BASIC DENSITY AND TRACHEID LENGTH IN JUVENILE AND MATURE WOOD IN *Pinus patula* FROM SOUTHERN TANZANIA

by

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Declaration

I, WINNYSTON NJILEKIRO RINGO, do hereby declare to the Senate of the University of Dar es Salaam that this thesis is my own original work and that it has not been submitted, in whole or in part, for a degree award in any other University.

Signed Ringo

Date 8/2/84

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SUMMARY

Variations in basic density and tracheid length were investigated on wood samples from 27 year old *Pinus patula* trees grown in Sao Hill, Southern Tanzania. The main objectives of the study were:

- to verify variations between and within trees
- to determine juvenile period and juvenile wood proportion in the stems
- to elucidate variations between and within juvenile and mature wood
- to relate juvenile wood basic density and tracheid length with those in mature wood.

Fifteen sample trees were randomly selected in two similar compartments in Msiwazi sub-management block. 2.5 cm thick disks were extracted from each sample tree at 1.3 m, 4 m, 8 m and 12 m heights.

Based on results from a preliminary investigation, data for the following variables were obtained for each second ring from pith to bark following one cardinal direction in each:

- ring distance from pith
- ring width
- latewood band width
- ring basic density
- earlywood and latewood basic densities
- earlywood and latewood tracheid lengths

Basic density was computed from oven dry weight and green volume. Tracheid length was measured by the projection technique. Earlywood and latewood tracheid lengths were obtained separately as the mean length of 30 unbroken tracheids. The average of the earlywood and latewood tracheid lengths constituted the ring tracheid length.

Juvenile period was determined for basic density and tracheid length as follows:

- In terms of the progressive increase in latewood density from pith to bark. A sharp increase indicated the end of the juvenile period.
- Since the tracheid length radial variation curves could not be used, it was decided to use the juvenile period established by latewood basic density.

The results of this investigation are:

- The mean volume weighted basic density is 412 kg/m^3 with a standard deviation of 28 kg/m^3. The mean volume weighted tracheid length is 3.08 mm with a standard deviation of 0.28 mm. Variation between trees was significant at 0.05 level.
- Basic density and tracheid length do not vary significantly between cardinal directions. The largest difference between the basic density means of the 4 directions is 5 per cent while it is 2 per cent for tracheid length.
- Basic density decrease significantly with height in the stem at 0.05 level. Basic density decrease from 454 kg/m^3 at 1.3 m to 369 kg/m^3 at 12 m. Overall tracheid length decreased significantly with height in the stem but the difference between heights 1.3 m and 4 m and that between 8 m and 12 m is not significant. The mean tracheid length at 1.3 m is 3.29 mm while that at 12 m is 2.71 mm.
- Ring basic density and tracheid length increase significantly with distance from pith and ring number but decrease significantly with ring width. Ring basic density increase significantly with latewood per cent. Ring basic density increase from 353 kg/m^3 at ring number 2 to 562 kg/m^3 at ring number 22 from pith. Tracheid length increase from 2.22 mm to 3.99 mm over the same

ring period. Basic density and tracheid lengths curves on ring number, indicate that at 27 years, the trees are still forming wood of increasing basic density and tracheid length.

- Ring number has a greater effect on basic density and tracheid length than ring width. At a fixed ring number, ring width exerts a negligible influence on both properties.
- Earlywood basic density does not vary significantly with position in the stem.
- Latewood basic density increases significantly with distance from pith and ring number but decreases significantly with ring width. At 1.3 m, for example, basic density increases from 404 kg/m^3 at ring number 2 to 611 kg/m^3 at ring number 22. The density increases gradually to about 470 kg/m^3 in the first 8 rings near the pith but thereafter more rapidly but does not reach a peak.
- Earlywood and latewood tracheid lengths increase significantly with distance from pith and ring number but decrease significantly with ring width. In earlywood, tracheid length increases from 2.14 mm at ring number 2 to 3.85 mm at ring number 22. The comparable increase for latewood tracheid length is 2.26 mm to 4.12 mm.
- Tracheid length and basic density in earlywood differ significantly from those of latewood originating from the same ring. The difference between the basic densities of the two bands increases with increase in ring number from pith.
- The juvenile period was found to extend to the 8th ring from pith. Its mean proportion in the stem is 49 per cent.
- The mean volume weighted basic density is 361 kg/m^3 for juvenile wood and 464 kg/m^3 for mature wood. The mean volume weighted tracheid lengths are 2.61 mm and 3.40 mm for juvenile wood

and mature wood respectively. Variation between trees is significant at 0.05 level.

- Radial variations within juvenile and mature wood are similar to those in whole stems for both basic density and tracheid length. Basic density increases from 353 kg/m^3 at ring 2 to 394 kg/m^3 at ring number 8 from pith. In mature wood basic density increase from 434 kg/m^3 at ring number 10 to 562 kg/m^3 at ring number 22. Basic density decrease significantly with height in the stem both in juvenile wood and mature wood. In juvenile wood basic density decrease from 376 kg/m^3 at 1.3 m to 354 kg/m^3 at 12 m. In mature wood the comparable values over the same height are 495 kg/m^3 to 433 kg/m^3. Tracheid length does not change significantly with height in stem in the juvenile and mature wood zones.
- Juvenile wood basic density and tracheid length are significantly correlated to those of mature wood.

It is recommended that:

- The high density long fibre slabs from the sawmill should be utilized in pulp and paper production preferably blending them with the fibres from young trees.
- Though the correlation between basic density and tracheid length and ring width is negative, the actual difference may not be of serious consequence on paper properties. What should be considered is the economics of plantation practices for increased growth rate.
- The intended rotation period of 15 years for pulp wood should be judged on the basis of high quality wood available from longer rotations and the economic implications of extended rotation age.

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LIST OF SYMBOLS

BD	Basic density, kg/m^3
MBD	Mature wood basic density
JBD	Juvenile wood basic density
TL	Tracheid length, mm
MTL	Mature wood tracheid length
JTL	Juvenile wood tracheid length
d	Ring distance from pith, mm
N	Ring number from pith
P	Latewood per cent
JP	Juvenile wood per cent
H	Height in the stem, m
s.d.	Standard deviation
c.v.	Coefficient of variation
w	Ring width, mm
u.b.	Under bark
C.V.	Confidence interval

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1. INTRODUCTION

About 360,000 square kilometres of Tanzania's land area is covered by forests of different types. The natural forests can be classified into three main groups, namely the Montane forests, the Woodland forests and the Miombo. The Mangrove forests along the coast form a special type of forest. Altogether 13 million hectares of the natural forests are gazetted and protected or managed by the appropriate National institutions. Both the number and quantities of current commercial timber species vary a great deal between the natural forests. Common to all, is the fast rate of their reduction mainly through unmonitored exploitation for various wood products, clearing for agricultural crops, cattle herding and annual fires.

The main forest product consumed in Tanzania is fuelwood estimated to be 36 million cubic metres a year assuming a 2 cubic metre annual per capita consumption. Poles for local house construction is the second most important wood use. Fuel wood will remain a principal forest product for Tanzanians for many years to come and its annual volumetric requirement is likely to increase each year as a consequence of both population growth and increased demand for pottery, tobacco and tea curing etc. Other wood products which will become more and more important are sawnwood, boards, poles and pulp and paper.

As the natural forests get depleted of the valuable commercial timber species, future wood raw material requirements for industries as well as for fuelwood and poles will be obtained more and more from plantations. Over the last three to four decades, considerable plantation area of both softwoods and hardwoods have been established. Today there are altogether about 70,000 hectares of plantation forest and it is expected to increase to 100,000 hectares by the end of the century.

More than 70 per cent of the total plantation area consists of conifers, 60 per cent of which are Pinus patula Schiede & Deppe. The Sao Hill Forest Project, which is today the largest forest plantation in Tanzania, has more than 50 per cent of its planted area under Pinus patula stands. The wood of this species will constitute about 85 per cent of the wood raw material requirement for the pulp and paper mill expected to start operating in 1984. This mill will have an annual capacity of 60,000 metric tons of paper. In addition mature stands of Pinus patula are now being processed in a sawmill producing about 15,000 m^3 of sawnwood annually. Some of the thinnings and tree tops are left in the stands and at least 15,000 m^3 of sawmill waste is today burned in an open fire.

The large investment in Pinus patula plantations necessitates thorough investigations of its wood structure, influence of growth factors on physical and chemical wood properties and of how the structure and properties change with tree age. Such knowledge can provide a basis of determining rotation age for sawnwood or pulpwood production. The 15 and 25-30 year rotations used today for pulpwood and sawnwood respectively are based on South African practice.

Wood density and tracheid length are recognized as two important wood characteristics for evaluating wood quality. These characteristics vary with tree age, genetical constitution and growth conditions. A relationship exists between wood density and wood strength properties and swelling and shrinkage of wood. Wood density is also related to pulp yield, effectiveness of glues in plywood production and the potential amount of heat obtainable from the wood.

Fibre length influences paper stength properties such as tensile strength, bulk and burst strengths. Fibre length also influences the ease with which paper sheet formation can be achieved.

This investigation was aimed at studying wood basic density and tracheid length variation in Pinus patula from Sao Hill with these specific objectives:

- To verify variations between trees and within trees and how the two properties are related to position in stems and ring width. The relationship between basic density and late wood per cent was also investigated.
- To determine the juvenile wood period and obtain the proportion of juvenile wood in the stems.
- To compare basic density and tracheid length of juvenile and mature wood and investigate their variation between and within trees.
- To find the relationship between juvenile wood basic density and tracheid length with those of mature wood.

2. LITERATURE REVIEW

2.1 Wood density

2.1.1 Definition

The density of a given substance is defined as its mass per unit volume. Wood density is defined as the mass of wood contained in a unit volume. The density values are commonly expressed in kg/m^3 or g/cm^3 in most countries except in United Kingdom and USA where it is expressed as lb/ft^3 (Desch 1980).

A piece of wood in its natural state is composed of the cell wall substances, extractives, water and air. It is logical therefore that the density of a given piece of wood will be influenced by the proportional amounts of these components at the time of measurement. In order to compare density values of woods originating from various sources such as different species or different parts of a stem it is important to consider the moisture content and extractive content of the wood at the time of measurement. The more common levels of moisture content at which wood densities are measured are 0 per cent, 12 per cent and above fibre saturation or 30 per cent (Brown *et al*. 1952). Wood extractives must also be considered where their proportional amounts in the wood can significantly influence the wood density (Jane 1970). Extractives are compounds of varying chemical composition such as gums, fats, waxes, resins, sugars, oils, starches, alkaloids and tannins. These compounds have been described by various authors (Hillis 1962). The types and amounts of extractives vary between species and within species. The amount of extractives vary from less than 1 per cent in some to more than 10 per cent in *Sequoia sempervirens* (Tsoumis 1968). In some tropical species extratives may constitute 30 per cent or more (Anderson 1962). In a given stem the quantity of extractives may vary outwards with distance from pith and with height in the stem (Gardner and Hillis 1962). Normally the extractives can be dissolved by water or organic solvents (Hillis 1962).

Definition of wood density based on different moisture contents are given in all standard textbooks (for example Panshin and de Zeeuw 1970). Other definitions of wood density based on what particular part of the wood is measured are presented in a review, (Elliott 1970). The density of wood based on green volume and oven dry weight is commonly referred to as basic density (Brown *et al*. 1952). This is the more commonly used form of expressing wood density, because it can be obtained easily and is convenient for use in the wood processing industries (Kollmann and Cote 1968).

2.1.2 Significance as quality indicator

Wood density is highly correlated with certain wood strength properties and is therefore used as a criterion of wood quality (Elliott 1970, Bendtsen 1978). It is reported that modulus of rupture, modulus of elasticity, compression strength parallel to the grain and shear strength show linear positive correlations with wood density in *Pseudotsuga menziensii* (Liska 1965). In *Pinus taeda*, modulus of rupture and modulus of elasticity are linearly correlated with wood density (Pearson and Gilmore 1971). Similar correlation is reported for five important pine species growing in USA. (Wahlgren *et al*. 1972).

Wood density is also correlated to pulp yield as well as some of the paper properties (Rydholm 1965, Einspahr 1972, Zobel *et al.* 1972). The higher the wood density the greater will be the pulp yield from a given pulping process (Britt 1970). Wood consisting of thin walled tracheids has low density, produce pulps with high tensile strength, bursting strength, fold endurance and sheet smoothness (Einspahr 1972). Wood with thick walled tracheids, i.e. high density, produce pulp with low tearing strength (Kloot 1976). In general the paper making properties of *Pinus caribaea*, *Pinus elliottii*, *Pinus taeda* and of *Araucaria cunninghamii* grown in Australia can be predicted from a knowledge of wood density and tracheid length (Watson *et al.* 1971). Similar findings are reported for *Pinus elliottii* and *Pinus taeda* grown in USA (Wangaard *et al.* 1966).

Wood density can further be used to estimate the amount of heat energy available from a given wood species because the amount of energy is positively correlated with the density of the wood (Tillman *et al.* 1981).

Heritability of wood density has been established for various conifers (Duffield 1961, Goggans 1961, Nicholls and Dadswell 1965, Paterson 1969, Einspahr 1972, Zobel *et al.* 1978). Based on the fact that the trait is heritable, seeds from high density mother trees are chosen for breeding seeds for plantation programmes (Paterson 1969, Einspahr 1972, Zobel *et al.* 1978).

To a certain extent in some tree species, the density of the wood formed in the stems can be manipulated by deliberate changes of the conditions under which the trees grow (Paul 1963). Changes in the growth conditions can be created by reducing competition between trees by thinning, pruning, fertilization and irrigation (Spurr and Hyvarinen 1954, Paul 1963, Klem 1972, Bendtsen 1978, Gardiner 1978, Nelson et al. 1980, Cown and McConchie 1980). Manipulation of wood density is very important where uniform wood density is desirable.

2.1.3 Methods of measurement

The existing techniques for measuring wood density can be grouped in two classes, namely the traditional gravimetric techniques and the more recently developed radiation techniques. The techniques are described in American, British, French and German standards for testing materials and therefore their explanation is not included here. Several points, however, need to be made. Wood density can be measured with satisfactory results and reasonably rapid by gravimetric methods so long as the specimens are not too small and can be prepared accurately (Hughes and Andrea 1974). In a review of gravimetric methods a standard gravimetric technique of low cost and relatively high accuracy is recommended (Hughes and Andrea 1974). The simplest gravimetric technique of determining wood density is to weigh the wood sample, determine its volume and then divide the weight by the volume. To obtain the sample weight is simple, but accurate volume determination is more difficult. A number of volume determination methods have been described (Polge 1966).

Green volume for basic density calculation can be obtained by the water displacement technique. Briefly the technique entails measuring the weight of a container almost full of water (W_1); and then with a wood sample submerged in the water (W_2).The sample volume is then the difference between W_2 and W_1. Conversion of the weight into volume is based on the assumption that at room temperature the density of water is 1 g/cm^3 (Brown et al. 1952). The following conditions must be observed:

- the submerged sample must not make contact with the walls or bottom of the water container
- the sample moisture content must be above fibre saturation point
- in case of very small samples the analytical balance used must be of adequate sensitivity.

Oven dry weight of the sample is obtained by drying the sample in an oven at 102-105°C to constant weight (Brown et al. 1952).

Gravimetric methods have two major limitations:

- It is not possible to obtain continuous data across an annual ring.
- The measurements are time consuming and thereby expensive.

Radiation techniques have two advantages:

- Continuous variation of wood density within growth rings can be determined.
- The measurements are fast.

However, gravimetric methods require less expensive equipment than radiation methods (Hughes and Andrea 1974).

The choice of technique should therefore be determined on the basis of the objectives to be achieved by the study as well as the capital available.

2.2 General basic density variation

2.2.1 Introduction

Wood density research started more than a century ago in Europe and a vast number of reports on wood density in angiosperms and gymnosperms have been published. It is clear that wood exhibits a greater range of variability than most other structural materials (de Zeeuw 1964).

Variation in wood density arise from endogenous and exogenous factors which in various combinations determine and modify the physiological process involved in the production of wood (Kramer 1957a, Larson 1964). Factors known to influence wood density can be grouped into 3 categories:

- inherent anatomical characteristics
- environmental factors
- age of the trees.

Wood density literature shows that considerable effort has been directed towards elucidating the relationship between environmental factors and the density of the wood formed (Bendtsen 1978). Environmental factors can either be a consequence of geographical location or silvicultural practices or both (Spurr and Hsiung 1954, Paul 1963).

Geographical locations may differ in soil type, photoperiod, thermoperiod and rainfall (Kramer 1957b, Leyton 1957, Wareing and Black 1957). These factors are known to influence tree crown development which in turn directly influences the type and amount of different cells formed (Larson 1957, 1964, 1969). Wood density surveys in the USA for pines have shown that there is a trend towards increasing wood density in several species from north-west to south-east, within the ranges of normal occurence in the coastal plains in direct relation to warm season rainfall (Saucier 1972, Ledig *et al*. 1975). In Europe wood basic density of *Pinus sylvestris* is reported to increase from north to south and with decrease in altitude (Echols 1958, Elliott 1970). This general trend with changes in altitude holds true for most other pines grown in temperate regions (Tsoumis and Panagiotidis, 1980). Increase in altitude in these regions also often implies poor soils (Larson 1957). In New Zealand wood density of *Pinus radiata* has a tendency to increase from south to north (Cown and Kibblewhite 1980). Wood density of *Pinus contorta* growing in Alberta, do not vary with geographical location (Taylor *et al*. 1982).

The effect of various silvicultural treatments such as thinning, pruning, fertilization and irrigation on wood density have been investigated by various workers (Bendtsen 1978).

Thinning in older stands can result in an increase or a decrease in wood density. The effect of thinning in 50 year old *Larix occidentalis* resulted in an increase in wood density for a 15 year period after thinning from 32 kg/m^3 to 49 kg/m^3 compared with an increase of 17 kg/m^3 in an unthinned plot (Lowery and Schmidt 1967). Thinning in 46 year old *Pinus ponderosa* resulted in a non-significant reduction in wood density (Echols 1972). An intensive thinning in a 25 year old *Pinus pinaster* stand resulted in a significant reduction in wood density, whereas less severe thinnings had little effect (Nicholls 1971). In Canada, thinning in a 45 year old stand of *Pinus banksiana* where 20 per cent of the basal area was removed, resulted in a small but statistically significant reduction in density of the wood laid down during the following 5 years (Scott *et al*. 1982). Reduction in wood density as a result of thinning is also reported for *Pinus radiata* grown in New Zealand (Cown 1974, Sutton and Harris 1974). Thinning is reported to have little effect on wood density of *Pinus patula* grown in South Africa (Turnbull 1947). Extensive studies of the effect of thinning on wood density of *Pinus sylvetris* grown in Sweden indicated a non-significant difference in wood density and latewood per cent between thinned and unthinned plots (Ericson 1966). Thinning in older stands of *Picea abies* in Sweden indicated that heavy thinnings caused a reduction in wood density by about 10 to 17 per cent (Ericson 1962, 1966). Thinning results in less competition between trees and an increased growth rate. Where wood density is unchanged or increased, it is partly a result of prolonged latewood growth due to greater soil moisture availability (Larson 1972).

Wood density is affected when heavy green pruning results in reduction in vigour of growth (Brazier 1976). Reduction in growth vigour is more pronounced at the stem base and leads to reduction in stem taper. Earlywood/latewood transition becomes more abrupt the greater the distance from the crown. The proportion of latewood in the lower stem increases (Larson 1969). Wood density has been reported to increase as a result of pruning of *Pinus radiata*, *Pinus palustris*, *Pseudotsuga taxifolia* and *Abies grandis* (Marts 1949, Gerscher and de Villiers 1963, Polge *et al*. 1973).

Effect of fertilization on wood density has been accorded considerable attention during the last two decades (Bendtsen 1978). The fertilizers may be applied at the time of planting, at the pole stage when rates of growth are slow and some years before final cropping to boost stem size and so improve conversion yields (Bendtsen 1978). Fertilizer applied during planting is of little significance on wood quality as very little proportion of the final wood volume is affected. In contrast, fertilizer application during the crop establishment phase affects the character as well as influencing the volume of juvenile wood (Gardiner 1978). Fertilization of a 6 year old Pinus radiata stand resulted in an increase in yield of 50 per cent but the wood density had a mean value 11 per cent below that of untreated trees. This reduction was attributed to increase in early wood proportion (McKinnell and Rudman 1973).

Reduction of wood density was reported for the same species following fertilization of a 7 year old stand. This reduction was also attributed to reduction in latewood per cent and lower minimum earlywood density (McKinell and Rudmann 1973). Reduction in wood density following fertilization is reported for 9 year old Pinus elliotti, 16 year old Pinus taeda, 45 year old Pinus banksiana (Williams and Hamilton 1961, Youngsberg et al. 1963, Zobel et al. 1978).

The effect of fertilizer treatment on older stands differ according to the character of the growth (Klem 1974, Brazier 1976, Bendtsen 1978). Where growth is very slow, the proportion of latewood is very low and starvation wood is produced (Klem 1933, Vorreiter 1954). Such wood responds to fertilizer application by an increase in ring width, the development of latewood, and an increase in wood density (Klem 1974, Brazier 1976). Fertilization of slow grown Pinus sylvestris in Finland resulted in production of higher density wood, while fertilization of fast grown stands in the same country resulted in production of wood of lower density (Jensen et al.

1967). Fertilization of slow grown Pinus sylvestris in Norway resulted in 5 per cent reduction in the density of the wood formed although the treatment gave a slight increase in late wood per cent (Klem and Halvorsen 1967). A reduction in wood density following stand fertilization is also reported for Picea abies (Klem 1974).

The effect of soil moisture availability has been investigated and some reports are available on forest irrigation and its effect on wood density (Panshin and de Zeeuw 1970). Irrigation of Pinus palustris resulted in formation of heavier wood due to increased latewood proportion (Paul and Marts 1931). Wood density in Pseudotsuga taxifolia has been found to be correlated with moisture availability (Chalk 1951). The proportion of latewood in Pinus elliottii is reported to increase with summer rainfall (Larson 1957). In Australia, irrigation of Pinus radiata stands during drought periods caused increase in latewood per cent of 14 per cent and density by 8.1 per cent compared to untreated stands (Nicholls 1971). Irrigation experiments on Pinus ponderosa indicated that the wood formed after treatment had a more gradual transition from earlywood to latewood (Howe 1968).

Basic density is known to be under genetical control (Einspahr 1972, Bendtsen 1978). It has also been found for the more commercially important timber species that heritability levels are reasonably high (Panshin and de Zeeuw 1970). Heritability is a measure of the relative degree to which a character is influenced by heredity as compared to environment. It is usually expressed in values from 0 to 1 or from 0 to 100 per cent and it represents the genetic control that exists over the encountered natural variation (Einspahr 1972). Basic density heritability estimates for various pine species have been established, for example, to lie between 0.3 to 0.7 for southern pine species (Einspahr 1972).

The effect of age on wood density was first investigated in Germany between 1874 and 1895 and today there are numerous reports on this subject (Larson 1957). It is apparent from the literature that there is no agreement on the effect of age on wood density (Elliott 1970). This disagreement is partly due to results based only on one factor i.e. ring number and disregarding the effect of ring width.

Investigation of the effect of ring width and ring number in pines grown in South Africa indicated that the density of wood formed in a particular year was not determined by its rate of growth but was proportionate to a function of age (Turnbull 1947). Density continued to increase steadily from pith outwards regardless of whether ring width increased or decreased. Definite correlations have been established between age and wood basic density in *Pinus taeda*, *Pinus banksiana* and *Pseudotsuga taxifolia* (Larson 1957). Ring width and age, however, had a non-significant correlation with wood basic density in *Pinus taeda* (Zobel and Rhodes 1955). Similar findings were reached for *Pinus ponderosa* (Cockrell 1944). More recently wood density has been found to be positively correlated to age in *Pinus radiata* (Cown 1974). In *Pinus radiata* it was found that difference between the first ring near the pith and the outer ring was about 40 per cent (Harris 1965).

2.2.2 Softwoods versus hardwoods

The patterns of wood density variations particular to softwoods and to hardwoods are reflections of the anatomical differences that exist between the two groups (Kollmann and Cote 1968). There are basically four major cell types occuring in wood, namely parenchyma cells, fibres, tracheids and vessel elements (Esau 1976). Hardwoods differ from softwoods in possessing vessels and are in general more complex than softwoods (Panshin and de Zeeuw 1970). Tracheids constitute more than 90 per cent of the tissue in softwoods whereas fibres occupy about 50 per cent of the wood in hardwoods.

The wood cell wall components differ slightly between hardwoods and softwoods (Kollmann and Cote 1968). The types and amounts of hemicelluloses in hardwoods are different from those in softwoods (Timell 1965). Differences also exist in quantity and composition of lignin (Browning 1963). The amount of cellulose is also slightly higher in softwoods than in hardwoods (Rydholm 1965). Such variability in chemical proportions may to some extent influence wood density.

During growth and development of wood in the trees, softwoods and hardwoods form reaction wood referred to as compression wood in the softwoods and tension wood in the hardwoods (Kollmann and Cote 1968). Reaction wood has greater density than normal wood. Compression wood is characterized by thick walled tracheids with rounded cross section while tension wood has a higher proportion of fibres and small and few vessels (Kollmann and Cote 1968).

Temperate grown softwoods and hardwoods form annual growth rings consisting of earlywood and latewood. Growth rings in hardwoods can be described as either being ring porous or diffuse porous. In ring porous hardwoods, earlywood vessels are larger than those formed later in the season, while in diffuse porous, the vessels have the same size throughout the growth season (Esau 1976). Wood of the same species may be ring porous in one region in the north temperate zone but exclusively diffuse porous further south (White and Robards 1966).

The contrast between earlywood and latewood is more pronounced in softwoods and in ring porous hardwoods than in diffuse porous. Wood density variation depends on both the variability in the densities and proportions of earlywood and latewood (Kollmann and Cote 1968, Warren 1979). For tropical grown ring porous hardwoods and conifers the contrast between earlywood and latewood may be less pronounced than in those from the temperate regions. For conifers from temperate regions latewood basic density may be two to three times that of earlywood (Kollmann and Cote 1968).

In both softwoods and hardwoods basic density tends to vary within the tree (Bergman 1949, Elliott 1970). In softwoods, generally, wood density increases from pith to bark. *Chamaecyparis* and *Thuja* are notable exceptions (Polge 1966).

In hardwoods, there exists four radial patterns:

- wood density increases from pith to bark as in *Eucalyptus viminalis* and *Eucalyptus obligua*
- wood density is highest near the pith, decreases outwards for the first few years and then increases to a maximum near the bark as in *Populus deltoides*
- density increases in the rings near the pith, then remains more or less constant or decreases in the last formed increment near the bark as in *Populus nigra* and *Eucalyptus marginata*
- density of the wood exhibits a general decrease from pith to bark as in *Fagus sylvatica*.

Axially, wood density in softwoods decreases with increasing height above ground, except in *Pinus contorta* and in *Pinus strobus* where wood density decreases with increasing height from ground in the lower trunk and then increases in the upper trunk (Panshin and de Zeeuw 1970). Three patterns of axial basic density variation is reported for hardwoods:

- decreasing uniformly, *Acer rubrum* and *Acer saccharinum*
- decrease in specific gravity for the lower part of the stem and increasing in the upper part of the stem, *Liriodendron tulipifera* and *Tectona grandis*
- increasing in stem from base to top in a non-uniform pattern, *Fraxinus pennsylvanica* .

The third is the more common pattern (Panshin and de Zeeuw 1970).

2.2.3 Density of the wood from *Pinus* species

2.2.3.1 Variation between species

The density of important pine species in Europe, North America, New Zealand, Australia and South Africa has been obtained (Elliott 1970). Comparison of mean basic densities of different species obtained from independent studies can be grossly misleading (Saucier 1972). In order to compare the densities of different species it is necessary to consider geographical location, whether plantation grown or natural mixed stands, age, sampling procedures and the method used to obtain results for any specific study. Table 2.1 shows basic density values for different pine species grown in different countries.

Table 2.1 Basic density of different pine species

Species	Country	Basic density,kg/m^3	Source
Pinus banksiana	USA	390	Rydholm (1965)
Pinus contorta	"	380	"
Pinus echinata	"	460	"
Pinus elliottii	"	560	"
Pinus palustris	"	540	"
Pinus ponderosa	"	380	"
Pinus resinosa	"	440	"
Pinus sylvestris	Europe	410	"
Pinus strobus	USA	340	"
Pinus taeda	"	470	"
Pinus radiata	N.Zealand	410	Cown and McConchie (1980)
Pinus patula	Tanzania	410	Ringo and Klem (1980)

It is quite clear despite the limitations imposed by differences in research approach, that the wood of different pine species vary considerably in their densities. Wood density surveys have been going on in the USA for various species with the objective of establishing, *inter alia*, variations between species (Saucier 1972, Zobel *et al*. 1972). The results of one of the studies have been reported for eleven *Pinus* species growing in natural stands in the eastern and southern part. The results from that investigation are more acceptable for between species comparisons. Fifty year old *Pinus palustris* and *Pinus pungens* of the same age had wood density difference of 21 per cent being higher in the former. 47 year old *Pinus taeda* had wood density 48 per cent higher than *Pinus strobus* of the same age. This study, though valid, does not show the distribution of the variation for each causal factor. It would be useful for example to know the proportion of the variation attributed to species differences and whether or not there was interaction between geographical location and species.

The factors that lead to variation between species include:

- differences in anatomical structure
- differences in latewood proportions and density
- genetical differences
- differences in environmental conditions.

2.2.3.2 Variation between trees

Variation in wood density between trees of the same species growing in the same stand has been studied for different species (Elliot 1970, Bendtsen 1978). Variation between trees is reported to be large (Taylor *et al*. 1982). Table 2.2 shows the range of wood density values obtained from trees grown in the same stands.

Table 2.2 Density range of some pine species

Species	Age	Site	No. of	Basic density, kg/m^3		
	years		trees	Mean	Range	Difference%
Pinus caribaea	11	Byfield	24	438	358-505	41
Pinus elliottii	11	Beerwah	8	417	375-464	24
" "	20	Beerwah	32	491	424-529	25
" "	11	Gympie	8	487	424-509	20
" "	11	Maryborough	8	442	408-487	19
Pinus patula	25	Sao-Hill	20	410	376-483	28
Pinus taeda	15	Beerwah	24	456	391-504	29

The figures for *Pinus caribaea*, *Pinus elliottii* and *Pinus taeda* are from Australia (Watson *et al.* 1971). *Pinus patula* values are from Tanzania (Ringo and Klem 1980). Variation between *Pinus contorta* grown in western USA is tremendous (Okkonen *et al.* 1972). A number of investigations have been carried out on the relationship between wood density and the status of the tree in a stand (Elliott 1970). The results are divergent, some showing wood density increasing with tree suppression (Bisset and Dadswell 1949, Spurr and Hsiung 1954, Ringo and Klem 1980). Results from other investigations show no correlation between wood density and position of tree in the stand (Turnbull 1947).

In other reports basic density was highest in codominant trees (Tsoumis and Panagiotidis 1980). In plantation grown trees there is more evidence indicating that the dominant trees show the lowest density as less suppression of trees in the stands results in less conspicous latewood and results in wood of low density (Jalava 1945, Larson 1957).

These large differences between trees are attributable to the factors already presented in 2.2.1. The extent of between tree variability will depend on the sampling procedure adopted for the individual assessment, the age of the trees, the silvicultural treatment which the trees were subjected to and the genetic constituent of the individuals.

2.2.3.3 Variation within trees in the axial direction

In order to interpret and compare the results from studies of wood density variation with height in tree it is important to recognize the sampling methods used (Elliott 1970). Basically there are three ways in which the sampling has been carried out:

- wood samples extracted at a fixed ring number from pith at different heights
- wood samples extracted at fixed ring number from bark at different heights
- wood samples are constituted of sectors running from pith to bark at different heights.

Generally basic density in Pinus species decreases with increasing height in the stem (Elliott 1970, Okkonen et al. 1972, Taylor et al. 1982). Deviations from this general rule are reported in Pinus contorta and Pinus strobus in which basic density decreases for the lower part of the trunk and increases in the top (Panshin and de Zeeuw 1970). Similar trend has been found in Pinus contorta, Pinus lambertiana and Pinus taeda (Okkonen et al. 1972, Lenhart et al. 1977). These deviations from the general rule may be attributed to inclusion of greater proportions of high density knots in the crown (Zobel, 1981). More than one axial pattern has also been reported to occur in Pinus resinosa from plantations and natural stands (Baker, 1967). The reasons leading to decrease in basic density with height in tree include:

- a decrease in number of rings in the mature wood zone (Okkonen et al. 1972, Cown and McConchie 1980, Taylor et al. 1982).
- decrease of both latewood proportion and latewood density in the rings near the pith with increasing height in the stem (Okkonen et al. 1972).

2.2.3.4 Variation within trees in the radial direction

The literature shows that radial variation is the most widely studied variation in pines (Elliott 1970). At any height in a stem the density of the wood may vary considerably (Nicholls and Dadswell 1963). There are three patterns of radial variation of wood density in pine species (Panshin and de Zeeuw 1970). They are:

- basic density increases from pith to bark
- basic density is high at the pith, decreases outwards for the first few years and then increases to a maximum near the bark
- basic density decreases from pith to bark.

The first is the more common trend reported in most pines. These include Pinus contorta, Pinus resinosa, Pinus sylvestris, (Tsoumis 1968). Others include Pinus montezumae, Pinus rudis, Pinus lutea, Pinus engelmanii, Pinus herrerai and Pinus patula (Zobel 1965). The second pattern is reported for Pinus radiata and Pinus ponderosa (Nicholls and Dadswell 1965, Panshin and de Zeeuw 1970).

The third pattern is reported in Pinus echinata (Gilmore 1967). In Pinus oocarpa and Pinus michoacana basic density did not change significantly from pith to bark (Zobel 1965). The last two patterns are exceptions rather than rule. More than one pattern has been reported in Pinus resinosa and Pinus radiata (Nicholls and Dadswell 1965, Cown and McConchie 1980). There could be several reasons leading to different results for different species or even within the same species (Elliott 1970). Perhaps the more common reason would be differences in the sampling units along the stem radius. Many of the studies used several blocks each comprised of several growth rings, thus making it impossible to trace individual ring values. In these studies the first trend is more commonly established (Nicholls and Dadswell 1963, Elliott 1970). Where individual rings were used the second trend is apparent (Nicholls and Dadswell 1965). This explanation hold true for the differences reported in Pinus radiata (Nicholls and Dadswell 1965, Cown and McConchie 1980). In the latter the samples were composed of 5 ring blocks while in the former individual rings were studied.

The ring width pattern near the pith may also influence the overall basic density pattern along the stem radius. Most of the investigations have been carried out in pines in which ring width increases in the first inner rings up to 5-15 rings, then decreases towards the bark (Elliott 1970). It is possible that for those pine species growing in plantations with ring width decreasing from pith to bark, the basic density follows the first trend (Zobel 1981). Radial variation in wood density is a function of many factors not completely understood (Taylor et al. 1982). Factors most obviously contributing to this variation include tree age, latewood proportion and latewood density. The latter two are controlled by heredity and environmental conditions (Larson 1957, Nicholls et al. 1964, Zobel 1965).

Direct correlation between ring number (age) and its wood density has been difficult to substantiate due to the decrease in ring width and increase in latewood per cent with increase in tree age (Larson 1957, Elliott 1970). Early investigations tended to emphasize the effect of growth rate, i.e. ring width on wood density (Turnbull 1947). Studies of effect of age on wood density have been carried out for various pine species grown in South Africa, New Zealand, Australia, Europe and USA (Larson 1957). Results have shown positive correlation between wood density and age in Pinus patula grown in Africa, Pinus elliottii, Pinus taeda, Pinus banksiana grown in USA (Turnbull 1947, Lindgren 1949, Yandle 1956). Similar trend is reported for Pinus sylvestris (Kollmann and Cote 1968). Different results have been reported for Pinus ponderosa in which changes in wood density could not be attributed to changes in age (Cockrell 1944).

The influence of ring width or growth rate on basic density has attracted the attention of many research workers (Klem 1942, Spurr and Hyvarinen 1954, Sjølte-Jørgensen 1967, Klem 1972, Harris et al.1976, Bendtsen 1978, Gardiner 1978, Scott et al. 1982, Taylor and Burton 1982). The results from these studies indicate that increased growth rate may result in significant reductions of wood density or nonsignificant effect or it may affect juvenile wood and mature wood differently. While exceptions may exist, increased growth rate in pines tend to reduce the density of the wood formed (Klem 1974). It should be noted, however, that increased growth rate resulting in formation of wider latewood bands of thick walled tracheids and narrow earlywood bands will increase ring basic density (Larson 1957, 1969). If increased growth rate resulted in formation of wider early wood band of thin walled tracheids and a narrow latewood band, ring basic density may be reduced. This phenomenon has been demonstrated in experiments in which photoperiod and soil moisture are altered (Larson 1969). The formation of false rings for example demonstrates variation within a typical annual ring (Larson 1969). Starvation wood covered under 2.2.1 is also a demonstration of decreased growth rate without increase in density of the wood formed.

The effect of cardinal direction on wood density has received little attention in comparison to other types of within tree variation. Research into the effect of direction on wood density was first performed on a few species in the early 1950 (Nylinder 1953, Gohre 1955, Liese and Dadswell 1959). In *Picea abies* there was a significant difference in wood density between sampling directions (Nylinder 1953). In other studies which involved *Pseudotsuga menziensii* and *Pinus radiata* no significant difference was found (Gohre 1955, Liese and Dadswell 1955). In *Pinus radiata* there was a significant effect of direction on the density of latewood. Later other studies reported non-significant in circumferential variation of wood density (Cooper 1960, Chalupka *et al.* 1977). Little variation of wood density with cardinal direction has been reported for *Pinus patula* grown in Central Africa (Adlard *et al.* 1979). It is important that in each study the condition of the sample trees is considered with respect to stem straightness. In leaning stems for example, the wood on the lower side consists of reaction wood (Nicholls and Dadswell 1963). If sampling involved taking samples from the lower side and opposite wood, then the differences can be appreciable (Jain and Seth 1980).

Investigations of the density of latewood and earlywood have been based on species with well defined latewood zones and the reports establish mean values for the two bands. Table 2.3 shows earlywood and latewood densities in some pine species. It is also noted that latewood definition adopted in most studies is that by Mork (1928). Latewood proportion tends to increase with ring number from pith (Lodewick 1933, Larson 1957, Taylor and Moore 1981). The axial and radial wood density trends are not clearly understood and demands more research (Warren 1979).

Generally, however, earlywood and latewood basic densities decrease with height in the stem (Larson 1957, Kollmann and Cote 1968). Outward from pith, there is a progressive decrease in earlywood basic density within the juvenile core (Paul 1963). Latewood basic density increases from pith to bark (Nicholls and Dadswell 1963, Larson 1957).

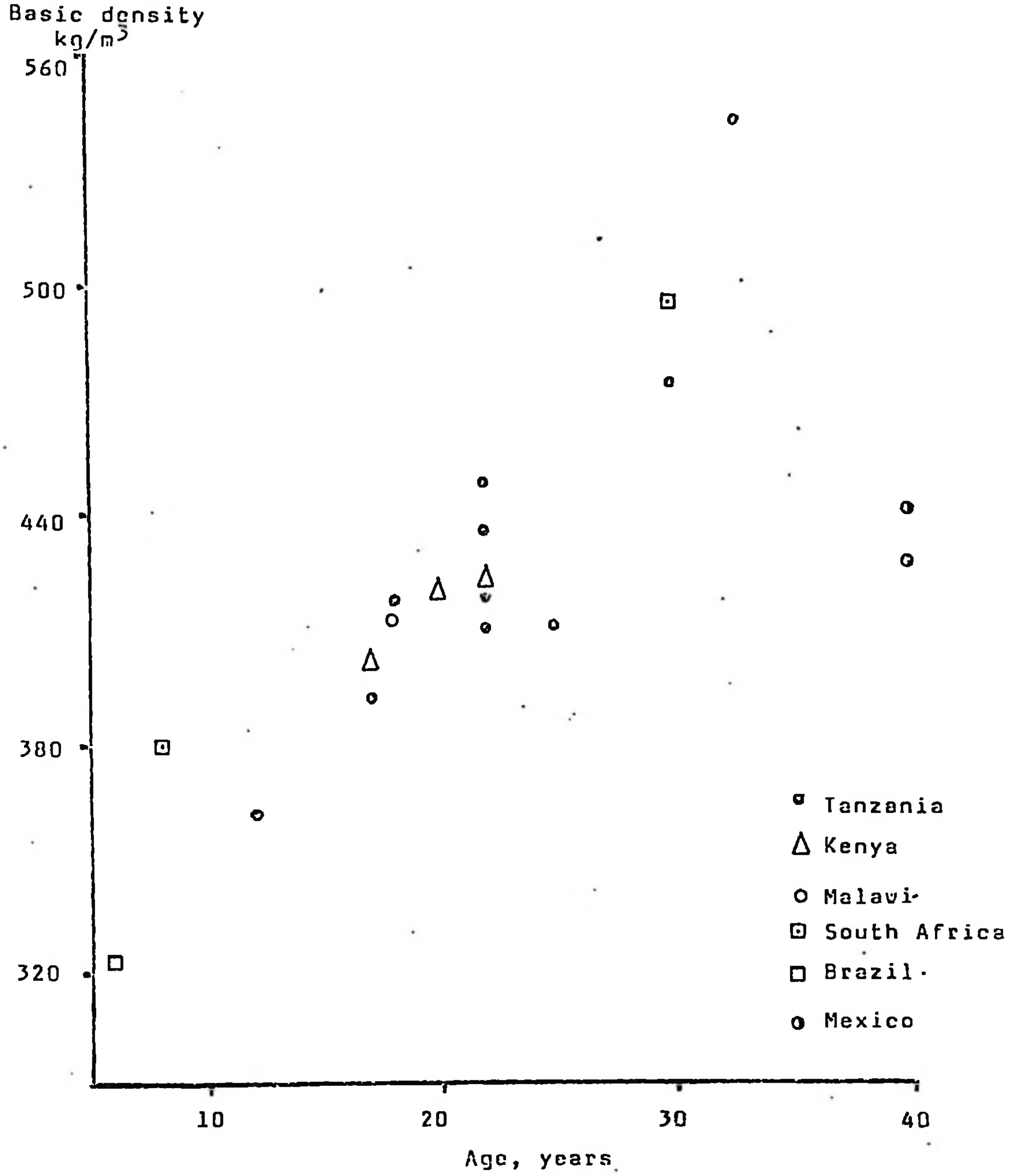
Table 2.3 Earlywood and latewood basic densities in five pines.

