JUVENILE - MATURE WOOD TRANSITION IN SECOND-GROWTH COASTAL DOUGLAS-FIR

By

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ABSTRACT

The transition from old-growth to second-growth British Columbia coastal Douglas-fir has resulted in reduction of log size and increased proportion of juvenile (core or crown-formed) wood. Determination of the zone of transition from juvenile to mature wood is critical to the definition of wood quality and timber value.

Thirteen unpruned, two pruned second-growth, and two unpruned plantation-grown coastal Douglas-fir trees were sampled to analyze the hypothesis that the transition in relative density from juvenile to mature wood occurs at the base of the live crown. X-ray densitometric techniques were utilized to determine yearly pith to bark relative density data of five cross-sectional discs from each tree. Segmented linear regression techniques were utilized to estimate the juvenile - mature wood transition age from the data.

The average number of growth increments from the pith at which juvenile - mature wood transition occurred on sections sampled at breast height, 20 percent and 40 percent of total height was 22.18.

When the hypothesis was tested on unpruned trees, before and after harvest, the juvenile - mature wood transition occurred below the base of the live crown.

When the hypothesis was tested on pruned trees, the transition occurred at the base of the live crown, which represented the upper limit of pruning height.

This information may provide a greater insight into juvenile - mature wood transition. It will likely assist in the determination of wood quality and economic value of forest products manufactured from second-growth coastal Douglas-fir.

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1.0 INTRODUCTION

Coastal Douglas-fir (Pseudotsuga menziesii (Mirb.) Franco) is found west of the Cascade Range in Washington and Oregon, west of the Coast Range in British Columbia and west of the Sierra Nevada in northern California. The north - south range of the species extends approximately 3400 km south from the central British Columbia coast (Lat. 55°N) (Fowells, 1965).

Coastal Douglas-fir is a relatively minor species in British Columbia. Reserves of coastal Douglas-fir in the Vancouver and Prince Rupert regions amount to approximately 126 million cubic metres, which represent six percent of the total mature timber and six percent of the annual timber harvested in 1980 (British Columbia Ministry of Forests, 1980). However, because of easy access, high quality and developed markets, Douglas-fir is highly demanded and the most intensively managed commercial species. For these reasons, the old-growth coastal Douglas-fir resource has been almost replaced by young and fast grown second-growth timber.

The transition to second-growth timber has resulted in reduction of log size and changes in the quality of the raw material. These changes are demonstrated by the increased proportion of juvenile (core or crown-formed) wood found in the second-growth timber. Compared to mature (stem-formed) wood, the juvenile wood of Douglas-fir is characterized by lower relative density, shorter tracheids, larger fibril angle, lower strength, lower percentage of latewood, lower transverse shrinkage, higher longitudinal shrinkage, lower cellulose content and higher lignin content (Bendtsen, 1978; Barrett and Kellogg, 1984, 1986; Jackson and Megraw, 1986; Jozsa and Kellogg, 1986; McKimmy, 1986). Such differences in wood properties are very important in the processing and manufacturing of lumber, veneer, chips and other forest products.

The future of the Canadian forest industry will depend upon the successful conversion and commercialization of forest products manufactured from second-growth timber. In order to maintain and improve wood supply the industry needs information to plan and predict the effects of intensive forest management on volume production, properties and value of second-growth timber (Kellogg, 1986).

The Tree and Stand Simulator (TASS) (Mitchell, 1975; Mitchell and Cameron, 1985) models the growth and yield of second-growth coastal Douglas-fir under different management conditions. This is a biologically oriented model which can simulate crowns of individual trees in a three-dimensional growing space in response to internal growth processes, environmental factors, physical restrictions and cultural practices. However, the model does not consider wood qualities or value of wood products.

In view of the above, Forintek Canada Corporation, the Pulp and Paper Research Institute of Canada, the Ministry of Forests and Lands of British Columbia and the University of British Columbia have initiated nine integrated projects to provide much of the technical information required for future utilization planning for second-growth coastal Douglas-fir (Kellogg, 1986). The purpose of this thesis project, which is one of the nine Douglas-fir Task Force projects, is to investigate the transition in relative density between juvenile and mature wood. The specific objective of this study is to test and analyze the hypothesis that:

> The relative density transition from juvenile to mature wood in individual growth increments of second-growth coastal Douglas-fir trees occurs at the base of the live crown.

To test this hypothesis, 13 unpruned, two pruned second-growth, and two unpruned plantation-grown trees were sampled and analyzed.

It is hoped that the results of this project will contribute to the understanding of how and when the relative density transition between juvenile and mature wood occurs. Furthermore, the results can help extend TASS to simulate the production of juvenile and mature wood, thus providing insight into interactions of stand dynamics and wood quality.

In addition, the findings of this project are likely to be of value to the Douglas-fir Task Force and the general forestry industry in the determination of wood quality and, ultimately, economic value of forest products in British Columbia.

2.0 LITERATURE REVIEW

2.1 Wood Formation

The physiological processes controlling wood formation in temperate zone trees are related to the seasonal activity of the vascular cambium and differentiation of its derivatives.

In coniferous trees, there is a high correlation between growth and development of the crown over time and wood formation along the stem (Larson, 1964, 1969). The physiology of wood formation must, then, be considered as an integral part of tree growth. This growth can be divided into two developmental stages, a primary stage originating in the vegetative terminal buds, and a secondary stage originating in the vascular cambium.

2.1.1 Primary Growth

The primary growth stage encompasses the elongation of the main stem and branches and the regulation of height growth and tree form. In temperate zone conifers, the seasonal primary growth begins as a result of an increase in temperature and day length in early spring (Wilcox, 1962; Panshin and de Zeeuw, 1980). These changes in environmental conditions initiate primary cell division after the rehydration, swelling and increase of hormonal and enzymatic activity in the apical meristems inside the vegetative buds. In Douglas-fir, this growth activation occurs in the last week of March at lower elevations (Owens, 1968; Allen and Owens, 1972).

As the growing season advances, more new cells are formed causing primary shoot elongation in the stem and branches. Subsequently, the newly formed cells undergo differentiation, resulting in changes in size, shape and function. In this manner, primary permanent tissues are differentiated from three meristematic tissues called protoderm, ground meristem and procambium (Kowlowski, 1971).

The protoderm develops an external protective layer called the epidermis. The ground meristem develops into the central pith and cortex. The procambium gives rise to the primary phloem and primary xylem and subsequently the vascular cambium.

The primary phloem is formed on the outer side of the procambium. It performs the function of mobilization and transport of sugar and other nutrients within the shoot apex. The primary xylem is formed on the inner side of the procambium and it performs the function of support and conduction of dissolved substances from the roots to the terminal shoots.

The vascular cambium, a secondary meristematic tissue responsible for the lateral growth of xylem (wood), and phloem (bark) tissues, is formed after completion of the differentiation of primary permanent tissues. It is made up of fusiform and ray cambial initial cells, and separates the xylem and phloem mother cells.

2.1.2 Secondary Growth

The secondary growth stage, as it relates to wood formation, can be summarized into the following developmental phases (Larson, 1969; Brown, 1970; Kozlowski, 1971; Wilson, 1984; Haygreen and Bowyer, 1982):

1. Awakening, rehydration and swelling of the dormant cambium at the beginning of the growing season;
2. Periclinal division of fusiform cambial initial cells resulting in the formation of new meristematic cells, and new xylem and phloem mother cells with cell division peaking a few weeks into the growing season, after which it decreases gradually until completed in early summer;

3. Differentiation of the xylem and phloem cambial mother cells passing through the phases of enlargement, and secondary wall formation and thickening; and
4. Finally, maturation of the newly formed xylem and phloem cells, thus completing the secondary wall thickening and lignification phases.

The annual addition of newly formed secondary phloem cells forms the bark, which is divided into a light coloured inner living bark and a dark outer dead bark. The annual additions of secondary xylem cells form concentric layers or rings of growth increments that are responsible for the increase in stem and branch diameters (Panshin and de Zeeuw, 1980). The annual growth increments are characterized by the formation of two zones called earlywood (springwood) and latewood (summerwood).

The most important anatomical differences between earlywood and latewood are the radial cell diameter and the secondary wall thickness. Such characteristics are known to be independent of each other (Richardson and Dinwoodie, 1960; Wodzicki, 1960). Their formation, particularly in pine trees, was explained by Wareing (1958) and Larson (1963, 1969) in the following two hypotheses.

The first is the hormonal or auxin hypothesis, which is related to the regulation of tracheid diameter. During the period of active shoot elongation and needle development in the spring, a high level of diffusible auxin is produced within the vegetative buds and transported downward along each branch, down the main stem and into the roots. Then, the cambial activity begins with the production of large diameter xylem tracheids classified as earlywood. Earlywood formation continues as long as the elongating shoots and developing needles compete for the stored and currently produced photosynthates. As the growing season advances, narrow diameter latewood tracheids are produced in response to the cessation of terminal growth, the reduction of auxin synthesis, and the increase of growth inhibiting substances. The formation of latewood tracheids begins at or near the base of the tree and tapers upwards to a point of extinction near the apex.

The second hypothesis explains the secondary cell wall thickening, which is related to the net amount of photosynthates that reach each tracheid after respiration requirements have been met. The competition for photosynthates among meristematic tissues decreases, and the rate of photosynthesis in the current year needles rapidly increases (Freeland, 1952; Clark, 1961). Thus, more photosynthates are available for both stem growth and secondary wall thickening of the latewood tracheids (Rutter, 1957).

2.1.3 Influence of the Crown on Wood Formation

The hormonal and the secondary wall thickness regulation hypotheses emphasize that earlywood and latewood tracheid formations are correlated to photosynthate availability and presence of auxin. These crown formed products determine the rate of cambial initial cell division and the degree of differentiation of the cambial derivatives. It is clear that the growth and development of the crown over time has a direct regulatory influence over wood formation in the stem (Larson, 1962, 1964).

Within the crown, the most vigorously active live branches will regulate the wood formation by a steady production of photosynthates and auxins. These branches are characterized by having complete growth increments along their length forming an active union with the main stem. As the branches start to compete for light and become older and longer, their vigor, given by the capacity of producing photosynthates and auxins, gradually decreases (Larson, 1969). This leads to a decrease in the current shoot length from the apex to the base of the live crown and from the tip to the base of the branch (Fraser, 1962; Forward and Nolan, 1964).

The decrease in branch vigor is followed by a period of senescence which starts at the lower crown branches. At this time the contribution of these branches to wood formation gradually decreases, leading to the formation of incomplete or absent growth increments at the branch base (Andrew and Gill, 1939; Reukema, 1959, 1961; Reeb, 1984). These senescent branches, which are still attached to the main stem, interrupt their contact with the main translocation pathways in the tree, resulting in diminishing contribution to wood formation until branch death occurs. Larson (1969) concluded that major changes in wood formation and quality occur below the living crown, or below the most active branches of the crown.

For tree growth analysis purposes, the height to live crown base has been defined in several ways. Smith et al. (1961) and Mitchell (1969, 1975) defined the height to live crown as the average distance from the ground to the lowest live branch in each of four quadrants. They also defined an average live crown height as the average height from the ground to the point of maximum crown spread or crown radius. This point occasionally represents the crown contact with the crowns of neighbouring trees. Reeb (1984) defined height to live crown base as the height from the ground to the whorl at which at least 75 percent of the branches are alive.

The number of growth increments at the base of the dead branches and the corresponding height positions can be utilized to determine the approximate crown base positions at younger ages.

The age of the tree also has an influence on wood formation. A young tree with a high percentage of the stem covered with active live branches will produce wide growth increments with a high proportion of earlywood tracheids. This is explained by the prolonged influence of the apical meristems on the cambial regions in the active live crown. As the tree grows older and distance from both the pith and the active live crown increases, the proportion of latewood tracheids in the growth increments gradually increases. Now, the cambial regions below the crown become less influenced by the apical meristems.

Consequently, two characteristic wood zones can be differentiated within the tree stem as a function of distance from the active live branches and number of growth increments from the pith. The first zone, called juvenile wood, forms a central core of wood around the pith extending from the base to the apex of the tree. The second, called mature wood, is formed around the juvenile wood core and below the living crown.

2.2 Juvenile and Mature Wood

A universal definition of the terms juvenile and mature wood has not been agreed upon, although such terms can arbitrarily describe the type of wood produced in relation to crown proximity and number of growth increments from the pith.

Several authors have defined juvenile and mature wood from different points of view. For instance, when considering the juvenile and mature wood stem positions in a tree, juvenile wood has been called core, inner, or pith-associated wood and mature wood has been called exterior, outer or non-pith-associated wood (Perry and Wang, 1958; Zobel _et al_., 1959; Moody, 1970).

Juvenile wood has been called immature or youthful wood and mature wood has been called old or adult wood, based on their respective physiological stages of maturity (Rendle, 1958, 1959, 1960). Juvenile wood has been called crown-formed wood, because it is formed inside the living crown, and mature wood has been called stem-formed wood due to its formation outside of the living crown (Trendelenburg, 1935; Cooper, 1960; Brunden, 1964; Larson, 1969, 1973).

The size of the juvenile wood core generally depends upon the growth rate, regardless of the species. Silvicultural practices such as fertilization, irrigation and thinning will tend to decrease crown recession and increase crown vigor, growth rate and the size of the juvenile wood core (Bendtsen, 1978; Briggs and Smith, 1986; Megraw, 1985; Oliver, 1986).

The proportion of the juvenile wood core in the stem is a function of the species, number of growth increments from the pith and distance from the active live crown (Paul, 1960; Bendtsen, 1978). This proportion tends to be high in early harvested trees and in open-grown trees. Increasing crown recession by delaying the harvesting age of stand-grown trees will decrease the juvenile wood proportion at harvest age. An abrupt change from juvenile to mature wood can also be achieved by pruning the live and vigorous lower branches in the crown (Marts, 1949; Gerischer and De Villiers, 1963; Smith, 1968; Larson, 1965, 1969; Cown, 1973; Polge et al., 1973; Plumptre and Austin, 1978).

It is evident that growth and development of the active live crown as a function of age will determine not only the characteristics of the tracheids formed, but also the quantity and quality of juvenile and mature wood in the stem.

Juvenile and mature wood must be considered as two different populations within the same tree because of their fundamental differences in wood quality (Panshin and de

Zeeuw, 1980). Such differences are determined primarily by the tracheids' anatomical structure and chemical composition, and secondarily by the derived physical wood properties.

2.2.1 Anatomical Structure Comparison

When considering the tracheid anatomical structure variations in stem cross-sections of most conifers, the length, diameter and secondary wall thickness of the juvenile wood tracheids increase progressively from the pith until they more or less stabilize in the mature wood (Bendtsen, 1978; Panshin and de Zeeuw, 1980; Megraw, 1985; Krahmer, 1986).

In softwoods, the length of mature wood tracheids can be up to three or four times greater than that of juvenile wood tracheids (Anderson, 1951; Dadswell, 1958; Dinwoodie, 1961). Many studies have shown that the tracheids in juvenile wood are shorter than in mature wood, regardless of height. These results were reported by Zobel and Kellison (1972) for loblolly pine (*Pinus taeda* L.), by Loo *et al*. (1985) for slash pine (*Pinus elliottii* Engelm.), by Wang and Micko (1984) for white spruce (*Picea glauca* (Moench.) Voss), by Erickson and Harrison (1974) and Jackson and Megraw (1986) for Douglas-fir, by Boone and

Chudnoff (1972) for Caribbean pine (*Pinus caribaea* Morelet.), by Cown (1975) for radiata pine (*Pinus radiata* D.Don), and by Wellwood and Jurazs (1968) for western redcedar (*Thuja plicata* Donn.).

The secondary wall thickness of the juvenile wood tracheids was reported to be less than that of mature wood tracheids by Zobel and Kellison (1972) for loblolly pine, by Isebrands *et al*. (1982) for larch (*Larix* spp.), by Cown (1975) for radiata pine and by Foelkel *et al*. (1976) for slash pine. Erickson and Harrison (1974) found that in Douglas-fir the radial and tangential diameter of the juvenile wood tracheid increased toward mature wood.

In addition to the above findings, the lumen size, and the microfibril angle of the S2 layer of the juvenile wood tracheids generally decrease toward mature wood, where they stabilize to some extent. The decrease in lumen size from juvenile to mature wood tracheids was reported by Zobel and Kellison (1972) for loblolly pine, by Foelkel *et al*. (1976) for slash pine, and by Cown (1975) for radiata pine. The decrease in microfibril angle from juvenile to mature wood tracheids was found by Meylan (1968) for radiata pine, by Boone and Chudnoff (1972) for Caribbean pine, and by Erickson and Arima (1974) for Douglas-fir.

Variations in the chemical composition of tracheids include the following. The holocellulose and alpha cellulose contents of the juvenile wood tracheids gradually increase from the pith until they begin to stabilize in the mature wood. However, an inverse relationship occurs with some hemicelluloses and lignin, which decrease from juvenile to mature wood. These trends can be seen from the data of Kirk et al. (1972) and Zobel and Kellison (1972) on loblolly pine, Schmidt and Smith (1961) on Caribbean pine, Wellwood and Smith (1962), Kennedy and Jaworsky (1960), Sastry and Wellwood (1971), Erickson and Harrison (1974), and Megraw (1985) on Douglas-fir.

In conclusion, in comparison to mature wood, the juvenile wood in Douglas-fir is characterized by smaller and shorter tracheids with thinner walls and larger microfibril angles, and by lower holocellulose and alpha cellulose contents and higher lignin and hemicellulose contents.

