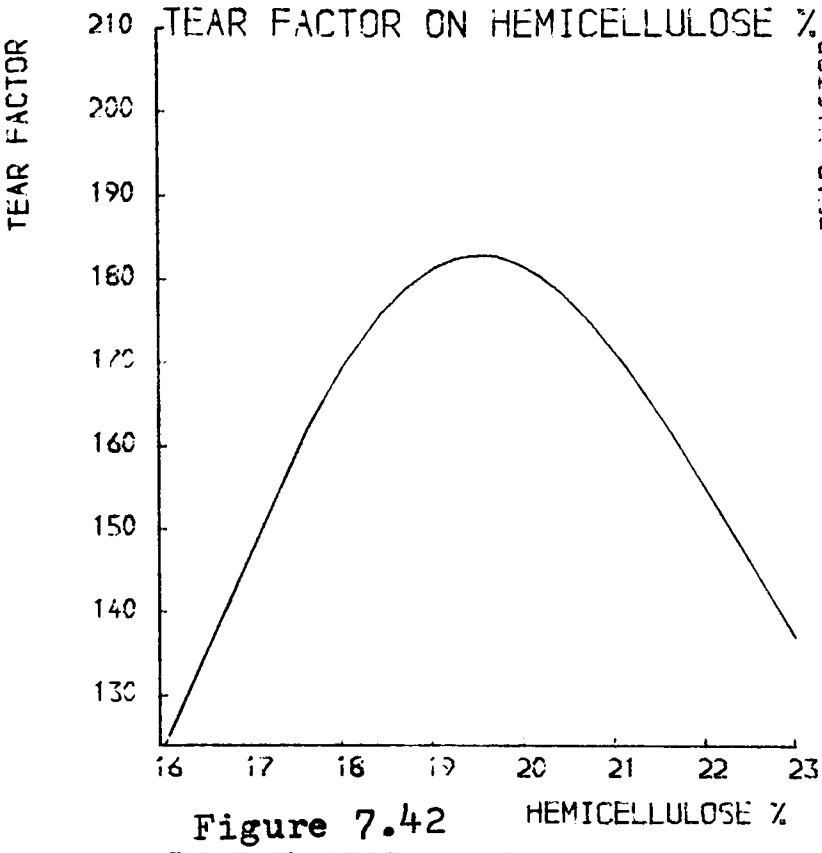


Figure 7.42

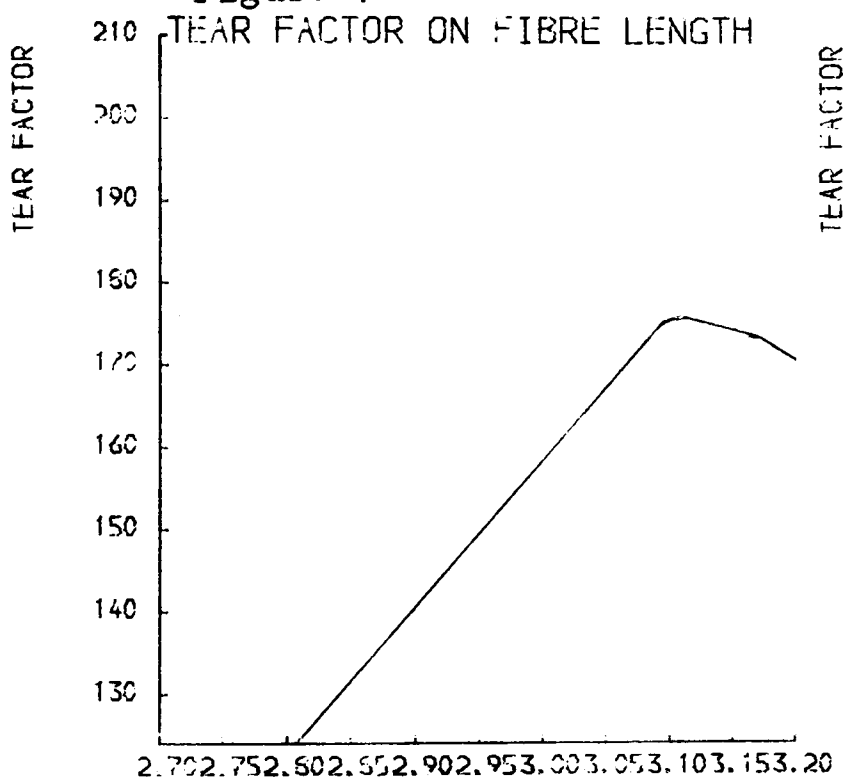


Figure 7.43 FIBRE LENGTH (MM)

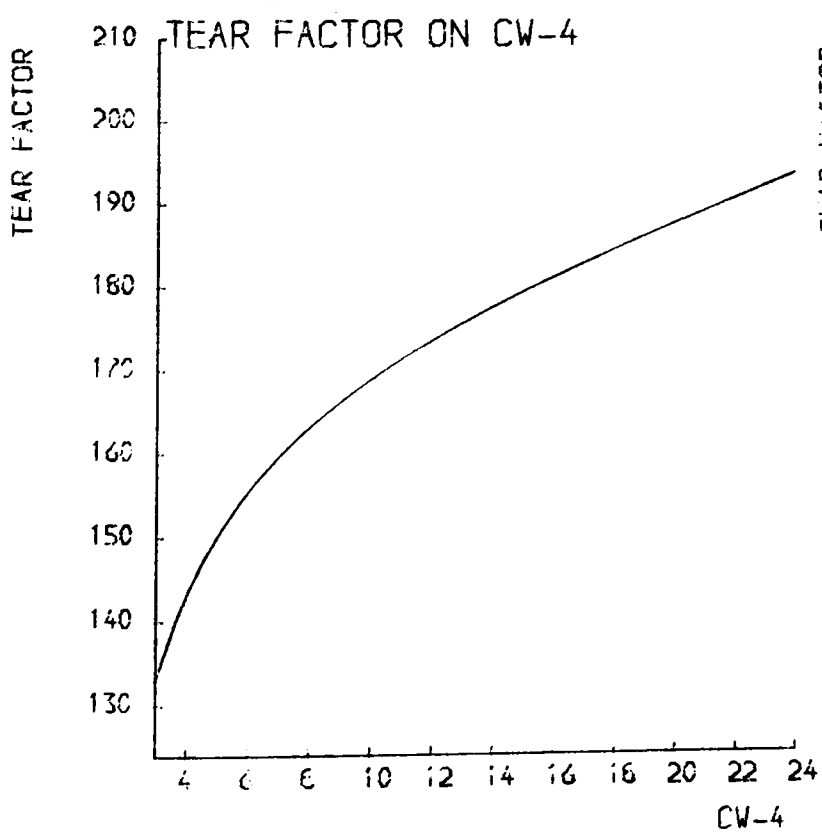
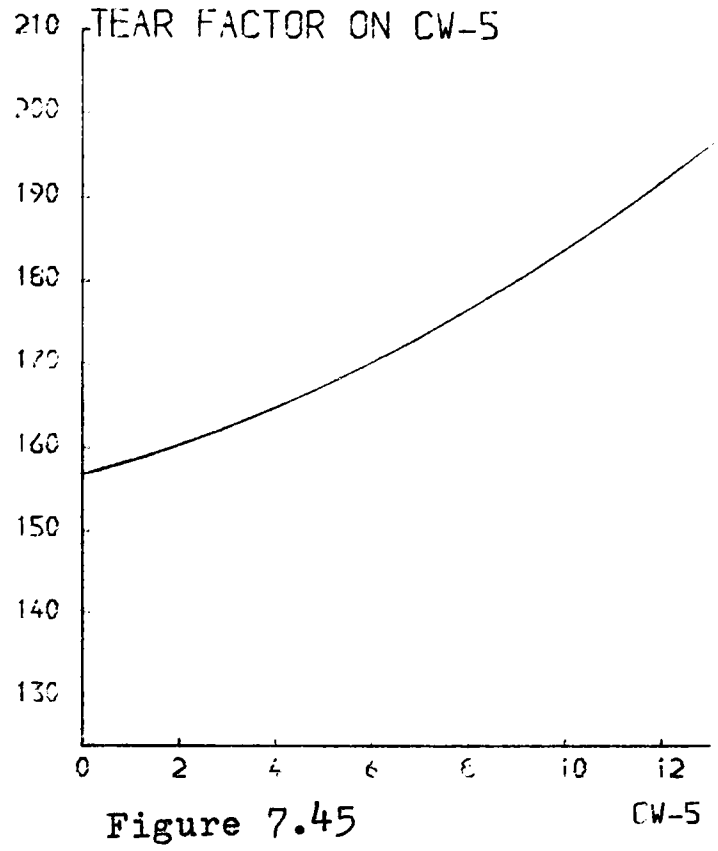


Figure 7.44



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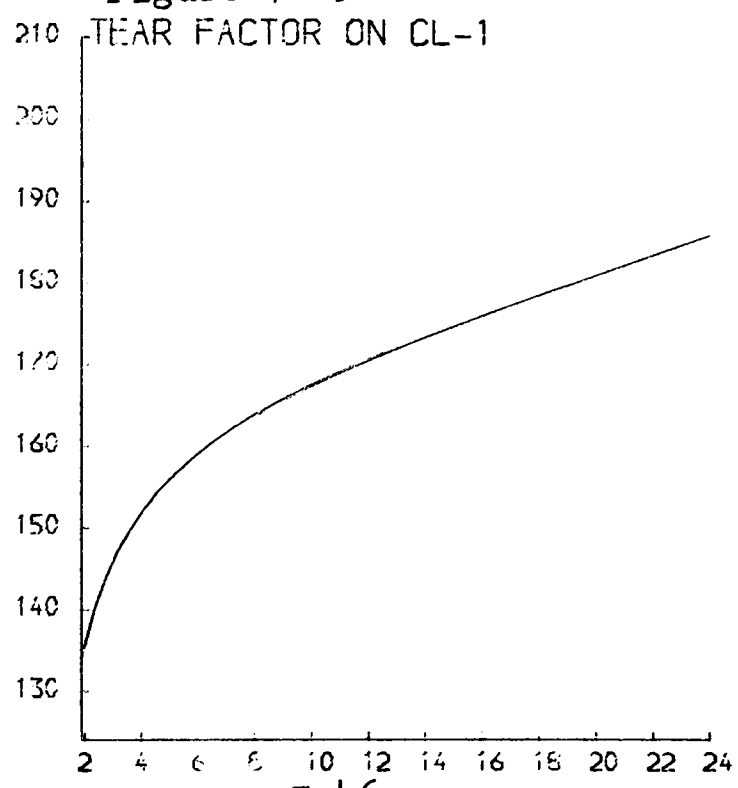

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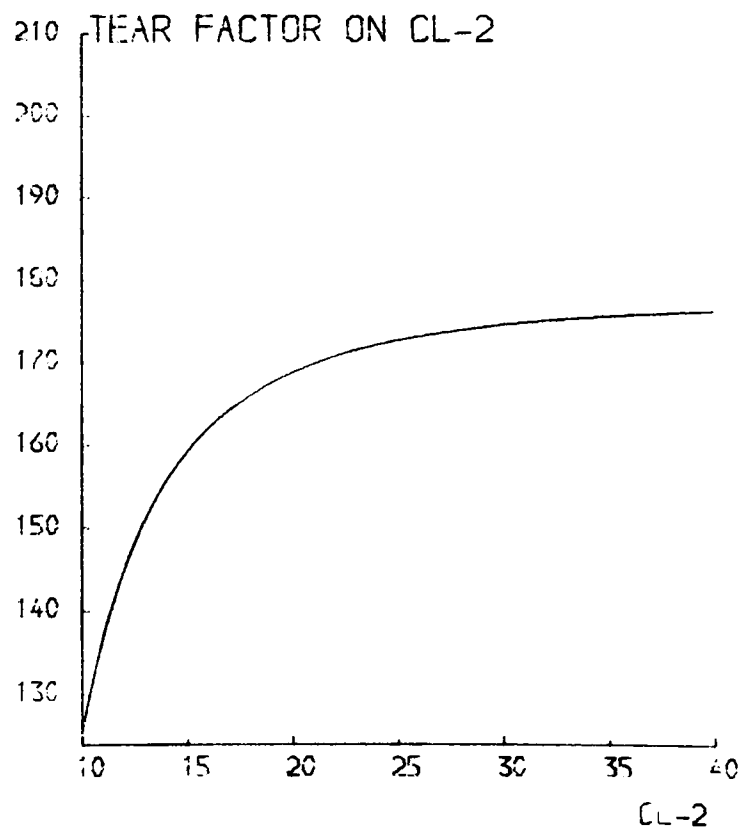

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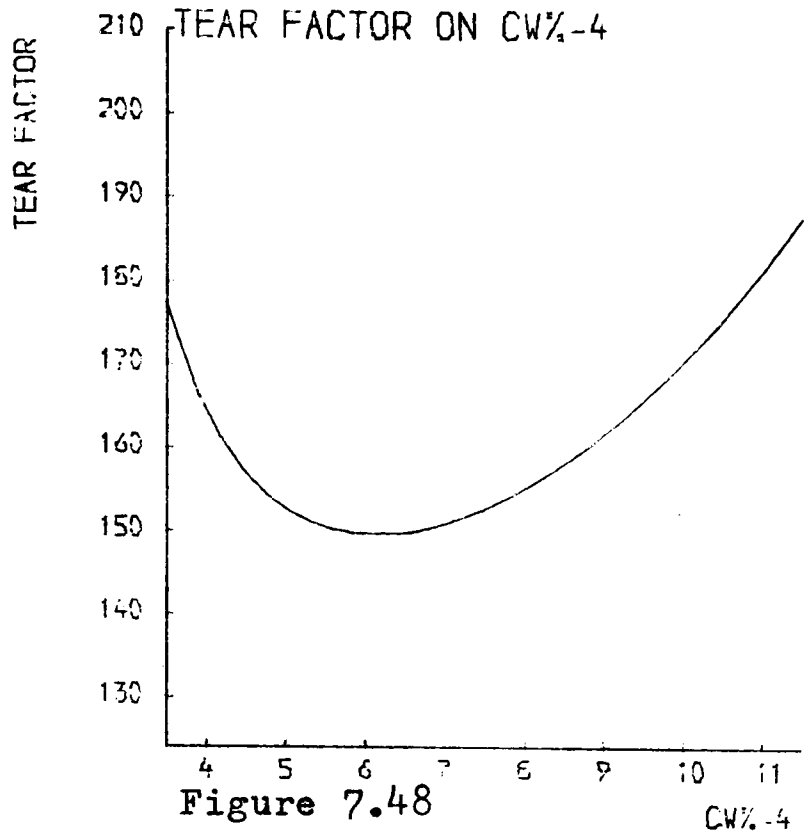
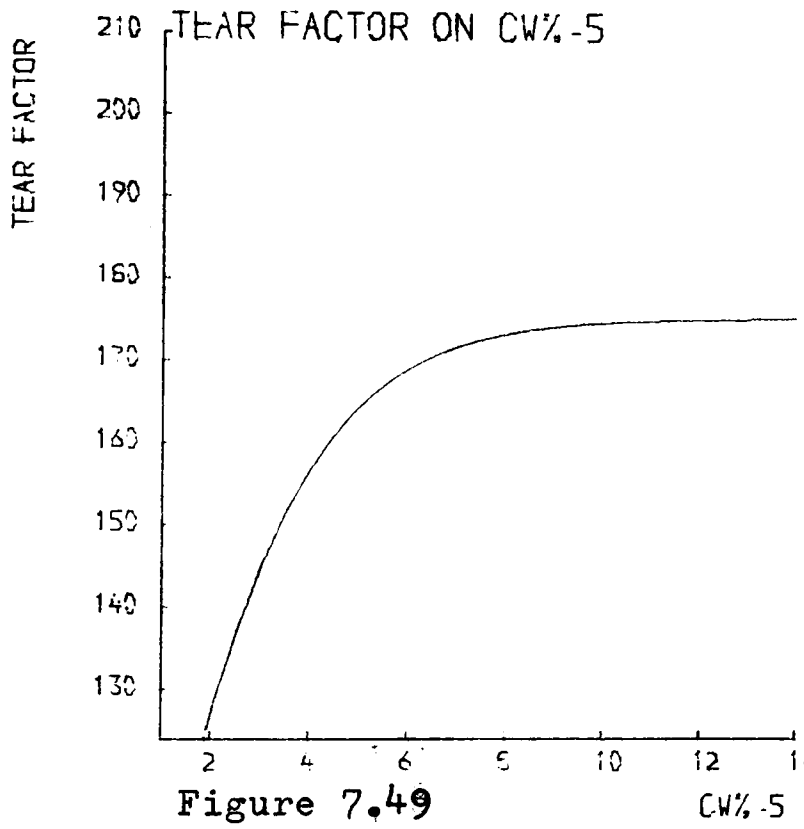


Figure 7.48



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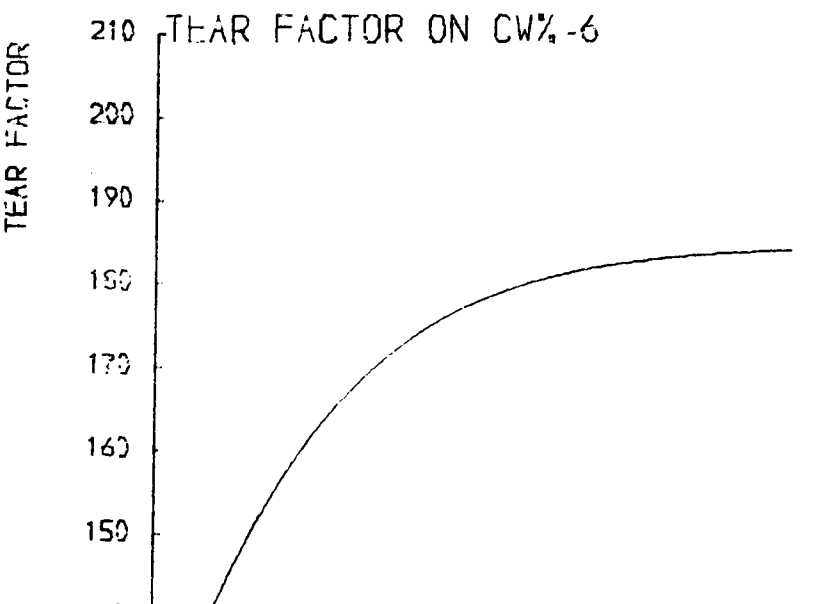


Figure 7.50

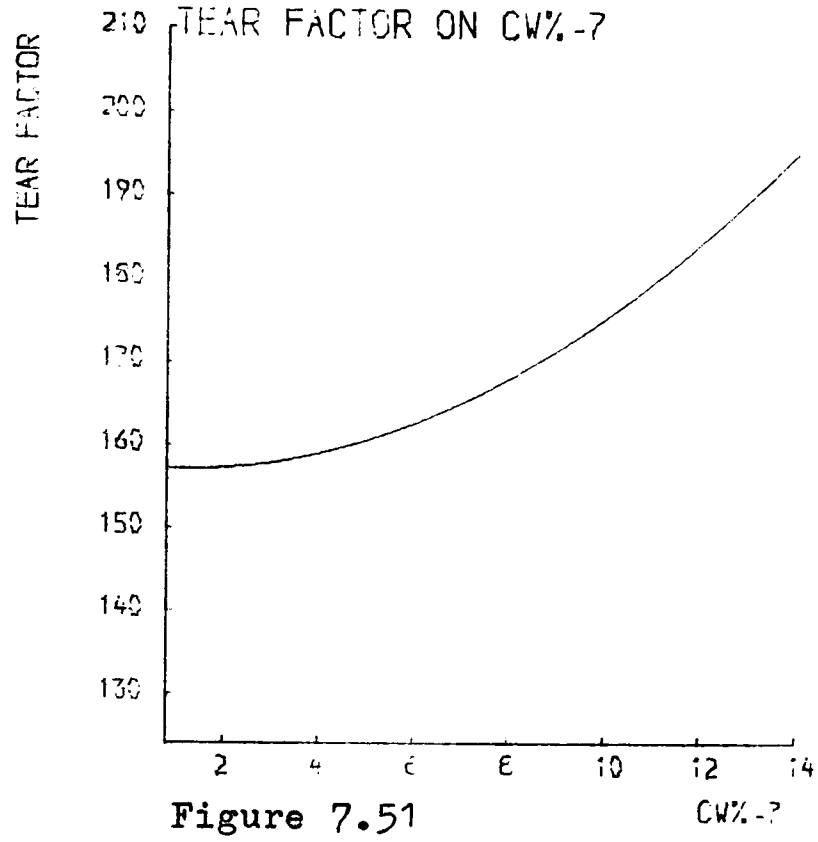


Figure 7.51

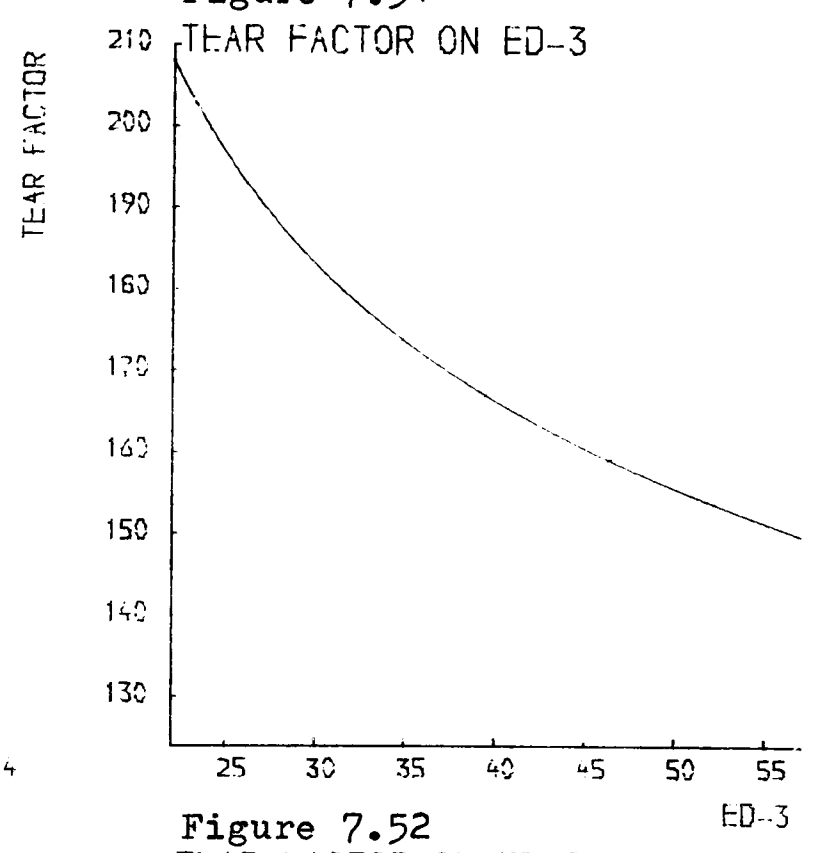
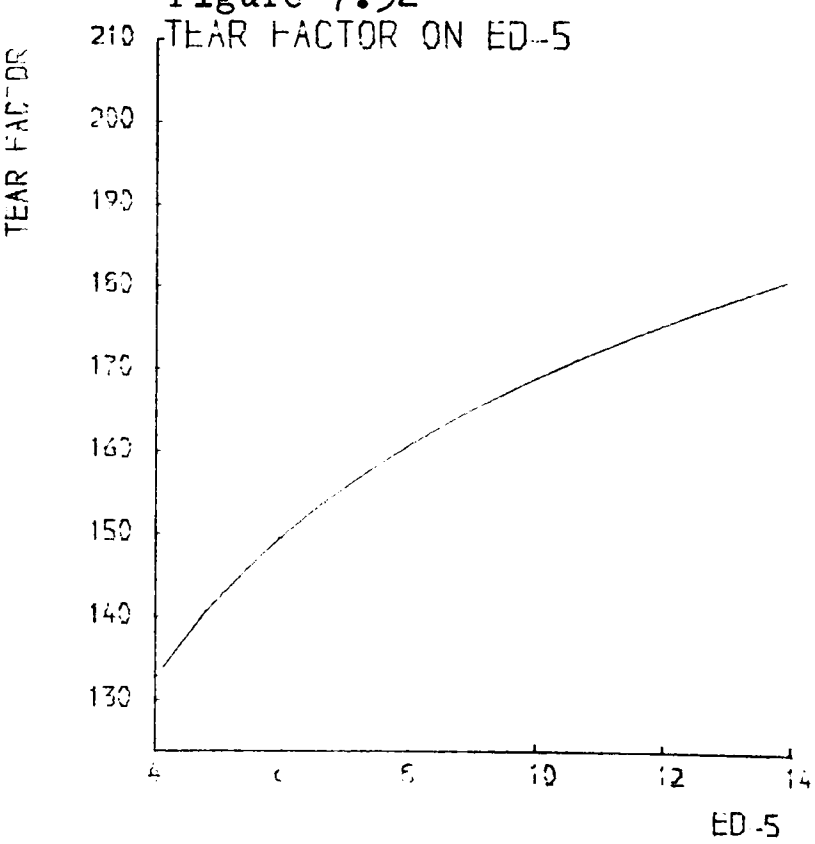


Figure 7.52



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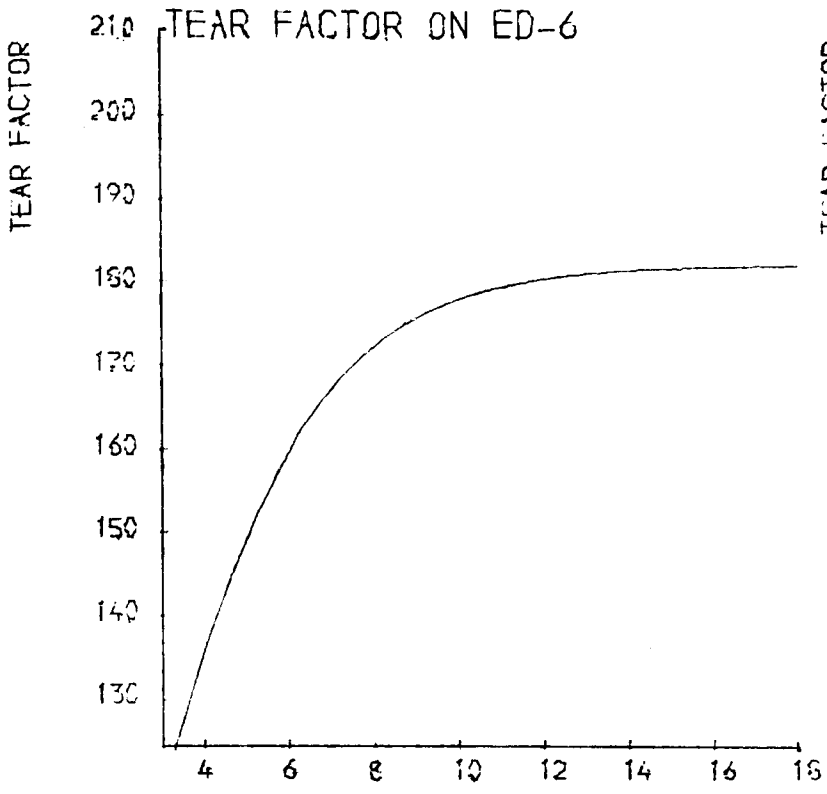

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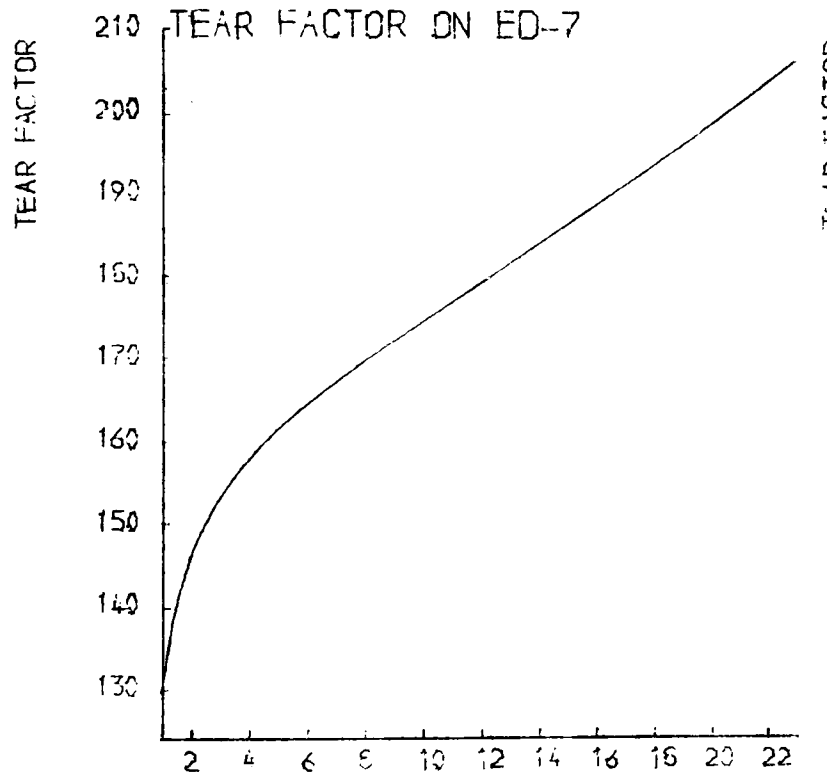

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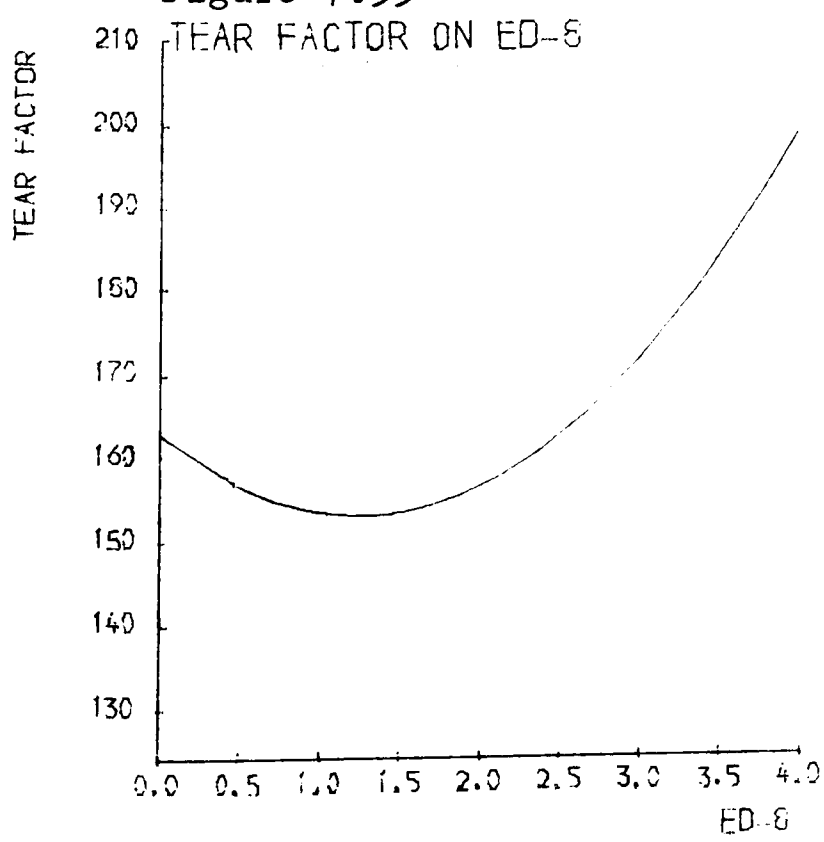


Figure 7.56

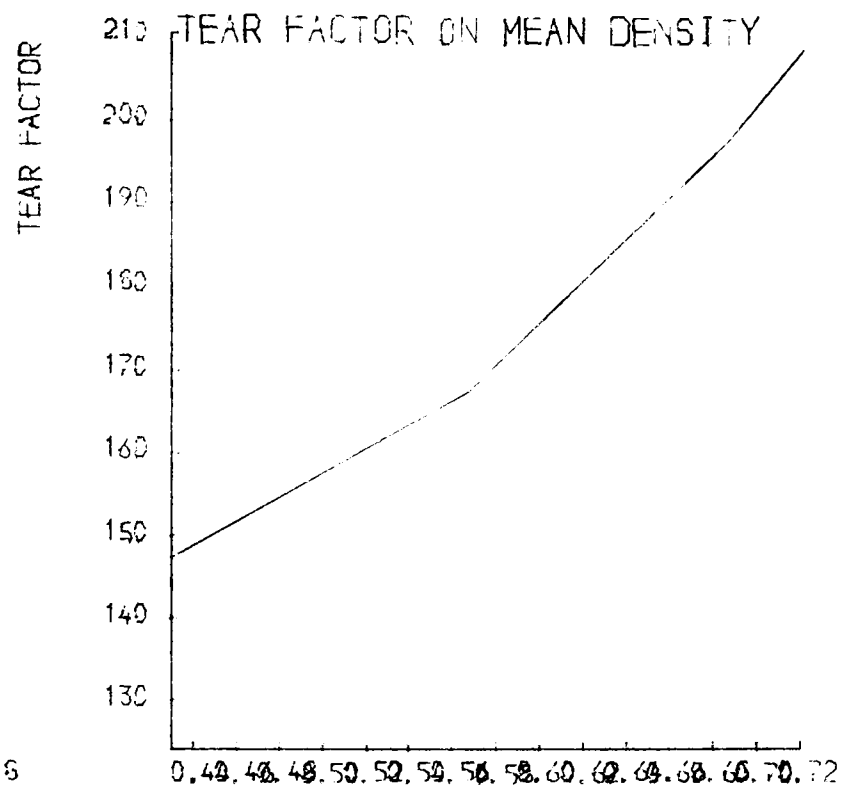
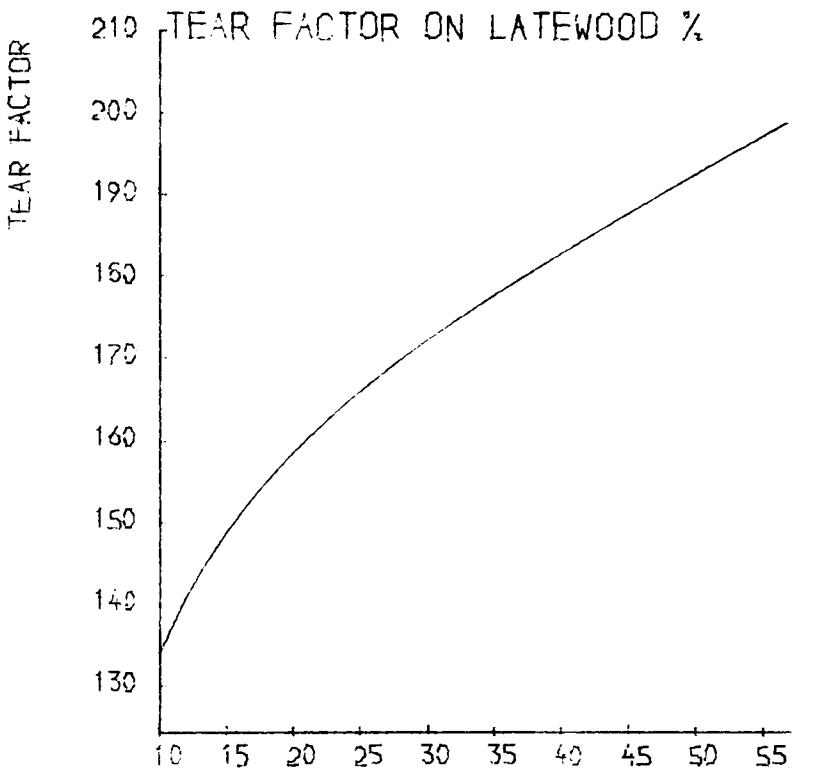


Figure 7.57



be used with confidence to predict TF. Considered overall, the regression 8.31 was probably the best predictor of TF.

5. Conclusion: The effect of wood characteristics on pulp properties

The principal conclusions that may be derived from the results presented in this chapter are summarised as follows:

1. The influence of the chemical composition of the wood on pulp properties.

Lignin was significantly and negatively correlated with TY% (R = -0.56**) and TF (R = -0.57**), and there was a positive but insignificant correlation with BF (R = 0.15 n.s.) and BL (R = 0.24, n.s.).

Holocellulose was significantly and positively correlated with TY% (R = 0.67***), but correlation with paper strength properties were not significant.

Alpha cellulose effects most of the paper strength properties, because of its effect on the ultimate fibre strength, fibre bonding and paper sheet characteristics. Alpha cellulose content was significantly and positively correlated with TY% (R = 0.81 ***) and with TF (R = 0.75***) and there were not significant and negative correlations with BF (R = -0.30 n.s.) and BL (R = -0.36 n.s.)

Hemicellulose was not significantly correlated with TY% (R = 0.0 n.s.) and TF (R = -0.32 n.s.), but positively and significantly correlated with BF (R = 0.50*) and BL (R = 0.49*). This supports previous findings that hemicellulose is important as a bonding agent (see literature review).

Total extractives were significantly and negatively correlated with TY%, but were not significantly correlated with paper strength.

2. The influence of fibre dimensions on pulp properties

Fibre length was not significantly correlated with TY% (R = 0.35 n.s) BF (R = 0.25 n.s.) and BL (R = 0.0 n.s.), but had a significant non-linear relationship. With BF (model 3, R = 0.48) and BL (model 3, R = 0.49). Cell wall thickness had a greater effect than fibre length on BF and BL. A possible explanation is that fibres of the same length can have different thickness of cell wall, and consequently fibre length has a non-linear relationship with BF and BL.

Fibre length exercised a greater influence on TF (positive) (R = 0.56 **) than on TY%, BF and BL. TF increased with an increase in fibre length up to an optimum length of about 3 mm, after which an increase in fibre length had no additional effect. It is noted that in this study, fibre length was measured from the pulps. Watson and Dadswell (1964) postulated that tearing strength of a pulp sample would increase with an increase in (wood) fibre length up to an optimum length of about 4 mm, after which an increase in fibre length has no additional beneficial effect. The sulphite mill of Wiggins Teape Co. in Scotland has an average pulp fibre length of 2.5 mm, and it is considered that lengths over 3 mm are difficult to use (see literature review).

The most important single factor in the multiple regressions, affecting BF, BL and TF is fibre length, when fibre length is eliminated from the mutliple regression equation, R^2 values with paper strength dropped very abruptly. The results of these multiple regressions however need to be treated with caution because of small number of observations of the dependent factor.

Cell lumen width and cell diameter data are the best single predictors of TY%. Combining cell diameter data alone or cell wall percentage data alone by multiple regression, could provide high values of R^2 with TY%. Cell wall data have seldom been used to predict TY%.

As regards fibre cross-sectional dimensions, only cell wall thickness and cell wall percentage data were significantly related to all the pulp properties. However, cell lumen data were significantly related to TY% and TF, while cell diameter data were only significantly correlated with TY%.

Cell wall thickness data provided the best indicators of BF and BL, but it was found that in the multiple regressions fibre length accounted for more of the variation than cell wall thickness. This was unexpected since a strong linear correlation is found between cell wall thickness and paper strength.

Fibre cross-sectional dimensions were good predictors of TY% and TF, but were not as good predictors of BF and BL. Multiple regression combining several variables can provide a better regression for predicting pulp properties, but these regressions must be regarded as of limited value for the reasons already stated.

Previous results (see literature review) showed that cell wall thickness was negatively correlated with BF and BL, but positively correlated with TF. Fibre length is positively correlated with paper strength (burst factor, breaking length and tear factor). Since cell lumen and cell diameter data are also weakly correlated to paper strength, it seems logical that fibre stiffness (FL/2CW) would have higher values of R with BF and BL than other ratios. Similarly, fibre index (2CW x FL) can be expected to have higher values of R with TF than other ratios.

Both fibre stiffness and fibre index have better R values with BF and TF than mean cell wall thickness and fibre length. No reports concerning the relationship of these two ratios to pulp properties were known to the writer. Most of the previous research was concerned mainly with Runkel ratio (2CW/CL), flexibility ratio (CL/CD) and slenderness (FL/CD) (see literature review).

Fibre dimension ratios when combined with other variables in multiple regressions provide higher values of R^2, but these regressions must be regarded as doubtful, for the reasons already stated.