Species	Ring band	Basic density, kg/m^3		Ratio	Source
		Range	Mean		
Pinus eliottii	Earlywood	210-330	275		Paul 1939
	Latewood	380-700	570	2.07	" "
Pinus echinata	Earlywood	210-330	267		" "
	Latewood	360-740	600	2.28	" "
Pinus taeda	Earlywood	250-360	310		" "
	Latewood	440-720	625	2.01	" "
Pinus polustris	Earlywood	220-320	280		" "
	Latewood	610-790	690	2.46	" "
Pinus patula	Earlywood	353-382	368		Fry and
	Latewood	418-528	469	1.27	Chalk 1957

2.2.4 Density of the wood from *Pinus patula*

Wood density of *Pinus patula* grown in various countries in Africa and Latin America is presented in table 2.4. Direct comparison of the different values can be misleading, due to the fact that the methods used in obtaining those results are not identical and secondly the age of the trees is not the same. Examination of the table and figure 2.1, however, shows that age of the trees studied affects the average values. A comparison of the mean values reported for the same age in South Africa and East Africa shows small differences (Wormald 1975). It has

Figure 2.1 The relationship between wood basic density and tree age in *Pinus patula* from various countries.



also been adduced that the densities of the wood of this species grown in different geographical locations are similar (Zobel 1965). The effect of site conditions on wood density cannot be ascertained, as there is only scanty knowledge regarding this subject. It is important to note that most existing stands in Africa were established on good sites with favourable growth conditions and hence the wide range in conditions necessary for comparison does not exist (de Villiers 1974). 22 years old materials from Tanzania and Uganda showed little difference (Kubelka 1969, Plumptre 1978).

Between tree variation is quite large (Zobel 1965, Turnbull 1947, Kubelka 1969, Plumptre 1978, Adlard *et al.* 1979, Ringo and Klem 1980, Palmer *et al.* 1982). In 37 year old *Pinus patula* grown in New Zealand wood basic density was found to increase from suppressed to dominant trees (New Zealand Forest Service 1949). In East Africa wood basic density is reported to decrease with stem dominance (Paterson 1969, Ringo and Klem 1980). In South Africa similar results were reported (Turnbull 1947). Variation between trees has been attributed to tree differences in genetic constituent (Zobel 1965, Paterson 1969). Silvicultural treatments are also reported to influence the density of the wood formed (Wormald 1975). Preliminary investigation into the effect of pruning and thinning of *Pinus patula* stands have shown that pruning reduced the rate of radial growth and increased wood density, whereas thinning gave the opposite effect (Plumptre and Austin 1978).

Available literature of wood density variation with height in the stem in *Pinus patula* is not in complete agreement. Little variation has been found in *Pinus patula* grown in Uganda (Plumptre 1978). Other reports show significant decrease of basic density with height in tree for trees growing in Tanzania and Kenya (Kubelka 1969, Paterson 1969, Ringo and Klem 1980). In one report on Brazilian grown Pinus patula 5-14 years old, basic density tended to increase from base to crown (Amaral et al. 1977). The results reported for the Brazilian materials, may be due to young age, resulting in obtaining more samples from the crown portion of each stem. It is well recognized that in pines the wood density in the crown may be higher than in the clear bole below (Panshin and de Zeew 1970). The discrepancy in the results may also be attributed to differences in sampling patterns (Elliott 1970).

Wood density has been reported to increase from pith outwards to bark at all heights in the stem of Pinus patula grown in Afica, New Zealand and Mexico (Turnbull 1947, New Zealand Forest Service 1949, Fry and Chalk 1957, Zobel 1965, Lema et al. 1979, Ringo and Klem 1980). The wood density may increase from 350 kg/m^3 to 500 kg/m^3 from 12 years to 30 years. In Mexico the wood density increased from a mean of 390 kg/m^3 at 10 years to 480 kg/m^3 at 40 years (Zobel 1965).

2.3 Basic density of juvenile and mature wood

2.3.1 Definitions

Examination of the cross-section from pith to bark in a softwood stem, particularly in a species with pronounced contrast between earlywood and latewood, shows certain changes in the structural pattern of successive annual rings (Dadswell 1958, Rendle 1960). The variations were described for the first time a century ago and have now been recorded by many workers (Elliott 1970). There can be recognized three

Table 2.4 Wood density of _Pinus patula_ from different countries.

Country	Locality	Age, years	Basic density, kg/m^3	Reference
Tanzania	Average for all sites	12	362	Bryce 1967 (1)
		17	391	"
		22	419	"
		30	475	"
		33	550	"
	Old-Moshi	22	449	Kubelka 1969
	Rongai	22	409	"
	Kigogo	22	435	"
	Meru	18	438	Lema _et al_. 1979
	Sao Hill	25	410	Ringo and Klem 1980
Kenya	Average for all sites	17	401	Paterson 1969
	Kaptagat	20	426	Palmer _et al_. 1982
Uganda	Southern Uganda	22	426	Plumptre 1978
Malawi	Viphya	18	454	Adlard _et al_. 1979
South Africa	Average for all sites	8	380	Turnbull 1947
		30	496	" "
Brazil		6	322	Moreschi _et al_. 1973
Mexico	Tlaxcala	40	430	Zobel 1965
	Puebla	40	440	"

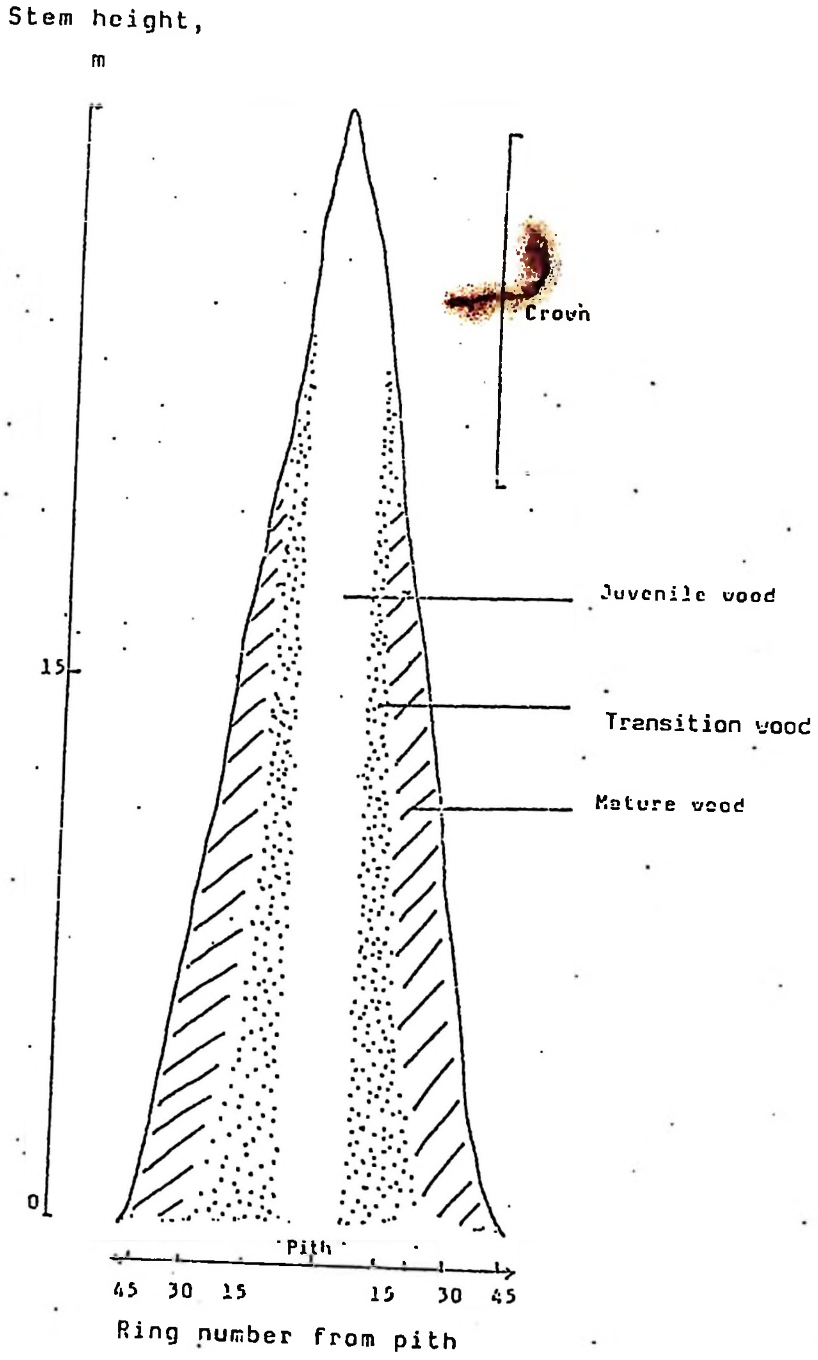
(1) Converted to basic density from air dry density

phases in the life of a tree, namely juvenile or immature phase, adult or mature phase and the senescent or overmature phase (Dadswell 1958). The observed changes in structure and composition of wood and how they are brought about and the extent to which they are influenced by external conditions of growth are not clearly known (Zobel _et al_. 1978). The wood near the pith and that near the bark in old trees are different and several definitions have been proposed (Harris 1981). The various names are crown formed wood, immature and mature wood, corewood and outerwood, juvenile and mature wood (Paul 1957, Dadswell 1958, Rendle 1960). The most popularly used terms are juvenile wood and mature wood (Larson 1969, Zobel 1981). The term juvenile wood is based upon arbitrary criteria and there is no acceptable definition by which it may be accurately identified (Larson 1969, Bendtsen 1978). Although it describes the type of wood produced in a young tree, the same or a very similar type of wood is also produced in the rings nearest the pith at all heights in the stem (Larson 1969). The location of juvenile wood, transition wood and mature wood in a stem is shown in figure 2.2. In this investigation the terms juvenile wood and mature wood are adopted for the two wood zones to designate core wood and outer wood respectively.

The properties of juvenile wood can be summarized as follows in relation to mature wood:

- lower specific gravity
- lower latewood per cent
- shorter tracheids
- tracheids with larger lumen diameter
- thinner cell walls
- larger fibrilar angle
- lower cellulose content
- higher lignin content
- lower strength
- higher longitudinal shrinkage
- lower transverse shrinkage
- more compression wood
- dull and lifeless appearance.

Figure 2.2. Example of juvenile and mature wood position in a stem.



The following wood characteristics can form the basis for demarkating juvenile wood from mature wood. The features can be taken as single or in combination (Elliott 1970, Harris 1981):

- ring wood density
- latewood density
- tracheid length or diameter
- cellulose proportion.

Wood basic density and tracheid length are more commonly applied in distinguishing the two types of wood (Bisset and Dadswell 1950b).

The demarkation between juvenile and mature wood has been carried out in four ways:

- In terms of the rapid and progressive changes in wood density and tracheid length with increase in age i.e. ring number from pith (Bisset and Dadswell 1950b, Zobel and McElwee 1958). In this approach a sharp increase in wood density or tracheid length indicates end of juvenile period (Panshin and de Zeeuw 1970). Immediately following juvenile wood will be transition wood as shown in figure 2.2.
- In terms of the changes in ring width from pith to bark (Paul 1957, 1960, Jane 1970). This technique relies on the relationship between tracheid length or wood density on ring width (Larson 1969) As ring width decreases with ring number from pith a ring width is reached below which mature wood is formed. This technique has a major limitation, that it can only work where growth rings are very distinct.

  Further if the reduction in ring width is gradual from pith to bark, it becomes difficult to single out the exact ring number after which mature wood is formed.

- The third method is the taking of an arbitrary ring number from pith designating the border between juvenile wood core and mature wood (Bannan 1965b, Zobel *et al*. 1972, Cown and McConchie 1980). This has so far been the most popularly followed approach and generally the first 10 growth rings have been considered to constitute the juvenile core. It is evident that most studies using this approach have not taken into account the presence of transition wood (Zobel *et al*. 1972).

- Juvenile core has been established by taking an arbitrary wood density value (Plumptre 1978). This is a very rarely used technique and appears only in one study.

The period during which only juvenile wood is produced in the stem is referred to as the juvenile period. Immediately following will be a period characterized by formation of transition wood. In the third period the stem produces mature wood. Most researchers generally agree that the juvenile period includes anywhere from 5-20 rings near the pith, depending on species (Rendle 1960, Zobel *et al*. 1972).

The juvenile period in pines growing in South USA is conveniently considered to last for ten years, whereas the actual period lies between 5 to 8 years (Bendtsen 1978). Juvenile period in *Pinus radiata* grown in Australia and New Zealand lasts for 10 to 15 years (Harris 1965).

The extent of the juvenile period in *Pinus patula* grown in East Africa has been established in one crop grown in Malawi (Adlard *et al*. 1979). The juvenile period was found to last for 6-8 years based on wood density radial variation. In Ugandan grown *Pinus patula* juvenile period extended for 4 to 6 years based on juvenile wood basic density value of 350 kg/m^3 (Plumptre 1978).

2.3.2 Proportion of juvenile wood in the stem

There are very few reports that specify the quantities of juvenile wood in the stems. On the other hand some reports have indicated the ring number to which juvenile wood extends in the stem (Einspahr 1972, Zobel *et al*. 1972, Bendtsen 1978, Cown and McConchie 1980). Juvenile wood proportion has been reported for a few species growing in the southern USA (Zobel *et al*. 1972). The amount of juvenile wood in a given stem will depend on the definition used to describe it and the age of the tree (Bendtsen 1978). The older the tree beyond the juvenile period, the smaller will be the proportion of juvenile wood. Also to be noted, juvenile wood proportion increases with height in the stem (Zobel *et al*. 1972). Juvenile wood proportion increases with increase in growth rate during the young stage of the tree (Dadswell 1958, Zobel 1981). Juvenile wood proportion is reported to be 10-20 per cent in *Pinus patula* grown in Uganda (Plumptre 1978). Definition of juvenile wood in this study was wood density near the pith with basic density equal to or less than 350 kg/m^3.

2.3.3 Variations within juvenile and mature wood

Radial basic density variation within the juvenile core has been reported for many hardwoods and softwoods. There are basically two patterns, namely:

- basic density increases with ring number outward from pith
- basic density decreases with ring number outward

from pith.

The first pattern is more common in softwoods and particularly in pines (Zobel et al. 1972). This pattern is reported in Pinus palustris , Pinus sylvestris, Pinus taeda, Pinus elliottii, Pinus contorta, Pinus patula and Pinus radiata (Bisset and Dadswell 1950b, Spurr and Hsiung 1954, Elliott 1970, Cown and McConchie 1980, Taylor and Burton 1982).

The second pattern is more common in hardwoods and has been established in Eucalyptus species, Tsuga heterophylla etc. (Krahmer 1966).

Radial wood basic density variations within the mature wood zone can be grouped into four patterns, namely:

- basic density increases outwards from pith
- basic density remains constant outwards from pith
- basic density fluctuates outwards from pith
- basic density decreases outwards from pith.

The first pattern is more common in softwoods and has been reported for many species including Picea sitchensis, Pinus radiata, Pinus strobus, Tsuga heterophylla (Nicholls and Dadswell 1963, Foulger 1966, Krahmer 1966). The fourth pattern is more common in hardwoods (Panshin and de Zeeuw 1970).

There is a general agreement among many research reports that mature wood basic density decreases with increasing height in the stem (Okkonen et al. 1972).

2.4 Tracheid length

2.4.1 Definition

Tracheids are longitudinally oriented cells found mainly in softwoods. In some species a few tracheids may be placed horizontally in association with rays and hence the term ray tracheid. Axial tracheids can be grouped into two categories based on their dimensions, namely earlywood and latewood tracheids. Latewood tracheids have thicker walls, smaller diameters and are longer than earlywood tracheids (Bisset and Dadswell 1950a, 1950b, Taylor and Moore 1981). Axial tracheids are 75 - 200 times longer than their diameter and for most species the tracheid length will be in the region of 2 to 5 mm (Dinwoodie 1961, Rydholm 1965). There are a few exceptions among softwoods with tracheids of shorter lengths such as in Araucaria and Sequoia (Jane 1970). In most softwoods the tracheid diameter average lies between 0.02 - 0.04 mm, but may range from 0.015 - 0.080 mm (Tsoumis 1968). Axial tracheids constitute about 90 per cent of the tissue in softwoods while the rest consist of ray tissue (Kollmann and Cote 1968).

Tracheids in hardwoods are present only in a few species and are considered to be transitional elements related to vessel members or fibres. The tracheids in hardwoods can be subgrouped into two, namely vascular and vasicentric tracheids. Description of tissues in hardwoods can be found in any standard wood technology text book, for example Desch (1980).

2.4.2 Significance as quality factor

The length of the tracheids is an important characteristic for the pulp and paper industry (Watson *et al.* 1971). The properties of paper will depend upon the structure and properties of the fibres from which it is manufactured (McIntosh 1970). Paper strength properties, i.e. tensile, burst, tear and fold strengths, have been found to have relationship with tracheid length (Dinwoodie 1965). In *Pinus radiata* for example paper tear strength increases with increasing fibre length. The coefficient of determination of the relationship between tear strength and fibre length was 0.895 (Kibblewhite 1980). Similar findings were reported ealier for the same species (Watson *et al.* 1971). Within the natural range, tracheid length influences interfibre bonding, which in turn affect the paper strength properties. Latewood tracheids which are longer than earlywood tracheids provide long contact surface with other tracheids in the paper sheet and hence better intertracheid bonding (McIntosh 1970).

Thin walled, short earlywood tracheids will tend to collapse into ribbon structures during pulping and sheet formation while thick walled tracheids remain stiff. Earlywood tracheids with well developed bordered pits, around which the fibril angle is large, imparts low tensile strength on paper.

Tracheid length is a heritable character and thus tree breeding for desirable length is possible (Einspahr 1972). Estimates of heritability, and expected genetic gains have been calculated for some pine species and some hardwoods. Heritability estimates for fibre length range from 0.56 to 0.97 for pines growing in Southern United States (Einspahr 1972).

Tracheid length variation within stems and between trees can be influenced by deliberate alterations of growth conditions (Brazier 1976). Manipulation of the growth environment of the tree which results in uniform wood raw materials is very important for manufacture of pulp and paper (Labosky and Ifju 1972).

2.4.3 Methods of measurement

Since Sanio's studies of tracheid length variation in *Pinus sylvestris* about a century ago many techniques have been developed and refined for accurate measurements of cell dimensions (Hughes and Andrea 1974). Basically the systems are based on the same principles. The main features of these systems include units such as specimen holder, micrometer, illuminator, magnifying unit and image surface unit. These systems differ widely in prices, speed of obtaining results and accuracy. The following is a description of a more recently developed technique used at the Forest Products Laboratory at Princess Risborough.

The lengths of cells are measured in the usual way by maceration of wood specimens and projection of their images on a translucent screen or on a papered surface. The lengths of projected images are measured with modified map measurers, which give an electrical pulse for every 1 cm or 5 cm of traverse. Pulses are recorded by an electronic counting unit which incorporates a specimen batch counter and a pulse counter, and also has a uniselector unit to display separately on a series of counters the lengths of images measured by 1 cm classes.

2.5 General tracheid and fibre length variation

2.5.1 Introduction

Studies of tracheid length and its variation in trees of commercial importance were started about a century ago in Germany (Bannan 1965b). The early investigations concentrated on tracheid length variation in a few species namely _Pinus sylvestris_, _Pinus banksiana_, _Picea sitchensis_, _Picea abies_ and _Pseudotsuga taxifolia_ (Dinwoodie 1961). In the late fourties and early fifties some hardwood species were studied with regard to fibre length variations mainly _Eucalyptus_ species grown in Australia. Fibre length of 49 hardwood species native to the USA was also obtained in the same period (Bergman 1949). These investigations have been carried out by botanists interested in the anatomical patterns purely for botanical studies and by foresters with the view to relating these variations to properties of wood products (Anderson 1951, Dinwoodie 1961, Bannan 1965a, Esau 1976).

It is apparent from available literature that some of the investigations were aimed at establishing the relationship between tracheid or fibre length and factors believed to influence it (Bendtsen 1978). At present it is not known exactly which factors and to what extent different factors do influence tracheid and fibre length (Brazier 1976). Despite this uncertainty the general conclusions tend to favour the following factors:

- environmental factors
- inherent anatomical charateristics
- age of the trees.

A considerable number of investigations have shown that tracheid or fibre length tend to vary with geographical location (Kollmann and Cote 1968, Tsoumis 1968). Variations with geographical race are reported in *Pinus sylvestris* (Echols 1958). Similar results are reported for *Pinus nigra* in which tracheid length increased from northeast to southwest across its natural range (Ledig *et al*. 1975). Variation with geographical location is also reported for Canadian grown *Pinus contorta*, *Pseudotsuga menziensii*, *Abies concolor*, and *Sequoia sempervirens* (Bannan 1965b). In New Zealand, tracheid length in *Pinus radiata* increase with decreasing latitude (Kibblewhite 1980). Tracheid length of *Pinus nigra* grown in Greece increased from north to south (Tsoumis and Panagiotidis 1980). For trees grown in the temperate regions wood tracheid length tend to increase with decreasing altitude and there seems to be a close relationship between tracheid length and temperature (Echols 1958). Similar trend has been demonstrated in the wood of *Pinus patula* grown in Tanzania (White *et al*. 1980).

The influence of silvicultural treatments on the tracheid length of the wood formed has been investigated for various species and several reviews have been presented (Spurr and Hyvarinen 1954, Dinwoodie 1961, Bannan 1965b, Brazier 1976, Bendtsen 1978). It is apparent from the reviews and later studies that increased growth rate may result in one of the following:

- decreased tracheid length (Posey 1964, Nicholls 1971, Cown 1973, Klem 1974).
- increased tracheid length (Saucier and Ike 1972)
- no change in tracheid length (Wooten *et al*. 1973)
- fluctuations in tracheid length (Dinwoodie 1961).

The differences between the independent studies can be explained by one or a combination of the following factors:

- species differences (Spurr and Hyvarinen 1954)
- differences in age of the treated trees (Klem 1974)
- differences of silvicultural treatments (Brazier 1976).

Investigations of tracheid or fibre length heritability have attracted considerable attention for the last half century (Bendtsen 1978). The objectives of the studies have been to verify the extent of heritability for species, and then make this information available to tree breeders (Einspahr 1972). Estimates of heritability and expected genetic gains are presented in 2.4.2 for pines growing in Southern USA. Among the hardwoods, heritability estimates have been made for _Populus_ _tremula_ and _Populus_ _deltoides_ (Einspahr 1972). Different races have been established in _Pinus_ _sylvestris_ obtained from its entire growth range (Echols 1958). Heritability estimates have been made for pines growing outside their natural range (Harris 1965, Paterson 1969). Genetic heritability concepts have been enhanced by tree breeding studies which indicate that hybridization in trees follows the usual laws governing inheritance in other plants (Einspahr 1972). The major difficulty, however, in tree breeding is that the time between seed production and mature wood formation in the crosses is so long that assessment of results is very slow. In order to reduce this time lag, attempts have been made to assess the desired qualities in wood produced by seedlings and branches of young trees. These methods are of only limited success because of the poor correlation between the young material of the progeny for a given character and the same character in a mature tree with identical genetic composition (Duffield 1961).

Examination of literature indicates that tracheid length increases with tree age (Spurr and Hyvarinen 1954, Dinwoodie 1961, Bannan 1964). The effect of age on tracheid length has been found to be more pronounced in young trees than in mature ones (Dinwoodie 1961). The causes of increase in tracheid length with age is presented in 2.5.2.

2.5.2 Softwoods versus hardwoods

Generally the tracheids in softwoods are much longer than the fibres in hardwoods when comparing trees of the same age. In the former tracheid length lies between 2-5 mm while in the latter it is between 1-2 mm (Rydholm 1965).

The shape, quantity and length of tracheids and fibres found in reaction wood differ markedly from those of normal wood (Tsoumis 1968). Tracheids in compression wood are about 30 per cent shorter than in normal wood (Kollmann and Cote 1968). In Pinus walichiana grown in India compression wood tracheids were found to be significantly shorter than those in normal wood (Seth and Jain 1977). There has been fewer investigations regarding tension wood fibre length (Tsoumis 1968). The results from the few investigations are rather mixed. Tension wood fibres have been reported to be longer than, equal to or shorter than normal wood fibres (Tsoumis 1968).

Earlywood and latewood tracheid and fibre length may differ considerably (Bisset and Dadswell 1950a, 1950 b, Labosky and Ifju 1972). Generally latewood tracheid length is greater than earlywood tracheid length (Taylor and Moore 1981). Latewood tracheid length has been found to be longer than those in earlywood in Pinus radiata (Chalk and Ortiz 1961).

Similar relationship was found in *Pinus sylvestris* (Helander 1933). Besides in *Pinus* species, a similar relationship has been reported in *Thuja occidentalis*, *Picea abies* and *Picea sitchensis* (Chalk 1930, Bannan 1954). The longest tracheids have been found in the transition zone from earlywood to latewood in *Picea sitchensis*, Pinus *elliottii* and *Pinus echinata* (Dinwoodie 1963, Jackson and Moore 1965). In hardwoods, latewood fibres are reported to be longer than earlywood fibres in *Eucalyptus regnans* (Bisset and Dadswell 1950a).

There is a general agreement that tracheid and fibre length varies with height in the stem both in softwoods and hardwoods (Spurr and Hyvarinen 1954, France and Mexal 1980). The general trend indicates that tracheid and fibre length increases with increasing height in the stem up to a certain distance then progressively decreases to the top of the stem (Bisset and Dadswell 1950a). The fibres are generally shorter near the stem apex than at the stem base (Kollmann and Cote 1968). The height in the stem with maximum fibre length tends to be different for different species, for example, it is 29 per cent of stem height in *Eucalyptus regnans* and between 15 and 40 per cent in *Pinus sylvestris* and *Picea abies* (Helander 1933, Bisset and Dadswell 1949). Some studies show deviations from the general trend, for example, in mature *Abies concolor* trees the minimum tracheid length occurs at the stump height and beyond 7 metre height in the stem, tracheid length does not vary significantly (Anderson 1951). In young and mature *Pinus ponderosa* there was no change in tracheid length above 2 metre height in the stem (Voorhies and Jameson 1969). In 26 years old *Pinus radiata* there was a uniform reduction in tracheid length from the base to the top of the trunk in any given growth increment (Nicholls and Dadswell 1962).

The same pattern has been shown in *Carya ovata*, *Liriodendron tulipifera* and *Thuja plicata* (Dinwoodie 1961). In *Sequoia gigantea* there was no significant difference in fibre length at different heights in the stem (Knigge and Wenzel 1982).

For any cross-section of a trunk the length of tracheids and fibres changes from pith to bark (Spurr and Hyvarinen 1954). This was first investigated in *Pinus sylvestris* by Sanio (Bergman 1949). Sanio found that at any height in the stem tracheid and fibre length increases from pith outwards until a definite size is reached beyond which the average length remains constant (Dinwoodie 1961). These findings were later found to hold for *Pseudotsuga taxifolia*, *Carya ovata*, *Sequoia sempervirens*, *Eucalyptus regnans* and many pine species (Bannan 1965b).

Results from many investigations are in agreement with Sanio's law as far as increase to a maximum from pith, but beyond that point some reports show increases, decreases or fluctuations (Taylor *et al*. 1982). Actual decrease after reaching the first peak is reported for *Fagus silvatica* and *Picea abies* (Dinwoodie 1961). In *Pinus caribaea* and *Pinus taeda* tracheid length was found to increase after reaching the maximum, but increased slowly. This trend is also reported in 100 year old trees of *Alnus glutinosa*, *Betula lutea*, *Liriodendron tulipifera*, *Acer pseudoplatanus* and *Fagus silvatica* (Panshin and de de Zeeuw 1970). In *Pinus palustris*, *Pinus strobus* and *Abies concolor* there were fluctuations after reaching the maximum (Dinwoodie 1961).

2.5.3 Tracheid length in *Pinus* species

2.5.3.1 Variation between species

Because of their importance as raw material in the pulp and paper industries, tracheid characteristics in many commercially important pine species have been studied (Taylor *et al*. 1982). In order to compare the tracheid length of wood of different pine species it is pertinent to consider tree age, growth conditions as well as sampling procedures used (Dinwoodie 1966, Cown and Kibblewhite 1980).

Table 2.5 shows tracheid length of various pine species grown in different geographical locations. Although the values can not be compared directly, it can be said that the differences between the mean values for pine species are rather insignificant and hardly important for the differences in paper properties of the corresponding pulps (Rydholm 1965). In most cases within species variation is larger than between species variation (Cown and McConchie 1980). What may be more varied between species would be the latewood/earlywood proportion (Kollmann and Cote 1968).

Table 2.5 Tracheid length of different pine species.

	Weighted tracheid length	Source
Pinus banksiana	3.5 mm	Rydholm 1965
Pinus contorta	3.5 "	" "
Pinus echinata	3.5 "	" "
Pinus elliottii	3.5 "	" "
Pinus palustris	3.5 "	" "
Pinus ponderosa	3.6 "	" "
Pinus resinosa	3.5 "	" "
Pinus sylvestris	3.0 "	" "
Pinus strobus	3.5 "	" "
Pinus taeda	3.5 "	" "
Pinus radiata	3.5 "	Cown and McConchie 1980

2.5.3.2 Variation between trees

Variability between trees within species may be greater or smaller than within tree variation (de Zeeuw 1964). Significant tree to tree tracheid length difference has been reported for many pine species both from plantations and from natural forests (Wheeler *et al.* 1966, Tsoumis 1968, Cown and McConchie 1980, Taylor *et al.* 1982). Two general influences contribute to this interspecies variability, namely growth factors and genetical factors (Bendtsen 1978, Zobel 1981). Growth factors are those changes in the immediate environment of the tree that increase or depress growth rate. The environmental factors influences the tree crown directly and the crown in turn influences cell growth and development (Larson 1969). The growth environment can be manipulated by thinning, pruning, irrigation, fertilization etc. Reduction of tracheid length is reported following fertilizer application for 12 and 16 year old Pinus taeda, 25 year old Pinus elliottii, Pinus sylvestris (Posey 1964, Nicholls 1971, Klem 1974). Similar reduction has been observed after thinning treatment in Pinus elliottii, Pinus radiata, and other pine species (Nicholls 1971, Cown 1974, Taylor and Burton 1982).

Availability of soil moisture has been shown to influence the percentage of latewood as well as ring width (Larson 1969). Optimal moisture conditions throughout the growth season promotes wide incremental growth in both earlywood and latewood. Lack of moisture curtails growth activity in the tree crown and reduces auxin production with consequent early onset of latewood formation and narrowing of the increment producing what is sometimes referred to as starvation wood (Brazier 1976). Accelerated growth tends to produce wood with short tracheids. Similar trend is evident where there is high moisture stress and reduced growth (Taylor et al. 1982).

Differences in genetic constituent contribute to between tree variation (Paterson 1969, Echols 1973).

2.5.3.3 Variation within trees in the axial direction

The relationship between tracheid length and height in stem was first studied by Sanio in Pinus sylvestris about a century ago (Spurr and Hyvarinen 1954). In that study, tracheid length within a given ring first increased in the stem to a certain height above which tracheid length decreased with increased height in the stem from ground. Sanio's findings were later verified in the same species and in other pine species including Pinus palustris, Pinus strobus, Pinus taeda, and Pinus densiflora (Dinwoodie 1961). More recently the same trend has been established in Pinus contorta (France and Mexal 1980). The height to maximum tracheid length in Pinus sylvestris was found to be between 15-40 per cent of stem height (Dinwoodie 1961). It is noted that the height with longest tracheids increases with increase in ring number from the pith (Spurr and Hyvarinen 1954, Bannan 1965b).

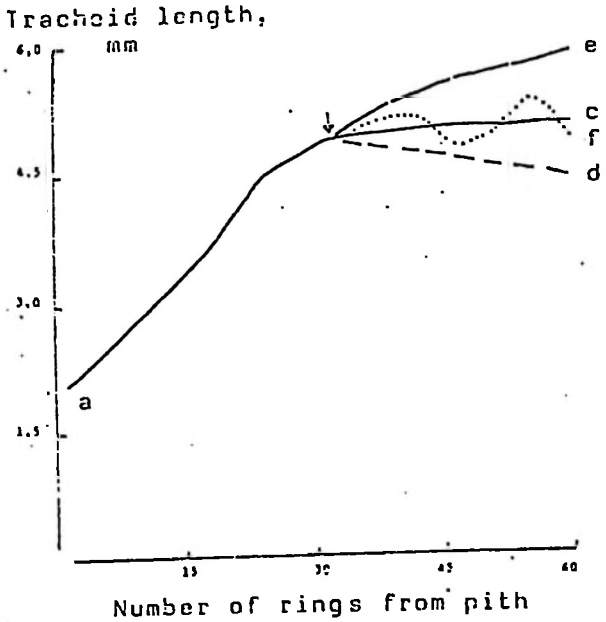
Reports on axial tracheid length variation in Pinus radiata are in disagreement. In trees grown in Australia tracheid length in any given increment decreased uniformly from the base to the top of the trunk (Nicholls and Dadswell 1962). In New Zealand grown Pinus radiata axial tracheid length variation followed Sanio's law (Cown and McConchie 1980). Other exceptions to the general rule have been reported in Pinus banksiana, and in young Pinus ponderosa (Dinwoodie 1961). In these pines there were no changes in tracheid length with height in the stem. More recently studies of Pinus contorta showed that tracheid length did not vary with stem height in the first 10 m (Taylor et al. 1982).

There does not seem to be an obvious explanation to the wide discrepancy between the results obtained from the various studies; but part of the differences could be attributed to different sampling patterns, tree age and tree growth rate. It is known that ring width increases with tree height. The change in tracheid length with height cannot therefore be assumed to be associated only with changes in height in the tree, but also with changes in ring width (Bannan 1965b, Bendtsen 1978). There is also evidence of a positive relationship between growth in height and cell length (Dinwoodie 1963, Bannan 1965a).

2.5.3.4 Variation within trees in the radial direction

Studies on tracheid length variation from pith to bark were first performed on Pinus sylvestris wood by Sanio in 1872 (Anderson 1951). His results showed that tracheid length increases from pith outwards at a given height until a definite size is reached beyond which the average tracheid length remained constant. Tracheid length near the pith may be between 1 and 2 mm but increases and may reach a maximum of 5 mm near the bark (Bisset and Dadswell 1950b). Results from subsequent investigations by other workers are divided. Most of the studies are in complete agreement only to the first part of the law, i.e. as the number of rings increases outwards from the pith tracheid length increases rapidly to the first peak. Beyond the first peak the results are divided and the more common patterns are shown in figure 2.3.

Figure 2.3 Radial tracheid length variation.



Sanio's findings, i.e. "ac" has been demonstrated in *Pinus taeda*, *Pinus densiflora*, *Pinus radiata*, *Pinus merkusii* and *Pinus elliottii* (Dinwoodie 1961, Cown and McConchie 1980). A decrease after the first peak i.e. "ad" has been shown to occur in *Pseudotsuga taxifolia* and *Picea abies* (Helander 1933). Increase after the peak i.e. "ae" has been reported in *Pinus taeda*, *Pinus elliottii*, *Pinus resinosa* , *Pinus ponderosa* and *Pinus strobus* (Panshin and de Zeeuw 1970). Some results also indicate inconsistent fluctuations after the first peak, "af", in *Pinus palustris*, *Pinus strobus* and *Pinus contorta* (Dinwoodie 1961).

The discrepancies among the results after the first peak are mainly due to difference in tree age and changes in the environment which affect the crown (Larson 1969). The period to the first peak varies with species and growth conditions, for example, it is 25-60 rings in *Pinus sylvestris* and 10-14 rings in *Pinus radiata* (Bisset and Dadswell 1950b, Taylor *et al*. 1982).

A generalized explanation of the underlying causes for cell length changes across a transverse section of a stem can be based on the maturation or age changes associated with the cambial initials and the xylem mother cells. The production of new initial cells in the cambial region theoretically should yield two initials of equal length after division (Bannan 1964). It has been shown that the derived cells are not always equal in length and the longest are favoured for continuation as cambial initials because they exhibit the greatest number of ray contacts and therefore produce more efficient functioning tracheids. The mean length of the cambial initials at any one period is a function of the rate of anticlinal division and the percentage survival.

In the first few years of growth after initiation of a cambium, the rate of anticlinal divisions is rapid and the survival rate is high with the result that the mean length of the initials and derived cells is short (Bannan 1964, Larson 1964). The rate of anticlinal division and the rate of survival of derived cells both decrease with increasing age of the cambium and result in longer initials. In addition the length of the initials is affected by the duration and the period in the growth season of anticlinal divisions. In the first few years anticlinal divisions occur throughout the growth season, as the tree matures and passes maturity the anticlinal division is confined to the later part of the growth season during formation of latewood (Larson 1964).

Growth rate affects the increase in length of the cambial initial cells. Fast growth retards the rate of length increase in cambial initials during the early years of activity of the cambium and delays the time of production of maximum length of cells.
Within the increment the xylem mother cells which are initially nearly identical in length to the cambial initials from which they were derived, divide with juvenile pattern in the rapid growing earlywood and produce cells which are shorter than the cambial initials. The reduction in length is proportional to the rate of growth (Panshin and de Zeeuw 1970).

Literature reports on earlywood and latewood tracheid length within individual growth rings of pine trees are contradictory and confusing (Taylor and Moore 1981). Latewood tracheid lengths have been reported to be longer than those of earlywood in Pinus radiata, Pinus sylvestris, Pinus taeda, Pinus elliottii and Pinus echinata (Bisset and Dadswell 1950b, McGinnes 1963, McMillin 1968, Ifju and Labosky 1972). No difference was found between the tracheids of the two wood bands in Pinus taeda and Pinus palustris (Jackson and Moore 1965). Recently tracheid length of latewood was found to not be consistently longer than those of earlywood in Pinus taeda (Taylor and Moore 1981). Despite these differences in the results obtained for various species, it is concluded that generally in normal wood latewood tracheids will be longer than earlywood tracheids from the same ring (Taylor and Moore 1981). This difference may range between 12 and 25 per cent. Table 2.6 shows tracheid length of earlywood and latewood from four pine species.

Table 2.6 Tracheid length of earlywood and latewood in the same ring in four pine species

Species	Age, years	Tracheid length, mm Earlywood	Latewood	Source
Pinus elliottii	45	4.2	4.4	Cole et al. 1966
Pinus radiata	-	3.2	3.6	Bisset and
Pinus sylvestris	-	3.0	3.2	Dadswell 1950b
Pinus taeda	35	3.5	4.0	Ifju and Labosky 1972

When the lengths of earlywood and latewood tracheids are plotted separately for a series of increments along a given radius, the peak value for both groups of measurements correspond to the curve of ring tracheid variation. The rate of increase in length is greater for latewood tracheids than for those in earlywood and the percentage difference increases gradually with age until a maximum is reached in the mature wood zone (Tsoumis 1968).

2.5.4 Tracheid length in *Pinus patula*

2.5.4.1 Variation between sites

Table 2.7 shows tracheid length values for *Pinus patula* wood from different countries.

Table 2.7 Tracheid length of *Pinus patula* from different countries.

Country	Locality	Age, years	Trach. length, mm	Source
Tanzania	Old Moshi	22	3.5	Kubelka 1969
	Msiwazi	11	3.17	" "
	Rongai	22	3.35	" "
	Kamanga	14	3.02	" "
	Endonet	15	3.29	" "
	Kigogo	22	3.84	" "
	Meru	19-22	3.60	White *et al.* 1980
Angola	-	-	2.7-4.9	Wormald 1975
Swaziland	Usutu	-	2.5-3.7	" "
Madagascar	-	-	3.6-4.2	" "
Kenya	Average	20	4.1	Paterson 1969
	"	30	4.4	" "
	Turbo	10	2.83	Palmer *et al.* 1982
	Kaptagat	10	2.36	" "
	Kaptagat	20	2.96	" "
Mexico	Tlaxcala	40	3.74	Zobel 1965
	Puebla	40	4.41	" "

Direct comparison of the results from the different investigations is not acceptable due to the differences in sampling procedures and age of the materials studied. It is, however, possible to compare results obtained in the same investigation but for different sites. The 22 year old wood from different sites in Tanzania showed a difference of 15 per cent between tracheid length of wood from Kigogo and Rongai, being higher in the former. Examination of the other variables in the study from Tanzania further shows that the Kigogo trees had a higher mean growth rate and latewood proportion than those from Rongai. The differences in length can be attributed to genetical differences and growth conditions. The seed for the entire crop of Pinus patula grown in East and Central Africa were obtained in South Africa (Paterson 1969). Other possible explanations could be attributed to environmental factors such as altitude and temperature (Wormald 1975, White et al. 1980). The large difference between the 20 year old materials grown in Kenya (Paterson 1969, Palmer et al. 1982) could be attributed to differences in sampling procedures. The materials studied from Kaptagat consisted of 10 sample trees which were pulped and measurements were made of both broken and unbroken fibres. This may explain at least in part the low value obtained. Also influencing differences in the mean values will be age (Turnbull 1947, Fry and Chalk 1957, Zobel 1965). Very little is known about the effect of thinning, pruning or initial spacing on tracheid length in the species when grown in different geographical or site conditions (Plumptre 1978).