2.2.2 Physical Properties Comparison

Anatomical and chemical differences among tracheids, as described, influence the physical properties and, therefore, the quality of juvenile and mature wood. To define wood quality, Larson (1969) stated:

> "During the wood formation process numerous factors both inside and outside the tree lead to variation in type, number, size, shape, physical structure and chemical composition of the wood elements. Wood quality is an arbitrary classification of these variations in the wood elements when they are counted, measured, weighed, analyzed or evaluated for some specific purpose."

The quality of wood, then, refers to its fitness for a particular utilization, each quality being determined by a certain number of properties. For instance, relative density, strength, elasticity, proportion of corewood, reaction wood, grain orientation, permeability, moisture content and presence of knots are some of the properties which determine the suitability of wood for a specific end use (Fielding, 1967; Haygreen and Bowyer, 1982).

When considering softwood as a raw material source for pulp and lumber production, relative density is one of the most important characteristics to be considered as a general indicator of wood quality. The reason is that relative density is highly correlated to pulp yield, paper-making properties and strength properties of timber (Barefoot et al., 1970; Gonzalez and Kellogg, 1978; Kellogg, 1982;).

2.2.2.1 Relative Density

Relative density, often called specific gravity in wood quality studies, expresses how much cell wall substance is present in a given volume of wood. Relative density is the ratio of the weight of a given volume of wood to the weight of an equal volume of water. It can be calculated based on oven-dry weight, and volume on oven-dry, air-dry or green condition.

The most common methods utilized to measure small wood samples relative density are gravimetric analyses (Smith, 1954; Ifju, 1969; Elliott, 1970) and x-ray densitometric techniques (Parker _et al_., 1973; Parker and Jozsa, 1973). The latter method is preferred because it easily provides a continuous readout of intra-ring and inter-ring components of cross-sectional wood cores, such as earlywood, latewood and total growth increment widths and relative densities.

Relative density of a given growth increment increases as the proportion of latewood increases and the tracheids become smaller and thicker-walled (Zobel and Talbert, 1984). In Douglas-fir, the average growth increment relative density is controlled mainly by the proportion of latewood tracheids, due to the fact that the relative density of such tracheids is between two and three times higher than that of earlywood tracheids (Ifju and Kennedy, 1962; Ifju _et al_., 1965).

In some species, the variations in relative density are primarily correlated to the number of growth increments from the pith (age) rather than to the growth rate. This means that the growth rates and relative densities of trees of comparable environment, species, age and height are virtually independent traits (Turnbull, 1937; Rendle and Phillips, 1957). In the case of Douglas-fir and many pine species, several studies have substantiated this trend (Goggans, 1961; Smith et al., 1966; McKimmy, 1966; Kennedy and Warren, 1969; De Guth, 1980; Pearson and Gilmore, 1980; Barrett and Kellogg, 1984; Pearson and Ross, 1984). In spruce and fir, however, fast growth rate is usually associated with low relative density (Hale and Fenson, 1931; Hale and Prince, 1940; Aldridge and Hudson, 1959; Chang and Kennedy, 1967).

Within tree relative density variation can be assessed in a horizontal, vertical or diagonal classification scheme (Duff and Nolan, 1953; Forward and Nolan, 1964). The horizontal scheme is the most studied and represents the horizontally or diametrically arranged sequence of growth increments from pith to bark. The vertical scheme represents the vertically arranged sequence of growth increments at the same cambial age. Finally, the diagonal scheme represents the diagonally arranged sequence of growth increments for the same calendar year.

According to the horizontal relative density variation, the juvenile wood relative density can be lower than, higher than or approximately the same as that of mature wood, depending upon species. The most common trend found is a low juvenile wood relative density which gradually increases from the pith to mature wood, where it stabilizes. This trend was described by Loo et al. (1985) for loblolly pine, by Foelkel et al. (1976) for slash pine, by Bower et al. (1976) for Caribbean pine, by Harris (1969a) for radiata pine, by Paul (1950), Wellwood (1952), Littleford (1961), Harris (1969a), Cown (1976), Gerhards (1979), and by Barrett and Kellogg (1984) for Douglas-fir.

The juvenile wood relative density in Douglas-fir was also found highest near the pith, decreasing rapidly in the first growth increments from the pith, then increasing outward to the mature wood (Chalk, 1953; Harris and Orman, 1958; Kennedy and Warren, 1969; Cown, 1976; Megraw and Nearn, 1972; Jozsa and Kellogg, 1986).

The juvenile wood relative density was found to be higher than that of mature wood by Boutelje (1968) for Norway spruce (Picea abies (L.) Karst.), by Taylor et al. (1982), and Wang and Micko (1984) for white spruce, by Jozsa and Kellogg (1986) for interior white spruce or interior Engelmann spruce (Picea engelmannii Parry), by Wood and Bryan (1960) for Sitka spruce (Picea sitchensis

(Bong.) Carr.), by Polge (1964), Wellwood and Jurazs (1968), and Jozsa and Kellogg (1986) for western redcedar, and by Wellwood and Smith (1962), Krahmer (1966), and Jozsa and Kellogg (1986) for western hemlock (Tsuga heterophylla (Raf.) Sarg.).

Little or no horizontal relative density variation between juvenile and mature wood was found by Harris (1969a) for balsam fir (Abies balsamea (L.) Mill.) and Norway spruce, and by Jozsa and Kellogg (1986) for lodgepole pine (Pinus contorta Dougl.) and interior Douglas-fir (Pseudotsuga menziesii var. glauca (Beissn.) Franco).

Considering the vertical relative density variation scheme, the juvenile (crown-formed) wood relative density was reported as significantly lower than that for mature (stem-formed) wood by Cooper (1960) and Brunden (1964) for red pine (Pinus resinosa Ait.). Wellwood (1952, 1960) studying the density variation of 130 Douglas-fir and 39 western hemlock, sampled at stump height, one-third total height and the top of the merchantable stem, found that relative density decreased significantly with increased height of the trees. In contrast, Polge (1964) and Wellwood and Jurazs (1968) found that the crown-formed wood relative density was higher than that of the stem-formed wood in western redcedar.

A slight vertical relative density variation, probably associated with the presence of compression wood in the growth increments close to the pith, has been found within the juvenile wood core of some species. For instance, a small density increase in the terminal portion of the live crown was reported by Harris and Orman (1958) and Kellogg and Kennedy (1986) for Douglas-fir, by Zobel _et al_. (1959) for loblolly pine and slash pine, and by Krahmer (1966) for western hemlock.

Finally, the diagonal relative density variation scheme is characterized by an initial decrease from the apex to approximately the limit of the live crown, followed by an increase toward the stem base. This trend can be seen from the data of Harris and Orman (1958) on Douglas-fir and Richardson (1961) on Corsican pine (_Pinus nigra_ var. _maritima_ (Ait.) Melville).

The most commonly found relative density variation patterns in Douglas-fir are summarized below.

1. Relative density variation patterns are primarily related to the proportion of the latewood tracheids and to the number of growth increments from the pith.
2. Relative density in juvenile wood is high near the pith and in the terminal portion of the live crown, decreases rapidly in the

first growth increments from the pith and increases outward toward the mature wood, where it stabilizes.

3. In interior Douglas-fir there is a slight or no relative density variation from juvenile to mature wood.

2.2.2.2 Other Properties

The physical properties of strength, elasticity and moisture content, in combination with the presence of knots and growth related defects, such as compression wood and spiral grain, determine the suitability of juvenile and mature wood for several end uses. The variations of the strength and elastic properties of juvenile and mature wood are mainly correlated to the respective variations in relative density.

In general, the strength and elasticity of dimension lumber manufactured completely from, or containing a high percentage of, juvenile wood, has been found to be less than the strength and elasticity of mature wood. This trend was reported by Boone and Chudnoff (1972) and Bower et al. (1976) for Caribbean pine, by Pearson and Gilmore (1971, 1980) and Pearson and Ross (1984) for loblolly pine, and by Wangaard and Zumwalt (1949), Littleford (1961), Gerhards (1979), Barrett and Kellogg (1984) and Senft *et al*. (1986) for Douglas-fir.

Juvenile wood moisture content has been reported to be higher than that of mature wood by Zobel *et al*. (1968) and Zobel *et al*. (1972) for loblolly and slash pine, and by Britt (1970) for loblolly pine.

Compression wood in the juvenile wood was reported by Boone and Chudnoff (1972) for Caribbean pine, by Crist *et al*. (1977) for jack pine (*Pinus banksiana* Lamb.) and eastern larch, and by Zobel and Kellison (1972) and Zobel *et al*. (1972) for loblolly and slash pines. In Douglas-fir, the possible presence of compression wood in juvenile wood has been suggested as the principle cause of the high density values observed in the growth increments close to the pith (Chalk, 1953; Harris and Orman, 1958; Kennedy and Warren, 1969; Kellogg and Kennedy, 1986).

High spiral grain angles in juvenile wood were reported by Harris (1969b) for radiata pine and by Zobel *et al*. (1972) for slash and loblolly pines. In Douglas-fir, Northcott (1957), Elliott (1958) and Woodfin (1969) observed that the most frequent spiral pattern was in the left direction near the pith, with the angle increasing in the first formed growth increments in the juvenile wood, and then changing gradually from left to right spirality as the tree age increased.

2.2.3 Juvenile - Mature Wood Transition Determination

Determination of the transition zone from juvenile to mature wood is critical for setting relative proportions, and important in definition of wood quality and timber value. This determination can be difficult, however, because as juvenile wood matures, the changes in its properties are gradual and often erratic.

The characteristics of change differ according to species and wood properties selected for analysis. For example, the mechanical properties and relative density of wood generally indicate maturity earlier than tracheid length and microfibril angle (Bendtsen, 1978; Megraw, 1985; Bendtsen and Senft, 1986).

Some species of spruce (Picea spp.), fir (Abies spp.) and cypress (Cuppressus spp.) are characterized by an indistinct juvenile - mature wood transition zone. Therefore, the differences in properties between juvenile and mature wood are difficult to observe (Zobel, 1984). In contrast, Douglas-fir and most hard pines, such as loblolly pine, slash pine and Caribbean pine, show a more distinct juvenile - mature wood transition zone.

Several subjective and objective methods have been utilized to define the transition zone between juvenile and mature wood.

2.2.3.1 Subjective Methods

The first, and perhaps the most general, method of determining the juvenile - mature wood transition zone from the subjective viewpoint is visual examination of stem cross sections or increments cores. For instance, Zobel et al. (1959) defined the transition zone for slash pine as the first five to eight growth increments from the pith, and for loblolly pine as the first seven to 11 growth increments from the pith, based on the dull and lifeless appearance of juvenile wood stem cross section samples when dried.

Yang et al. (1986) defined the transition zone in eastern larch (Larix laricina (Du Roi) K. Koch) as the first four to 45 growth increments from the pith, depending on the sampling height. The transition zone was visually determined in two cm wide diametric strip wood samples based on the light colour and width of growth increments in the juvenile zone.

Other authors have defined the transition zone by comparing the wood properties of young trees with the wood properties of old trees. Zobel and Kellison (1972) used this method when defining the transition zone as the first ten growth increments from the pith, by comparing the wood properties of 11-year-old juvenile to 30-year-old mature loblolly pine trees. Boone and Chudnoff (1972) and Bower et al. (1976) utilized the same approach when comparing plantation grown and forest grown Caribbean pine trees.

The transition zone can also be defined by comparing the wood properties of juvenile (crown-formed) wood to mature (stem-formed) wood. The age at the base of the live crown can then be identified as the transition age between juvenile and mature wood. Brunden (1964), studying red pine, found that the length and relative density of stem-formed tracheids were significantly higher than those from crown-formed wood. He did not, however, consider the age at the base of the live crown. Cooper (1960) found that red pine stem-formed wood relative density was significantly higher than that of the crown-formed wood. He identified the age at the base of the live crown as approximately 20 years.

Finally, the juvenile - mature wood transition zone has been determined on the basis of changes in certain anatomical or physical wood properties between the closest and farthest growth increments from the pith. The transition zone is defined as the location where the values of these properties begin to remain constant. In southern and tropical pines, the transition zone ranges from six to 15 growth increments from the pith (Zobel and McElwee, 1958; Pearson and Gilmore, 1980; Bendtsen, 1978; Zobel, 1984; Senft et al., 1985). In Japanese larch (Larix leptolepis (Sieb. and Zucc.) Endl.) and white spruce, the transition zone has been reported as the first ten growth increments from the pith by Isebrands and Hunt (1975) and by Taylor et al. (1982).

In Douglas-fir, the transition zone has been reported as the first 15 to 20 growth increments from the pith (Wellwood and Smith, 1962; McKimmy, 1966; Erickson and Arima, 1974; Erickson and Harrison, 1974; McKimmy and Campbell, 1982; Barrett and Kellogg, 1984; Senft et al., 1985; Jackson and Megraw, 1986; Senft et al., 1986; Jozsa and Kellogg, 1986).

2.2.3.2 Objective Methods

Recently, some researchers have utilized more objective methods to define the zone of transition between juvenile and mature wood. For instance, Shiokura (1984) used a logarithmic regression equation to relate tracheid length to the number of growth increments from the pith (age). The transition zone was defined when a one percent tracheid length difference was recorded between two consecutive growth increments. The transition ages at different heights were 11 to 19 on Japanese larch, 14 to 18 on Sakhalin fir (Abies sachalinensis Mast.) and on Hondo spruce (Picea jezoensis (Sieb. and Zucc.) Carr.) and 20 to 22 on Japanese red cedar (Cryptomeria japonica (L.F.) Don).

Yang et al. (1986) utilized two simple linear regression models to relate tracheid length to number of growth increments from the pith. The first model was fitted in the juvenile wood zone, where the length of tracheids increased, and the second was fitted in the mature wood zone, where the length of the tracheids remained constant. The transition zone, which was determined as the age at which the juvenile and mature regression models intersected, was found to be from ten to 44, depending on tree height.

Loo et al. (1985), studying the genetic variation in the time of transition from juvenile to mature wood in loblolly pine, utilized a combination of three methods to define the transition age, and considered the properties of specific gravity and tracheid length. The first method involved fitting two simple linear regression models to the data, which were plotted as functions of age. The age of the transition was estimated as the age at which the second model (mature wood) showed the best fit, determined by the smallest residual sum of squares. The second method was used when the best fitted mature wood model, using the first method, showed a negative slope. In this case, the slope of the mature wood model was held constant at zero, assuming that the mature wood values fluctuate around the constant mean. The third method was a visual examination, used when the data points did not conform to the former two patterns of variation. The mean ages of transition were found to be 11.45 and 10.30 years for specific gravity and tracheid length, respectively.

Bendtsen and Senft (1986) applied three methods to both individual tree and average values of strength, elasticity, specific gravity, cell length and fibril angle to determine the transition ages for loblolly pine and cottonwood (Populus deltoides Bartr.). The methods used were segmented regression analysis, discriminate analysis, and analysis of slope. None of these methods produced a consistent demarcation between juvenile and mature wood because of the large variability among values from tree to tree and year to year. Therefore, visual interpretations of the data and data plots were used to determine the transition ages, which were, depending on the property analyzed, 12 to 18 for loblolly pine and 17 to 18 for cottonwood.

In conclusion, it can be said that the age of the juvenile - mature wood transition ranges from five to 18 years in southern and tropical pines, from 15 to 20 years in Douglas-fir, and from four to 44 years in the rest of the species described, depending on the sampling height and wood property analyzed. In some species of spruce, fir and cypress, the juvenile - mature wood transition zone is not clearly defined.

3.0 MATERIALS AND METHODS

In order to test the project hypothesis, 13 unpruned, two pruned second-growth, and two unpruned plantation-grown coastal Douglas-fir trees were sampled from nine stands as follows.

Six second-growth stands were selected on the west and east coasts of Vancouver Island, British Columbia as a part of the Douglas-fir Task Force Project (Kellogg, 1986). The stands were approximately 50 years old and growing on sites of medium to good productivity. Ten dominant and codominant Douglas-fir trees of uniform growth rate (growth increments of approximately four to five mm per year) were selected from each stand by the Task Force for basic wood property studies. The two felled trees per stand with the most intact crowns were selected for the present study of the transition from juvenile wood to mature wood. Five additional trees were selected to extend sampling to pruned stands, and to sites of different productivity. One tree was measured in each of two 37-year-old plantations growing on soil of high (marine clay) and low (gravel outwash) productivity located west of Campbell River. One unpruned 21 year-old tree, and two pruned trees of 51 and 45 years of age were sampled from the University of British Columbia

Research Forest at Haney. The pruned trees were approximately 15 cm D.B.H. and approximately 14 m tall when the lower one-third of the live crown was removed to a height of four to five metres in 1954.

The location of the stands is shown in Figure 1, while stand characteristics are given in Table 1. Sample tree data are shown in Table 2.

3.1 External Tree Characteristics

The external tree characteristics were categorized as stem and crown respectively. The following stem measurements were made and recorded:

1. Age at stump;
2. Total tree height;
3. Internodal distances over the length of the stem;
4. Height to base of live crown (distance from the ground to the lowest whorl which has three or more live branches); and
5. Inside and outside bark diameters of five cross-sectional discs, eight to 16 cm thick, cut from breast height, and positions 20, 40, 60 and 80 percent of total tree height.

These measurements were taken to estimate the curve representing cumulative height growth over number of growth increments from the pith for each tree. The cross-sectional discs were taken to Forintek Canada Corporation's x-ray densitometry laboratory in Vancouver for further analysis.