3. The influence of the physical properties of wood on pulp properties

Density, as would be expected, was one of the main factors associated with TY% and paper strength. The proportions of wood in various density classes, mean density (ED) and latewood percentage were highly correlated with TY% and TF. However, the correlations with bursting and breaking strengths were rarely statistically significant and simple regressions were not practically useful to predict values for these properties from density data. Density data in combination with other variables however, gave high values for R^2.

Compression wood was not significantly correlated with BF and BL, but significantly and negatively correlated with TY% and TF.

There were appreciable differences between trees in the yield and quality of pulp. The volume of wood produced by the fastest growing tree was more than four times that of the slowest growing tree. With respect to the weight of pulp per volume of wood, the fastest growing tree yielded 42% of pulp, whilst the slowest growing tree yielded 47%. However, there was no great difference in paper strength beween pulp from the fastest and slowest growing trees (see later section).

4. The classes of those variables which formed had a low percentage of wood (such as CW-1, CD-1, ED-1 and ED-8), and the classes forming a high percentage of the wood but which contained a mixture of earlywood and latewood (such as ED-4, CW-3 and CL-3 and CD-4) have low or insignificant correlation coefficients with pulp properties.

The influence of mean values (ED, CW, CL, CD and CW%) on pulp properties was often negligible when compared with the distribution of density, cell dimensions in terms of the amounts in the various classes (ED-X, CW-X, CL-X, CD-X and CW%-X).

For all pulp strength properites the best correlations are with the proportions of wood of high density (above 0.66 g/cc, ED-5 to ED-7) with thick cell walls (above 12 μ, cW-3 to CW-5).

5. The statistical significance of the correlation coefficients suggests that precise regression predictions will be obtainable for TY% and TF with less precise estimations of BF and BL. The inverse relationship (linear R = -0.57 **) and positive relationship of BF and BL of TF with BL (linear R = 0.81 ***), and the good correlations obtained between TF and density data and fibre cross-sectional dimensions data, suggest that species, sites and even individual trees may be characterized inexpensively from small samples.

6. From this investigation, it seems that wood density data are more important in explaining variation in pulp properties than fibre length. An increase in paper strength could be accomplished by selecting and breeding for higher wood density, which would increase tear strength. Theoretically increased burst strength and breaking length could then be obtained through additional beating, but this would increase the time required for pulping and the power requirements.

7. Because of the possibilities for genetic improvement of wood and fibre properties, it may be worth attempting to produce a more uniform raw material in order to reduce process variation and to operate more efficiently. The possibility of growing trees with optimum fibre quality and still having reasonably high density and growth rate will remain an intriguing challenge. Van Buijtenen (1969) proposed an approach to this problem which involves tree selection for smaller-diameter and thinner-walled fibres in such a way as not to reduce the cell wall volume or density of the wood.

In this study, with pulp properties assessed at 500 c.s.f. and 35 Kappa number, all trees were in the sack Kraft range and liner board range. The sample of 20 trees represents the range of variation in growth and in wood properties likely to be encountered with this species in Fiji. Since all trees produced pulp and paper within the range of acceptable quality, the most important factors for consideration are those that affect the cost of pulp. It was apparent that increased growth rate does not present a detriment to pulp quality. This situation leaves wood density as probably the most significant factor in determining wood costs for a given amount of pulp.

8. To improve wood uniformity and paper strength, it is suggested that the most desirable trees for growing and pulping are those with the following characteristics:

a. Fast growth rate

b. Mean density about 0.58 g/cc

c. Latewood percentage about 25%

d. Large percentage of wood in ED-4 (0.51 - 0.65 g/cc)

e. Above average fibre length.

The reasons for choosing the above conditions were based as follows:

a. Fast tree growth did not present a detriment to pulp quality but increased pulp yield per tree which is most important factor.

b. BF and BL decreased little, but TY% increased rapidly with an increase in density to about 0.58 g/cc. After density reached about 0.58 g/cc, BF and BL began to decrease at a faster rate, and the increase in TY% gradually slowed down (Figures 7.15, 7.29 and 7.39). TF was reasonably high (TF about 170) when density was about 0.58 g/cc. Also, it was noted that tree density was weakly correlated (r = -0.42) with growth rate (based on tree volume divided by age). In this study, no trees in the sub-sample(20 trees) were in fact between 0.59 - 0.62 g/cc. Any trees with density over 0.62 g/cc, had growth rates considerably lower than average, but for mean tree density from the lowest (0.43 g/cc) to about 0.58 g/cc, the growth rate changed very little.

c. BF and BL (Figures 7.30 and 7.40) decreased little, but TY% (Figure 7.16) increased rapidly with increasing latewood percentage from lowest (10%) to about 25%. After reaching 25% of latewood percentage, BF began to decrease faster but TY% increased very little. The value of TY%, BF, BL and TF were reasonably high with 25% of latewood.

d. An increase in the amount of wood in ED-4 (0.51 - 0.65 g/cc) class did not significantly decrease the values of BF, BL and TF. It therefore seems likely that an increase in the amount of medium density wood (ED-4), but without increasing the latewood percentage, would be desirable for paper strength and pulp yield.

e. Above average fibre length will improve paper strength.

9. Although there is an inverse relationship between TF and BL (R = -0.57 **), TF was not significantly correlated with BF (R = -0.31 n.s.).

BF and BL have a close relationship (R = 0.81 ***). In this study, some trees had good values for TF and BF and BL. The following table lists, five trees of this sort:

Tree No.	TF	BF	BL	ED g/cc	L%	Growth rate	Pulp yield (kg)
2	184.0	65.89	9396	0.63	38.8	0.018	65.40
9	179.7	64.74	9319	0.56	29.6	0.027	93.61
11	172.7	67.22	9404	0.57	29.3	0.023	81.55
15	179.5	67.40	9233	0.44	15.4	0.037	96.53
18	174.0	67.43	9269	0.55	30.2	0.28	95.08

Comparing these five trees, tree number 2 and 11 had low growth rate and pulp yield. Trees number 9, 15 and 18 were good in all respects. It should be noted that one of these trees (tree 15) had mean density and latewood percentage different from the suggested ideal value. The suggested ideal values were based on regression lines. However, it is clear that there are considerable between tree differences in pulping properties and it seems very likely that pulp quality could be improved by selection and breeding, based on evaluation of growth rate, density and latewood percentage.

Chapter 8

GENERAL CONCLUSIONS AND DISCUSSIONS

In this chapter some of the main results will be reviewed and summarised. Suggestions for the properties and uses of the wood of the species will be given.

1. Measurement of wood properties

In this investigation, the choice of measurements was mainly guided by the works of Hughes (1970), Brown (1969), Lantican (1972) and Paraskevopoulou (1973).

With tracheid cross-sectional dimensions, it was difficult to distinguish earlywood and latewood in the samples. To simplify measurement, it was decided to measure tracheids along radii from pith outward to the bark at each one mm interval. This sampling system does not separate earlywood and latewood exactly, and was therefore different to that of Lantican (1972) and Paraskevopoulou (1973). It does provide a measure of the variability of cell dimensions in each annual ring and useful data for comparison with some other characteristics. The precision indices for these features with the sampling system adopted were considered to be satisfactory.

To investigate the effects of variation and the patterns of distribution of density and tracheid cross-sectonal dimensions, it was decided to separate these characteristics into several classes. There were very few previous investigations to follow. Except for Echols (1972, 1973, density only), no reports concerning distribution were

known to the writer. Echols in 1972 and 1973 worked on P. ponderosa with a mean density about 0.4 g/cc. In his work, the range of wood densities observed was divided into 14 classes (0.20 to 0.90 g/cc interval). The characteristic pattern of wood density distribution obtained with all trees resembled a chi-squared curve. In the present study, P. caribaea had a large within tree and between tree variation in wood density, ranging from 0.05 g/cc (lowest) to 1.30 g/cc (highest). It was found difficult to follow Echol's method (0.05 g/cc interval), which would have required 24 classes and made it laborious and difficult to compare with other characteristics. In this study, it was therefore decided to separate density into eight classes only with intervals of 0.15 g/cc.

2. Variation within trees

2.1 Variation in the axial direction

For all features examined, differences due to height levels, were found to be small. There was general confirmity between the axial patterns of variation exhibited by the individual trees and those based on pooled data from 20 trees. Changes in the axial direction were either linear or quadratic.

For the data of the 20 trees pooled, the tables, figures and simple regression analysis, disclosed that no significant differences were associated with levels in ring width, compression wood, cell lumen width and cell diameter. Levels were significantly and negatively related to mean density, cell wall thickness and cell wall percentage. These effects, however, as shown by the R^2 value of simple regressions were found to be generally weak, and the ranges of value levels were small.

The relatively small variation with height is an important practical consideration, since large within tree variation, particularly in density, is a very undesirable characteristic. The fact that there is little variation between trees in the pattern of variation with height also may make it possible to compare trees on the basis of sampling in the lower bole.

Similar results for levels were obtained by Lantican (1972) and Paraskevopoulou (1973) for P. caribaea var. hondurensis and P. caribaea var caribaea respectively. It therefore seems likely that reliable estimates of tree mean values for density and other features can be based on measurements of only one height level. This would save considerable time and expense.

2.2 Variation in the radial direction

Analyses of variance of data representing the breast height measurements of ring width and ring density from the original sample of 120 trees, disclosed very highly significant differences between ring positions for the mean values of ring width and ring density and the effect of rings accounted for the largest part of the total variation (VC% = 81.6, 29.4).

The high value of the variance component for the effect of age in variation in ring width is a reflection of rapid growth when trees are free of competition in early years followed by a marked reduction of growth rate, probably coinciding with closure of the canopy.

For the sub-sample (20 trees), the tables, figures and simple regressions showed very considerable between ring differences in ring width, density, cell wall thickness and cell wall percentage. These features showed marked quadratic patterns of changes in the radial direction at all heights. The differences between rings in cell lumen width and cell

diameter, however, were found to be small. Cell lumen width and cell diameter increased up to ring number 2 and then showed very little change with further increase in ring number. In general, changes in any of the features which showed variations with increasing age (ring number) from the pith were more pronounced in the first few rings than in the outer rings sampled.

All features examined showed fairly marked tree to tree variation in their patterns of development in the radial direction. Some trees showed little change with age from the pith, but others showed considerable changes with age from the pith.

The radial patterns of variation of the different features varied from level to level within some trees, but showed little variation with height in others.

3. Variation between sites, between plots and between trees

Analysis of variance was used to examine ring width and density for the original sample of 120 trees. There were no significant differences between sites in the mean values for ring width (VC% = 0.84). There were highly significant differences between plots, but the variance component was very small (VC% = 0.64). It therefore seems that there were no major differences in conditions at the tree sites influencing rate of tree growth.

There were highly significant differences between sites in the mean values for density with a considerable component of variance (VC% = 12.3), but no significant differences between plots (VC% = 0). This indicated that the relationship between ring density and ring width was weak. The results of this investigation showed that ring density was negatively correlated with ring width but only significant at the 5% level (R = -0.48).

Since density is determined by cell size and amount of cell wall material, differences in density between sites and between plots were reflected in differences in cross-sectional dimension features. For the three sites separately (20 trees sample), simple regression showed that there were considerable differences in cell lumen width and cell diameter associated with ring number, year number, ring width, % height level and distance from pith, but small differences in cell wall thickness and cell wall percentages.

The non significant between site differences in ring width and the significant between site differences in density could result from sampling a different range of genotypes at each site or could have been caused by a site effect. The differences are large enough to warrant further investigation.

Ring width and mean ring density showed statistically significant between tree differences with large variance component for density (VC% = 1.3 and 27.6). For the tracheid cross-sectional dimensions between trees differences were also considerable.

The between tree differences in density indicate that it should be possible to select trees for breeding in order to improve wood quality.

4. Variation as explained by morphological characteristics

Linear regressions were calculated to relate whole tree value of all features for 20 trees to morphological characteristics. In this investigation, results showed that these characteristics (tree height, tree volume, diameter, at breast height, crown width and crown length) cannot be used for estimation of whole tree values of any of the features studied, and consequently are of no value in stratifying a stand in terms of wood quality.

This agrees with the conclusion of Zobel and Rhodes (1955) and Fielding and Brown (1960) that such factors accounted for little of the variation in wood quality between trees, and that genetical factors must be of primary importance.

5. Possibility of predicting whole tree value

In this study, it was shown that whole tree values for wood density and tracheid cross-sectional dimensions can be validly predicted from samples taken at the 5% height level (normally close to breast height). In fact, for wood density, 15% and 25% height levels were better for predicting tree density, but for cross-sectional dimensions 5% height had a higher correlation with whole tree mean values than other % height levels.

It may not be advisable, however, to apply these regression equations derived from Fiji samples to P. caribaea from another area and certainly not to another species.

6. Density distribution and tracheid cross-sectional dimensions distribution

In this study, an attempt was made to assess the importance of distribution of wood characteristics and what use can be made of this information. Echols (1972, 1973), working on ponderose pine was also interested in these problems.

When considered along with mean values for density, the pattern of distribution of density provides a measure of wood uniformity and may suggest its degree of suitability for end uses. For example, if the growth rings are wide, with light earlywood and extremely hard latewood rings, the wood would be rejected by moulding manufacturers and perhaps degraded in veneer plants. One-inch boards made from it would tend to cup from differential strinkage and would be subject to splitting from nails. Pulp mills would take it, but processing may have to be

varied, giving excessive cooking for earlywood while pulping latewood adequately. Manufacturers of furniture or decorative materials perhaps would like it.

On the other hand, the growth rings may be just as wide, but the earlywood may be a little denser, with thicker cell walls, and the latewood may be considerably less dense, with thinner secondary cell walls. The resulting wood could still have the same density, but would be more uniform. The moulding manufacturers, for example, could machine it routinely. The veneer plant would peel it easily. It would make good, stable, nailable 1-inch boards. Pulp mill processing should be more easily controlled. With high density and uniformity, it would make fine, predictably strong construction timber.

To achieve greater uniformity in wood, we should concentrate on reducing the relative amounts of extremely thin - and thick - walled tracheids formed at the beginning and end of the growing seasons respectively. Rather than the chi-squared type of curve, a uniform wood would produce a normal curve - high in the middle and tapering abruptly at the ends. It seems that there may be a possibility of selecting trees of P. caribaea for greater uniformity of wood density.

Characteristic patterns of distribution wood density classes and tracheid cross-sectional dimensions classes, resembling a chi-squared curve, bi-nomial and bi-model curves were found in the sub-sample (20 trees). The most obvious differences between tree occurred because of differences in the amounts of the highest and lowest distribution classes. This study, confirmed Echols' (1972, 1973) conclusions that wood uniformity appeared to be controlled by the relative amounts of very high and low density wood, with high densities exercising the greatest influence.

7. Correlations between variables

The objective of this section was to examine the relationships between wood density, tracheid dimensions and some selected wood properties such as latewood percentage, compression wood and percentage and wood chemical contents. All results presented in this section are based on pooled data (20 trees). The simple correlation between the principal variables considered in this part of the investigation are summarized in Table 8.1.

There is general agreement between the results of this study and those available in the literature regarding the correlations between density and tracheid cross-sectional dimensions.

a. All of the tracheid cross-sectional dimensions show highly significant correlations with density and latewood percentage, which are in turn rather strongly correlated with each other.

b. In the present study, it has been shown that pulp fibre length was not significantly correlated with any variables. Lantican (1972 P.caribaea) demonstrated that tracheid length was only weakly correlated with most of the earlywood and latewood tracheid cross-sectional dimensions examined, and was not significantly correlated with density. It therefore seems that tracheid length in P. caribaea could be altered without serious changes in tracheid cross-sectional dimensions and density.

c. The relationship between density, and latewood percentage, and cell wall percentage was very close (r = 0.96, and 0.98 respectively). It therefore seems that extracted density can be expressed as a function of cell wall percentage or latewood percentage. Selection for a high proportion of latewood in P.caribaea will imply selection for high density.

Table 8.1

MATRIX ØF SIMPLE CØRRELATIONS

VAR	E D	HØLØ	ALPH	HEMI	LIGN	EXTR	L %	C0 %
E D	1.0000	0.4952	0.8104	-0.2397	-0.4880	-0.3192	0.9632	-0.3696
HØLØ	0.4952	1.0000	0.6229	0.5756	-0.4679	-0.6501	0.4220	-0.6585
ALPH	0.8104	0.6229	1.0000	-0.2812	-0.7145	-0.5232	0.8351	-0.4729
HEMI	-0.2397	0.5756	-0.2812	1.0000	0.1730	-0.2505	-0.3553	-0.3134
LIGN	-0.4880	-0.4679	-0.7145	0.1730	1.0000	0.1806	-0.4859	0.5346
EXTR	-0.3192	-0.6501	-0.5232	-0.2505	0.1806	1.0000	-0.3161	0.3502
L %	0.9632	0.4220	0.8351	-0.3553	-0.4859	-0.3161	1.0000	-0.2887
C0 %	-0.3696	-0.6585	-0.4729	-0.3134	0.5346	0.3502	-0.2887	1.0000
C W	0.9133	0.3327	0.7649	-0.3915	-0.4935	-0.1186	0.8998	-0.1967
C L	-0.8803	-0.4804	-0.6874	0.1293	0.4323	0.4164	-0.8310	0.4682
C D	-0.7430	-0.4599	-0.5632	0.0246	0.3501	0.4544	-0.6890	0.4901
CW %	0.9805	0.4055	0.7915	-0.3299	-0.4985	-0.2500	0.9604	-0.3233
F L	0.3246	0.2177	0.4191	-0.1710	-0.2175	-0.1750	0.3721	-0.3484

VAR	C W	C L	C D	CW %	F L
E D	0.9133	-0.8803	-0.7430	0.9805	0.3246
HØLØ	0.3327	-0.4804	-0.4599	0.4055	0.2177
ALPH	0.7649	-0.6874	-0.5632	0.7915	0.4191
HEMI	-0.3915	0.1293	0.0246	-0.3299	-0.1710
LIGN	-0.4935	0.4323	0.3501	-0.4985	-0.2175
EXTR	-0.1186	0.4164	0.4544	-0.2500	-0.1750
L %	0.8998	-0.8310	-0.6890	0.9604	0.3721
C0 %	-0.1967	0.4682	0.4901	-0.3233	-0.3484
C W	1.0000	-0.6574	-0.4504	0.9328	0.3243
C L	-0.6574	1.0000	0.9689	-0.8795	-0.2248
C D	-0.4504	0.9689	1.0000	-0.7357	-0.1598
CW %	0.9328	-0.8795	-0.7357	1.0000	0.2994
F L	0.3243	-0.2248	-0.1598	0.2994	1.0000

PARTIAL CØRRELATIØNS BETWEEN DEPENDENT VARIABLE (E D)
AND EXPLANATØRY VARIABLES

	HØLØ C L	ALPH C D	HEMI CW %	LIGN F L	EXTR	L %	C0 %	C W
E D	-0.1847 0.1071	-0.1847 -0.1072	-0.1847 0.5133	-0.3058 -0.2187	-0.1473	0.6782	-0.2546	-0.1079

* 0.4227 significance at 5%
** 0.5368 significance at 1%
*** 0.6524 significance at 0.1%

The very high degree of correlation found between density and cell wall thickness, cell lumen width and cell diameter (R = 0.91, -0.88, -0.74 respecitvely), raises the possibility of predicting certain tracheid cross-sectional dimensions with high accuracy on the basis of measurements of density (or the reverse).

8. The relationship between wood properties and pulp properties

The final characteristics of pulp or of a sheet of paper are a result of the combined effect of all the structure of the wood, its chemical composition and, of course, the pulping process. Good prediction equations resulted from the simple regressions of pulp yield percentage and tear factor on features of tracheid cross-sectional dimensions and their distribution, wood density and its distribution and chemical composition of wood on P.caribaea. It seems that simple regression analysis can be used to predict these pulp properties from wood properties.

There were less precise estimations of burst factor and breaking length from simple regressions on wood properties. Some multiple regressions had high values of R^2, but they had a large number of terms in relation to the number of observation of pulp properties (20) and therefore cannot be used with confidence to predict pulp properties.

It must also be pointed out that the relationships established apply only to the range of wood properties considered in this study and may not apply to P. caribaea wood possessing substantially larger or smaller values for fibre dimensions and density than were observed in this sample.

Since the sulphate process is one involving partial solution of carbohydrates and lignin compounds of varying molecular weights in an alkaline medium, chemical properties as expected, predominated in total yield relationships rather than wood physical and structural characteristics.

In this investigation, cell wall thickness was the most important indicator of burst factor and breaking length. Density was the most important factor in explaining variation in tear factor.

From this study it seems that trees of lower density produce paper strength at least as good as those from the higher density trees. Only tear factor was lower and this was still within the range acceptable for linerboards. Therefore, it is concluded the pulp and paper industry need not be concerned that low density trees of this species will significantly reduce the quality of the raw material. In fact, for some uses, quality may be improved.

A more serious aspect of a reduction in density is its effect on pulp yield, which is directly related to wood density. Selection of trees for fast rate of growth may be the most profitable action to take, because although mean tree density will be lower, the total amount of wood substance produced per hectare per annum may be greater.

9. Tree improvement possibilities

The aim of tree breeding is to produce timber with specific properties for particular end uses and minimal variation. Climatic conditions and silivicultural treatments of plantations are involved as well as genetical factors and strictly speaking progeny testing is required to separate these effects.

From this study it seems that in selecting and breeding of P.caribaea in Fiji for the pulp and paper industry, primary emphasis should be placed on improving growth rate, tree form and wood uniformity, followed by further selection within this group for the desirable wood properties determined by the final product.

Considering the between tree differences demonstrated in this study, it seems that improvement of wood quality in P.caribaea can be approached in two ways. The first is to attempt to modify the feature of interest in some desirable direction, for example, to increase density or cell wall thickness (or the reverse), and the second is to increase the uniformity of the feature, by producing trees which have more uniform patterns of development. This can be achieved in part by thinning, pruning and fertilization and in part by breeding control and seed selection.

It is well known that thinning and fertilisation can influence wood density to some extent. It appears likely that thinning is associated with a reduction in density. The intensity and type of thinning will also influence the variation in density between remaining trees. Fertilisation has also been shown to reduce mean tree density and latewood percentage, and fertilised trees generally had a more gradual gradient in mean ring density from the pith outwards. Klemm (1967), McKinnell (1970), Larson (1972), Gladstone and Gray (1973) and Isebrand and Hunt (1975) found that fertilisation increased the within ring density range, usually by a reduction in minimum density, but sometimes combined with an increase in maximum density. Mean tree density and latewood percentage were also reduced.

In this study, growth rate was weak negative correlation with wood density (R = - 0.42). Some trees of faster than average growth rate also had higher than average density (e.g. tree 52-84 = 0.58 g/cc 0. 606 m^3). However, the fastest tree growth rate was about four times greater than the slowest tree growth rate (0.606 m^3 - 0.149 m^3). This was a far greater difference than the disparity between the density values (0.44 g/cc - 0.72 g/cc). Consequently, fast growth rate is advantageous from the economical view point.

To improve wood uniformity and paper strength, it is suggested that the most desirable trees for growing and pulping are those with the following characteristics.

a. Fast growth rate

b. Mean density about 0.58 g/cc

c. Latewood percentage about 25%

d. Large percentage of wood in ED-4 (0.51 - 0.65 g/cc)

e. Above average pulp fibre length.

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APPENDIX I

A - CONDITIONS OF SITES SAMPLED

(1) SEAQAQA

(i) Locality

Latitude : 16° 33' S
Longitude : 179° 8' E

Elevation : 90 m (300 feet approximately) above mean sea level.

(ii) Climatic Conditions

The general rainfall and climatic environment of the area corresponds to classification 1 of Twyford and Wright ("The Soil Resources of the Fiji Islands") i.e. :-

Lowland climate with strong dry season

Mean annual temperature	-	25.6°C (78°F)
Mean annual rainfall	-	1400 - 2540 mm (55 - 100 inches)
Average number of months with less than 10 mm (4 inches) rainfall	-	5½
Average number of months with less than 6 mm (2.36 inches) rainfall	-	3
Average soil moisture deficit during any part of year	-	76 mm (3 inches) Aug - Nov
Average surplus moisture for leaching during any part of year	-	305 mm (12 inches) Jan - April
Thornthwaite rational classification	-	$C_2A'a'r$

Temperature

Records for Seaqaqa Forest Station are not available. The following statistics refer to Seaqaqa District Farm, approximately 6 km from the Dept. of Forestry Station and approximately 4 km from the plantation sampled. Period of records : 13 - 16 years, over July 62 - Feb 78.

a) Mean monthly maximum

Jan	-	30.5°C (86.9°F)	July	-	28.5°C (83.3°F)
Feb	-	30.6°C (87.1°F)	Aug	-	28.8°C (83.8°F)
March	-	30.4°C (86.7°F)	Sept	-	29.6°C (85.3°F)
April	-	30.1°C (86.2°F)	Oct	-	29.5°C (85.1°F)
May	-	29.3°C (84.7°F)	Nov	-	30.0°C (86.0°F)
June	-	29.1°C (84.4°F)	Dec	-	30.7°C (87.3°F)

b) Mean monthly minimum

Jan	-	21.3°C (70.3°F)	July	-	16.8°C (62.2°F)
Feb	-	21.4°C (70.5°F)	Aug	-	17.0°C (62.6°F)
March	-	21.3°C (70.3°F)	Sept	-	18.1°C (64.6°F)
April	-	20.4°C (68.7°F)	Oct	-	19.3°C (66.7°F)
May	-	18.9°C (66.0°F)	Nov	-	19.5°C (67.1°F)
June	-	18.1°C (64.6°F)	Dec	-	20.4°C (68.7°F)

c) Number of days per annum with minimum temperature below 0°C (32°F).

Nil

Rainfall and Humidity

Full records for Seaqaqa Forest Station are not available. The following figures are based on what information is recorded, supplemented with data from Seaqaqa District Farm, approximately 6 km from the Dept. of Forestry Station and approximately 4 km from the plantation sampled. Period of recrods: Jan 1958 - June 1975.

a) Mean monthly rainfall

Jan	-	393 mm (15.5 inches)	July	-	86 mm (3.4 inches)
Feb	-	505 mm (19.9 ")	Aug	-	65 mm (2.6 ")
March	-	472 mm (18.6 ")	Sept	-	110 mm (4.3 ")
April	-	312 mm (12.3 ")	Oct	-	168 mm (6.6 ")
May	-	83 mm (3.3 ")	Nov	-	238 mm (9.4 ")
June	-	75 mm (3.0 ")	Dec	-	331 mm (13.0 ")

b) Annual rainfall

2838 mm (111.7 inches)

c) Longest period recorded with less than 51 mm (2 inches) of rainfall per month.

Five month period May - Sept., 1966.

d) Mean monthly relative humidity

The closest station from which records are available is Waiqele, approximately 22.5 km directly from the plantation site.

	0600 hrs	1200 hrs		0600 hrs	1200 hrs
Jan	95.9	70.3	July	93.4	61.4
Feb	96.7	72.2	Aug	92.8	60.4
March	97.4	71.4	Sept	92.9	60.4
April	96.7	69.9	Oct	91.6	61.8
May	95.3	65.6	Nov	93.7	64.3
June	94.4	65.2	Dec	94.6	64.8

Period of records: April 1957 - Feb 1978, excluding 1971 (part of), 1972, 1973, and 1974 (part of).

(iii) Topography and Edaphic Conditions

Geology : The rocks from which the soil is derived are andesites, andesitic tuffs and basalt.

Slope : Gentle, with the sampled plantation having a slight north-easterly aspect.

Soil : Ferruginous latosol, Bua gravely clay, described by Twyford and Wright typically as follows:

"- - - - three inches of dark reddish brown gravely clay, friable, with a strongly developed medium nutty structure, overlying about eight inches of reddish brown firm clays, compact in places and with a moderately developed fine nutty structure, on eight inches of weak red firm mealy clay of a moderately developed medium blocky structure, occasionally slightly mottled and this overlies a compact, varicoloured mealy clay with much decomposing basalt."

Acid soluble phosphate, exchangeable calcium, magnesium and potassium contents are all low to very low. The pH is 4.4 - 4.9.

Drainage : Adequate natural drainage.

(iv) Natural Vegetation

The site typically supports naturally poor fern (Dicranopteris linearis) and mission grass (Pinnisetum polystachyon), with vadra (Pandanus sp.), nokonoko (Casuarina equisetifolia), the occasional guava (Psidium guajava) and clumps of bamboo (Bambusa vulgaris).

Vegetation now within the sampled plantation is restricted, with the reduction in light, but would include scattered goat weed Ageratum conyzoides), sour grass (Paspalum conjugatum), hibiscus burr (Urena lobata), blue rat's tail (Stachytarpheta urticaefolia), mint weed (Hyptis pectinata), white ginger (Amomum cevuga), with the climber mile-a-minute (Mikania micrantha).

(v) Plantation History

Seed origin : Seed source Belize, but records do not indicate exact origin. However, from collections made at that time, it is safe to assume it was Mountain Pine Ridge.

Nursery practice: Seeds broadcast in raised, shaded seed beds, germination occurring 7-10 days after sowing. 10 days after germination seedlings were transplanted into 50 mm (2 inch) diameter polythene pots, in which they remained until planting out 7-9 months later. The pots contained a mixture of shredded, sterilised forest soil, gravel dust or sharp sand, mycorrizal soil and NPK fertiliser. Newly potted seedlings were shaded for about 3 weeks, being watered morning and evening. Watering was reduced shortly before planting out to help harden off the seedlings.

Method of planting : Initial site preparation involved light scrub cutting and burning of the grass and fern. Planting pits at 2.7 m x 2.7 m (9 feet x 9 feet) were dug and the seedlings planted with the polythene pot carefully removed to keep the tube of soil intact round the roots.

Date of planting: Jan - Feb 1960.

Tending : 1961 : Weeding and modest beating up operations.

1962 : Removal of some remaining competing scrub.

1964 : Pruning to ⅓rd overall height

1965 : Following Feb 1965 storms, wind damaged stems were removed.

1968 : High pruning to 6.7 m (22 feet), 247 stems/h (100 stems/acre)

1969 ; Climber cutting and thinning.

The original increment cores were collected in October, 1970, and the sample discs towards the end of 1972. (See Appendix 1B "Field Sampling and Collection of Material").

(vI Mensurational Data

The specific sample plots from which increment cores were collected had the following basic statistics prior to core sampling:-

Plot 1 - Mean height 16.7 m (54.9 feet), mean bh diameter 20.9 cm (8.2 ins)

2 - Mean height 17.5 m (57.3 feet), mean bh diameter 22.4 cm (8.8 ")

Three 0.04 ha (0.1 acre) plots were established within the plantation in January 1970, i.e. 8 months before increment cores were collected, and these gave the following average statistics:

Times pruned	-	2
Average height of pruning	-	8.5 m (28 feet)
Times thinned	-	2
No. of trees in plot	-	24
Dominant mean height	-	17.9 m (58.6 feet)
Dominant mean diameter	-	24.9 cm (9.82 inches)
Plot mean height	-	16.3 m (53.5 feet)
Basal area - sq ft/acre	-	81.3
- m^2/ha	-	18.7
Plot volume (ub) - cuft/acre	-	1580
- m^3/ha	-	110.6

No additional mensurational data is available for the crop immediately prior to collection of the disc samples in November, 1973.

(2) NAUSORI HIGHLANDS

(i) Locality

Latitude : 17° 48' S

Longitude : 177° 36' E

Elevation : 509 m (approximately 1670 feet) above mean sea level.

(ii) Climatic Conditions

The general rainfall and climatic environment of the area borders on classification 5 of Twyford and Wright ("The Soil Resources of the Fiji Islands") i.e. :-

Upland climate with a moderate dry season

Mean annual temperature	-	19.4°C (67°F)
Mean annual rainfall	-	2030 - 3810 mm (80 - 150 inches)
Average no. of months in year with less than 10 mm (4 inches) of rainfall	-	4
Average no. of months in year with less than 6 mm (2.36 inches) rainfall	-	1

Temperature (Dept. of Forestry, Nausori Highlands Station, period of records 1966 - 73, excluding 1969/70).

a) Mean monthly maximum

Jan	-	27.9°C (82.2°F)	July	-	25.0°C (77.0°F)
Feb	-	27.9°C (82.2°F)	Aug	-	25.7°C (78.3°F)
March	-	27.6°C (81.7°F)	Sept	-	26.7°C (80.1°F)
April	-	27.0°C (80.6°F)	Oct	-	26.2°C (79.2°F)
May	-	26.3°C (79.3°F)	Nov	-	27.7°C (81.9°F)
June	-	25.8°C (78.4°F)	Dec	-	28.1°C (82.6°F)

b) Mean monthly minimum

Jan	-	20.1°C (68.2°F)	July	-	16.2°C (61.2°F)
Feb	-	19.7°C (67.5°F)	Aug	-	15.7°C (60.3°F)
March	-	19.6°C (67.3°F)	Sept	-	16.9°C (62.4°F)
April	-	18.8°C (65.8°F)	Oct	-	17.7°C (63.9°F)
May	-	17.6°C (63.7°F)	Nov	-	18.0°C (64.4°F)
June	-	16.9°C (62.4°F)	Dec	-	19.6°C (67.3°F)

c) Number of days per annum with minimum temperature below 0°C (32°F):

Nil

(ii) Rainfall and Humidity (Dept of Forestry, Nausori Highlands Station, period of records 1961 - 75).

a) Mean monthly rainfall

Jan	- 357 mm (14.1 inches)		July	- 49 mm (1.9 inches)	
Feb	- 493 mm (19.4 ")		Aug	- 54 mm (2.1 ")	
March	- 483 mm (19.0 ")		Sept	- 81 mm (3.2 ")	
April	- 195 mm (7.7 ")		Oct	- 148 mm (5.8 ")	
May	- 73 mm (2.9 ")		Nov	- 212 mm (8.3 ")	
June	- 62 mm (2.4 ")		Dec	- 371 mm (14.6 ")	

b) Annual rainfall

2578 mm (101.5 inches)

c) Longest period recorded with less than 51 mm (2 inches) of rainfall per month

Five month period, June - Oct., 1966.

d) Mean monthly relative humidity

No statistical information available.

(iii) Topography and Edaphic Conditions

Geology : The plantation area is a plateau of Mba Volcanic Group rocks. Mudstones are exposed at the crest of the plantation but the characteristic augite-olivine basalt (lava) is apparent, with the typical weathering colours - red of the altered olivine, brown augite, yellowish or ochre groundmass on weathered rock surfaces, and a thick red soil overall.

Slope : Slight to moderate, up to 15°, with a westerly aspect.

Soil : Ferruginous latosol, from basic parent materials, Lewa red and brown clays. The redder colour phase is appropriate to the plantation area, described by Twyford and Wright typically as follows:

"- - - - - five inches of reddish brown very friable clay with a strongly developed fine and very fine nutty and fine granular structure, on ten inches of red friable clay, of strongly developed medium and fine blocky structure breaking easily to very fine fragments, very hard to dig, on red friable clay with a moderately coarse blocky structure, breaking easily to fine angular fragments and very hard to dig".

Drainage : Adequate natural drainage within plantation area.

(iv) Natural Vegetation

Prior to planting the site was dominated by mission grass (Pinninsetum polystachyon) and fern, with scattered guava (Psidium guajava).

Within the plantation, light mission grass remains apparent with the climber mile-a-minute (Mikania micrantha).

(v) Plantation History

Seed origin : As for Seaqaqa

Nursery practice : " " "

Method of planting : Spacing 3.0 m x 2.4 m (10 feet x 8 feet). Other comments as for Seaqaqa.

Date of planting : Feb/March 1961.

Tending :

1961 - Application of 85 g (2 ounces) NPK fertiliser per tree.

1962 - Weeding, with disc harrowing on the flats.

1965 - Hurricane damaged trees removed.

1968 - Thinned to 990 trees/ha (400/acre)
Pruning to 3.9 m (12 feet) 370 stems/ha (150/acre)

- Cattle introduced for grazing trials within plantation.

1972 - Plantation significantly damaged by Hurricane Bebe, October, 1972.

(vi) Mensurational Data

The specific plots sampled had the following basic statistics immediately prior to core sampling:-

Plot 1 - Mean height 18.5 m (60.8 feet); average bh diameter 23.1 cm (9.1ins)

Plot 1 - Mean height 19.1 m (62.8 feet); average diameter 23.8 cm (9.4 inches)

Other mensurational plots established within the plantation on the dates shown indicated the following general crop statistics:

	Plot A		Plot B	
	13.7.70	26.6.73	13.7.70	26.6.73
Age	9.5 yrs	12.5 yrs	9.5 yrs	12.5 yrs
Stems - per acre	325	270	245	210
per ha	805	667	605	519
Basal area - sq ft/acre	152	169	99	140
- m^2/ha	34.9	38.9	22.7	32.0
Volume - cu.ft/acre	3112	4372	1851	3152
- m^3/ha	217.7	305.9	129.5	220.5
Mean height - feet	57.1	76.2	52.0	66.6
- m	17.4	23.2	15.9	20.3
Mean bh diameter - inches	9.2	10.7	8.6	11.0
- cm	23.4	27.2	21.8	27.9

(3) DRASA

(i) Locality

Latitude : 17° 35' S

Longitude : 177° 32' E

Elevation : 65 m (210 feet approximately) above mean sea level.

(ii) Climatic Conditions

The general rainfall and climatic environment of the area corresponds to classification 1 of Twyford and Wright ("The Soil Resources of the Fiji Islands"), i.e.

Lowland climate with stong dry season

See details recorded under (1) SEAQAQA.

Temperature

Closest available figures come from the Fiji Sugar Corporation Station in Lautoka, approximately 10 km directly from Drasa Forest Reserve. Period of records : 1961 -73.

a) Mean monthly maximum

Jan	-	30.3°C (86.6°F)	July	-	27.9°C (82.3°F)
Feb	-	30.4°C (86.7°F)	Aug	-	28.0°C (82.4°F)
March	-	30.2°C (86.3°F)	Sept	-	28.6°C (83.5°F)
April	-	29.8°C (85.6°F)	Oct	-	28.8°C (83.9°F)
May	-	29.1°C (84.3°F)	Nov	-	29.3°C (84.8°F)
June	-	28.8°C (83.8°F)	Dec	-	30.0°C (86.0°F)

b) Mean monthly minimum

Jan	-	23.8°C (74.8°F)	July	-	20.0°C (68.0°F)
Feb	-	23.9°C (75.0°F)	Aug	-	19.8°C (67.7°F)
March	-	23.6°C (74.4°F)	Sept	-	20.9°C (69.6°F)
April	-	22.8°C (73.1°F)	Oct	-	21.3°C (70.4°F)
May	-	21.3°C (70.4°F)	Nov	-	22.3°C (72.2°F)
June	-	20.7°C (69.3°F)	Dec	-	23.1°C (73.6°F)

c) Number of days per annum with maximum temperature below 0°C (32°F):

Nil.

Rainfall and Humidity

Rainfall records refer to the Fiji Sugar Corporation Station at Drasa, immediately adjacent to Drasa Forest Reserve. Period of records : 1955 - 75. Relative humidity records refer to the Fiji Sugar Corporation Station in Lautoka, 10 km from Drasa Forest Reserve. Period of records : 1961 - 73.

a) Mean monthly rainfall

Jan	-	306mmm (12.0 inches)	July	-	46 mm (1.8 inches)
Feb	-	400 mm (15.7 ")	Aug	-	56 mm (2.2 ")
March	-	468 mm (18.4 ")	Sept	-	79 mm (3.1 ")

April	- 190 mm (7.5 ")		Oct	- 94 mm (3.7 ")	
May	- 83 mm (3.3 ")		Nov	- 158 mm (6.2 ")	
June	- 71 mm (2.8 ")		Dec	- 181 mm (7.1 ")	

b) Annual rainfall

2132 mm (83.9 inches)

c) Longest period recorded with less than 51 mm (2 inches) of rainfall per month

6 month period May - Oct., 1966.

d) Mean monthly relative humidity

Jan	-	73%	July	-	73%
Feb	-	76%	Aug	-	68%
March	-	78%	Sept	-	69%
April	-	77%	Oct	-	68%
May	-	74%	Nov	-	68%
June	-	74%	Dec	-	71%

(iii) Topography and Edaphic Conditions

Geology : Consists of lava flows of the Ba Basaltic Group.