2.5.4.2 Variation between and within trees

Although a modest number of investigations of tracheid length variation has been published, none of them shows or discusses the extent of variation between trees. It is implied in two reports, that there are trees with significantly longer tracheids than others and these constitute a good source of seeds for tree breeding (Kubelka 1969, Paterson 1969).

Radial tracheid length variation has been reported by several workers and they agree that tracheid length increases from pith to bark (Fry and Chalk 1957, Zobel 1965, Kubelka 1969, Paterson 1969, White *et al*. 1980). It is reported that the tracheids in *Pinus patula* grown in Tanzania attain maximum length at about 18-21 years (Kubelka 1969). In Mexican grown *Pinus patula* tracheid length tends to reach a peak between 25-30 years. In 18 year old *Pinus patula* grown in Northern part of Tanzania, tracheid length had not reached a peak (White *et al*. 1980). The increase in tracheid length is accompanied by a decrease in ring width and an increase in latewood proportion. No studies have been made on the effect of ring width and latewood proportion on tracheid length in *Pinus patula*.

2.6 Tracheid length in juvenile and mature wood

2.6.1 Definition and proportion

Definitions of juvenile wood and techniques of its demarkation have been presented in 2.3.1. The definition of juvenile wood that holds most when tracheid length is used to establish the juvenile period is the one after Rendle (1960). Juvenile wood is described as the wood near the pith in which tracheid length progressively increases in successive growth rings. The juvenile period established by tracheid length may not be similar to that established on the basis of basic density (Zobel 1981). Use of more than one wood characteristic may form a more valid basis of identifying the juvenile period (Dinwoodie 1961).

The proportion of juvenile wood will depend on tracheid length value defining juvenile wood, tree age and growth conditions. It is apparent that the first

5-10 rings have in most pines been considered to constitute the juvenile wood when using basic density and tracheid length as criteria.

Table 2.8 shows tracheid lengths of the two woods in some pines.

Table 2.8 Juvenile and mature wood tracheid length in som pine species.

Species	Age, years	No.of ring in JW	Tracheid length,mm JW	Tracheid length,mm MW	Source
Pinus patula	40	1-10	2.89	4.25	Zobel 1965
Pinus patula	40	1-10	3.32	5.25	" "
Pinus rigida	21	1-7	2.60	3.50	Cole *et al*. 1966
Pinus serotia	21	1-7	2.60	3.50	" " "
Pinus taeda	35	1-10	3.23	4.28	Barefoot *et al*. 1970
Pinus radiata	52	1-10	3.45	4.43	Kibblewhite 1980

JW Juvenile wood
MW Mature wood

2.6.2 Variation within juvenile and mature wood

Most investigations report variations between whole tree values, or variation from pith to bark, and very few seem to have treated juvenile and mature wood separately. In a study of *Pinus taeda* wood, juvenile and mature wood tracheid lengths were found to vary significantly between trees (Cole *et al*. 1966). Axial tracheid length variations of juvenile and mature wood has been reported by a few authors (Cown and McConchie 1980). Most of the reports agree that following the same ring from tree base to top, tracheid length increases to a maximum and then decreases towards the top of the tree (Dinwoodie 1961, Panshin and de Zeeuw 1970, Cown and McConchie 1980). The slope is generally greater in mature wood than in the juvenile wood (Dadswell 1958, Wheeler *et al*. 1966).

Radial tracheid length variation in juvenile and mature wood can best be explained by considering the general pith to bark curve, this time describing the juvenile and mature wood separately. The radial trends for both wood zones are shown in figure 2.3.

3. MATERIALS AND METHODS

3.1 The study area

The Sao Hill Forest Project is the largest forest plantation in Tanzania, located at 8° 35′ S and 35° 20′ E. The altitude ranges between 1500 and 2000 metres above sea level, the highest point being 2029 m. The forest terrain is rolling grassland interrupted by rivers and streams. The mean annual rainfall based on a period of over 70 years is 1300 mm with a minimum of 700 mm and a maximum 2000 mm. The temperatures are mild by tropical standards, and there may be occassional frost during June and July. The mean monthly temperature is about 10 °C while the mean monthly maximum temperature is 23 °C.
The soils are kaolinitic with a low base exchange capacity well suited for certain tropical pines. Table 3.1 shows the three main blocks in the project and their areas.

Table 3.1. Area of the main blocks in the Sao Hill Forest Project in 1980

Main blocks	Management blocks	Area, ha	
		Total area	Planted area
Sao Hill	Makabila, Irunda Uringa, Mabihana Nyololo, Kigogo and Ngwasi	31,135	17,571
Mbahve-Mtukulembe	Msiwazi,Gulosilo Ifimbo, Ihalimba, Usokame, Nundereand Maritikira	57,296	5,924
Mgololo-Ruhndji	Mgololo, Ruhudji	23,164	
Total		111,595	23,495

Source: Mlowe and Macha 1980.

In addition to *Pinus patula* a number of other tree species are grown in the project, see table 3.2. The table shows distribution of the species by area and age classes.

Table 3.2. Species, area in ha and age classes in the Sao-Hill Forest Project in 1980

Species	Age class, years					
	≤ 5	6-10	11-15	16-20	21-25	≥ 26
Pinus patula	17779	946	1022	504	153	41
Pinus elliottii	1600	1092	1034	627	-	-
Pinus radiata	-	-	-	-	174	5
Pinus caribaea	-	275	-	-	-	-
Cupressus lusitanica	7	2	-	-	-	7
Eucalyptus spp	286	952	-	-	-	-
Others	272	867	824	385	37	-

Source: Mlowe and Macha 1980

3.2 Field procedures

3.2.1 Compartment selection

It was decided that the material to be studied should be confined to only one site class from the oldest stands. The oldest stands were a rational choice as they provided wood samples of a widest growth ring range. The materials were therefore collected from compartments MS 9a and MS 10a in Msiwazi management block.

The two compartments were planted in 1953 at an initial spacing of 2.44 x 2.44 metres and were supposed to have been thinned in 1962, 1966, 1970 and 1974 and pruned in 1955, 1957, 1959 and 1961.

Observation of the stands at the time of sampling indicated that the said schedule had not been adhered to, instead they seem to have been thinned and pruned only twice. No proper plantation tending records were available. Since the two compartments occupied a similar micro-climate, were of the same age and did not show any differences in the way they had been treated, they were considered to be one population. The stands had a mean dbh of 33.8 cm and a mean total height of 30 m, based on 50 randomly measured trees in the compartments. The standard deviations were 5.4 cm and 6.4 m for dbh and total height respectively. The values ranged from 22.1 to 47.4 cm for dbh and 20.6 to 33.4 m for total height.

3.2.2 Selection of sample trees

Fifteen sample trees were selected at a predetermined interval along a transect running diagonally across the two compartments ensuring that they were evenly spread along the entire distance. Trees at the stand edges were excluded. Any potential sample trees with defects, for example leaning trees or trees with multiple leaders were rejected and instead replaced with neighbouring trees. Before felling, the diameters at breast height of each sample tree were measured in two directions followed by marking the 4 cardinal directions. After felling, the total height of each tree was measured.

3.2.3 Tree sampling

Four 2.5 cm thick disks were extracted from each sample tree at 1.3 m, 4 m, 8 m and 12 m heights. Prior to extraction of the disks crosswise diameters were measured at each disk position and the disks were marked to show the tree number, height and the cardinal directions. Data for the sample trees are presented in table 3.3.

Table 3.3 Mean diameters and total tree heights for the 15 sample trees.

Statistic	Diameters at different tree heights				Total tree height, m
	1.3	4	8	12	
Mean, cm	35.6	33.9	28.5	24.9	30
s.d., cm	4.5	5.6	4.2	3.9	48
c.v., %	12.6	16.5	14.7	15.7	16
Range, cm	27.0-44.0	25.8-40.6	22.6-34.9	20.4-30.8	23.8-34.3

3.3 Sample preparation

Four radial strips of about 2 centimetre width were extracted from each disk, one from each cardinal direction. As the strips had rough surfaces after they were sawn from the disks it was necessary to plane them with the use of surgical blades.

In order to reduce errors in measuring ring and latewood widths, a straight line running from pith to bark was drawn on the cross-section of each radial strip. After the strips had been saturated with water, the ring and latewood borders were marked on the line by small pricks using a sharp needle and a binocular microscope.

As the borders near the pith were difficult to ascertain, marking was started from the outermost ring and comparisons were made for each ring on the four strips obtained from the same disk.

Separation of strips and growth rings into smaller subsamples were accomplished using a thin, sharp pointed chiesel.

Maceration of the wood samples was achieved by using potassium chlorate crystals and concentrated nitric acid after the Schultze method (Sass 1951). After washing the pulp from each wood sample the fibres were stained with safranin and then mounted on slides making sure that the individual fibres were as separate as possible. Table 3.4 shows the number of samples used to determine basic density and tracheid length.

Table 3.4 Number of samples for basic density and tracheid length measurement.

Tree Height	Basic density Whole ring	 Earlywood	 Latewood	Number of tracheids Earlywood	 Latewood
1,3	165 (33)[x]	165	165	4,950	4,950 (3960)
4	150 (30)	150	150	4,500	4,500
8	120 (24)	120	120	3,600	3,600
12	105 (21)	105	105	3,150	3,150
Sub total	540 (108)	540	540	16,200	16,200
Grand total		1 728		36,360	

[x] Figures in brackets show the additional measurements from preliminary investigation.

3.4 Measurements on the samples

Growth ring and latewood widths were measured on wet samples using a vernier caliper with an accuracy of 0.01 mm under a binocular microscope.

Prior to measuring sample green volume, the samples were soaked in water for a couple of days to get them water saturated. Green volume was then obtained by the water displacement technique. In order to check accuracy during weighing, the balance precision was intermitently checked with standard weights. The first checking was done every day before any measurements on the samples were made. To remove excess water on the sample surfaces the wood samples were rolled several times in cotton gauze cloth. In addition, care was maintained during measuring so that the samples did not make contact with the walls of the water container on the balance. The measurements were made to 0.0001 g.

The samples were later dried in an oven at a temperature of 102-104 °C to constant weight. In order to establish the 0 per cent moisture content, five samples from each batch were withdrawn from the oven, weighed and returned to the oven. This was repeated at regular time intervals on the same samples until no weight changes were recorded. The dried samples were transferred into desiccator, cooled and weighed to the one tenth of a milligram. Since dry wood absorbs moisture from the atmosphere extremely fast it was important to observe that once a sample was removed from the descicator it was weighed as quickly as possible. In addition, the balance precision was checked as explained in the foregoing section on green volume.

The length of 30 unbroken tracheids were measured from each sample using a micro-projector. The image was projected on to a paper screen with a magnification of 60 x. The length of the fibres was measured in millimetres to a precision of 0.001 mm.

3.5 Preliminary investigations

Prior to the main study, preliminary investigations were carried out with the following specific objectives:

- to verify whether wood basic density and tracheid length varied significantly with cardinal directions
- to verify tracheid length variation within early-wood and latewood bands.

This information would then form a basis for the sampling procedure for the main study.

3.5.1 Basic density and tracheid length

Effect of cardinal direction on wood density and tracheid length was investigated in 3 trees. The trees were selected so as to represent large, intermediate and small diameters. Basic density was studied at heights 1.3, 4, 8 and 12 m while tracheid length was studied only at 1.3 m height.

Ring basic densities were obtained for each second ring from pith to bark in the 4 cardinal directions at each height. The values from a given direction at the same height in the 3 trees were considered to be one sample. This gave 4 samples at each height which were then subjected to analysis of variance.

Tracheid lengths were obtained for each second ring from pith to bark in the 4 cardinal directions at breast height for three trees.

Each direction therefore had 33 values which constituted one sample. The 4 samples were then subjected to analysis of variance.

The results from the preliminary investigation showed that basic density and tracheid length were not significantly different in the 4 cardinal directions.

3.5.2 Tracheid length variation within rings

The effect of radial position on tracheid length within growth rings was investigated on materials obtained from 3 trees and only at breast height. Each second ring from pith to bark in the north direction in each tree was divided tangentially into 4 bands such that there was inner earlywood, outer earlywood, inner latewood and outer latewood. The tracheid lengths of these portions were obtained separately. A paired 't' test was used to test for significant difference between the two earlywoods as one pair and the two latewoods as the other pair. The inner and outer portions of each earlywood and latewood did not differ significantly.

Based on the results obtained in the preliminary investigation it was decided to use radial strips from only one cardinal direction at each height in the stem for both wood density and tracheid length in the main study. Also, since tracheid length differences within earlywood and within latewood were non-significant, it was decided that whole rings should be divided only into two bands, namely earlywood and latewood. The average of the tracheid length of the two bands would constitute whole ring tracheid length.

3.6 Determination of juvenile period

Due to the lack of an internationally recognized definition of juvenile wood, that should be used world wide in all studies of wood density and tracheid length variations with regard to changes in age, it was necessary to institute one that would fit the Sao Hill plantation material.

Based on critical examination of the density and tracheid length variations obtained in this study, see chapter 4.2, figure 4.7 and information available in literature and techniques used, see chapter 2.3.1 and 2.6.1, the juvenile wood for Pinus patula grown at Sao-Hill was established on the basis of latewood basic density radial variation.

3.7 Formulas and statistical methods

3.7.1 Basic density of individual samples

The following formula was used:

$$BD = \frac{\text{Oven dry weight}}{\text{Green volume}} \qquad 1$$

where: Green volume = $W_2 - W_1$ in which
W_2 = weight of contanier+ water + sample
W_1 = weight of container + water

3.7.2 Volume weighted basic density for trees, juvenile wood and mature wood

The following formula was used:

$$WBD=\frac{\sum_{i=1}^{3} V_iBD_i}{\sum_{i=1}^{3} V_i} \qquad 2$$

where V_i = Volume of whole log, juvenile wood and mature wood .

BD_i = mean ring basic density for the two log ends

3.7.3 Axial basic density and tracheid length variation

Axial variation of basic density and tracheid length was established by analysis of variance with the following common AOV table.

Source of variation	d.f.
Between heights	3
Within heights	56
Total	59

3.7.4 Tracheid length

The following formulas were used:

a) individual sample tracheid length:

$$TL=\frac{\sum_{i}^{30} l_i}{30} \qquad 3$$

were l_i = length of one fibre

b) ring tracheid length:

$$RTL=\frac{\sum_{1}^{60} l_i}{60} \qquad 4$$

c) area weighted tracheid length at a given stem height was computed according to Brazier (in Paterson 1969):

$$AWTL=\sum_{i=1}^{n}\frac{RTL_i(\Pi r_i^2-\Pi r_i^2-1)}{\Pi R^2} \qquad 5$$

where n = number of rings
r_i = radius to and including ring i
r_{i-1} = radius to ring i-1

d) volume weighted tracheid length:

$$VWTL=\frac{\sum_{i=1}^{3} RTL_i V_i}{\sum_{1}^{3} Vi} \qquad 6$$

where RTL_j = mean tracheid length for the two ends of the log
V_i = volume of each log in a given tree

3.7.5 Radial variation of wood density and tracheid length

Radial variation of wood basic density and tracheid length was established using regression equations of the second degree polynomial:

$$BD = B_o + B_1 X_i + B_2 X_i^2 + ei \qquad 7$$

where BD = basic density at a given position in stem

X_i = ring number or distance from pith or latewood per cent

ei = random error term, normally distributed with zero mean and variance 0

Multiple linear regression equations were used to establish the relationship between the two factors basic density and tracheid length:

$$BD = B_o + B_1 X_1 + B_2 X_2 + ei \qquad 8$$

where BD = basic density

X_1 = ring number from pith

X_2 = ring distance from pith or ring width

ei = as in formula no. 7

$$TL = B_o + B_1 X_1 + B_2 X_2 + ei \qquad 9$$

where TL = tracheid length

X_1 = ring number from pith

X_2 = ring distance from pith or ring width

ei = as in formula no. 7

3.7.6 Wood density and tracheid length relationships between juvenile and mature wood

The relationships between juvenile wood basic density and mature wood basic density and that of juvenile wood tracheid length and mature wood tracheid length were established by simple linear regression equations as follows:

$$MBD = B_o + B_1 JBD + ei \qquad 10$$
$$MTL = B_o + B_1 JTL + ei \qquad 11$$

where MBD = mature wood basic density
JBD = juvenile wood basic density
MTL = mature wood tracheid length
JTL = juvenile wood tracheid length
ei = as in formula nr. 7

3.7.7 Whole log, juvenile wood and mature wood volumes

Log volume was computed by Smallin's formula (Spurr 1952):

Juvenile volume in a given log:

$$\left(\frac{\Pi r^2_{t8} + \Pi r_{b8}}{2}\right) L \qquad 12$$

where L = Log length
r_{t8} = radius at the top end of the log to the 8th ring
r_{b8} = radius at the bottom end of the log to 8th ring

Mature wood volume:

Mature wod volume = log volume - juvenile wood volume 13

4. RESULTS

4.1 General basic density variation

4.1.1 Variation between trees

4.1.1.1 Overall variation

Analysis of the tree volume weighted basic densities gave the results shown in table 4.1.

Table 4.1 Volume weighted basic density

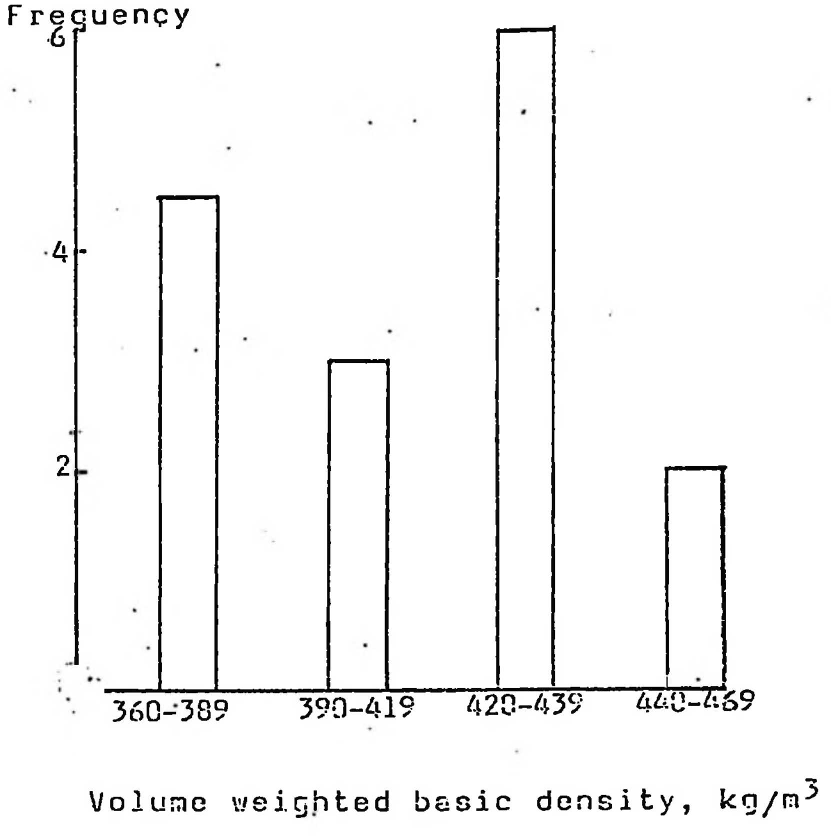
Statistic	
Mean, kg/m^3	412
s.d., kg/m^3	28
c.v., per cent	6.8
Range, kg/m^3	367-464
Confidence interval, kg/m^3	412-455

A student's 't' test showed that there is a significant difference between trees at the 1 per cent level. The difference between the heaviest and the lightest trees is considerable, about 27 per cent when expressed as a fraction of the lower value. The relationship between tree volume weighted basic density and tree dbh was obtained by a simple regression method. A similar equation was obtained for the relationship between tree volume weighted basic density and juvenile wood proportion in the stems. The equations were:

$$BD = 525-2.2\ dbh, \text{ with } r = -0.4985^{xx}$$
$$BD = 480-1.256\ JP, \text{ with } r = -0.5900^{xx}$$

The tree volume weighted basic density frequency distribution is shown in figure 4.1 where each basic density class is equal to one standard deviation. The individual tree densities are shown in appendix 1.

Figure 4.1 Volume weighted basic density frequency distribution.



4.1.1.2 Variation at different tree heights

In order to clarify basic density variations at different heights in the stem the mean ring basic densities at each height were subjected to statistical analysis. The results in table 4.2 shows that there is greater variations at 8 m and 12 m heights for which the coefficients of variation are 7.8 and 7.2 per cent respectively compared to 6.2 and 6.4 per cent for the lower heights. Appendix 2 shows the density values for individual heights.

Table 4.2 Basic density at 4 heights in the stem

Statistic	Height, m			
	1.3	4	8	12
No. of rings per tree	11	10	8	7
Mean, kg/m^3	454	416	390	369
s.d., kg/m^3	28	27	31	26
c.v., %	6.2	6.4	7.8	7.2
Range, kg/m^3	416-504	369-460	332-437	328-402

4.1.1.3 Variation at different growth rings

Basic densities at different rings for 1.3 m height are shown in table 4.3. The following deductions can be drawn from the table:

- The standard deviations are comparatively lower at rings 2, 4, 6 and 8 than at the outer rings.
- The standard deviations of the wood formed in the same growing seasons in different trees range between 21 and 41 kg/m^3 and do not follow any consistent pattern with tree age.
- The difference between the lightest and the heaviest woods formed in the same seasons do not follow any consistent trend with tree age.

Table 4.3 Basic density at different growth rings at 1.3 m.

Statistic	Ring number from pith										
	2	4	6	8	10	12	14	16	18	20	22
Mean, kg/m^3	353	362	388	397	434	423	476	493	525	546	562
s.d., kg/m^3	21	25	27	25	35	35	39	38	41	37	31
c.v., %	5,8	7	7	6,1	7.9	7.8	8.3	7.8	7.9	6.8	5.5
d^1	27.3	29.6	26.1	28.0	35.5	31.8	29.1	27.5	26.4	23.8	18.2

1 Difference between the lightest and the heaviest in per cent

Tables 4.4 and 4.5 show the relationship between basic density and ring width and latewood per cent for rings 4, 8, 12, 16 and 20. It is apparent from the tables that neither of the two factors affect wood density significantly.

Table 4.4 Relationship between basic density and ring width at the same ring at 1.3 m.

Ring number	Equation	Correlation coefficient	Mean ring width, mm
4	BD= 0.3593-0.0002W	- 0.01879	12.74
8	BD= 0.4310-0.0024W	- 0.3149	10.47
12	BD= 0.4552-0.0005W	- 0.0428	5.32
16	BD= 0.4992-0.0015W	- 0.0912	3.88
20	BD= 0.5367+0.0031W	+ 0.1431	2.73

BD is based on g/cm^3

Table 4.5 Relationship between basic density and latewood per cent at the same ring at 1.3 m.

Ring number	Equation	Correlation coefficient	Mean latewood, per cent
4	BD= 0.3430+0.0006P	0.2362	24.6
8	BD= 0.3989+0.0002P	0.2249	34.7
12	BD= 0.4649+0.0009P	0.4429	39.3
16	BD= 0.4751+0.0012P	0.4486	48.4
20	BD= 0.4806+0.0012P	0.4091	53.7

BD is based on g/cm^3

4.1.2 Variation within trees

4.1.2.1 Variation with cardinal directions

The ring basic densities for 4 directions, presented in appendix 3, were subjected to analysis of variance to test for significant differences. The analysis of variance table is shown in appendix 4. The results indicate that basic density does not vary significantly with cardinal direction in any of the 4 heights. The mean difference between the lowest and the highest density values in the different directions ranged between 1.4 and 4 per cent. Table 4.6 shows the mean ring densities for each height in the 4 cardinal directions and per cent difference between the lowest and highest values.

Table 4.6 Mean ring basic density in kg/m^3 for 4 cardinal directions at 4 heights in the stem.

Height, m	West	Direction East	North	South	Per cent difference
1.3	452	458	452	448	2.3
4	411	421	406	414	3.6
8	391	392	394	397	1.4
12	362	376	377	374	4

4.1.2.2 Axial variation

The mean basic densities at each height presented in appendix 2 were analysed to show possible axial variation by simple regression analysis. The equation shown below was obtained and indicates that wood basic density decreases significantly with increasing height in the stem. The difference between 1.3 m and 12 m mean values was about 23 per cent. The regression equation and correlation coefficient were:

$$BD = 455-7.5\ H, \text{ with } r = -0.6725^{xx}$$

4.1.2.3 Radial variation

The relationship between ring basic density and distance from pith, ring number, per cent latewood and ring width were established at each height by regression equations. Appendices 5a, 5b, 5c and 5d show the regression lines and the scatter of the data points. In order to illustrate the actual trends the mean ring basic densities at each height were plotted on the same variables. The mean ring basic densities are shown in appendix 6.

Multiple linear regression equations were computed for the relationship between ring basic density and distance from pith, ring number, latewood per cent and ring width.

The main results which are presented in tables 4.7, 4.8, 4.9, and 4.10 for the regression equations and figures 4.2, 4.3, 4.4 and 4.5 for the curves were that:

- At all heights ring basic density increases significantly with increase in distance from pith, ring number and latewood per cent and decreases significantly with increases in ring width.
- The effect of ring width on ring basic density is less pronounced at 8 m and 12 m heights than at 1.3 m and 4 m heights. At 1.3 m and 4 m heights ring basic density is strongly affected by changes in ring width in the 3 mm to 5 mm range.
- The density curves at 4 m and 8 m heights tend to show inflection when plotted on ring distance from pith and ring number, see figures 4.2 and 4.3, while those at 1.3 m are still increasing.

The following conclusions are warranted by the results in tables 4.11 and 4.12 which show the multiple linear regression equations:

- At all heights, growth ring number can not be said to have a greater effect on ring basic density than either ring distance from pith or ring width.
- At all heights, ring basic density increases with ring number and decreases with increasing ring width.

Table 4.7 Regression equations and correlation coefficients for the relationship between ring basic density and distance from pith.

Height, m	Regression equation	Correlation coefficient
1.3	$BD = 0.3310 + 0.0016d - 0.0000d^2$	0.9370^{xx}
4	$BD = 0.3243 + 0.0011d - 0.0000d^2$	0.9499^{xx}
8	$BD = 0.3312 + 0.0011d - 0.000d^2$	0.9158^{xx}
12	$BD = 0.3375 + 0.0007d - 0.0000d^2$	0.6570^{xx}

BD is based on g/cm^3

Table 4.8 Regression equations and correlation coefficients for the relationship between ring basic density and ring number from pith.

Height, m	Regression equation	Correlation coefficient
1.3	$BD = 0.3403 + 0.0100N - 0.0000N^2$	0.9126^{xx}
4	$BD = 0.3025 + 0.0159N - 0.0004N^2$	0.8266^{xx}
8	$BD = 0.3133 + 0.0128N - 0.0002N^2$	0.8521^{xx}
12	$BD = 0.3179 + 0.0124N - 0.0003N^2$	0.7859^{xx}

BD is based on g/cm^3

Table 4.9 Regression equations and correlation coefficents for the relationship between ring basic density and latewood per cent.

Height, m	Regression equation	Correlation coefficient
1.3	$BD = 0.3158 + 0.0038P - 0.0000P^2$	0.6243^{xx}
4	$BD = 0.3021 + 0.0037P - 0.0000P^2$	0.6837^{xx}
8	$BD = 0.2825 + 0.0039P - 0.0000P^2$	0.4980^{xx}
12	$BD = 0.2963 + 0.0021P - 0.0000P^2$	0.6603^{xx}

BD is based on g/cm^3

Table 4.10 Regression equations and correlation coefficients for the relationship between ring basic density and ring width.

Height, m	Regression equation	Correlation coefficient
1.3	$BD = 0.6146 - 0.0283W + 0.0008W^2$	-0.8360^{xx}
4	$BD = 0.5196 - 0.0153W + 0.0003W^2$	-0.7989^{xx}
8	$BD = 0.4976 - 0.0141W + 0.0003W^2$	-0.7991^{xx}
12	$BD = 0.4334 - 0.0038W + 0.0001W^2$	-0.4949^{xx}

BD is based on g/cm^3

Table 4.11 Multiple linear regression equations and correlation coefficients for the relationship between ring basic density and ring number and distance from pith.

Height, m	Regression equation	Correlation coefficient
1.3	$BD= 0.34196+0.01143N-0.00015d$	0.9142^{xx}
4	$BD= 0.3262+0.0473N-0.00043d$	0.8347^{xx}
8	$BD= 0.32785+0.0099N-0.0012d$	0.8504^{xx}
12	$BD= 0.33624+0.00918N-0.0002d$	0.7828^{xx}

BD is based on g/cm^3

Table 4.12 Multiple linear regression equations and correlation coefficients for the relationship between ring basic density and ring number and ring width.

Height, m	Regression equation	Correlation coefficient
1.3	$BD= 0.3721+0.0090N-0.0023W$	0.9235^{xx}
4	$BD= 0.3915+0.00543N-0.00335W$	0.7040^{xx}
8	$BD= 0.3580+0.0070N-0.00171W$	0.7240^{xx}
12	$BD= 0.3416+0.00696N-0.0005W$	0.6247^{xx}

BD is based on g/cm^3

Figure 4.2 Ring basic density variation with distance from pith at 4 heights in the stem.

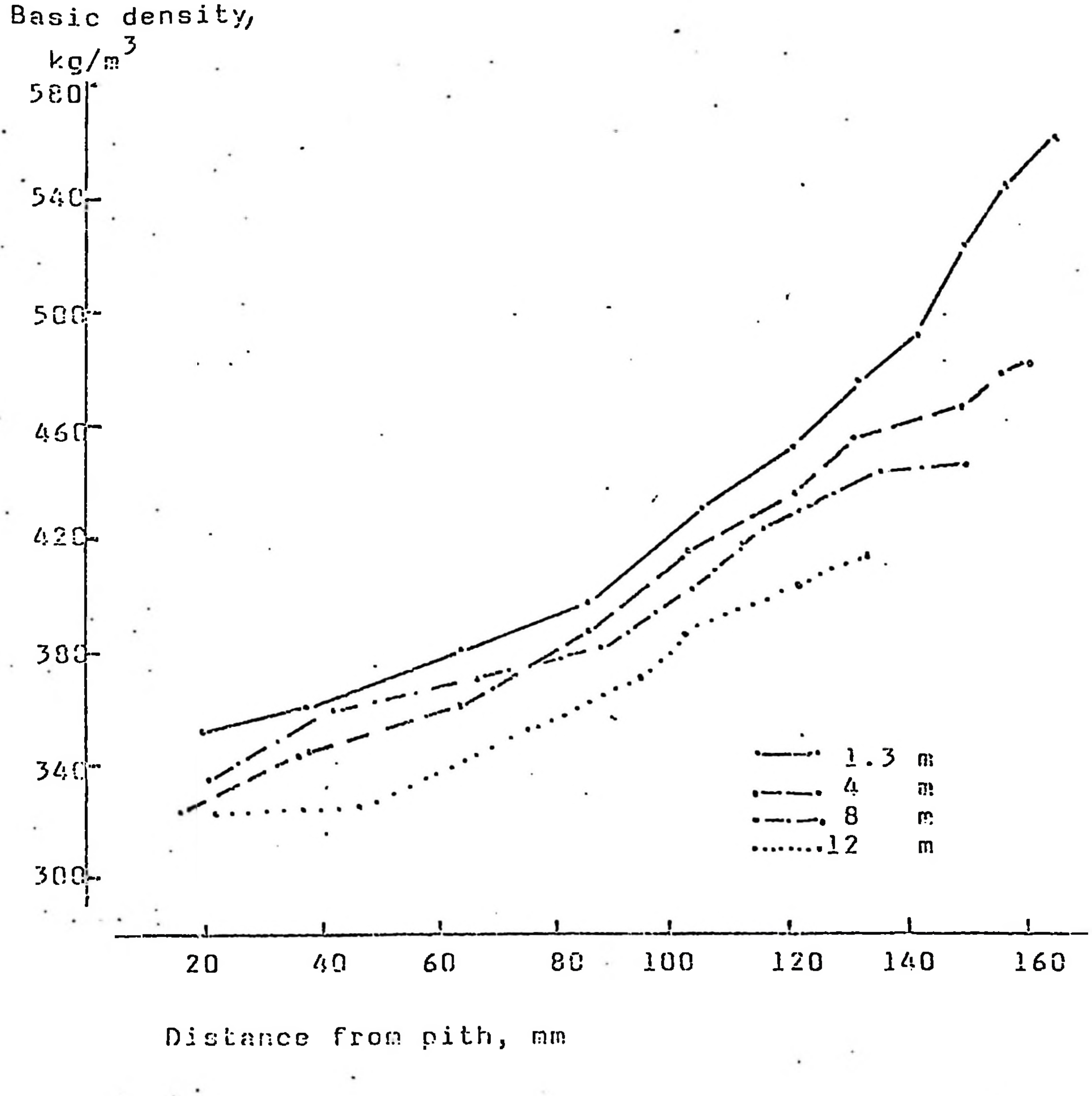


Figure 4.3 Ring basic density variation with ring number from pith at 4 heights in the stem.

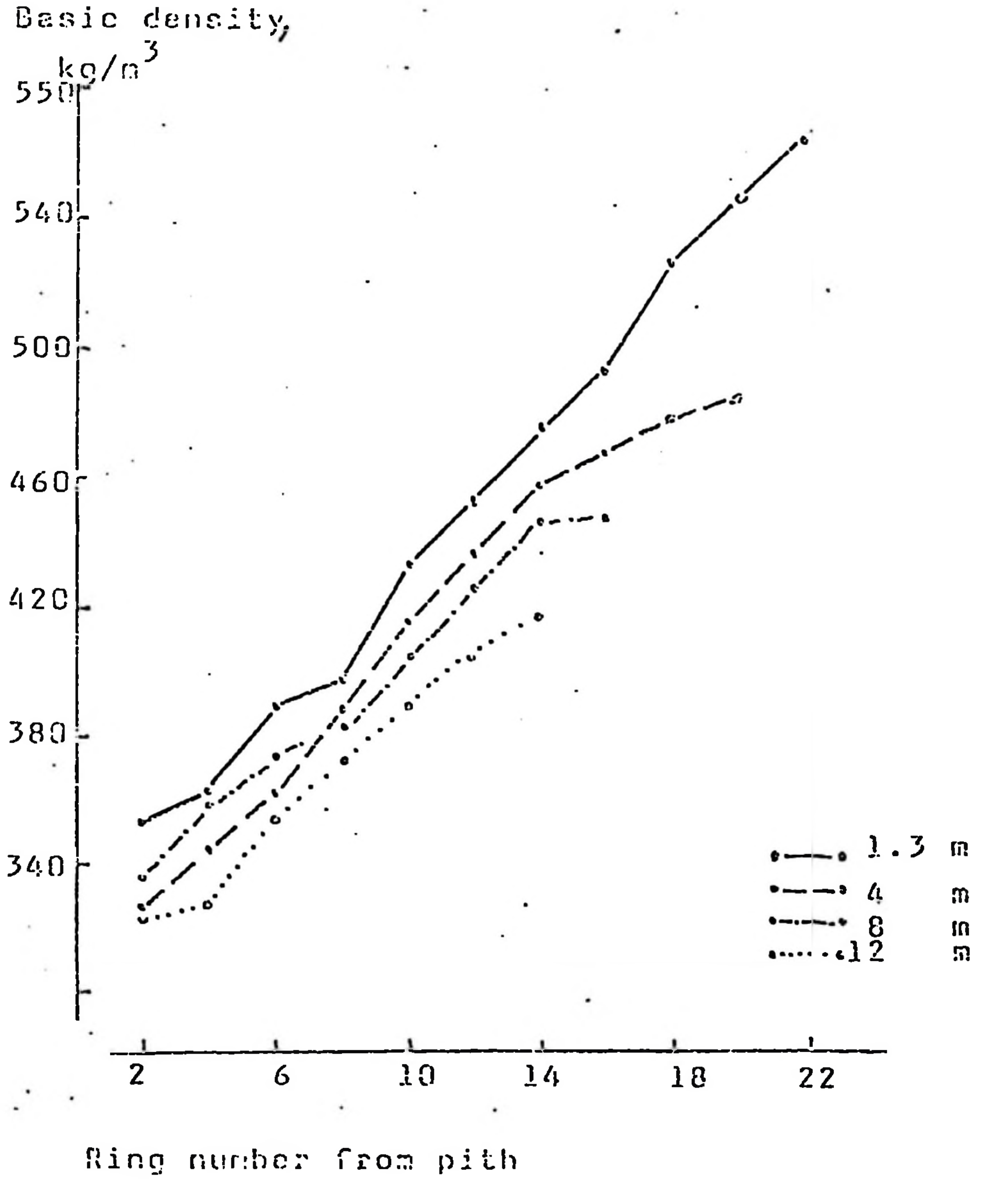


Figure 4.4 Ring basic density variation with latewood per cent at 4 heights in the stem.

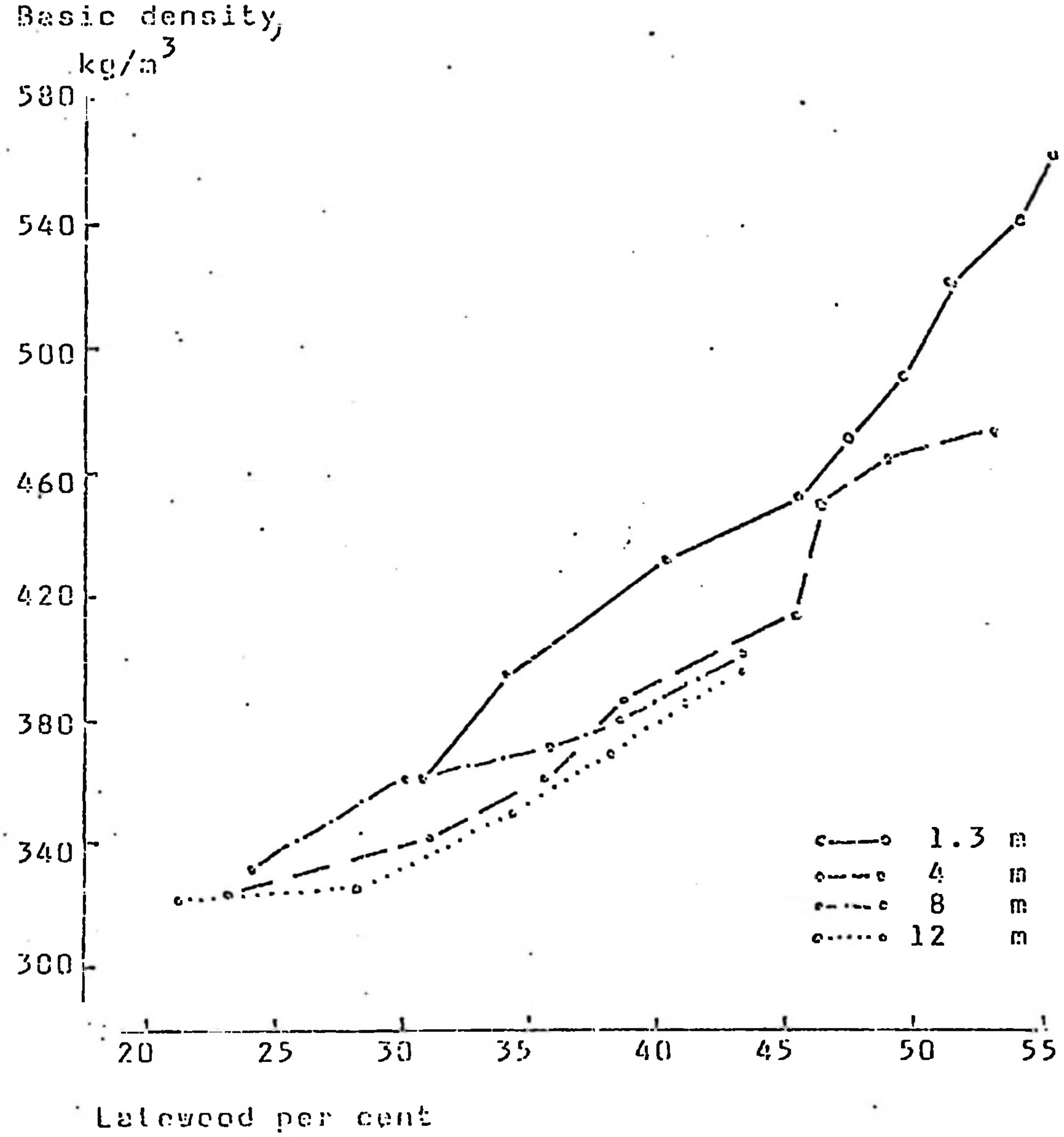
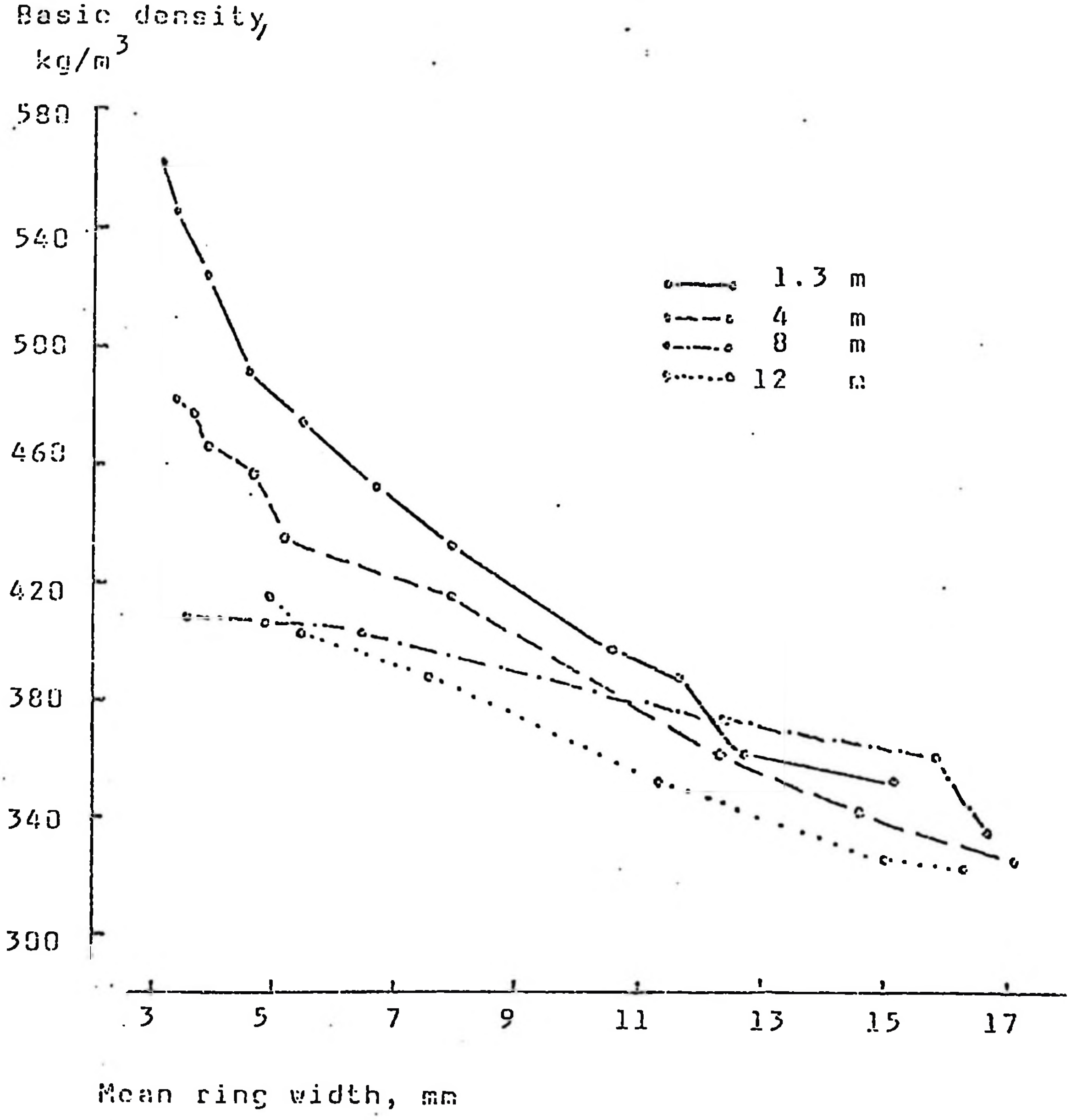


Figure 4.5 Ring basic density variation with ring width at 4 heights in the stem.