To study the actual crown characteristics, crown cover, live branches and height to base of the live crown were measured as follows. The crown cover, or ground area covered by the vertical projection of each crown, was measured using a metric tape and a Suunto clinometer with a 90 degree scale (Husch et al., 1982). An average crown radius was estimated from six to seven crown radii measurements taken every 45 degrees around the perimeter of the crown and towards competing trees (Table 3).

Length and height position of two live branches of similar diameter from opposite sides of every second whorl were measured from each tree. The height to base of live crown was determined by measuring the distance from the ground to the lowest whorl which had three or more live branches. In addition, an average crown height was calculated as a function of the average crown radius, which represented the maximum length of the branches located at the widest part of the crown. Average crown height was estimated in order to relate the results of this project to the Ministry of Forests and Lands Tree and Stand Simulator Model (TASS) (Mitchell, 1975, 1980; Mitchell and Cameron, 1985). The procedure for estimating average crown height is summarized in Appendix 1 and the results are contained in Table 3.

To study the development of the crown over time, two representative dead branches or branch stubs were collected from every second or third branch whorl. Each branch was examined to determine the number of growth increments at the base, which represented the age at which the branch stopped producing growth increments. Discs of one cm thickness were cut from each branch base, labelled and sanded. The growth increments in each branch disc were counted and recorded using a low power stereoscopic microscope. The number of growth increments in each branch disc and the corresponding whorl height position were utilized to determine the approximate position of the base of the live crown at younger ages. An example of this determination is shown in Appendix 2.

3.2 Internal Tree Characteristics

To study the internal tree characteristics, x-ray densitometric techniques were utilized to determine growth increment relative density data. Linear regression techniques were utilized to estimate the juvenile - mature wood transition age from the data.

3.2.1 X-Ray Densitometric Analyses

For the x-ray densitometric evaluation, a total of 85 cross-sectional discs (17 trees, five sample heights) of eight to 16 cm thick, were sampled. On each disc, two average radii sections at least 90 degrees apart were measured and labelled, avoiding knots, resin pockets and compression wood. The average radii were first cut into strips of one cm thick and 10 cm wide. They were then re-cut into smaller sample strips, five mm wide in the tangential direction and six mm thick along the grain, resembling increment cores. The wood sample strips were utilized for x-ray densitometric analysis following the procedures explained in detail by Parker and Jozsa (1973) and by Parker et al. (1973, 1980). A summary of these procedures is presented in Appendix 3.

A total of 170 wood core radii were scanned using the above procedure. The relative density values were expressed on an oven-dry volume and weight basis. Annual pith to bark relative density profiles (average relative density of two core radii growth increments per sample section) were plotted to determine the annual growth increment relative density variation patterns as a function of number of growth increments from the pith and height position on the stem of each sample tree, as shown in Figure 2, for Sample Tree 1A5.

3.2.2 Juvenile - Mature Wood Transition Determination

After plotting the relative density profiles of each sample section, a visual examination was done to detect the lowest relative density value and a possible juvenile - mature wood zone based on the shape of the profile. Two categories of profiles were identified. The first category included the relative density profiles which showed fairly constant relative density values from the pith to bark, without a clear definition of transition zone. In this case, a simple linear regression model was fitted to each profile, starting from the lowest relative density value outwards, and it was assumed that the profile represented juvenile wood entirely.

The second category included the profiles that showed an initial decrease in relative density in the first growth increments from the pith, followed by a gradual linear increase for a certain number of increments, then a final levelling off outwards. This relative density variation pattern indicated the possible evidence of a transition zone in the profile. To determine such transition zone, a segmented regression analysis of each relative density profile was done as described below (Hudson, 1966; Draper and Smith, 1981).

1. A segmented regression model, which combines two linear segments, was fitted to each of the profiles starting at the lowest relative density value. The model utilized was:

$$\hat{y} = b_0 + b_1 b_2 + b_3(x - b_2)$$

where:

$\hat{y}$ = predicted value (relative density)

b_0 = intercept of first line segment

b_1 = slope of first line segment

b_2 = transition age estimate

b_3 = slope of second line segment

x = independent variable (number of growth increments from the pith)

2. The best fitted model was determined by minimizing the total residual sum of squares of every possible division of the points between the first and the second segment. This method is called the Least Squares Line of Best Fit and is given by:

$$\sum_{i=1}^{n} e^2_i = \sum_{i=1}^{n} (y_i - \hat{y}_i)^2$$

where:

$\sum_{i=1}^{n} e^2_i$ = residual sum of squares

y_i = observed values (relative density)

$\hat{y}_i$ = predicted values (relative density)

The division and set of estimates that gave rise to the smallest residual sum of squares was selected. This was done by means of a Fortran program which included non-linear optimization routines (Appendix 4).

3. The constraints of this procedure were that the first segment must start at the lowest relative density data point and that the intersection point between the two segments must be between two consecutive growth increments that split the data set.

4. The point of intersection between the two linear segments was identified to determine the number of growth increments (age) at which the transition from juvenile to mature wood occurred.

5. To verify the need for a segmented regression analysis, a statistical "F" test was done, calculating the ratio between the mean sum of squares residual value of a simple linear regression model and that of a segmented regression model, both fitted to the same profile (Figures 3a and 3b). When the "F" ratios calculated were greater than the "F" values tabulated by Pearson and Hartley (1954) the segmented regression model was chosen to determine the juvenile - mature wood transition zone. When the "F" ratios calculated were lower than the "F" values tabulated, the simple regression model was chosen and the juvenile - mature wood transition zone could not be determined. In this case, it was assumed that the relative density profile represented juvenile wood entirely.
6. The determinations of the transition zone by the segmented regression analysis were checked against the corresponding profile to ensure that the regression model used was the most reasonable choice with respect to the data.

After determination of the juvenile - mature wood transition age for each relative density profile, relationships between number of growth increments from the pith and tree height position of both transition zone and base of the live crown were established. These within tree and between tree relationships were utilized to test the project hypothesis, and can be used to further extend the TASS model (Mitchell, 1975, 1980; Mitchell and Cameron, 1985) for predicting the volume of both juvenile and mature wood. In addition, average juvenile and mature annual growth increment relative densities were determined to observe the within tree and between tree relative density variations.

4.0 RESULTS AND DISCUSSION

Table 2 gives a summary of sample tree characteristics. The plantation-grown and second-growth trees were dominant and codominant with ages at breast height ranging from 21 to 63 years, diameters at breast height from 19.8 to 68.2 cm and total heights from 16.8 to 44.7 m. These plantation-grown and second-growth trees were analyzed separately from the pruned trees. It must be noted that sample trees were selected from the nine sites without attempting to achieve a representation of the total population.

4.1 X-Ray Densitometric Analyses

Summaries of the relative density values of 15 trees for sections sampled at breast height, 20 percent, 40 percent, 60 percent and 80 percent of total tree height are presented in Tables 4 to 8 respectively. For each sample section, relative density is expressed as the mean of all annual growth increment means. Pith to bark relative density profiles are illustrated for Sample Tree 1A5 in Figure 2.

The general relative density variation pattern of all sections sampled at breast height showed an initial decrease from the pith to a point within the second through tenth growth increments followed by a linear increase which gradually stabilized outwards over subsequent growth increments from the pith. Overall mean relative density for these sections was 0.523, with a maximum of 0.625 and a minimum of 0.413. The number of growth increments varied from 21 to 63 (Table 4).

At 20 percent of total height the relative density variation pattern was similar to that of all sections at breast height. Overall mean relative density was 0.485, with a maximum of 0.589 and a minimum of 0.389. The number of growth increments varied from 17 to 53 and sample height from 3.3 to 8.5 m (Table 5).

Sections sampled at 40 percent of total height showed an initial decline in relative density from the pith to a point within the third through fifteenth growth increments, followed by a gradual increase outwards. In a few cases, a gradual decrease outwards was observed also. Overall mean relative density for these sections was 0.467, with a maximum of 0.549 and a minimum of 0.400. The number of growth increments ranged from 13 to 45 and sample height from 5.1 to 17.2 m (Table 6).

At 60 percent of total height there was an initial decline in relative density from the pith to a point within the fourth through fourteenth growth increments, followed by a moderate increase outwards. Overall mean relative density for these sections was 0.462 with a maximum of 0.551 and a minimum of 0.410. The number of growth increments varied from eight to 31 and sample height from 9.9 to 25.8 m (Table 7).

The sections sampled at 80 percent of total height showed an initial decrease in relative density from the pith to a point within the fourth through twelfth growth increments, followed by an irregular and moderate increase outwards. Overall mean relative density for these sections was 0.478 with a maximum of 0.556 and a minimum of 0.437. The number of growth increments varied from four to 19 and sample height varied from 13.4 to 36.1 m (Table 8).

From the above results, it would appear that the horizontal relative density variation pattern at the five sample heights is characterized by an initial decrease from the pith followed by a gradual increase and stabilization outwards, particularly in the lower sections (i.e. breast height, 20 and 40 percent of total height). Similar horizontal relative density variation patterns for Douglas-fir trees were reported by Paul (1950), Wellwood (1952), Chalk (1953), Littleford (1961), Harris (1969a), Kennedy and Warren (1969), Cown (1976), Gerhards (1979), Barrett and Kellogg (1984), and by Jozsa and Kellogg (1986).

The vertical overall mean relative density for sections at breast height to 60 percent of total height (Tables 4 to 8) showed a decrease from 0.523 to 0.462, followed by an increase to 0.478 for sections at 80 percent of total height. In percentages, the decrease in relative density from breast height (100 percent) represented approximately seven, 10, 12 and eight percent respectively. This indicates that, in general, relative density decreases with height of sampling. Qualitatively similar density vertical variation patterns were reported by Wellwood (1952, 1960), and by Megraw (1986).

4.2 Juvenile - Mature Wood Transition Determination

A total of 75 relative density profiles (15 trees, five sample height positions per tree) were investigated in order to detect transition zones between juvenile and mature wood. The profiles were divided into two categories based on the configuration of the data points pertaining to relative density and number of growth increments from the pith.

The first category involved a total of 38 profiles characterized by having no clear definition of a juvenile - mature wood transition zone. In general, these profiles showed an initial decrease in relative density from the pith to a point within the fourth through thirteenth growth increments, followed by a gradual increase, decrease or levelling off outwards. To illustrate such trends, simple linear regression models were fitted to each profile, starting from the lowest relative density value outwards, assuming that they represented juvenile wood entirely (Appendices 5a to 19a).

Table 9 shows a summary of the distribution and characteristics of these profiles among sample heights. The average number of growth increments was 18.42, ranging from 4 to 33, and the average section height was 20.99 m, ranging from 1.30 to 36.10 m. It can be seen that about 80 percent of the cases for which no evidence of juvenile - mature wood transition zone was found were at sections 60 and 80 percent of total height. In 15 percent of the cases no transition was found at 40 percent of total height. Only in five percent of the cases was no transition found at sections sampled at breast height and 20 percent of total height, corresponding to the younger sampled tree, i.e. RF1 (Appendix 19).

From the above, it is concluded that mature wood and therefore the juvenile - mature wood transition zone, was not present in the upper 40 percent of the stem nor in lower sections containing few growth increments from the pith (i.e. 13 to 33).

The second category comprises relative density profiles which gave evidence of a transition zone. These profiles, in general, showed an initial relative density decrease in the first growth increments from the pith, followed by a gradual increase over several additional growth increments, then a final levelling off outwards.

A total of 37 profiles from 14 trees were investigated in this section. Segmented linear regression models, starting at the lowest relative density value, were fitted to these profiles in order to determine the juvenile - mature wood transition zone (Appendices 5a to 18a). The point of intersection between the two linear segments corresponding to the segmented model was identified as the number of growth increments from the pith (age) at which the transition from juvenile to mature wood occurred.

Table 10 gives a summary of the transition ages of each tree sample section, determined using segmented linear regression models. To verify the need of such models, the "F" ratio of the mean sum of squares residual value of a simple linear regression model to that of a segmented model, both fitted to each relative density profile, was calculated for each sample section (Table 10). In all cases, the calculated "F" ratios were greater than one, indicating that the segmented regression model showed a smaller sum of squares residual value, thus a better data fit. The probability level at which the calculated "F" ratios were statistically significant varied from 0.001 to 0.470. Despite such a large range of level of significance, it was assumed that the segmented model was the best representation of the high variability among the values in some data sets, particularly considering that 56 percent of the "F" ratios were within the 0.30 level of probability.

Figure 4a illustrates the distribution of sample section heights over the number of growth increments from the pith (age) at which the transition occurred, when segmented regression models were fitted to the relative density profiles. As can be seen, no systematic variation trend was found, indicating that transition age and sample height are independent. Table 11 gives a summary of average transition ages by sample section heights. These averages were 22.36, 22.86, 20.89 and 22.18 years for sections sampled at breast height, 20 percent, 40 percent of total height and for all sections, respectively. The similarity of the average transition ages also indicates that transition age and height of sampling are not related. In addition, the average transition age of 22.18 years for all sections was very close to the maximum reported transition age for Douglas-fir, which is 20 years (McKimmy and Campbell, 1982; Barrett and Kellogg, 1984; Senft et. al., 1985; Jozsa and Swan, 1986).

4.2.1 Juvenile - Mature Wood Relative Density Values

Annual juvenile and mature wood relative density values were determined to observe within tree and between tree relative density variations. Summaries of relative density values for each tree are presented in Appendices 20a to 20o. Table 12 summarizes the relative density profiles which illustrated no clear juvenile - mature wood transition zone. These profiles, considered as representative of juvenile wood, had an average number of growth increments from the pith of 18.42 and an overall mean relative density of 0.467 ranging from 0.416 to 0.551.

Table 13 summarizes the relative density profiles which showed a defined juvenile - mature wood transition zone. For these profiles, the average numbers of growth increments contained within the juvenile and mature wood were 22.18 and 19.95, respectively. All sample sections mean relative densities were 0.472, 0.533 and 0.501 for juvenile, mature and total respectively.

Table 14 summarizes relative density values for juvenile and mature wood. This is a combination of the results shown in Tables 12 and 13. The overall average numbers of growth increments representing juvenile and mature wood were 20.28 and 19.95, respectively. The juvenile wood transition value is almost identical to the reported maximum transition value of 20 growth increments. The overall mean juvenile wood relative density was 0.469, ranging from 0.410 to 0.561. The lowest juvenile wood relative density values were found at sections sampled at 20 and 40 percent of tree height. The overall mean mature wood relative density was 0.533 (14 percent greater than that for juvenile wood), ranging from 0.474 to 0.594.

4.3 Base of the Live Crown

A total of 120 dead branches were sampled from 12 trees in order to approximate individual height to live crown base curves before harvest, as illustrated in Appendix 2. Table 15 shows a summary of the average number, height position, and number of growth increments found at the base of dead branches in each tree. Figure 4b illustrates the overall distribution of the branches among trees as a function of height position in stem and number of growth increments at the branch base. As can be seen, the general trend was that the number of growth increments found in dead branches increased with tree height.

It is important to note that as the branches get older, their vigor decreases, leading to the formation of incomplete or absent growth increments at the branch base (Andrew and Gill, 1939; Reukema, 1959, 1961). Although few live branches located at the crown base were examined, the tendency was to find some discrepancies between the number of growth increments at the branch base and that of the tree stem at the point of intersection. Growth increment counts showed five to eight fewer growth increments in the lower crown branches than in the stems at points of intersection.

Reukema (1959) stated two possible reasons for this apparent failure of branches in forming growth increments. The first was that the cell formation ceased during the latter years of the branch's life. The second was that a considerable decrease in cambial activity at this time produced very narrow growth increments, i.e. one to two cells wide, without earlywood and latewood differentiation.

From the above, it can be concluded that despite the fact that the lower crown branches appeared healthy, with plentiful foliage, they are probably no longer part of the functional crown. This may introduce some possibility of error when the base of the live crown is reconstructed based upon the number of growth increments found at the base of dead branches. In addition, this represents an argument in favor of pruning lower crown live branches.

Table 3 summarizes the crown characteristics measured for the sampled trees at time of harvest. As illustrated, the overall crown base height, estimated as the height from the ground to the lowest whorl at which three or more live branches were located, was 19.7 m, ranging from 9.0 to 24.8 m. The overall average crown height, estimated as a function of the average crown radius (Appendix 1) was 24.2 m, ranging from 12.0 to 35.0 m. In some cases, this position was also identified as the crown contact or point of intersection with neighbouring trees. This was done by looking at symptoms of whipping or breaking damage on the terminal shoots of the branches.

Figures 5a and 5b illustrate the observed data distribution and height prediction linear regression models for crown base height and average crown height as functions of total tree height. Figure 6 shows the former linear regression models with the addition of the observed total tree heights for each tree. As can be seen, both crown base height and average crown height increase with increasing total tree height at a very constant rate of change. This indicates a fairly consistent within and between crown measurement variation as a function of total height.

4.4 Relationships Between Juvenile - Mature Wood Transition and Base of the Live Crown

A series of graphical representations were prepared in order to clarify the project hypothesis. Figure 7 shows two hypothetical curves representing total tree height and height to crown base over the number of growth increments from the pith at breast height. If the project hypothesis is correct, the curve representing height to crown base will also represent the points of juvenile - mature wood transition occurring at different heights and ages in the tree. Alternatively, if the hypothesis is not correct, the height to crown base will not be coincident with the points at which the juvenile - mature wood transition occurs.

Figure 8 illustrates the height to crown base before harvest, the observed base of the live crown and calculated average crown height, i.e. distance from the ground to the widest part of the crown, at harvest.

The next step is to relate the former crown height positions to the corresponding juvenile - mature wood transition points. These relationships can, then, be established before or after harvest in order to test the project hypothesis as follows.