Slope : The area is generally undulating, with the sampled plantation having a north-easterly aspect, sloping up to 20° approximately.

Soil : The general area is characterised by ferruginous latosols from parent materials of basic and intermediate composition, i.e. a similar broad soil type to that at Seaqaqa. These are the "Talasiga" (sun baked") soils, induced by repeated destruction of the natural plant cover.

Drainage : Adequate natural drainage.

(iv) Natural Vegetation

The natural vegetation is similar to that of Seaqaqa, with mission grass, fern, scattered guava and nokonoko scrub.

Lighter mission grass and fern remain dominant within the plantation areas.

(v) Plantation History

Seed origin : As for Seaqaqa

Nursery practice : " " "

Method of planting : Spacing 3.0 m x 2.4 m (10 feet x 8 feet). Other comments as for Seaqaqa.

Date of planting: Feb 1961, (3.6 ha, 9 acs)

Tending :

1961 - Weeding
1962 - Weeding
1964 - 0.8 ha (2 acs) low pruned.
1965 - Removal of some overhead scrub.
- Remaining 2.8 ha (7 acs) low pruned.
1968 - Pruned to half height.
1969 - Thinned to 740 stems/ha (300/acre).
1972 - Removal of stems damaged in Oct 1972 hurricane.

(Core samples were collected in Aug. 1970 and disc samples in mid and late 1973).

(vi) Mensurational data

The specific plots from which the core samples were taken, prior to collection had mean diameters and height as follows:

Plot 1 - Mean height 15.6 m (51.2 feet); mean $\hat{}^{bh}$ diameter (ob) 19.8 cm (7.8 inches)

Plot 2 - Mean height 11.4 m (37.5 feet); mean $\hat{}^{bh}$ diameter (ob) 14.5 cm (5.7 inches)

Other routine mensurational plots within the plantation gave the following crop statistics on the dates indicated:

	PLOT 98A		PLOT 99A	
	6.7.70	28.6.73	17.5.71	28.6.73
Age	9.5 yrs	12.5 yrs	10.5 yrs	12.5 yrs
Stems-per acre	210	140	220	160
-per ha	519	346	544	395
Basal area - sq ft/acre	66.5	59.9	72.2	62.4
- m^2/ha	15.3	13.7	16.6	14.3
Volume - cu.ft/ac	1222	1166	1415	1300
- m^3/ha	85.5	81.6	99.0	91.0

Mean ht-ft	51.1	56.8	54.5	60.7
-m	15.6	17.3	16.6	18.5
Mean bh diam-ins	7.6	8.8	7.7	8.5
-cm	19.3	22.4	19.6	21.6

(4) Meteorological data

Rainfall and temperature readings from plantation sites at **Seaqaqa, Nausori** Highlands,and Drasa-Lololo.

A word of explanation follows:

(a) Meteorological Services :The data were taken from the central files of the Meteorological Services headquarters at Laucala Bay,Suva where such data are collected periodically from various field stations throughout Fiji.

(b) Seaqaqa Forestry Station : Only rainfall data were collected at the Seaqaqa Forestry Station. The monthly entries appearing in parentheses were abstracted from rainfall records of the Seaqaqa District Farm, an agricultural station about 4 miles from the Forestry Station. Temperature readings were copied from the Seaqaqa District Farm file.

(c) Nausori Highlands : Both rainfall and temperature data were supplied from Nausori Highlands Forestry Station records.

(d) Drasa-Lololo : Rainfall data were supplied from the Drasa-Ba meteorological station, a distance of approximately 20 miles from Lololo, and the temperature data from records of the Fiji Sugar Corporation's mill at Lautoka, a distance of some 1 2 miles from Lololo.

Seaqaqa Forestry Station

Annual rainfall (mm) records for the period 1961-1973

Year No.	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Year
1961	263.7	439.7	173.7	274.3	110.2	119.4	53.8	77.7	213.4	62.7	195.1	750.1	2733.8
1962	547.9	598.2	238.5	292.6	132.1	158.8	7.4	4.6	35.3	129.3	464.3	302.8	2912.4
1963	571.5	260.6	326.9	236.2	212.1	51.6	45.7	121.7	30.0	49.3	161.0	286.8	2353.3
1964	154.7	683.0	750.8	(149.6)	36.8	36.8	51.3	110.2	123.0	238.0	240.5	317.0	2891.7
1965	447.8	(1055.6)	577.9	130.6	(134.4)	(0)	187.7	10.2	83.3	71.4	102.6	102.1	2903.6
1966	694.4	296.7	297.4	281.4	18.8	0	29.7	14.0	45.7	72.1	84.6	169.9	2004.8
1967	359.7	435.1	690.9	402.1	34.0	(11.9)	(5.6)	10.7	89.4	80.0	59.2	(77.7)	2109.5
1968	(-)	410.7	629.7	279.1	78.0	(188.7)	(26.2)	73.2	(-)	(120.7)	(302.5)		2108.8
1969	543.8	1003.6	663.2	681.7	13.2	34.3	11.7	25.4	(33.8)	47.0	178.3	(289.1)	3525.1
1970	(401.6)	(363.2)	(473.2)	(188.7)	170.4	284.0	17.8	0	(47.0)	152.4	484.9	397.0	2980.2
1971	186.2	642.4	582.2	165.1	95.3	96.3	43.9	161.3	87.1	314.5	384.3	891.3	3649.9
1972	550.0	187.0	518.0	70.0	99.3	38.0	66.0	110.2	115.0	572.0	124.2	408.4	2858.1
1973	136.5	440.3	741.7	446.5	133.4	23.3	(185.4)	(79.4)	(128.6)	(77.6)	(232.0)	225.6	2850.3

* Data in parentheses taken from Seaqaqa District Fram

Seaqaqa District Fram

Mean temperature (°C) records for the period 1962-1973

Year No.	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
1962							22.1	22.5	23.7	24.7	24.5	25.0
1963	25.4	25.5	25.8	-	23.6	24.0	23.7	23.0	23.2	23.7	25.3	25.6
1964	25.3	26.2	26.1	25.3	24.2	23.1	21.9	23.7	23.5	23.7	25.0	24.9
1965	27.0	25.7	25.7	24.8	23.4	22.1	22.4	22.2	22.8	26.0	23.9	24.8
1966	26.0	25.2	26.3	25.6	23.9	23.4	21.9	22.0	24.1	23.9	24.1	25.2
1967	25.7	25.7	24.8	25.4	23.9	22.6	21.4	22.8	26.4	24.2	24.1	24.8
1968	-	25.2	-	23.2	22.7	24.3	23.1	22.3	-	-	24.1	25.8
1969	25.8	26.8	26.8	25.0	23.7	23.4	21.7	22.8	22.7	24.2	24.9	25.8
1970	25.4	26.5	25.9	25.8	24.6	24.3	23.9	23.0	22.8	-	25.0	26.0
1971	25.6	25.4	25.5	24.6	23.6	23.8	23.0	23.6	23.7	23.5	25.2	25.5
1972	25.4	25.8	25.7	25.4	24.1	23.8	22.2	23.1	24.3	23.8	24.8	26.2
1973	26.3	26.9	26.4	26.5	25.1	23.7	23.4	23.0	23.7	24.4	24.7	-

Nausori Highland Forestry Station

Annual rainfall (mm) records for the period 1961-1973

Year No.	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Year
1961	180.3	503.2	206.2	250.7	61.2	9.7	49.5	196.6	191.3	62.7	264.7	695.5	2671.6
1962	562.9	554.2	650.0	142.0	72.1	57.7	84.3	2.0	18.3	135.1	270.8	197.4	2754.4
1963	959.6	329.7	357.6	214.1	120.1	-	-	138.4	-	26.2	206.8	904.0	2494.5
1964	-	546.4	1041.4	151.9	35.6	116.8	27.4	18.5	-	154.4	245.4	-	2439.4
1965	415.3	1267.5	478.3	172.7	153.2	30.5	14.2		158.8	33.3	25.9	212.9	2962.4
1966	485.9	185.4	439.4	228.9	49.8	167.4	6.1	36.1	26.7	24.1	177.8	241.6	1916.7
1967	430.8	569.5	570.7	292.1	47.0	0	13.7	2.5	82.6	177.8	80.5	103.9	2320.3
1968	188.5	382.3	591.8	140.2	42.7		38.6	37.1	29.0	62.7	90.7	214.4	1874.3
1969	113.8	-	188.5	30.5	17.8	2.5	26.7	3.8	-	-	-	-	367.5
1970	-	-	309.4	127.3	145.5	130.6	94.2	-	97.5	106.9	-	-	1011.4
1971	268.5	-	-	-	-	-	-	46.2	65.5	271.5	297.7	180.6	1130.0
1972	-	302.0	374.1	152.0	83.0	1524.0	215.9	165.4	37.3	521.5	63.8	324.2	3763.2
1973	134.1	406.7	622.5	205.8	11.9	-	4980.9	17.7	-	-	-	-	6379.6

Mean temperature (°C) records for the period 1966-1973

Year No.	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
1966	24.3	-	24.4	23.6	21.7	19.9	20.5	19.7	21.5	21.7	22.3	23.3
1967	23.7	24.4	24.3	23.1	21.7	21.0	20.2	21.8	22.4	21.9	23.3	24.3
1968	24.3	23.8	24.3	22.9	22.1	22.6	21.9	20.3	21.4	22.0	23.2	24.9
1969	-	-	-	-	-	-	-	-	-	-	-	-
1970	-	-	-	-	-	-	-	-	-	-	-	-
1971	24.5	-	-	-	-	-	-	20.9	-	22.6	22.9	23.2
1972	-	23.2	22.4	23.3	22.2	20.6	19.6	20.1	21.5	21.7	23.0	24.1
1973	23.9	24.8	24.2	23.8	23.1	-	21.2	21.3	-	-	-	-

Drasa-Ba Met Station

Annual rainfall (mm) records for the period 1961-1973

Year No.	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Year
1961	134.1	783.1	136.4	277.6	33.8	39.4	47.8	180.6	95.3	42.2	408.7	459.2	2638.0
1962	388.1	257.3	356.1	158.2	78.0	27.7	65.3	5.3	37.3	30.0	220.2	134.9	1758.4
1963	474.5	164.6	333.0	335.3	191.0	107.2	121.9	87.9	258.8	48.3	163.8	120.7	2406.9
1964	69.9	662.2	941.1	112.5	27.2	97.3	26.4	46.0	62.0	67.8	97.0	122.4	2331.7
1965	421.6	580.6	491.0	106.4	191.3	6.9	11.2	33.8	196.6	28.2	8.6	27.4	2103.6
1966	125.0	251.7	293.1	276.1	48.5	20.6	4.3	31.8	7.6	6.1	73.4	169.9	1309.6
1967	440.4	379.5	418.3		27.2	0	11.4	-	41.1	145.3	80.3	51.8	1585.0
1968	241.6	192.0	456.9	136.1	25.1	118.1	60.2	35.6	43.4	86.9	41.1	-	1437.1
1969	82.3	141.0	98.8	63.2	17.8	4.1	27.7	3.0	53.8	73.2	190.2	157.7	912.9
1970	260.4	479.8	215.6	122.7	178.3	191.3	115.8	0	46.5	43,7	166.9	279.9	2098.3
1971	259.6	409.7	340.4	105.9	114.8	66.8	18.8	36.1	71.4	174.0	143.8	341.4	2484.7
1972	480.9	268.5	247.4	101.8	112.4	31.7	21.3	18.7	17.9	72.6	93.2	192.9	1659.3
1973	102.8	326.1	627.0	102.2	10.6	226.4	147.0	60.0	59.4	18.6	126.4	156.3	1962.8

Lautoka Mill nearest to Lololo Area (Fiji Sugar Corporation data)

Annual mean temperature (°C) records for the period 1961-1973

Year No.	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Mean
1961	27.6	26.7	26.8	26.3	25.9	25.2	24.1	23.3	25.4	24.4	25.6	26.3	25.7
1962	26.7	27.1	26.6	26.6	25.2	24.0	23.3	23.3	24.3	25.7	25.7	26.1	25.4
1963	26.3	26.7	26.4	26.5	24.6	24.9	24.2	23.9	24.3	24.4	26.1	26.7	25.4
1964	27.1	27.2	26.9	26.6	25.6	25.2	23.6	24.9	25.1	25.8	26.6	26.3	25.9
1965	26.7	26.9	26.6	25.9	24.7	23.7	23.7	23.1	23.6	24.0	25.3	26.6	25.1
1966	27.8	26.7	27.1	26.2	24.9	24.3	23.7	23.2	24.6	25.0	26.1	26.2	25.5
1967	26.7	27.0	26.6	26.6	24.8	23.7	23.8	24.2	25.8	24.8	25.3	26.8	25.5
1968	27.2	27.6	27.8	25.8	24.6	25.6	24.3	23.7	24.4	24.9	25.5	26.8	25.6
1969	27.7	27.8	27.6	26.8	25.1	25.1	23.2	23.8	24.3	25.4	25.6	26.8	25.7
1970	27.2	27.4	27.2	26.6	25.3	25.2	24.7	23.9	24.5	25.3	26.1	26.5	25.8
1971	26.9	26.9	27.1	26.4	25.2	25.4	24.3	24.8	25.4	25.7	-	-	
1972	26.6	26.8	26.7	26.3	25.3	24.1	23.7	24.1	25.2	25.5	26.0	27.2	25.6
1973	27.5	28.2	27.7	26.9	26.2	25.1	26.4	24.4	25.0	25.2	26.1	26.5	26.1

APPENDIX 1

B. - FIELD SAMPLING AND COLLECTION OF MATERIAL /1

1. DEMARCATION OF SAMPLE PLOTS

Plots for sampling were selected to cover the range of site types which would normally be planted in any large scale afforestation operation, within the limits of available plantations. The plots were sited in the oldest plantations available that were reasonably fully and evenly stocked and that were representative of the crops that could be expected on that site type:-

Drasa Forest Reserve	-	Plot 1 P61 Comp. 3B19	(bottom plot)
	-	Plot 2 P61 Comp. 3B19	(top plot)
Seaqaqa Forest Reserve	-	Plot 1 P60	(front plot)
	-	Plot 2 P60	(rear plot)
Nausori Highlands	-	Plot 1 P61	(inner plot)
	-	Plot 2 P61	(outer plot)

The plots defined were square or rectangular in shape, approximately 0.2 h (0.5 acre) in size and contained approximately 100 trees. The plots were permanently demarcated with posts and indication trenches, with the plot boundaries running mid-way between rows of trees. Plot dimensions to the nearest 0.15 m (0.5 ft) and compass direction to the nearest degree were recorded for each plot.

Each tree within the plot was numbered with an aluminium tag and nail, the nail corresponding exactly to the 1.83 m (6 ft) mark on the upper side of the stem. The aluminium tag was supplemented with a painted number.

Girth at breast height of all trees was measured to the nearest 0.25cm (0.1 inch), breast height being located by measuring 46 cm (18 inches) from the 1.83 m (6 ft) mark with a standard measure.

/1 At the time sampling was undertaken imperial measure was used. Units have been converted to metric equivalents and this has involved some loss of accuracy. The original imperial units quoted are the precise ones.

2. SELECTION OF SAMPLE TREES

(i) Height. The height of each sample tree was recorded to the nearest 0.3 m (1 foot), using a hypsometer.

(ii) Stem alignment. The angle of any lean was measured by suspending a plumb bob at points on the bole 4.9 m (16 ft) from the ground, to ascertain the place where the bob, when at ground level was at a maximum distance from the stem above the basal swelling, i.e. 30 cm (1 foot) from the ground on the upper side. This distance was recorded in cm (inches) and the compass direction of maximum lean noted.

(iii) Stem form. A rigid rod 4.6 m (15 ft) in length was placed with its bottom 30 cm (1 foot) from the ground, to fit as closely as possible against the side of the stem showing greatest distortion. The maximum deflection from the rod of any bend or bends in the stem was recorded, together with its distance from the bottom of the rod. Where there were two or more clear points of deflection, i.e. bends separated by portions of the stem in contact with the rod, then each was recorded separately. Where a bend was made up of two or more bows or curves, only the maximum deflection was recorded. Similar measurements were made on the side of the stem at right angles in a clockwise direction from the side of greatest deflection.

(iv) Crown characteristics. Crown diameter was assessed by eye, by marking on the ground the extent of the projection of the crown. Widths at maximum and minimum diameter to the nearest 0.15 m (0.5 ft) were recorded. Crown length was recorded by measuring lengths to the lowest live branch and to the lowest whorl (to the nearest 0.30 m (1 foot)) using measuring rods, and deducting from total tree height taken by hypsometer.

(v) Adjacent trees. For each sample tree, the numbers of the five nearest trees were recorded, together with their distance and compass bearing to the nearest 10°.

3. CORE SAMPLING OF SELECTED TREES

From each sample tree, one 12 mm boring was taken at the middle of the internode nearest to breast height. Actual height was recorded. Where nodes were not clearly identified, borings were taken at breast height.

Samples were taken:-

(i) in leaning trees, from the upper side, in the direction of lean, right through the stem, with the compass bearing of the line of boring being noted to the nearest 5°.

(ii) in upright stems, in the direction of the prevailing wind, noting compass bearing.

Samples were clearly identified to indicate site, plot number and tree number, direction of boring, and were treated against sapstain before being consigned by air to the CFI, Oxford.

4. HURRICANE BEBE - OCTOBER, 1972

Subsequent to the consignment of the increment cores, the sample plots were damaged by Hurricane Bebe. The Nausori Highlands and Drasa plots were badly affected. Minor damage only was sustained at Seaqaqa.

5. SECOND STAGE SAMPLING

Following assessment of increment cores, CFI identified the following sample trees for further examination (January, 1973):-

Density class	Site	Plot No.	Tree No.	
Over 0.65 g/cm^3	Drasa	2	11	
	"	1	57	
	Seaqaqa	2	79	
	"	1	45	
0.6-0.65 g/cm^3	Nausori H.lands	1	44	
	Drasa	1	71	
	Seaqaqa	1	8	
	"	1	36	
0.55-0.60 g/cm^3	Seaqaqa	2	51	
	"	2	37	
	"	2	84	
	"	1	31	
0.5-0.55 g/cm^3	Drasa	1	6	
	Nausori H.lands	1	51	(NH-1/45)
	Seaqaqa	2	6	(NH-1/20)
	Seaqaqa	1	64	
0.45-0.5 g/cm^3	Nausori H.lands	1	40	
	"	1	24	(NH-1/82, NH-1/98)
	Seaqaqa	2	1	
	Seaqaqa	1	55	

(Numbers bracketed refer to original selections which had to be changed because of hurricane damage).

The specific objects of the sampling at this stage were redefined:-

(i) To estimate the extent of between tree differences in pulping properties, in the hope of being able to establish relationships between pulping characteristics of individual trees and some structural features

or properties which could be easily measured (e.g. density and pattern of density determined at breast height, cellulose-lignin content from breast height samples, and possibly fibre dimensions).

(ii) To estimate the extent of genotype-site interaction, in the hope of distinguishing the effects of environment superimposed on the basic genetical pattern of wood development.

To meet object (i), all sample trees as detailed above were felled, and 30 cm (1 foot) billets taken from 5%, 15%, 25%, 35%, 45%, 55%, 65% and 75% of total height.

Appraisal of pulping properties was undertaken by Tropical Products Institute.

6. CLONAL/SITE TRIALS

To meet object (ii), at time of felling, vegetative material was collected from the following trees, for grafting on to root stock and ultimately for planting out in a variety of contrasting sites. The final aim was to replicate the 10 trees 5 times at 5 sites:-

Density class	Site	Plot No.	Tree No.
Over 0.65 g/cm^3	Seaqaqa	2	1
	Nausori H.lands	1	40
0.6-0.65 g/cm^3	Seaqaqa	1	64
	Drasa	1	6
0.55-0.6 g/cm^3	Seaqaqa	2	84
	Seaqaqa	1	31
0.5-0.55 g/cm^3	Nausori Highlands	1	44
	Seaqaqa	1	8
0.45-0.5 g/cm^3	Seaqaqa	2	79
	Drasa	2	11

In the absence of adequate root stock, some of the initial vegetative material, as an interim measure, was grafted on to natural regeneration in Drasa Compt. 2B4, 2B5. At Seaqaqa, additional Seaqaqa material was grafted to roadside natural regeneration adjacentto the P.60 plantations.

Shortfalls in grafting material, and some failures, restricted the grafts available for planting and prevented all trees in all plots from being established at the same time.

The five selected sites were located at Drasa, Nabou, Nausori Highlands, Colo-i-Suva and Seaqaqa.

At each site the 10 trees were replicated as below:-

	A	B	C	D	E	F	G	H	I	J
1	S2-79	NH1-40	S2-84	S1-8	S2-1	D2-11	S1-64	S1-31	NH1-44	D1-6
2	S2-1	S1-31	S2-79	NH1-40	NH1-44	D1-6	S2-84	D2-11	S1-64	S1-8
3	S1-64	D2-11	S2-1	D1-6	S2-79	S1-31	NH1-44	S1-8	S2-84	NH1-40
4	NH1-44	D1-6	S1-64	S1-31	S2-84	S1-8	S2-79	NH1-40	S2-1	D2-11
5	S2-84	S1-8	NH1-44	D2-11	S1-64	NH1-40	S2-1	D1-6	S2-79	S1-31

Planting spacing was 3.0 m x 2.4 m (10 ft x 8 ft) and the plots were surrounded by two buffer strips of routine ungrafted planting stock.

At time of planting, if a graft from a particular tree was not available, routine planting stock was put in to provide root stock for field grafting at a later date. If further potted grafts became available, the routine stock was uprooted and discarded.

As at 15.5.78, the position was as follows:-

Drasa

Grafts and buffer surround planted 16.1.75. All grafts surviving.

Nabou

Grafts and buffer surround planted 5.2.75. Twelve blanks, filled on the following dates:

A3	S1-64	27.11.75	E5	S1-64	2.3. 76
B2	S1-31	27.11.75	F3	S1-31	27.11.75
B3	D2-11	27.11.75	H1	S1-31	27.11.75
C4	S1-64	2. 3.76	I2	S1-64	2. 3.76
D4	S1-31	27.11.75	J4	D2-11	27.11.75
D5	D2-11	27.11.75	J5	S1-31	27.11.75

Nausori Highalands

Grafts and buffer surround planted 3.2.75. Fifteen blanks, filled on the following dates:

A3	S1-64	27.11.75	G1	S1-64	27.11.75
B2	S1-31	27.11.75	G3	NH1-44	2. 3.76
B3	D2-11	27.11.75	H1	S1-31	27.11.75
C4	S1-64	27.11.75	H2	D2-11	27.11.75
D4	S1-31	27.11.75	I2	S1-64	27.11.75
D5	D2-11	27.11.75	I5	S2-79	27.11.75
F1	D2-11	27.11.75	J4	D2-11	27.11.75
F3	S1-31	27.11.75	J5	S1-31	27.11.75

Colo-i-Suva

Buffer surround planted 2.1.75. Grafts planted 14.1.75. Thirteen blanks, filled on the following dates:-

B2	S1-31	11.3. 76	F4	S1-8	11. 3.76
B3	D2-11	11.3 76	H 1	S1-31	11. 3.76
B4	D1-6	dead - no replacement	H2	D2-11	24.12.75
D4	S1-31	11. 3.76	I1	NH1-44	11. 3.76
D5	D2-11	24.12.75	J4	D2-11	24.12.75
F1	D2-11	24.12.75	J5	S1-31	11. 3.76
F3	S1-31	dead - no replacement			

Seaqaqa

Buffer surround planted 27.1.75. Grafts planted 18.3.75. Twelve blanks, filled on the following dates:-

A3	S1-64	dead - no replacement	F3	S1-31	28.10.76
B2	S1-31	27.11.75	G1	S1-64	27.11.75
B3	D2-11	dead - no replacement	H1	S1-31	27.11.75
C4	S1-64	27.11.75	I2	S1-64	27.11.75
D4	S1-31	27.11.75	J4	D2-11	5.10.76
E5	S1-64	27.11.75	J5	S1-31	27.11.75

Note 1

The initial blanks in the plots arose either from a shortage of required grafts at the time, or failure of the planted grafts, necessitating replacement.

Some surplus grafted material for some of the trees remained and rather than discard it, it was planted as an extension to the Drasa and Seaqaqa plots.

At Seaqaqa, five surplus grafts - S2-1; S1-31; S2-84; D1-6 and S1-8 - were planted on 5.10.76.

At Drasa, thirty surplus grafts were planted on 25.5.76:

NH1-40 - 2 plants	S1-31 - 2 plants
NH1-44 - 1 "	S1-64 - 1 "
D1-6 - 3 "	S2-1 - 5 "
D2-11 - 3 "	S2-79 - 4 "
S1-8 - 5 "	S2-84 - 4 "

In the Drasa extension plantings (only), the original 3.0 m x 2.4 m (10 ft x 8 ft) spacing was not followed. In this case each grafted tree was separated by a single buffer tree, between and within lines. Planting spacing of the grafts was therefore 6.0 m x 2.4 m (20 ft x 16 ft).

APPENDIX II

MEAN DENSITY AT BREAST HEIGHT (ØRIGINAL DATA-120 TREES)

TABLE ØF SITE * PLØT * TREE MEANS

SITE	PLØT	TREE	MEANS
1	1	1	0.5598
1	1	2	0.8096
1	1	3	0.5972
1	1	4	0.5092
1	1	5	0.6605
1	1	6	0.5237
1	1	7	0.4898
1	1	8	0.6482
1	1	9	0.4884
1	1	10	0.7765
1	1	11	0.5385
1	1	12	0.6498
1	1	13	0.5194
1	1	14	0.6641
1	1	15	0.5662
1	1	16	0.5865
1	1	17	0.5658
1	1	18	0.5038
1	1	19	0.5794
1	1	20	0.5765
1	2	1	0.6309
1	2	2	0.5853
1	2	3	0.5575
1	2	4	0.4342
1	2	5	0.6466
1	2	6	0.5615
1	2	7	0.6133
1	2	8	0.5472
1	2	9	0.5358
1	2	10	0.6011
1	2	11	0.5160
1	2	12	0.4907
1	2	13	0.4569
1	2	14	0.7642
1	2	15	0.6206
1	2	16	0.5806
1	2	17	0.5755
1	2	18	0.4674
1	2	19	0.5798
1	2	20	0.5042
2	1	1	0.7382
2	1	2	0.6171
2	1	3	0.5773
2	1	4	0.8513
2	1	5	0.6670
2	1	6	0.6256
2	1	7	0.7920
2	1	8	0.7674
2	1	9	0.6663
2	1	10	0.7397
2	1	11	0.7147
2	1	12	0.6767

1	1	13	0.6364
1	1	14	0.5997
1	1	15	0.7648
1	1	16	0.6071
1	1	17	0.5153
1	1	18	0.6443
1	1	19	0.7670
1	1	20	0.7112
2	1	1	0.7032
2	1	2	0.6550
2	1	3	0.6286
2	1	4	0.7872
2	1	5	0.6211
2	1	6	0.6907
2	1	7	0.6798
2	1	8	0.6272
2	1	9	0.5843
2	1	10	0.7589
2	1	11	0.8179
2	1	12	0.6945
2	1	13	0.6372
2	1	14	0.7557
2	1	15	0.7480
2	1	16	0.6208
2	1	17	0.6760
2	1	18	0.6863
2	1	19	0.5565
2	1	20	0.7140
3	1	1	0.6544
3	1	2	0.7426
3	1	3	0.5691
3	1	4	0.6881
3	1	5	0.5963
3	1	6	0.5814
3	1	7	0.6835
3	1	8	0.7360
3	1	9	0.5014
3	1	10	0.6640
3	1	11	0.8435
3	1	12	0.4814
3	1	13	0.6137
3	1	14	0.6463
3	1	15	0.7375
3	1	16	0.4938
3	1	17	0.6322
3	1	18	0.6282
3	1	19	0.5470
3	1	20	0.5130
3	2	1	0.5503
3	2	2	0.7906
3	2	3	0.5019
3	2	4	0.6629
3	2	5	0.7497
3	2	6	0.6411
3	2	7	0.5295
3	2	8	0.6197
3	2	9	0.6108
3	2	10	0.7181
3	2	11	0.5537
3	2	12	0.6066
3	2	13	0.5942
3	2	14	0.5687
3	2	15	0.5808
3	2	16	0.5623
3	2	17	0.6672
3	2	18	0.6974
3	2	19	0.6657
3	2	20	0.6704

OVERALL MEAN = 0.6292
STANDARD ERROR OF A MEAN = 0.0271
COEFFICIENT OF VARIATION = 4.31 PERCENT
STANDARD ERROR OF A DIFFERENCE = 0.0384

MEAN DENSITY AT BREAST HEIGHT OF SITES AND PLOT (ORIGINAL DATA=120 TREES)

TABLE OF SITE MEANS

SITE	MEAN
1	0.5771
2	0.6830
3	0.6274

OVERALL MEAN = 0.6292
STANDARD ERROR OF A MEAN = 0.0128
COEFFICIENT OF VARIATION = 2.04 PERCENT
STANDARD ERROR OF A DIFFERENCE = 0.0182

TABLE OF SITE * PLOT MEANS

PLOT / SITE	1	2
1	0.5906	0.5635
2	0.6840	0.6821
3	0.6277	0.6271

OVERALL MEAN = 0.6292
STANDARD ERROR OF A MEAN = 0.0183
COEFFICIENT OF VARIATION = 2.91 PERCENT
STANDARD ERROR OF A DIFFERENCE = 0.0259

Appendix III

Table 3.1 Effect of varying the values of the number of positions (distance of interval)and the number of rows per position and number of cells per row on the variance of the mean (Vmean),standa -rd error (SE) and coefficient of variability (precision index PI) : radial cell wall thickness.

Positions	Rows	cells	Vmean	SE (U)	PI	Efficiency %
56	1	1	0.099821	0.31595	5.92	33.2
56	5	2	0.066300	0.25749	4.82	50.0
62.2	1	1	0.090161	0.30027	5.62	36.8
62.2	5	2	0.059887	0.24472	4.58	55.4
70	1	1	0.079857	0.28259	5.29	41.5
70	5	2	0.053043	0.23031	4.31	62.5
80	1	1	0.069875	0.26434	4.95	47.4
80	5	2	0.046413	0.21544	4.03	71.4
93.3	1	1	0.059914	0.24477	4.58	55.3
93.3	5	2	0.039796	0.19949	3.74	83.3
112	1	1	0.049911	0.22341	4.18	66.4
112	1	2	0.044688	0.21139	3.96	74.2
112	1	3	0.042946	0.20724	3.88	77.2
112	1	4	0.042076	0.20512	3.84	78.8
112	1	5	0.041554	0.20385	3.82	79.8
112	2	1	0.040089	0.20022	3.75	82.7
112	2	2	0.037478	0.19359	3.63	88.5
112	2	3	0.036607	0.19133	3.58	90.6
112	2	4	0.036172	0.19019	3.56	91.7
112	2	5	0.035911	0.18950	3.55	92.3
112	3	1	0.036815	0.19187	3.59	90.0
112	3	2	0.035074	0.18728	3.51	94.5
112	3	3	0.034494	0.18573	3.48	96.1
112	3	4	0.034204	0.18494	3.46	96.9
112	3	5	0.034030	0.18447	3.45	97.4
112	4	1	0.035179	0.18756	3.51	94.2
112	4	2	0.033873	0.18405	3.45	97.9
112	4	3	0.033438	0.18286	3.42	99.1
112	4	4	0.033220	0.18226	3.41	99.8
112	4	5	0.033089	0.18190	3.41	100.2
112	5	1	0.034196	0.18492	3.46	96.9
112	5	2	0.033152	0.18208	3.41	100.0
112	5	3	0.032804	0.18112	3.39	101.1
112	5	4	0.032629	0.18064	3.38	101.6
112	5	5	0.032525	0.18035	3.38	101.9
140	1	1	0.039929	0.19982	3.74	83.0
140	5	2	0.026521	0.16285	3.05	125.0
187	1	1	0.029893	0.17289	3.24	110.9
187	5	2	0.019856	0.14091	2.64	166.9
280	1	1	0.019964	0.14130	2.65	166.1
280	5	2	0.013261	0.11515	2.16	250.0
560	1	1	0.009982	0.09991	1.87	332.1
560	5	2	0.006630	0.08143	1.52	500.0

Table 3.2 Effect of varying the values of the number of positions (distance of interval) and the number of rows per position and number of cells per row on the variance of the mean (Vmean),standard error (SE) and coefficient of variability (precision index PI) :radial lumen width.

Positions	Rows	Cells	Vmean	SE	PI	Efficiency %
56	1	1	2.0536	1.4330	4.21	36.62
56	5	2	1.5041	1.2264	3.60	50.00
62.2	1	1	1.8489	1.3597	3.99	40.68
62.2	5	2	1.3542	1.1637	3.42	55.54
70	1	1	1.6429	1.2817	3.77	45.78
70	5	2	1.2033	1.0969	3.22	62.50
80	1	1	1.4375	1.1990	3.52	52.32
80	5	2	1.0529	1.0261	3.02	71.43
93.3	1	1	1.2326	1.1102	3.26	61.02
93.3	5	2	0.9028	0.9502	2.79	83.31
112	1	1	1.0268	1.0133	2.98	73.20
112	1	2	0.9567	0.9781	2.87	78.60
112	1	3	0.9333	0.9661	2.84	80.60
112	1	4	0.9216	0.9600	2.82	81.60
112	1	5	0.9146	0.9564	2.81	82.20
112	2	1	0.8638	0.9294	2.73	87.10
112	2	2	0.8288	0.9104	2.68	90.10
112	2	3	0.8171	0.9039	2.66	92.00
112	2	4	0.8113	0.9007	2.65	92.70
112	2	5	0.8078	0.8988	2.64	93.10
112	3	1	0.8095	0.8997	2.64	92.90
112	3	2	0.7862	0.8867	2.61	95.70
112	3	3	0.7784	0.8823	2.59	96.60
112	3	4	0.7745	0.8800	2.59	97.10
112	3	5	0.7721	0.8787	2.58	97.40
112	4	1	0.7824	0.8845	2.60	96.10
112	4	2	0.7648	0.8746	2.57	98.30
112	4	3	0.7590	0.8712	2.56	99.10
112	4	4	0.7561	0.8695	2.56	99.50
112	4	5	0.7543	0.8685	2.55	99.70
112	5	1	0.7661	0.8753	2.57	98.20
112	5	2	0.7521	0.8672	2.55	100.00
112	5	3	0.7474	0.8645	2.54	100.60
112	5	4	0.7450	0.8632	2.54	100.90
112	5	5	0.7436	0.8624	2.53	101.10
140	1	1	0.8214	0.9063	2.66	91.56
140	5	2	0.6016	0.7757	2.28	125.02
187	1	1	0.6150	0.7842	2.30	122.29
187	5	2	0.4504	0.6711	1.97	166.98
280	1	1	0.4107	0.6409	1.88	183.13
280	5	2	0.2860	0.5348	1.57	262.97
560	1	1	0.2054	0.4532	1.33	366.16
560	5	2	0.1504	0.3878	1.14	500.07

Table 3.3 Effect of varying the values of the number of positions (distance of interval) and the number of rows per position and number of cells per row on the variance of the mean (Vmean), standard error (SE) and coefficient of variability (precision index PI) :tangential cell wall thickness.

Positions	Rows	Cells	Vmean	SE	PI	Efficiency %
56	1	1	0.2788	0.5280	9.14	38.8
56	5	2	0.2162	0.4650	8.05	50.0
62.2	1	1	0.2510	0.5010	8.67	43.1
62.2	5	2	0.1855	0.4306	7.45	58.3
70	1	1	0.2230	0.4722	8.17	48.5
70	5	2	0.1730	0.4159	7.20	62.5
80	1	1	0.1951	0.4417	7.64	55.4
80	5	2	0.1442	0.3797	6.57	75.0
93.3	1	1	0.1673	0.4090	7.08	64.6
93.3	5	2	0.1297	0.3602	6.23	83.3
112	1	1	0.1394	0.3733	6.46	77.6
112	1	2	o,1333	0.3652	6.32	81.1
112	1	3	0.1313	0.3624	6.27	82.3
112	1	4	0.1303	0.3610	6.25	82.9
112	1	5	0.1297	0.3602	6.23	83.3
112	2	1	0.1206	0.3473	6.01	89.6
112	2	2	0.1176	0.3429	5.93	91.9
112	2	3	0.1166	0.3414	5.91	92.7
112	2	4	0.1161	0.3407	5.90	93.1
112	2	5	0.1158	0.3402	5.89	93.4
112	3	1	0.1143	0.3381	5.85	94.6
112	3	2	0.1123	0.3351	5.80	96.3
112	3	3	0.1116	0.3341	5.78	96.8
112	3	4	0.1113	0.3336	5.77	97.1
112	3	5	0.1111	0.3333	5.77	97.3
112	4	1	0.1112	0.3334	5.77	97.2
112	4	2	0.1097	0.3312	5.73	98.6
112	4	3	0.1092	0.3304	5.72	99.0
112	4	4	0.1089	0.3300	5.71	99.2
112	4	5	0.1088	0.3298	5.71	99.4
112	5	1	0.1093	0.3306	5.72	98.9
112	5	2	0.1081	0.3288	5.69	100.0
112	5	3	0.1077	0.3282	5.68	100.4
112	5	4	0.1075	0.3279	5.67	100.6
112	5	5	0.1074	0.3277	5.67	100.7
140	1	1	0.1115	0.3339	5.78	97.0
140	5	2	0.0865	0.2941	5.09	125.0
187	1	1	0.0835	0.2889	4.98	129.5
187	5	2	0.0647	0.2544	4.40	167.1
280	1	1	0.0558	0.2361	4.09	193.7
280	5	2	0.0432	0.2079	3.60	250.2
560	1	1	0.0279	0.1670	2.89	387.5
560	5	2	0.0216	0.1470	2.54	500.5

Table 3.4 Effect of varying the values of the number of positions (distance of interval) and the number of rows per position and number of cells per row on the variance of the mean (Vmean), standard error (SE) and coefficient of variability (precision index PI) :tangential lumen width.

Positions	Rows	Cells	Vmean	SE	PI	Efficiency %
56	1	1	1.17	1.0817	3.41	21.5
56	5	2	0.5034	0.7095	2.23	50.0
62.2	1	1	1.0534	1.0263	3.23	23.9
62.2	5	2	0.4532	0.6732	2.12	55.5
70	1	1	0.9360	0.9675	3.05	26.9
70	5	2	0.4027	0.6346	2.00	62.5
80	1	1	0.8190	0.9050	2.85	30.7
80	5	2	0.3524	0.5936	1.87	71.4
93.3	1	1	0.7022	0.8380	2.73	35.8
93.3	5	2	0.3022	0.5497	1.73	83.3
112	1	1	0.5850	0.7649	2.41	43.0
112	1	2	0.5514	0.7426	2.34	45.6
112	1	3	0.5402	0.7350	2.32	46.6
112	1	4	0.5346	0.7312	2.30	47.1
112	1	5	0.5313	0.7289	2.30	47.4
112	2	1	0.3809	0.6172	1.94	66.1
112	2	2	0.3641	0.6034	1.90	69.1
112	2	3	0.3585	0.5988	1.89	70.2
112	2	4	0.3557	0.5964	1.88	70.8
112	2	5	0.3540	0.5950	1.87	71.1
112	3	1	0.3129	0.5593	1.76	80.4
112	3	2	0.3017	0.5492	1.73	83.4
112	3	3	0.2979	0.5458	1.72	84.5
112	3	4	0.2961	0.5441	1.71	85.0
112	3	5	0.2950	0.5431	1.71	85.3
112	4	1	0.2788	0.5281	1.66	90.3
112	4	2	0.2704	0.5200	1.64	93.1
112	4	3	0.2676	0.5173	1.63	94.1
112	4	4	0.2662	0.5160	1.63	94.5
112	4	5	0.2654	0.5152	1.62	94.8
112	5	1	0.2584	0.5084	1.60	97.4
112	5	2	0.2517	0.5017	1.58	100.0
112	5	3	0.2495	0.4995	1.57	100.9
112	5	4	0.2484	0.4984	1.57	101.3
112	5	5	0.2477	0.4977	1.57	101.6
140	1	1	0.4680	0.6841	2.15	53.8
140	5	2	0.2014	0.4487	1.41	125.0
187	1	1	0.3504	0.5919	1.86	71.8
187	5	2	0.1508	0.3883	1.22	167.0
280	1	1	0.2340	0.4837	1.52	107.6
280	5	2	0.1007	0.3173	1.00	250.0
560	1	1	0.1170	0.3421	1.08	215.1
560	5	2	0.0503	0.2244	0.71	500.4

Number of positions convert to length of interial in 112 mm randon selected radii as below:

Position	Length of interval (mm)
56	2
62.2	1.8
70	1.6
80	1.4
93.3	1.2
112	1.0
140	0.8
187	0.6
280	0.4
560	0.2

APPENDIX IV

Mean values of morphological characteristics measured in 1970.