4.1.2.4 Earlywood and latewood variation

Since it is clear from the data that earlywood basic density does not vary significantly with position in the tree, analysis of the same was deemed unnecessary and was performed only for latewood. Tables 4.13, 4.14 and 4.15 show the regression equations of the relationship between latewood basic density and distance from pith, ring number, and ring width while appendices 7a, 7b and 7c presents the scatter diagrams and regression lines for separate heights. Figures 4.6, 4.7 and 4.8 show the curve trends at each height for latewood and earlywood basic densities plotted on the three variables. Table 4.16 shows the mean basic density at each ring for the 4 heights. Based on the regression equations in tables 4.13, 4.14 and 4.15 and the curves in figures 4.6, 4.7 and 4.8 the following conclusions are pertinent:

- Latewood basic density increases significantly with distance from pith and ring number but decreases significantly with increase in ring width.
- Latewood basic density increases gradually in the first 100 mm from pith but thereafter more rapidly, see figure 4.6, latewood and earlywood basic density curves did not culminate in the materials studied.

Table 4.13 Regression equations and correlation coefficients for the relationship between latewood basic density and distance from pith.

Height, m	Regression equation	Correlation coefficient
1.3	$BD=364.7 + 2.0d - od^2$	0.87959^{xx}
4	$BD=378.2 + 1.2d - od^2$	0.83189^{xx}
8	$BD=362.6 + 2.1d - od^2$	0.69177^{xx}
12	$BD=372.2 + 0.8d - od^2$	0.78377^{xx}

Table 4.14 Regression equations and correlation coefficients for the relationship between latewood basic density and growth ring width.

Height, m	Regression equation	Correlation coefficient
1.3	$BD=688.3-28.6W+8W^2$	-0.81678^{xx}
4	$BD=619.3-15.8W+2W^2$	-0.76591^{xx}
8	$BD=603.5-18.4W+4W^2$	-0.75696^{xx}
12	$BD=512.1-4.3W+1W^2$	-0.61835^{xx}

Table 4.15 Regression equations and correlation coefficients for the relationship between latewood basic density and ring number

Height, m	Regression equation	Correlation coefficient
1.3	$BD=364.7+17.9N-3N^2$	0.8876^{xx}
4	$BD=357.9+18.4N-3N^2$	0.8438^{xx}
8	$BD=361.5+17.9N-4N^2$	0.75816^{xx}
12	$BD=350.6+19N-5N^2$	0.72646^{xx}

Table 4.16 Mean basic density in kg/m^3 of earlywood and latewood bands for various growth rings

Ring no.	Height, m							
	1.3		4		8		12	
	Early wood	Late wood	Early wood	Late wood	Early wood	Late wood	Early wood	Late wood
2	298	404	301	432	301	401	298	389
4	305	430	289	432	302	421	304	412
6	324	441	318	429	333	426	351	423
8	334	456	360	442	341	455	345	439
10	366	480	389	482	347	461	335	459
12	359	536	334	532	349	518	352	511
14	361	573	339	560	347	544	355	536
16	364	584	345	577	353	546		
18	368	604	356	574				
20	372	621	348	591				
22	379	611						

Figure 4.6 Earlywood and latewood basic density variation with distance from pith at 4 heights in the stem.

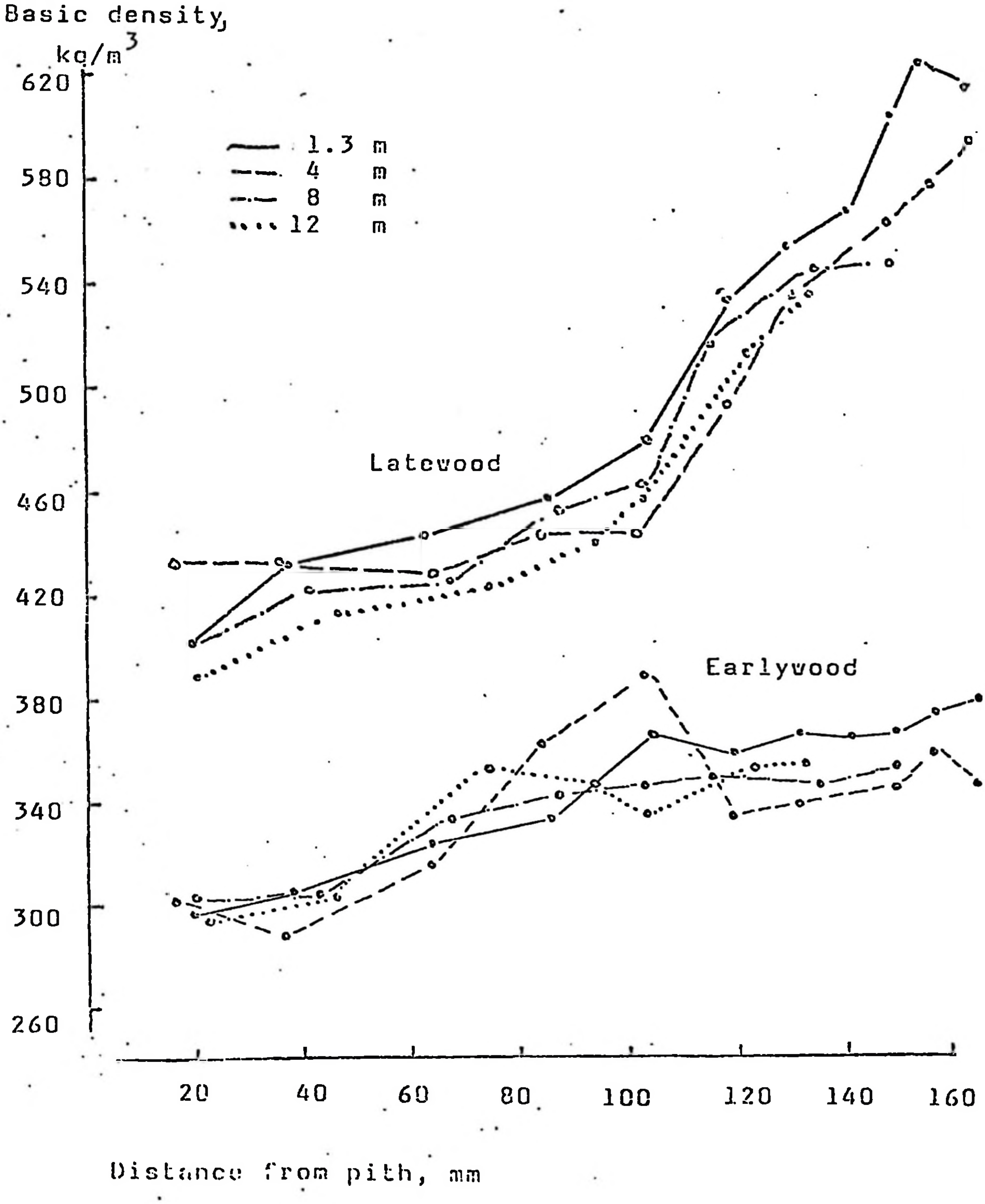


Figure 4.7 Earlywood and latewood basic density variation with ring number from pith at 4 heights in the stem.

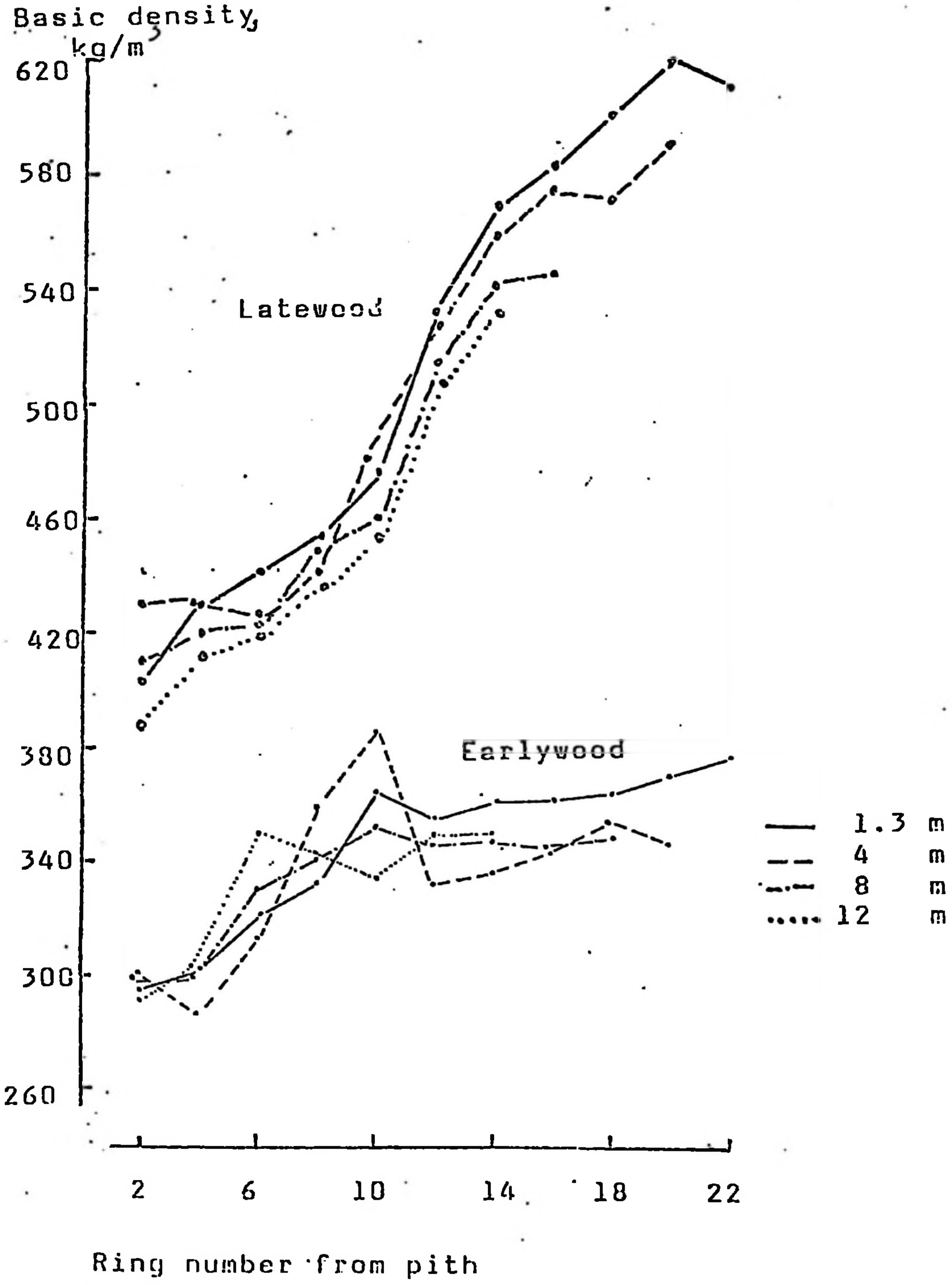
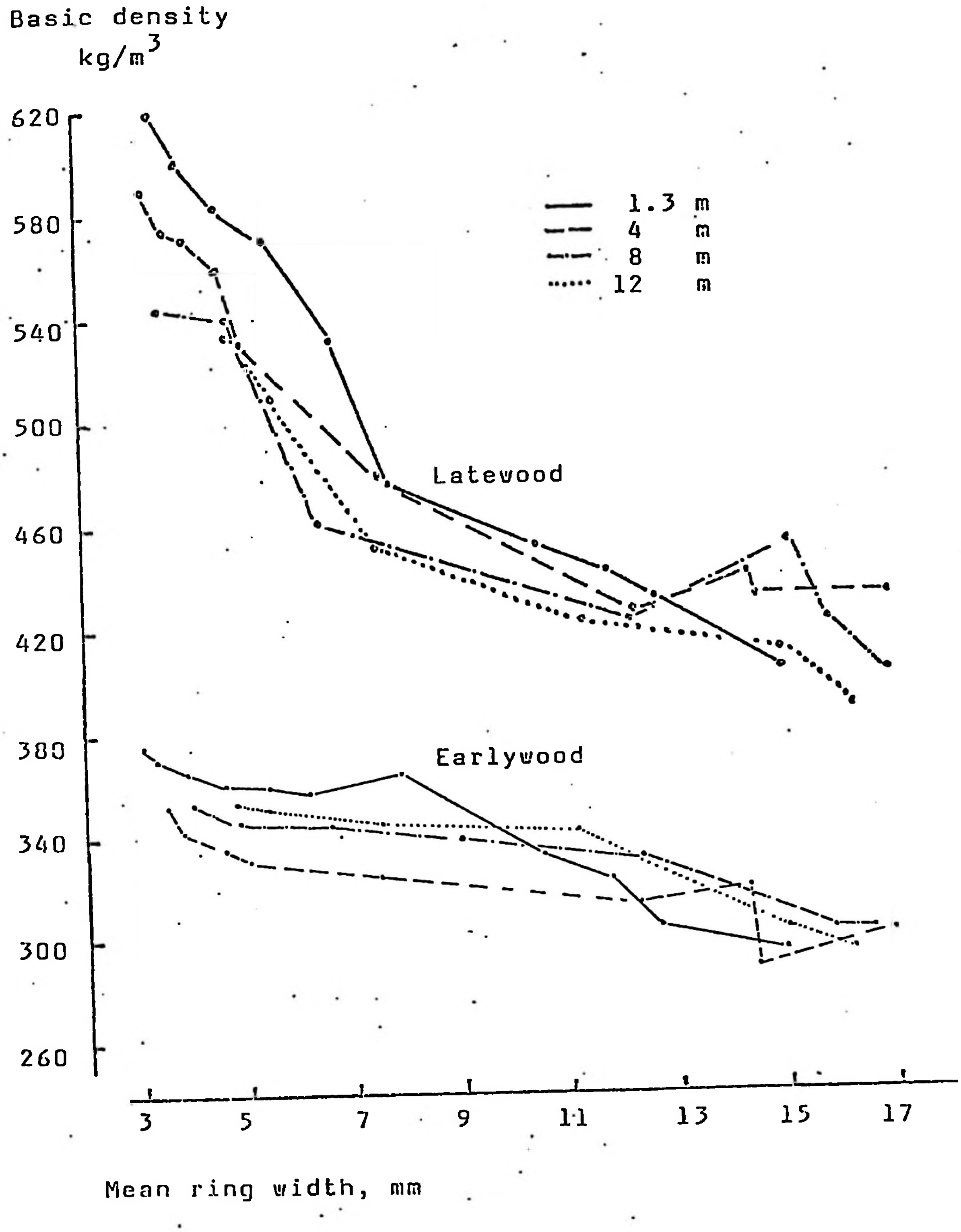


Figure 4.8 Earlywood and latewood basic density variation with ring width at 4 heights in the stem.



4.2 Basic density of juvenile wood and mature wood

4.2.1 Definition of juvenile wood

In order to quantify and describe juvenile wood density it was necessary to determine critical basic density value to demarcate juvenile and mature woods. After a thorough examination of the density curves for whole ring, earlywood and latewood on ring number, it was decided to use the curve of latewood basic density on ring number to establish the juvenile period. This was deemed possible based on the definition that a consistent rise in basic density indicates the end of juvenile period. The juvenile period was therefore found to last to the 8th ring from pith, see figure 4.7. The mean ring basic density of 397 kg/m^3 at ring 8 from pith was therefore considered to demarcate juvenile wood from mature wood. Ring number 9 outwards to bark consists of mature wood.

4.2.2 Proportion of juvenile wood in the stem

The mean log volume under bark and juvenile wood proportion is shown in table 4.17. The results in this table show that the juvenile wood proportion in the stem increases with height in the stem. The mean proportion of juvenile wood in the stem is about 49 per cent with a range of 34.9 - 82.2 per cent. The juvenile wood proportion in the individual sample trees is presented in appendix 8.

Table 4.17 Proportion of juvenile wood.

Statistics	Log 0-4 m	 4-8 m	 8-12 m
Mean volume u.b., m^3	0.354	0.288	0.219
Proportion, %	37.1	53.7	71.3
Range, %	24.2-63.2	30.5-89.7	50.1-95.3

4.2.3 Basic density variation between trees

4.2.3.1 Juvenile wood

Table 4.18 shows the juvenile wood volume weighted basic density for the sample trees. The volume weighted basic densities for juvenile wood from different sample trees were subjected to a student's 't' test to find out whether there was significant difference between trees. The results showed that there was a significant difference between the densities of juvenile wood originating from different stems. The difference between the lightest and the heaviest juvenile woods was about 18 per cent. The density values for each tree is shown in appendix 9.

Table 4.18 Juvenile wood volume weighted basic density.

Statistic	
Mean, kg/m^3	361
s.d., kg/m^3	16
c.v., %	4.4
Range, kg/m^3	325-383
95 % C.I., kg/m^3	352-370

The basic densities at the same height in the stems were also analysed to verify variations between them. The results are shown in table 4.19. There is a significant difference between heights with slightly higher variation at 12 m and 1.3 m than at 4 m or 8 m heights in the juvenile core.

Table 4.19 Juvenile wood basic density at the same heights.

	Height, m			
Statistic	1.3	4	8	12 m
Mean, kg/m^3	376	365	361	354
s.d., kg/m^3	21	15	18	22
c.v., %	5.6	4.2	4.8	6.3
Range, kg/m^3	336-413	335-384	333-381	323-385
95 % C.I.kg/m^3	364-388	357-373	356-366	348-360

Based on the data presented in table 4.3 of basic densities at different rings for 1.3 m heights it is apparent that the coefficients of variation within the juvenile core are quite similar. The coefficient of variation lie between 5.8 per cent and 7 per cent. The juvenile wood density values for each stem at the 4 sampling heights are shown in appendix 10(a).

4.2.3.2 Mature wood

The volume weighted basic densities of mature wood were obtained and analysed giving the results shown in table 4.20. The data was subjected to a student's 't' test in order to find out whether the differences between mature wood of different trees is significantly different. The results indicate that mature wood basic density varies significantly between trees with the largest difference being about 14 per cent. The data values for each tree are shown in appendix 9.

Table 4.20 Mature wood volume weighted basic density

Statistic	
Mean, kg/m^3	464
s.d., kg/m^3	15
c.v., %	3.2
Range, kg/m^3	439-500
95 % C.I., kg/m^3	455-472

The basic densities at different heights were also analysed and gave the results presented in table 4.21. The results show that mature wood variation is significant at all heights.

Table 4.21 Mature wood basic density at the same heights.

	Height, m			
Statistic	1.3	4	8	12
Mean, kg/m^3	495	463	449	433
s.d., kg/m^3	21	20	12	8
c.v., %	4.2	4.3	2.7	1.8
Range, kg/m^3	462-530	425-500	427-462	424-452
95 %, C.I.,kg/m^3	483-507	452-474	442-456	428-437

Variation of mature wood basic densities at the same growth rings can be interpreted from table 4.3. It is evident from that table that the inner rings in the mature wood, i.e. ring number 10, 12 and 14 show greater variation than the outer rings. Ring number 22 and 20 has a relatively low variation. Variation between trees was significant at all rings.

4.2.4 Basic density variation within trees

4.2.4.1 Juvenile wood

The mean basic densities for juvenile wood at each height were subjected to analysis of variance to determine whether its density is dependent on tree height. The analysis of variance table is presented in appendix 10(b). In order to verify radial variation within the juvenile wood zone, the ring density values at each height were subjected to analysis of variance. The analysis of variance tables are shown in appendix 11. The results show that basic density is significantly correlated with tree height from ground and with radial position in the tree. Basic density decreases with height and increases from ring number 2 to ring number 8 at all heights. The difference between the mean values at 1.3 m and 12 m heights is 6 per cent while that between the mean values for ring number 2 and ring number 8 at 1.3 m height is 12 per cent.

4.2.4.2. Mature wood

Analysis of variance was performed on the mean basic densities for mature wood at the 4 heights so as to verify any significant difference between them. The analysis of variance table is presented in appendix 12. In order to verify any radial variation within the mature wood zone, mean ring data beginning with ring number 10 outwards at heights 1.3 m, 4 m and 8 m were subjected to analysis of variance. Height 12 m was not taken as it consisted of too few samples. The analysis of variance tables are shown in appendix 13. The results show that mature wood density values at the three heights are significantly different. The difference between the mean values at 1.3 m and 8 m heights is about 10 per cent. Mature wood density increases significantly with ring number. The difference at 1.3 m height between ring number 10 and 22 is about 30 per cent.

4.2.5 Relationship between juvenile wood and mature wood basic densities

In order to verify the relationship between basic density of juvenile wood and that of mature wood, the volume weighted values were used to establish a simple regression equation. In this case juvenile wood was the independent variable. The results shown in the following equation is that volume weighted mature wood basic density is highly correlated with juvenile wood weighted basic density. The equation is:

$$MBD = 186.6 + 77.65JBD, \text{ with } r = 0.7392^{xx}$$

4.3 General tracheid length variation

4.3.1 Variation between trees

4.3.1.1. Overall variation

The results shown in table 4.22 were obtained from analysis of the tree volume weighted tracheid length presented in appendix 1. The tree volume weighted tracheid length were subjected to a student's 't' test to establish variation between trees. The results indicate that tracheid length vary significantly between trees. The difference between the shortest and the longest mean volume weighted tracheid lengths is about 35 per cent.

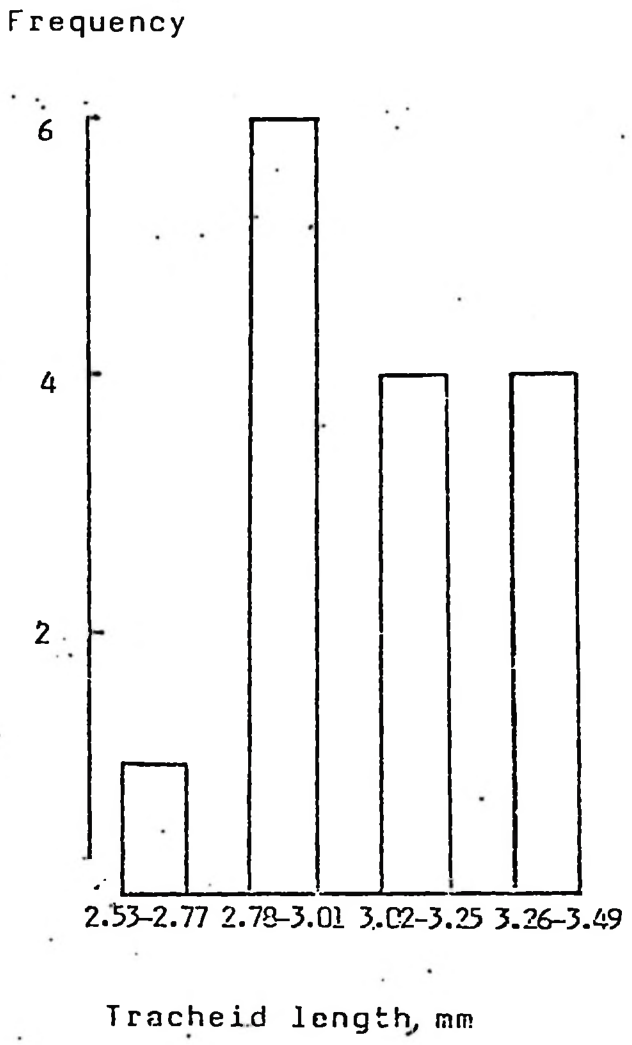
Table 4.22 Tree volume weighted tracheid length.

Statistic	
Mean, mm	3.08
s.d., mm	0.242
c.v., %	7.8
Range, mm	2.53-3.42
95 % C.I., mm	2.95-3.21

The distribution of the tree volume weighted tracheid lengths for the 15 sample trees is shown in figure 4.9. Each tracheid length class width is equivalent to one standard deviation. The relationship between tracheid length and dbh was obtained by using linear regression equation. The equation is:

$$TL = 3.3 - 0.0064dbh, \text{ with } r = 0.2236$$

Figure 4.9 Volume weighted tracheid length frequency distribution.



4.3.1.2 Variation at different tree heights

The weighted tracheid lengths at the same height were analysed to verify variation between trees for each of the 4 heights in the stem. The results show that at each of the 4 heights in the stems tracheid length varies significantly between trees. It is also observed that variation between trees at heights 1.3 m and 4 m is lower than at 8 m and 12 m heights. The difference between the lowest and the highest values is about 30 per cent for 1.3 m and 4 m and about 50 per cent for 8 m and 12 m. Table 4.23 shows tracheid length values at the 4 heights.

Table 4.23 Weighted tracheid length in mm at 4 heights in the stem.

	Height, m			
Statistic	1.3	4	8	12
Mean, mm	3.29	3.10	2.84	2.71
s.d., mm	0.27	0.26	0.33	0.31
c.v., %	8.3	8.3	11.5	11.5
Range, mm	2.84-3.75	2.75-3.57	2.13-3.30	2.2-3.24
Difference between lowest and highest value	32	30	55	48
95 % C.I.,mm	3.14-3.44	2.96-3.24	2.66-3.02	2.54-2.88

4.3.1.3 Variation at different growth rings

The results shown in table 4.24 were obtained from analysis of tracheid length variation at different rings from pith at 1.3 m. The main results are:

- Variation at the same rings is significant between trees.

- Tracheid length variation for the same rings originating from different trees tend to be greater in the rings near the pith.

Table 4.24 Tracheid length in different growth rings at 1.3 m height in the stem.

Ring number	Mean, mm	s.d., mm	c.v., %	Range, mm
2	2.22	0.287	12.9	1.81-2.68
4	2.46	0.277	11.3	2.13-2.95
6	2.69	0.309	11.5	2.01-3.22
8	2.87	0.309	10.8	2.1 -3.35
10	3.06	0.297	9.7	2.34-3.59
12	3.24	0.355	10.9	2.53-3.85
14	3.37	0.357	10.6	2.84-3.95
16	3.57	0.368	10.3	3.01-4.11
18	3.68	0.325	8.8	3.20-4.25
20	3.86	0.270	7.0	3.32-4.36
22	3.99	0.268	6.7	3.43-4.45

Tables 4.25 and 4.26 show the relationship between tracheid length and ring width and ring basic density for ring number 4, 8, 12, 16 and 20. The results show that tracheid length is not significantly correlated to ring width except at ring no. 4 and that tracheid length is not significantly correlated to ring basic density.

Table 4.25 Relationship between tracheid length and ring width at the same ring.

Ring no.	Equation	Correlation coefficient
4	TL= 2.03 + 0.046W	0.5331^{x}
8	TL= 2.8 + 0.008W	0.1452
12	TL= 3.30 + 0.001W	0.0064
16	TL= 3.63 - 0.005W	0.1087
20	TL= 3.78 + 0.002W	0.3248

Table 4.26 Relationship between tracheid length and ring basic density at the same ring.

Ring no.	Equation	Correlation coefficient
4	TL= 2.55 + 0.00003BD	0.1711
8	TL= 3.07 - 0.00004BD	0.1928
12	TL= 3.32 - 0.00001BD	0.0677
16	TL= 3.53 + 0.00003BD	0.2079
20	TL= 3.85 + 0.000003BD	0.0264

4.3.2 Variation within trees

4.3.2.1 Variation with cardinal direction

The data shown in appendix 14 for the 4 cardinal directions was subjected to analysis of variance to determine the effect of sampling direction on tracheid length. The analysis of variance table is presented in appendix 15. The results indicate that tracheid length from the 4 cardinal directions do not differ significantly. Table 4.27 presents the mean tracheid lengths for the 4 directions. It is noted that the samples drawn from the east has the highest mean value while those from north has the lowest value. The difference between these two values is 5 per cent.

Table 4.27 Tracheid lengths in 4 cardinal directions.

Statistic	South	North	West	East
Mean, mm	3.32	3.25	3.26	3.41
s.d., mm	0.632	0.553	0.596	0.755

4.3.2.2 Axial variation

An analysis of variance was performed on the weighted tracheid length shown in table 4.28 in order to determine whether the difference between the four heights was significant. The analysis of variance table is shown in appendix 16. The results show that there is a significant difference between heights. Tracheid length decreases with stem height. The means at the 4 heights were compared in order to test which ones differed significantly using the least significance difference technique. The results show that tracheid length at 1.3 m and at 4 m do not differ significantly from each other. Similarly at 8 m and at 12 m the tracheid lengths do not differ significantly. The difference between 1.3 m and 12 m is significant. The difference between the mean values at the two heights is 21.4 per cent.

4.28 Weighted tracheid length in mm, at 4 heights in 15 stems.

Tree no.	Heights, m 1.3	4	8	12
1	3.27	2.98	2.83	2.30
2	3.75	2.85	3.22	2.83
3	3.12	3.07	2.13	2.33
4	3.31	3.24	2.85	2.99
5	3.41	3.57	2.46	2.63
6	3.49	3.20	2.44	2.85
7	3.52	3.41	3.30	3.23
8	2.92	2.76	2.56	2.51
9	3.28	3.06	3.06	3.04
10	3.61	3.41	2.79	2.47
11	2.83	2.75	2.90	2.69
12	3.05	2.74	2.96	3.24
13	3.63	3.11	3.11	2.66
14	3.29	3.40	3.27	2.70
15	2.94	2.96	2.68	2.20

4.3.2.3 Radial variation

Regression equations established for the relationship between tracheid length and distance from pith, ring number and ring width are shown in tables 4.29, 4.30 and 4.31. The scatter diagrams and regression lines for separate heights are presented in appendix 17a, 17b and 17c. In order to illustrate the trends the mean ring tracheid length were plotted on the same variables and are shown in figures 4.10, 4.11 and 4.13. The main results from the regression equations and the figures are that:

- Ring tracheid length increases significantly with both distance from pith and ring number.

- The curves of tracheid length on distance from pith and ring number had not reached a peak.
- Ring tracheid length decreases significantly with increases in ring width, more so in the 3 mm to 4.5 mm ring width range.

Multiple linear regression equations for the relationship between ring tracheid length and ring number and distance from pith on one hand and tracheid length and ring number and ring width are shown in tables 4.32 and 4.33. The following conclusions can be made from the equations:

- Except at height 12 m, ring tracheid length increased significantly with both ring number and distance from pith. In both cases ring number had a greater effect than both distance from pith and ring width.
- At all heights ring tracheid length decreases significantly with ring width.

Table 4.29 Regression equations and correlation coefficients for the relationship between ring tracheid length and distance from pith.

Height, m	Regression equation	Correlation coefficient
1.3	$TL= 2.1386+0.0095d+0.0000d^2$	0.8351^{xx}
4	$TL= 1.8314+0.00769d-0.00005d^2$	0.7402^{xx}
8	$TL= 1.906+0.0191d-0.0001d^2$	0.6662^{xx}
10	$TL= 2.0012+.0.113d-0.0000d^2$	0.6836^{xx}

Table 4.30 Regression equations and correlation coefficients for the relationhip between ring tracheid length and ring number.

Height, m	Regression equation	Correlation coefficient
1.3	$TL= 2.0293+0.1149N-0.0012N^2$	0.8696^{xx}
4	$TL= 1.9415+0.1455N-0.0027N^2$	0.8013^{xx}
8	$TL= 1.8656+0.1689N-0.0036N^2$	0.7506^{xx}
12	$TL= 2.0067+0.1123N-0.0010N^2$	0.7535^{xx}

Table 4.31 Regression equations and correlation coefficients for the relationship between ring tracheid length and ring width.

Height, m	Regression equation	Correlation coefficient
1.3	$TL= 4.3550-0.2146W+0.0061W^2$	0.7484^{x}
4	$TL= 4.0184-0.1279W+0.0061W^2$	0.7670^{x}
8	$TL= 4.1597-0.1759W+0.0041W^2$	0.7415^{x}
12	$TL= 3.7422-0.1479W+0.0038W^2$	0.7119^{x}

Table 4.32 Multiple linear regression equations and correlation coefficients for ring tracheid length on ring number and distance from pith.

Height, m	Regression equation	Correlation coefficient
1.3	TL= 2.07812+0.05839N+0.00381d	0.8836^{xx}
4	TL= 2.17812+0.08568N+0.00006d	0.8013^{xx}
8	TL= 2.06269+0.09194N+0.00147d	0.7527^{xx}
12	TL= 2.06991+0.10805N-0.00128d	0.7544^{xx}

Table 4.33 Multiple linear regression equations and correlation coefficients for ring tracheid length on ring number and ring width.

Height, m	Regression equation	Correlation coefficient
1.3	TL= 2.09856+0.08894N-0.00256W	0.8762^{xx}
4	TL= 2.68838+0.06328N-0.02979W	0.8165^{xx}
8	TL= 2.76103+0.06586N-0.03651W	0.7563^{xx}
12	TL= 2.52007+0.06362N-0.02351W	0.7698^{xx}

Figure 4.10 Relationship between ring tracheid length and distance from pith at 4 heights in the stem.

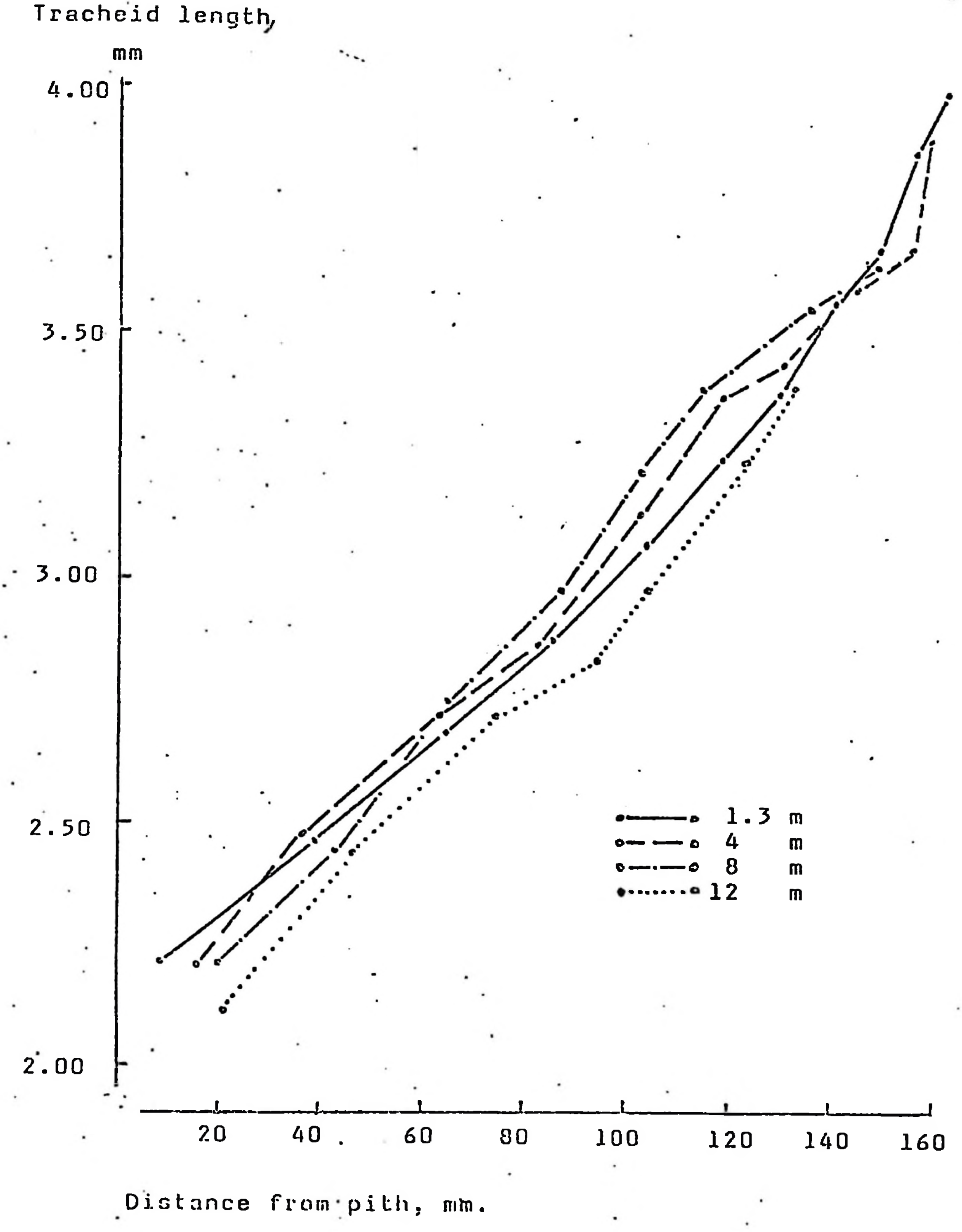


Figure 4.11 Relationship between ring tracheid length and ring number from pith at 4 heights in the stem.