4.4.1 Hypothesis Testing Before Harvest

Appendices 5b to 19b illustrate individual and overall (Figures 9a, 10a and 10b) relationships for total height, height to crown base and height to juvenile - mature wood transition points as functions of number of growth increments from the pith at breast height. In addition, the height to the lowest relative density values in each sample section was also plotted to establish relationships with the former curves (Figure 9b and Appendices 5b to 19b). The lowest relative density values presented in Figure 4c and Table 16, were the starting points for the segmented and simple linear models fitted to each profile. From Appendices 5b to 19b, the following individual tree characteristics are summarized below.

1. The curves representing height over number of growth increments from the pith at breast

height were very similar and can be classified within Site Classes I and II (i.e. good and medium good) for coastal Douglas-fir, according to Bruce (1981). The exception was tree CR1 (Appendix 17b) which was sampled from low productivity Site Class IV (i.e. medium poor).

2. The lowest relative density curves were, in general, lower and parallel to the total height curves. The average difference between the number of growth increments between these curves was 7.1, with a range of two to 15 and a standard deviation of 2.9 (Table 16). This suggests not only a very consistent pattern of decreasing relative density in the first growth increments from the pith, but also a tendency to find the lowest relative density value within a constant short distance from the tree apex at any height of sampling. This distance probably represents the upper one-third of the live crown.

3. The height to crown base curves were parallel to the total height curves up to the region between 20 and 40 percent of the tree height,

and then they diverged towards the direction of the live crown base at harvest. This is to be expected, since the number of growth increments in branches increases with tree height up to the base of the live crown, and then decreases towards the apex.

4. The height to crown base curves were also parallel and sometimes coincident with the lowest relative density curves, particularly at lower sample heights. Therefore, it would appear that there is a biological connection between the number of growth increments found at the base of dead branches and that at which the annual increment relative density value is lowest. This would suggest that the productivity of a branch decreases with age, due to the declining photosynthetic efficiency and retention of needles. Growth increment relative density decreases proportionally until reaching a minimum value when the branch stops producing growth increments.

5. The data points representing height position and number of growth increments from the pith at which the juvenile - mature wood

transition occurs were lower and generally parallel to the former three curves (i.e. total height, lowest relative density, and crown base) for equal numbers of growth increments from the pith. The height difference between the height to crown base and the transition points slightly decreased with increasing sample height. This suggests that juvenile - mature wood transition occurs below the total height curve, the lowest relative density curve and the crown base curve, with a moderate tendency to approach the crown base curve at higher sample heights.

To illustrate general height variation trends, data from twelve trees were utilized to estimate the following overall height prediction models:

$$y = 1.0909x^{0.9633}\ 0.9968^{x}$$

y = total height
x = growth increments from pith
r = 0.9781 (correlation coefficient; 60 observations)

$$y = -3.5855 + 0.8954x - 0.0037x^{2}$$

y = lowest relative density height
x = growth increments from pith
r = 0.9324 (correlation coefficient; 60 observations)

$$y = -6.3482 + 1.0073x - 0.0088x^2$$

y = crown base height
x = growth increments from pith
r = 0.9089 (correlation coefficient; 120 observations)

$$y = -6.9988 + 0.4853x$$

y = juvenile - mature wood transition height
x = growth increments from pith
r = 0.7174 (correlation coefficient; 37 observations)

Trees CR1, CR2 and RF1 were not included in these models because they lacked either dead branch measurements or juvenile - mature wood transition determination. Figures 9a, 9b, 10a and 10b illustrate the observed data points and corresponding height prediction models for total height, lowest relative density height, crown base height and juvenile - mature wood transition height as a function of number of growth increments from the pith at breast height.

Figure 11 combines the former four height prediction models with the addition of diagrammatic representations of trees at different states of development, to facilitate the interpretation of the results. It can be seen that the overall models follow the same variation patterns as those already described for individual observations on each tree.

The lowest relative density curve was parallel and very close to the total height curve. This suggests that a minimum growth increment relative density value is likely to be found within a short distance from the tree apex. The crown base curve was parallel to the total height curve up to about 40 percent of the total height where it started to diverge towards the position of the live crown base at harvest. This curve was also parallel and very closely related to the lowest relative density curve, particularly at lower sample heights.

The simple linear regression model fitted to the points representing juvenile - mature wood transition was lower and parallel to the curves already described. However, due to the distribution of the data, this regression line does not accurately represent the mean values of the sections sampled at breast height and 40 percent of total height, as shown in Figure 10b.

From the relative density point of view, Figure 11 can also be interpreted as a vertical relative density variation pattern. In this pattern, a maximum growth increment relative density value is found near the tree apex, a minimum value found within the upper one-third of the crown and a gradual increase in value found toward, and past, the crown base until the juvenile - mature wood transition zone, close to the base of the tree. The juvenile and mature growth increment mean relative density values reported in Table 14 support the interpretation of such a characteristic vertical relative density variation pattern. Similar variation patterns were found by Chalk (1953) and by Harris and Orman (1958).

The height difference between height to crown base and height to transition point, for equal numbers of growth increments from the pith, as a function of transition height, was plotted in Figure 12a. A definite downward trend with increasing transition height can be seen. Figure 12b illustrates the height difference between total tree height and height to transition point as a function of transition height. In this case, a slight downward trend with increasing transition height was also found, although the correlation coefficient was not significant at the 0.05 level of probability, i.e. $r = -0.2531$ (37 observations).

Table 17 shows the average height differences between height of juvenile - mature wood transition points, height to crown base and total height. The average differences between height of transition points and height to crown base were 10.25, 8.71 and 3.85 m for sections sampled at breast height, 20 and 40 percent of total height, respectively. The average differences between height to transition points and total height were 18.95, 18.51 and 14.59 m for sections sampled at breast height, 20 and 40 percent respectively. These average height differences confirm the variation trends shown in Figures 12a and 12b. When considering all sampled sections, the average juvenile

- mature wood transition height was found at 7.95 and 17.72 metres below the crown base and the tree apex (Table 17).

From the above, since the transition did not occur at the base of the crown, it is concluded that the hypothesis, when analyzed before harvest, has not been proven.

As discussed earlier, it is important to point out that discrepancies between the number of growth increments at the branch base and that of the tree stem at the point of intersection are likely to occur. Therefore, the height to crown base position at earlier ages, estimated by counting the number of growth increments at the base of the dead branches, can be overestimated. For instance, fewer growth increments in the lower crown branches than in the stem at points of intersection would define a higher position of the crown base, thus, a greater height difference between the transition point and the crown base.

From the above, it is concluded that the differences between height of transition points and height of crown base could be reduced to a point at which the hypothesis could be proven, i.e. juvenile - mature wood transition occurs at the base of the live crown. However, the extent of this reduction was not intensively investigated in the project.

4.4.2 Hypothesis Testing After Harvest

The results of testing the project hypothesis after harvest are difficult to validate because a time gap will be required in order to confirm whether the transition between juvenile and mature wood occurs at the actual base of the live crown. However, a possible alternative is to estimate the occurrence of juvenile - mature wood transition heights as functions of earlier ages and heights at which the transition took place, i.e. before harvest. These height estimates, then, are based upon the calculation of an average of transition ages, called average transition height A, and an average of transition heights from the tree apex, called average transition height B, as shown in Figure 13.

Figure 14 illustrates the number of growth increments corresponding to the juvenile - mature wood transition, i.e. determined using segmented regression models, from sections sampled at breast height, 20 and 40 percent, and overall section averages (average of transition ages) for each tree. Figure 15 illustrates the differences between total heights and earlier juvenile - mature wood transition heights from sections sampled at breast height, 20 and 40 percent, and overall section averages (average transition height B) for each tree.

For each tree, the average transition age was converted to average transition height A by interpolation from the curve representing height over number of growth increments from the pith at breast height (Appendices 5b to 18b). Both average transition heights A and B were calculated because no systematic data variation trend within and between trees was detected, as shown in Figures 14 and 15.

Observed data distribution and height prediction models for average transition heights A and B, crown base height and average height as functions of total tree height are shown in Figures 16a, 16b, 5a and 5b respectively.

Figure 17 shows a combination of the former four linear regression models with the addition of the corresponding total tree height of each tree. It can be seen that the height positions pertaining to average crown, average transition A, live crown base and average transition B increased with increasing total tree height. The slopes of these models indicated relatively constant rates of height change. The average crown height regression line was located higher than those corresponding to the average transition height A, live crown base height and average transition height B. The average transition height A regression line was higher than that corresponding to average transition height B and to live crown base height. Only one tree at the lower height end showed a live crown base higher than the average transition height A, reversing the variation pattern established at the higher height end.

The same relationships can be seen in the summary of average height differences presented in Table 18. The average difference between total height and average crown height, average transition height A, crown base height and average transition height B were 10.26, 12.63, 14.76 and 17.91 m, respectively. Since earlier results showed that the overall average of juvenile - mature transition height was found 17.72 m below the tree apex (Table 17), it can be stated that average transition height B, located 17.91 below the tree apex, would better represent the possible occurrence of transition from the tree apex at harvest.

The average height difference between transition height A and average crown height was 2.16 m and between transition height A and live crown base height it was -2.21 m (Table 18). The correlation coefficients obtained between transition height A, average crown height and live crown base height were 0.7936 and 0.8419, respectively (Table 19). The average height difference between average transition height B and average crown height was -3.12 m, and between average transition height B and live crown base height it was -7.50 m (Table 18). The correlation coefficients between average transition height B, average crown height and live crown base height were 0.5888 and 0.7340, respectively (Table 19).

From the above, it can be summarized that average transition height A occurred below the average crown height and above the live crown base height. Average transition height B occurred below both the average crown height and the live crown base height. Neither of the calculated juvenile - mature wood average transition heights A nor B occurred at the base of the live crown position after harvest. Average transition height A seemed to be closer to the average crown height and the live crown base height than the average transition height B. However, assuming that the transition would be likely to occur below the base of the live crown position, as demonstrated earlier, the average transition height A might overestimate the height of the transition. Average transition height B, then, would better represent the possible occurrence of the transition after harvest.

As illustrated in Table 17 and Figure 12a, the difference between height to live crown base and height to transition points before harvest decrease with increasing tree height. The average height differences were 10.25, 8.71 and 3.85 m for sections sampled at breast height, 20 and 40 percent of total tree height respectively (Table

17). Assuming that these height differences will continue to decrease with tree height, the average transition height B found at 3.12 m (Table 18) below the observed base of the live crown position seemed a very reasonable estimate of the occurrence of the transition after harvest.

In view of the above, it is concluded that the average juvenile - mature wood transition height B, calculated as a function of earlier transition height positions, best represents an actual estimate of transition occurrence. Since neither of the estimated average transition heights A nor B occurred at the base of the live crown position, it follows that the hypothesis when analyzed after harvest is not proven.

The similar results found when testing the hypothesis before and after harvest can be, in part, supported by Larson (1969) who stated that:

> "The major changes in wood formation and quality occur in the lower stem beneath the living crown or beneath the most active branches of the crown."

In this project, the transition from juvenile to mature wood occurred below the arbitrary definition of live crown base, i.e. height to the lowest whorl which has three or more live branches. However, Larson's interpretations of the juvenile - mature wood transition, the extension of the living crown and location of the most active branches in the crown, may not be biologically coincident with the results of this project. This suggests that a wrong definition of what is in reality the base of the live crown, as it relates to wood formation, may also lead to a wrong answer when testing the project hypothesis.

4.5 Pruned Trees

As was stated in the literature review, pruning of live and vigorous lower branches in the crown can produce a faster change from juvenile to mature wood, therefore reducing the proportion of juvenile wood core in a given tree. In this project, two pruned trees were analyzed in order to investigate the effects of pruning on annual increment relative wood density. The results were then analyzed to determine their relationship to the project hypothesis.

Figures 18 and 19 show the relative density profiles as a function of number of growth increments from the pith. As shown, additional sample sections at ten percent of total tree height were included because they were located within the pruning area. This area comprised the lower one-third of the live crown, representing a height of approximately four to five metres, i.e. below the sample sections at 20 percent of total height. In these figures, the arrows in the relative density profiles on the sections sampled at breast height and 10 percent of total height indicate the year in which the pruning was done, i.e. 1954 or 30 years before the trees were harvested.

The relative density profiles of sections sampled at breast height and 10 percent of total tree height in tree RF2 showed a gradual initial increase or decrease in the first growth increments from the pith, followed by a sudden increase soon after the pruning was done, and a final gradual decrease outwards.

The relative density profiles for the same sample sections in tree RF3 showed a similar variation pattern, until after pruning was done, and then they distinctively showed a final levelling off outwards. This suggests that relative density can be increased by pruning of lower crown live branches.

The different relative density variation patterns of these trees after pruning was probably due to the fact that RF2 was more dominant and open grown than RF3. Therefore, RF2 was able to overcome the effects of pruning in a relatively short time.

The numbers of growth increments from the pith, before pruning, at breast height and 10 percent of total height were 21 and 17 for tree RF2, and 15 and 13 for tree RF3. The overall average number of growth increments of the former sections was 16.5. This average number also represents an estimate of the juvenile - mature transition occurrence, since it delimits two different relative density variation patterns from the pith. For both trees, the mean relative density for juvenile wood was 0.441, ranging from 0.370 to 0.490. The mean relative density for mature wood was 0.494 (nine percent greater than that for juvenile wood), ranging from 0.640 to 0.410 (Appendices 20p and 20q).

When the overall average number of growth increments at which the transition occurred after pruning, i.e. 16.5, was compared to that corresponding to trees without pruning, i.e. 22.18 (Table 11), the difference was about 26 percent.

From the above, it is concluded that pruning of lower crown live branches can produce both an increase in annual increment mean relative density and a decrease in the proportion of juvenile wood in Douglas-fir by accelerating the occurrence of juvenile - mature wood transition. Since only two trees were analyzed, these results should be treated as exploratory. However, they are good indicators of possible benefits in addition to obtaining more clear wood, when pruning lower crown live branches. Furthermore, assuming that these branches contribute little or nothing to stem wood formation, while utilizing tree resources, it might be worthwhile to consider the pruning of young-growth Douglas-fir.

When relating these results to the project hypothesis, it would appear that pruning can accelerate the juvenile - mature wood transition, which otherwise would need more time in which to happen. Then, if in fact the transition occurs below the base of the live crown in unpruned trees, the transition could be shifted upwards by pruning lower crown live branches.

In view of the above, it is concluded that when the project hypothesis was tested on pruned trees, the juvenile - mature wood transition would occur at the modified base of the live crown, which represents the upper limit of pruning height. Therefore, the hypothesis can be proven as correct. It is important to note that more research on pruned trees is needed for further development of these results.

5.0 CONCLUSIONS

1) The horizontal annual increment mean relative density variation pattern at the five sample heights was characterized by an initial decrease to a point within the first growth increments from the pith, followed by a gradual increase and stabilization outwards, particularly in the lower sample sections (i.e. breast height, 20 and 40 percent of total tree height).

2) The vertical annual increment mean relative density variation pattern was characterized by a decrease with increasing tree height.

3) Based on the variation pattern of the data points, pertaining to annual increment relative density and number of growth increments from the pith, no evidence of juvenile - mature transition zone was found primarily at sections sampled at 60 and 80 percent of total tree height. The average number of growth increments from the pith for these sections was 18.42, ranging from 4 to 33.

4) A greater evidence of juvenile - mature wood transition zone was found at sections sampled at breast height, 20

and 40 percent of total tree height. The average numbers of growth increments at which juvenile - mature wood transition occurred, when segmented regression models were fitted to relative density profiles, were 22.36, 22.86, 20.89 and 22.18 for sections sampled at breast height, 20 percent, 40 percent of total height and for all sections, respectively. Segmented regression analysis, therefore, produced a fairly consistent demarcation between juvenile and mature wood, among sample heights, despite the large variability among the values in some of the relative density profiles.

5) The overall annual increment mean mature wood relative density was 14 percent higher than that for juvenile wood. The lowest annual increment mean juvenile wood relative density was found at sections sampled at 20 and 40 percent of total tree height.

6) Individual and overall height relationships, before harvest, for total height, height to crown base, height to the lowest relative density value and height to juvenile - mature wood transition point as functions of number of growth increments from the pith indicated that the:

a. Lowest relative density curve was parallel and very close to the total height curve, suggesting that a minimum growth increment relative density value is likely to be found in the first growth increments from the pith and within a short distance from the tree apex;

b. Height to crown base curve was parallel to the total height curve up to about 40 percent of the total height where it started to diverge towards the live crown base position at harvest;

c. Height to crown base curve was also parallel and sometimes coincident with the lowest relative density curve, indicating a possible biological connection between the number of growth increments at the base of dead branches and that at which the annual increment relative density value is lowest; and

d. Simple linear model fitted to the points indicating juvenile - mature wood transition was lower and parallel to the curves described previously.

7) Observed data distribution and height prediction models, after harvest, for total height, average crown height, live crown base height, average transition height A (estimated as a function of earlier transition ages) and average transition height B (estimated as a function of earlier transition heights) indicated that:

   a. The average crown height positions were higher than the positions corresponding to average transition A, live crown base and average transition B;
   b. The average transition A height positions were located between those positions corresponding to the average crown and base of the live crown;
   c. The average transition B height positions were located below those positions corresponding to the average crown and the base of the live crown; and
   d. Assuming that the transition would be likely to occur below the live crown base position, the average transition height A might overestimate the height of the transition, then, the average transition height B would better represent the possible occurrence of the transition after harvest.

8) Pruning of lower crown live branches produced both an increase in the annual increment relative density and a decrease in the proportion of juvenile wood by accelerating the juvenile - mature wood transition. The average number of growth increments at which the transition occurred after pruning was 16.5.