Breast height density (g/cc)	Diameter at breast height (mm)	Crown width (m)	Crown length (m)
0.5786	241.1066	5.18	9.14
0.7386	193.7992	4.57	8.84
0.6757	174.0813	3.35	10.36
0.7092	198.4204	4.72	9.45
0.4971	253.1721	5.49	11.89
0.4846	287.8593	6.40	14.63
0.6174	233.6200	3.66	12.19
0.5612	236.6558	3.66	8.84
0.6239	223.5430	5.79	14.02
0.6374	238.1964	2.13	5.18
0.6241	235.2758	4.11	11.28
0.8229	212.4306	4.88	12.19
0.4875	207.7336	2.44	13.41
0.4934	293.2096	6.10	10.67
0.4804	261.5249	5.79	10.06
0.5400	255.7407	3.96	7.62
0.5914	251.2417	4.57	12.80
0.5515	243.7795	4.88	8.84
0.6428	238.1452	5.79	10.06
0.6377	315.9771	3.96	12.50

Mean values of density,compression wood percentage,latewood percentage,wood value and day matter in 20 trees.

Tree number		Age	Unextracted density (g/cc)	extracted density (g/cc)	Compression wood %	Latewood %	Wood volume (m^3)	Dry Matter (kg)
1	D1-6	12	0.5220	0.5221	0.81	14.9873	0.235	122.9
2	D1-57	12	0.6329	0.6258	0.21	38.7900	0.214	137.1
3	D1-71	12	0.5731	0.5684	2.03	27.0995	0.149	86.8
4	D2-11	12	0.6489	0.6339	5.06	44.5921	0.166	110.1
5	NH1-24	12	0.4468	0.4416	8.97	13.5772	0.370	162.8
6	NH1-40	12	0.4654	0.4413	14.50	10.1054	0.526	235.1
7	NH1-44	12	0.5655	0.5539	3.73	26.7562	0.395	218.3
8	NH1 -51	12	0.5241	0.5070	2.44	18.4291	0.253	129.4
9	S1-8	13	0.5742	0.5576	2.94	29.6281	0.352	203.5
10	S1-31	13	0.5807	0.5643	3.23	28.3957	0.289	172.5
11	S1-36	13	0.5790	0.5649	1.60	29.2779	0.302	175.0
12	S1-45	13	0.7336	0.7212	3.25	56.7841	0.256	189.7
13	S1-55	13	0.4846	0.4796	3.65	13.8441	0.235	112.1
14	S1-64	13	0.5160	0.4921	0.59	17.0792	0.422	214.7
15	S2-1	13	0.4413	0.4383	1.46	15.4311	0.476	209.4
16	S2-6	13	0.5618	0.5536	4.90	32.6606	0.357	197.2
17	S2-37	13	0.5502	0.5350	3.47	21.8085	0.467	256.7
18	S2-51	13	0.5627	0.5543	0.68	30.1720	0.367	202.3
19	S2-79	13	0.6722	0.6405	1.78	39.9683	0.317	213.4
20	S2-84	13	0.5846	0.5755	3.79	31.6317	0.606	356.3

Percentage of wood in different density classes

Tree number	D1-6	D1-57	D1-71	D2-11	NH1-24	NH1-40	NH1-44	NH1-51	S1-8	S1-31
Class										
ED-1 (0.05-0.20 g/cc)	0.0205	0.0495	0.0000	0.0818	0.0160	0.0481	0.1242	0.0388	0.4270	0.3111
ED-2 (0.21-0.35 g/cc)	2.9230	5.8155	2.1750	4.8352	35.2729	25.7779	6.6873	7.3822	14.7024	11.8706
ED-3 (0.36-0.50 g/cc)	57.2630	36.0328	41.1046	33.2719	40.3988	51.5715	50.7566	53.8441	42.3825	42.0716
ED-4 (0.51-0.65 g/cc)	24.8062	19.3122	29.6209	17.2190	10.7351	12.4971	15.6757	20.3058	12.8600	17.3510
ED-5 (0.66-0.80 g/cc)	6.3208	10.3083	12.8044	13.5128	7.2642	4.9161	7.8362	9.4212	8.3577	7.7683
ED-6 (0.81-0.95 g/cc)	2.9942	9.7885	8.5601	17.7385	4.3610	3.9726	7.3475	6.1705	7.1160	8.3688
ED-7 (0.96-1.10 g/cc)	3.2933	14.7914	5.4108	12.5557	1.8351	1.0651	8.8212	2.8375	11.2624	9.4861
ED-8 (Greater than 1.11 g/cc)	2.3789	3.9018	0.3241	0.7849	0.1169	0.1515	2.7513		3.8920	2.7726

Tree number	S1-36	S1-45	S1-55	S1-64	S2-1	S2-6	S2-37	S2-51	S2-79	S2-84
Class										
ED-1 (0.05-0.20 g/cc)	0.0616	0.0447	0.2782	0.1381	0.8049	0.3475	0.1416	0.1083	0.2533	0.3029
ED-2 (0.21-0.35 g/cc)	7.4217	1.3573	11.4026	10.0699	43.0441	18.4806	5.4255	8.5291	2.4818	6.5887
ED-3 (0.36-0.50 g/cc)	43.1522	22.2781	57.2938	57.1574	30.8511	32.0355	52.0029	42.2565	28.9713	40.6317
ED-4 (0.51-0.65 g/cc)	20.0872	19.5358	17.1813	15.5554	9.8688	16.4758	20.6215	18.9341	28.3253	20.8450
ED-5 (0.66-0.80 g/cc)	11.7576	13.5619	6.1375	7.4668	5.5508	11.7122	9.1559	13.2731	14.5033	12.0809
ED-6 (0.81-0.95 g/cc)	9.1805	16.2863	4.9044	6.9006	6.0681	13.0527	5.9866	11.2263	10.0518	11.0275
ED-7 (0.96-1.10 g/cc)	7.2978	22.8063	2.6821	2.6887	3.5845	7.8355	5.4926	5.4772	11.8546	8.1282
ED-8 (Greater than 1.10 g/cc)	1.0424	4.1295	0.1202	0.0231	0.2278	0.0601	1.1734	0.1953	3.5586	0.3951

	20 trees	Tree-0.49 g/cc	Tree 0.5-0.59 g/cc	Tree greater than 0.6 g/cc
Class				
ED-1 (0.05-0.20 g/cc)	0.1799	0.26	0.17	0.11
ED-2 (0.21-0.35 g/cc)	11.6122	25.11	8.38	3.63
ED-3 (0.36-0.50 g/cc)	42.7664	47.45	45.23	30.14
ED-4 (0.51-0.65 g/cc)	18.3901	13.17	19.78	21.10
ED-5 (0.66-0.80 g/cc)	9.6855	6.27	10.04	12.97
ED-6 (0.81-0.95 g/cc)	8.5551	5.24	8.28	13.47
ED-7 (0.96-1.10 g/cc)	7.4603	2.37	6.85	15.50
ED-8 (Greater than 1.11 g/cc)	1.3500	0.13	1.12	3.09

Mean values of tracheid dimensions and their derived ratios

Tree number		CW	CL	CD	CW%	FL	2CW/CL	CL/CD	FL/CD	FL/2CW	2CWxFL
1	D1-6	6.6o74	33.7364	4o.3438	3o.452o	2.78o	o.3917	o.8362	68.9	168.3991	36.7371
2	D1-57	8.2542	29.13o9	37.3851	39.7439	3.o75	o.5667	o.7792	82.3	186.2688	5o.7633
3	D1-71	7.2745	29.3432	36.6177	36.1782	3.oo5	o.4958	o.8o13	82.1	2o6.5434	43.7197
4	D2-11	8.7212	28.o9o8	36.812o	42.3964	3.o2o	o.62o9	o.7631	82.o	173.1413	52.676o
5	NH1-24	6.oo84	41.5222	47.53o7	24.6182	2.845	o.2894	o.8736	59.9	236.7519	34.1878
6	NH1-4o	6.3233	4o.95o1	47.2734	25.6873	2.915	o.3o88	o.8662	61.7	23o.4967	36.8648
7	NH1-44	8.o146	35.6586	43.6732	34.6186	3.o8o	o.4495	o.8165	7o.5	192.1493	49.3699
8	NH1-51	7.32o7	38.9636	46.2843	3o.2837	3.115	o.3758	o.8418	67.3	212.7529	45.6o8o
9	S1-8	8.3418	34.9o86	43.25o4	35.5822	3.2oo	o.4779	o.8o71	74.o	191.8o51	53.3875
1o	S1-31	8.o778	36.9693	45.o471	33.6o57	3.o9o	o.437o	o.82o7	68.6	191.2649	49.92o8
11	S1-36	6.6828	31.7984	38.4812	32.4768	3.o9o	o.42o3	o.8263	8o.3	231.19o5	41.2997
12	S1-45	9.9928	27.2564	37.2492	46.4496	3.15o	o.7332	o.7317	84.6	157.6135	62.9546
13	S1-55	6.2493	37.4256	43.6749	27.4123	3.2o5	o.334o	o.8569	73.4	256.4287	4o.o58o
14	S1-64	6.2968	36.1132	42.41oo	28.6o7o	3.o55	o.3487	o.8515	72.o	242.5835	38.4734
15	S2-1	6.o355	39.64o2	45.6757	26.o958	3.o65	o.3o45	o.8679	67.1	253.9143	36.9976
16	S2-6	7.7o72	34.1949	41.9o21	34.6o99	2.98o	o.45o8	o.8161	71.1	193.3257	45.9349
17	S2-37	7.333o	34.8389	42.172o	33.3436	2.815	o.421o	o.8261	66.8	191.94o5	41.2848
18	S2-51	7.o161	33.1281	4o.1442	32.8548	3.21o	o.4236	o.8252	8o.o	228.7596	45.o434
19	S2-79	9.5437	33.1344	42.6781	4o.1697	3.o5o	o.5761	o.7764	71.5	159.7913	58.2166
2o	S2-84	7.6135	33.9933	41.6o68	34.1812	2.97o	o.4479	o.817o	71.4	195.o483	45.2242

2CW/CL:Runkel ratio

CL/CD:Flexibility ratio

FL/CD:Slenderness ratio

FL/2CW:Fibre stiffness

2CWxFL:Fibre index

CW:cell wall thickness (u) CL:cell lumen width (u) CD:cell diameter (u) CW%:cell wall percentage

Percentage of wood in different cell wall thickness classes

Tree number	D1-6	D1-57	D1-71	D2-11	NH1-24	NH1-40	NH1-44	NH1-51	S1-8	S1-31
Class										
CW-1 (0.0-4.0 u)	11.6901	9.8926	8.5698	7.4054	21.9047	9.6295	5.4731	5.1373	12.3726	8.3359
CW-2 (4.1-8.0 u)	68.7852	47.4078	60.1526	42.8855	60.0187	73.6149	62.1067	67.8837	52.1233	55.2369
CW-3 (8.1-12.0 u)	11.2860	21.3768	20.9448	26.9964	11.8976	11.4828	13.0795	18.3215	12.2153	19.8116
CW-4 (12.1-16.0 u)	5.3238	17.8422	8.5526	19.3157	5.4915	3.7806	13.3980	6.3912	11.1122	10.4599
CW-5 (Greater than 16.1 u)	2.9149	3.4806	1.7803	3.3971	0.6874	1.4922	5.9427	2.2663	12.1766	6.1557

Tree number	S1-36	S1-45	S1-55	S1-64	S2-1	S2-6	S2-37	S2-51	S2-79	S2-84
Class										
CW-1	22.2957	3.8678	13.4862	12.7404	24.2582	11.4312	4.9778	13.8981	2.3150	7.9809
CW-2	51.5510	34.8732	67.6679	68.2480	57.2645	50.8071	66.0175	54.6327	46.1994	56.2376
CW-3	14.5289	27.6075	14.5739	13.3216	11.8793	23.0904	19.1635	23.0057	23.8869	21.5450
CW-4	9.1089	24.3481	3.0229	5.6900	5.7099	12.9218	8.0319	8.0691	15.0761	12.1569
CW-5	2.5146	9.3034	1.2491	0.0000	0.8880	1.7495	1.8092	0.3944	12.5226	2.0796

Class	Drasa	Nausori Highlands	Seaqaqa	Pooled data(20 trees)
CW-1	9.3895	10.5362	11.4967	10.8832
CW-2	54.8078	65.9060	55.0716	57.1857
CW-3	20.1510	13.6954	18.7191	18.0007
CW-4	12.7586	7.2653	10.4757	10.2902
CW-5	2.8932	2.5972	4.2369	3.6402

Percentage of wood in different lumen width classes

Tree number	D1-6	D1-57	D1-71	D2-11	NH1-24	NH1-40	NH1-44	NH1-51	S1-8	S1-31
Class										
CL-1 (0.00-20.00 u)	7.9619	19.1238	13.8315	20.9299	1.9225	1.9009	13.6328	5.2342	16.2757	9.4998
CL-2 (20.01-30.00 u)	21.0887	31.9471	36.7283	38.0641	12.1466	10.7574	17.2230	14.9832	14.9510	17.1445
CL-3 (30.01-40.00 u)	48.9998	36.9930	42.3153	30.8693	28.2659	30.7638	27.4757	31.1034	30.7478	30.3903
CL-4 (40.01-50.00 u)	20.8140	11.9361	6.8120	9.7738	35.8372	39.7529	33.3161	33.7893	29.3879	31.1389
CL-5 (Greater than 50.01 u)	1.1355	0.0000	0.3129	0.3629	21.8278	16.8251	8.3524	14.8898	8.6376	11.8264

Tree number	S1-36	S1-45	S1-55	S1-64	S2-1	S2-6	S2-37	S2-51	S2-79	S2-84
Class										
CL-1	13.7944	23.7902	4.5568	6.5117	6.2529	10.6444	12.1727	7.7961	12.5041	8.6470
CL-2	24.2203	39.5680	15.2086	18.3804	13.2347	24.1161	18.9444	28.8997	25.6867	26.7577
CL-3	43.5331	27.5366	37.8854	37.3490	27.3176	33.4833	35.0876	40.0295	35.2990	34.4114
CL-4	17.4736	8.8627	33.6209	32.2141	35.3706	24.8173	26.5966	20.5886	22.7453	25.5806
CL-5	0.9785	0.2425	8.7283	5.5448	17.8242	6.9388	7.1987	2.6861	3.7648	4.6033

	Drasa	Nausori Highlands	Seaqaqa	Pooled data (20 trees)
Class				
CL-1	15.4619	5.6726	11.0372	10.8492
CL-2	31.9571	13.7776	22.2593	22.5025
CL-3	39.7944	29.4022	34.4226	34.4929
CL-4	12.3340	35.6739	25.6998	25.0215
CL-5	0.4528	15.4738	6.5812	7.1340

Percentage of wood in different cell diameter classes

Tree number	D1-6	D1-57	D1-71	D2-11	NH1-24	NH1-40	NH1-44	NH1-51	S1-8	S1-31
Class										
CD-1 (0.00-20.00 u)	0.0174	0.0000	0.0000	0.0117	0.0010	0.0130	0.2334	0.0000	0.0000	0.0000
CD-2 (20.01-30.00 u)	5.4443	12.8432	14.8299	16.1606	1.1026	1.5389	5.6456	2.3734	5.3851	3.6140
CD-3 (30.01-40.00 u)	43.3164	55.2725	56.2027	53.5356	19.2948	17.4088	31.1321	22.6311	29.4249	27.2500
CD-4 (40.01-50.00 u)	43.6479	29.7831	27.7255	28.0144	40.1861	43.7336	35.0938	41.6719	44.4998	41.1615
CD-5 (Greater than 50.01 u)	7.5740	2.1012	1.2369	2.2777	39.4155	37.3058	27.8950	33.3236	20.6902	27.9745

Tree number	S1-36	S1-45	S1-55	S1-64	S2-1	S2-6	S2-37	S2-51	S2-79	S2-84
Class										
CD-1	0.0000	0.0115	0.0000	0.0010	0.0000	0.0075	0.0000	0.0132	0.0073	0.0000
CD-2	12.2513	12.6240	4.4415	6.8020	3.9704	8.4988	10.2814	8.8899	4.7232	5.4534
CD-3	45.4939	56.4363	26.9373	32.8520	25.6937	33.6122	29.5811	41.1110	32.8494	39.9767
CD-4	36.7050	27.4789	47.6923	42.9168	34.9401	39.5620	39.7509	40.0968	44.0310	39.4862
CD-5	5.5498	3.4494	20.9289	17.4282	35.3959	18.3195	20.3866	9.8891	18.3891	15.0837

	Drasa	Nausori Highlands	Seaqaqa	Pooled data (20 trees)
Class				
CD-1	0.0073	0.0619	0.0101	0.0199
CD-2	12.3195	2.6651	7.2446	7.3437
CD-3	52.0831	22.6167	35.1015	36.0006
CD-4	32.2927	40.1714	39.8601	38.4089
CD-5	3.2975	34.4850	17.7904	18.2307

Percentage of wood in different cell wall percentage classes

Tree number	D1-6	D1-57	D1-71	D2-11	NH1-24	NH1-40	NH1-44	NH1-51	S1-8	S1-31
Class										
CW%-1 (0.00-20.00 %)	18.3762	15.0806	9.8183	11.6893	50.7273	36.8180	26.2997	25.0575	27.4944	25.9081
CW%-2 (20.01-30.00 %)	49.1086	27.5017	37.7743	24.8511	27.1235	41.5800	33.9774	38.8204	32.4963	32.2314
CW%-3 (30.01-40.00 %)	17.0545	15.3561	20.6240	16.5604	9.0395	10.9854	10.4842	15.3011	10.6761	14.0970
CW%-4 (40.01-50.00 %)	4.9438	11.0523	11.0165	9.4822	5.0611	4.5355	5.7258	9.1117	4.0398	7.8328
CW%-5 (50.01-60.00 %)	1.8371	10.1126	9.2799	12.9412	6.1035	2.5520	6.0900	4.9015	4.9971	7.3788
CW%-6 (60.01-70.00 %)	3.1696	12.5118	5.9019	15.7936	1.0133	2.6401	9.0528	3.3827	6.1701	5.1481
CW%-7 (Greater than 70.01 %)	5.5102	8.3847	5.5851	8.6831	0.9313	0.8892	8.3701	3.4251	14.1264	7.4037

Tree number	S1-36	S1-45	S1-55	S1-64	S2-1	S2-6	S2-37	S2-51	S2-79	S2-84
Class										
CW%-1	26.7807	7.6742	35.6971	30.4384	49.7927	24.7522	19.4218	23.6201	10.4196	20.8760
CW%-2	34.5831	19.0847	35.9155	40.9024	26.0547	28.7007	40.5732	30.6928	28.6647	34.0578
CW%-3	14.0354	17.6708	14.3913	9.2379	8.1984	11.3817	13.9085	17.0746	20.9883	14.3329
CW%-4	4.9600	11.3165	6.4838	7.6762	3.6139	10.6661	8.0897	11.1291	11.4610	10.1136
CW%-5	6.8760	14.3947	2.7475	5.2689	5.7075	12.0334	7.4931	8.9081	7.2703	8.4805
CW%-6	6.0524	15.5582	2.5628	4.7548	5.2006	9.8522	4.5115	6.6849	11.3304	9.2865
CW%-7	6.7124	14.3008	2.2019	1.7213	1.4322	2.6136	6.0021	1.8903	9.8657	2.8526

	Drasa	Nausori Highlands	Seaqaqa	Pooled data (20 trees)
Class				
CW%-1	13.7411	34.7256	25.2396	24.8371
CW%-2	34.8089	35.3753	31.9964	33.2347
CW%-3	17.3988	11.4526	13.8327	14.0699
CW%-4	9.1237	6.1085	8.1152	7.9156
CW%-5	8.5427	4.9118	7.6297	7.2687
CW%-6	9.3442	4.0222	6.8200	6.7689
CW%-7	7.0405	3.4041	5.9269	5.6451

Appendix V

EXPERIMENTAL METHODS IN PULPING INVESTIGATIONS

1. Apparent density of wood

The method used was TAPPI Standard method T 18 m—53 using one piece approximately one inch thick from each log received.

The green volume was determined by weighing the disc, which had been soaked in water until it was saturated, immersed in water. The oven-dry weight was determined by weighing the disc after it had been dried to constant weight at 105° ± 3°C.

The apparent density is expressed as: $\frac{\text{oven-dry weight}}{\text{Green (soaked) volume}}$

2. Chemical analysis

The chemical analyses were carried out on a composite sample. A portion of the chips prepared for pulping trials was ground in an Apex knife mill and the fraction of groundwood which passed through a British Standard 40 mesh (420 microns) sieve and was retained on a British Standard 60 mesh (250 microns) sieve used for analysis.

The methods used were:

Alcohol benzene solubility	TAPPI T 6 m—59
Holocellulose	Wise, Murphy, D'Addieco
Alpha-cellulose	TAPPI T 203 os—61
1% Caustic soda solubility	TAPPI T 4 m—59
Lignin	TAPPI T 13 m—54

The fractions soluble in alcohol-benzene and 1% caustic soda are expressed as oven-dry extractives per cent oven-dry wood.

The alpha-cellulose and lignin are expressed oven-dry per cent oven-dry wood.

The holocellulose cellulose was dried by washing in acetone and storing at room temperature in a desiccator until constant weight. Under these conditions the holocellulose was found to have a moisture content of 2 per cent. In calculating the result allowance was made for this moisture content and the result is reported as oven-dry holocellulose per cent oven-dry wood.

3. Pulping methods

The chips used for pulping were prepared by sawing the log into discs approximately ¾ inch thick and then splitting along the grain with a mechanical guillotine to give a chip approximately ¾ inch x ¼ inch thick. This damages the fibres less than commercial chipping.

Laboratory pulping was carried out in an electrically-heated, stainless steel, rotating pressure vessel.

The method used was the sulphate (Kraft) process, which was selected as being the most promising process for use on tropical woods in tropical conditions. The active chemicals are sodium hydroxide and sodium sulphide.

The concentration of chemicals is calculated according to the following definitions:

(a) Active Alkali = $NaOH + Na_2S$ expressed as Na_2O per cent on oven-dry wood.

(b) Sulphidity = $\frac{Na_2S \times 100}{NaOH + Na_2S,}$ all the compounds expressed as Na_2O.

A sulphidity of 25 per cent was used in each of these experiments, chosen because published information shows there to be generally little variation in pulp quality with changes in sulphidity in the range of 20 to 30 per cent.

The cooked chips were washed free of superficial black liquor and broken up in a propeller type disintegrator to simulate the disintegration occurring during blowing a commercial digester; the pulp was screened using a plate with 0.15 mm wide slits, to remove shive, and collected on a 150 mesh (per linear inch) sieve.

The yield of pulp was determined by drying the whole of the screened pulp in a stream of air to about 10% moisture. The total weight of air dry screened pulp and the moisture content of an aliquot were determined for calculating the yield of oven-dry pulp.

The total alkali in the black liquor was determined by titrating an ashed aliquot of black liquor with hydrochloric acid. The Active Alkali remaining was determined by titrating an aliquot of black liquor after removing the sodium salts which are the reaction products of digestion by precipitation with barium chloride. The Active Alkali consumed was the difference of these results.

4. Unbleached pulp evaluation

The Kappa Number was determined by TAPPI standard method T 236 m–60. This method is identical with the International Committee for Chemical Analyses Method ICCA 1:59 which has been adopted throughout the world.

The amount of permanganate consumed by pulp under specified conditions is measured and, for pulp yields of less than 70 per cent, the percentage of Klason lignin approximately equals Kappa Number XO.15.

The pulp was evaluated by preparing and testing standard sheets, from pulp which had been air dried, according to the proposals of the 'Second Report of the Pulp Evaluation Committee to the Technical Section of the (British) Papermakers' Association'. The sheets of approximately 60 g/m^2 were tested after conditioning at 20° ± 1°C and 65 per cent relative humidity. The methods given in this report are practically identical with those in TAPPI Standard T 205 m–58. The effect of air drying is to lower the strength of the unbeaten pulp, but, except for specific scattering coefficient, the effect on beaten pulps is small.

The pulps were beaten in a PFI Mill using a pulp consistency of 10 per cent, a beating pressure of 3.4 kgF (33.3N) per cm of bar length and a difference between the peripheral speeds of the beating elements of 2 m/sec.

The methods used for physical examination of each set of sheets were:

(a) Thickness: Ten measurements made on ten sheets placed one on top of another using a dead weight micrometer.

(b) Breaking length and stretch; Twelve strips 15 mm wide tested using a Schopper-type tensile tester with the jaws initially 9 cm apart.

(c) Tear: Using a Marx-Elmendorf tear tester; normally a group of three were torn at one time through 44 mm in 2 places (i.e. total tearing distance is 3 x 2 x 44 = 264 mm), three readings being obtained in this way. Sheets with high tearing strength were torn either in pairs or singly and suitable adjustment was made to the calculation of the tear factor.

(d) Burst: Eighteen tests using a Frank Schopper-Dalen type pneumatic burst tester.

(e) Fold: 15 mm strips folded through 312° and the number of double folds recorded before the strip broke under a load of 7.85 N (800 gF).

(f) Air porosity: Four sheets tested using a closed top Gurley Densometer with a 20 ounce inner cylinder. The time for 100 ml of air to pass through 1 sq. inch was measured by the automatic timing attachment.

(g) Basis weight and moisture content: Determined by weighing six rectangles of 250 cm^2 after standard conditioning and after drying to constant weight at 105° + 3°C.

Results are reported as follows, where possible, independent of basis weight, but otherwise referring to an oven-dry basis weight of approximately 60 g/m^2.

Basis weight: Grams per square metre, oven-dry (W)

Thickness: Thickness of a single sheet, in microns.

Bulk* $\dfrac{\text{Thickness}}{W}$

Burst Factor* $\dfrac{\text{Average burst in g/cm}^2}{W}$

Tear Factor* $\dfrac{\text{Tearing force for a single sheet in g x 100}}{W}$

Breaking Length* $\dfrac{\text{Average tensile strength in kg x 66 700}}{W}$

The result is expressed in metres.

*results which are independent of basis weight.

The ease with which water parts from the pulp was determined by two methods. The first, the drainage time determined on the standard sheet machine, is the time in seconds for water at 20°C to flow from a pulp suspension through the wire from a height 350 mm above the wire until the formed sheet is no longer immersed. The procedure used was that described in the 'Second Report of the Pulp Evaluation Committee' and is similar to that given in TAPPI Standard T 221 os–63.

The second, the Canadian Standard freeness is an empirical measure of the rate at which water will separate from a one litre suspension of 3 grams of pulp through a standard perforated plate, in apparatus calibrated by the Pulp and Paper Research Institute of Canada. The method is described in the 'Second Report of the Pulp Evaluation Committee, TAPPI Standard T 227 m–58 and in Canadian Pulp and Paper Association Standard C1.

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Table 1. Format for analysis of variance

Entry	Test against entry	Source of variation	Degrees of freedom	Fixed (F) or Random (R) effect	Expectation mean square
1	4	Trees	19	R	$V_r + 2V_{bd} + 8V_d + 64V_t$
2	3	Cooks	3	F	$V_r + 2V_{bd} + 8V_d + 16V_{ct} + 320\phi_c$
3	4	Cooks x Trees	57	R	$V_r + 2V_{bd} + 8V_d + 16V_{ct}$
4	9	Duplicates in cooks and trees	80	R	$V_r + 2V_{bd} + 8V_d$
5	6	Beating times	3	F	$V_r + 2V_{bd} + 16V_{bt} + 320\phi_b$
6	9	Beats x Trees	57	R	$V_r + 2V_{bd} + 16V_{bt}$
7	8	Beats x Cooks	9	F	$V_r + 2V_{bd} + 4V_{bct} + 80\phi_{bc}$
8	9	Beats x Cooks x Trees	171	R	$V_r + 2V_{bd} + 4V_{bct}$
9	10	Beats x (Duplicates in cooks and trees)	240	R	$V_r + 2V_{bd}$
10		Replicates in all samples	640	R	V_r

Table 2. Relative importance of sources of variation (variance components expressed as percentages of total variation) for 17 pulp properties

Source of variation	Degrees of freedom	Total yield	Screened yield	Canadian standard freeness	Drainage time	Basis weight	Thickness	Air Porosity	Smoothness - glazed	Smoothness - rough	Bulk
Trees	19	27.34	48.64	0.94	4.94	3.39	31.82	2.25	89.79	91.35	31.56
Cooks	3	67.46	40.43	2.30	6.23	0.58	8.09	7.96	0.20	0.34	7.19
Cooks x Trees	57	0.00	2.62	0.00	1.06	0.00	0.00	1.58	0.36	0.00	0.13
Duplicates in Cooks and Trees	80	5.19	8.31	0.46	0.75	17.95	1.97	0.48	3.01	1.15	1.56
Beating Time	3	0.00	0.00	92.52	54.52	1.85	52.85	31.91	0.15	0.74	54.69
Beating Time x Trees	57	0.00	0.00	1.40	7.84	2.43	1.51	6.30	4.83	4.42	1.34
Beating Time x Cooks	9	0.00	0.00	0.98	11.19	0.00	0.01	24.63	0.11	0.26	0.06
Beating Time x Cooks x Trees	171	0.00	0.00	0.00	2.60	1.54	0.00	4.80	0.09	0.23	0.00
Beating Time x (Duplicates in Cooks and Trees)	240	0.00	0.00	0.18	2.40	0.00	0.00	6.30	0.00	0.02	0.00
Replicates in all samples	640	0.00	0.00	1.22	8.46	72.27	3.74	13.78	1.46	1.49	3.47

	Degrees of freedom	Burst factor	Breaking length	Stretch	Breaking length x Stretch	Tear factor	Double folds	Brightness			
Trees	19	11.04	13.42	24.51	8.92	46.40	44.58	8.07			
Cooks	3	0.89	0.33	3.39	1.79	3.03	1.43	42.64			
Cooks x Trees	57	0.89	1.10	1.56	2.61	0.03	1.02	0.37			
Duplicates in Cooks and Trees	80	0.53	0.58	10.90	3.59	3.08	3.51	3.17			
Beating Time	3	81.39	78.46	5.14	60.90	35.60	24.00	39.48			
Beating Time x Trees	57	2.06	0.68	7.29	3.11	4.03	3.80	3.52			
Beating Time x Cooks	9	0.00	0.01	0.38	0.10	0.72	0.32	0.37			
Beating Time x Cooks x Trees	171	0.00	0.00	0.00	0.00	0.00	0.00	0.00			
Beating Time x (Duplicates in Cooks and Trees)	240	0.00	0.00	0.00	0.00	0.00	0.00	0.00			
Replicates in all samples	640	3.20	5.41	46.83	18.99	7.11	21.34	2.38			

Table 3. Tree means for 18 pulp properties

	Total yield %	Screened yield %	Canadian standard freeness	Drainage time (secs)	Basis Weight (gm/m^2)	Thickness (mm)	Air porosity (secs)	Smoothness - glazed	Smoothness - rough	Bulk (ml/g)	Burst factor	Breaking length (m)	Stretch %	Breaking length x stretch	Tear factor	Double folds (Kohler-Moll 800g)	Brightness (Elrepho R-457)	
Significance of tree effect /2	***	***	***	***	*	***	***	***	***	***	***	***	***	***	***	***	***	N.A. /1
Standard error of a mean	0.21	0.18	5.18	0.02	0.17	0.46	4.54	0.09	0.05	0.01	0.43	59.25	0.07	540.66	2.24	26.69	0.14	N.A. /1
Tree identity																		
D1/6	46.9	46.2	578.0	4.6	59.7	94.4	18.4	8.3	5.6	1.6	58.5	8768.2	3.8	33505.7	138.5	1088.2	13.0	37.19
D1/57	47.7	46.1	566.4	4.5	60.3	101.8	14.3	6.3	8.3	1.7	58.0	8590.4	4.2	35947.2	203.5	1073.0	13.0	37.45
D1/71	46.0	44.1	551.0	4.5	60.3	94.6	35.8	5.5	8.1	1.6	60.9	8903.6	4.1	36375.0	168.2	1266.8	13.1	38.03
D2/11	47.4	44.6	565.4	4.6	60.0	99.7	9.8	8.2	6.1	1.7	51.8	7823.9	4.4	34312.0	176.6	1096.9	11.7	49.61
NH1/24	44.2	43.2	573.6	4.6	60.0	91.3	33.5	8.1	5.2	1.5	57.4	8477.5	4.2	35290.4	149.6	1306.5	13.1	40.83
NH1/40	42.4	42.2	572.2	4.6	60.2	89.4	35.4	8.1	4.9	1.5	55.9	8222.9	4.3	35350.8	137.2	1254.7	13.5	34.78
NH1/44	46.8	45.0	567.3	4.7	60.2	101.6	17.9	8.3	6.3	1.7	55.2	8266.9	4.2	34385.5	170.8	1088.8	13.0	41.78
NH1/51	43.7	42.0	594.8	4.4	60.6	95.7	16.0	5.5	8.1	1.6	57.4	8092.1	4.4	35170.5	177.0	1306.1	12.6	40.72
S1/8	46.0	44.8	563.8	4.7	60.4	105.8	11.6	8.7	6.8	1.6	55.9	8356.2	4.4	36348.3	189.6	1039.2	13.6	38.48
S1/31	45.5	44.6	549.9	4.7	60.6	102.1	31.5	8.5	6.4	1.7	49.4	7430.2	4.6	33779.3	183.9	1147.2	13.1	37.88
S1/36	46.6	45.9	540.3	4.7	60.4	98.4	19.9	5.9	8.0	1.6	58.8	8600.1	4.1	35344.4	180.7	1235.3	13.8	36.73
S1/45	47.1	45.2	536.2	4.7	60.4	107.7	18.1	6.8	8.3	1.8	50.5	7507.8	4.7	35746.0	211.6	906.7	13.2	35.06
S1/55	46.4	46.0	561.7	4.7	60.6	94.0	39.3	5.5	7.9	1.6	65.8	9533.4	4.1	38949.4	148.7	1479.5	14.1	31.53
S1/64	45.6	44.7	594.4	4.5	60.3	95.4	10.1	8.3	5.6	1.6	57.4	8020.5	4.8	38510.2	202.4	1724.2	13.8	38.14
S2/1	46.1	45.8	564.2	4.6	60.6	96.4	37.3	8.2	5.7	1.6	59.0	8477.6	4.6	38956.0	186.6	1646.3	14.7	31.31
S2/6	46.5	45.7	564.3	4.6	60.4	96.2	25.2	5.8	8.1	1.6	49.1	7417.8	4.2	30806.0	170.1	1152.6	13.4	34.19
S2/37	44.8	44.3	562.1	4.6	60.1	94.0	19.3	5.5	8.0	1.6	58.7	8730.7	4.0	34700.0	148.4	1219.4	14.0	32.01
S2/51	47.0	45.1	593.8	4.5	60.4	98.6	6.2	5.8	7.9	1.6	58.6	8388.5	4.4	36537.3	191.0	1421.7	13.4	37.54
S2/79	47.1	46.4	527.0	4.8	60.3	103.4	39.7	8.6	6.7	1.7	49.6	7405.4	4.5	33062.9	191.9	1020.1	13.1	34.03
S2/84	45.8	45.0	577.3	4.5	60.5	96.6	18.2	8.4	5.9	1.6	55.0	7947.0	4.5	35828.0	191.0	1398.6	13.0	34.45
Mean	45.98	44.85	565.18	4.61	60.32	97.86	22.86	7.21	6.89	1.62	56.14	8248.04	4.33	35467.88	175.86	1243.59	13.31	37.09

/1 Not analysed by analysis of variance

/2 *** Significant at 0.1% probability level
* Significant at 5.0% probability level

Table 4. Mean values of burst factor, breaking length and tear factor estimated at 500 C.S.F and 35 kappa.