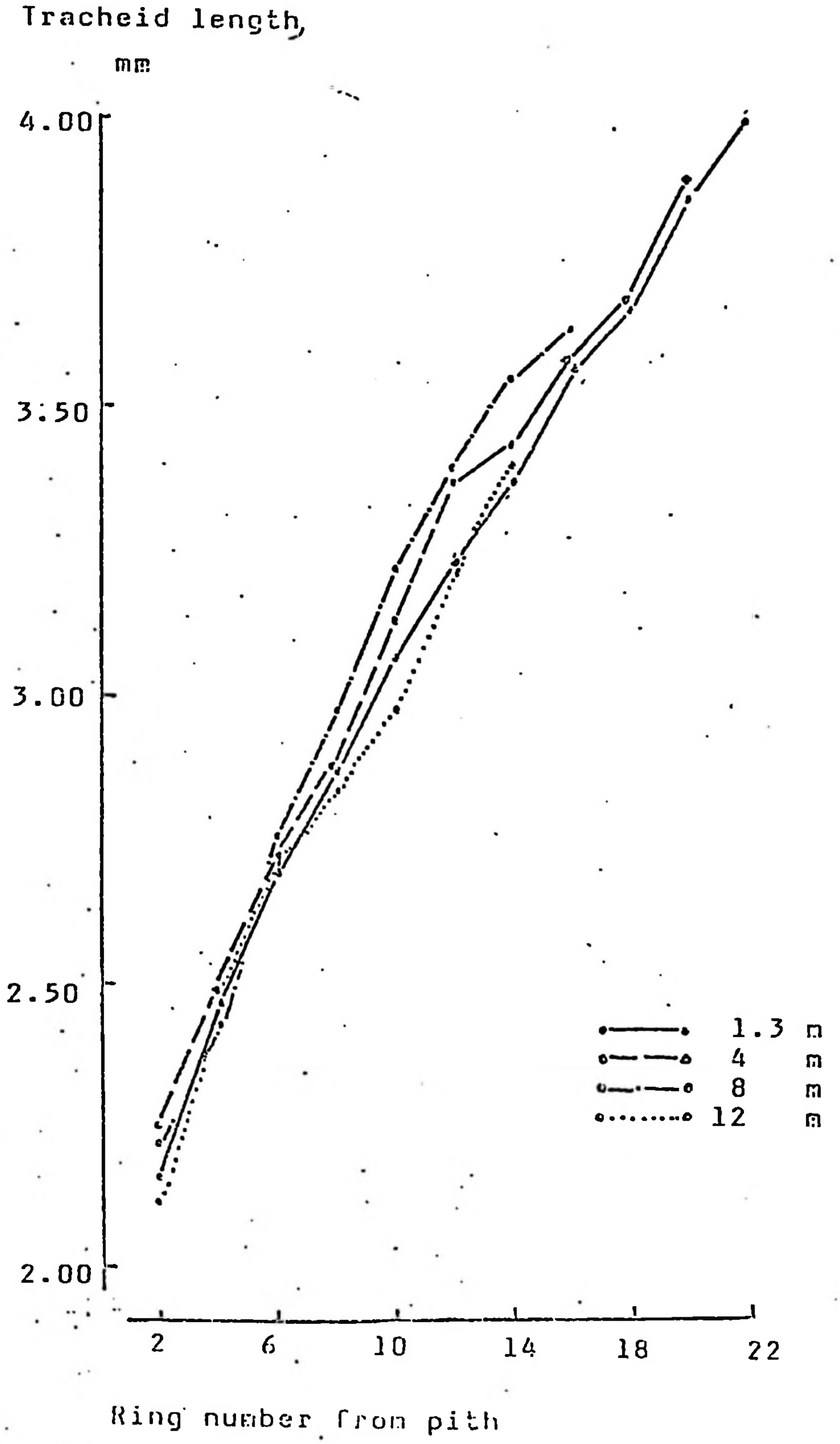
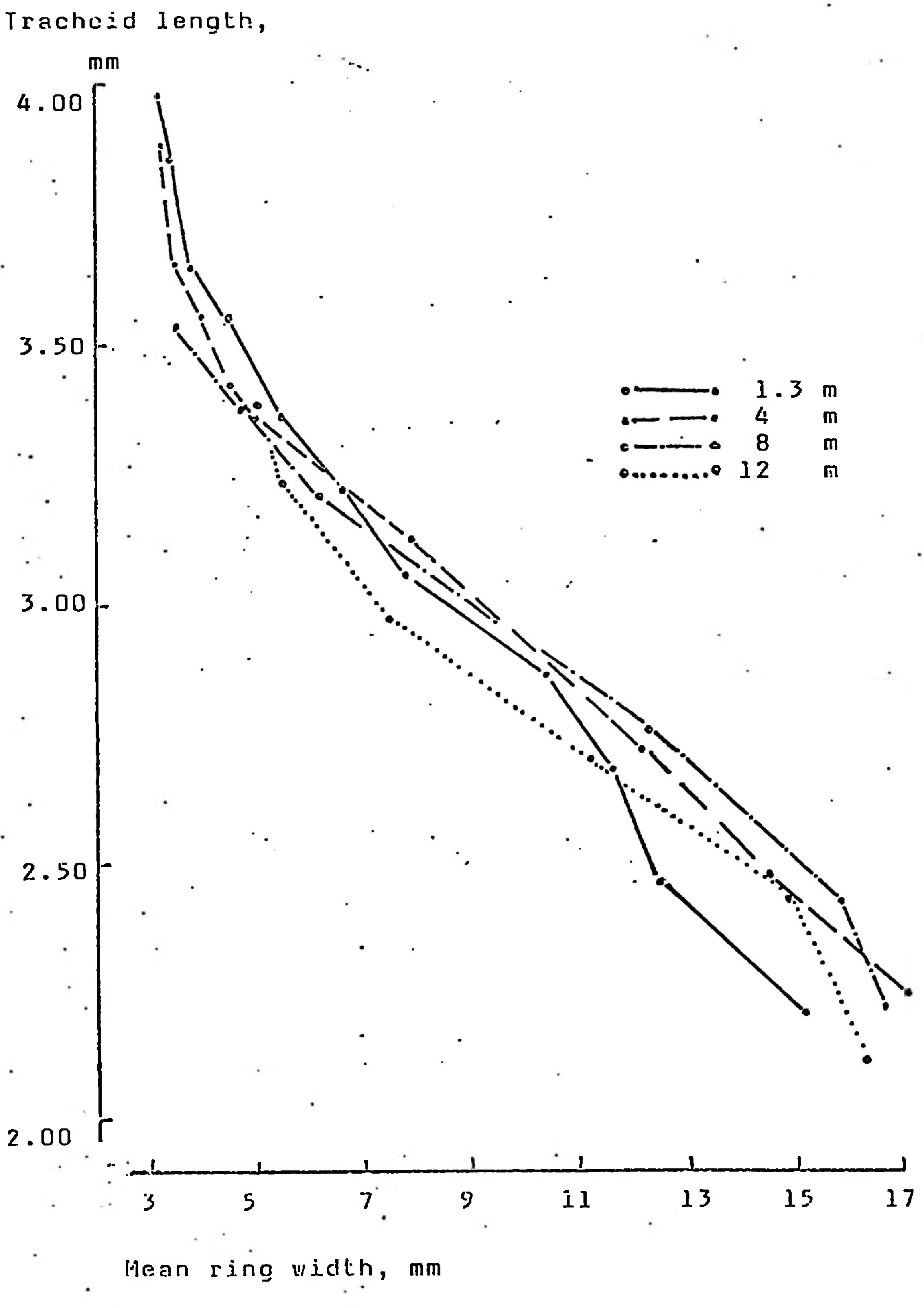


Figure 4.12 Relationship between ring tracheid length and ring width at 4 heights in the stem.



4.3.2.4 Earlywood and latewood variation

The relationships between earlywood tracheid length and distance from pith, ring number and ring width are shown by the regression equations in tables 4.34, 4.35 and 4.36. Scatter diagrams and the regression lines for each height are shown in appendices 18a-c. Appendix 18d shows the earlywood and latewood tracheid lengths for various rings at the heights in the 15 trees. Figures 4.13, 4.14 and 4.15 show the trend of earlywood tracheid length variation with the said variables. Similar expressions for the relationships between latewood tracheid length and the three variables are shown in tables 4.37, 4.38 and 4.39. The curves for the mean values are shown on figures 4.16, 4.17 and 4.18. Appendices 19a-c show the scatter diagrams and regression lines for the individual heights. The main results are:

- The tracheid lengths of both bands in the 4 heights increase significantly with distance from pith and ring number, but decrease significantly with increase in ring width.
- When plotted on ring number, earlywood and latewood tracheid lengths increase more rapidly than when plotted on distance from pith.
- The mean tracheid length values for various rings at 4 m and 8 m are slightly higher than those at 1.3 m and 12 m heights.

Table 4.34 Regression equations and correlation coefficients for the relationship between earlywood tracheid length and distance from pith.

Height, m	Regression equation	Correlation coefficient
1.3	$TL= 2.0815+0.0097d+0.0000d^2$	0.8283^{xx}
4	$TL= 2.0628+0.0091d+0.0000d^2$	0.7688^{xx}
8	$TL= 1.8708+0.0190d-0.0001d^2$	0.7137^{xx}
12	$TL= 1.9378+0.011d-0.0000d^2$	0.6964^{xx}

Table 4.35 Regression equations and correlation coefficients for the relationship between earlywood tracheid length and ring number.

Height, m	Regression equation	Correlation coefficient
1.3	$TL= 1.9519+0.1260N-0.0018N^2$	0.8406^{xx}
4	$TL= 1.8356+0.1388N-0.0022N^2$	0.8427^{xx}
8	$TL= 1.8117+0.1761N-0.0038N^2$	0.7893^{xx}
12	$TL= 1.9318+0.1028N+0.0004N^2$	0.7766^{xx}

Table 4.36 Regression equations and correlation coefficients for the relationship between earlywood tracheid length and ring width

Height, m	Regression equation	Correlation coefficient
1.3	$TL= 4.2181-0.1964W+0.0053W^2$	0.7263^{xx}
4	$TL= 3.9840-0.1459W+0.0026W^2$	0.7916^{xx}
8	$TL= 4.1530-0.1822W+0.0045W^2$	0.7251^{xx}
12	$TL= 3.8436-0.1756W+0.0047W^2$	0.7455^{xx}

Figure 4.13 Relationship between earlywood tracheid length and distance from pith at 4 heights in the stem.

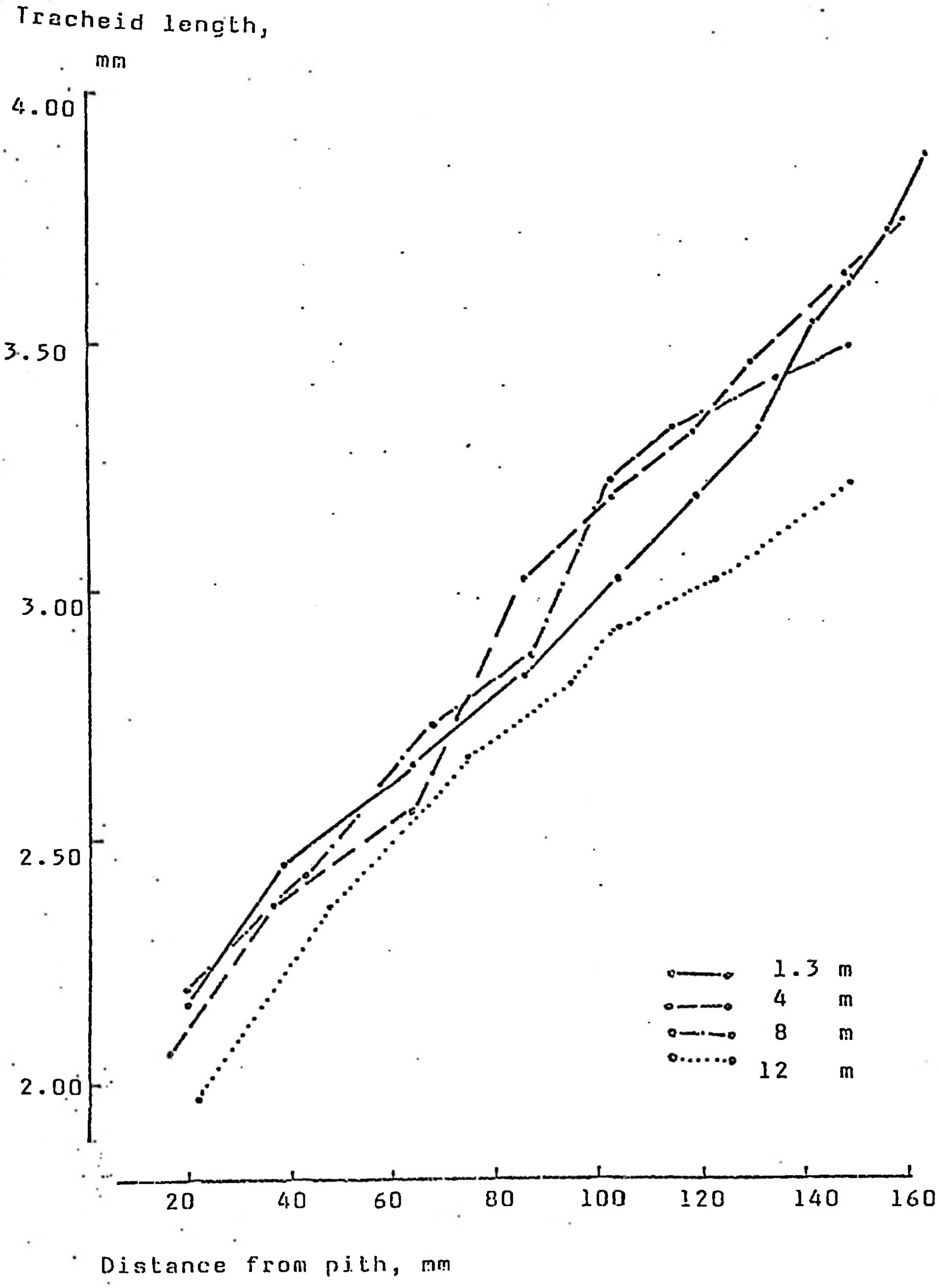


Figure 4.14 Relationship between earlywood tracheid length and ring number from pith at 4 heights in the stem.

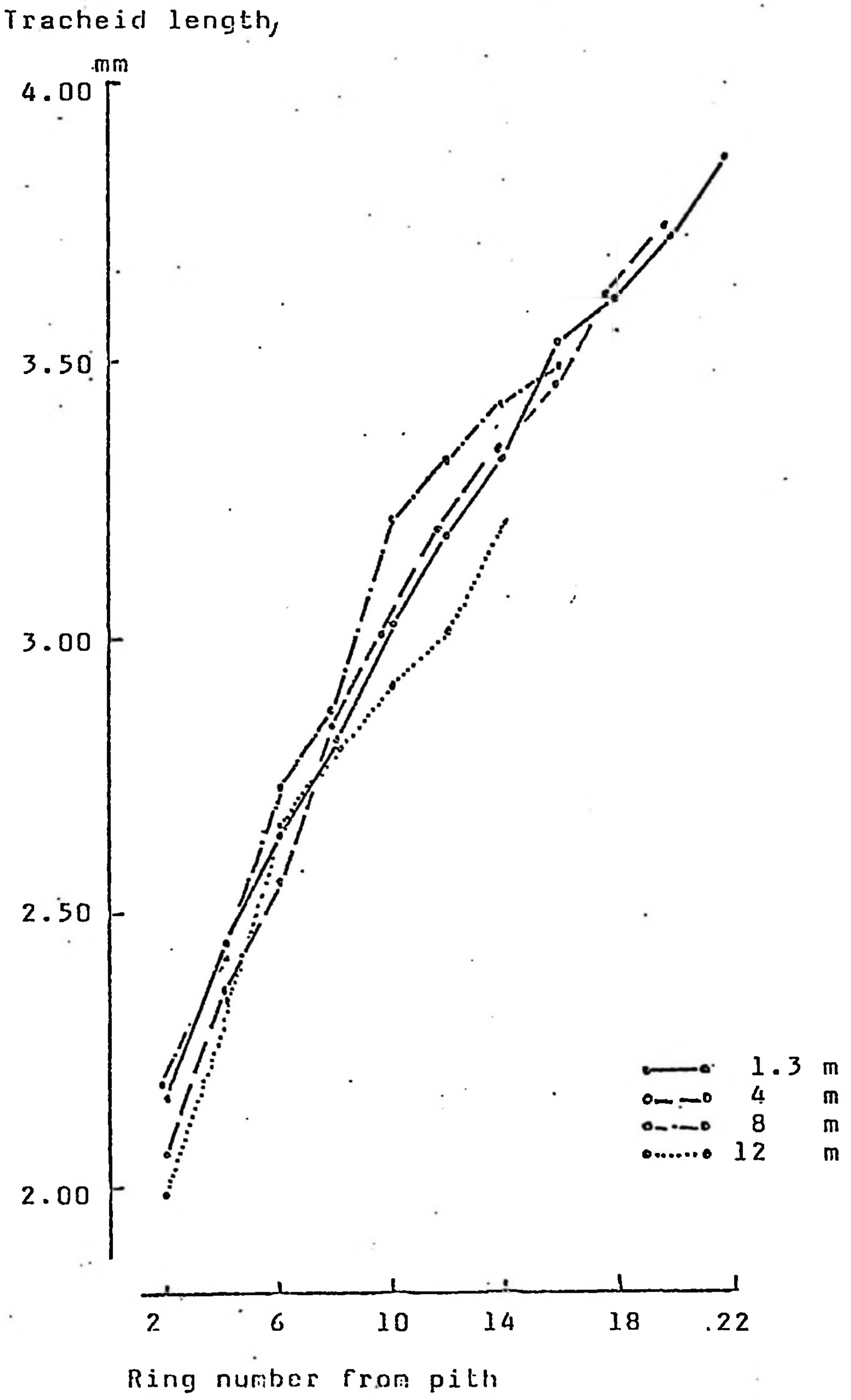


Figure 4.15 Relationship between earlywood tracheid length and mean ring width at 4 heights in the stem.

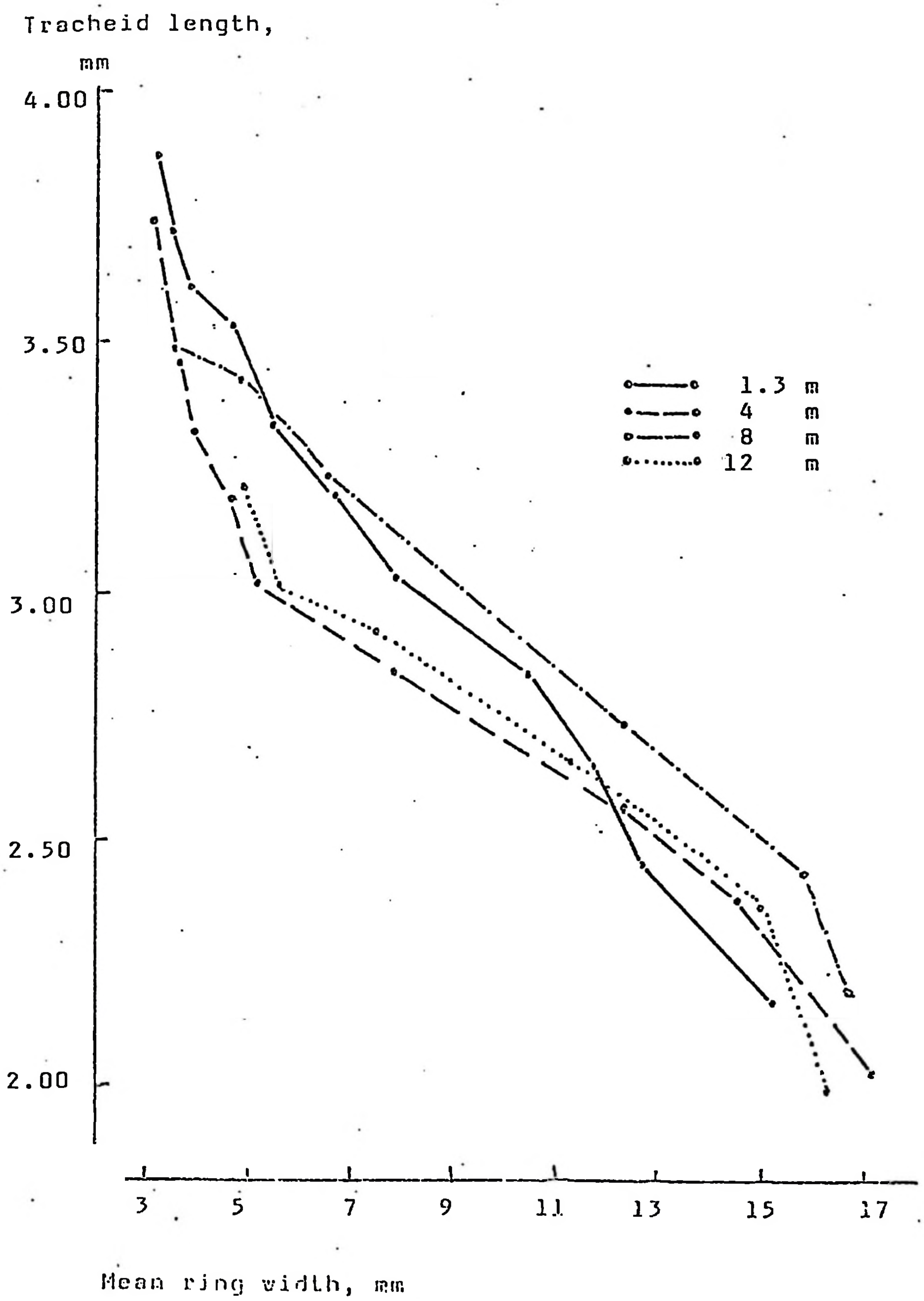


Table 4.37 Regression equations and correlation coefficients for the relationship between latewood tracheid length and distance from pith.

Height, m	Regression equation	Correlation coefficient
1.3	$TL= 2.1904+0.0099d-0.000d^2$	0.8145^{xx}
4	$TL= 2.1078+0.0100d-0.0000d^2$	0.8172^{xx}
8	$TL= 1.9708+0.0193d-0.0001d^2$	0.7299^{xx}
12	$TL= 2.06996+0.0101d-0.0000d^2$	0.6756^{xx}

Table 4.38 Regression equations and correlation coefficients for the relationship between latewood tracheid length and ring number.

Height, m	Regression equation	Correlation coefficient
1.3	$TL= 2.1336+0.1045N-0.007N^2$	0.8622^{xx}
4	$TL= 1.9826+0.1423N-0.0026N^2$	0.8105^{xx}
8	$TL= 1.9647+0.1694N-0.0036N^2$	0.7562^{xx}
12	$TL= 2.1126+0.0881N-0.0010N^2$	0.7766^{xx}

Table 4.39 Regression equations and correlation coefficients for the relationship between latewood tracheid length and ring width.

Height, m	Regression equation	Correlation coefficient
1.3	$TL = 4.3921 - 0.2860W + 0.0058W^2$	0.7338^{xx}
4	$TL = 4.0556 - 0.1338W + 0.0021W^2$	0.7819^{xx}
8	$TL = 4.3845 - 0.2095W + 0.0058W^2$	0.7318^{xx}
12	$TL = 3.9112 - 0.1684W + 0.0046W^2$	0.7134^{xx}

Figure 4.16 Relationship between latewood tracheid length and distance from pith at 4 heights in the stem.

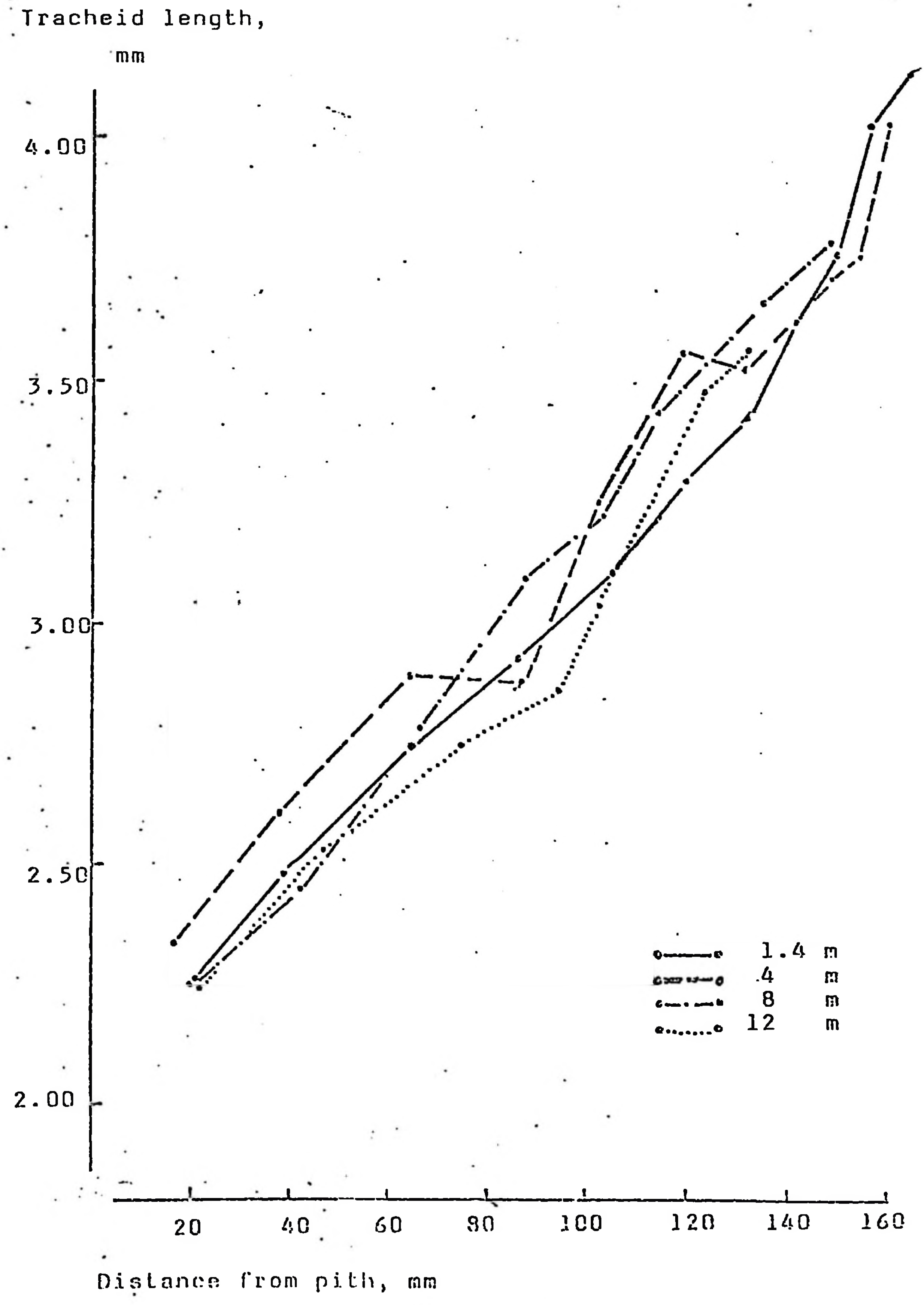


Figure 4.17 Relationship between latewood tracheid length and ring number from pith at 4 heights in the stem.

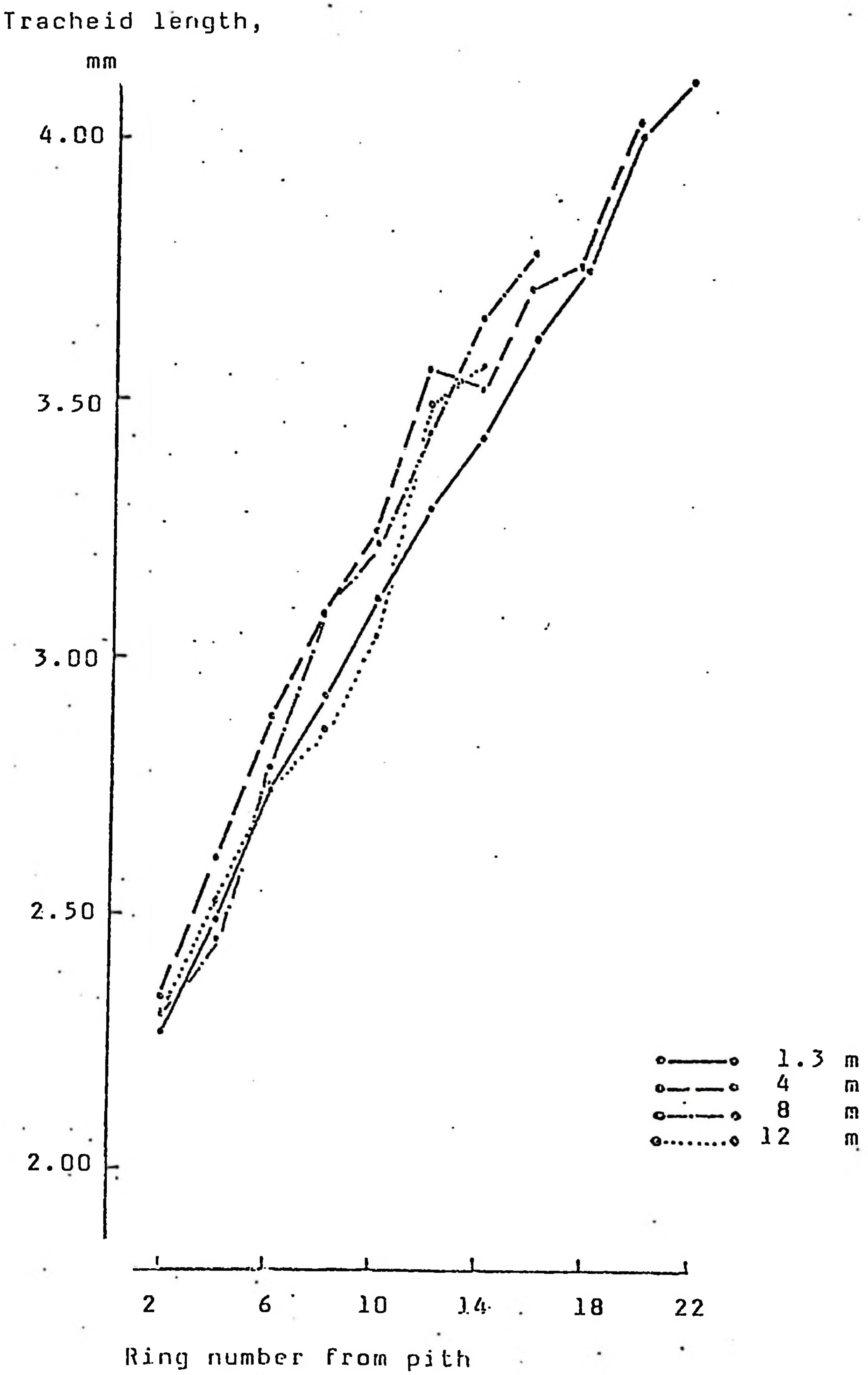
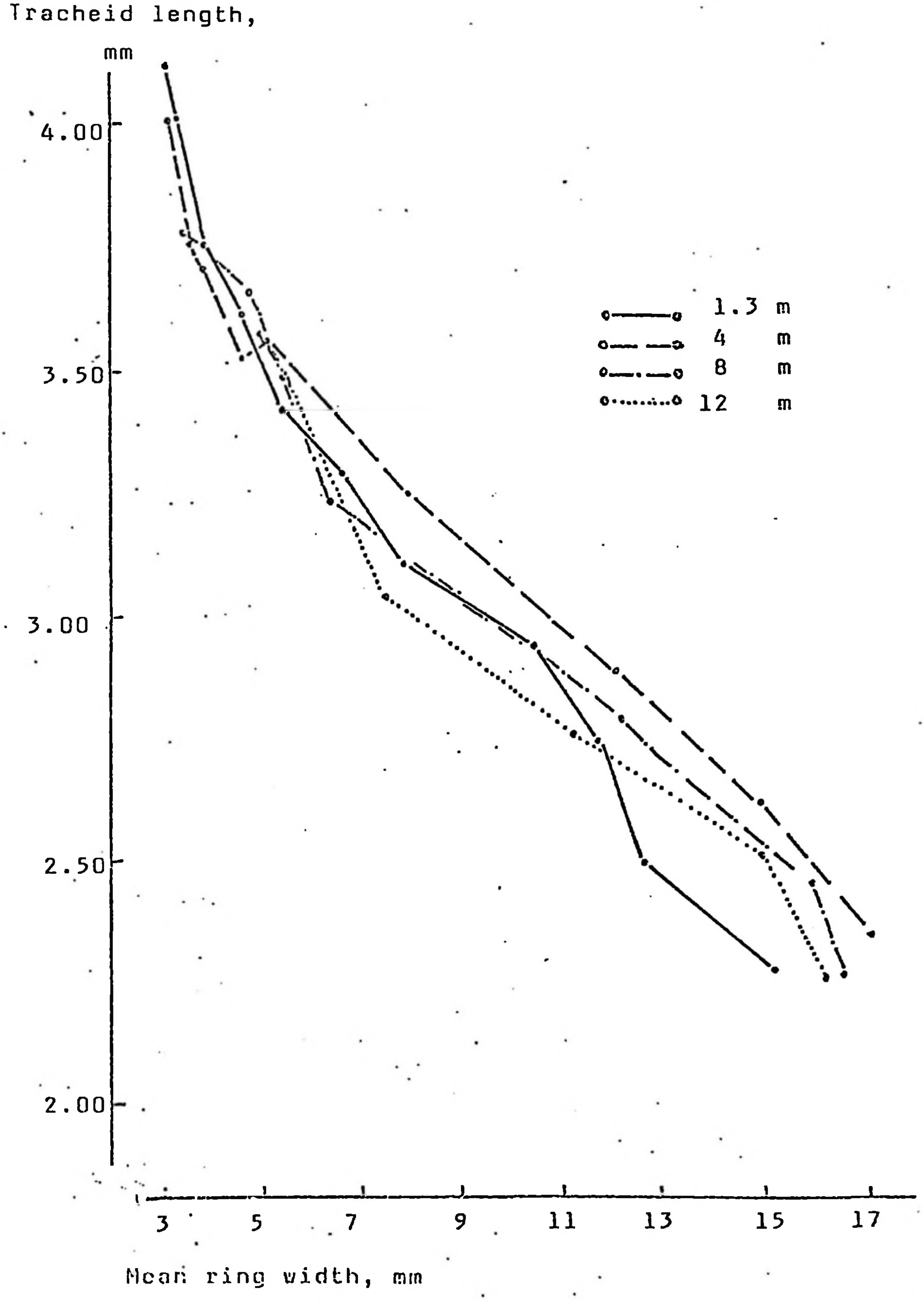


Figure 4.18 Relationship between latewood tracheid length and ring width at 4 heights in the stem



A paired 't' test was used to test the difference between tracheid lengths of earlywood and latewood. The results indicate that latewood tracheids are significantly longer than earlywood tracheids. Table 4.40 shows the mean difference between earlywood and latewood tracheid length of different growth rings at 1.3 m.

Table 4.40 Mean difference and 't' values for 't' test on difference between earlywood and latewood tracheid length.

Ring number	2	4	6	8	10	12	14	16	18	20	22
Mean difference, mm	0.16	0.07	0.16	0.07	0.08	0.13	0.098	0.07	0.13	0.12	0.25
't'	3.42^{xx}	3.35^{xx}	3.62^{xx}	0.79^{x}	4.02^{xx}	3.12^{xx}	3.71^{xx}	2.12^{xx}	6.06^{xx}	1.38^{x}	2.4^{xx}

The earlywood and latewood tracheid lengths at the 4 heights were subjected to analysis of variance to find out whether there was a significant difference between them. The analysis of variance tables are shown in appendices 20 and 21 for earlywood and latewood respectively. The results indicate that the tracheid lengths of the two bands decrease significantly with height in tree.

4.3.2.5 Variation within earlywood and latewood bands

The tracheid lengths of the inner and outer earlywood and those of latewood were subjected to a 't' test. The data is presented in appendix 22. The results show that there is neither significant difference between the inner and outer earlywood portions nor between inner and outer latewood portions. The inner and outer earlywood portions differ by about 4 per cent while the difference between the other pair is about 3 per cent. In both bands the outer portions had the longer fibres. Table 4.41 shows tracheid lengths for the 4 growth ring portions.

Table 4.41 Tracheid length of 4 portions of a growth ring.

Statistic	Earlywood		Latewood	
	Inner	Outer	Inner	Outer
Mean, mm	2.8	2.9	2.9	3.0
S.d., mm	0.41	0.50	0.41	0.46
c.v., %	14.6	17.1	13.6	15.1
Range, mm	2.1-3.5	2.0-3.8	2.2-3.7	2.3-4.0
95 % C.I.,mm	2.6-3.0	2.64-3.20	2.7-3.2	2.7-3.3

4.4 Tracheid length of juvenile wood and mature wood

4.4.1 Definition of juvenile wood

It is apparent from the radial tracheid length pattern at all heights in the stems that tracheid length does not reach a peak. In order to ascertain the length of the juvenile period it is therefore not possible to apply the same technique used in the case of basic density. It was decided that the juvenile period established by latewood basic density should also apply for tracheid length.

4.4.2 Proportion of juvenile wood in the stem

The first 8 growth rings near the pith constitute the juvenile wood core, exactly the same zone established using wood density in 4.2.1 and therefore the proportion of juvenile wood is as reported there.

4.4.3 Tracheid length variation between trees

4.4.3.1 Juvenile wood

Table 4.42 presents the volume weighted tracheid length for juvenile wood. The results show that the between tree variation is significant. The shortest and the longest volume weighted juvenile wood tracheid lengths differ by about 62 per cent. Individual tree juvenile wood tracheid lengths are shown in appendix 9.

Table 4.42 Juvenile wood volume weighted tracheid length.

Statistic	
Mean, mm	2.61
s.d., mm	0.284
c.v., %	10.9
Range, mm	2.03-3.28
95 % C.I., mm	2.45-2.77

Table 4.43 shows tracheid length variations at different heights. The results indicate that the variation at different heights is significant. Variation tend to be higher in 8 m height. Juvenile wood tracheid length for individual trees is shown in appendix 23.

Table 4.43 Juvenile wood tracheid length at 4 heights in the stem.

	Height, m			
Statistic	1.3	4	8	12
Mean, mm	2.56	2.60	2.53	2.50
s.d., mm	0.26	0.29	0.33	0.29
c.v., %	10.2	11.3	12.5	11.4
Range, mm	2.04-3.05	2.11-3.14	1.94-3.02	2.09-3.13
95 % C.I.,mm	2.42-2.70	2.44-2.76	2.35-2.71	2.34-2.66

Tracheid length variation at different growth rings are presented in appendix 24. Based on the variations shown, it is apparent that tracheid length variation tends to increase with ring number from pith within the juvenile wood, this is when the absolute values of the standard deviations are considered, for the coefficients of variation do not follow any consistent pattern.

4.4.3.2 Mature wood

Table 4.44 shows the volume weighted tracheid length of mature wood. The results show that the between tree values are significantly different. A comparison of the lowest and highest volume weighted tracheid lengths shows a difference of 34 per cent. Individual tree volume weighted tracheid length values are shown in appendix 9.

Table 4.44 Volume weighted tracheid length of mature wood.

Statistic	
Mean, mm	3.40
s.d., mm	0.24
c.v., %	7
Range, mm	2.99-3.93
95 % C.I., mm	3.27-3.53

The mean tracheid lengths of mature wood were subjected to statistical analysis in order to verify their variations. Table 4.45 shows the mature wood tracheid length at different heights while appendix 25 shows individual values at the 4 sampling heights. It is noted that variation at heights 1.3 m and 12 m is lower than for the intermediate heights. Between tree variation is significant at all heights.

Table 4.45 Mature wood tracheid length at 4 heights in the stem.

	Height, m			
Statistic	1.3	4	8	12
Mean, mm	3.45	3.49	3.29	3.17
S.d., mm	0.32	0.36	0.37	0.26
c.v., %	9.2	10.4	11.3	8.20
Range, mm	3.03-4.0	2.99-4.15	2.62-3.85	2.71-3.69
95% C.I.mm	3.27-3.63	3.29-3.69	3.09-3.49	3.03 3.31

Variations at different growth rings are presented in appendix 24. Based on the values for 1.3 m height the following observation can be made for the mature wood zone:

- Variation at rings number 10, 12, 14 and 16 are considerably higher than for rings 18, 20 and 22.

4.4.4 Tracheid length variation within trees

4.4.4.1 Juvenile wood

The mean tracheid lengths for juvenile wood shown in appendix 23 were subjected to analysis of variance to test for axial variation between the 4 heights. The analysis of variance table is presented in appendix 26. The results show that there is no significant difference in juvenile wood tracheid length between heights.

4.4.4.2 Mature wood

The mean mature wood tracheid lengths at each height shown in appendix 25 were subjected to analysis of variance, the results of which were that there is no significant difference between the four heights. The analysis of variance table is shown in appendix 27.

The results in table 4.24 and in figure 4.11 indicate that tracheid length increases significantly from ring number 10 to ring number 22.

4.4.5 Relationship between juvenile wood and mature wood tracheid length

The relationship between volume weighted juvenile wood tracheid length and that of mature wood was established by a simple linear regression equation. The equation which is shown below indicates that the two are significantly correlated. The equation is:

$$MTL = 1.7847 + 0.6212JTL, \text{ with } r = 0.7340^{xx}$$

5 DISCUSSION

5.1 Wood density

5.1.1 Variation between trees

5.1.1.1 Overall variation

The mean basic density of Pinus patula wood of 412 kg/m^3 found in this investigation falls within the normal range for this species, see table 2.1. This value is, however, slightly low considering that the trees were 27 years old when sampled compared to the mean values of 449, 435 and 426 kg/m^3 reported for 22 year old trees from Tanzania and Uganda (Kubelka 1969, Plumptre 1978). The lower value may be attributed to differences in genetical constituents of the different trees or differences in growth conditions or both (Wormald 1975). The seed for all the crop in East and Central Africa was obtained from South Africa, where Pinus patula had been introduced much earlier. The separate effect due to genetical factors can not be verified in this study. The more likely causes of the difference would be due to environmental factors which influence the crown development which again influences the proportion of juvenile wood in the stems (Bendtsen 1978, Zobel 1981). In Sao Hill, using the definition in this study, the proportion of juvenile wood depends on the annual growth rate within the first 8 rings near the pith.

The significant variation between trees established in this study confirms earlier findings for the same species (Kubelka 1969, Paterson 1969, Ringo and Klem 1980). Similar observations have been made for other pine species, see table 2.2. The coefficient of variation of 6.8 per cent obtained is lower than the 10 per cent normally expected from similar studies of temperate grown Pinus species (Rydholm 1965). Coefficients of variation of 11 pine species grown in South-East United States ranged between 7 and 11 per cent (Okkonen et al. 1972). The results in this study point to the fact that fast grown Pinus patula from plantations in sub-tropical conditions may have wood of more uniform density than comparable materials from the slow grown pines in temperate regions. More studies are necessary to clarify the latter.