9) When testing the project hypothesis on unpruned trees, before and after harvest, the transition in relative density from juvenile to mature wood did not occur at the base of the live crown, as defined. In both cases, the transition occurred below the base of the live crown. Therefore, the hypothesis has not been proven.

10) When the hypothesis was tested on pruned trees, the juvenile - mature wood transition did occur at the base of the live crown, which represented the upper limit of pruning height. The hypothesis in this case has, therefore, been proven.

11) Results of hypothesis testing seemed to depend upon the definition given to the base of the live crown. Further research needs to be done, not only to find a more precise definition of what should biologically be considered the base of the live crown, but also to investigate the implication of such definition on wood formation.

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Table 1. Douglas-fir stand characteristics.

Location	Coordinates Latitude	Longitude	Biogeo-climatic Zone (1)	Organization	Age (B.H.) (2)	Height (m) (2)	Crown Rad. (m) (2)	Crown Length (m) (2)	D.B.H. (cm) (2)	Density (stem/ha) ha) (3)	Basal Area (m sq/ha) (3)	Douglas-fir % (3)
Ladysmith	49° 00'N	123° 52'W	CDFb	Crown Forest Industries	54	42.2	5.7	17.3	54.5	-	-	-
Cassidy	49° 04'N	123° 55'W	CDFb	MacMillan Bloedel	58	41.7	4.6	17.7	57.8	654	46.1	100
Campbell River	50° 00'N	125° 17'W	CDFb	B.C. Forest Products	53	38.8	4.2	17.5	52.7	395	43.3	100
Lake Cowichan	48° 48'N	124° 09'W	CWHa1	C.I.P. Inc.	39	33.6	3.4	17.1	38.4	381	42.1	43
Lizard Lake	48° 35'N	124° 08'W	CWHb1	B.C. Forest Products	46	35.8	3.3	18.1	45.8	705	50.7	34
Jordan River	48° 24'N	124° 08'W	CWHb1 - CWHa1	Western Forest Products	52	40.3	3.4	15.9	52.5	523	51.8	40
Haney	49° 17'N	122° 30'W	CWHa2 - CWHb2	U.B.C. Research Forest	48	-	-	-	-	-	-	70
Hart	50° 02'N	125° 20'W	CDFb	B.C. Ministry of Forests	37	-	-	-	-	-	-	100
Menekay	50° 02'N	125° 19'W	CDFb	B.C. Ministry of Forests	35	-	-	-	-	-	-	100

(1) Biogeoclimatic Zone Classification (Klinka et al., 1979).

CDFb: Coastal Douglas-fir - wetter subzone
CWHa1: Coastal Western Hemlock - Vancouver Island, wetter subzone
CWHa2: Coastal Western Hemlock - Pacific Range, wetter subzone
CWHb1: Coastal Western Hemlock - Windward Submontane Maritime, drier subzone
CWHb2: Coastal Western Hemlock - Windward Montana Maritime, drier subzone

(2) Based on the average of ten dominant and codominant trees per stand.

(3) Based on prism cruise information.

Table 2. Sample tree characteristics.

Sample Tree No.	Location	Age (B.H.)	D.B.H. (cm)	Height (m)	Collection Date	Comments
1A5	Ladysmith	56	46.8	37.0	May, 1985	second-growth
1A7	Ladysmith	51	46.1	37.0	May, 1985	second-growth
1B6	Cassidy	53	49.2	44.7	May, 1985	second-growth
1B11	Cassidy	63	49.1	36.1	May, 1985	second-growth
1C1	Campbell River	54	47.3	40.0	May, 1985	second-growth
1C6	Campbell River	53	49.1	38.0	May, 1985	second-growth
1D5	Lake Cowichan	33	45.5	32.0	June, 1985	second-growth
1D6	Lake Cowichan	35	43.2	29.5	June, 1985	second-growth
1E3	Lizard Lake	43	39.4	35.0	June, 1985	second-growth
1E8	Lizard Lake	47	68.2	36.0	June, 1985	second-growth
1F7	Jordan River	53	57.5	41.5	June, 1985	second-growth
1F10	Jordan River	52	52.7	39.0	June, 1985	second-growth
RF1	Haney	21	26.8	23.3	April, 1985	second-growth
RF2	Haney	51	68.3	31.7	April, 1985	second-growth pruned
RF3	Haney	45	44.0	29.7	January, 1986	second-growth pruned
CR1	Hart	37	19.8	16.8	October, 1985	plantation-grown
CR2	Memekay	35	36.7	31.5	October, 1985	plantation-grown

Table 3. Tree crown characteristics.

Sample Tree No.	Location	Height (m)	Age (B.H.)	Crown Length (m) (1)	Crown Base Height (m) (1)	Crown Base Age (1)	Average Crown Length (L) (m) (2)	Average Crown Height (m) (2)	Average Crown Age (2)	Crown Radius (BL) (m)	Coefficient Values (b)
1A5	Ladysmith	37.0	56	14.8	22.2	28	14.3	22.7	27	4.65	3.952
1A7	Ladysmith	37.0	51	13.6	23.4	29	10.0	27.0	23	4.68	4.956
1B6	Cassidy	44.7	53	21.9	22.8	28	13.0	31.7	17	4.23	3.806
1B11	Cassidy	36.1	63	15.3	20.8	35	15.1	21.3	34	4.40	3.625
1C1	Campbell River	40.0	54	15.9	24.1	29	13.8	26.4	26	3.61	3.612
1C6	Campbell River	38.0	53	13.2	24.8	24	11.1	26.9	19	3.70	3.701
1D5	Lake Cowichan	32.0	33	16.9	15.1	20	12.0	19.9	13	3.47	3.262
1D6	Lake Cowichan	29.5	35	11.3	18.2	16	8.5	21.0	13	3.40	3.966
1E3	Lizard Lake	35.0	43	17.9	17.1	21	13.2	22.2	17	4.01	3.588
1E8	Lizard Lake	36.0	47	14.4	21.6	25	8.8	27.2	17	3.66	4.204
1F7	Jordan River	41.5	53	18.1	23.4	28	7.7	33.8	15	3.24	4.080
1F10	Jordan River	39.0	52	14.2	24.8	29	8.7	30.3	21	2.91	3.362
RF1	Haney	23.3	21	14.3	9.0	12	8.1	15.2	6	2.64	3.213
RF2	Haney	31.7	51	21.0	10.7	39	-	-	-	-	-
RF3	Haney	29.7	45	18.1	11.6	33	-	-	-	-	-
CR1	Hart	16.8	37	6.7	9.4	22	3.9	12.8	16	1.48	3.239
CR2	Nemekay	31.5	35	12.8	18.7	19	5.6	25.9	9	2.80	4.420
Averages (3)		34.5	46	14.7	19.7	24	10.2	24.2	18	3.50	3.799

(1) Base of the live crown height observed as the lowest part of the crown with three or more live branches.

(2) Average crown height estimated as tree height minus L, where L is given by the following equation:

$$L = c\,(e^{BL/(bd)} - 1)$$

L = crown length or distance from terminal leader to branch base
c = coefficient describing the shape of the crown (estimated for Douglas-fir as 6.1 m)
BL = crown radius
b = coefficient relating branch growth to height growth
d = coefficient compensating for branch crooks (estimated for Douglas-fir as 0.975)
e = 2.71828

(3) Overall averages not including pruned trees RF2 and RF3.

Table 4. Summary of relative density values for sections at breast height (B.H.).

Sample Tree No.	Location	Height (m)	Number of Growth Increments	Relative Density Mean	S.D.	Maximum	Minimum
1A5	Ladysmith	1.30	56	.542	.062	.640	.380
1A7	Ladysmith	1.30	51	.569	.057	.660	.430
1B6	Cassidy	1.30	53	.520	.055	.650	.420
1B11	Cassidy	1.30	63	.543	.057	.680	.430
1C1	Campbell River	1.30	54	.558	.053	.660	.440
1C6	Campbell River	1.30	53	.566	.062	.700	.440
1D5	Lake Cowichan	1.30	33	.474	.034	.540	.420
1D6	Lake Cowichan	1.30	35	.488	.062	.600	.380
1E3	Lizard Lake	1.30	43	.595	.049	.680	.500
1E8	Lizard Lake	1.30	47	.487	.044	.590	.390
1F7	Jordan River	1.30	53	.551	.061	.650	.430
1F10	Jordan River	1.30	52	.537	.060	.640	.430
RF1	Haney	1.30	21	.429	.041	.530	.360
CR1	Hart	1.30	37	.536	.070	.670	.410
CR2	Memekay	1.30	35	.444	.039	.510	.340
All Trees		1.30	46	.523	.054	.625	.413

Table 5. Summary of relative density values for sections sampled at 20 percent of total height.

Sample Tree No.	Location	Height (m)	Number of Growth Increments	Relative Density Mean	S.D.	Maximum	Minimum
1A5	Ladysmith	7.55	47	.468	.063	.620	.360
1A7	Ladysmith	7.20	44	.520	.071	.650	.370
1B6	Cassidy	8.55	45	.504	.055	.590	.400
1B11	Cassidy	7.10	53	.489	.037	.590	.410
1C1	Campbell River	8.00	47	.494	.049	.570	.390
1C6	Campbell River	7.60	46	.502	.059	.600	.380
1D5	Lake Cowichan	6.40	27	.482	.039	.560	.430
1D6	Lake Cowichan	5.90	29	.437	.043	.520	.350
1E3	Lizard Lake	7.10	32	.498	.038	.590	.440
1E8	Lizard Lake	7.20	41	.463	.057	.610	.360
1F7	Jordan River	8.30	46	.490	.061	.610	.380
1F10	Jordan River	7.80	46	.485	.052	.570	.390
RF1	Haney	4.54	17	.423	.035	.500	.380
CR1	Hart	3.34	34	.543	.076	.680	.420
CR2	Nemekay	6.40	29	.483	.049	.580	.370
All Trees		6.85	39	.485	.052	.589	.389

Table 6. Summary of relative density values for sections sampled at 40 percent of total height.

Sample Tree No.	Location	Height (m)	Number of Growth Increments	Relative Density Mean	S.D.	Maximum	Minimum
1A5	Ladysmith	14.90	40	.445	.049	.540	.370
1A7	Ladysmith	15.10	39	.480	.045	.570	.380
1B6	Cassidy	17.20	32	.495	.042	.570	.420
1B11	Cassidy	14.20	45	.478	.033	.580	.410
1C1	Campbell River	16.00	39	.468	.032	.520	.400
1C6	Campbell River	15.20	36	.496	.040	.560	.430
1D5	Lake Cowichan	12.80	20	.475	.035	.550	.430
1D6	Lake Cowichan	11.90	23	.450	.037	.550	.400
1E3	Lizard Lake	14.00	26	.450	.024	.510	.390
1E8	Lizard Lake	14.40	33	.456	.039	.530	.370
1F7	Jordan River	16.40	38	.473	.040	.570	.420
1F10	Jordan River	15.90	39	.472	.030	.530	.410
RF1	Haney	9.00	13	.398	.054	.500	.340
CR1	Hart	5.10	31	.486	.069	.620	.390
CR2	Memekay	25.77	22	.488	.028	.540	.440
All Trees		13.59	32	.467	.040	.549	.400

Table 7. Summary of relative density values for sections sampled at 60 percent of total height.

Sample Tree No.	Location	Height (m)	Number of Growth Increments	Relative Density			
				Mean	S.D.	Maximum	Minimum
1A5	Ladysmith	22.2	28	.460	.038	.560	.400
1A7	Ladysmith	22.5	31	.479	.054	.670	.410
1B6	Cassidy	25.8	24	.478	.027	.540	.440
1B11	Cassidy	21.3	29	.479	.031	.560	.430
1C1	Campbell River	24.1	29	.448	.023	.510	.410
1C6	Campbell River	22.8	25	.478	.034	.550	.410
1D5	Lake Cowichan	19.2	14	.456	.034	.510	.390
1D6	Lake Cowichan	17.7	17	.428	.041	.530	.360
1E3	Lizard Lake	21.0	17	.417	.017	.450	.400
1E8	Lizard Lake	21.6	25	.420	.034	.500	.360
1F7	Jordan River	24.9	22	.497	.056	.650	.430
1F10	Jordan River	23.4	26	.495	.026	.550	.460
RF1	Haney	13.6	8	.445	.042	.510	.400
CR1	Hart	9.9	17	.485	.025	.540	.450
CR2	Memekay	24.8	20	.459	.048	.630	.400
All Trees		20.6	22	.462	.035	.551	.410

Table 8. Summary of relative density values for sections sampled at 80 percent of total height.

Sample Tree No.	Location	Height (m)	Number of Growth Increments	Relative Density Mean	S.D.	Maximum	Minimum
1A5	Ladysmith	29.4	13	.440	.030	.510	.410
1A7	Ladysmith	29.9	18	.499	.038	.600	.450
1B6	Cassidy	36.1	12	.479	.052	.610	.420
1B11	Cassidy	28.4	19	.488	.032	.570	.450
1C1	Campbell River	32.0	15	.411	.015	.460	.400
1C6	Campbell River	30.4	12	.499	.035	.560	.430
1D5	Lake Cowichan	25.6	8	.540	.027	.580	.500
1D6	Lake Cowichan	23.6	8	.468	.027	.510	.420
1E3	Lizard Lake	28.0	9	.483	.031	.560	.450
1E8	Lizard Lake	28.8	14	.454	.030	.530	.420
1F7	Jordan River	33.7	14	.517	.058	.640	.450
1F10	Jordan River	31.2	19	.420	.042	.560	.430
RF1	Haney	18.2	4	.492	.025	.520	.460
CR1	Hart	13.4	7	.485	.040	.540	.430
CR2	Memekay	25.8	16	.493	.041	.590	.440
All Trees		27.6	13	.478	.035	.556	.437

Table 9. Summary of the distribution of relative density profiles which showed no juvenile - mature wood transition.

Section Height	Number of Sections	Height				Juvenile Wood Growth Increment			
		Mean	S.D.	Max.	Min.	Mean	S.D.	Max.	Min.
B.H.	1	1.30	-	1.30	1.30	21.00	-	21.00	21.00
20%	1	4.54	-	4.54	4.54	17.00	-	17.00	17.00
40%	6	10.83	3.31	14.40	5.10	23.67	7.37	33.00	13.00
60%	15	20.59	4.26	25.80	9.95	22.13	6.50	31.00	8.00
80%	15	27.63	5.83	36.10	13.38	12.53	4.58	19.00	4.00
All Sections	38	20.99	8.58	36.10	1.30	18.42	7.45	33.00	4.00

Table 10. Transition determination by comparing simple against segmented linear regression models on relative density profiles.

Sample Tree No.	Location	Section Height	Juvenile - Mature Wood Transition Age (years)	Simple Linear Model 1 D.F.	Simple Linear Model 1 Mean Square (x 10^{-3})	Segmented Linear Model 2 D.F.	Segmented Linear Model 2 Mean Square (x 10^{-3})	"F" Value Model 1 / Model 2	"F" Prob. P > F
1A5	Ladysmith	B.H.	22	50	2.081	48	1.623	1.281	0.20
		20%	28	41	1.971	39	1.857	1.061	0.42
		40%	25	23	1.660	21	1.480	1.121	0.40
1A7	Ladysmith	B.H.	19	41	2.058	39	1.468	1.401	0.14
		20%	24	35	2.609	33	1.743	1.496	0.14
		40%	24	31	1.303	29	0.841	1.548	0.10
1B6	Cassidy	B.H.	16	44	1.302	42	1.129	1.153	0.32
		20%	17	35	0.751	33	0.666	1.128	0.37
		40%	18	24	0.564	22	0.542	1.055	0.40
1B11	Cassidy	B.H.	32	56	1.738	54	1.247	1.394	0.11
		20%	25	50	1.373	48	0.863	1.590	0.05
		40%	16	41	1.176	39	1.023	1.150	0.34
1C1	Campbell River	B.H.	19	47	1.182	45	0.915	1.292	0.19
		20%	25	41	0.868	39	0.597	1.454	0.02
		40%	29	32	0.482	30	0.463	1.042	0.42
1C6	Campbell River	B.H.	15	47	2.258	45	1.980	1.141	0.33
		20%	35	41	2.247	39	1.813	1.239	0.26
		40%	26	31	2.284	29	1.006	2.270	0.00
1D5	Lake Cowichan	B.H.	19	30	0.861	28	0.844	1.020	0.43
		20%	20	23	0.759	21	0.712	1.070	0.44

Table 10. Transition determination by comparing simple against segmented linear regression models on relative density profiles (cont.).

Sample Tree No.	Location	Section Height	Juvenile - Mature Wood Transition Age (years)	Simple Linear Model 1 D.F.	Simple Linear Model 1 Mean Square (x 10^{-3})	Segmented Linear Model 2 D.F.	Segmented Linear Model 2 Mean Square (x 10^{-3})	"F" Value Model 1 / Model 2	"F" Prob. P > F
1D6	Lake	B.H.	17	30	1.015	28	0.878	1.156	0.35
	Cowichan	20%	15	24	0.661	22	0.542	1.220	0.31
1E3	Lizard	B.H.	28	32	1.069	30	0.985	1.085	0.41
	Lake	20%	26	25	0.785	23	0.762	1.031	0.47
		40%	11	19	0.405	17	0.293	1.378	0.25
1E8	Lizard	B.H.	34	41	1.055	39	0.930	1.134	0.35
	Lake	20%	26	31	1.220	29	1.019	1.197	0.32
1F7	Jordan	B.H.	25	45	1.633	43	0.801	2.037	0.01
	River	20%	25	39	1.086	37	0.422	2.573	0.00
		40%	24	28	1.418	26	0.852	1.664	0.10
1F10	Jordan	B.H.	24	49	1.338	47	0.985	1.358	0.15
	River	20%	22	39	1.465	37	1.023	1.425	0.14
		40%	15	35	0.557	33	0.448	1.244	0.27
CR1	Hart	B.H.	20	28	1.576	26	1.331	1.183	0.25
		20%	19	22	1.905	20	1.019	1.873	0.07
CR2	Menekay	B.H.	23	24	0.930	22	0.797	1.166	0.32
		20%	13	23	0.866	21	0.798	1.087	0.42

Table 11. Summary of the distribution of relative density profiles which showed juvenile - mature wood transition.