Tree identity	Burst factor	Breaking length	tear factor
D1-6	64.11	9296	129.9
D1-57	65.89	9396	184.0
D1-71	68.05	9813	155.8
D2-11	59.68	8890	159.8
NH1-24	64.71	9388	136.6
NH1-40	61.10	8992	128.9
NH1-44	63.29	9054	160.1
NH1-51	63.80	9006	159.9
S1-8	64.74	9319	179.7
S1-31	66.23	8147	179.4
S1-36	67.22	940[illegible]	172.7
S1-45	58.49	84[illegible]	209.5
S1-55	74.64	10640	135.5
S1-64	63.77	8604	185.8
S2-1	67.40	9233	179.5
S2-6	56.31	8376	161.7
S2-37	65.63	9648	142.7
S2-51	67.43	9269	174.0
S2-79	57.41	8085	192.7
S2-84	62.47	8694	184.9

Table 5. Tree means for six chemical constituents of wood expressed as a percentage of oven dry weight of original wood

Tree identity	1% NaOH solubility	Alcohol benzene solubility	Total extractives	Holocellulose	α-Cellulose	Lignin
D1/6	10.5	1.4	3.5	64.0	42.1	27.3
D1/57	9.8	0.9	3.2	65.2	45.1	26.8
D1/71	11.3	1.3	4.3	63.8	42.0	28.3
D2/11	11.0	1.0	3.3	61.1	44.4	28.3
NH1/24	10.7	1.2	3.2	62.3	40.0	30.1
NH1/40	13.4	4.1	6.3	57.6	39.9	29.1
NH1/44	11.4	1.9	3.9	62.6	43.6	29.0
NH1/51	13.7	4.2	6.9	61.4	40.4	28.5
S1/8	10.7	1.9	3.9	63.0	44.2	27.2
S1/31	10.9	2.0	3.7	62.9	43.3	27.8
S1/36	9.6	1.0	3.1	65.9	43.6	28.6
S1/45	11.0	2.2	4.5	64.9	45.9	26.8
S1/55	9.5	1.0	3.0	65.6	42.7	28.4
S1/64	12.0	3.0	4.9	61.8	41.7	28.9
S2/1	11.4	3.1	5.0	62.7	43.4	26.4
S2/6	11.3	1.7	3.8	64.0	43.6	27.7
S2/37	12.0	2.7	5.1	64.6	41.9	28.2
S2/51	10.5	1.5	3.8	64.1	43.1	28.0
S2/79	10.9	1.8	3.9	67.1	46.0	26.9
S2/84	10.7	1.8	3.7	64.2	44.7	27.8

Table 6. Proportions of fibres in pulp retained by screens of different mesh size, and weighted mean fibre length

Tree identity	Retained 10	Pass 10 Retained 14	Pass 14 Retained 20	Pass 20 Retained 28	Pass 28 Retained 35	Pass 35 Retained 65	Pass 65 Retained 200	Pass 200 Mesh	Length (weighted) mm
D1/6	31.10	24.00	16.95	8.60	8.90	4.70	1.35	4.45	2.780
D1/57	50.45	17.40	12.55	6.30	5.80	3.15	0.70	3.60	3.075
D1/71	47.40	16.75	13.50	6.85	7.00	4.50	0.90	3.10	3.005
D2/11	49.15	16.20	12.70	6.50	6.75	4.10	1.10	3.50	3.020
NH1/24	35.65	23.40	14.90	8.10	7.60	4.05	1.40	4.85	2.845
NH1/40	40.80	20.15	14.55	7.25	7.45	4.50	1.50	3.75	2.915
NH1/44	51.00	16.90	11.70	5.95	6.35	3.45	1.15	3.40	3.080
NH1/51	53.30	15.45	12.10	6.40	6.35	3.15	0.85	2.35	3.115
S1/8	61.50	11.90	9.60	4.70	5.15	3.20	0.95	2.95	3.200
S1/31	50.40	17.70	12.40	6.70	5.90	3.35	0.95	2.55	3.090
S1/36	53.75	13.70	11.70	6.05	6.70	4.55	1.35	2.20	3.090
S1/45	55.00	16.05	9.85	6.65	6.40	3.45	0.80	1.85	3.150
S1/55	61.55	11.90	9.60	4.50	5.40	3.60	1.25	2.20	3.205
S1/64	54.15	13.65	11.05	5.50	6.35	3.60	1.05	4.70	3.055
S2/1	51.75	15.95	12.10	5.75	5.70	4.30	1.20	3.25	3.065
S2/6	43.80	18.90	14.60	7.50	7.30	4.00	1.15	2.75	2.980
S2/37	60.30	24.45	17.95	10.00	8.00	5.10	1.45	2.35	2.815
S2/51	60.30	13.40	10.00	4.75	5.35	3.40	1.05	1.85	3.210
S2/79	50.10	16.50	11.90	7.35	6.55	3.70	1.15	2.80	3.050
S2/84	44.70	18.30	13.35	7.85	7.15	3.90	1.35	3.40	2.970

Table 7. Cooking condition means for 18 pulp properties

Property	Significance of difference	Condition				Std. error of a mean
		1	2	3	4	
Kappa number	N.A./1	47.6	41.5	33.7	24.4	-
Total yield (%)	***	48.2	46.9	45.4	43.4	0.09
Screened Yield (%)	***	45.7	45.5	44.9	43.2	0.10
Canadian std. freeness	***	596.2	574.8	558.9	530.8	2.20
Drainage Time (secs)	***	4.5	4.6	4.6	4.8	0.01
Basis weight (g/m^2)	n.s.	60.4	60.4	60.2	60.2	0.07
Thickness (mm)	***	100.5	98.9	97.1	94.9	0.20
Air porosity (secs)	***	8.0	13.0	20.5	50.0	2.75
Smoothness - glazed	*	7.3	7.3	7.2	7.1	0.04
Smoothness - rough	***	6.9	7.0	6.9	6.8	0.02
Bulk (ml/g)	***	1.7	1.6	1.6	1.6	0.003
Burst factor	***	56.0	57.3	56.9	54.4	0.33
Breaking length (m)	**	8161.9	8282.7	8370.7	8176.8	44.37
Stretch (%)	***	4.4	4.4	4.3	4.2	0.03
Breaking length x Stretch	***	35922.9	35955.0	35895.5	34098.0	333.61
Tear factor	***	181.2	178.5	175.6	168.1	1.01
Double folds	***	1235.7	1271.1	1277.0	1190.5	13.86
Brightness (Elrepho)	***	12.4	12.3	13.4	15.2	0.07

/1 Not analysed by analysis of variance

/2 *** Significant at 0.1% probability level ** Significant at 1.0% probability level
* Significant at 5.0% probability level n.s. Not significant at 5.0% probability level

Table 8. Beating time means for 18 pulp properties

Property	Significance of difference	Beating time, minutes				Std. error of a mean
		1	3	5	7	
Kappa number	N.A. /1	37.09	37.09	37.09	37.09	-
Total yield (%)	N.A. /1	46.0	46.0	46.0	46.0	-
Screened yield (%)	N.A. /1	44.8	44.8	44.8	44.8	-
Canadian std.freeness	***	739.8	662.3	512.9	345.7	4.96
Drainage time (secs)	***	4.3	4.4	4.6	5.1	0.03
Basis weight (g/m^2)	**	60.3	60.3	60.2	60.5	0.06
Thickness (mm)	***	106.2	98.3	94.7	92.2	0.25
Air porosity (secs)	***	0.65	2.02	10.01	78.76	4.158
Smoothness-glazed	N.S. /2	7.3	7.2	7.1	7.2	0.07
Smoothness - rough	**	7.1	6.8	6.8	6.9	0.06
Bulk (ml/g)	***	1.8	1.6	1.6	1.5	0.004
Burst factor	***	40.1	55.7	62.3	66.4	0.43
Breaking length (m)	***	6386.6	8196.4	8965.0	9444.2	33.86
Stretch (%)	***	4.4	4.4	4.3	4.2	0.03
Breaking length x Stretch	***	28314.6	35979.9	38165.1	39411.9	291.88
Tear factor	***	200.4	180.2	166.5	156.3	1.51
Double folds	***	1039.8	1225.3	1309.4	1462.2	15.54
Brightness (Elrepho)	***	15.2	13.2	12.5	12.3	0.09

/1 Not analysed by analysis of variance
*** Significant at 0.1% probability level

/2 Not significant at 5.0% probability level
** Significant at 1.0% probability level

Definitions of pulp values determined

1) Total yield expressed as oven-dry pulp % oven-dry wood.

2) Screened yield. expressed as oven-dry pulp % oven-dry wood after screening on a flat-bed screen with 15 mm slots.

3) Kappa number - a measure of the way in which pulp reduces potassium permanganate under specified conditions. It is an indirect method of determining the lignin content of pulp.

4) Canadian standard freeness - a measure of the way pulp and water separate. The higher the reading the more easily pulp and water separate.

5) Drainage time - a different measure of the way pulp and water separate using the British Standard Sheet Machine. A low reading means that the pulp and water separate easily.

6) Basis weight - the oven dry weight of a sheet expressed as g/m^2. The quantity of pulp taken was intended to give a sheet of 60 g/m^2. The actual value determined, which fell between 59 and 61 g/m^2, was used in subsequent calculations.

7) Thickness - the thickness of a single sheet measured in a dead-weight micrometer reported in micrometres.

8) Air porosity - time (in seconds) for 100 cm^3 of air to pass through an area of 6.45 cm^2 of a single sheet of paper, using a Gurley densitometer.

9) Smoothness - measured on both sides of the sheet. The rate at which air leaks across a metering land is measured. Since the rate of leakage is related to the mean gap between the land and the paper surface the Parker Print. Surf instrument is calibrated in micrometres.

10) Bulk - the volume in cm^3 of 1 g of pulp. Calculated from thickness and basis weight.

11) Burst factor - the force necessary to burst a hole in a single sheet divided by the basis weight.

12) Breaking length - a measure of the tensile strength of paper, calculated from the force required to break a strip of paper and the basis weight. Units are metres.

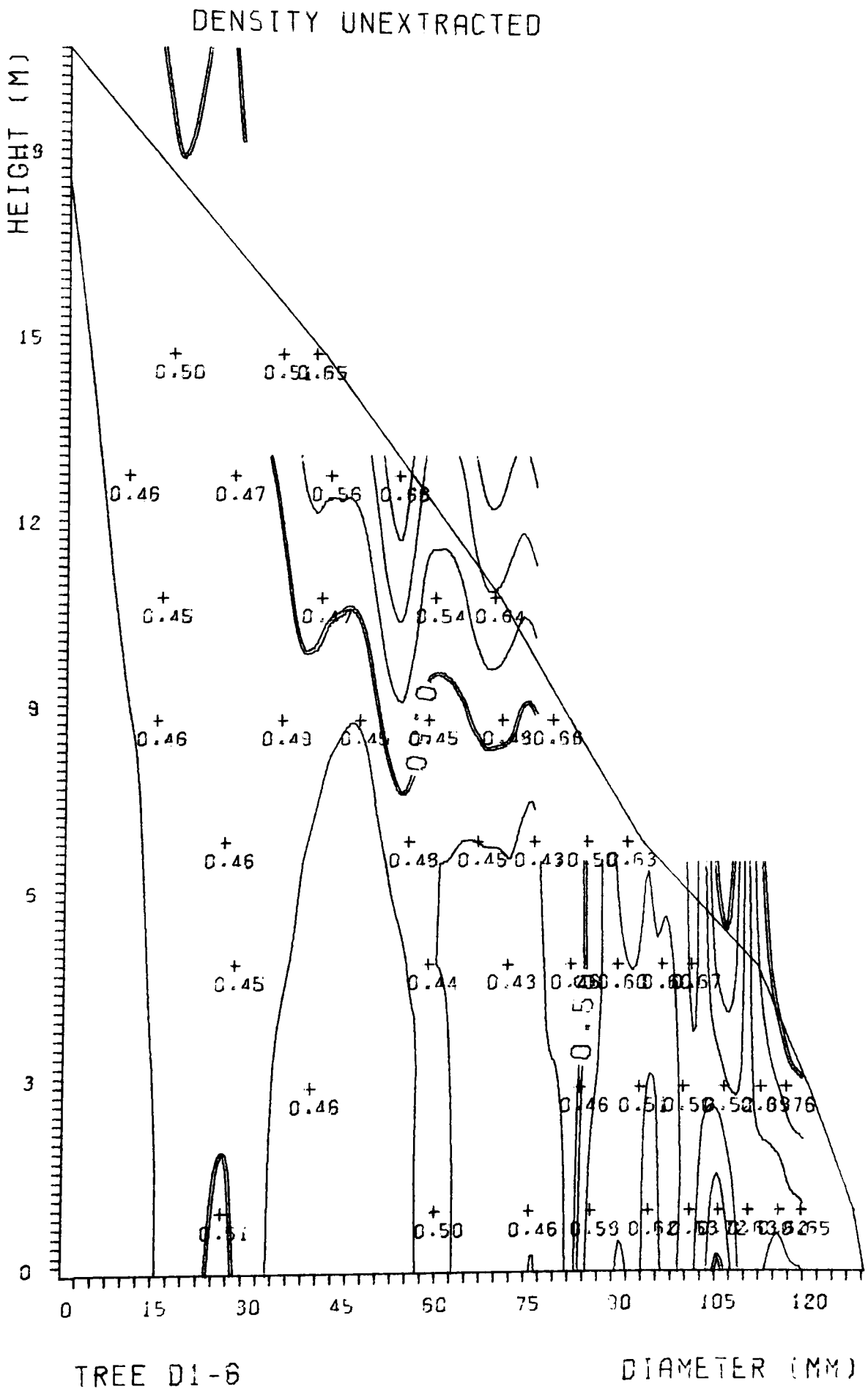
13) Stretch - the amount paper stretches before breaking in tension. Expressed as a percentage of the original length.

14) Tear factor - the force required to tear the paper in a standard way divided by the basis weight.

15) Double folds - the number of double folds given before a 15 mm strip of paper breaks under a load of 7.85N, using a Kohler-Molin Instrument.

16) Brightness - the reflectance of light of 457 nm wavelength from an opaque mat of sheets, using an Elrepho reflectometer. The value is expressed as a percentage of the reflectance of freshly prepared magnesium oxide.

APPENDIX VI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90
105
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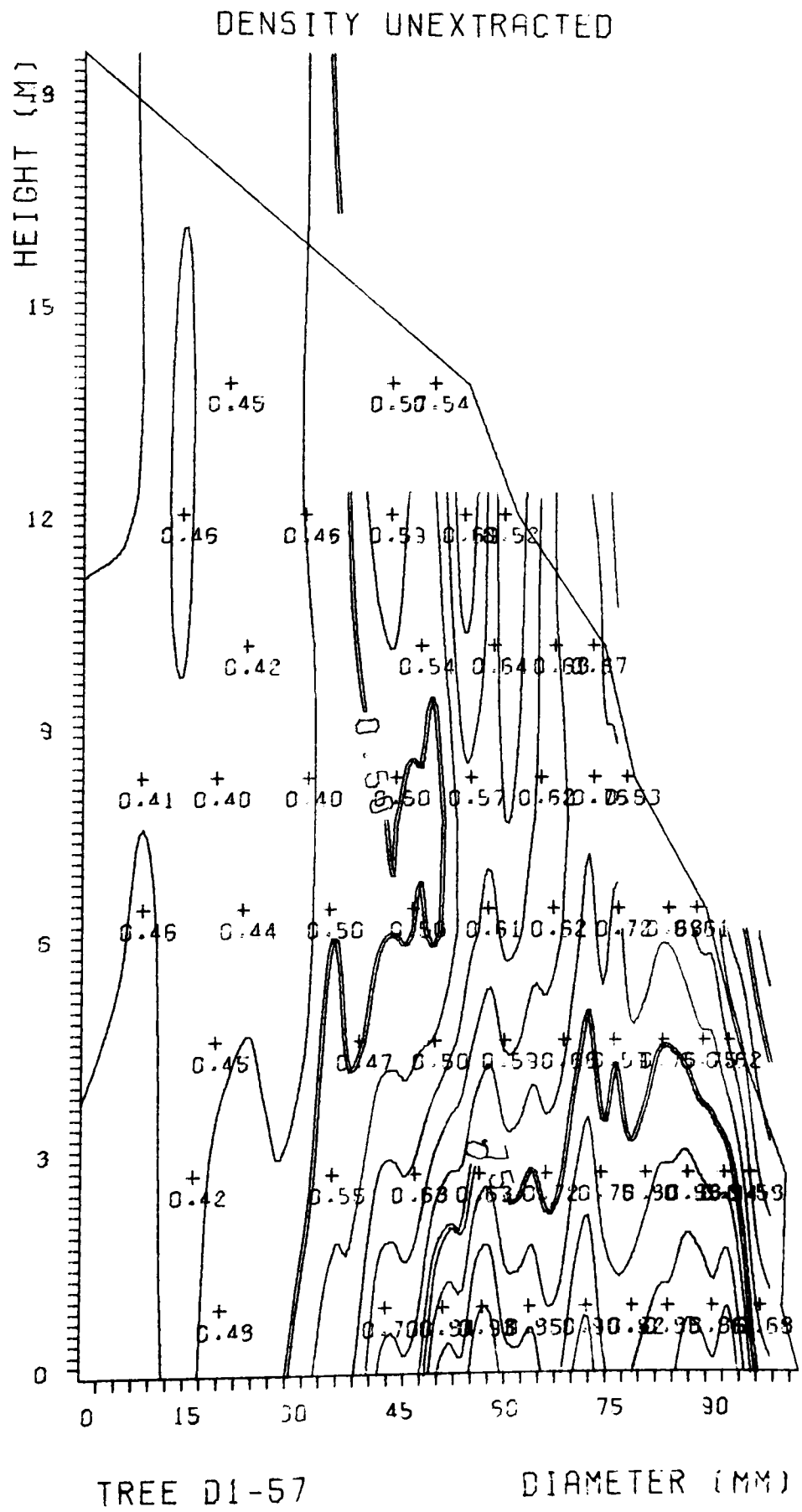
TREE D1-6
DIAMETER (MM)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0.40
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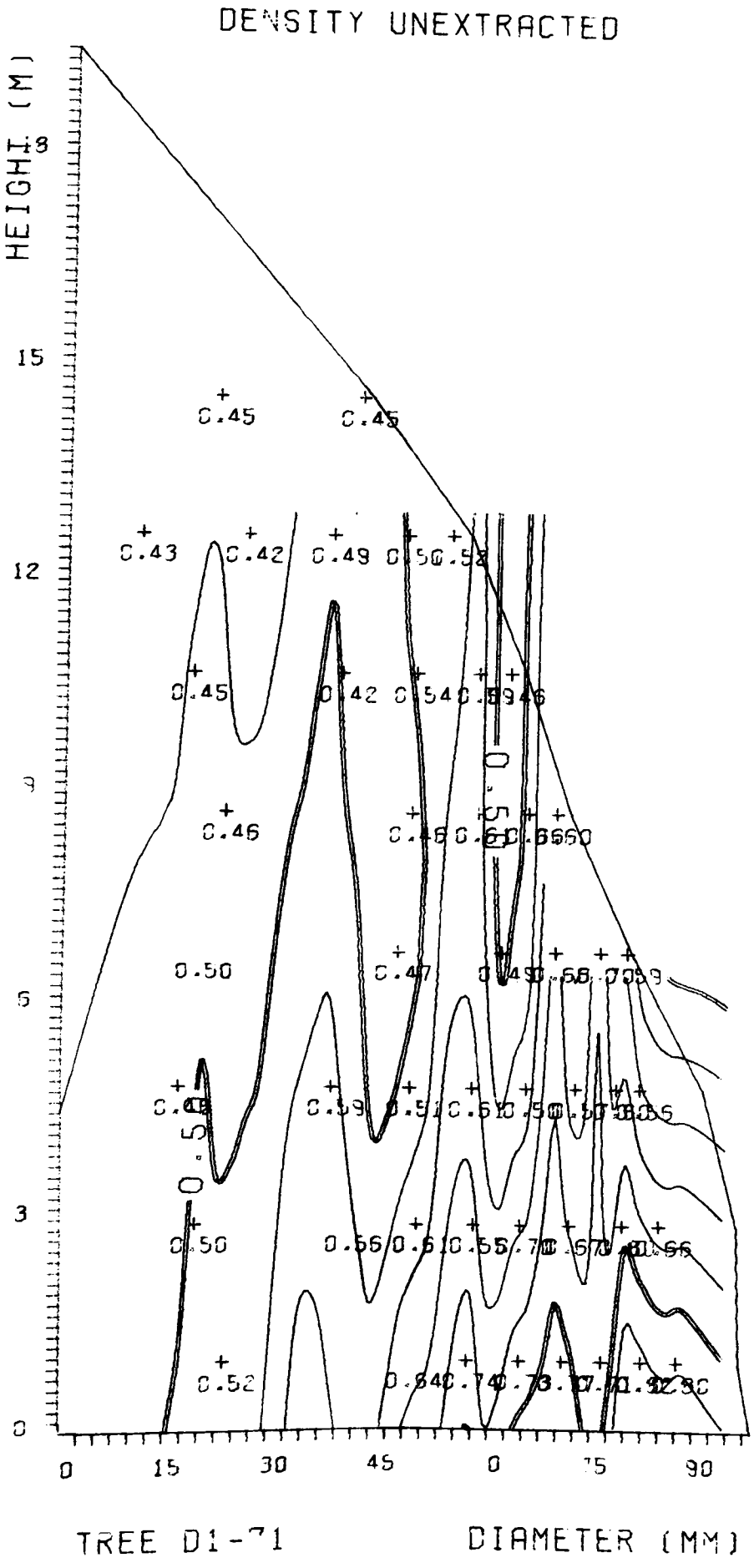
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0.49
0.50
0.53
0.45
0.42
0.54
0.46
0.46
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0
75
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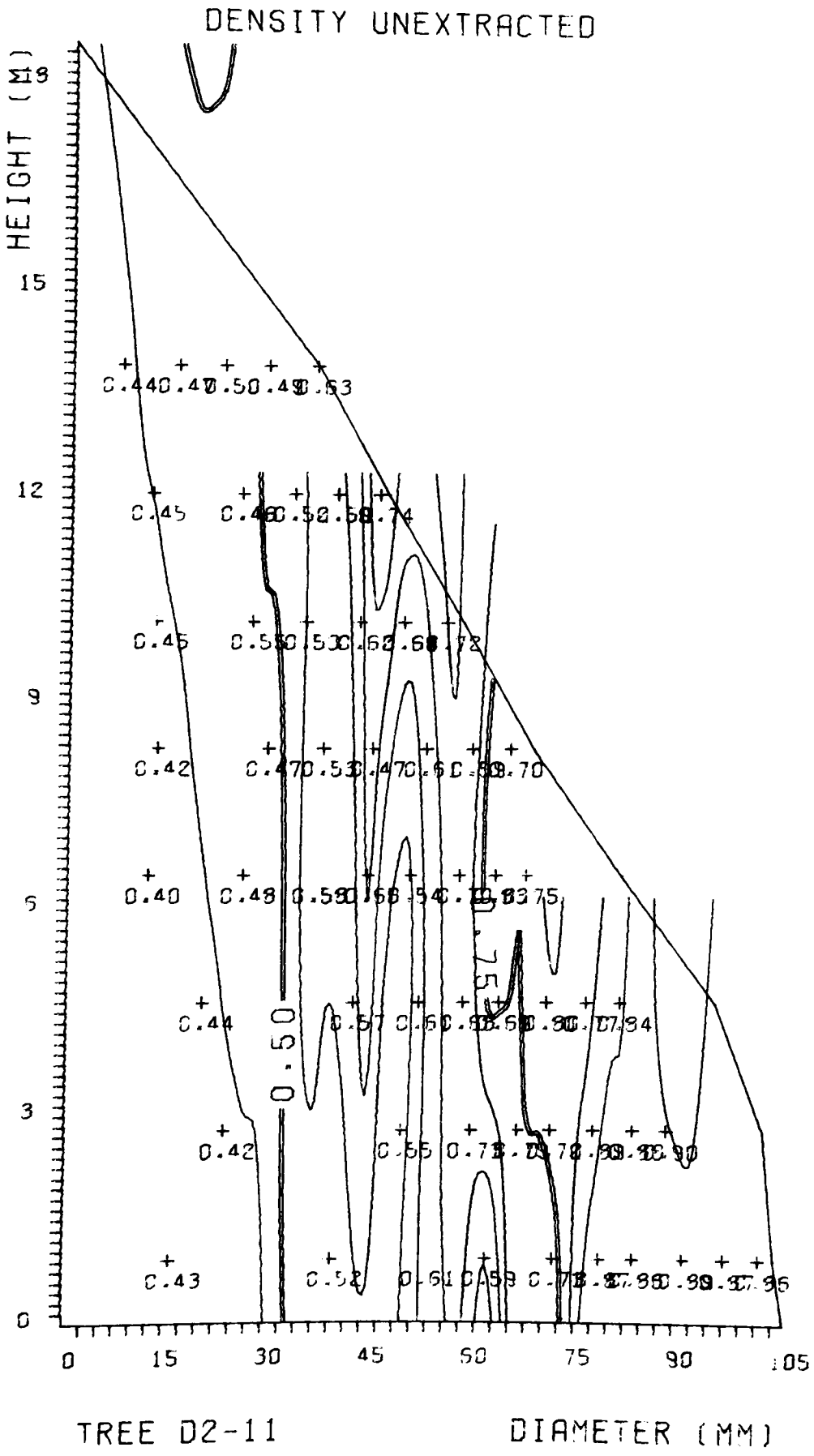
TREE D1-71
DIAMETER (MM)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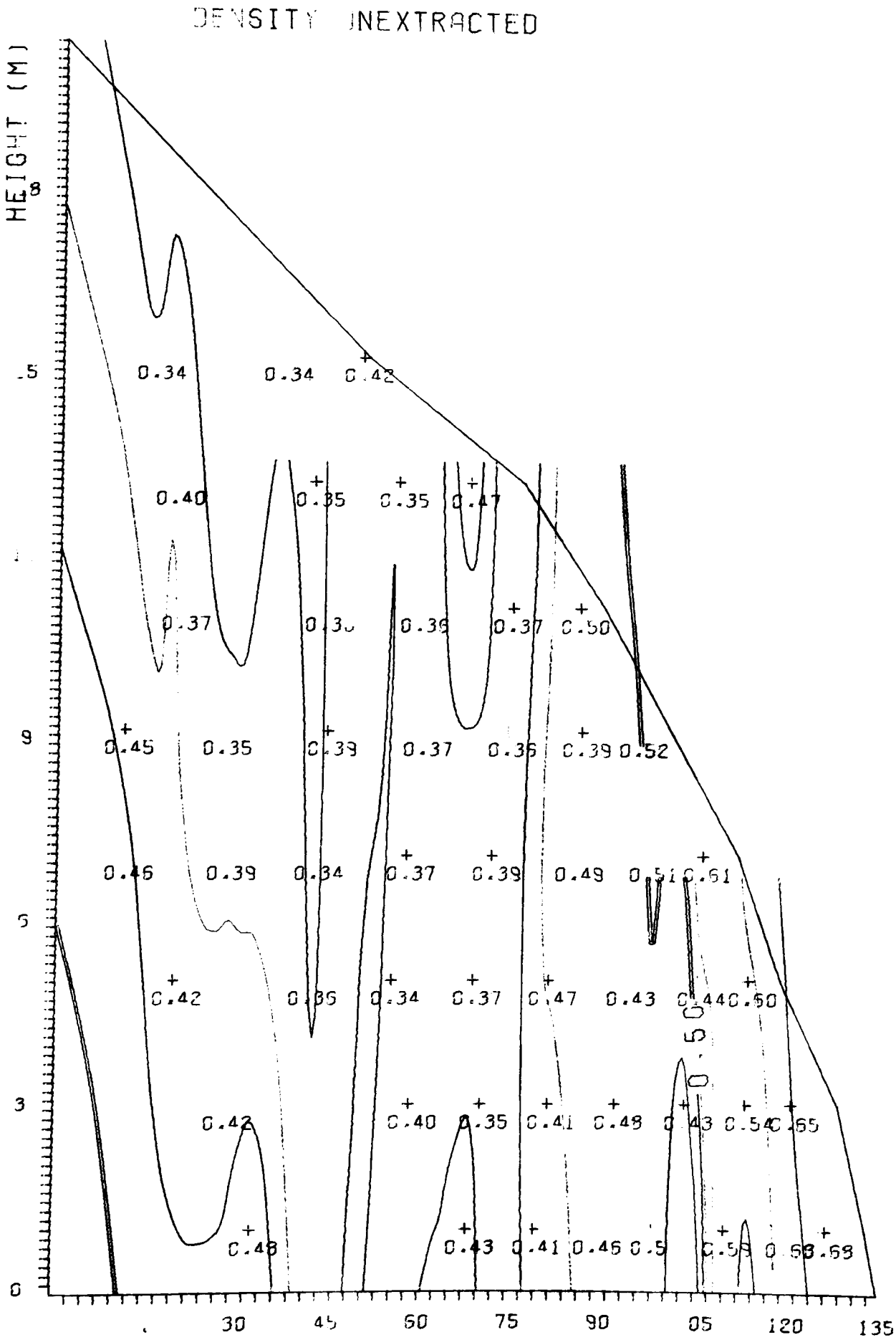
60
75
90
105
TREE D2-11
DIAMETER (MM)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0.37
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0.50
0.45
0.35
0.39
0.37
0.36
0.39
0.52
0.46
0.39
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0.39
0.49
0.51
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0.36
0.34
0.37
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0.43
0.44
0.50
0.42
0.40
0.35
0.41
0.48
0.43
0.54
0.65
0.48
0.43
0.41
0.46
0.5
0.58
0.68
0.68
30
45
60
75
90
05
120
135
TREE NH1-24
DIAMETER (MM)

DENSITY UNEXTRACTED

HEIGHT (M)

21

18

15

12

9

6

3

0

0.46 0.41 0.34

0.50 0.37 0.35 0.38 0.52

0.42 0.42 0.37 0.39 0.48

0.34 0.38 0.41 0.39 0.42

0.69 0.45 0.47 0.41 0.41 0.37

0.42 0.42 0.38 0.41 0.46

0.62 0.49 0.44 0.49 0.58 0.52

0.47 0.46 0.46 0.48 0.50 0.58

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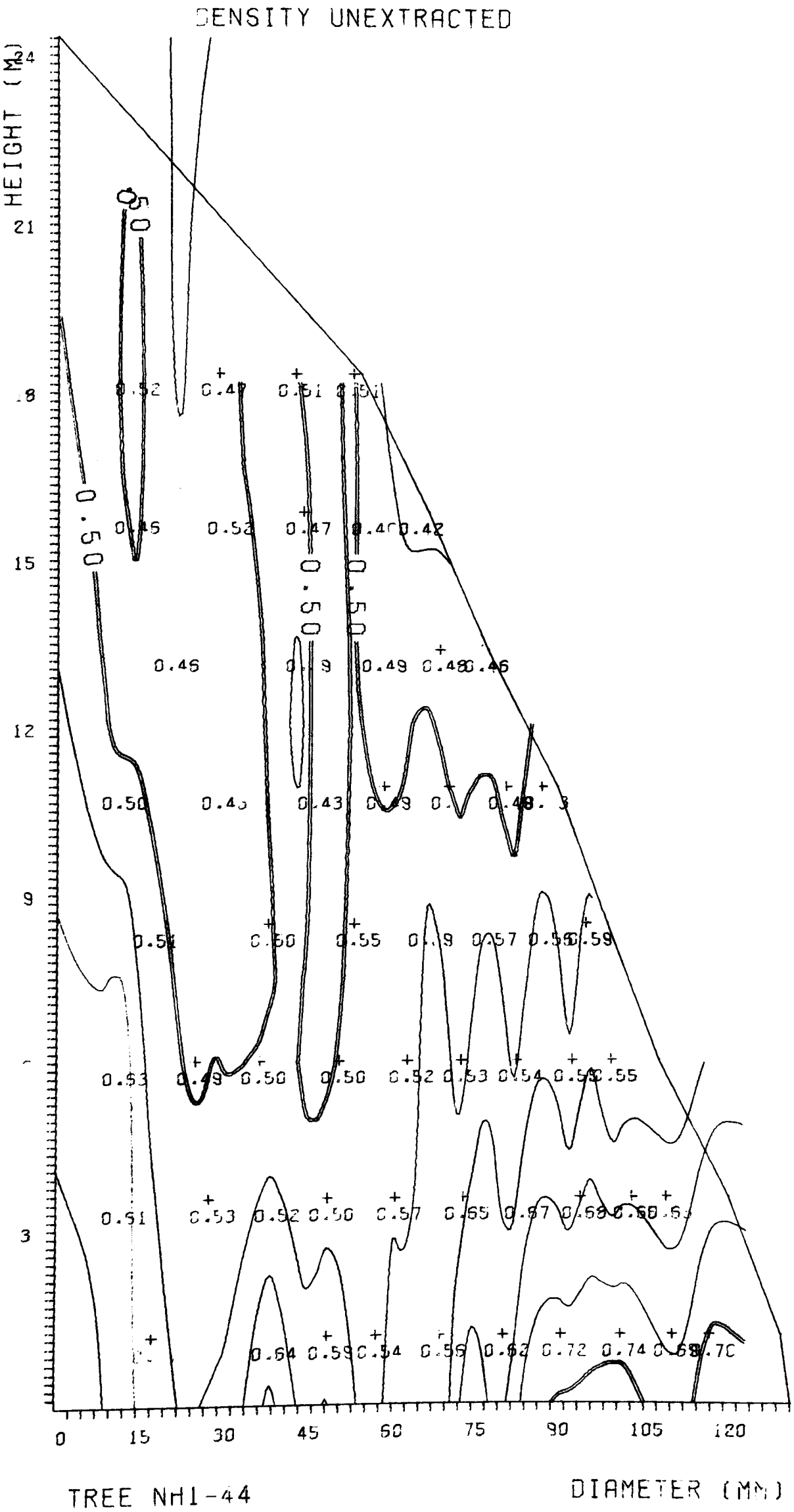
DIAMETER (MM)

TREE NH1-40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105
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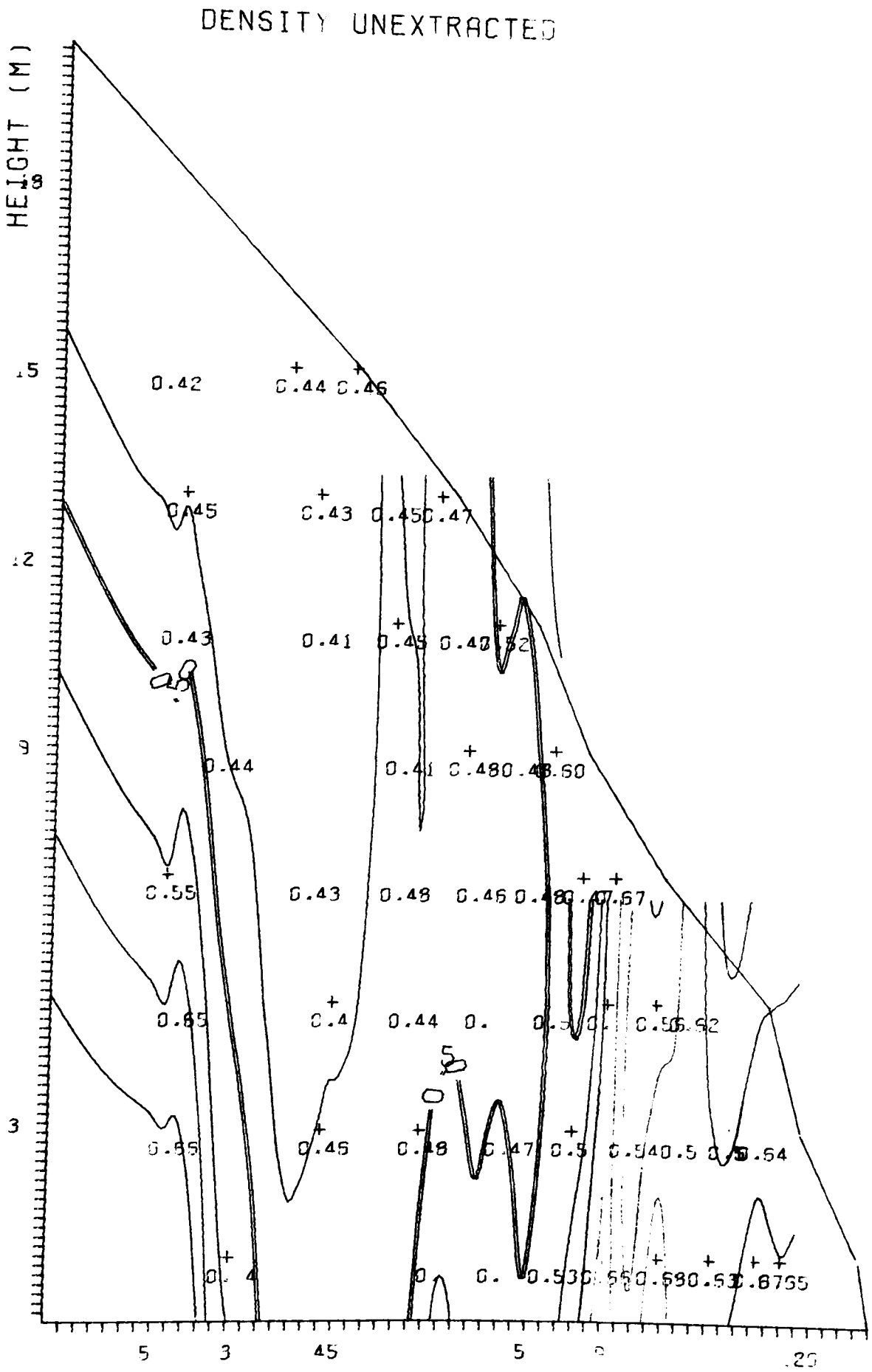
TREE NH1-44
DIAMETER (MM)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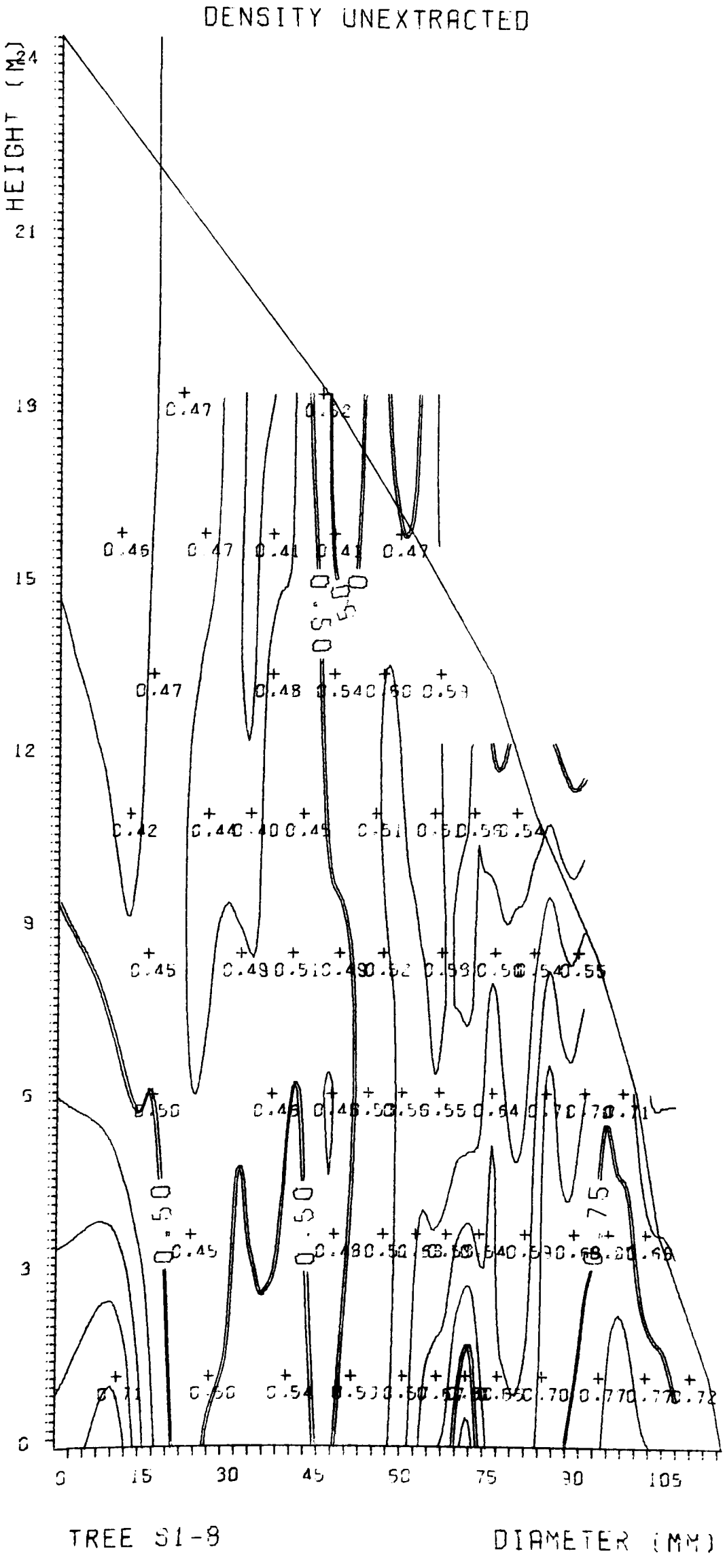
DIAMETER (MM)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60
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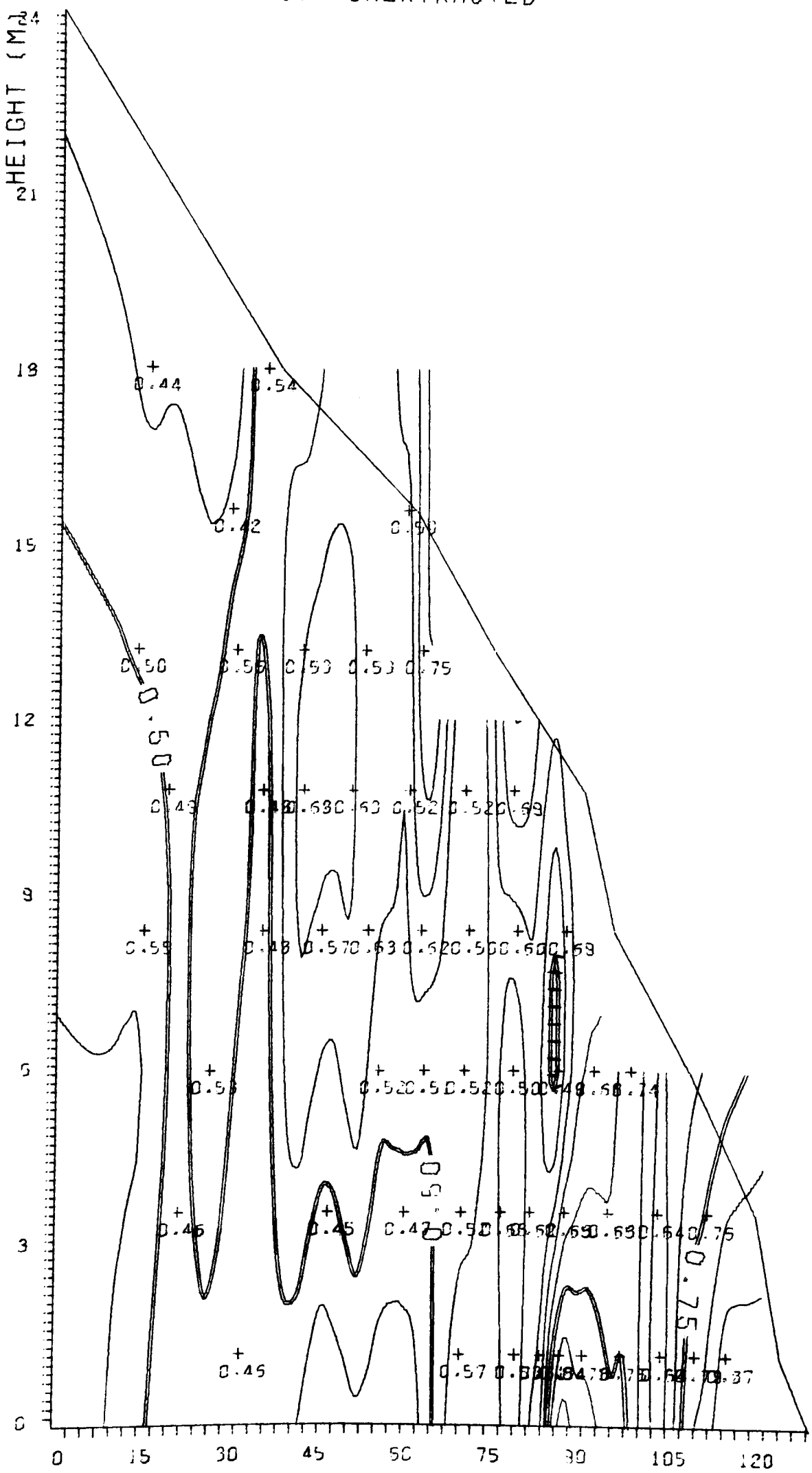
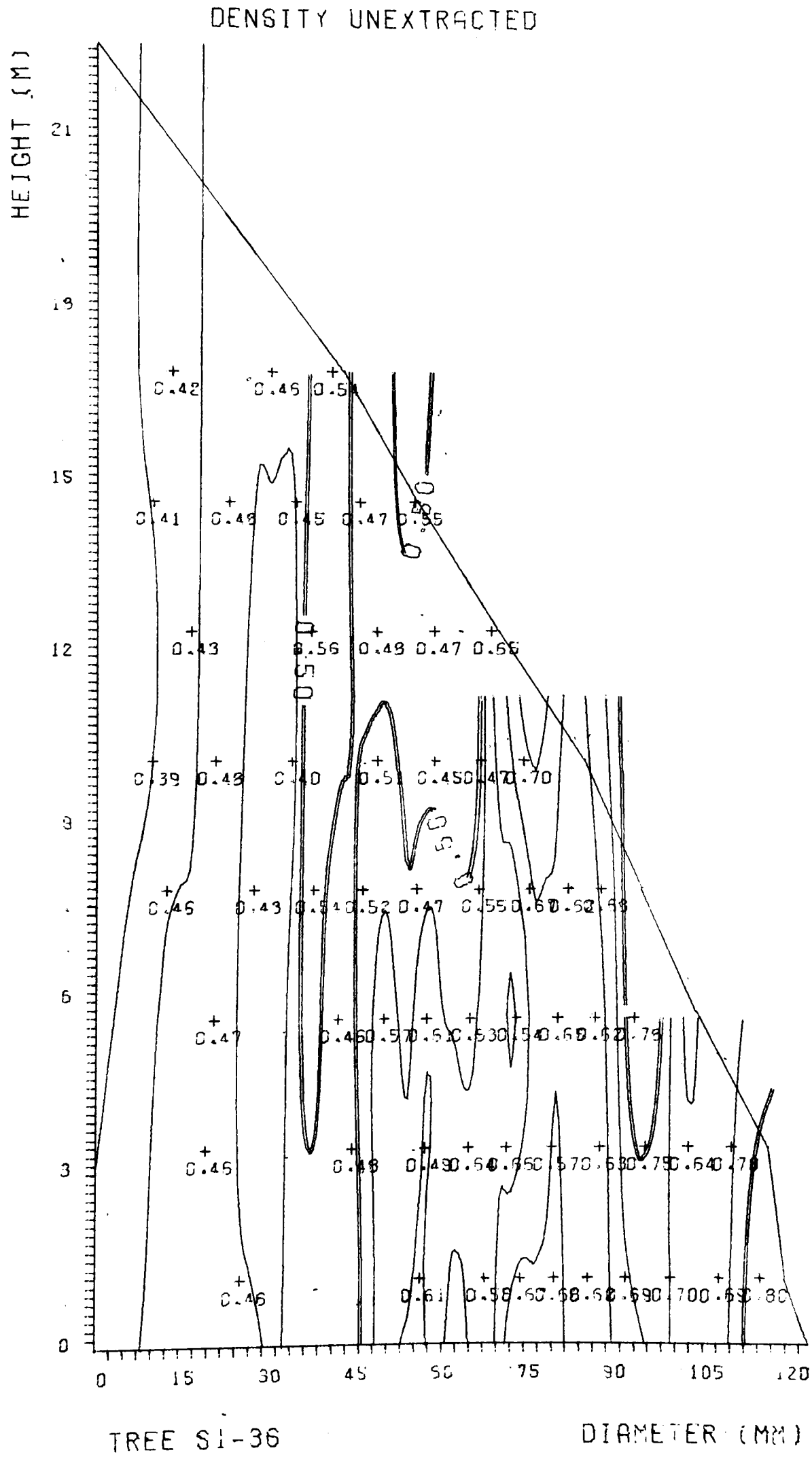
90
105
TREE S1-8
DIAMETER (MM)