The negative relationship between basic density and dbh obtained for the Pinus patula and presented in 4.1.1.1 confirms earlier findings (Paterson 1969, Lema et al. 1978, Ringo and Klem 1980). The decrease in basic density with increase in tree dbh may be attributed in part to proportional amounts of juvenile wood in the stems as indicated by the equation in 4.1.1.1. Similar argument has been advanced for pine species grown elsewhere (Kibblewhite 1980, Harris 1981, Zobel 1981).

5.1.1.2 Variation at different heights and at different rings

The results found in this investigation confirm those reported earlier from Sao Hill (Ringo 1977). Similar large variation has been reported for pine species grown in temperate and sub-tropical regions (Okkonen et al. 1972, Taylor et al. 1982). It is noted that the standard deviation of 28 kg/m^3 and coefficient of variation of 6.2 per cent at breast height are very close to those obtained for the whole tree volume weighted basic density. The values for whole tree were 28 kg/m^3 and 6.8 per cent. This information may be used in determination of sample size for wood density studies in the future.

A possible explanation for the large variation between trees at the same heights in stem can be differences in the stem form and in the length of annual internodes (Okkonen *et al*. 1972). The results obtained in this investigation cannot be used to verify the causal factors for the large variation observed.

Variation between density of wood formed in the same year in different trees has been reported earlier for *Pinus patula* subjected to different silvicultural treatments (Turnbull 1947, Plumptre 1978). The results found in this investigation, table 4.4, concur with the findings that for a given age or ring number, basic density tends to decrease slightly with increasing growth rate. Similar findings are reported in *Pinus elliottii*, *Pinus radiata*, *Pinus banksiana*, *Pinus taeda* and many other pine species (Larson 1957, Sutton and Harris 1974, Scott *et al*. 1982, Taylor *et al*. 1982).

It is important to stress that for significant reductions to occur in wood density the range between the slow and the fast growing trees must be wide enough (Larson 1957).

At ring number 12 from pith, based on the equation from 1.3 m, table 4.4, it will be necessary to double the ring width from 5.32 mm to 9.1 mm, in order to reduce the mean basic density by about 10 per cent.

At a given ring number, basic density was more strongly correlated to latewood proportion in the ring than ring width as illustrated by the correlation coefficients in tables 4.4 and 4.5.

Similar results are reported for other species (Paul 1939, Larson 1957, Cole et al. 1966, Ifju and Labosky 1972). The correlation between ring basic density and latewood per cent obtained in this investigation is lower than the correlation coefficient in other studies. The difference may be attributed to the differences in the ratios between earlywood basic density and latewood basic density. The ratio is lower in the fast grown Pinus patula than in the slow grown trees as evident in table 2.3.

5.1.2 Variation within trees

5.1.2.1 Variation in axial direction

The results confirm earlier findings on 25 year old Pinus patula grown in Sao-Hill (Ringo and Klem 1980). Basic density decrease with height in the stem. Similar results for Pinus patula were reported even earlier (Turnbull 1947, Plumptre 1978). Table 5.1 shows the more likely causes of the trend to be:

- increase in the relative proportion of juvenile wood with height in the stems
- overall decrease in juvenile and mature wood basic densities with height in the stems.

Table 5.1 Juvenile and mature wood proportion and basic density at 4 heights in the stem.

Height, m	Juvenile wood		Mature wood	
	Proportion, %	Mean BD, kg/m^3	Rings no.	Mean BD, kg/m^3
1.3	52	376	9-22	495
4	56	365	9-20	463
8	64	361	9-18	449
12	72	354	9-14	433

5.1.2.2 Variation in radial direction

The radial pattern is in agreement with the first part of Sanio's results on radial basic density in *Pinus sylvestris*. Basic density increases in this investigation from pith to bark but do not seem to have reached its maximum. This observation is in agreement with the findings reported for 13 year old *Pinus patula* grown in Kenya (Fry and Chalk 1957). Similarly the same pattern was found in Sao Hill for 25 year old *Pinus patula* (Ringo and Klem 1980). The same findings are reported for 16-18 year old *Pinus patula* from Meru Forest Project (Lema *et al*. 1978). The reason for not verifying the entire curve observed in *Pinus sylvestris* and other pines is tree age (Fry and Chalk 1957, Zobel 1981). Materials sampled from older *Pinus patula* stands in Mexico showed culmination between 30-40 years (Zobel 1965).

The relationship between basic density and distance from pith established for *Pinus patula* in this investigation has been reported before for other pine species (Anderson 1951).

The relationship between basic density and age has been reported before for *Pinus patula* wood (Turnbull 1947, Fry and Chalk 1957, Kubelka 1969, Paterson 1969, Lema *et al*. 1978, Plumptre 1978, Ringo and Klem 1980). These reports are unanimous in their findings that basic density increases with age. The results obtained in this investigation concur with those earlier findings. It is apparent in figure 5.1 that both ring and latewood basic densities increase sharply from pith to bark while that of earlywood increases less sharply. It is also observed that ring width decreases from pith to bark.

The positive correlation between latewood per cent and whole ring basic density established in this investigation has been reported before for 13 year old *Pinus patula* grown in Kenya (Fry and Chalk 1957). A similar relationship has been established for other pine species (Paul 1939, Larson 1957, Elliott 1970). The correlation coefficient obtained in this study is lower than that for slow grown pines with wide zones of mature wood in which the ratio of earlywood to latewood basic density is more than 2 (Paul 1963). The low ratio between earlywood to latewood basic density in this study may explain part of the low correlation found.

Earlier work on *Pinus patula* grown in Kenya leads to the conclusion that age and ring width together influence radial wood density variation (Fry and Chalk 1957). The results in this investigation are in agreement with those findings as evident in the multiple linear regression equations shown in table 4.12. The results in this study, however, indicate that age is more important than ring width. The equation shows, for example, that at ring number 10, ring number contributes about 5 times more than ring width to basic density. These findings tend to confirm earlier work in South African grown *Pinus patula* (Turnbull 1947). The same relationship has been found in *Pinus radiata* grown in New Zealand and Australia (Kibblewhite 1980). Fluctuations of ring width within the range of 3 mm - 4.5 mm in mature wood zone results in considerable changes in basic density. In figure 4.5, an increase in ring width from 3.3 to 4.5 mm causes the basic density curve to drop from 550 kg/m^3 to 490 kg/m^3. These results tend to confirm an earlier hypothesis that within the mature wood zone, ring width is the more important factor influencing wood density (Elliott 1970).

The pattern of the radial basic density curve is a reflection of the changes in cellwall thickness (Fry and Chalk 1957). These changes are brought about through changes in crown size, age and distance from the crown (Larson 1957 1964). Thinning, pruning and rainfall were the main stand factors which may have influenced the crown development and position. The stands were to be thinned and pruned following the schedule presented in 3.2.1. It is not possible to evaluate the effect of each treatment or rainfall on the basis of the results in this investigation.

5.1.3 Juvenile and mature wood

5.1.3.1 Juvenile period and juvenile wood proportion in the stems

The juvenile periods of various pine species have been approximated using the criteria presented in 2.3.1. It is apparent that juvenile period depends on species and the actual definition adopted for its estimation (Bendtsen 1978). Comparison of juvenile periods of different tree species must therefore take those factors into consideration. The juvenile period in _Pinus patula_ has been reported by other workers as being 4-6 years and 6-8 years in Uganda and Malawi respectively (Plumptre 1978, Adlard _et al_. 1979). In Uganda, the juvenile period consisted of rings near the pith with basic density of up to 350 kg/m^3. In the Malawian material, the radial basic density curve was used. Pines grown in United States have been reported to have juvenile periods ranging between 5-11 years (Zobel 1978). The mean basic density of juvenile wood in the American pines is generally 10 per cent lower than mean tree value. The juvenile period of 8 rings from pith used in this investigation is not necessarily different from that reported before for *Pinus patula* as the value of juvenile wood basic density of 397 kg/m^3 used in this study was higher. Based on the curves in figure 5.1, the juvenile period lasts to approximately 8 rings from pith, i.e. exactly the same period obtained by arbitrarily selecting the 10 per cent below mean ring density value at 1.3 m. The mean ring width at the 8th ring is 10.6 mm. Taking the ring width criterion, it can therefore be said that consecutive rings near the pith with 10.6 mm width or more constitute the juvenile core.

The proportion of juvenile wood in *Pinus patula* has been reported only in one study from Uganda (Plumptre 1978). For any meaningful comparison of results from juvenile wood proportion studies, it is pertinent to consider the definitions of juvenile wood and the age of the trees as specified in 2.3.2. Direct comparison of the results found in this investigation and those from Uganda is therefore not possible, as the criteria of juvenile wood demarkation are different. It may be noted, however, that at age of 8 years, the stems of *Pinus patula* grown at Sao Hill are composed of juvenile wood only. The proportion of juvenile wood in 25 year old *Pinus taeda* from U.S.A. was 55 per cent when juvenile period is assumed to extend to the 10th annual ring (Zobel *et al*. 1972).

5.1.3.2 Variation between trees

Juvenile and mature wood basic density variation has been reported for Ugandan grown *Pinus patula* in which variation between trees for the two wood zones was consistently large in 4 different sites (Plumptre 1978). The actual values are not included in the report. In 40 year old *Pinus patula* grown in Mexico the difference between the lightest and heaviest juvenile wood and mature wood was 11 per cent and 8 per cent respectively. The juvenile wood was defined as the wood in the first 10 rings near the pith (Zobel 1965). The results in this investigation may not be directly comparable to those earlier reports, but tend to suggest that there will always be a significant difference between trees no matter how wide the juvenile wood zone is. This is clearly demonstrated by the variation at the same rings shown in table 4.3. Juvenile wood and mature wood basic densities are reported to be significantly different between trees in Pinus radiata grown in New Zealand, Pinus palustris and Pinus virginiana grown in U.S.A. (Zobel et al. 1972, Kibblewhite 1980). The difference between the lightest and the heaviest values in the New Zealand report are 20 per cent for juvenile wood and 35 per cent for mature wood.

The coefficients of variation for juvenile and mature wood basic densities are lower than those for whole trees, pointing to the fact that each wood zone should be treated as a separate population (Elliott 1970). Causes for the variation are as presented for whole trees in 5.1.1.1.

5.1.3.3 Variation within trees

Decrease in wood density with height in the stem was less pronounced for juvenile wood than in mature wood and whole disk wood over the investigated height range. Figure 5.2 shows the basic density variation with height in the stem for juvenile and mature wood as well as for whole disk wood.

Figure 5.1 Ring width, latewood per cent, whole ring, and earlywood and latewood basic density variation with ring number from pith at 1.3 m.

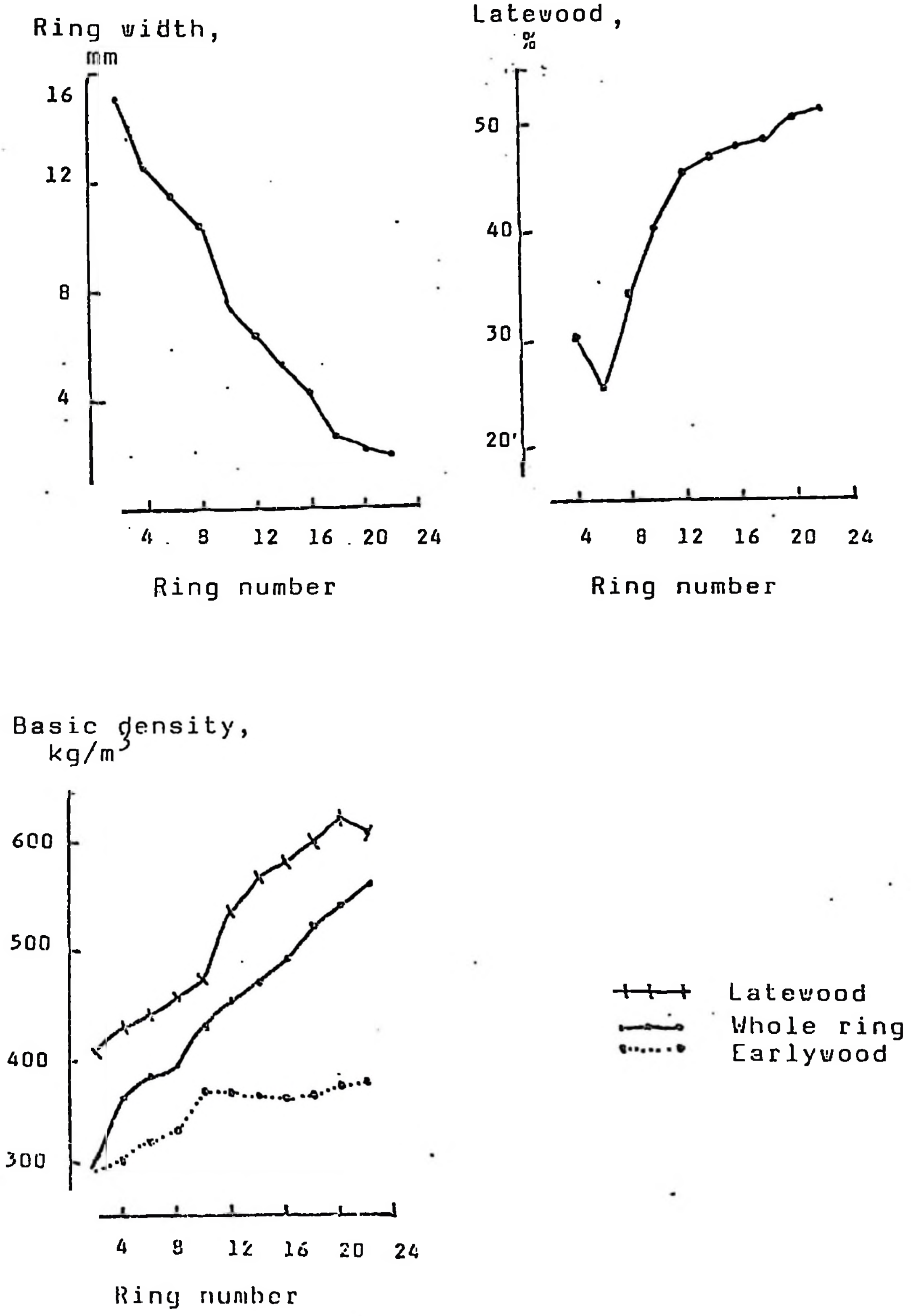
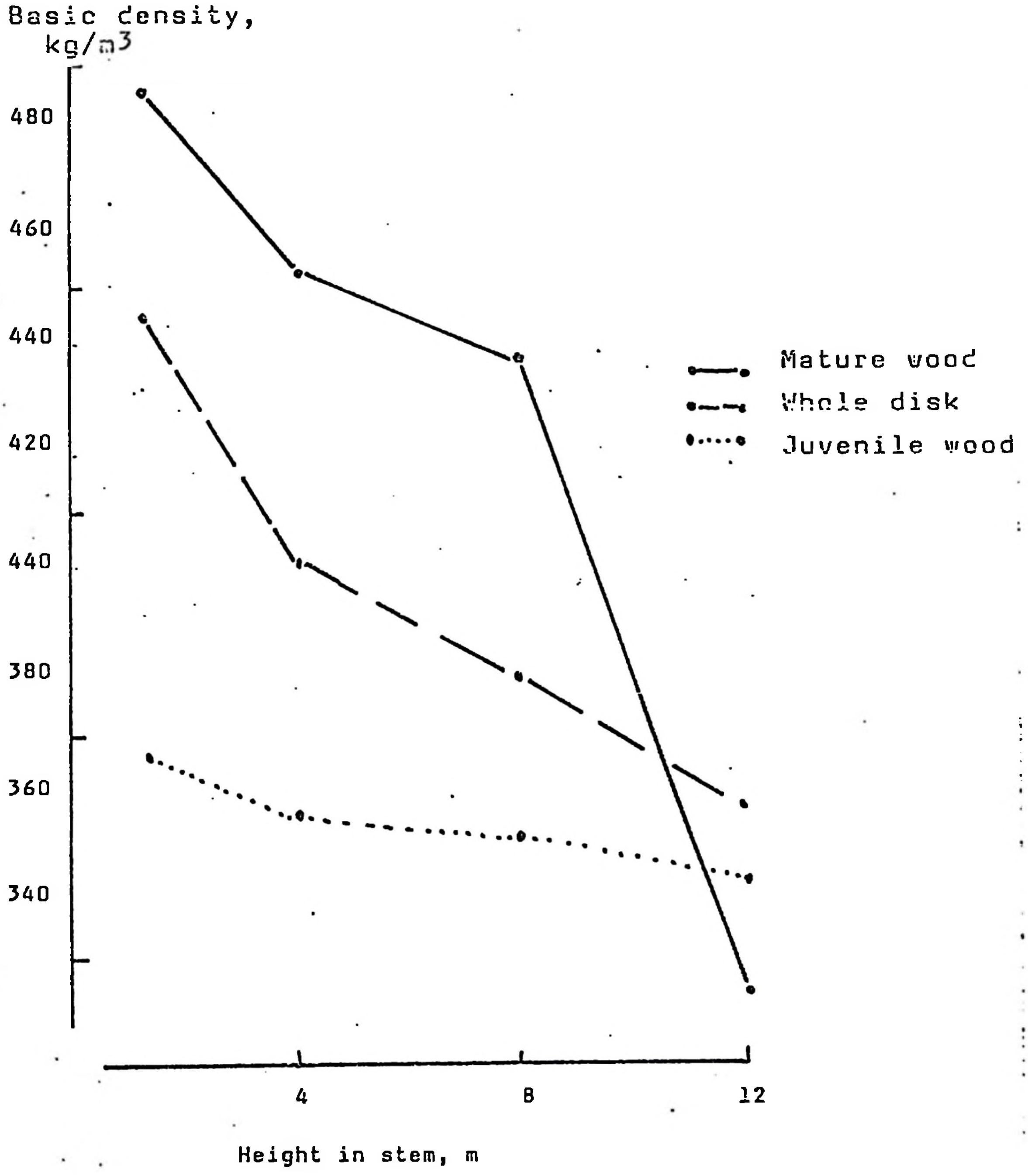


Figure 5.2 Whole disk, juvenile and mature wood basic density variation with height in the stems.



The decrease in basic density of juvenile wood is less pronounced because of the fact that at each height in the stem juvenile wood is composed of the same number of rings unlike mature wood and whole disk wood as shown in table 5.1. A similar phenomenon is reported in Pinus elliottii, Pinus palustris and Pinus virginiana wood (Zobel et al. 1972).

5.1.4 Relationship between juvenile wood and mature wood

The relationship between juvenile wood basic density and mature wood basic density is dependent on species and the actual definition of juvenile wood used. Tree age will also influence the correlation (Zobel et al. 1972). A study of the correlation between the densities of juvenile and mature wood in Pinus patula showed that whole tree basic density in 20 year old trees could reliably be predicted from breast height increment core basic density of juvenile wood (Plumptre 1978). Juvenile wood in that study consisted of the first 4 rings from the pith. Trees with high density juvenile wood would always have high density mature wood. The results observed in this investigation confirm the Ugandan findings. The correlation between the densities of the two woods in the stems may be controlled by genetical and environmental factors (Bendtsen 1978).

5.2 Tracheid length

5.2.1 Variation between trees

5.2.1.1. Overall variation

The mean tracheid length of 3.08 mm obtained in this investigation lie within the range of 2-5 mm reported by other authors for Pinus patula, see table 2.7. This value is about 13 per cent lower than the means reported for other pine species from temperate regions. The difference between the mean tracheid length in this investigation and that of temperate pines may be attributed to high proportion of juvenile wood in the materials used in this study.

The significant difference between trees observed in this study confirm earlier work by other authors (Zobel 1965, Kubelka 1969, Paterson 1969). Such large variation has also been reported for plantation grown Pinus radiata, Pinus contorta and Pinus nigra (Cown and McConchie 1980, Tsoumis and Panagiotidis 1980, Taylor *et al*. 1982). The non-significant negative relationship between tracheid length and dbh shown in 4.3.1 has been reported before for this species (Paterson 1969). Similar results have been found in most pine species (Taylor and Burton 1982).

The factors controlling the between tree tracheid length variation may be similar to those controlling between tree basic density variation (Larson 1969).

5.2.1.2 Variation at different heights and at different rings

Large variations have been found in tracheid length values between trees when sampled at 1.3 m height (Paterson 1969). Variation at the same heights have been reported to be large for Pinus contorta grown in Canada. In that species, tracheid length showed greater variation between trees at the same heights in the stem. The variation was greater higher up in the stems than at 1.3 m (Taylor *et at*. 1982).

The results in table 4.2 concur with the findings in Pinus contorta that at all sampling points along the stem axis, tracheid length varied significantly between trees. Although the sampling points were confined to the lower 12 metres of the stems, the results obtained in this study further indicate that variation is greater between heights higher up in the stems. The coefficient of variation was 8.3 per cent at 1.3 m compared to 11.5 per cent at 8 and 12 m. It is not possible to explain this variation using the results from this investigation.

The relationship between tracheid length and growth rate has been studied before for South African grown Pinus patula (Turnbull 1947). It was concluded that in a given ring number growth rate has a less pronounced effect on tracheid length. In this investigation tracheid length was not significantly influencd by ring width as shown in table 4.24. Unlike results from previous reports, increase in growth rate resulted in a non-significant increase in tracheid length at ring number 4, 8, 12 and 20. Variations at the same rings tended to be greater between the rings near the pith as shown in table 4.23. These results tend to confirm those found for Pinus patula grown in Mexico (Zobel 1965).

The relationship between tracheid length and basic density in Pinus patula has not been investigated before. The results in table 4.25 imply that tracheid length and ring basic density are not significantly correlated. These findings tend to concur with the hypothesis that tracheid length and cellwall thickness which is the main factor influencing wood density are under different physiological control mechanisms (Larson 1969). Tracheid length is a function of the number of fusiform generations which depends on the rate of anticlinal and periclinal divisions in the cambium (Bannan 1964, 1965a).

5.2.2 Variation within trees

5.2.2.1 Variation in axial direction

The relationship between tracheid length and height in the stem has not been reported before for *Pinus patula*. In this investigation tracheid length decreases with height in the stem as shown in table 4.22 from a mean of 3.29 mm at 1.3 m to a mean of 2.71 mm at 12 metre height. These results do not agree with those established by most workers for other pines, but concur with the trend reported for a 26 year old *Pinus radiata* tree from Australia (Nicholls and Dadswell 1962). In the latter study tracheid length decreased from 4.4 mm at 1.3 m to 2.0 mm at stem top. The results in this investigation need to be treated with caution, because they have been obtained from only a few sample points in the stem. There is need to investigate this relationship by making more itensive stem sampling before any firm conclusions can be made.

5.2.2.2 Variation in radial direction

The pattern of tracheid length variation over successive rings from pith to bark in *Pinus patula* has been reported earlier (Turnbull 1947, Zobel 1965, Paterson 1969, White *et al*. 1978). Tracheid length increases with increasing ring number from pith. The results observed in this study, see figures 4.10 to 4.18, concur with the findings that tracheid length increases from pith outwards. The pattern of radial tracheid length variation in pines has been described in terms of distance from pith, ring number or age and ring width (Bisset and Dadswell 1950b, Anderson 1951, Bannan 1964, 1965b, Harris 1965, Taylor and Burton 1982). The results shown in figures 4.10 to 4.18 and tables 4.28 to 4.38 for the Sao Hill material are in agreement with the ealier findings for this species. The relationship was much stronger between tracheid length and ring number than with distance from pith and ring width, see tables 4.31 and 4.32. Increase in average tracheid length from pith to bark can be explained by the increase in earlywood and latewood tracheid length from pith to bark which again reflects the increase in length of fusiform initials from pith outwards (Bannan 1965a). This general increase in cell length is related to age or number of generations of the cambium (Bannan 1964). The rate of division of the cambium is a reflection of the growth conditions of the trees (Richardson 1964). The amount of elongation of fusiform initials between successive periclinal divisions is less during production of a narrow than a wide ring and the cummulative cell elongation through several narrow rings exceeds that through single wide ring having the same total width (Bannan 1965b). According to the same authour the time factor is very important in cambial cell elongation especially when growth rate declines. Increased periclinal divisions that lead to wide growth increments result in shorter tracheids. A regression equation of tracheid length on ring width from pith to bark at different sampling points in the stem, has been reported before for other pines (Elliott 1960, Cown and McConchie 1980, Taylor and Burton 1982). The results from this investigation agree with those findings that increased growth ring width has a tendency to reduce the tracheid length.

For the crop at Sao Hill, fluctuations in growth rate, i.e. fluctuations in rate of periclinal and anticlinal divisions, may have been caused by fluctuations in moisture availability and soil nutrient status (Fry and Chalk 1957). Temperature is less important as it rarely falls below 10 °C. It is not possible to assess the contribution of silvicultural operations performed on the crop as all factors tend to operate simultaneously and isolation of individual factors is not possible in this study. It is apparently clear that increased growth rate within 3-5 mm ring width range causes considerable reductions in tracheid length, see figure 4.12. An increase of ring width from 3.5 mm to 5 mm gives a tracheid length drop from 3.96 mm to 3.46 mm. This ring width range is normal for the first 15-50 rings from the pith. These observations concur with earlier reports for Picea sitchensis (Elliott 1960).

5.2.3 Juvenile and mature wood

5.2.3.1 Variation between trees

Tracheid length of juvenile wood and mature wood in any species and its variations between and within trees depends on the actual definitions used for the two woods as explained in 2.3.1, 2.6.1 and 5.1.3.1. A definition that incorporates a large number of rings around the pith will give a higher mean juvenile tracheid length value than one that limits the juvenile core to a fewer rings. The mean tracheid length of juvenile wood and mature wood in Pinus patula can be deduced from results of radial tracheid length investigations.

In the mature stems the 10 rings near the pith may constitute the juvenile core. The mean tracheid length of juvenile wood in 10 year old Pinus patula grown in Kenya, see table 2.7, were 2.36 mm and 2.83

mm (Palmer _et al_. 1982). The mean tracheid length was 3.1 mm for the first 10 rings in Mexican grown _Pinus patula_ (Zobel 1965). Although not directly comparable to those results, the mean tracheid length of 2.61 mm obtained for juvenile wood in this study falls within the expected range.

The mean tracheid length in mature wood obtained for _Pinus patula_ in this study, though not directly comparable to the results from Mexico, tends to suggest that mature wood tracheid length in Mexico is about 20 per cent longer than at Sao Hill.

Between tree variation in juvenile and mature wood tracheid length has been reported to be large in _Pinus patula_ (Fry and Chalk 1957, Kubelka 1969). The results in this investigation tend to confirm this earlier observation. The coefficients of variation of 10.9 per cent and 7 per cent for juvenile wood and mature wood respectively, see tables 4.42 and 4.44, indicate that between tree variation is much greater for juvenile wood than for mature wood. The large variation between trees has been attributed to genetical differences and environmental factors (Paterson 1969).

5.2.3.2 Variation within trees

Juvenile wood and mature wood tracheid length variation with height in the stems of _Pinus patula_ have not been documented before. The results from this study show that tracheid length in juvenile and mature wood do not vary significantly with height in the stem. These observations tend to confirm earlier findings in other pines that there is less pronounced change in tracheid length in juvenile wood than in mature wood with increasing height in the stem

(Richardson 1964, Cown and McConchie 1980). The trend in the juvenile wood may be a result of investigating rings with the same growth ring composition at each height in the stem, in which the tracheids are derived from fusiform initials of about the same age (Bannan 1965a). There do not seem to be an obvious explanation for the trend within the mature wood zone. It is necessary to study this aspect of variation further.

The increase in tracheid length from pith outwards within the juvenile core established for _Pinus patula_ in this study concur with those reported earlier for this species (Zobel 1965, Kubelka 1969, Paterson 1969, White _et al_. 1980). These results are also in agreement with the general pattern established for most pine species (Bisset and Dadswell 1950b, Spurr and Hyvarinen 1954, Nicholls and Dadswell 1962, Bannan 1965b, Kibblewhite 1980).

It is apparent that the pattern of tracheid length within the juvenile core is a function of age (Bannan 1954). This hypothesis has been verified in this study, see equations in tables 4.25 and 4.30.

Within the mature wood zone, tracheid length increased from the inner ring outwards to the bark. This finding illustrates the fact that at 27 years, the fusiform initials in _Pinus patula_ are still increasing in length and that culmination of tracheid length had not been attained. These results tend to agree with those found in Mexican grown _Pinus patula_, where tracheid length culminated after the 30th ring from pith (Zobel 1965).

5.2.4 Relationship between juvenile wood and mature wood

Correlation between juvenile wood and mature wood tracheid length in Pinus patula has not been reported before and very scanty information exists on other pines. The results in this study tend to confirm observations in Pinus radiata grown in Australia, in which a strong relationship was established between juvenile wood tracheid length and mature wood tracheid length (Bisset and Dadswell 1950b). Similar findings can be deduced in the same species from New Zealand (Cown and McConchie 1980). It has been found that uniformity in the stem and hence the relationship between juvenile wood and mature wood tracheid length is genetically controlled (Zobel 1981). It is not possible to ascertain the extent of genetic influence on the results obtained for Pinus patula in this study.

6 PRACTICAL SIGNIFICANCE OF THE RESULTS

6.1 Effect of growth rate on wood density and tracheid length

The results from this study indicate that wood density and tracheid length vary with radial growth rate of the trees. Two factors are important:

- The 8-10 first growth rings from the pith, the juvenile wood, will always have lower basic density and shorter tracheids than the mature wood further out in the stem.
- Both juvenile wood and mature wood show decrease in basic density and tracheid length with increase in growth rate.

The practical significance of this is that the quality of the wood produced in plantations to a certain extent can be influenced by management practices:

- Fast growth will give large volumes of low density, short tracheid wood.
- Slow growth will give smaller volumes, but these will have higher density and longer tracheids.
- Short rotations will give trees which contain mainly light juvenile wood, independent of growth rate.
- Longer rotations will give trees with larger proportions of the heavier, mature wood.

With the different end-uses in mind, the following arguments must be considered:

- Wood with high strength is found in slow growing trees because the core of light juvenile wood will be small and the narrow ringed mature wood outside the juvenile core will have high basic density.

- Wood which will give high pulp yield per m^3 is also found in slow growing trees since the core of light juvenile wood will be small and the mature wood will be heavy. Maximum dry matter production, however, and thereby maximum pulp yield in a stand per ha and per year may still be obtained under fast growth if the extra volume produced compensates for the lower basic density.

6.2 Rotation age

The results obtained in this study are important in selecting stand rotation age:

- In the 27 year old trees, wood density and tracheid length increase almost linearly from pith to bark.
- The juvenile period extends to ring number 8 and it constitutes about half of the wood in the lower 12 m of the tree, and more in the upper part.
- The earlywood basic density to latewood basic density ratio increases with tree age.

These results have the following practical implications:

- High quality logs will be obtained from long rotations due to the high proportion of denser mature wood.
- Wood from short rotations will have poorer mechanical and physical properties due to the high proportion of juvenile wood.
- Wood from long rotations may be less uniform as the difference between earlywood and latewood basic densities increase with ring number from pith.
- Short rotations will give wood with shorter

tracheid lengths than that from mature wood.

Since rotation age will depend on the final product the following arguments are relevant:

- Where the wood raw material is to be used to produce sawnwood for structural purposes its mechanical and physical properties will be better if the wood is from mature wood, from older stands and therefore long rotations.
- For the pulp and paper industry, tracheid length which influences paper quality and wood basic density which influences pulp yield are important. Wood with high mean tracheid length and basic density will be obtained from older trees.
- In comparison with that of short rotations, wood from long rotations will have a higher ratio between earlywood and latewood basic densities and thereby large difference between their cell wall thicknesses. Since cell wall thickness affects paper properties it is important that the effect of increased latewood cell wall thickness is considered.

Figures 6.1 and 6.2 show dry matter production at Sao Hill under the current silvicultural practices in site class 30. The following formulae were used:

Dry matter quantity = Green volume x basic density

Total dry matter = Dry matter in stand + Dry matter of last thinnings

Actual dry matter in stand = Current stand volume x mean volume weighted basic density

Current annual increment = Total stand dry matter in year A + 1 - Total stand dry matter in year A

Mean annual increment = $\frac{\text{Total dry matter}}{\text{Actual stand age}}$

The volume values are based on Mlowe and Macha (1980).

The effect of extended rotation age on wood properties is favourable but the decision on exact rotation age will be dictated by the economics of the time extension.

6.3 Wood for energy production

The wood from the plantations can be used in the wood industries at Sao Hill to generate heat for a number of operations:

- Power for sawmill machinery and kiln drying of sawn wood.
- Steam generation for the digester in pulping and evaporation of the black liqueur.
- Village requirements.

The types of woodfuel will be:

- Branches and stem tops.
- Slabs from the sawmill.
- Sawdust, edgings and off-cuts from the sawmill.

Figure 6.1 Dry wood production in site class 30.
Total production and actual weight in stand.

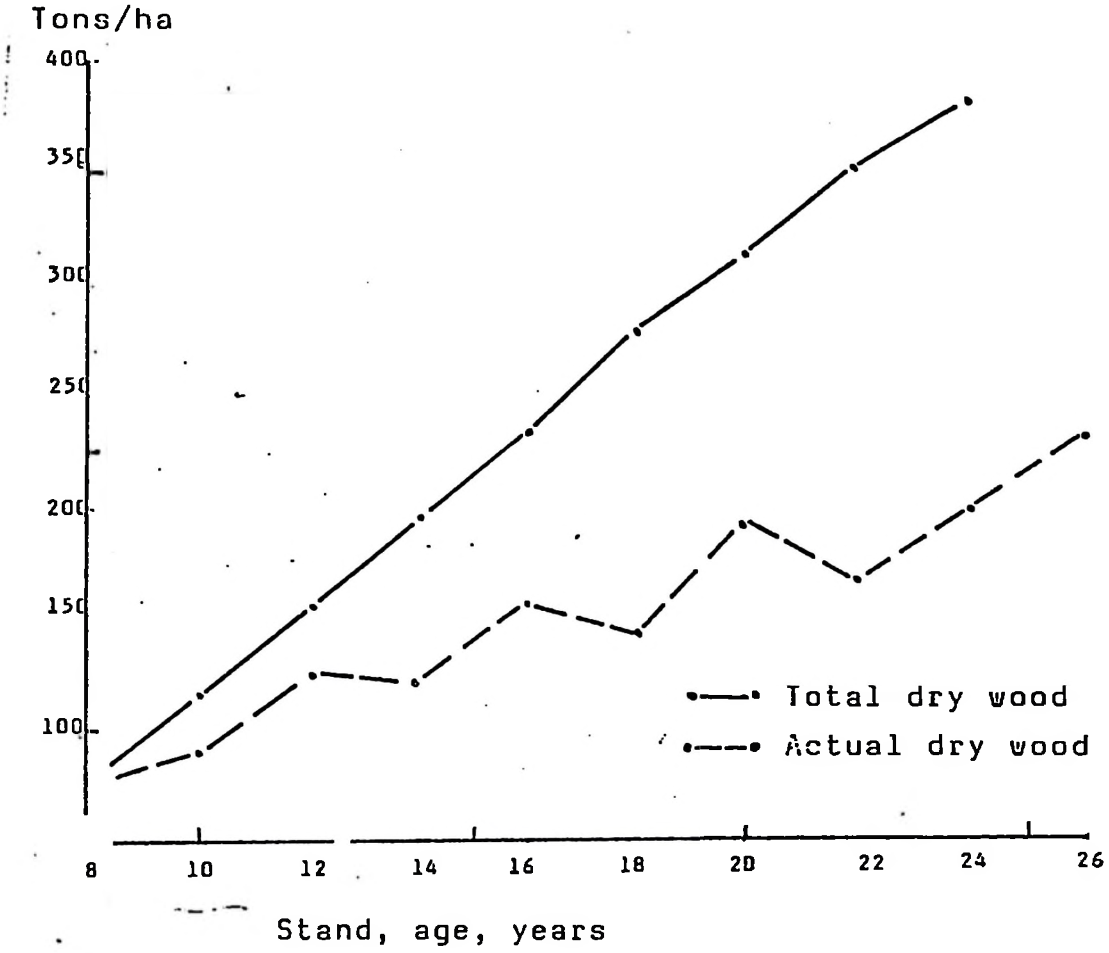
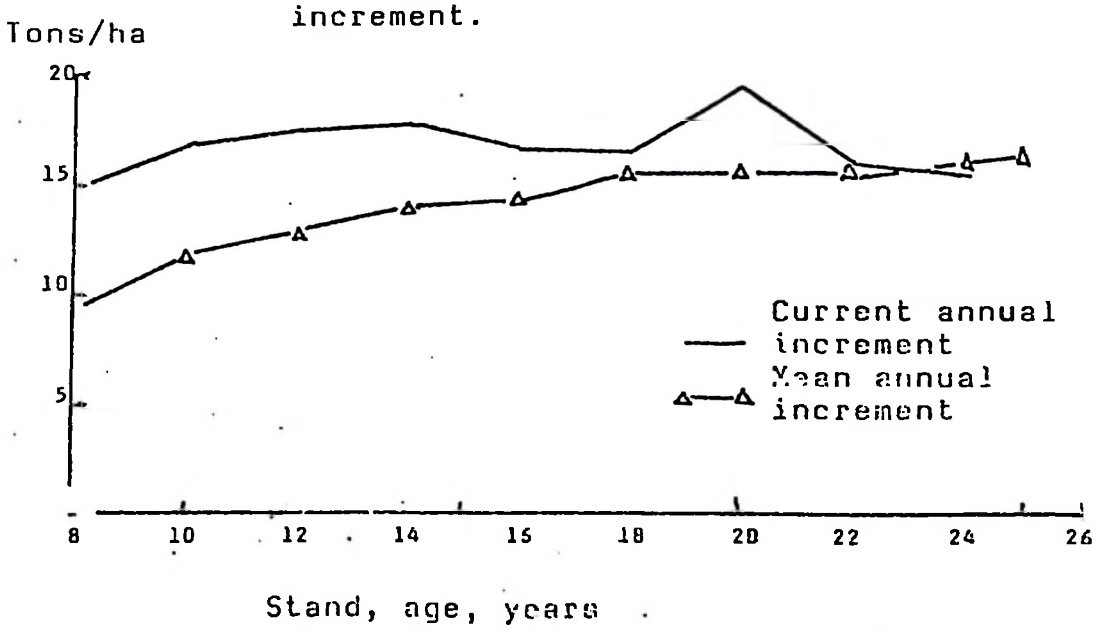


Figure 6.2 Dry wood production in site class 30.
Current annual increment and mean annual increment.



The results on wood density variations found in this investigation are pertinent in the utilization of the wood for energy production. The amount of heat that can be obtained from wood depends on the wood density and moisture content. The most important consideration to be made is:

- The wood near the pith will provide less heat compared to the high density wood in the slabs of mature wood. The results in this investigation show that juvenile wood basic density is 361 kg/m^3 compared to 464 kg/m^3 for mature wood. Assuming a combustion value of 20,000 kJ/kg dry wood (Tillman *et al*. 1981), one m^3 juvenile wood will give 7.22MJ compared to 9.28MJ available from one m^3 mature wood.

6.4 Wood raw material allocation

The results obtained in this study are relevant in the allocation of wood raw material to the various processing mills. In allocating wood, the following factors should be considered:

- Size and shape of the raw materials.
- Wood density and thereby its strength properties.
- Wood tracheid length and thereby its suitability for paper making.
- Overall economics of the entire Sao Hill wood industries complex.

Table 6.1 shows an ideal wood raw material allocation system, based on wood properties, to the two main forest industries at Sao Hill. The wood raw material is divided into different categories on the basis of age and type.

A most important consequence of this discussion is that sawmill waste in the form of slabs, since these are made up of mainly mature wood, should be utilized in a pulp mill. The slabs constitute a raw material which may give nearly 30 per cent higher yield and 50 per cent or more longer tracheids than regular stem wood from young pulpwood trees.

Table 6.1 Wood raw material allocation to various mills

Type of material	Tree age, years	Sawmill	Pulp and paper mill
Stem wood	10	-	x
	14	-	x
	18	x	x
	22	x	x
	25+	x	-
Toplogs	10	-	x
	14	-	x
	18	-	x
	22	-	x
	25+	-	x
Sawmill waste	slabs		x
	sawdust		(x)
	off-cuts		x
	planer shavings		x

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Appendix 1. Tree dbh, volume weighted basic density and tracheid length.

Tree No.	Vol.wt. B.D., kg/m^3	Vol.wt. TL., mm	Dbh., cm
1	370	3.01	39.9
2	422	3.12	34.8
3	367	2.98	35.0
4	398	3.21	43.3
5	422	2.99	35.8
6	407	3.15	33.1
7	376	4.42	41.5
8	406	2.53	30.6
9	426	3.31	29.0
10	433	3.41	31.7
11	413	2.90	35.2
12	435	3.07	32.8
13	383	2.91	44.0
14	464	3.39	37.1
15	452	2.78	32.5

Appendix 2. Basic density in kg/m^3 at 4 heights in the stem.

Tree No.	Height in the stem, m			
	1.3	4	8	12
1	422	381	341	328
2	471	424	411	365
3	406	377	332	311
4	433	402	386	353
5	466	433	401	375
6	450	424	381	369
7	417	392	344	330
8	452	411	385	374
9	470	434	402	386
10	475	432	413	374
11	459	415	386	401
12	478	428	437	395
13	426	369	378	386
14	489	459	413	402
15	504	460	434	388

Appendix 3. Ring basic densities in kg/m^3 for 4 cardinal directions at 4 heights in 3 trees.