Section Height	Number of Sections	Height (m)				Total Number of Growth Increments				No. of Juvenile-Mature Wood Trans. Growth Increments			
		Mean	S.D.	Max.	Min.	Mean	S.D.	Max.	Min.	Mean	S.D.	Max.	Min.
B.H.	14	1.30	-	1.30	1.30	47.50	9.33	63.00	33.00	22.36	5.77	34.00	15.00
20%	14	7.03	1.03	8.55	3.34	40.43	8.44	53.00	27.00	22.86	5.72	35.00	13.00
40%	9	15.43	1.04	17.20	14.00	37.11	5.40	45.00	26.00	20.89	6.05	29.00	11.00
All Sections	37	6.91	5.59	17.20	1.30	42.30	9.07	63.00	26.00	22.18	5.71	35.00	11.00

Table 12. Summary of the relative density values of the profiles which showed no juvenile - mature wood transition.

Section Height	Number of Sections	Number of Growth Increments			Relative Density											
					Juvenile Wood				Mature Wood				Total			
		Juvenile Wood	Mature Wood	Total	Mean	S.D.	Max.	Min.	Mean	S.D.	Max.	Min.	Mean	S.D.	Max.	Min.
B.H.	1	21.00	-	21.00	.429	.041	.530	.360	-	-	-	-	.429	.041	.530	.360
20%	1	17.00	-	17.00	.423	.035	.500	.380	-	-	-	-	.423	.035	.500	.380
40%	6	23.66	-	23.66	.459	.044	.548	.395	-	-	-	-	.459	.044	.548	.395
60%	15	22.13	-	22.13	.462	.035	.551	.410	-	-	-	-	.462	.035	.551	.410
80%	15	18.42	-	18.42	.481	.035	.556	.437	-	-	-	-	.481	.035	.556	.437
All Sections	38	18.42	-	18.42	.467	.031	.551	.416	-	-	-	-	.467	.031	.551	.416

Table 13. Summary of the relative density values of the profiles which showed juvenile - mature wood transition.

Section Height	Number of Sections	Average Number of Growth Increments			Relative Density											
					Juvenile Wood				Mature Wood				Total			
		Juvenile Wood	Mature Wood	Total	Mean	S.D.	Max.	Min.	Mean	S.D.	Max.	Min.	Mean	S.D.	Max.	Min.
B.H.	14	22.36	24.71	47.50	.491	.046	.601	.417	.563	.034	.630	.496	.529	.055	.634	.417
20%	14	22.86	17.57	40.43	.460	.046	.566	.389	.529	.032	.592	.474	.490	.054	.596	.389
40%	9	20.89	16.22	37.11	.461	.037	.537	.406	.491	.027	.540	.439	.473	.037	.550	.403
All Sections	37	22.18	19.95	42.30	.472	.044	.572	.404	.533	.032	.594	.474	.501	.050	.599	.403

TABLE 14. Overall summary of relative density values for juvenile and mature wood.

Section Height	Number of Sections	Average Number of Growth Increments: Juvenile Wood	Average Number of Growth Increments: Mature Wood	Average Number of Growth Increments: Total	Relative Density, Juvenile Wood: Mean	Juvenile Wood: S.D.	Juvenile Wood: Max.	Juvenile Wood: Min.	Mature Wood: Mean	Mature Wood: S.D.	Mature Wood: Max.	Mature Wood: Min.	Total: Mean	Total: S.D.	Total: Max.	Total: Min.
B.H.	15	22.67	24.71	45.73	.487	.046	.596	.413	.563	.034	.630	.496	.523	.054	.625	.413
20%	15	22.47	17.57	38.86	.457	.045	.561	.389	.529	.032	.592	.474	.485	.052	.589	.389
40%	15	22.00	16.22	31.73	.460	.040	.541	.401	.491	.027	.540	.439	.467	.040	.549	.400
60%	15	22.13	-	22.13	.462	.035	.551	.410	-	-	-	-	.462	.035	.551	.410
80%	15	12.53	-	12.53	.481	.035	.556	.437	-	-	-	-	.481	.035	.556	.437
All Sections	75	20.28	19.95	30.20	.469	.040	.561	.410	.533	.032	.594	.474	.483	.043	.547	.410

Table 15. Summary of sampled dead branch characteristics.

Tree Number	Number of Branches	Height Position (m)				Number of Growth Increments			
		Mean	S.D.	Max.	Min.	Mean	S.D.	Max.	Min.
1A5	5	17.8	4.218	22.2	12.2	13.4	5.983	20.0	6.0
1A7	7	15.5	7.378	23.4	5.2	11.1	5.550	22.0	6.0
1B6	11	13.0	6.374	22.0	3.4	12.0	2.932	18.0	8.0
1B11	13	11.2	6.037	20.8	2.4	18.3	5.360	26.0	11.0
1C1	10	17.4	5.316	24.1	8.0	16.5	4.648	24.0	10.0
1C6	11	16.6	4.576	24.1	10.5	14.2	4.051	22.0	9.0
1D5	9	8.3	4.431	15.1	2.0	10.7	1.481	13.0	9.0
1D6	9	10.0	5.394	17.7	2.7	10.5	2.006	15.0	8.0
1E3	10	8.4	4.773	16.0	2.2	10.2	2.699	15.0	7.0
1E8	12	12.9	5.886	21.6	3.3	14.6	2.839	19.0	10.0
1F7	12	12.4	6.640	22.4	2.5	11.0	3.604	18.0	7.0
1F10	11	13.9	6.311	23.4	4.2	8.4	2.583	13.0	6.0
All Trees	120	12.9	6.226	24.1	2.0	12.7	4.628	26.0	6.0

Table 16. Summary of lowest relative density values.

Tree Number	Number of Sections	Height Position (m)				Lowest Relative Density Number of Growth Increments			
		Mean	S.D.	Max.	Min.	Mean	S.D.	Max.	Min.
1A5	5	15.1	11.207	29.4	1.3	7.4	2.302	11.0	5.0
1A7	5	15.2	11.474	29.5	1.3	7.2	1.483	9.0	5.0
1B6	5	17.8	13.757	36.1	1.3	6.8	2.168	9.0	4.0
1B11	5	14.5	10.839	28.5	1.3	6.0	3.536	10.0	2.0
1C1	5	16.3	12.269	32.0	1.3	5.2	0.837	6.0	4.0
1C6	5	15.5	11.613	30.4	1.3	5.8	2.049	8.0	4.0
1D5	5	13.1	9.717	25.6	1.3	5.8	4.438	13.0	2.0
1D6	5	12.1	8.926	23.6	1.3	7.2	4.087	13.0	4.0
1E3	5	14.3	10.648	28.0	1.3	7.0	1.871	10.0	5.0
1E8	5	14.7	10.981	28.8	1.3	9.8	3.834	15.0	5.0
1F7	5	16.9	12.882	33.7	1.3	7.4	1.140	9.0	6.0
1F10	5	15.9	11.928	31.2	1.3	7.4	5.367	14.0	2.0
CR1	5	6.6	4.954	13.4	1.3	9.0	1.581	11.0	7.0
CR2	5	12.8	9.714	25.8	1.3	7.8	1.924	10.0	5.0
All Trees	70	14.3	10.229	36.1	1.3	7.1	2.904	15.0	2.0

Table 17. Differences between height of juvenile - mature wood transition point, height of crown base and total height.

Section Height	Height Difference Between Transition Point and Crown Base					Height Difference Between Transition Point and Total Height				
	# Obs.	Mean	S.D.	Max.	Min.	# Obs.	Mean	S.D.	Max.	Min.
B.H.	12	10.25	3.802	17.22	6.09	14	18.95	5.875	28.97	8.65
20%	12	8.71	3.404	13.23	2.52	14	18.51	4.324	23.54	7.23
40%	9	3.85	3.280	6.72	-3.15	9	14.59	4.081	22.02	9.78
All Sections	33	7.95	4.311	17.22	-3.15	37	17.72	5.118	28.97	7.23

Table 18. Summary of height difference statistics.

First Height Measurement	Second Height Measurement	Number of Observations	Height Difference (m)			
			Mean	S.D.	Max.	Min.
Total height	Live crown base height	15	14.76	3.399	21.90	6.80
Total height	Average crown height	15	10.26	3.295	15.10	4.00
Average crown height	Live crown base height	15	4.50	2.920	10.40	0.20
Total height	Average transition A	14	12.63	3.835	18.76	7.13
Total height	Average transition B	14	17.91	4.172	25.28	8.06
Average transition A	Average transition B	14	5.28	4.388	16.35	0.11
Average transition A	Live crown base height	14	2.16	3.658	8.90	-4.36
Average transition A	Average crown height	14	-2.21	3.971	-9.96	5.17
Average transition B	Live crown base height	14	-3.12	3.737	-10.88	3.04
Average transition B	Average crown height	14	-7.50	4.993	-17.94	-1.52

Table 19. Correlation matrix for live crown base height, average crown height, average transition height A and average transition height B.

	Live Crown Base Height	Average Crown Height	Average Transition Height A	Average Transition Height B
Live Crown Base Height	1.0000			
Average Crown Height	0.8402 **	1.0000		
Average Transition Height A	0.8419 **	0.7936 **	1.0000	
Average Transition Height B	0.7340 **	0.5888 *	0.7407 **	1.0000

* Significant at the 0.05 level

** Significant at the 0.01 level

(14 observations)

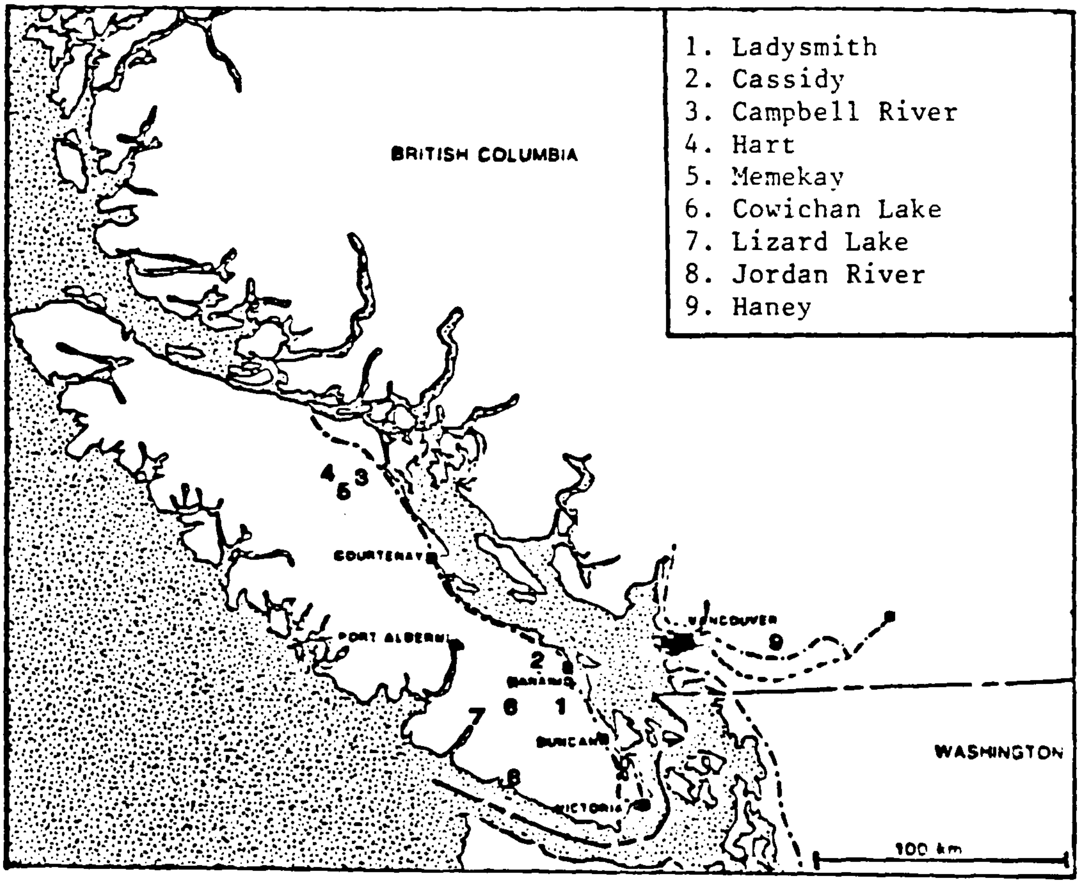


Figure 1. Location of Douglas-fir stands.

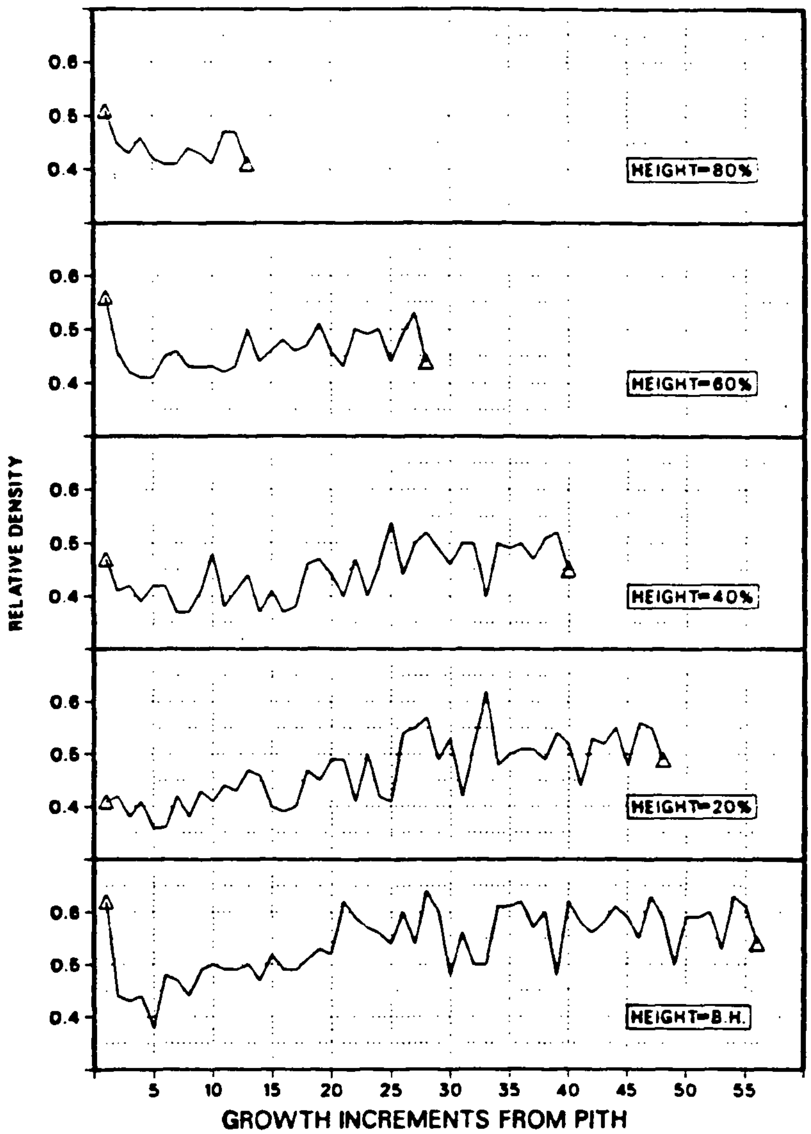


Figure 2. Pith to bark relative density profiles for sample tree 1A5.

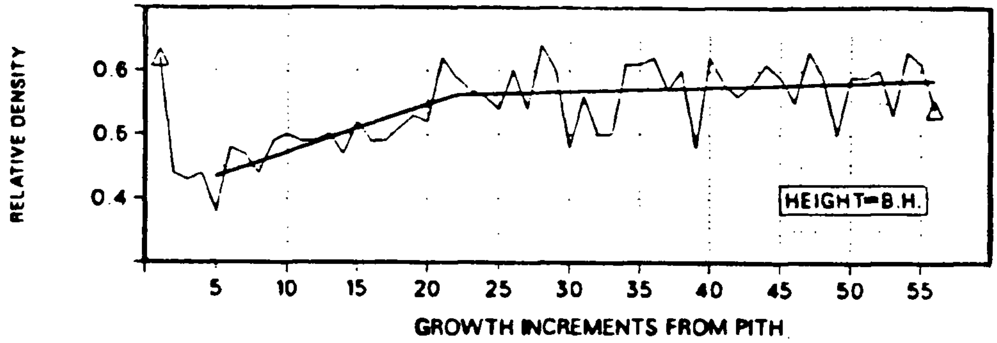


Figure 3a. Segmented linear regression model on pith to bark relative density profile for a sample radius.