DENSITY UNEXTRACTED



TREE S1-31

DIAMETER (MM)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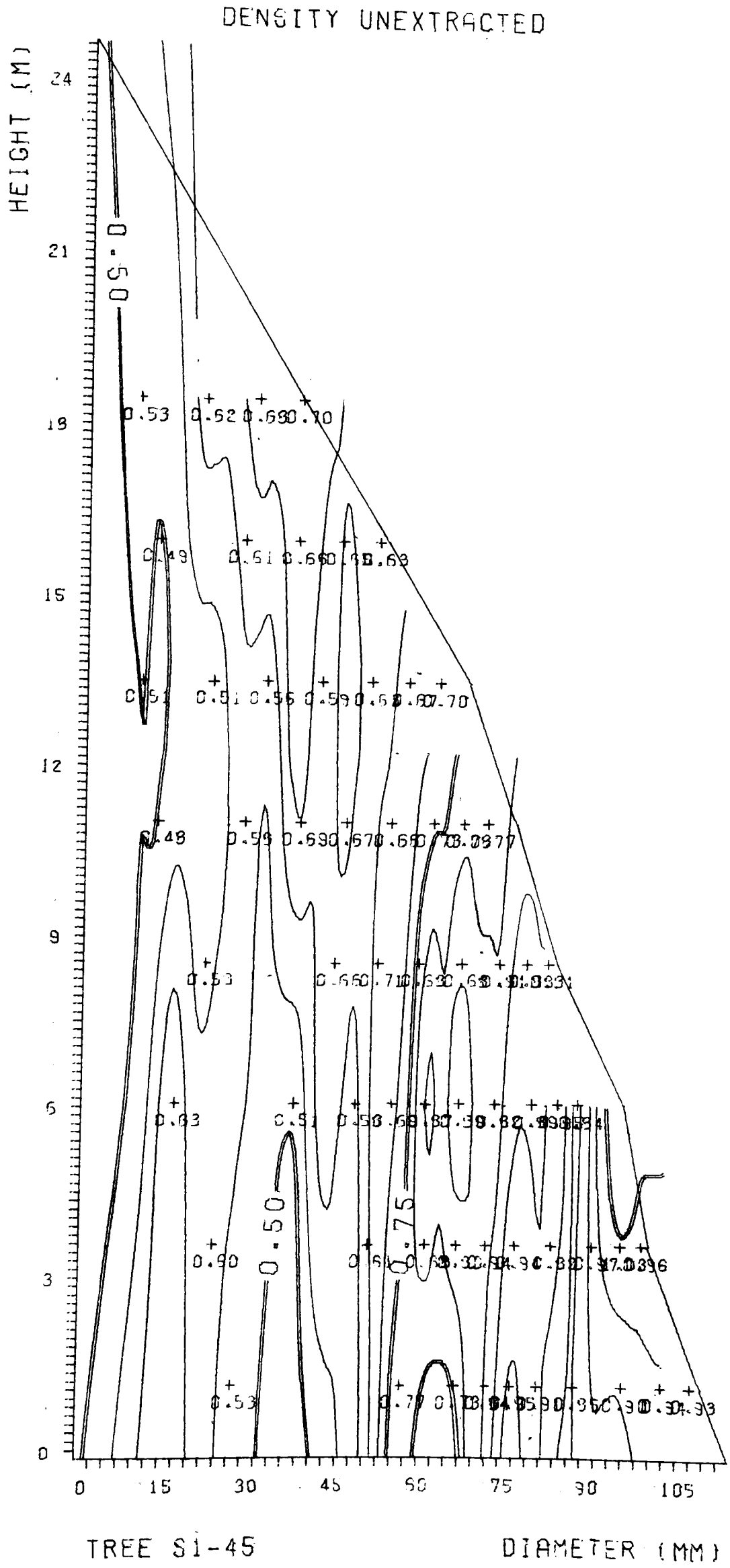
90
105
120
TREE SI-36
DIAMETER (MM)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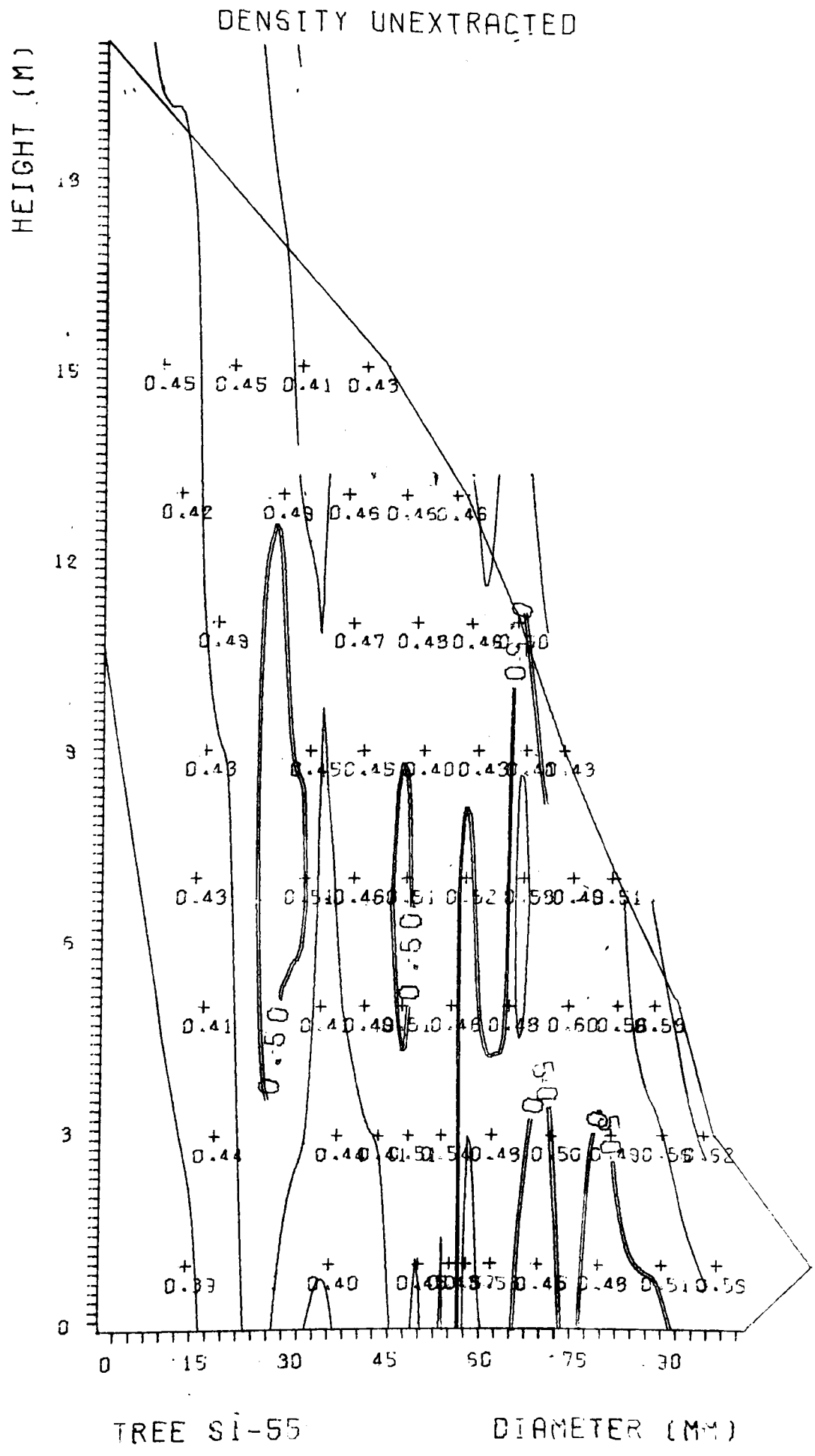
60
75
90
105
TREE SI-45
DIAMETER (MM)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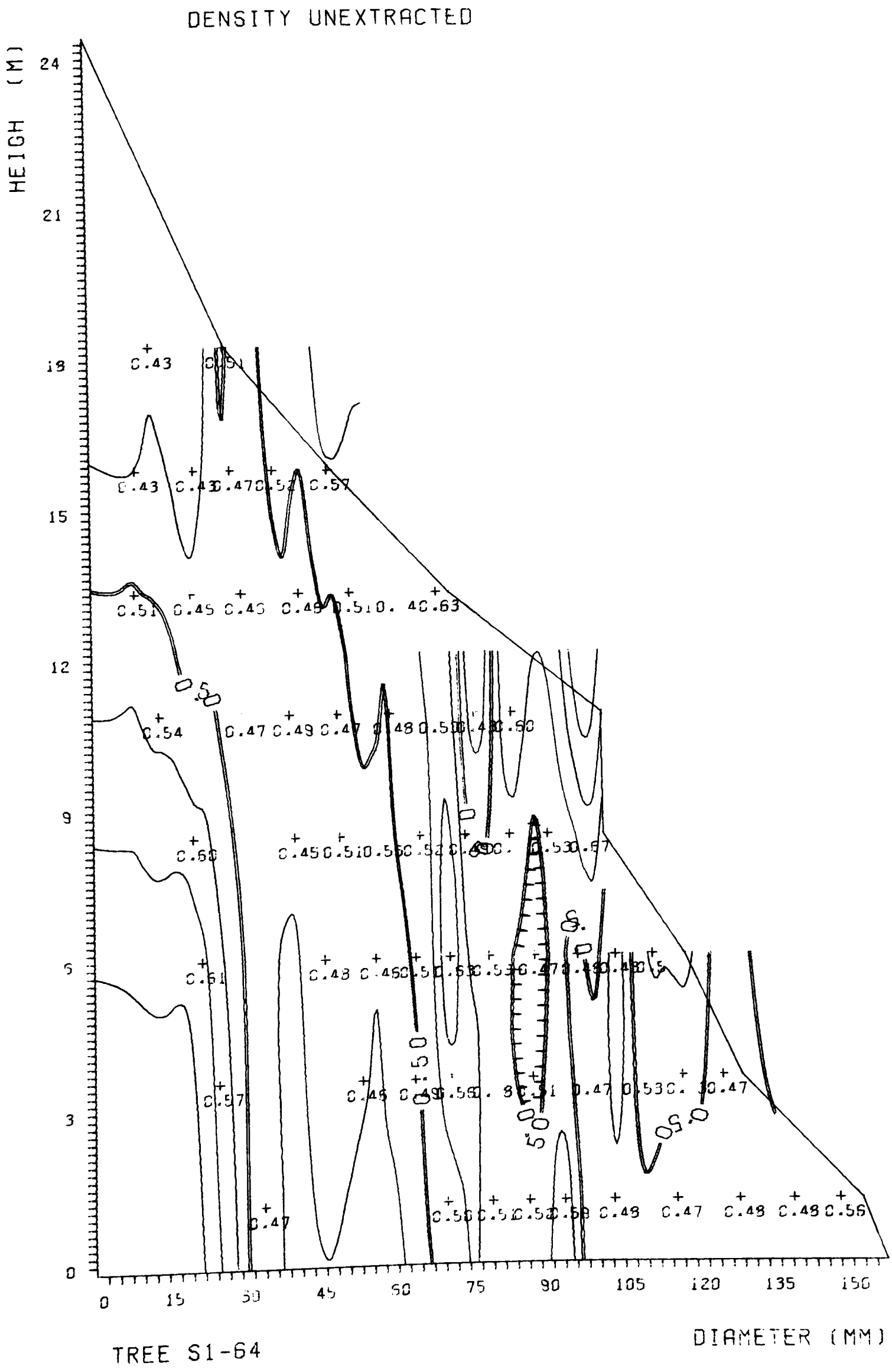
60
75
90
TREE SI-55
DIAMETER (MM)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15
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90
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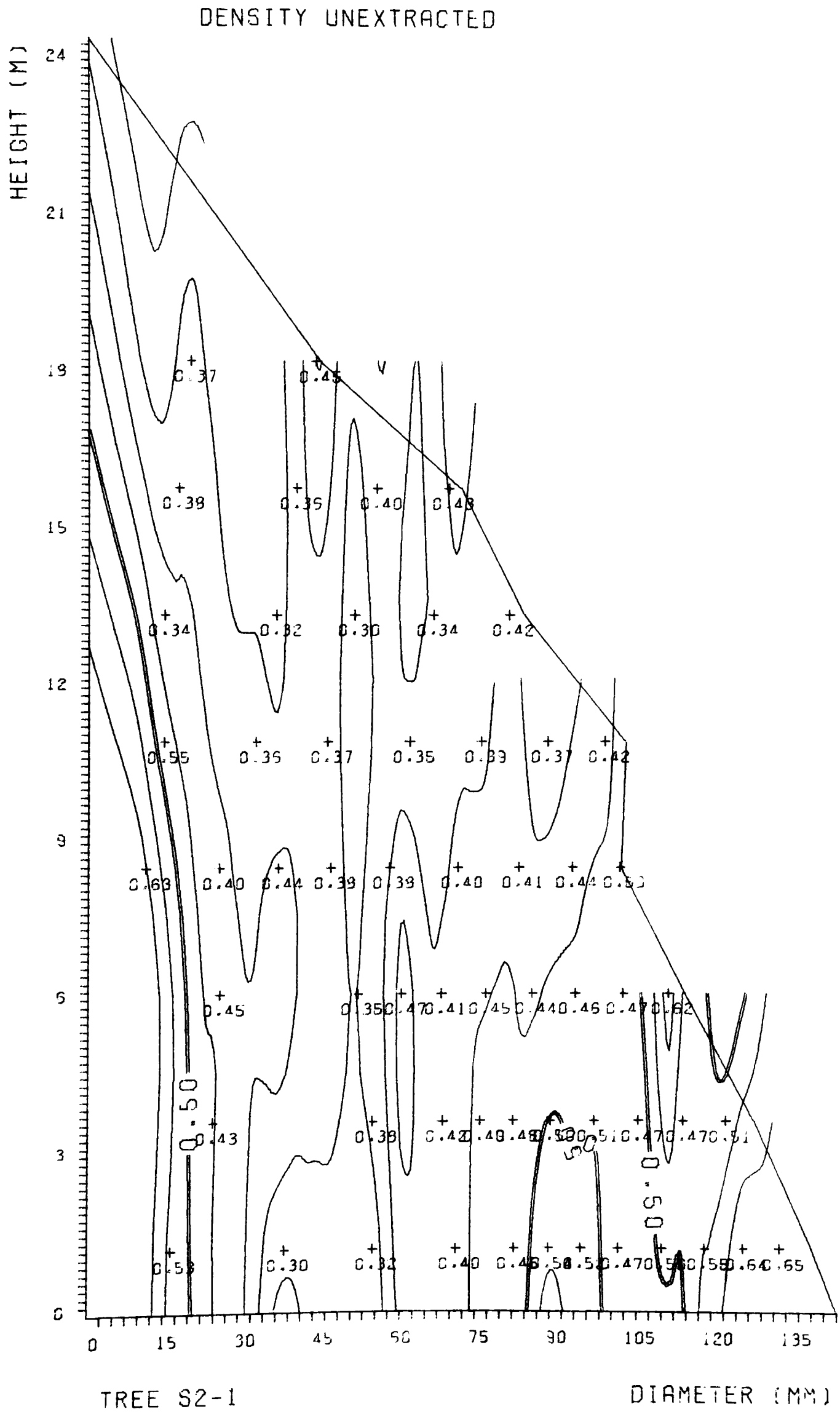
120
135
150
DIAMETER (MM)
TREE S1-64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45
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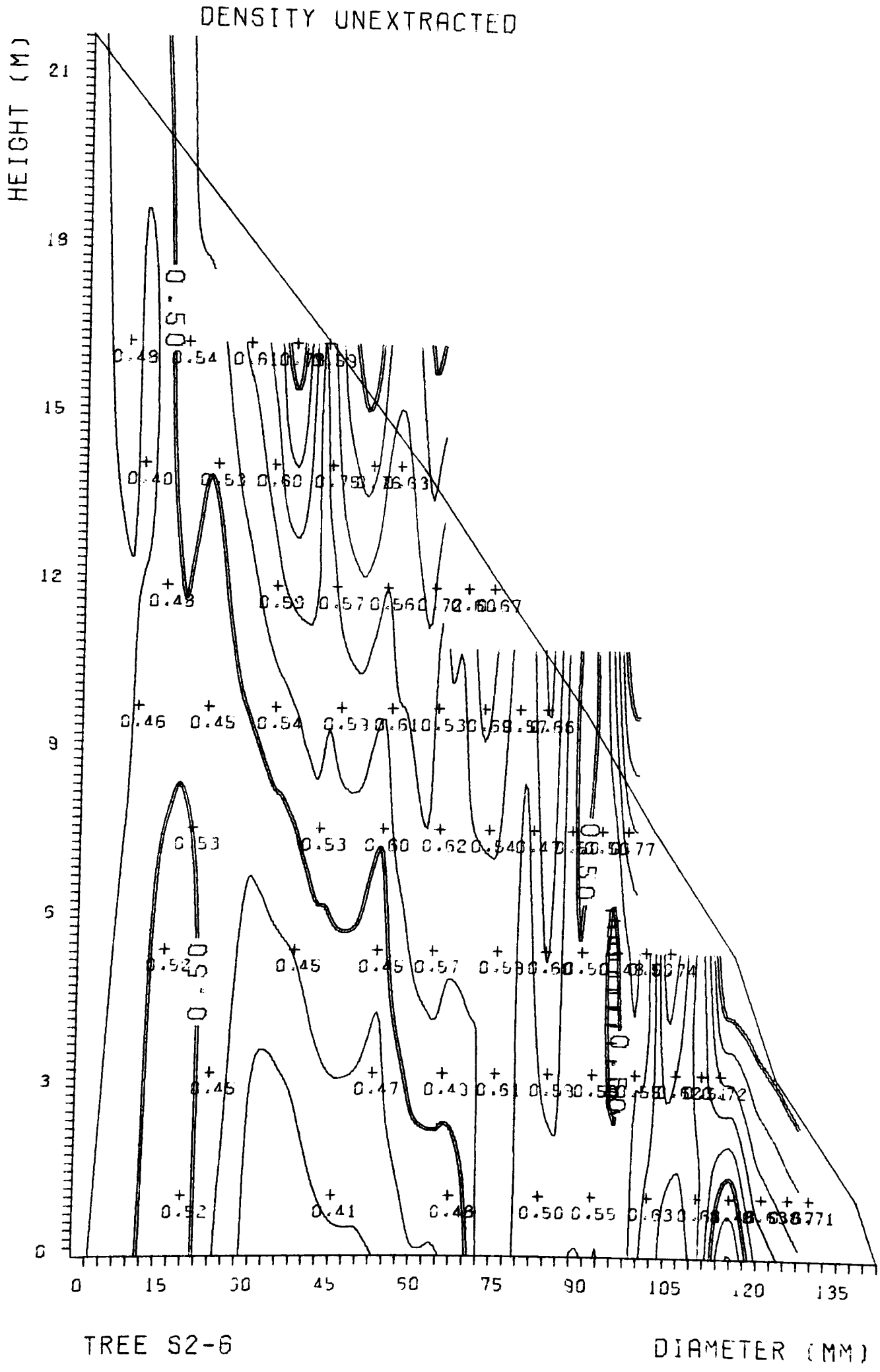
75
90
105
120
135
TREE S2-1
DIAMETER (MM)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HEIGHT (M)
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15
12
9
6
3
0
0.50
0
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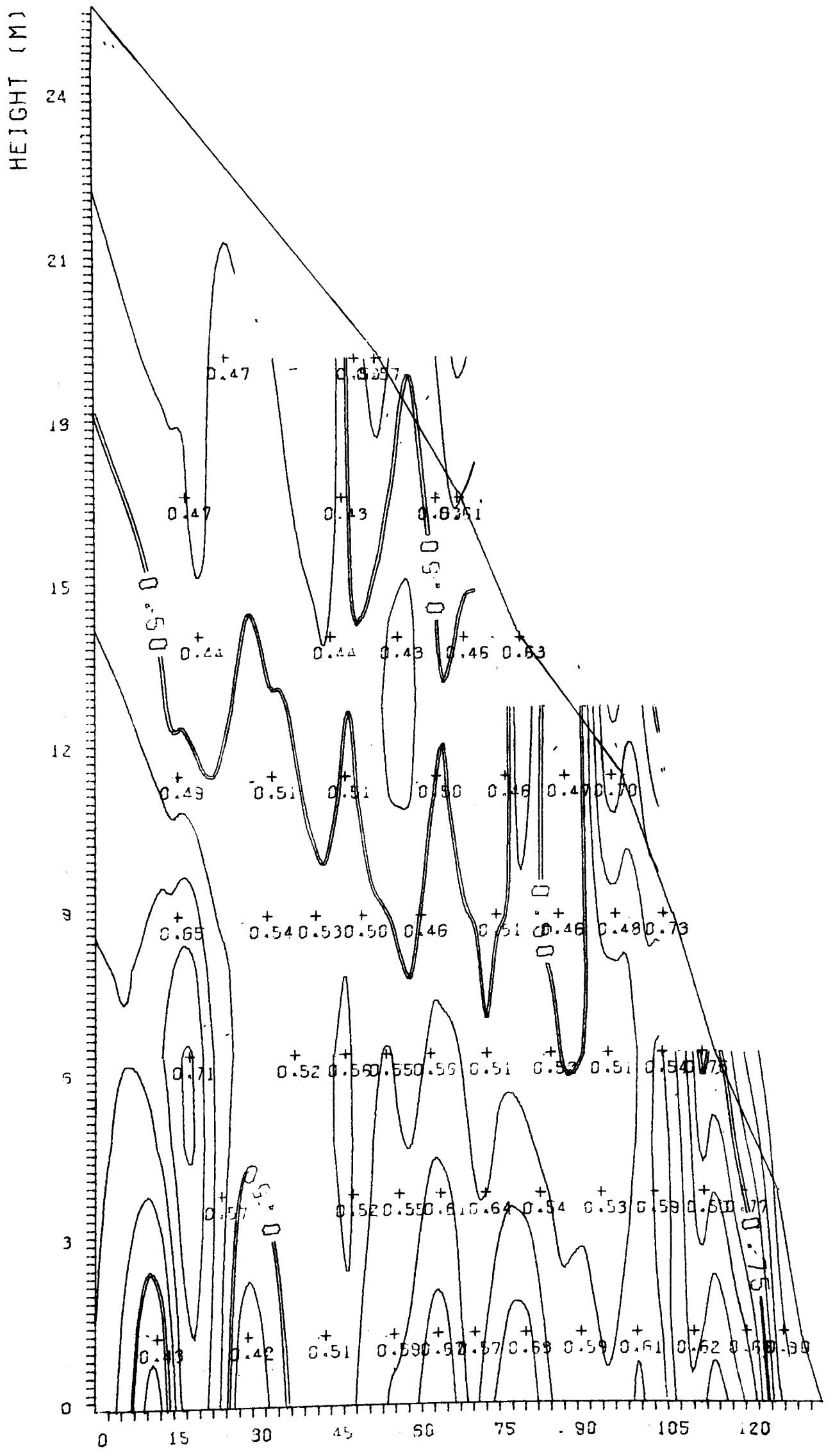
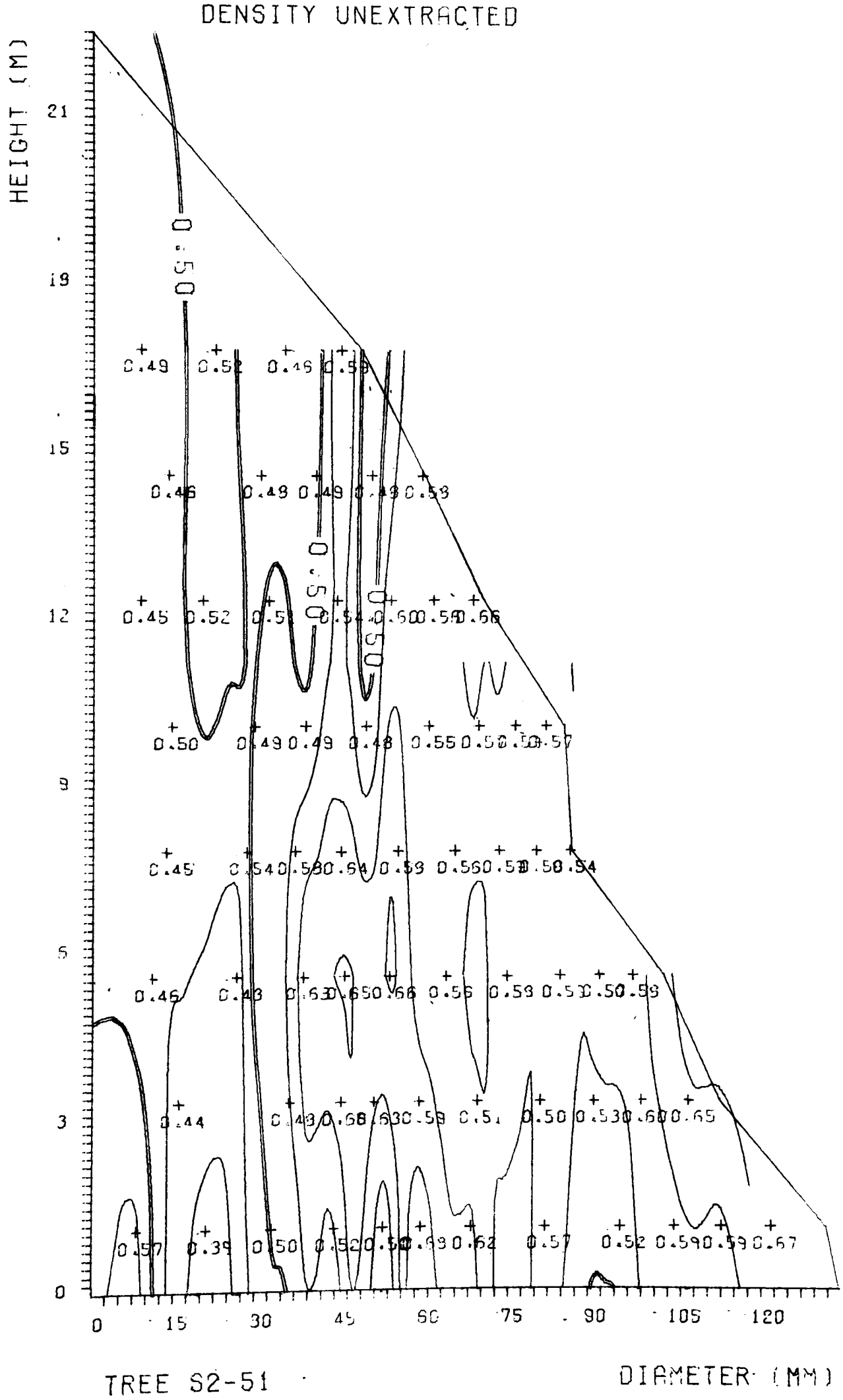
30
45
50
75
90
105
120
135
TREE S2-6
DIAMETER (MM)