			Ring number										
		Tree	2	4	6	8	10	12	14	16	18	20	22
1.3 m	WEST	1	321	363	391	415	435	446	456	454	554	524	584
		2	334	368	402	430	452	472	518	556	552	542	543
		3	287	381	378	382	416	432	465	466	483	463	479
	EAST	1	334	373	368	384	415	436	442	463	514	541	561
		2	325	390	429	459	449	488	532	478	487	555	496
		3	320	390	386	410	445	442	458	499	461	530	492
	NORTH	1	328	370	370	408	407	434	461	471	509	526	546
		2	336	381	412	423	435	511	498	496	526	549	524
		3	333	393	377	401	420	452	474	437	446	469	531
	SOUTH	1	340	362	381	396	420	435	449	471	502	543	507
		2	331	372	391	400	431	446	451	470	493	552	508
		3	290	388	372	394	418	462	457	462	477	483	540
4 m	WEST	1	320	344	402	376	419	455	424	473	467	472	
		2	343	361	350	387	433	443	430	417	531	491	
		3	335	341	342	365	360	445	454	469	437	476	
	EAST	1	327	384	359	384	421	463	457	467	460	487	
		2	351	366	334	386	421	435	410	421	512	527	
		3	352	355	335	381	391	432	437	413	433	455	
	NORTH	1	328	366	366	396	402	439	449	446	460	484	
		2	342	370	364	398	402	455	430	425	487	482	
		3	318	338	324	363	417	427	402	420	436	422	
	SOUTH	1	324	340	340	381	439	467	463	455	461	462	
		2	353	379	385	406	427	447	431	453	471	477	
		3	327	326	350	387	441	457	403	433	443	466	

Appendix 2. Basic density in kg/m^3 at 4 heights in the stem.

Tree No.	Height in the stem, m			
	1.3	4	8	12
1	422	381	341	328
2	471	424	411	365
3	406	377	332	311
4	433	402	386	353
5	466	433	401	375
6	450	424	381	369
7	417	392	344	330
8	452	411	385	374
9	470	434	402	386
10	475	432	413	374
11	459	415	386	401
12	478	428	437	395
13	426	369	378	386
14	489	459	413	402
15	504	460	434	388

Appendix 3. Ring basic densities in kg/m^3 for 4 cardinal directions at 4 heights in 3 trees.

			Ring number										
		Tree	2	4	6	8	10	12	14	16	18	20	22
		1	321	363	391	415	435	446	456	454	554	524	584
	WEST	2	334	368	402	430	452	472	518	556	552	542	543
		3	287	381	378	382	416	432	465	466	483	463	479
		1	334	373	368	384	415	436	442	463	514	541	561
	EAST	2	325	390	429	459	449	488	532	478	487	555	496
1.3 m		3	320	390	386	410	445	442	458	499	461	530	492
		1	328	370	370	408	407	434	461	471	509	526	546
	NORTH	2	336	381	412	423	435	511	498	496	526	549	524
		3	333	393	377	401	420	452	474	437	446	469	531
		1	340	362	381	396	420	435	449	471	502	543	507
	SOUTH	2	331	372	391	400	431	446	451	470	493	552	508
		3	290	388	372	394	418	462	457	462	477	483	540
		1	320	344	402	376	419	455	424	473	467	472	
	WEST	2	343	361	350	387	433	443	430	417	531	491	
		3	335	341	342	365	360	445	454	469	437	476	
		1	327	384	359	384	421	463	457	467	460	487	
	EAST	2	351	366	334	386	421	435	410	421	512	527	
4 m		3	352	355	335	381	391	432	437	413	433	455	
		1	328	366	366	396	402	439	449	446	460	484	
	NORTH	2	342	370	364	398	402	455	430	425	487	482	
		3	318	338	324	363	417	427	402	420	436	422	
		1	324	340	340	381	439	467	463	455	461	462	
	SOUTH	2	353	379	385	406	427	447	431	453	471	477	
		3	327	326	350	387	441	457	403	433	443	466	

Appendix 3 continued

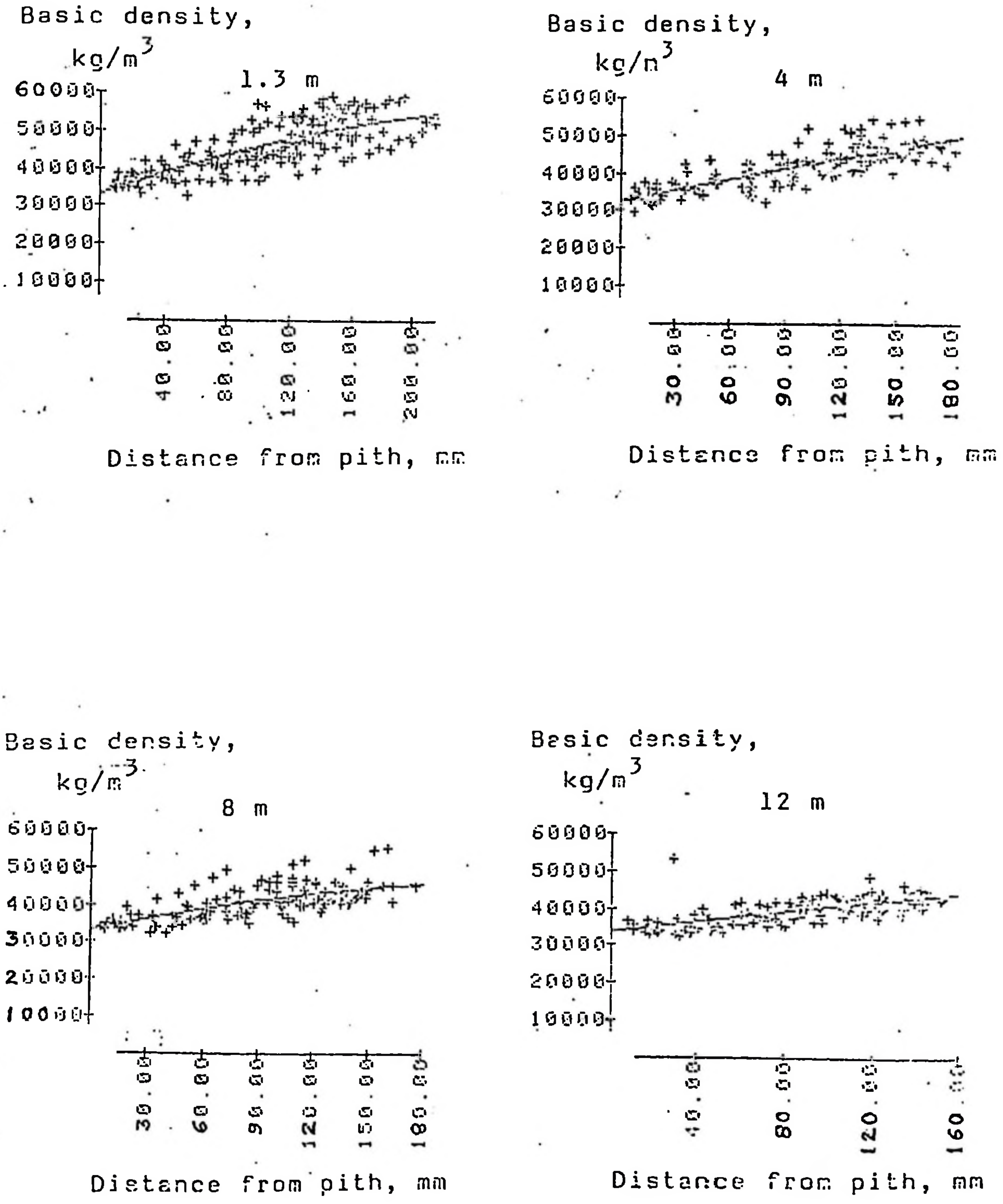
			2	4	6	8	10	12	14	16	18	20	22
		1	283	338	368	380	402	413	413	451			
	WEST	2	325	360	392	419	400	428	414	456			
		3	323	340	385	394	396	413	432	455			
8 m		1	322	328	369	402	415	428	422	446			
	EAST	2	330	361	363	391	418	423	438	445			
		3	305	335	371	380	393	408	444	450			
		1	300	311	377	407	423	420	437	450			
	NORTH	2	331	351	372	403	407	431	448	443			
		3	321	363	379	396	418	437	439	455			
		1	318	322	357	404	419	417	438	467			
	SOUTH	2	307	331	374	386	441	437	446	451			
		3	325	372	389	392	430	424	450	453			
		1	286	331	367	371	407	418	404				
	WEST	2	306	349	344	346	404	319	409				
		3	323	334	382	391	417	409	394				
12 m		1	298	330	356	376	407	398	406				
	EAST	2	309	343	356	400	402	403	408				
		3	341	361	378	409	401	403	404				
		1	302	332	363	397	395	409	391				
	NORTH	2	318	352	361	392	380	415	398				
		3	326	354	361	396	410	402	414				
		1	319	339	351	387	420	401	410				
	SOUTH	2	302	345	389	398	387	404	389				
		3	301	341	366	381	398	402	412				

Appendix 4. AOV tables for basic density variation with cardinal directions at 4 heights in the stem.

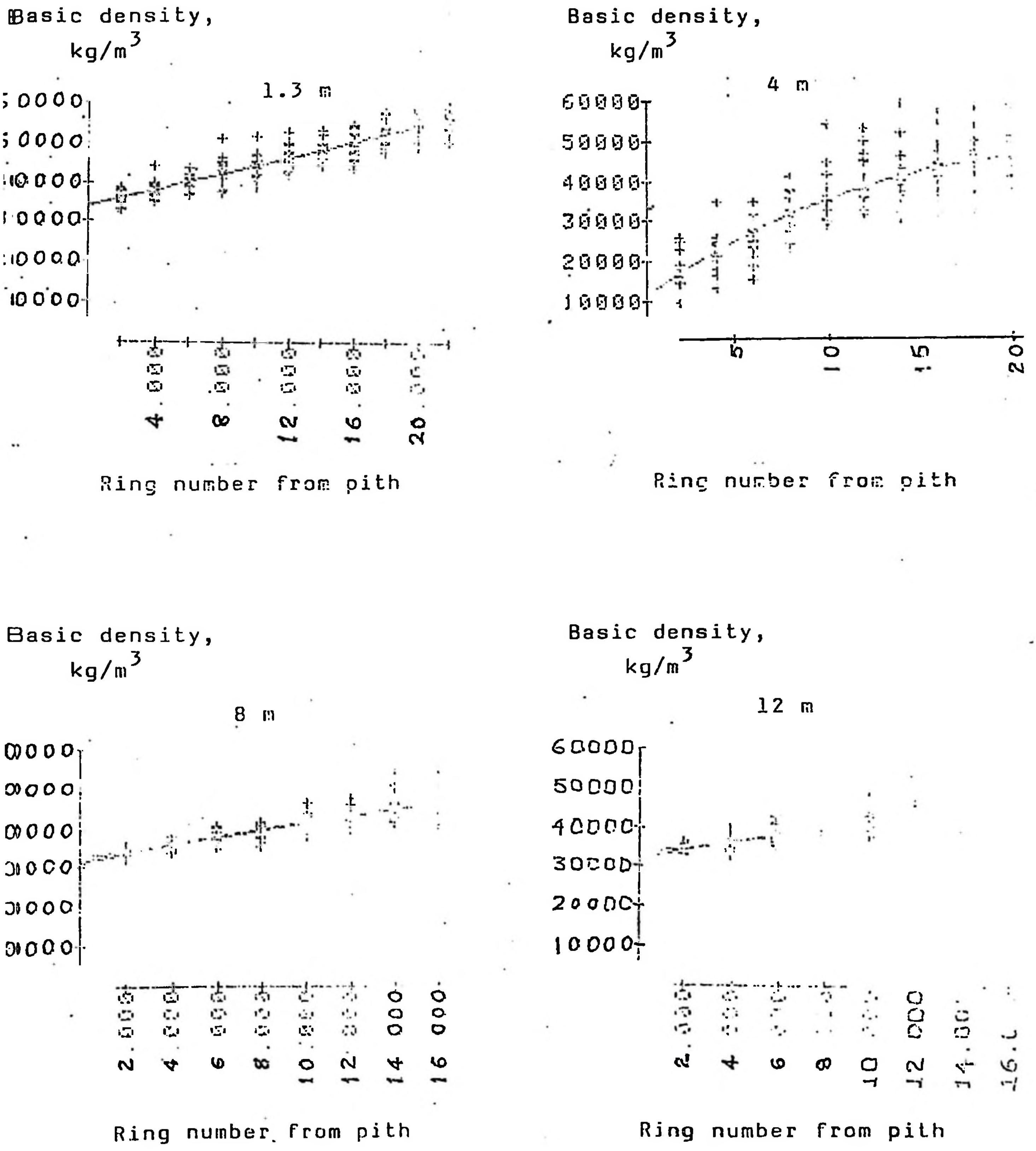
Height	Source of variation	d.f.	Sum of squares	Mean square	F
1.3	Between directions	3	0.0017155	0.0005985	0.12946
	Within directions	128	0.591755	0.004623	
	Total	131	0.593551		
4	Between directions	3	0.00334978	0.00111659	0.4157538
	Within directions	116	0.3115417022	0.0026857043	
	Total	119	0.314891478		
8	Between directions	3	0.00039 0136	0.0001323379	0.06315
	Within directions	92	0.192805158	0.0020957	
	Total	102	0.19320217		
12	Between directions	3	0.002335821	0.000778607	0.565983
	Within directions	73	0.1004240	0.001375672	
	Total	76	0.10275985		

Computations are based on g/cm^3

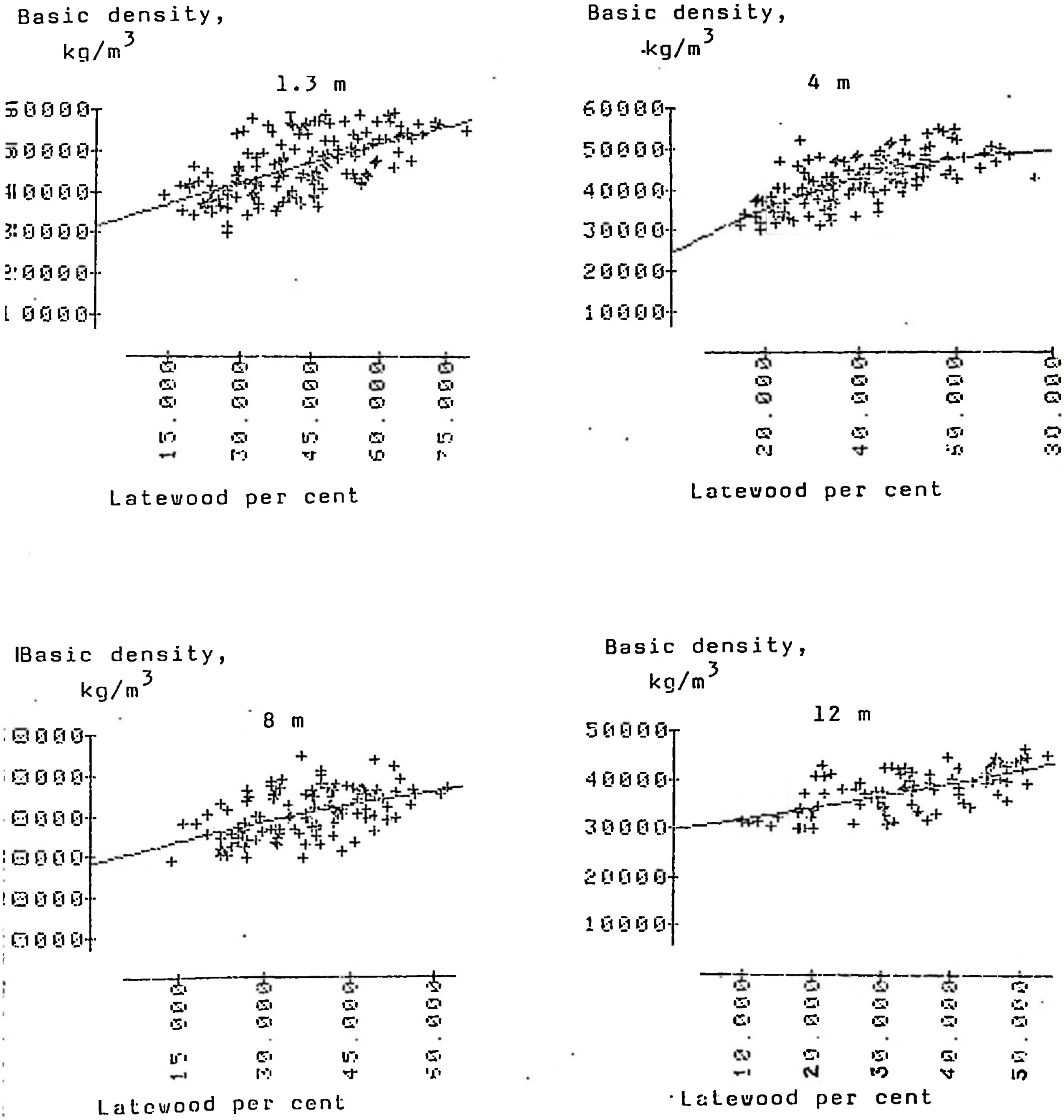
Appendix 5(a). Scatter diagrams and regression lines of ring basic density on distance from pith at 4 heights in the stem.



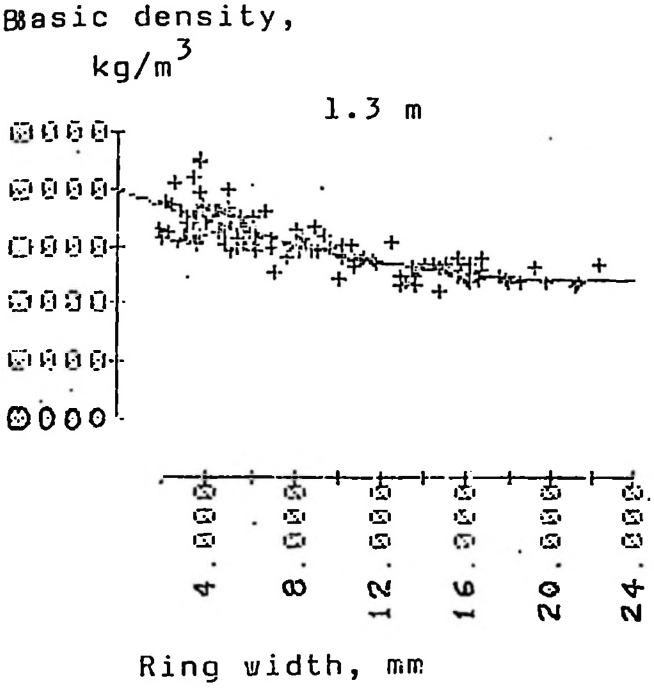
Appendix 5(b). Scatter diagrams and regression lines of ring basic density on ring number at 4 heights in the stem.

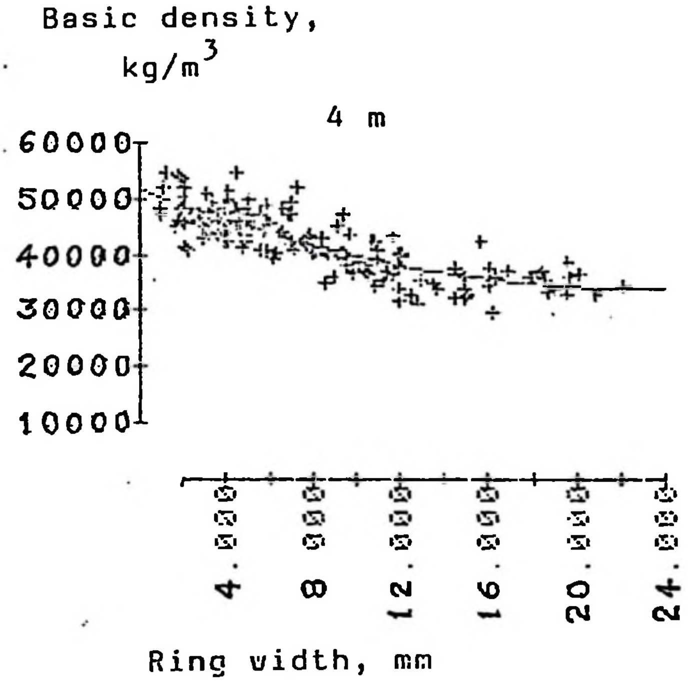


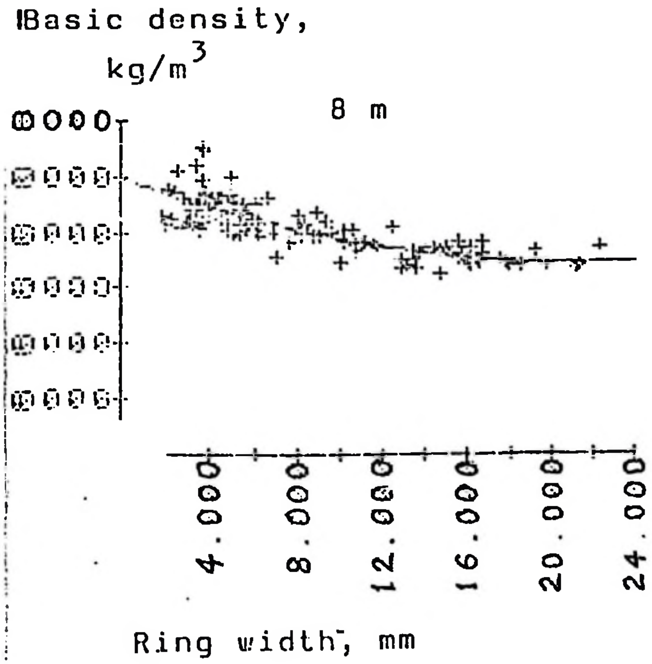
Appendix 5(c). Scatter diagrams and regression lines of ring basic density on latewood per cent at 4 heights in the stem.

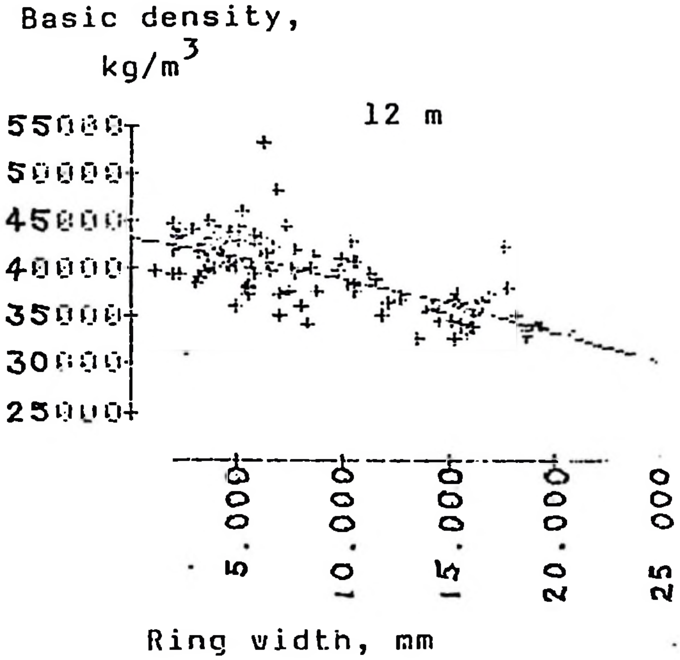


Appendix 5(d). Scatter diagrams and regression lines of ring basic density on ring width at 4 heights in the stem.





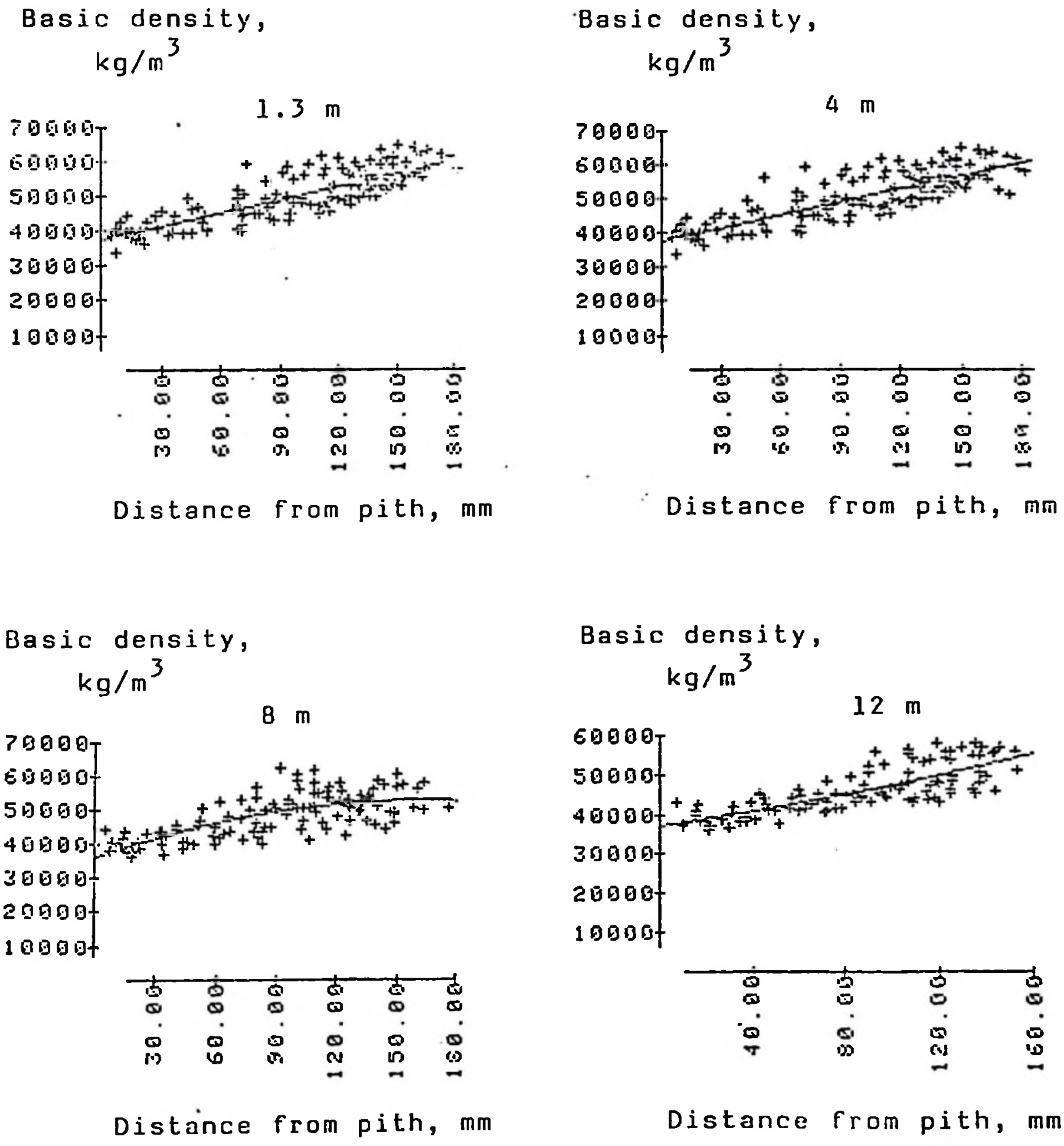




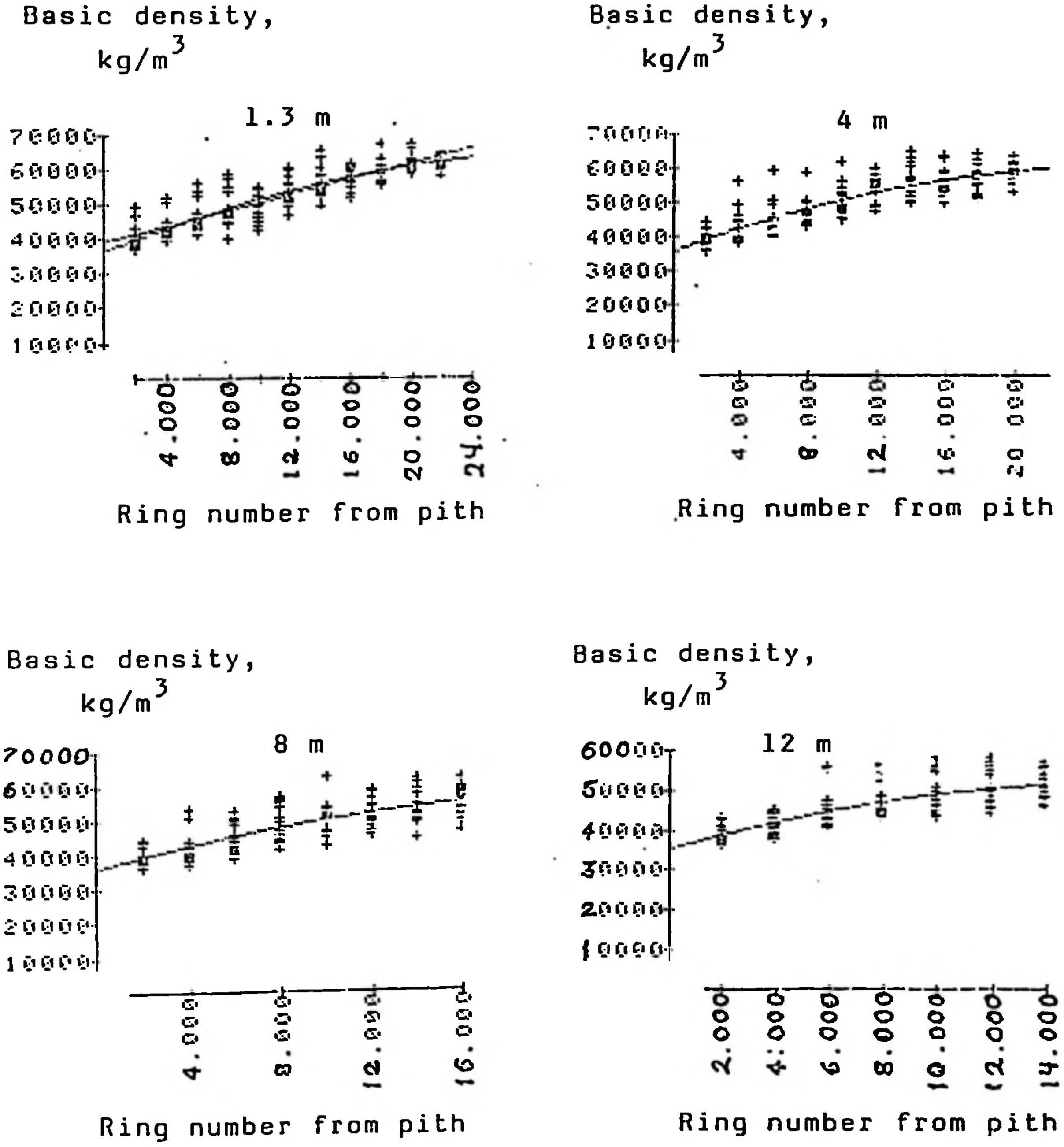
Appendix 6. Mean ring basic density in kg/m^3 at 4 heights in the stem.

Ring number	Height in stem, m 1.3	4	8	12
2	353	326	321	323
4	362	343	338	326
6	388	360	360	352
8	394	389	375	371
10	434	417	404	388
12	453	438	425	403
14	476	457	445	416
16	493	466	448	
18	525	479		
20	546	483		
22	562			

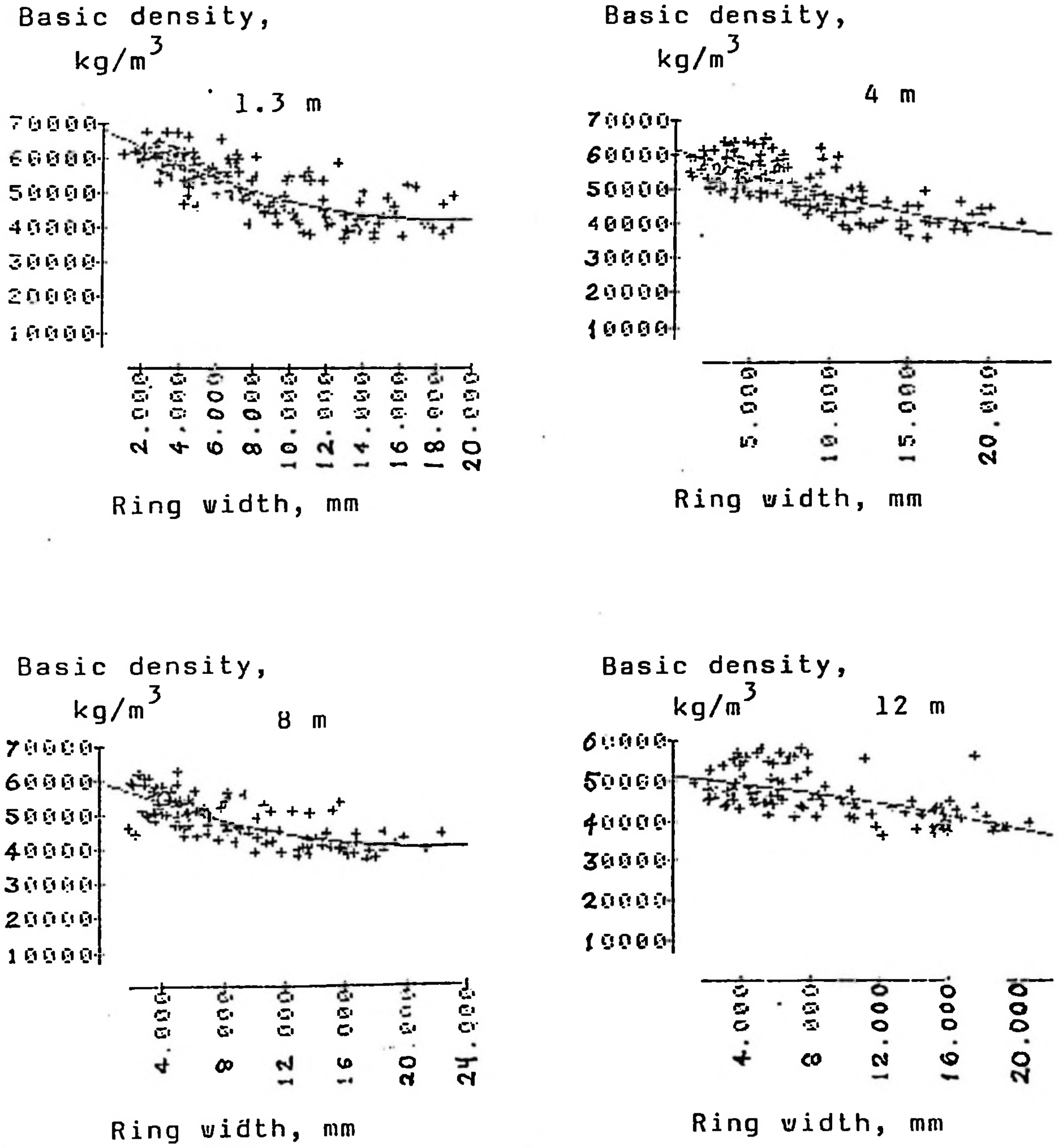
Appendix 7(a). Scatter diagrams and regression lines of latewood basic density on distance from pith at 4 heights in the stem.



Appendix 7(b). Scatter diagrams and regression lines of latewood basic density on ring number at 4 heights in the stem.



Appendix 7(c). Scatter diagrams and regression lines of latewood basic density on ring width at 4 heights in the stem.



Appendix 8. Juvenile wood proportion in the individual sample trees.

Tree No.	Juvenile wood proportion, %
1	69.3
2	52.1
3	82.2
4	47.1
5	50.8
6	51.6
7	56.2
8	42.1
9	53.1
10	79.3
11	52.0
12	43.2
13	55.9
14	34.9
15	38.6

Appendix 9. Volume weighted basic density and tracheid length for juvenile wood and mature wood.

Tree No.	Juvenile Wood		Mature Wood	
	BD, kg/m^3	TL, mm	BD, kg/m^3	TL, mm
1	340	2.71	440	3.33
2	375	2.67	484	3.26
3	325	2.62	439	3.27
4	344	2.63	456	3.58
5	366	2.48	477	3.34
6	372	2.42	462	3.52
7	358	3.28	455	3.93
8	350	2.03	466	2.94
9	373	2.92	475	3.44
10	376	2.89	482	3.77
11	370	2.33	468	3.36
12	375	2.69	459	3.18
13	350	2.43	450	3.53
14	352	2.65	486	3.48
15	383	2.35	500	3.13

BD - basic density

TL - tracheid length

Appendix 10(a). Juvenile wood basic density in kg/m^3 at 4 heights in the stem.

Tree No.	Height in the stem, m			
	1.3	4	8	12
1	356	345	341	328
2	391	375	379	356
3	338	335	333	311
4	336	359	342	323
5	389	366	373	343
6	365	377	381	352
7	361	384	344	330
8	387	340	341	348
9	394	373	370	355
10	397	380	371	374
11	378	368	367	374
12	391	362	380	375
13	344	350	339	385
14	398	381	371	383
15	412	380	381	371

Appendix 10(b). AOV table for juvenile wood basic density variation with height in the stem.

Source of variation	d.f.	Sum of squares	Mean sum of squares	F
Between heights	3	0.0037914	0.0012638	2.978^*
Within heights	56	0.0237626	0.0004243	
Total	59	0.027554		

Computation based on g/cm^3

Appendix 11. AOV tables for juvenile wood basic density radial variation at 4 heights in the stem.

Height, m	Source of variation	d.f.	Sum of squares	Mean sum of squares	F
	Between rings	3	0.196283	0.065427	8.3266**
1.3	Within rings	56	0.440029	0.007858	
	Total	59	0.2402859		
	Between rings	3	0.32933	0.10977	13.428**
4	Within rings	56	0.457921	0.008177	
	Total	59	0.78725		
	Between rings	3	0.252606	0.084202	8.094964**
8	Within rings	56	0.58250	0.00104	
	Total	59	0.835107		
	Between rings	3	0.230412	0.00768	9.9033**
12	Within rings	56	0.467995	0.0008357	
	Total	59	0.698408		

Computations based on g/cm^3

Appendix 12. AOV table for mature wood basic density variation with height in the stem.

Source of variation	d.f.	Sum of squares	Mean square	F
Between heights	3	0.031576	0.0105253	36.8336**
Within heights	56	0.0160022	0.00028575	
Total	59	0.0475724		

Computations based on g/cm^3

Appendix 13. AOV tables for mature wood basic density radial variation at 3 heights in the stem.

Height, m	Source of variation	d.f.	Sum of squares	Mean square	F
1.3	Between rings	6	0.2075468	0.034591	23.6411**
	Within rings	98	0.143391	0.001463	
	Total	104	0.350938		
4	Between rings	5	0.048599	0.0097198	8.1709**
	Within rings	84	0.099923	0.00118956	
	Total	89	0.148522		
8	Between rings	3	0.0188647	0.006288	4.1475*
	Within rings	56	0.084904	0.00151613	
	Total	59	0.10376853		

Computations based on g/cm^3

Appendix 14. Ring tracheid lengths in mm for 4 cardinal directions at 1.3 m heights in trees no. 1, 2 and 9.