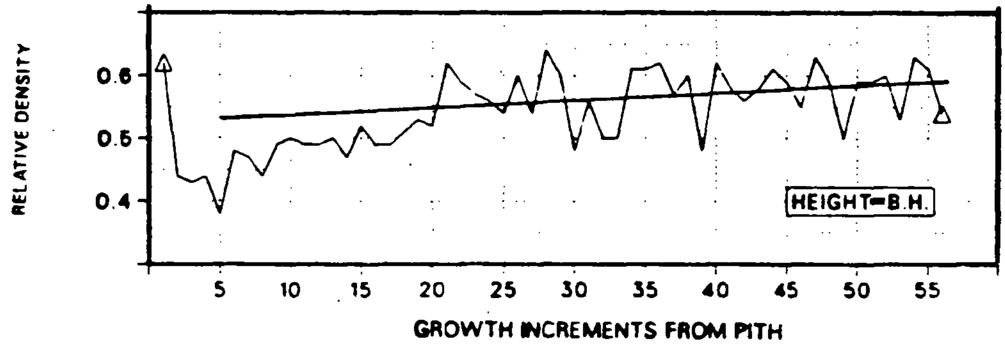


Figure 3b. Simple linear regression model on pith to bark relative density profile for a sample radius.

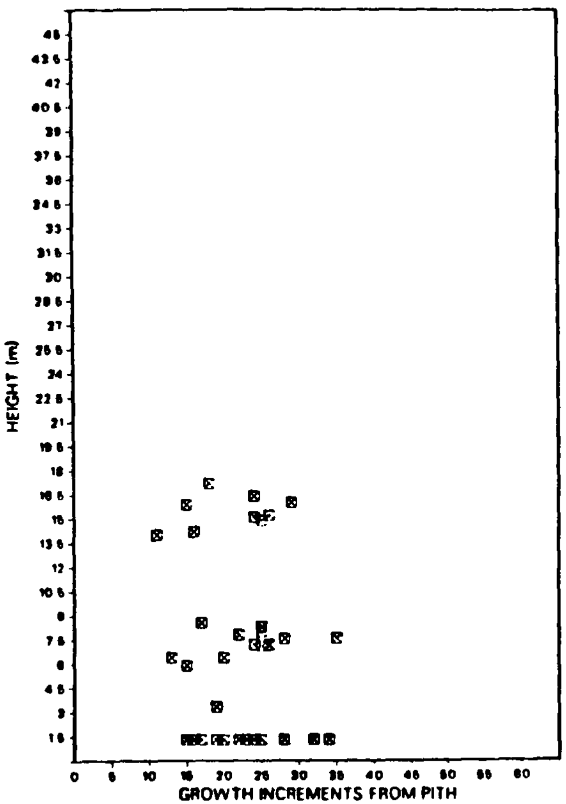


Figure 4a. Scatter plot of height over number of growth increments at which juvenile - mature wood transition occurs.

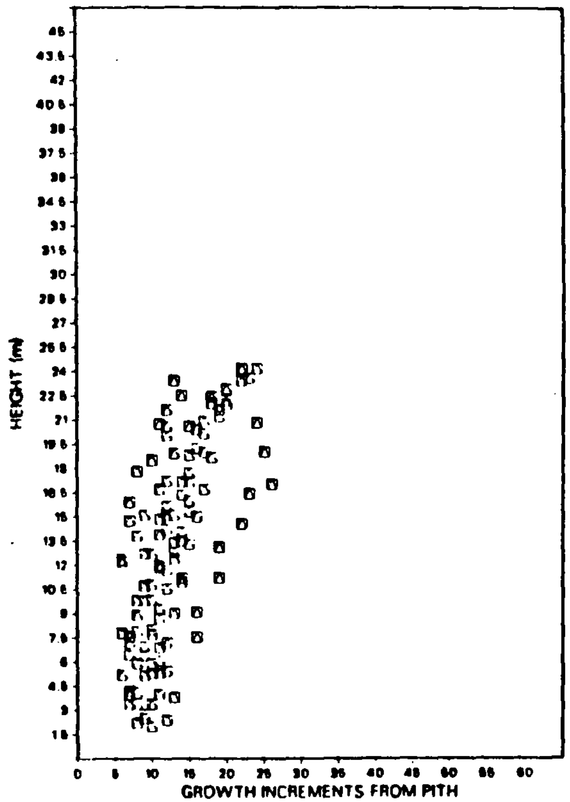


Figure 4b. Scatter plot of height over number of growth increments at the base of dead branches for all trees.

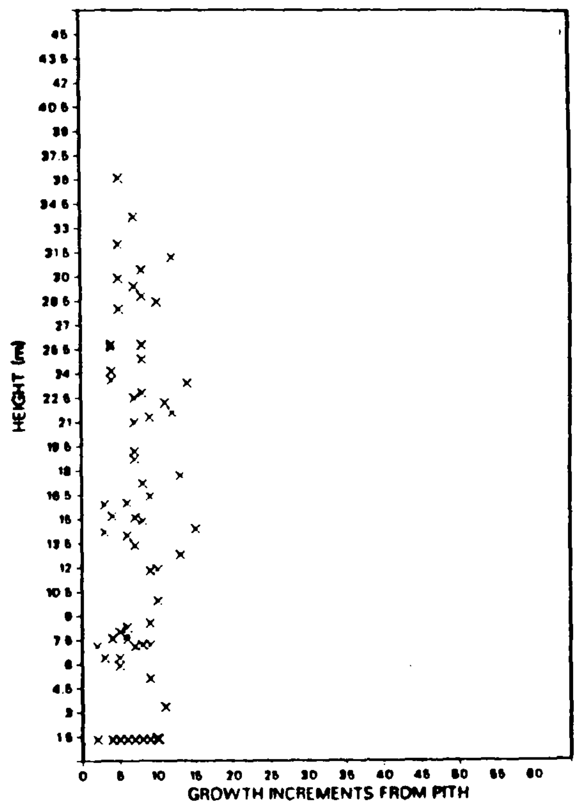


Figure 4c. Scatter plot of height over number of growth increments which indicates the lowest relative density value in the profile.

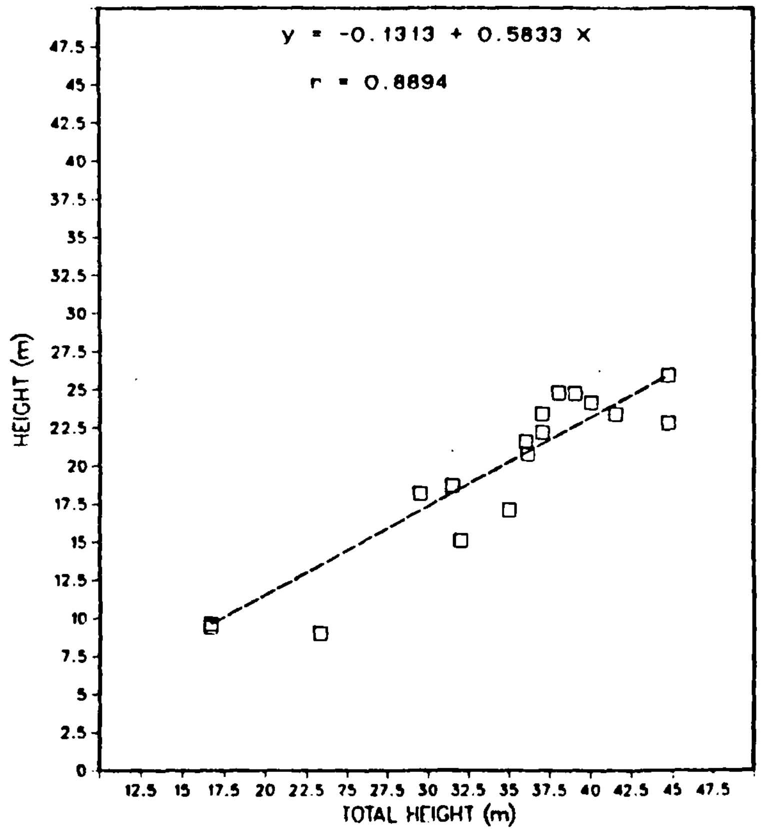


Figure 5a. Scatter plot and height prediction model for crown base height over total height.

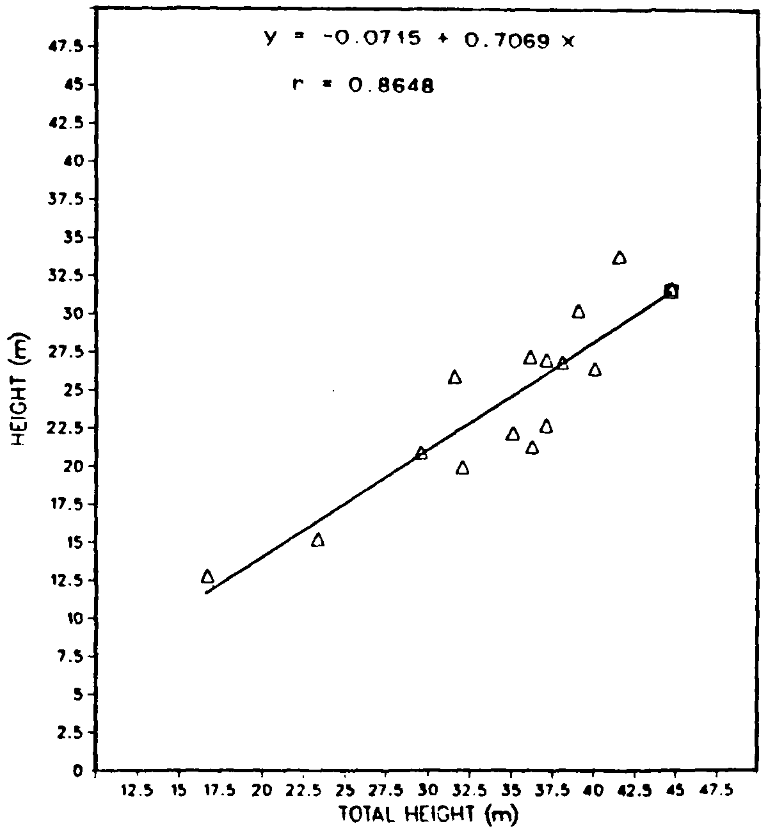


Figure 5b. Scatter plot and height prediction model for average crown height over total height.

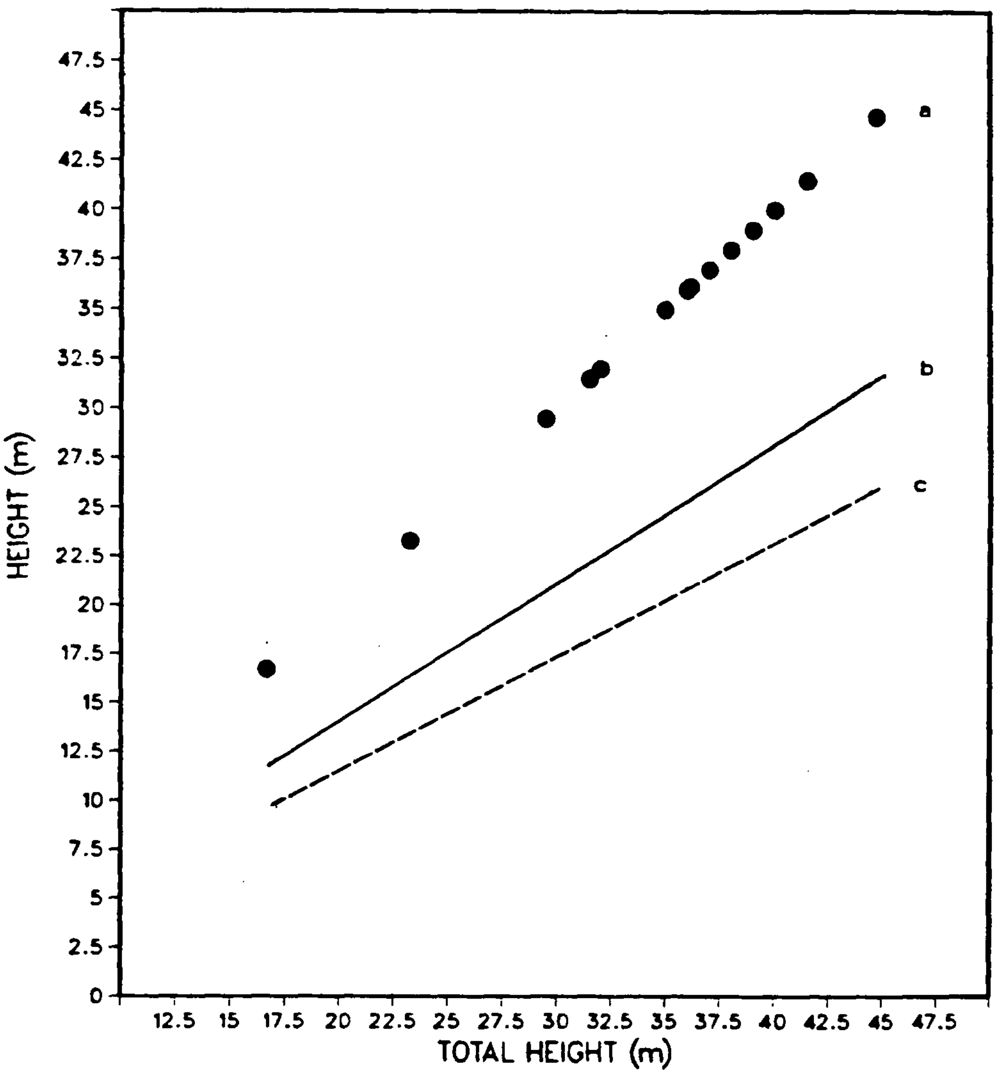


Figure 6. Scatter plot of a) total height and height prediction models over total height; for: b) average crown height; and c) crown base height.

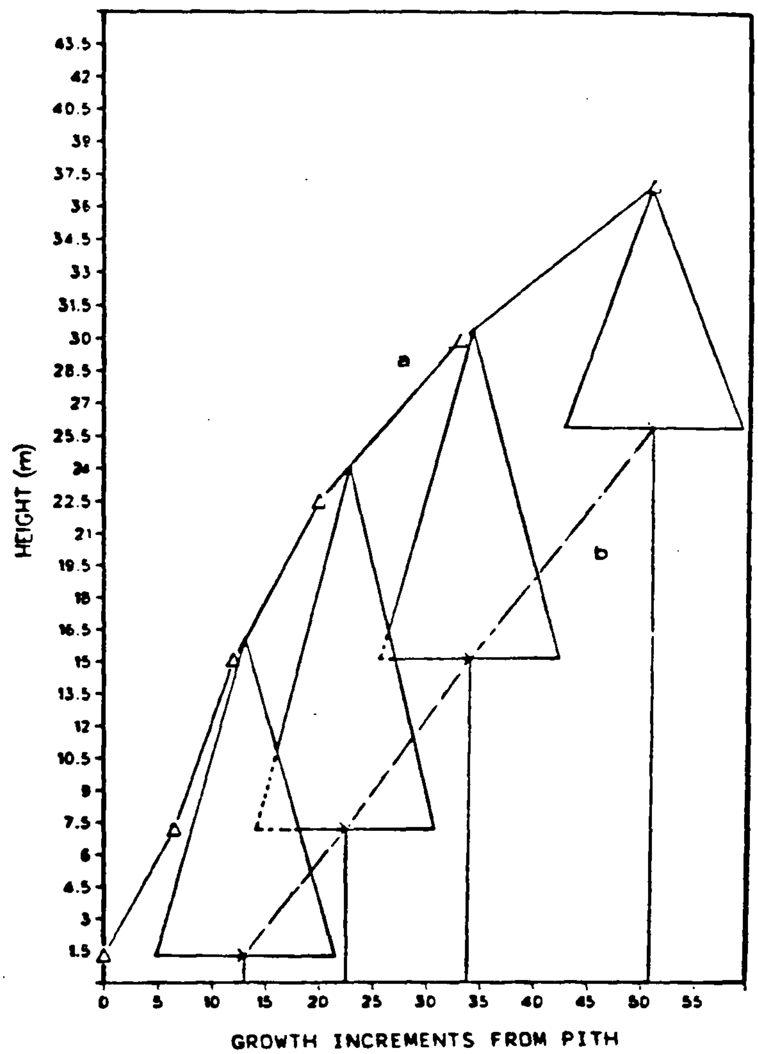


Figure 7. Graphical representation of: a) total tree height; and b) crown base height over number of growth increments from the pith at breast height.