DENSITY UNEXTRACTED



TREE S2-37

DIAMETER (MM)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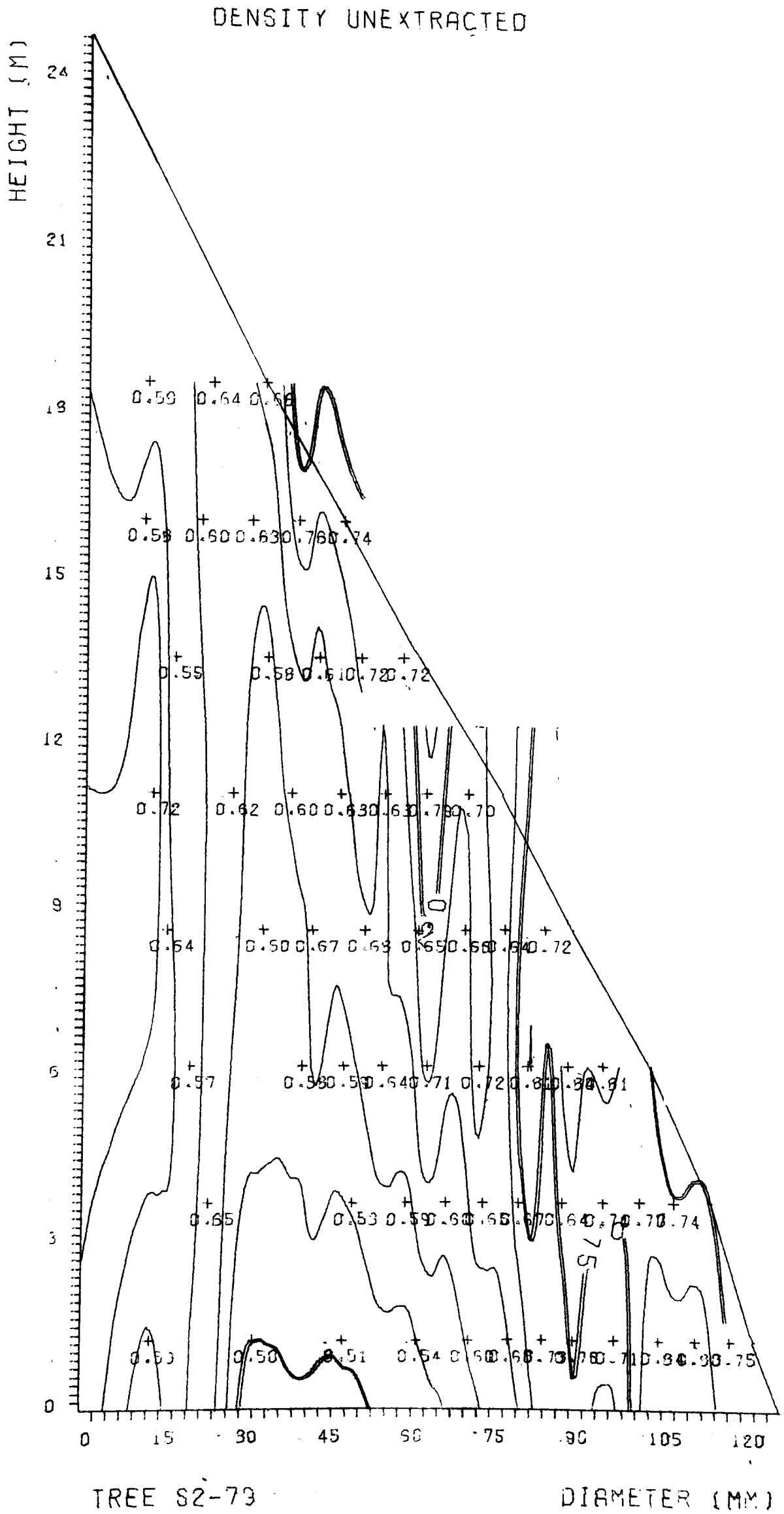
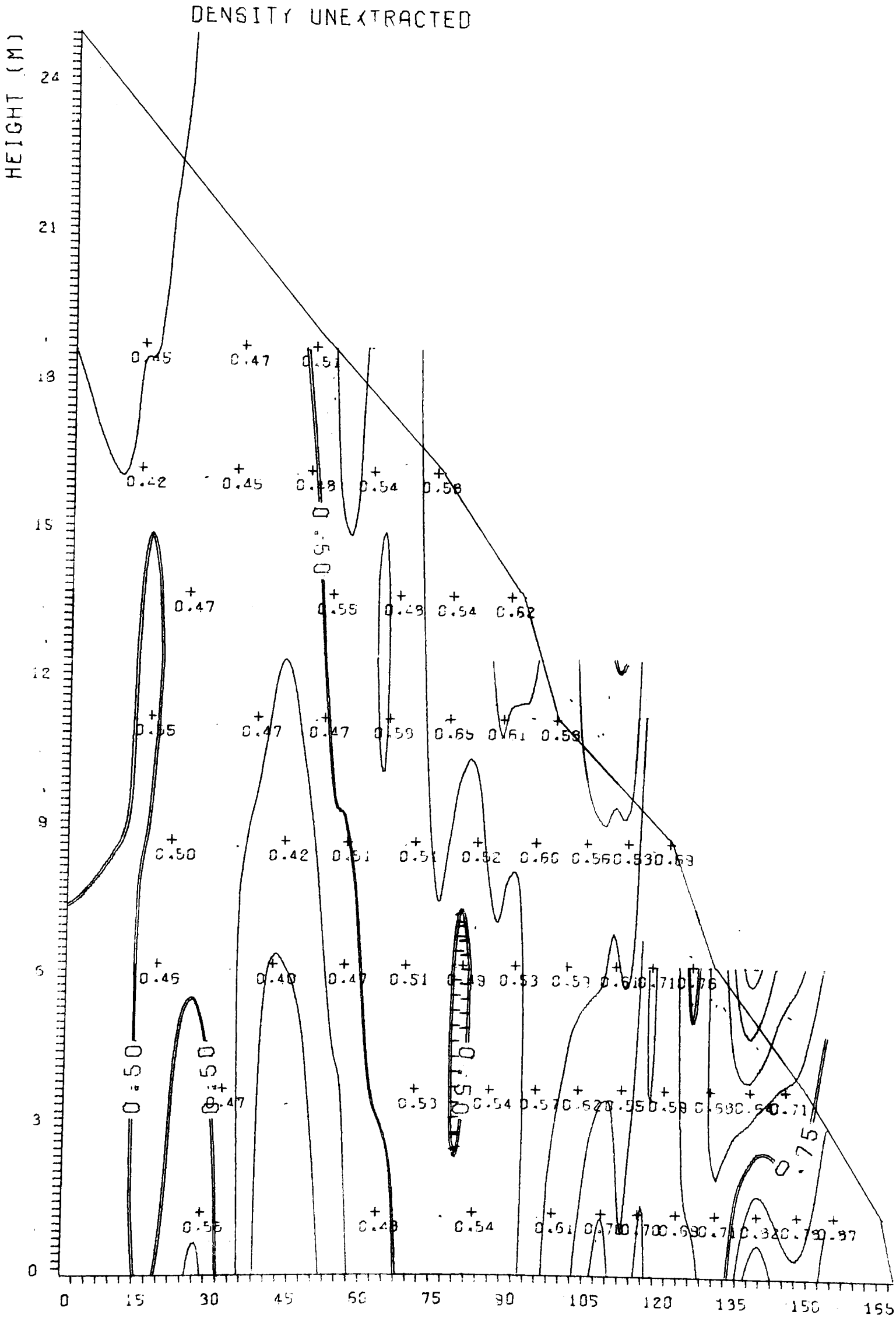
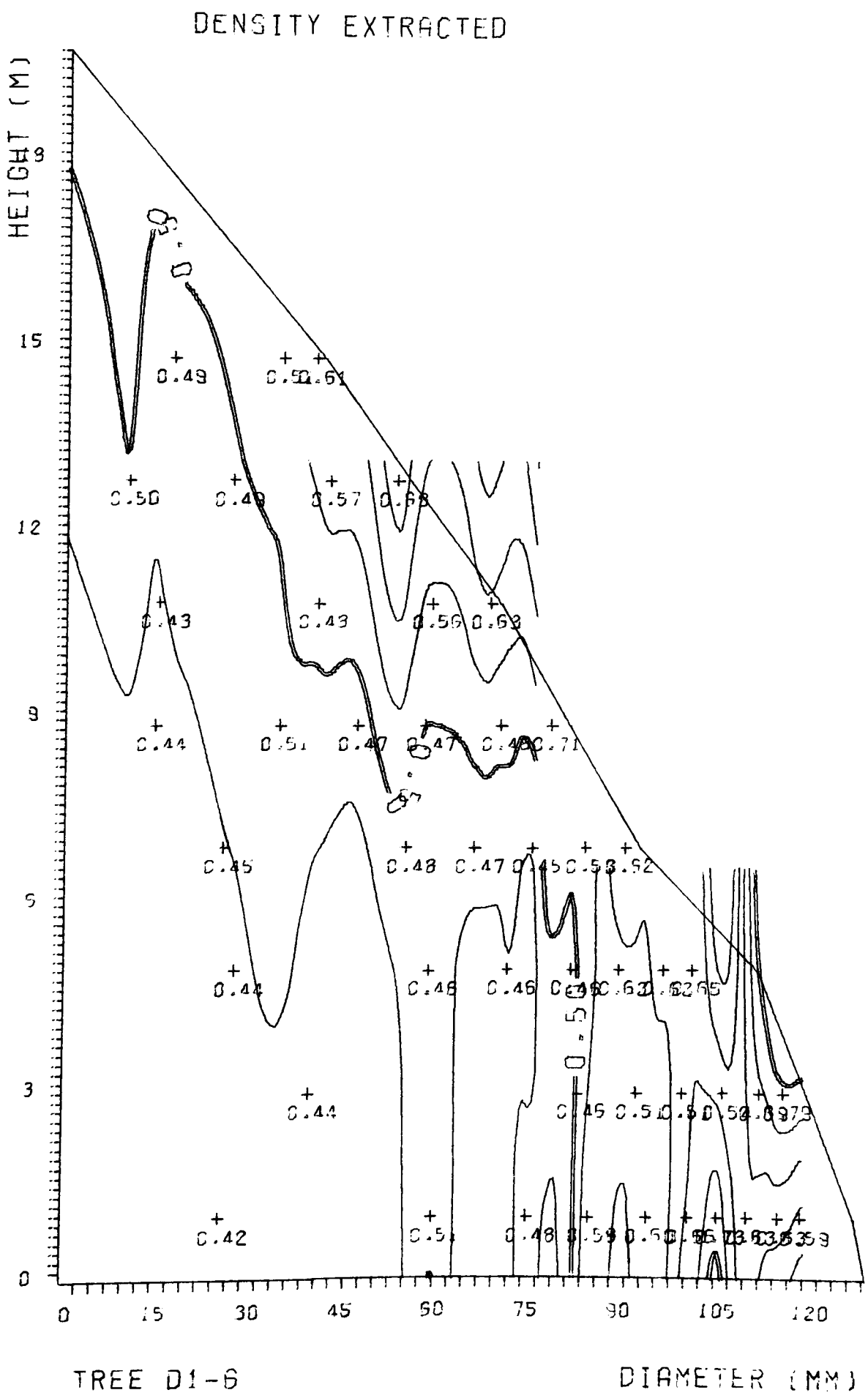
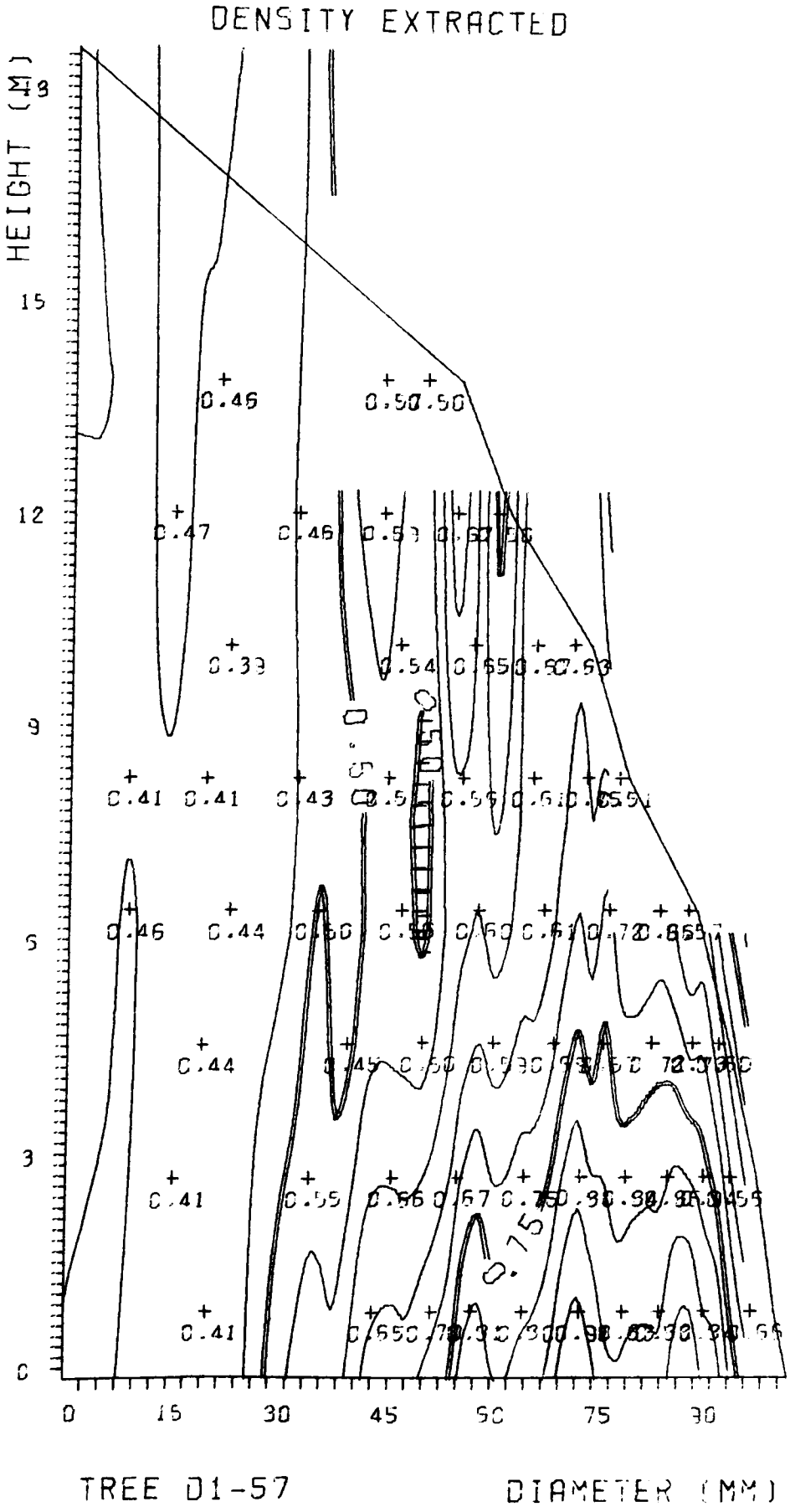
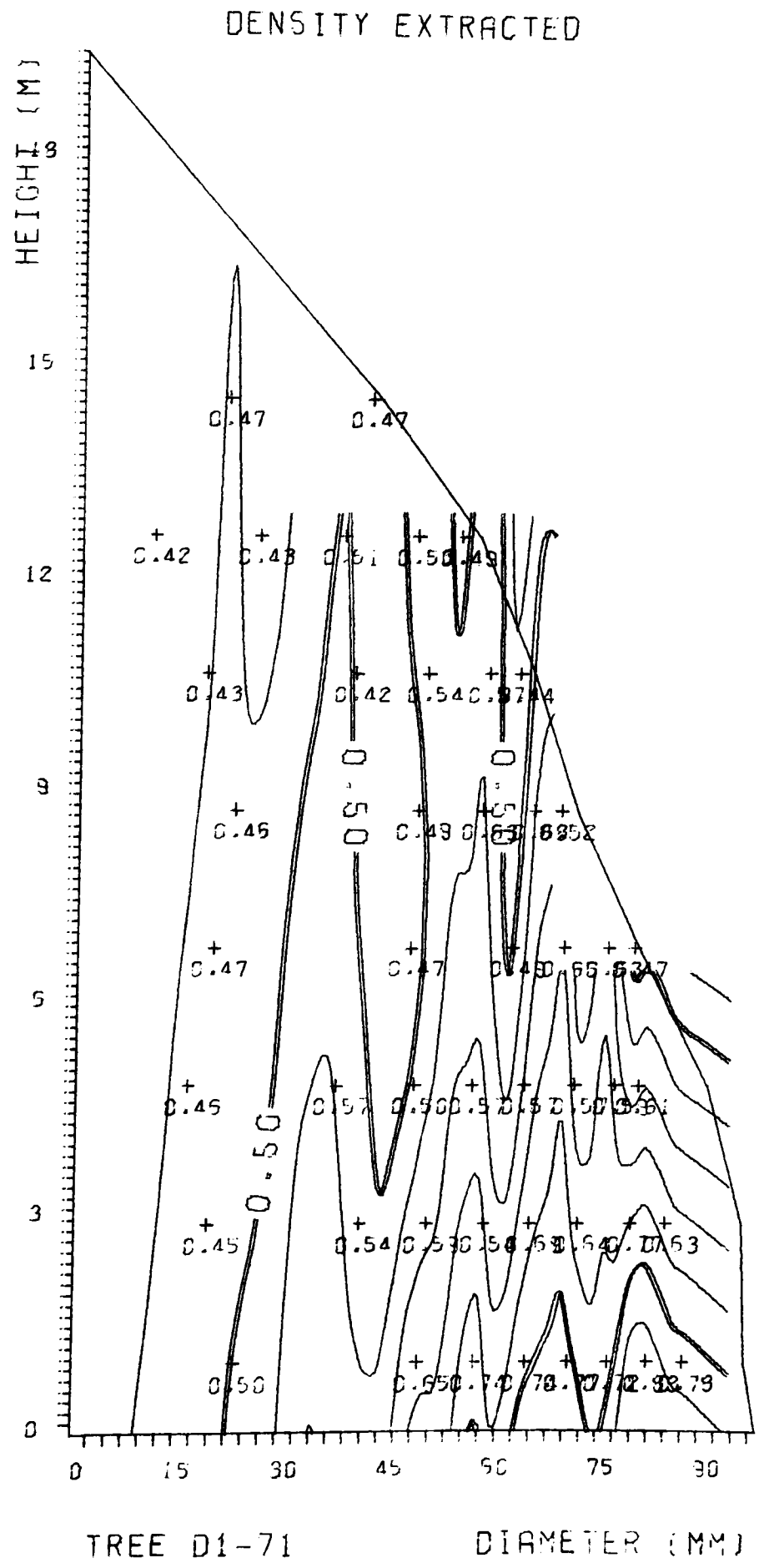
0
0.50
0.50
0.50
0.49 0.52 0.46 0.50
0.46 0.49 0.49 0.48 0.53
0.45 0.52 0.50 0.54 0.60 0.59 0.66
0.50 0.49 0.49 0.48 0.55 0.50 0.57
0.45 0.54 0.58 0.64 0.59 0.56 0.58 0.54
0.46 0.48 0.63 0.65 0.66 0.56 0.59 0.50 0.58
0.44 0.48 0.68 0.63 0.59 0.51 0.50 0.53 0.68 0.65
0.57 0.39 0.50 0.52 0.58 0.62 0.57 0.52 0.59 0.59 0.67
0 15 30 45 60 75 90 105 120
TREE S2-51
DIAMETER (MM)

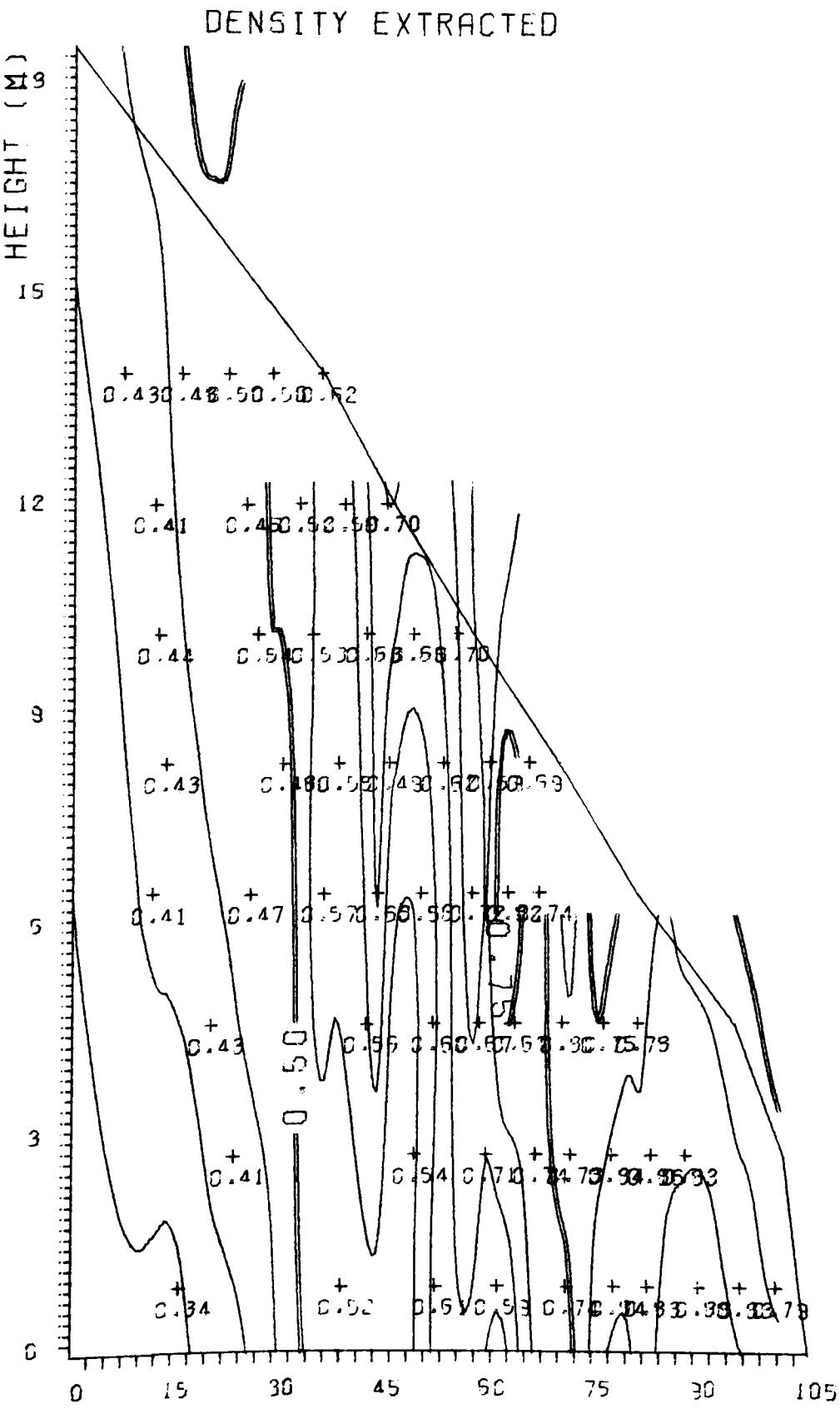

DENSITY UNEXTRACTED
HEIGHT (M)
24
21
18
15
12
9
6
3
0
0
15
30
45
60
75
90
105
120
TREE S2-73
DIAMETER (MM)

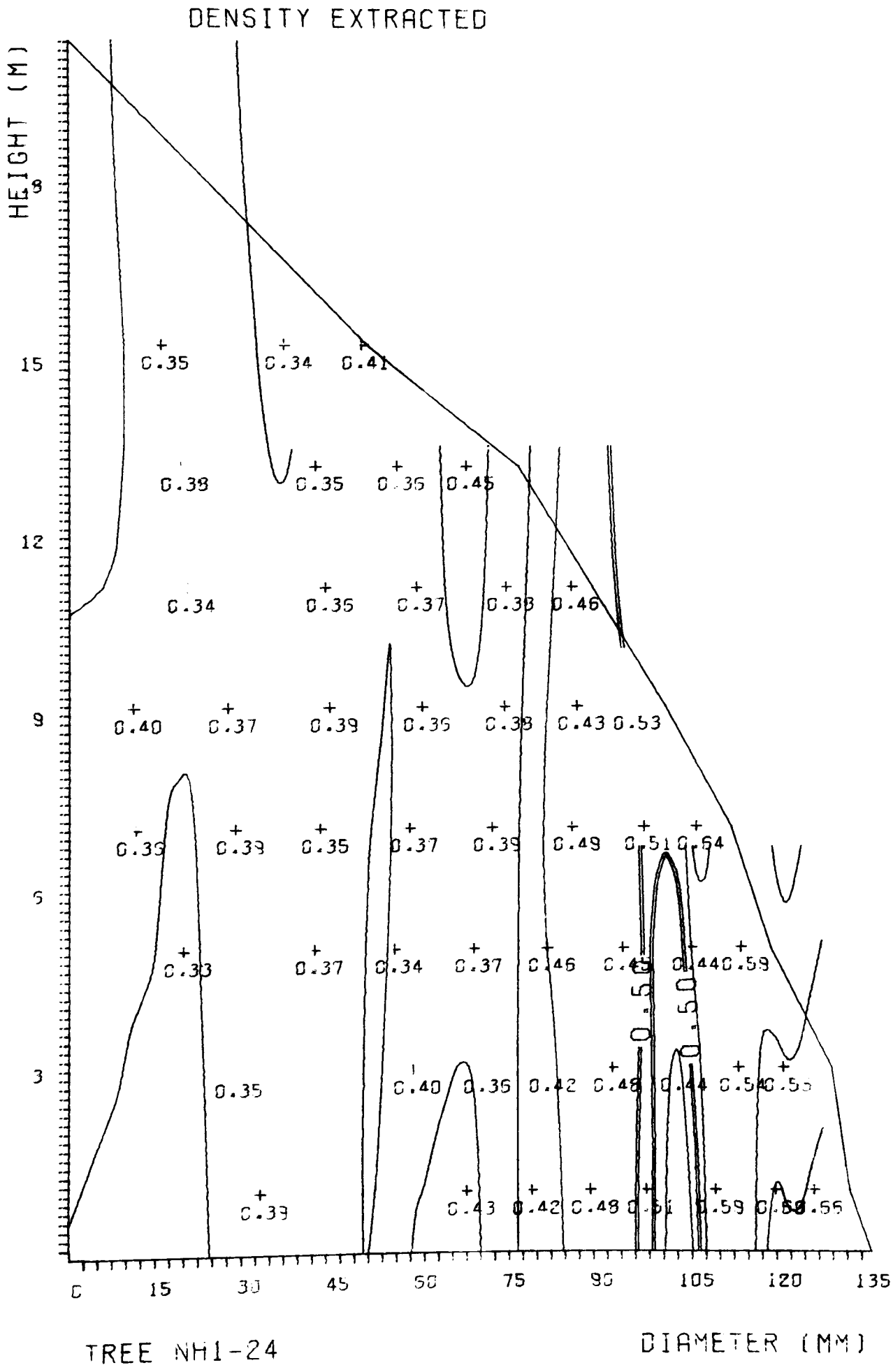

DENSITY UNEXTRACTED
HEIGHT (M)
24
21
18
15
12
9
6
3
0
0
15
30
45
60
75
90
105
120
135
150
155
0.50
0.75
TREE S2-84
DIAMETER (MM)

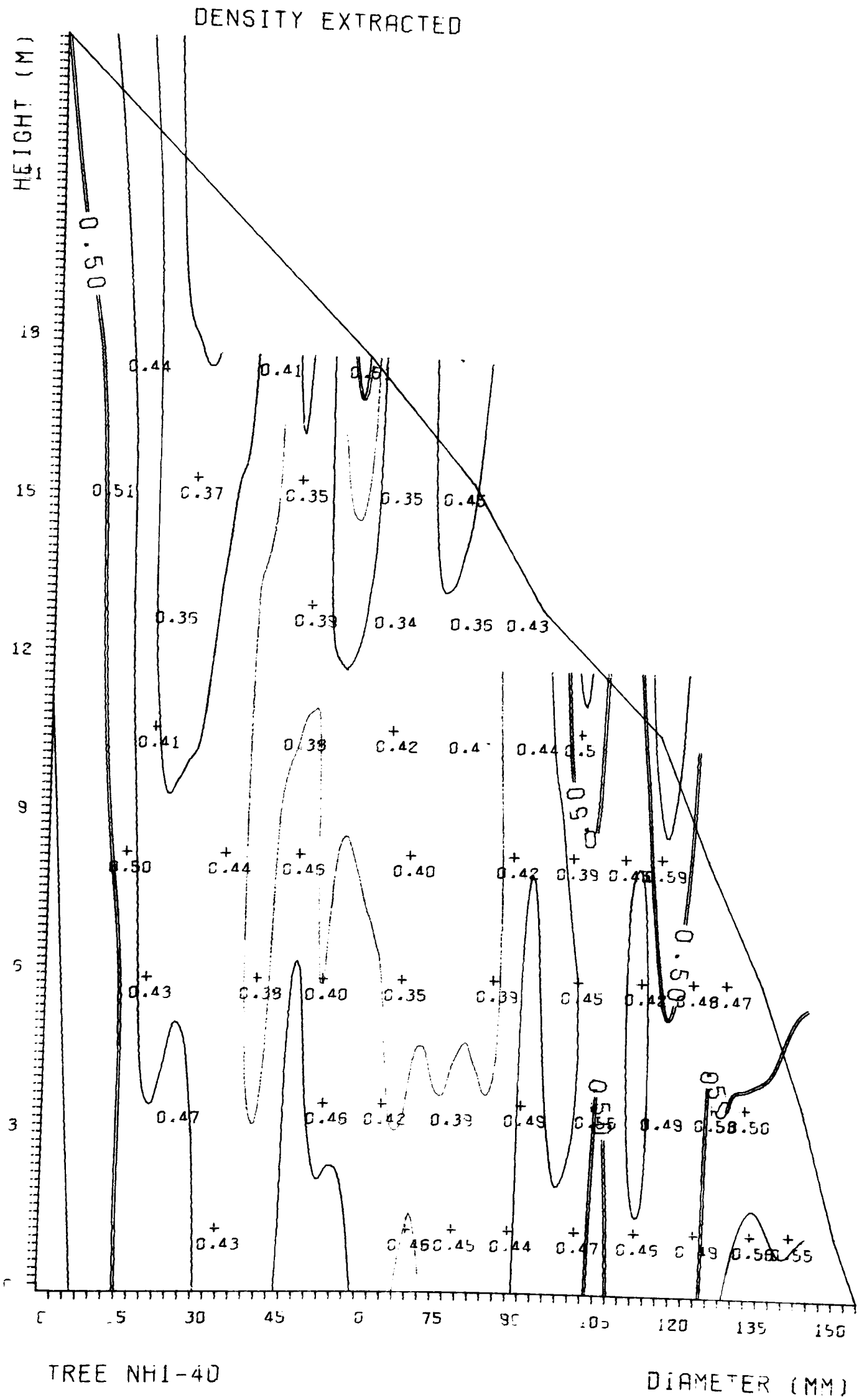

DENSITY EXTRACTED
HEIGHT (M)
0
3
6
9
12
15
0
15
30
45
60
75
90
105
120
TREE D1-6
DIAMETER (MM)

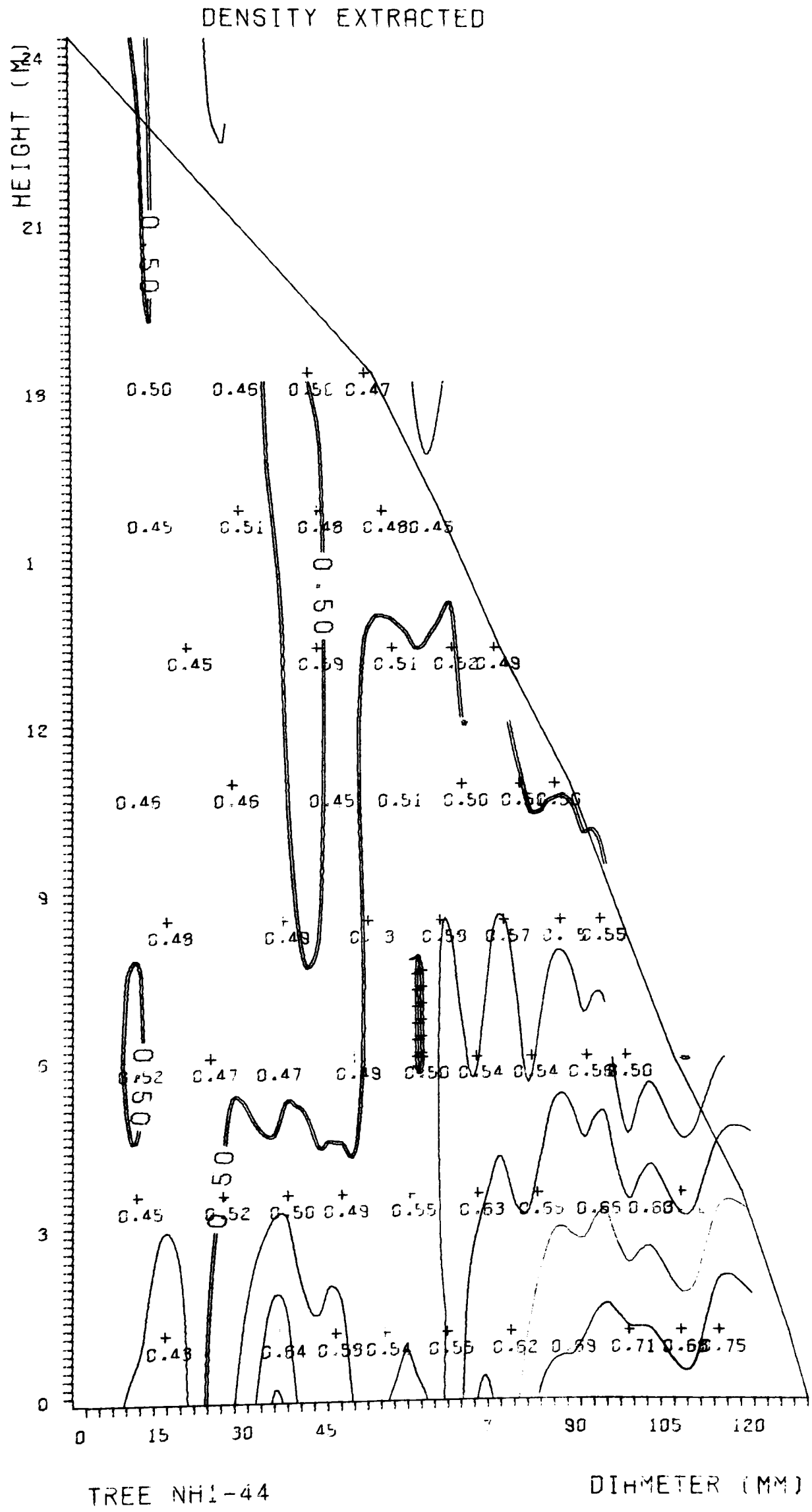

DENSITY EXTRACTED
HEIGHT (M)
0
3
6
9
12
15
0
15
30
45
60
75
90
TREE D1-57
DIAMETER (MM)

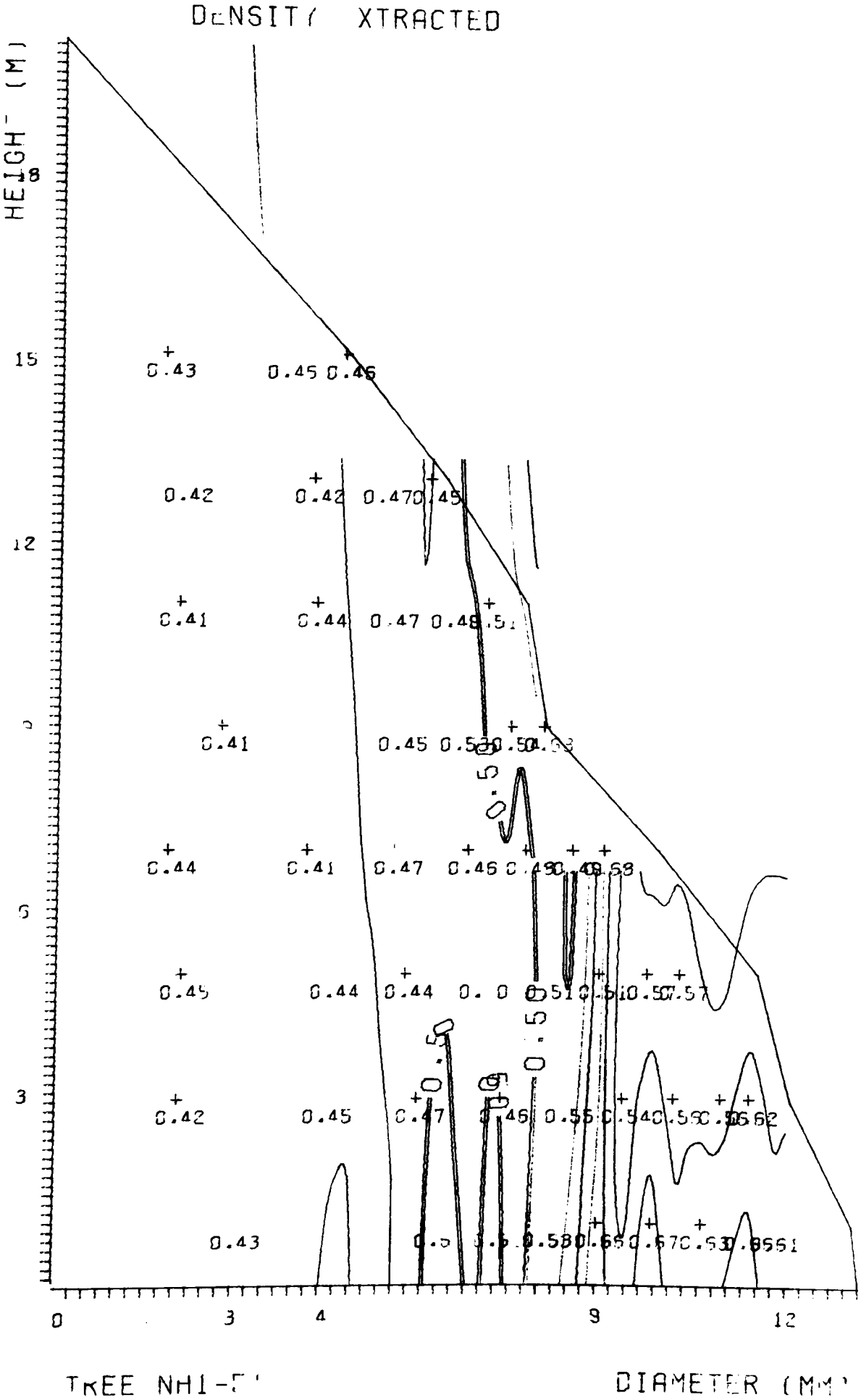

DENSITY EXTRACTED
HEIGHT (M)
18
15
12
9
6
3
0
0.50
0
15
30
45
60
75
90
TREE D1-71
DIAMETER (MM)

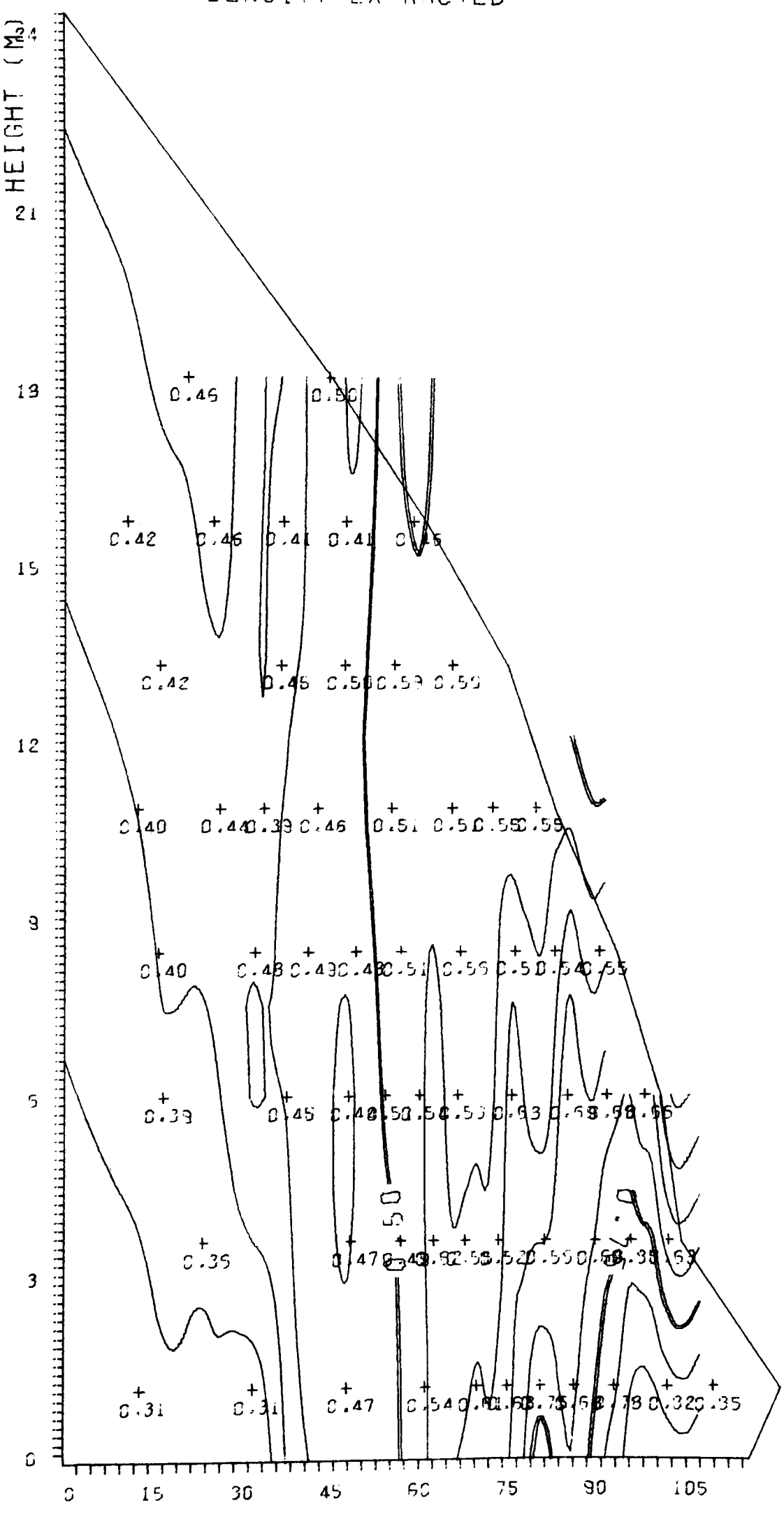

DENSITY EXTRACTED
HEIGHT (M)
0
3
6
9
12
15
0
15
30
45
60
75
90
105
0.50
TREE D2-11
DIAMETER (MM)

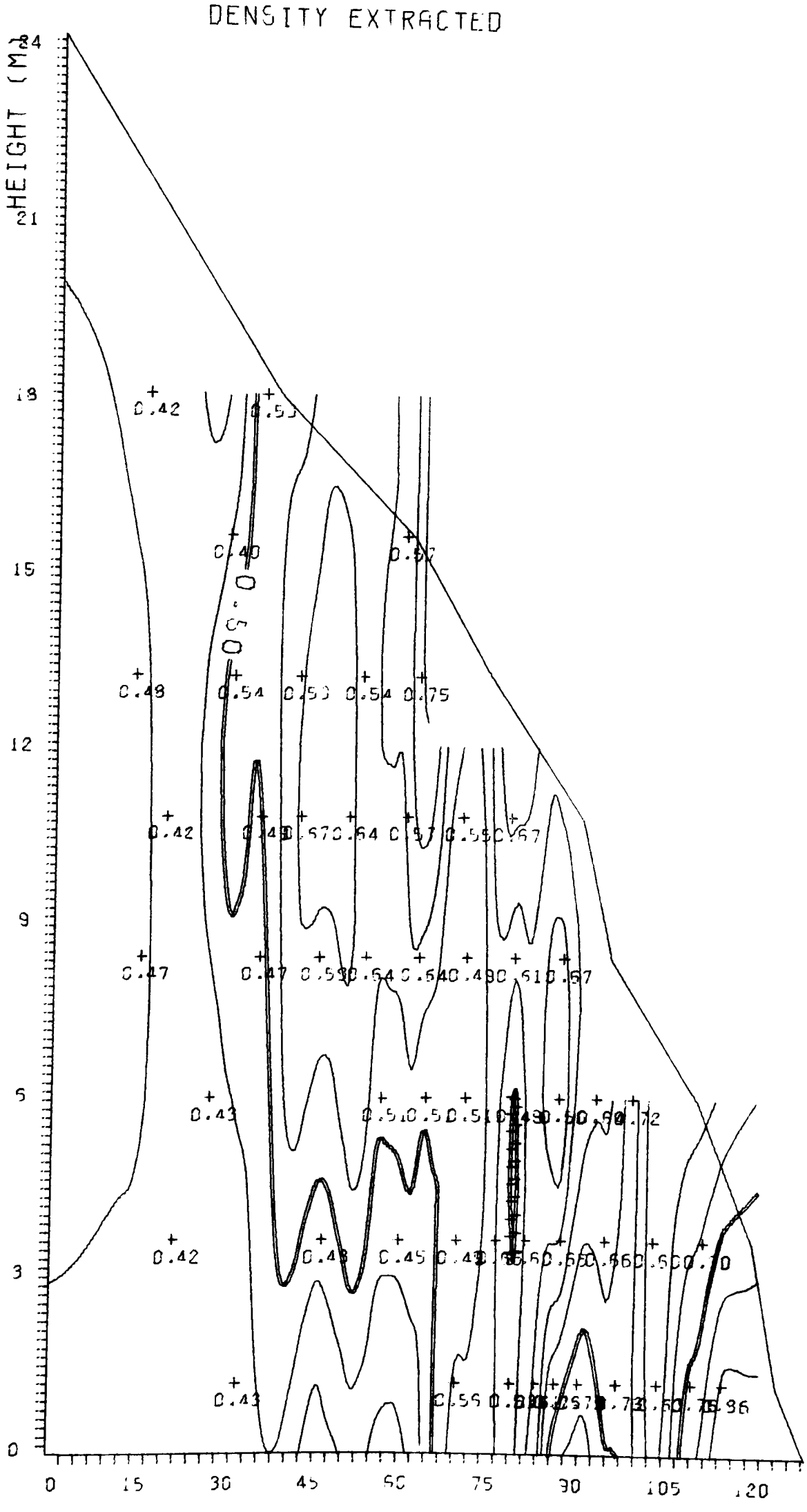

DENSITY EXTRACTED
HEIGHT (M)
18
15
12
9
6
3
0
15
30
45
60
75
90
105
120
135
0.35
0.34
0.41
0.38
0.35
0.36
0.45
0.34
0.35
0.37
0.38
0.46
0.40
0.37
0.39
0.36
0.38
0.43
0.53
0.39
0.39
0.35
0.37
0.39
0.49
0.51
0.54
0.33
0.37
0.34
0.37
0.46
0.45
0.44
0.59
0.50
0.50
0.35
0.40
0.36
0.42
0.48
0.44
0.54
0.55
0.39
0.43
0.42
0.48
0.51
0.59
0.56
TREE NH1-24
DIAMETER (MM)