Ring No.	North			South			East			West		
	1	2	9	1	2	9	1	2	9	1	2	9
2	2.16	2.65	2.19	2.19	2.40	2.19	3.45	2.27	2.19	2.19	2.31	2.27
4	2.35	2.86	2.30	2.37	2.79	2.37	2.34	2.43	2.79	2.35	2.59	2.55
6	2.67	2.95	2.63	2.33	3.10	2.45	2.47	2.45	3.31	2.43	2.76	3.00
8	3.08	2.98	2.77	3.06	3.35	2.67	2.99	2.53	3.56	2.59	2.26	3.26
10	3.27	3.26	3.12	3.3	3.69	3.00	3.25	2.46	3.90	3.20	3.64	3.50
12	3.61	3.42	3.15	3.57	4.01	3.20	3.54	2.65	4.00	3.27	3.79	3.61
14	3.76	3.31	3.39	3.73	3.97	3.48	3.64	2.65	4.23	3.46	3.94	3.63
16	3.85	3.65	3.50	3.83	3.99	3.63	4.00	3.87	4.30	3.38	3.91	3.59
18	3.94	3.62	3.50	3.90	4.02	3.61	4.19	3.84	4.35	3.78	3.98	3.50
20	4.05	3.85	3.66	3.94	4.07	3.67	4.13	3.80	4.37	3.84	3.95	3.56
22	4.17	3.97	3.67	4.05	4.10	3.66	4.43	3.81	4.36	3.94	3.81	3.68

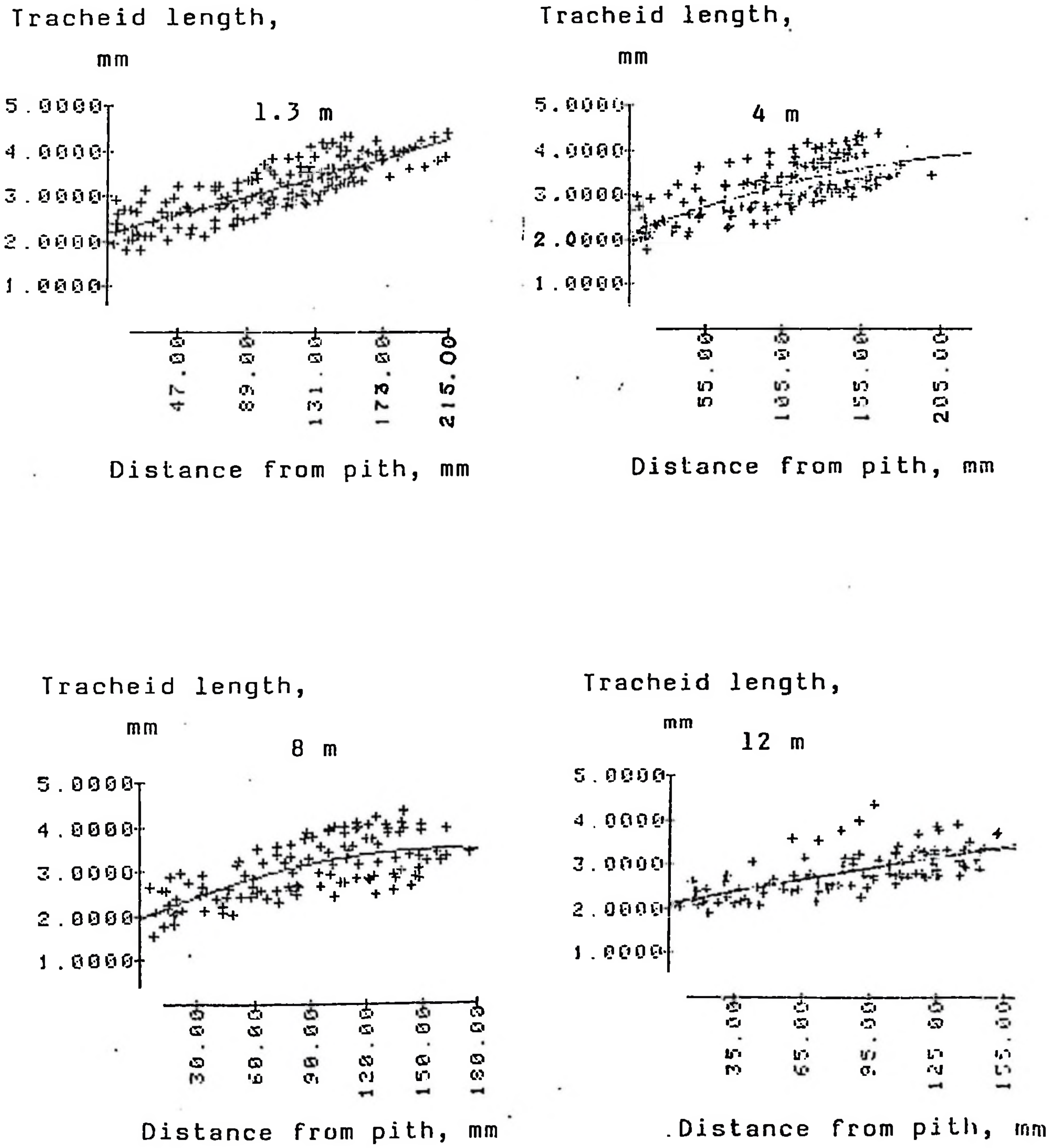
Appendix 15. AOV table for the relationship between ring tracheid length and cardinal directions at breast height.

Source of variation	d.f.	Sum of squares	Mean square	F
Between directions	3	0.551328	0.1837760	.4373
Within directions	128	53.78169274	0.42016947	
Total	131	54.3302082		

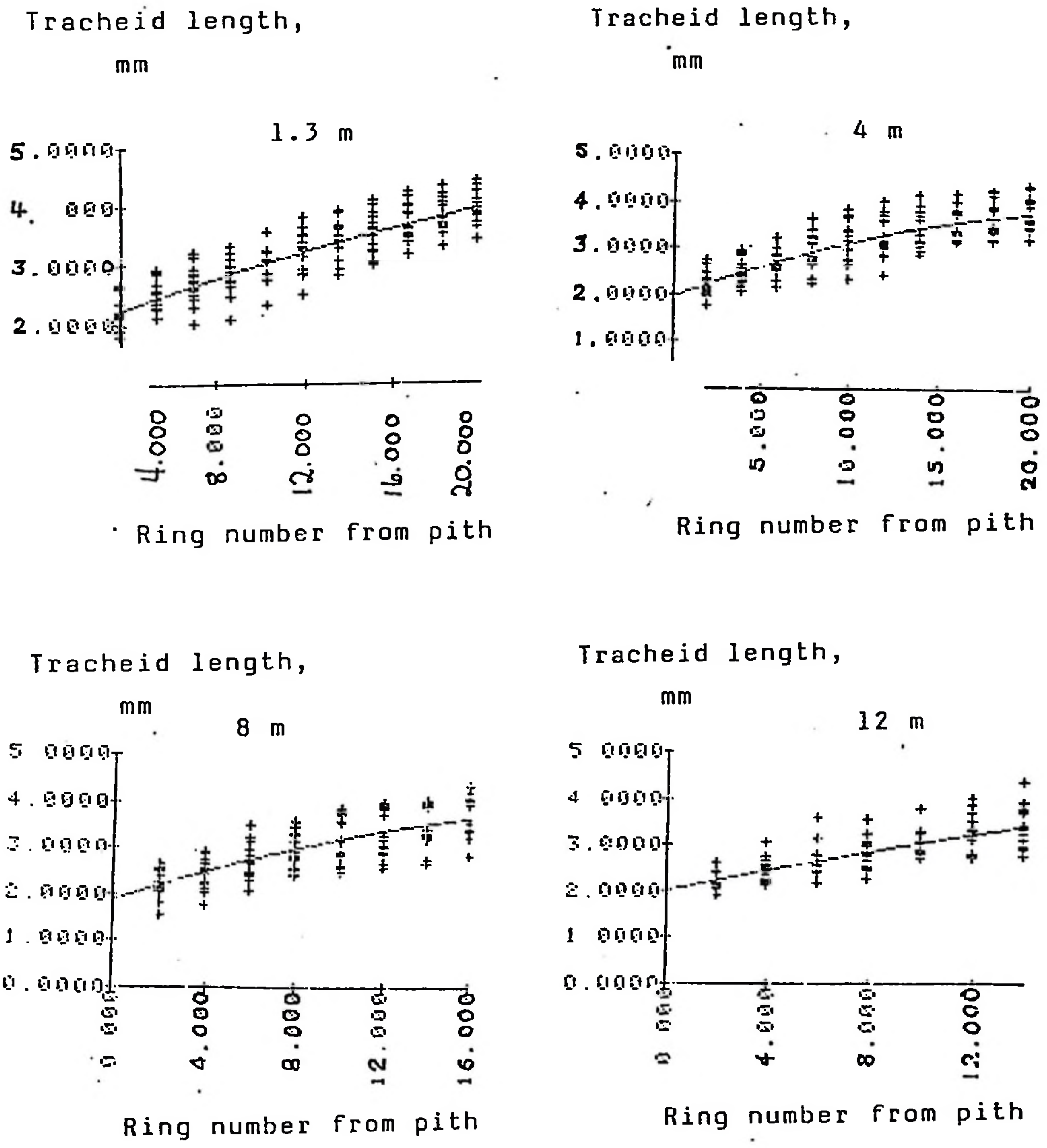
Appendix 16. AOV table for ring tracheid length variation with height in the stem.

Source of variation	d.f.	Sum of square	Mean square	F
Between heights	3	2.915616	0.971871922	10.4259**
Within heights	56	0.9718719	0.09321734	
Total	59	3.8874879		

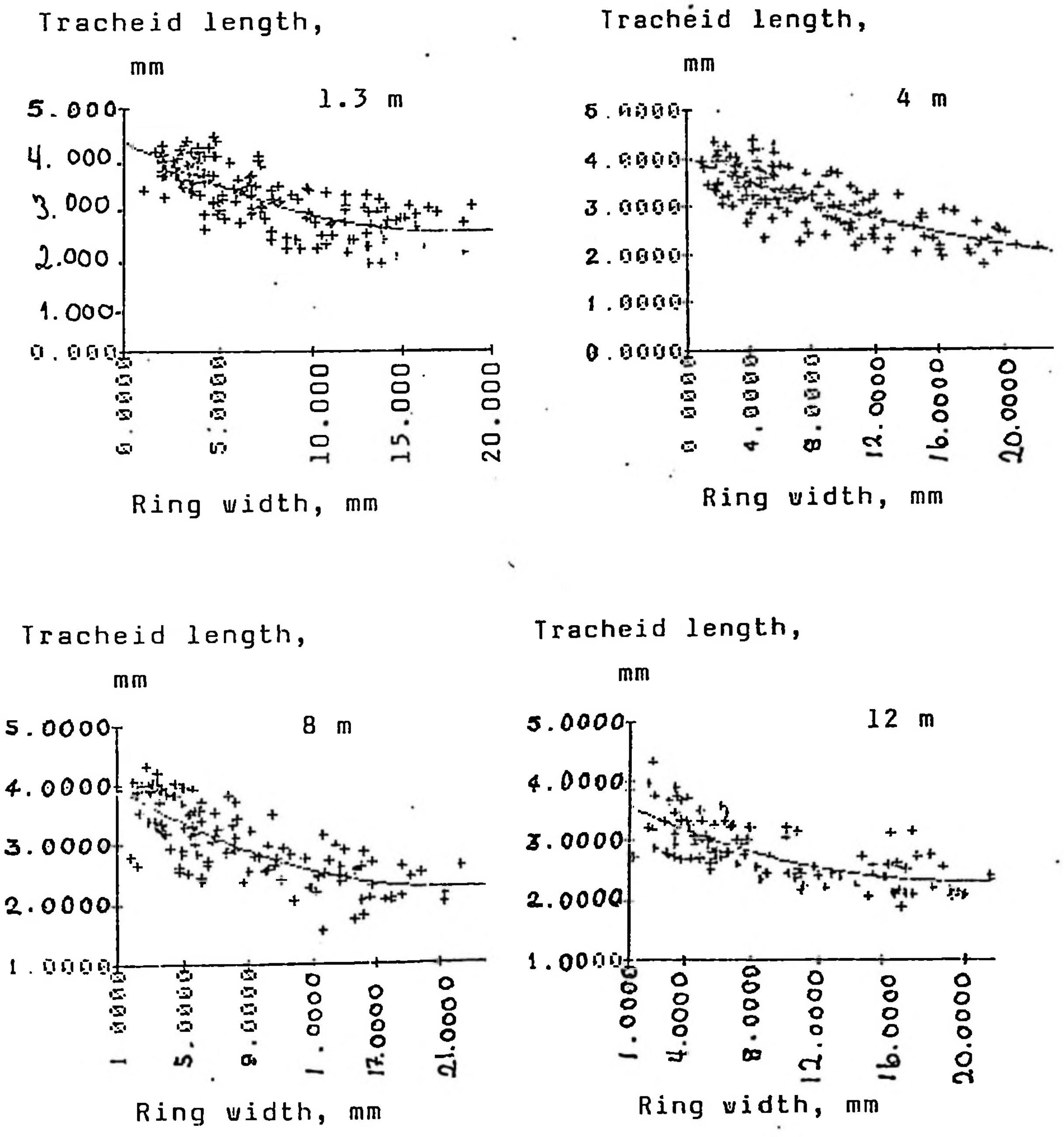
Appendix 17(a). Scatter diagrams and regression lines of ring tracheid length on distance from pith at 4 heights in the stem.



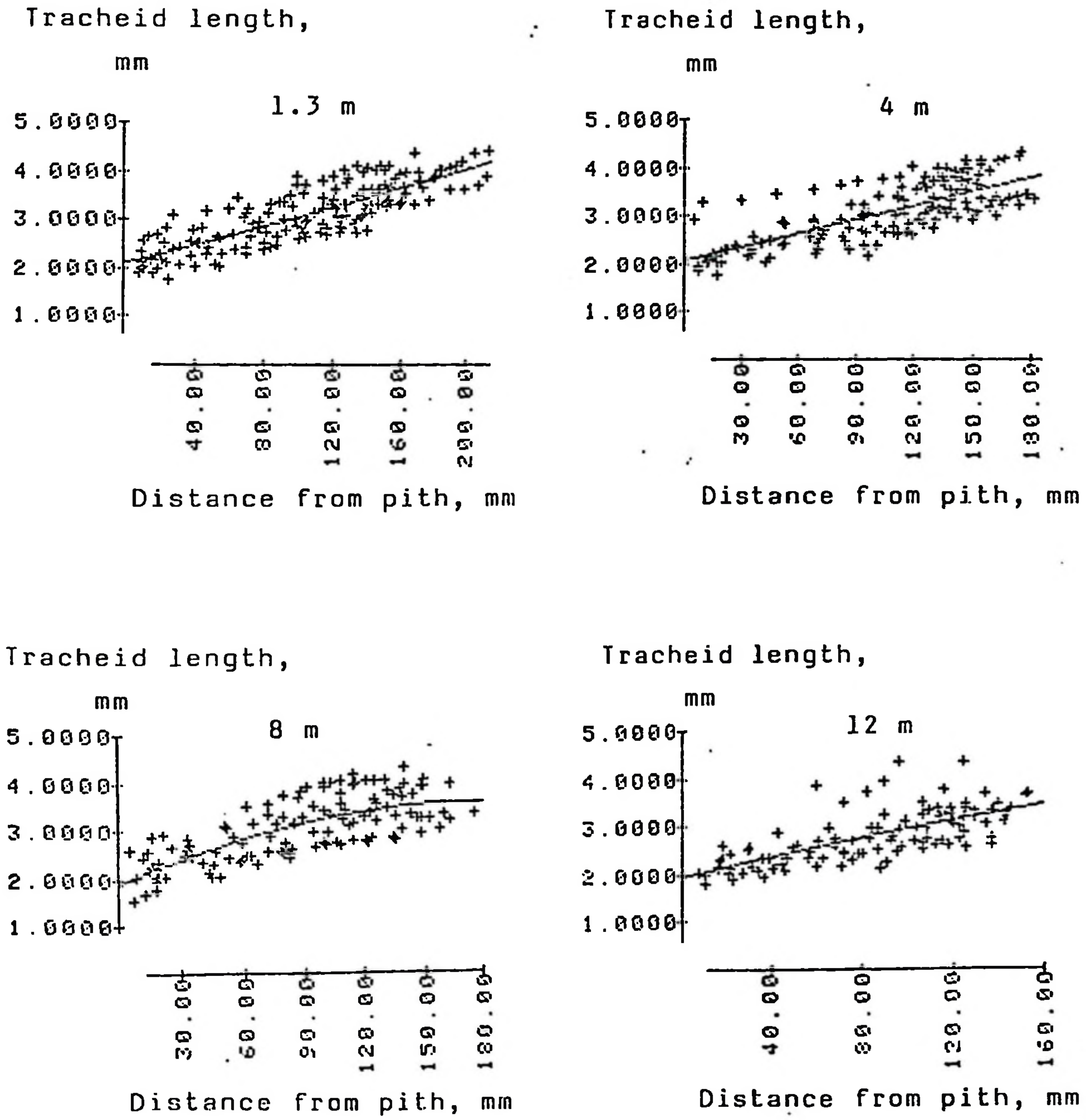
Appendix 17(b). Scatter diagrams and regression lines of ring tracheid length on ring number at 4 heights in the stem.



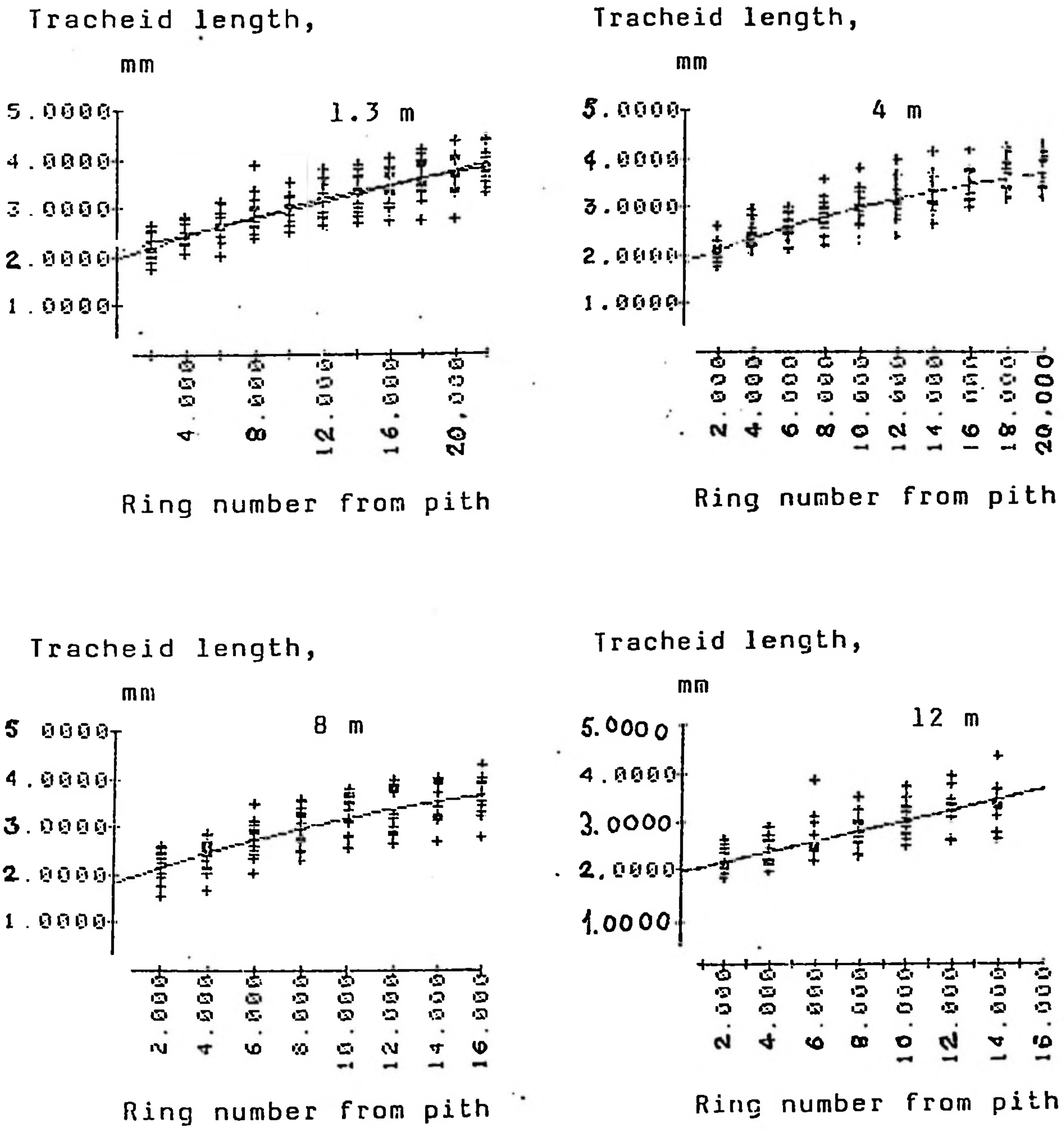
Appendix 17(c). Scatter diagrams and regression lines of ring tracheid length on ring width at 4 heights in the stem.



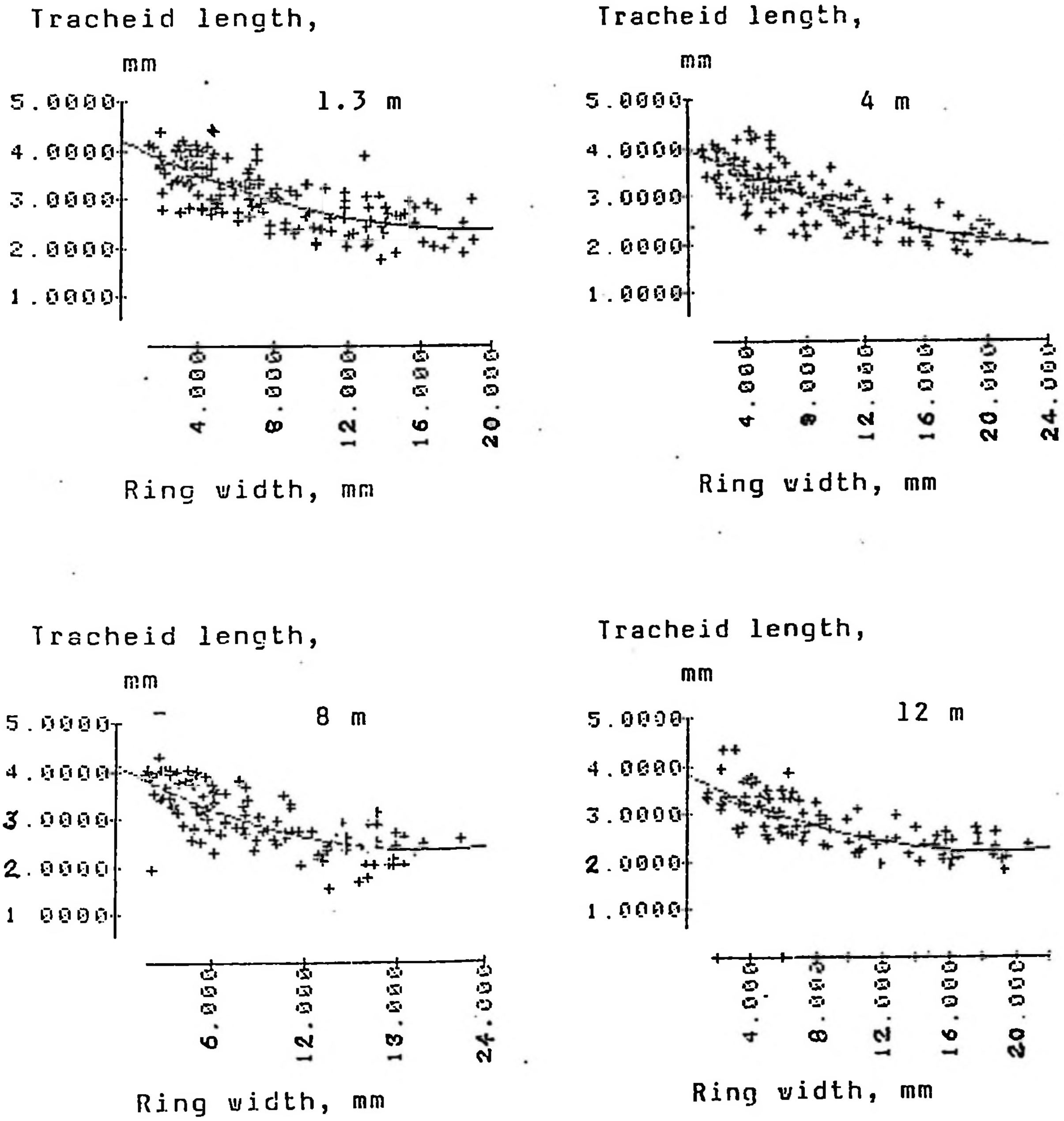
Appendix 18(a). Scatter diagrams and regression lines of earlywood tracheid length on distance from pith at 4 heights in the stem.



Appendix 18(b). Scatter diagrams and regression lines of early wood tracheid length on ring number at 4 heights in the stem.



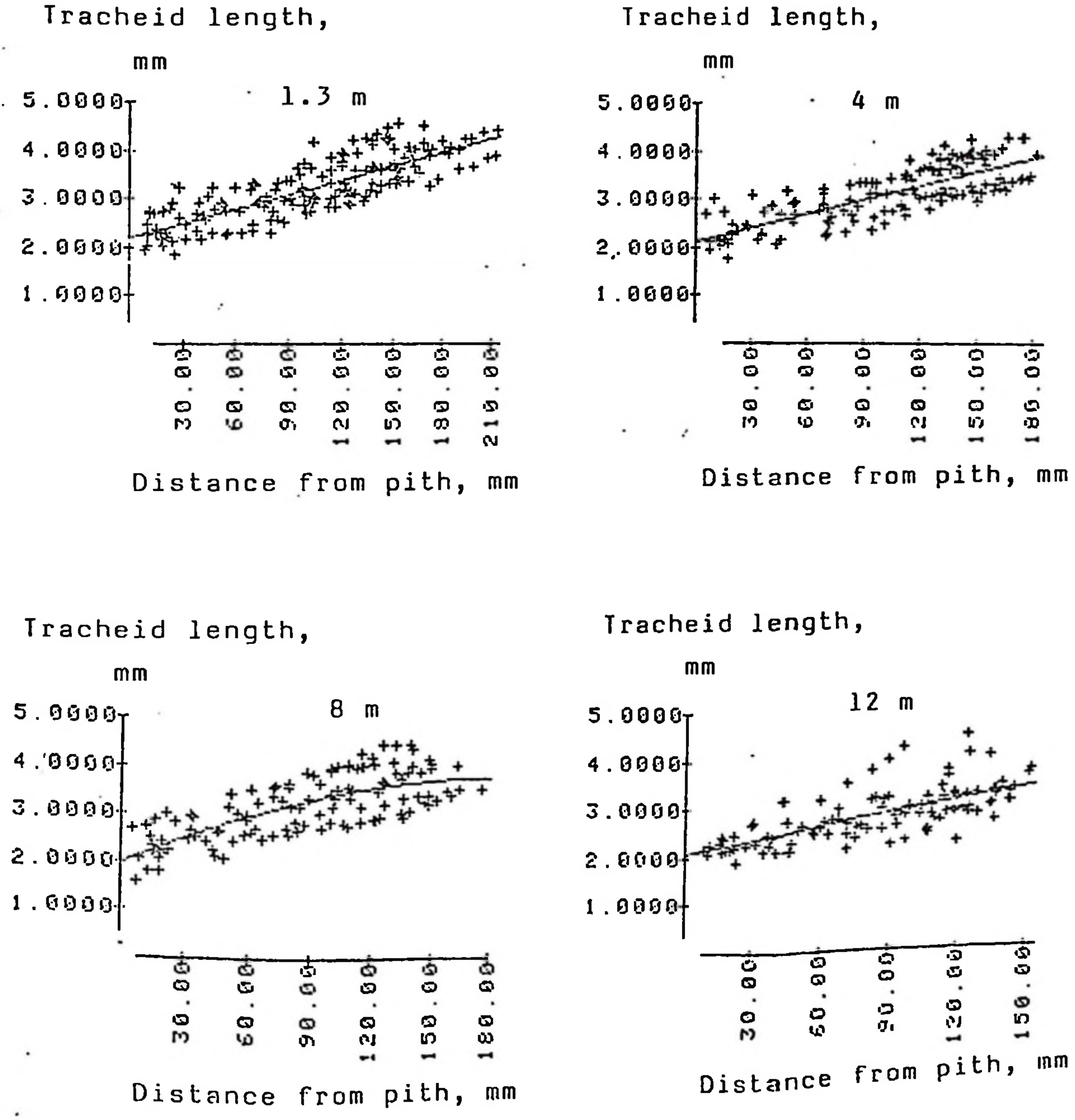
Appendix 18(c). Scatter diagrams and regression lines of earlywood tracheid length on ring width at 4 heights in the stem.



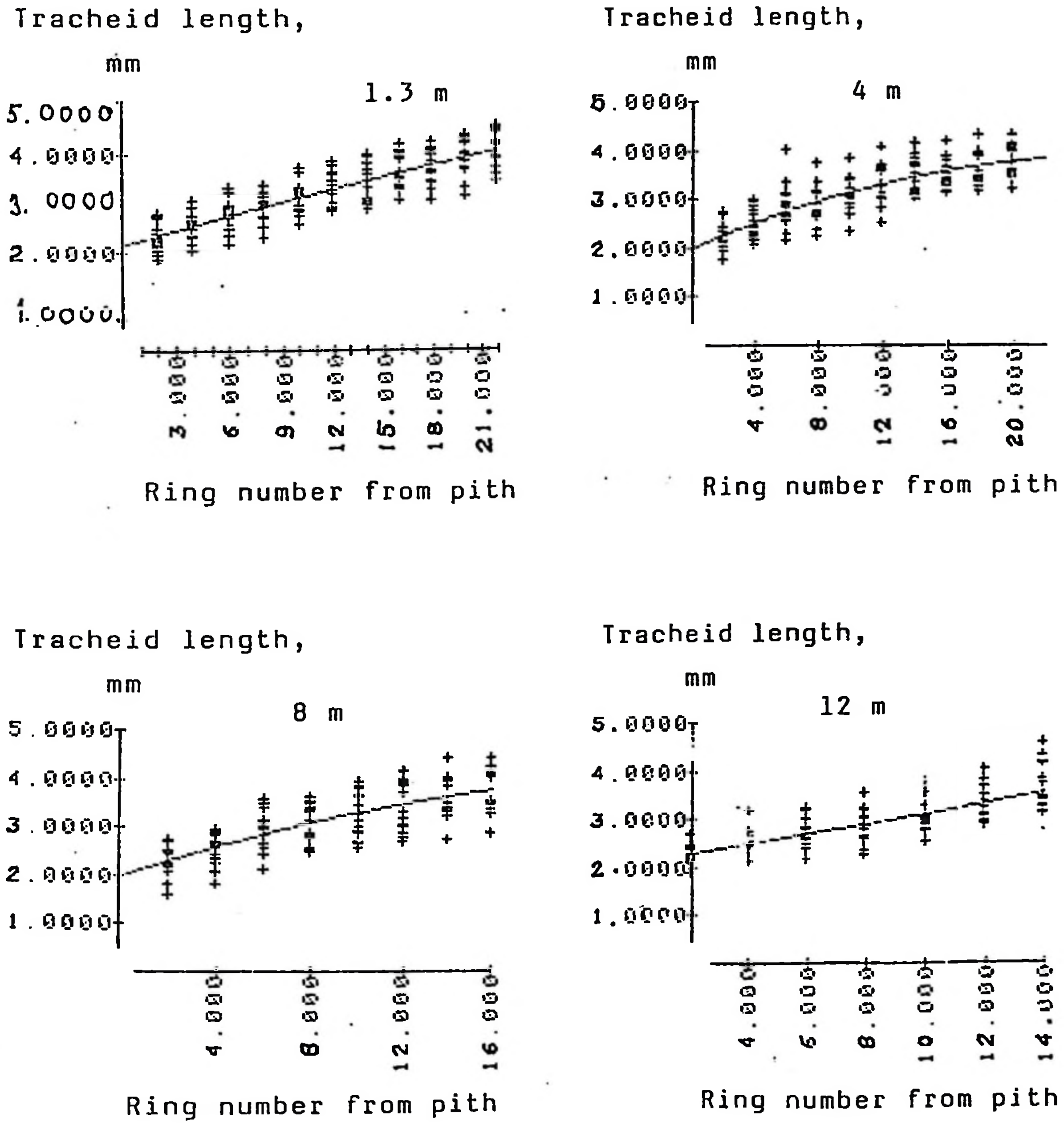
Appendix 18(d). Earlywood and latewood mean tracheid lengths in mm for various rings at 4 heights in the stem.

Height, m	Wood type	2	4	6	8	10	12	14	16	18	20	22
1.3	Earlywood	2.16	2.44	2.64	2.82	3.02	3.18	3.32	3.53	3.60	3.72	3.87
	Latewood	2.27	2.48	2.74	2.93	3.10	3.29	3.42	3.61	3.75	4.01	4.12
4	Earlywood	2.07	2.37	2.55	2.84	3.01	3.18	3.32	3.45	3.60	3.74	
	Latewood	2.34	2.60	2.89	2.88	3.25	3.56	3.52	3.70	3.75	4.04	
8	Earlywood	2.18	2.42	2.73	2.86	3.21	3.32	3.42	3.48			
	Latewood	2.25	2.45	2.78	3.09	3.23	3.44	3.66	3.78			
12	Earlywood	1.97	2.35	2.65	2.80	2.91	3.00	3.20				
	Latewood	2.25	2.53	2.75	2.87	3.04	3.48	3.57				

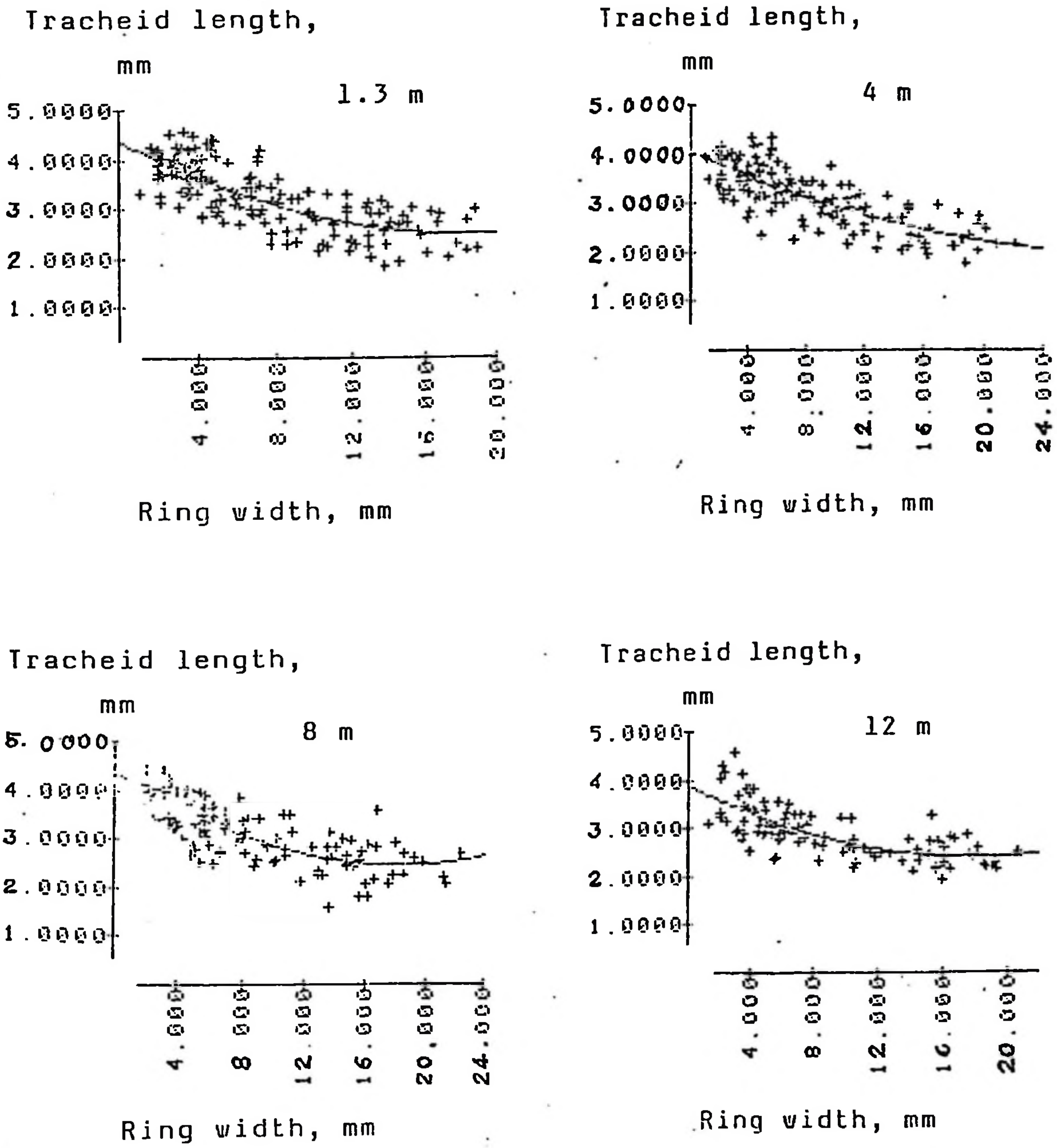
Appendix 19(a). Scatter diagrams and regression lines of latewood tracheid length on distance from pith at 4 heights in the stem.



Appendix 19(b). Scatter diagrams and regression lines of latewood tracheid length on ring number at 4 heights in the stem.



Appendix 19(c). Scatter diagrams and regression lines of latewood tracheid length on ring width at 4 heights in the stem.



Appendix 20. AOV table for earlywood tracheid length variation with height in the stem.

Source of variation	d.f.	Sum of squares	Mean sum of square	F
Between heights	3	1.14499	0.38167	4.08451*
Within heights	56	5.23277	0.093442	
Total	59	6.37777		

Appendix 21. AOV table for latewood tracheid length variation with height in the stem.

Source of variation	d.f.	Sum of squares	Mean sum of squares	F
Between heights	3	0.99828	0.33276	3.70556*
Within heights	56	5.502881	0.0898	
Total	59	6.0270933		

Appendix 22. Ring tracheid lengths in mm of inner and outer bands of earlywood and latewood at 1.3 m height in trees no. 1, 2 and 9.

Ring No.	EARLYWOOD						LATEWOOD					
	Inner portion			Outer portion			Inner portion			Outer portion		
	1	2	9	1	2	9	1	2	9	1	7	9
2	2.07	2.57	3.13	2.02	2.43	2.07	2.21	2.78	2.21	2.34	2.78	2.32
4	2.44	2.92	2.23	2.32	2.65	2.37	2.30	2.88	2.27	2.31	3.00	2.32
6	2.50	2.87	2.64	2.70	2.98	2.49	2.69	2.93	2.649	2.77	3.02	2.72
8	2.86	2.86	2.57	3.21	2.94	2.70	3.14	3.06	2.98	3.10	3.07	2.84
10	3.13	3.20	2.84	3.41	3.23	3.27	3.07	3.32	3.20	3.45	3.29	3.16
12	3.64	3.16	3.02	3.65	3.28	3.24	3.53	3.57	3.19	3.61	3.47	3.42
14	3.52	3.32	3.36	3.85	3.25	3.23	3.70	3.32	3.42	3.96	3.37	3.53

Appendix 23. Mean tracheid length in mm of juvenile wood at 4 heights in the stem.

Tree no.	Height, m			
	1.3	4	8	12
1	2.54	2.65	2.73	2.76
2	2.86	2.54	2.83	2.54
3	2.33	2.59	2.64	2.92
4	2.66	2.43	2.76	2.77
5	2.93	2.89	2.21	2.20
6	2.75	2.42	2.32	2.46
7	2.72	3.07	2.72	2.46
8	2.04	2.11	1.94	2.09
9	2.47	2.95	3.02	3.13
10	3.05	3.14	2.89	2.42
11	2.34	2.47	2.27	2.28
12	2.33	2.22	2.16	2.32
13	2.57	2.37	2.49	2.26
14	2.43	2.67	2.77	2.59
15	2.36	2.40	2.30	2.38

Appendix 24. Mean, standard deviation, range and coefficient of variation of tracheid lengths in mm for various rings.

Height		Growth ring number 2	4	6	8	10	12	14	16	18	20	22
	Mean	2.215	2.461	2.690	2.873	3.062	3.235	3.371	3.569	3.677	3.863	3.991
1.3	s.d.	0.287	0.277	0.309	0.309	0.2973	0.3551	0.357	0.368	0.325	0.270	0.2681
	Range	1.81-2.68	2.13-2.95	2.01-3.22	2.1-3.35	2.34-3.59	2.53-3.85	2.84-3.95	3.01-4.11	3.20-4.25	3.32-4.36	3.43-4.45
	c.v.	12.9	11.3	11.5	10.8	9.7	10.9	10.6	10.3	8.8	7.0	6.7
	Mean	2.205	2.485	2.727	2.860	3.130	3.371	3.421	3.576	3.676	3.891	
4	s.d.	0.267	0.3127	0.334	0.373	0.4229	0.390	0.400	0.368	0.378	0.351	
	Range	1.77-2.76	2.06-2.98	2.15-3.24	2.07-3.24	2.33-3.84	2.86-4.16		3.14-4.20	3.18-4.29	3.24-4.37	
	c.v.	12.1	12.6	12.3	14.3	13.5	11.6	11.7	10.3	10.3	9.3	
8	Mean	2.213	2.433	2.757	2.973	3.216	3.381	3.540	3.630			
8	s.d.	0.309	0.309	0.387	0.409	0.479	0.512	0.498	0.476			
	Range	1.55-2.64	1.75-2.90	2.07-3.50	2.38-3.60	2.46-3.84	2.55-3.98	2.65-4.23	2.81-4.32			
	c.v.	14.5	12.7	14.0	13.8	14.9	15.1	14.1	13.1			
	Mean	2.11	2.442	2.701	2.823	2.975	3.239	3.385				
	s.d.	0.215	0.265	0.386	0.339	0.308	0.405	0.436				
12	Range	1.89-2.6	2.1-3.05	2.16-3.57	2.23-3.52	2.68-3.77	2.7-3.99	2.74-4.32				
	c.v.	10.2	10.8	14.3	12.0	10.3	12.5	12.8				

Appendix 25. Mean tracheid lengths in mm of mature wood at 4 heights in the stem.

Tree no.	Height, m 1.3	4	8	10
1	3.79	3.25	3.05	3.01
2	3.58	3.14	3.18	3.33
3	3.31	3.25	3.25	3.31
4	3.11	3.75	3.82	3.31
5	3.03	3.96	2.62	2.71
6	3.33	3.62	3.70	3.36
7	3.79	4.15	3.81	3.30
8	3.15	2.99	2.69	2.79
9	3.43	3.39	3.46	3.69
10	4.00	3.95	3.36	2.98
11	3.06	3.71	3.15	3.10
12	3.30	3.10	3.16	3.31
13	3.94	3.75	3.18	2.81
14	3.73	3.13	3.85	3.41
15	3.23	3.13	3.02	3.18

Appendix 26. AOV table for axial variation of juvenile wood tracheid length.

Source of variation	d.f.	Sum of squares	Mean square	F
Between heights	3	0.06356	0.0211883	0.24369
Within heights	56	4.86905	0.0869473	
Total	59	4.93261		

Appendix 27. AOV table for the mature wood tracheid length variation with height in stem.

Source of variation	d.f.	Sum of squares	Mean square	F
Between heights	3	0.956378	0.3187927	2.7166
Within heights	56	6.57148	0.1173478	
Total	59	7.5278583		