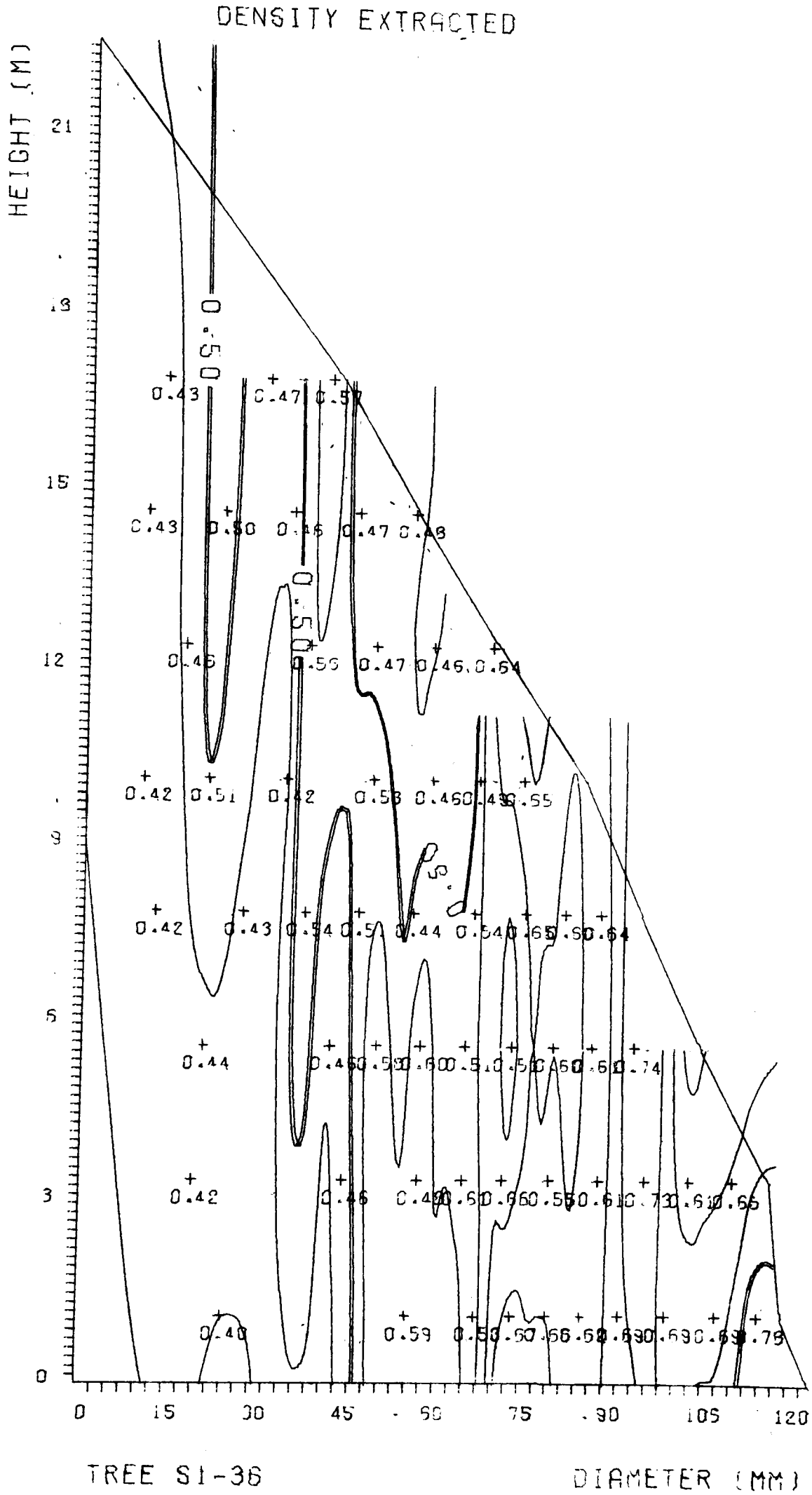

DENSITY EXTRACTED
HEIGHT (M)
TREE NH1-40
DIAMETER (MM)

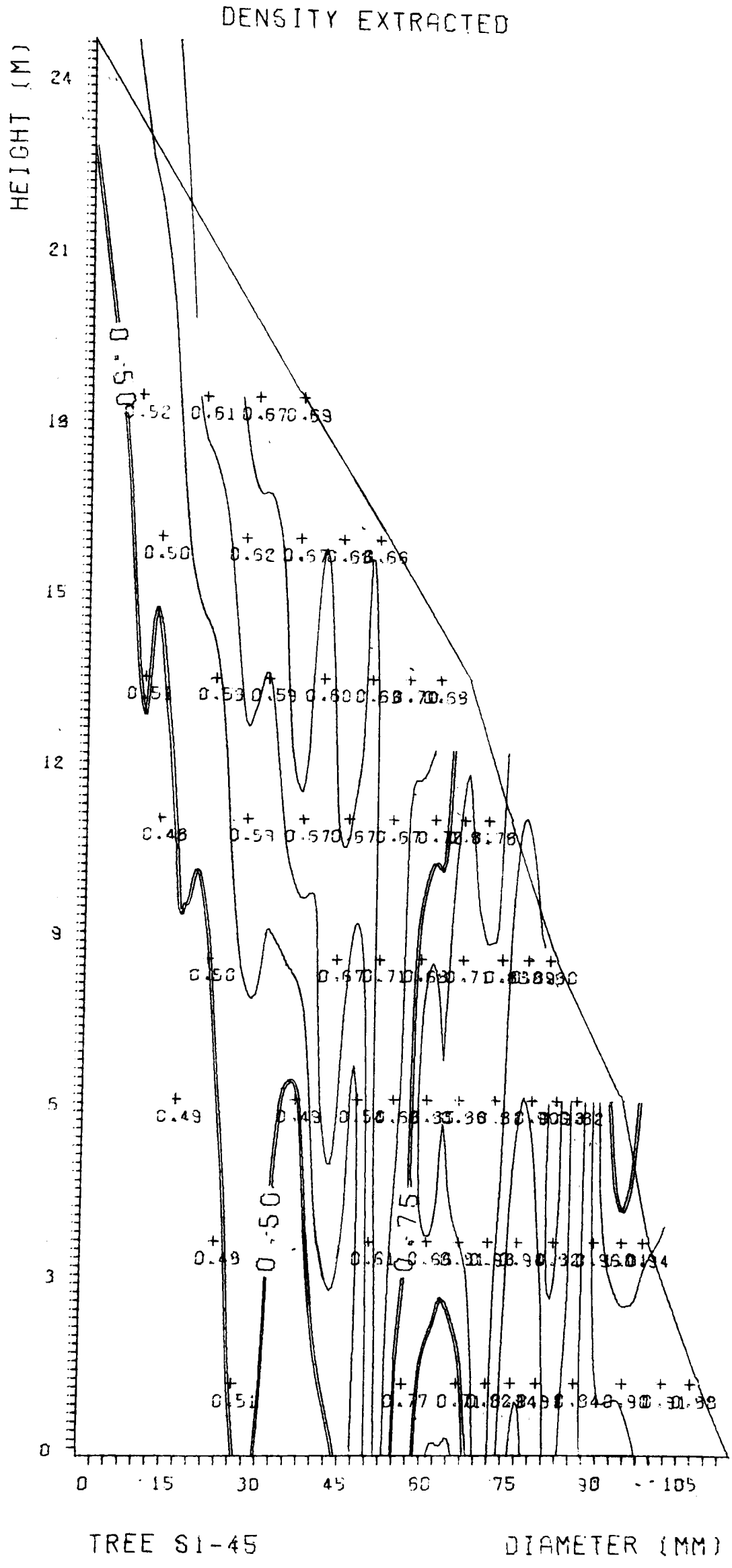

DENSITY EXTRACTED
HEIGHT (M)
24
21
18
1
12
9
6
3
0
0
15
30
45
90
105
120
TREE NH1-44
DIAMETER (MM)

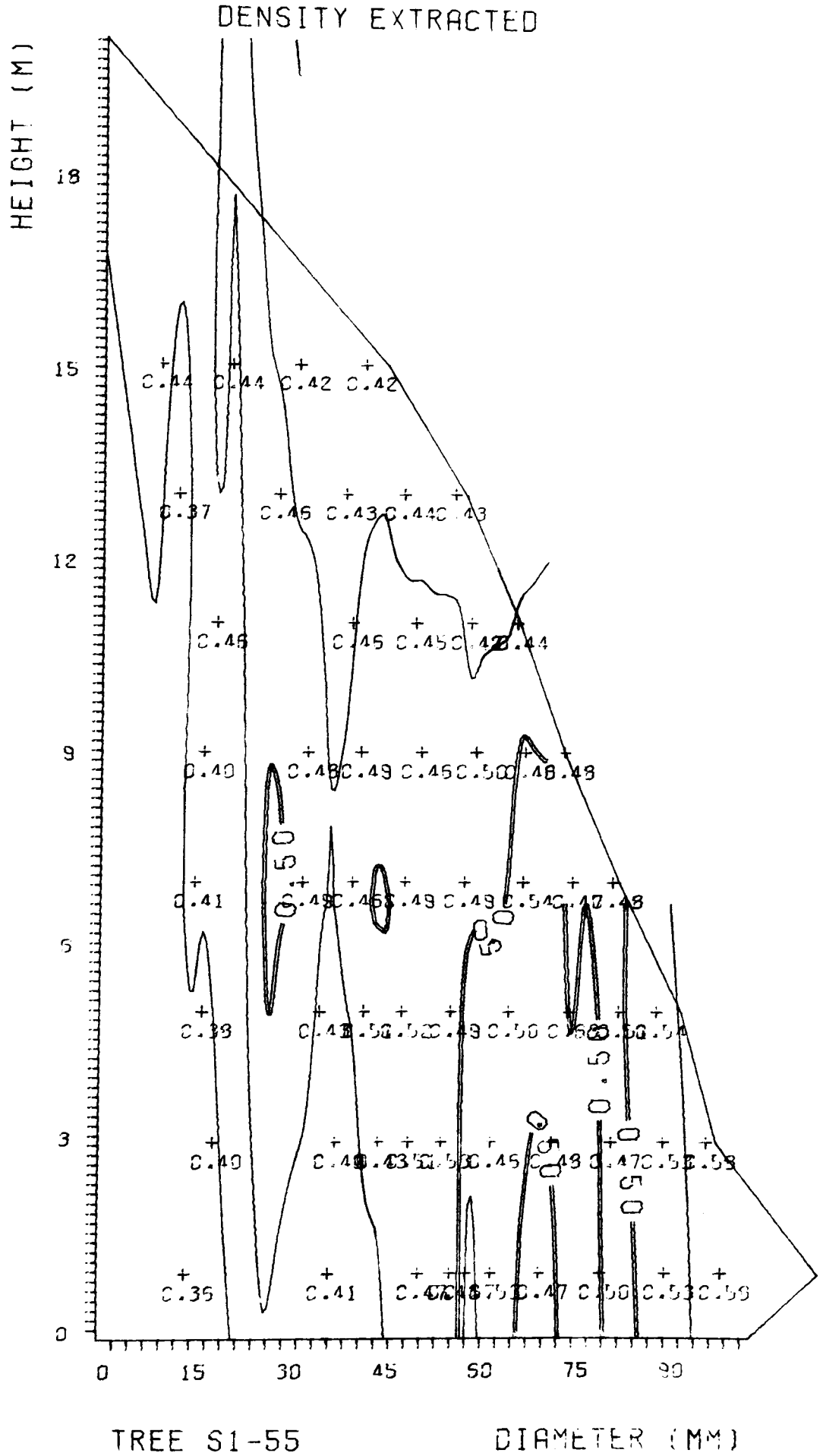

DENSITY XTRACTED
HEIGHT (M)
18
15
12
9
6
3
0
3
4
9
12
TREE NHI-
DIAMETER (MM)


DENSITY EXTRACTED
HEIGHT (M)
21
18
15
12
9
6
3
0
0
15
30
45
60
75
90
105
TREE S1-8
DIAMETER (MM)

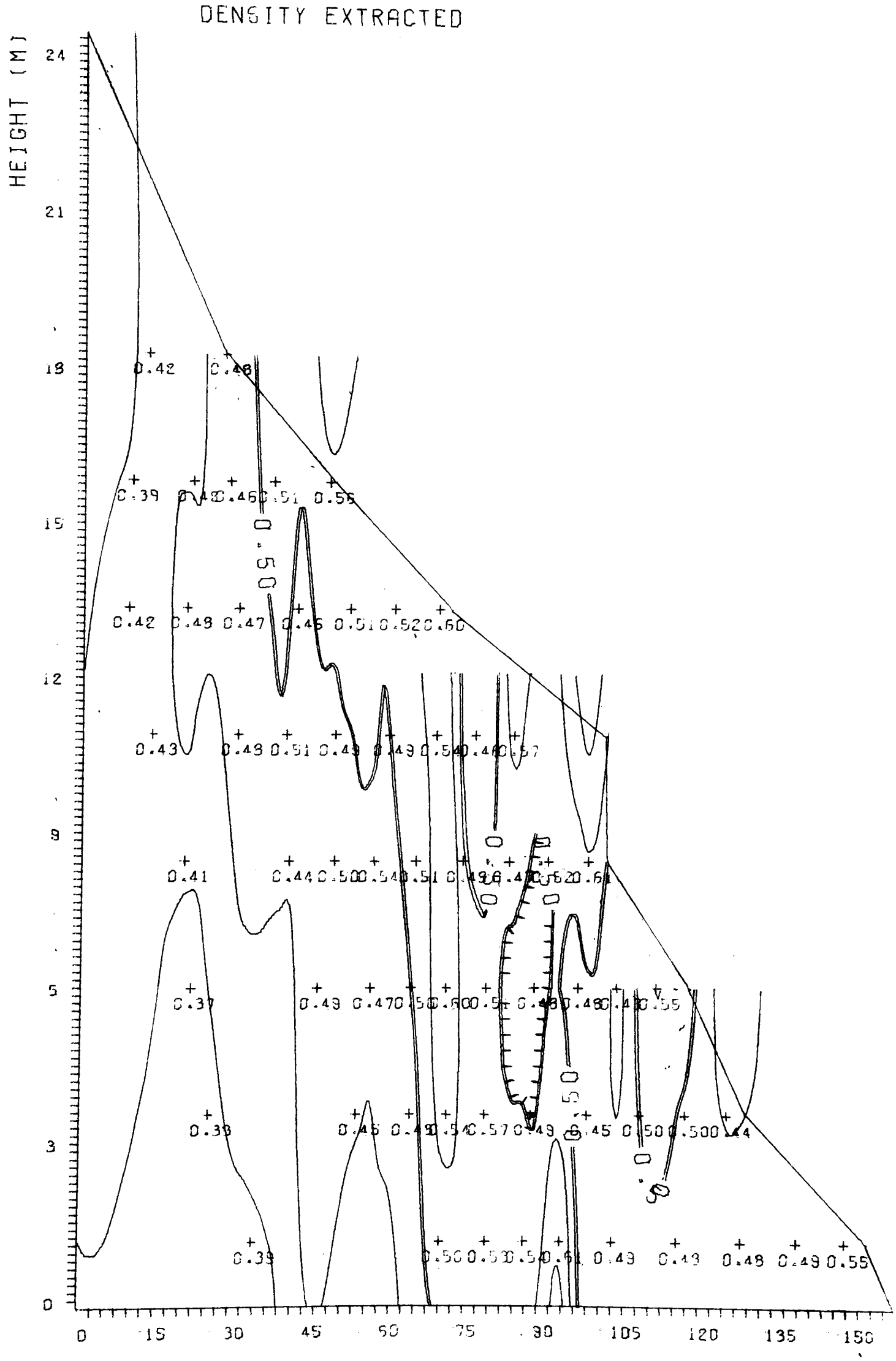

DENSITY EXTRACTED
HEIGHT (M)
24
21
18
15
12
9
6
3
0
0
15
30
45
60
75
90
105
120
TREE S1-31
DIAMETER (MM)


DENSITY EXTRACTED
HEIGHT (M)
21
18
15
12
9
6
3
0
0.50
0.50
0.50
0.50
0 15 30 45 60 75 90 105 120
TREE S1-36
DIAMETER (MM)


DENSITY EXTRACTED
HEIGHT (M)
24
21
18
15
12
9
6
3
0
0.50
0.75
0
15
30
45
60
75
90
105
TREE S1-45
DIAMETER (MM)

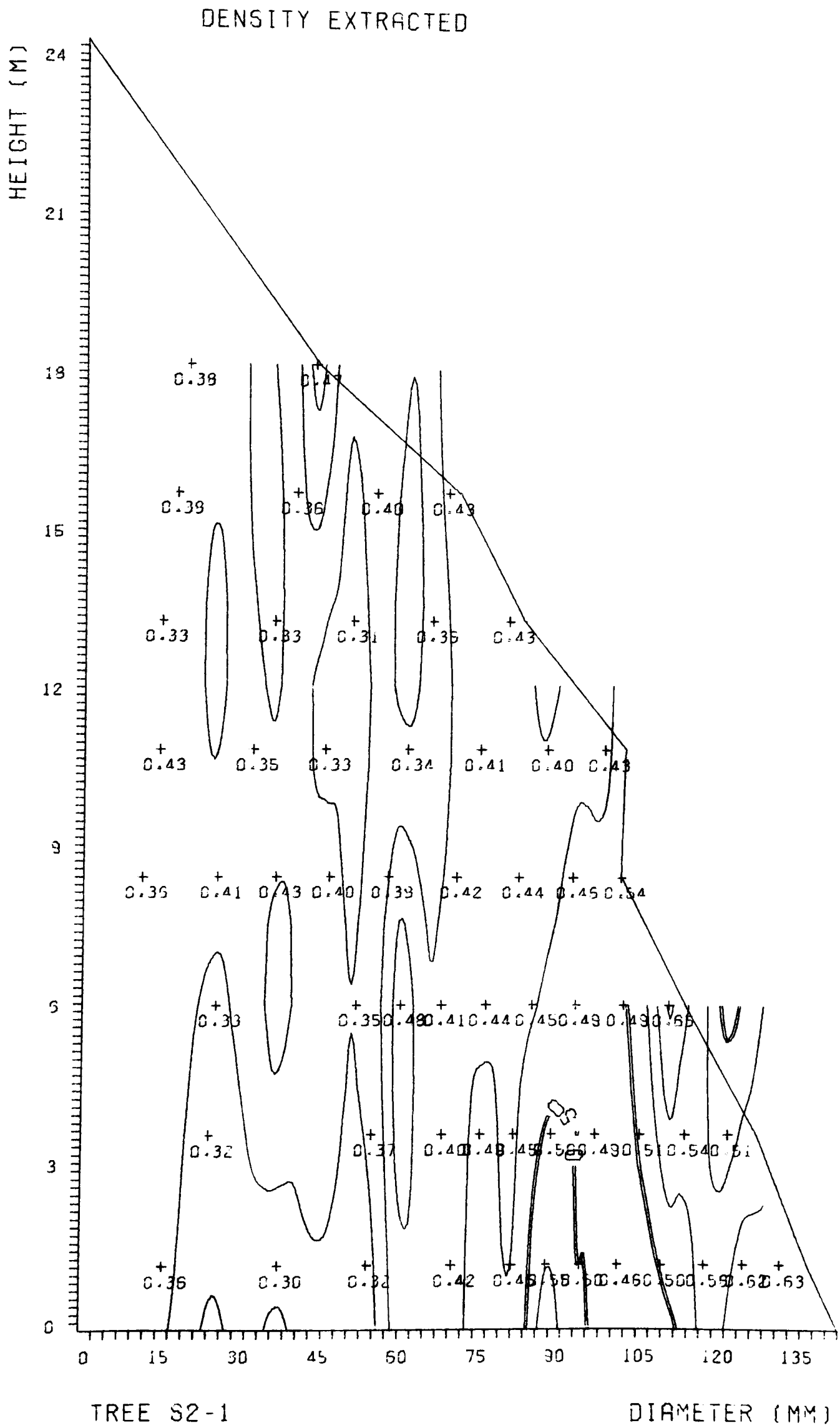

DENSITY EXTRACTED
HEIGHT (M)
18
15
12
9
6
3
0
0
15
30
45
60
75
90
TREE S1-55
DIAMETER (MM)

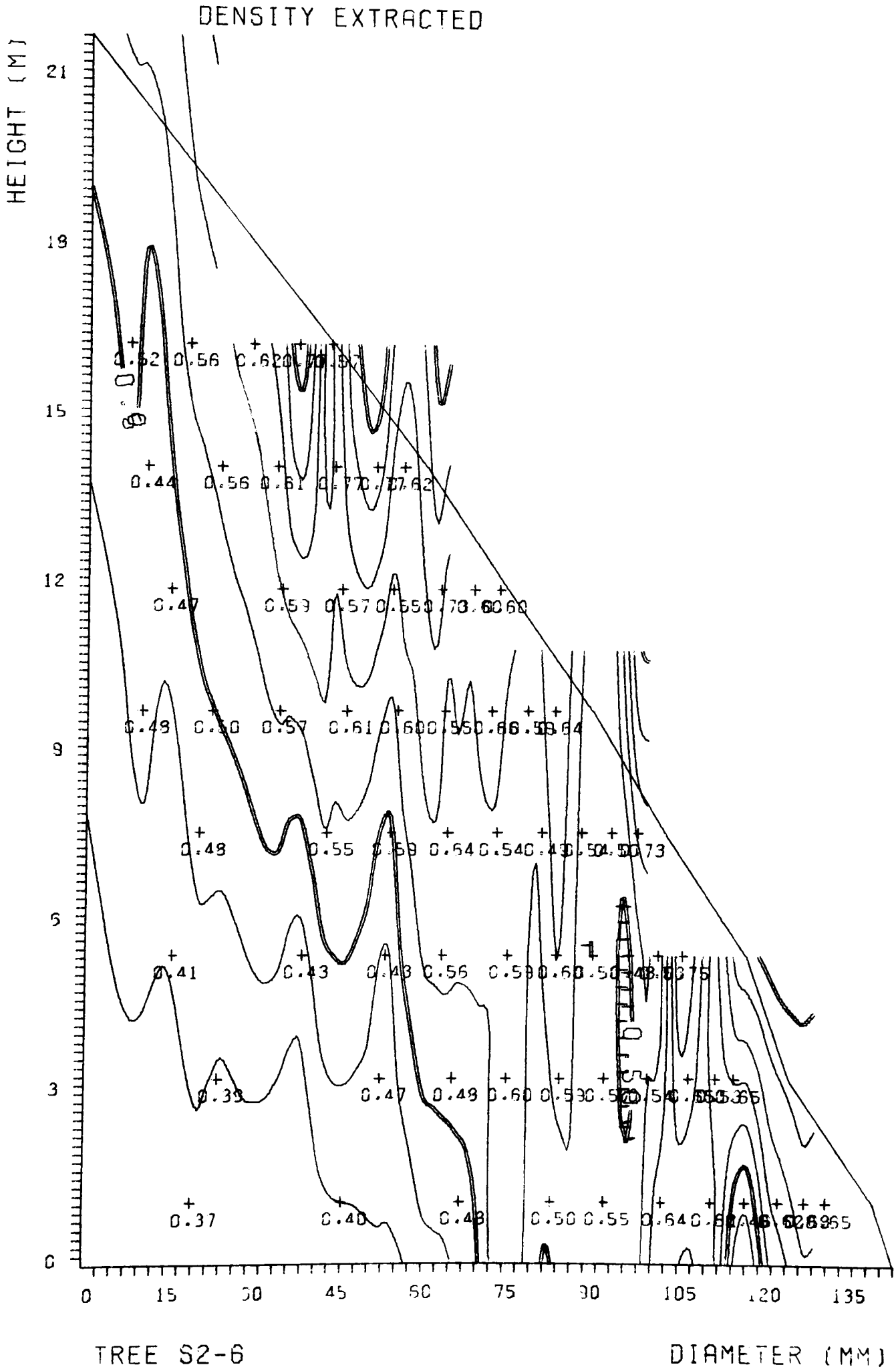
DENSITY EXTRACTED



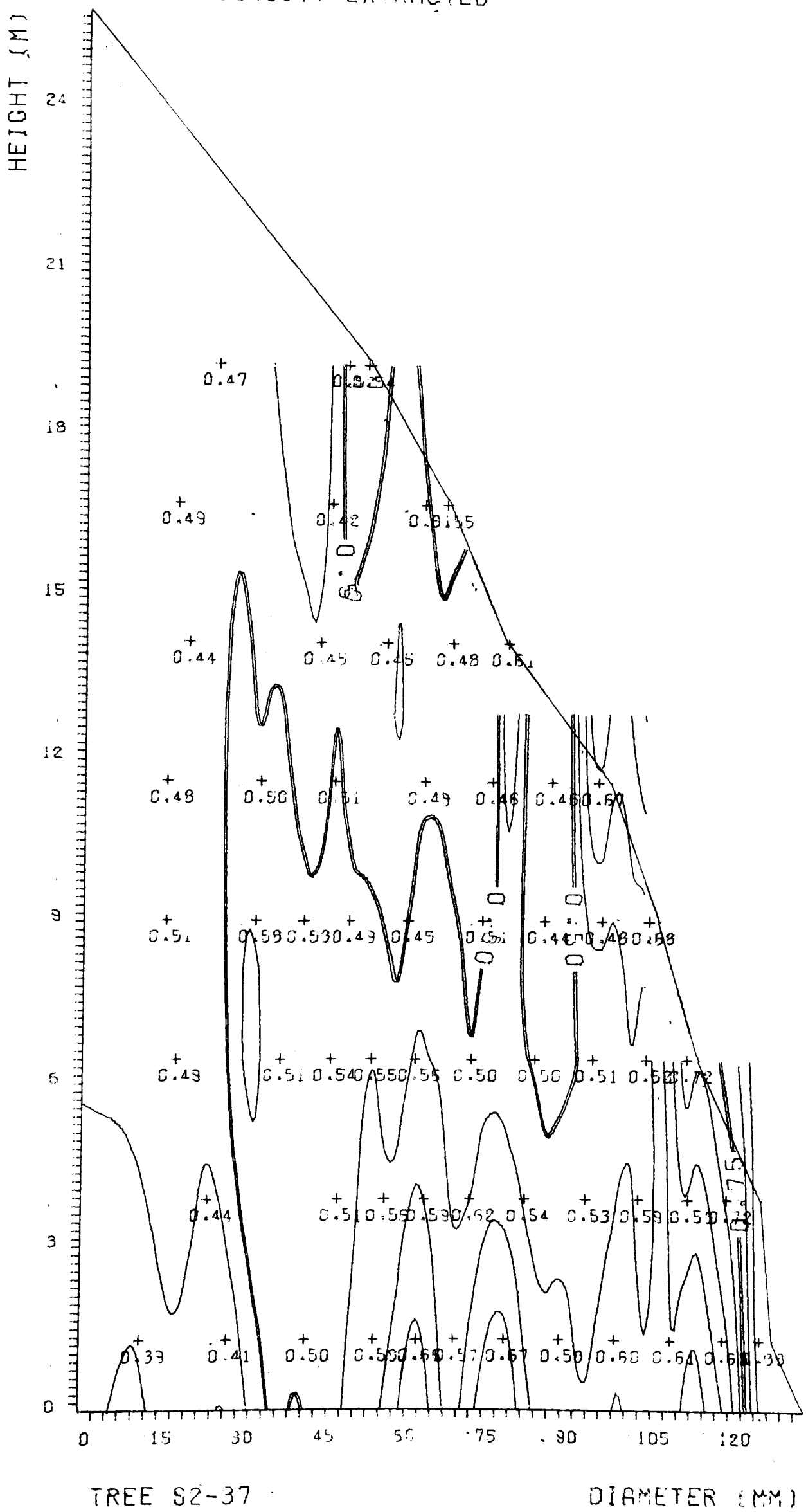
TREE S1-64

DIAMETER (MM)


DENSITY EXTRACTED
HEIGHT (M)
24
21
18
15
12
9
6
3
0
0.38
0.39
0.36
0.40
0.43
0.33
0.33
0.31
0.35
0.43
0.43
0.35
0.33
0.34
0.41
0.40
0.43
0.36
0.41
0.43
0.40
0.39
0.42
0.44
0.45
0.54
0.33
0.35
0.41
0.44
0.45
0.49
0.32
0.37
0.36
0.30
0.42
0.46
0.46
0.63
0
15
30
45
60
75
90
105
120
135
TREE S2-1
DIAMETER (MM)

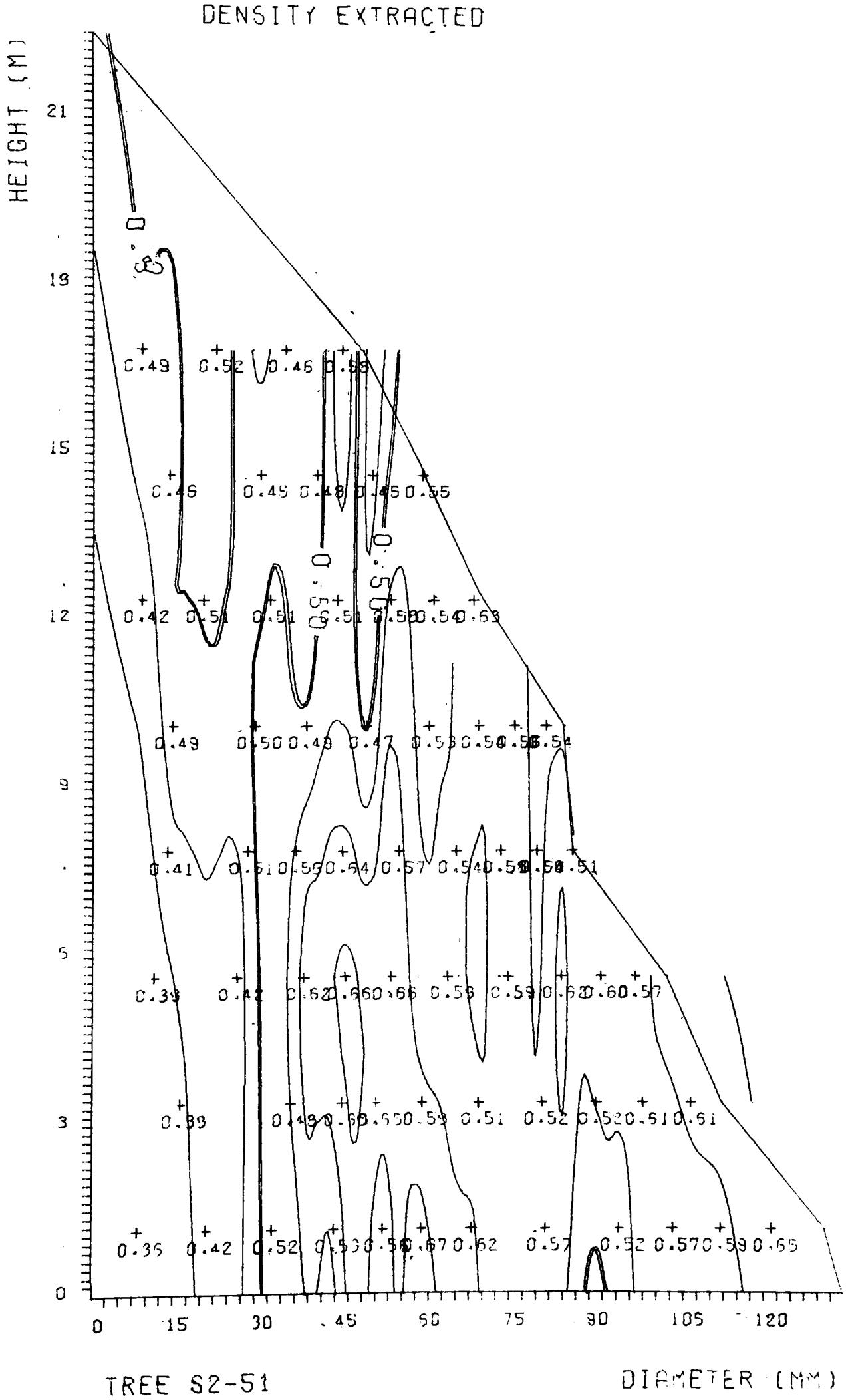

DENSITY EXTRACTED
HEIGHT (M)
21
18
15
12
9
6
3
0
0.62 0.56
0.44 0.56 0.61
0.47 0.59 0.57
0.48 0.50 0.57 0.61
0.48 0.55
0.41 0.43
0.39 0.47 0.48
0.37 0.40 0.48 0.50 0.55 0.64
0 15 30 45 60 75 90 105 120 135
TREE S2-6
DIAMETER (MM)

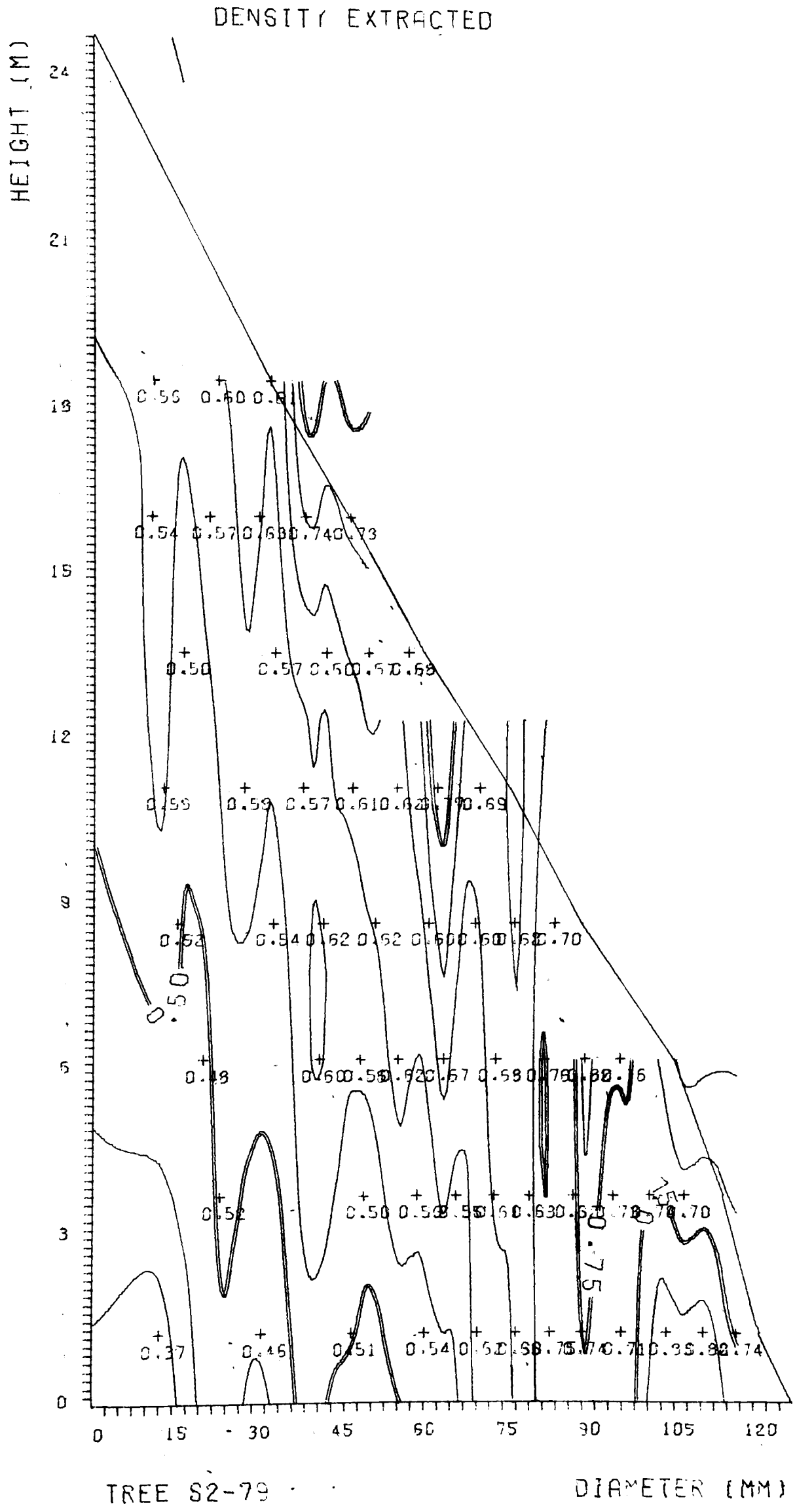
DENSITY EXTRACTED

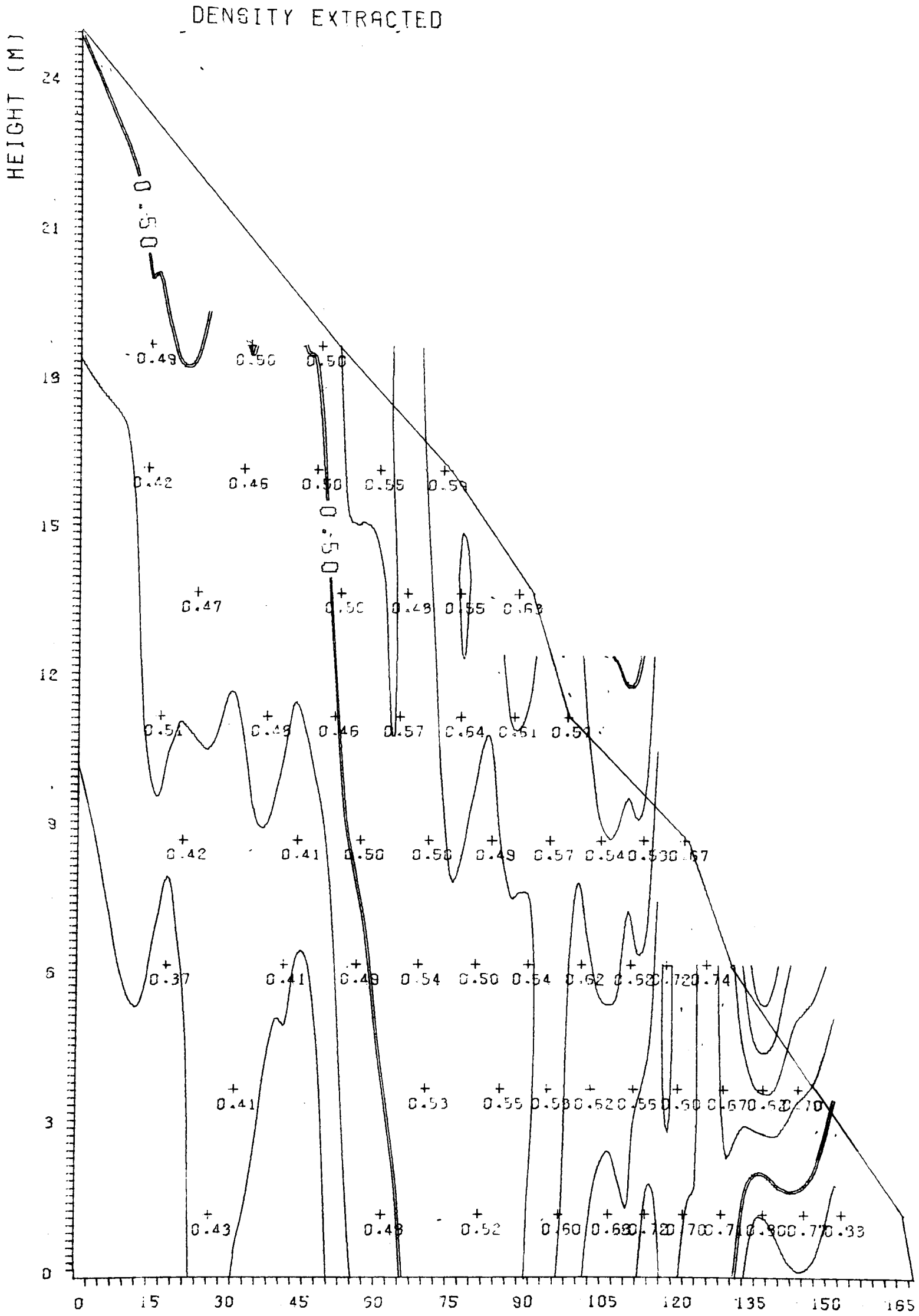


TREE S2-37

DIAMETER (MM)


DENSITY EXTRACTED
HEIGHT (M)
21
19
15
12
9
6
3
0
0.49
0.52
0.46
0.46
0.49
0.48
0.45
0.55
0.42
0.51
0.51
0.51
0.58
0.54
0.63
0.49
0.50
0.48
0.47
0.53
0.54
0.41
0.51
0.59
0.64
0.57
0.54
0.58
0.51
0.39
0.42
0.62
0.66
0.66
0.58
0.59
0.62
0.60
0.57
0.39
0.48
0.66
0.65
0.58
0.51
0.52
0.52
0.61
0.61
0.36
0.42
0.52
0.53
0.58
0.67
0.62
0.57
0.52
0.57
0.59
0.65
0
15
30
45
60
75
90
105
120
TREE S2-51
DIAMETER (MM)


DENSITY EXTRACTED
HEIGHT (M)
24
21
18
15
12
9
6
3
0
0.50
0.75
0 15 30 45 60 75 90 105 120
TREE S2-79
DIAMETER (MM)


DENSITY EXTRACTED
HEIGHT (M)
24
21
19
15
12
9
6
3
0
0
15
30
45
60
75
90
105
120
135
150
165
TREE S2-84
DIAMETER (MM)