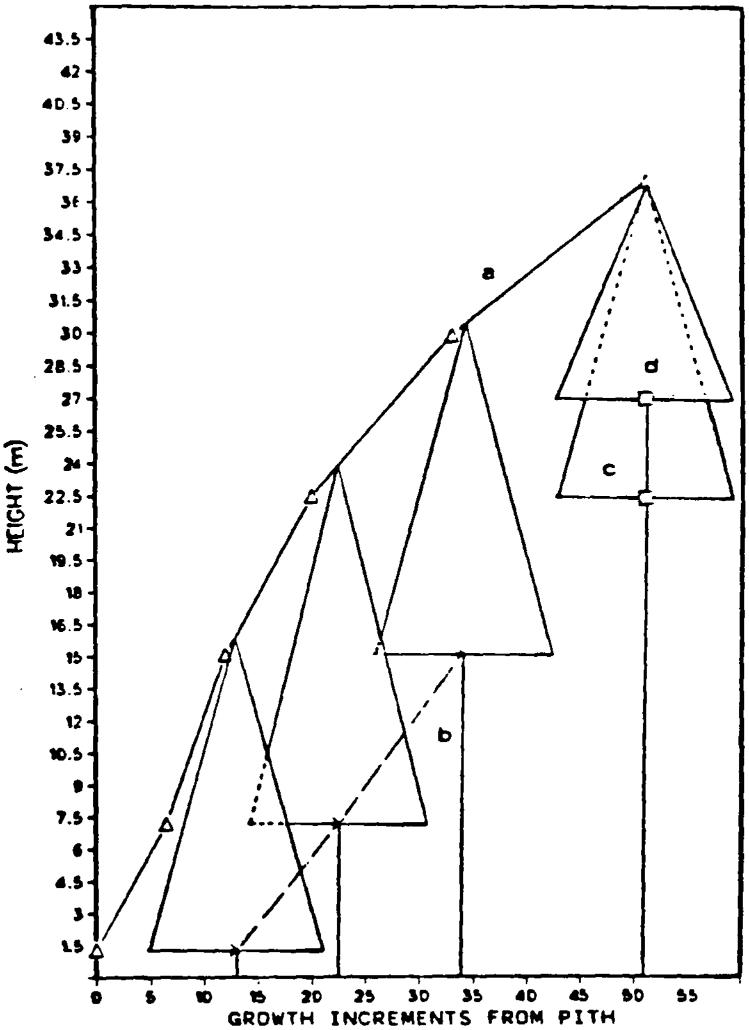


Figure 8. Graphical representation of: a) total tree height; b) crown base height before harvest; c) live crown base height at harvest; and d) average crown height at harvest over number of growth increments from the pith at breast height.

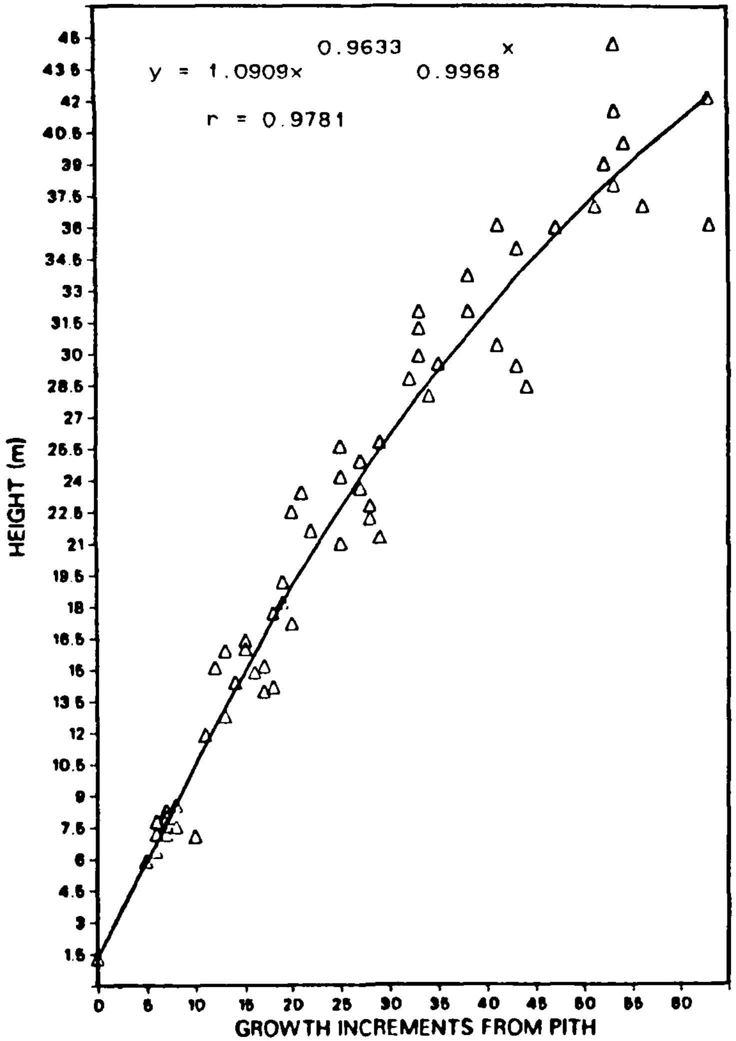


Figure 9a. Scatter and height prediction model for total tree height over number of growth increments from the pith at breast height.

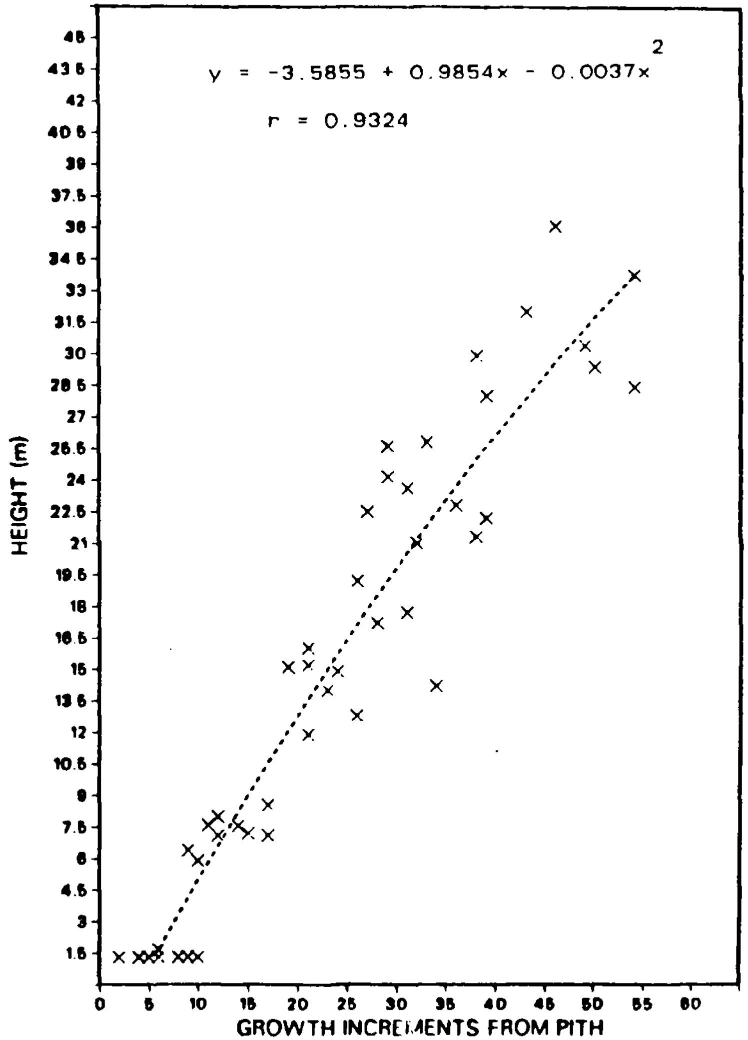


Figure 9b. Scatter and height prediction model for lowest relative density over number of growth increments from the pith at breast height.

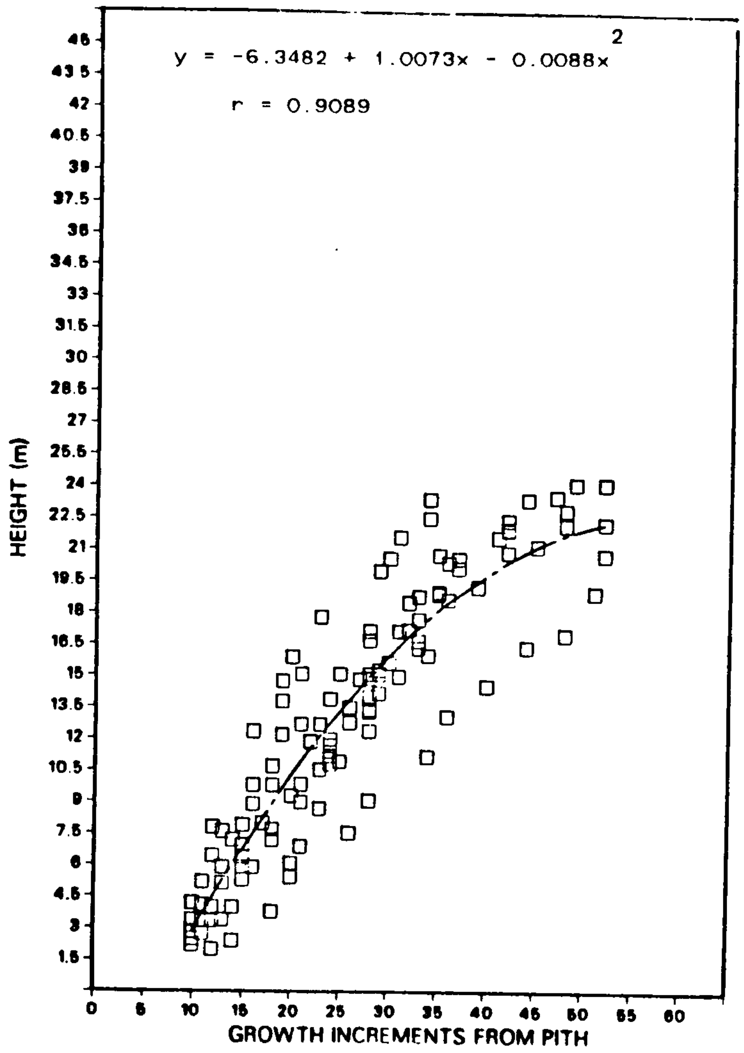


Figure 10a. Scatter and height prediction model for height to crown base over number of growth increments from the pith at breast height.

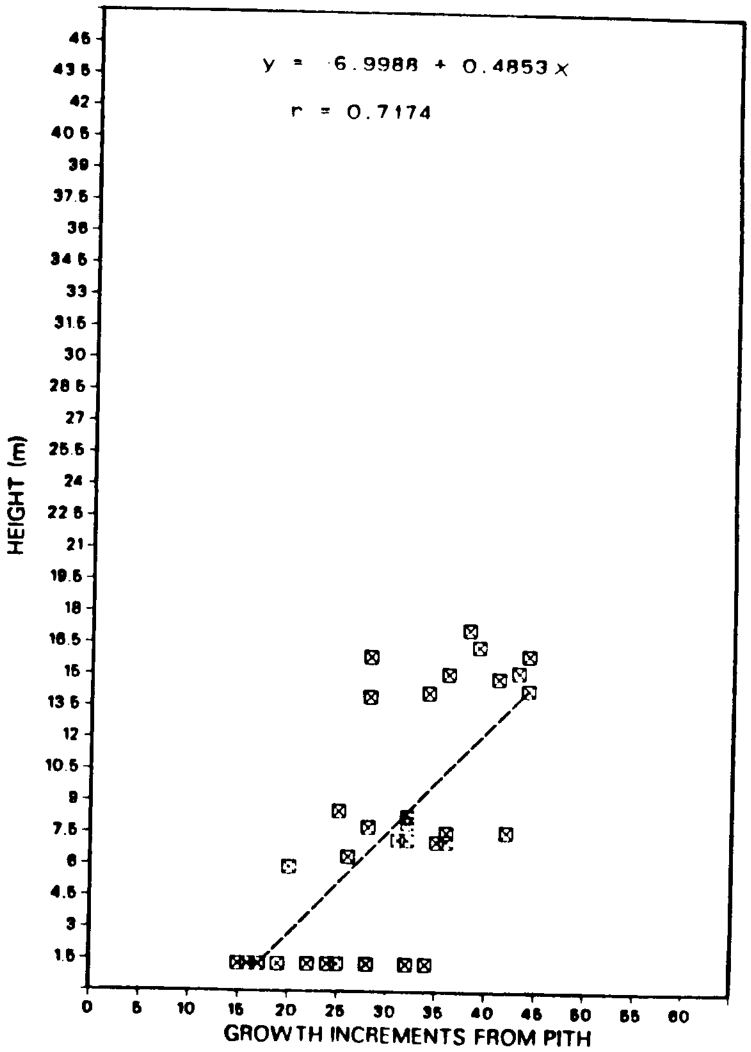


Figure 10b. Scatter and height prediction model for juvenile - mature wood transition points over number of growth increments from the pith at breast height.

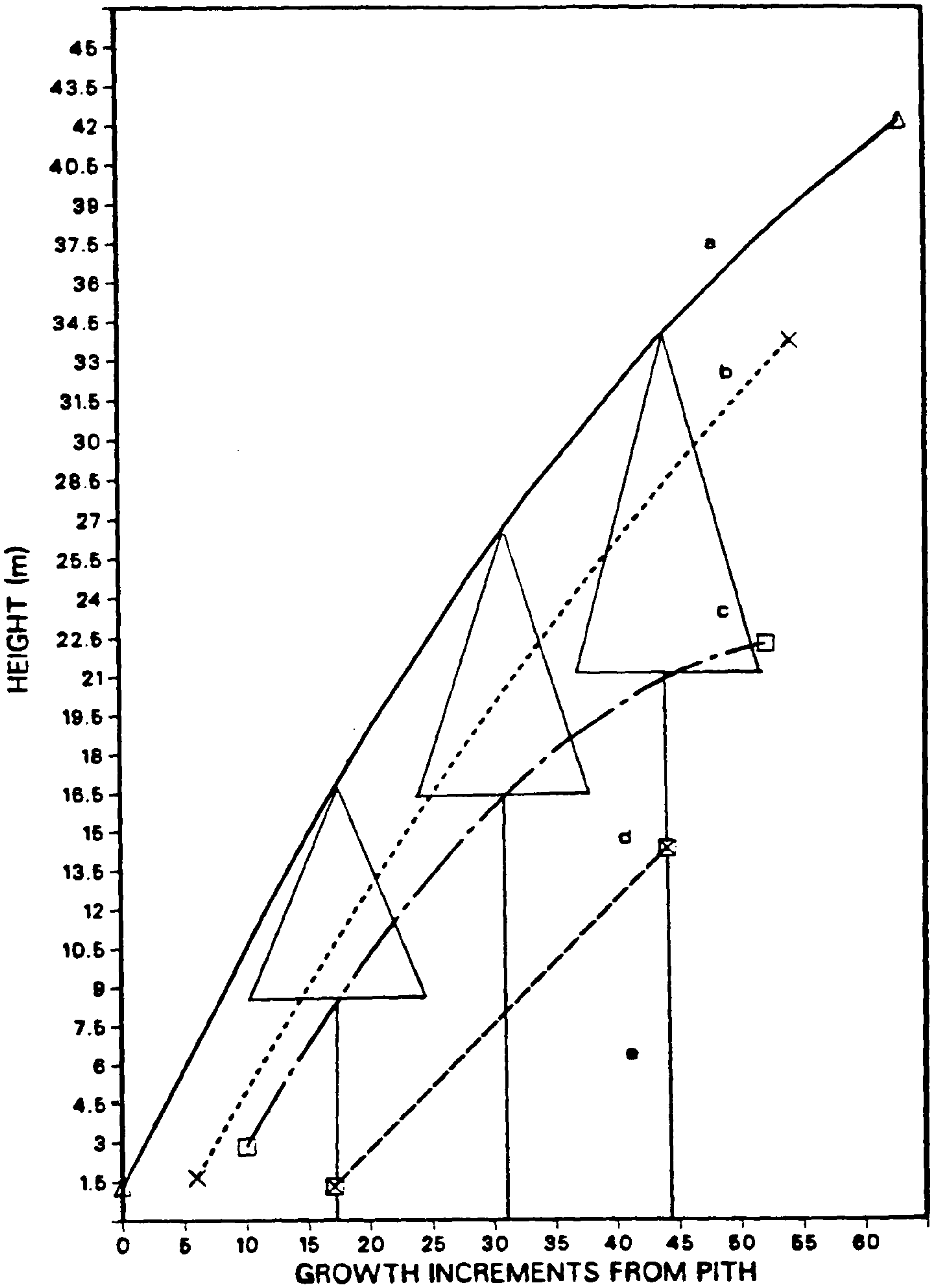


Figure 11. Height prediction models for: a) total tree height; b) lowest relative density height; c) crown base height; d) juvenile - mature wood transition height over number of growth increments from the pith at breast height; and e) diagramatic tree representations.

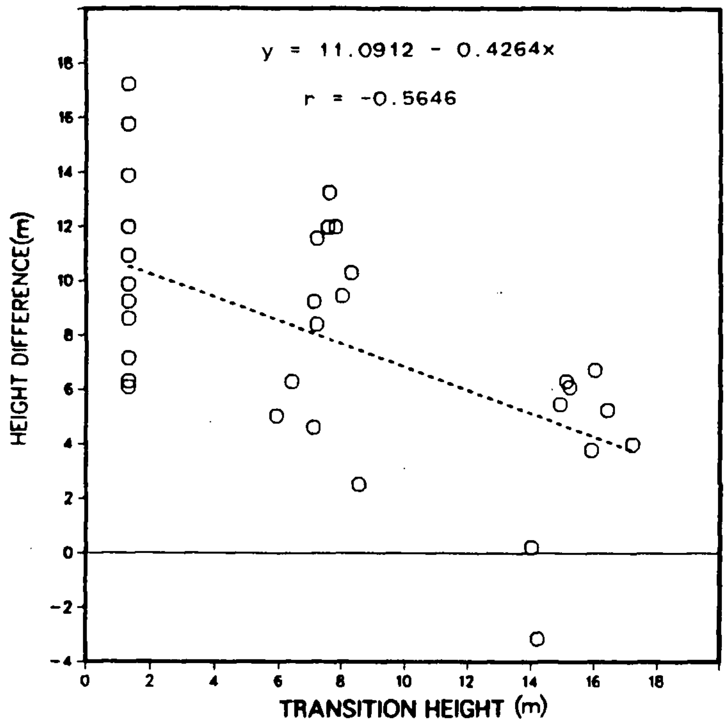


Figure 12a. Scatter and height prediction model for the difference between crown base height and juvenile - mature wood transition height over juvenile - mature wood transition height.

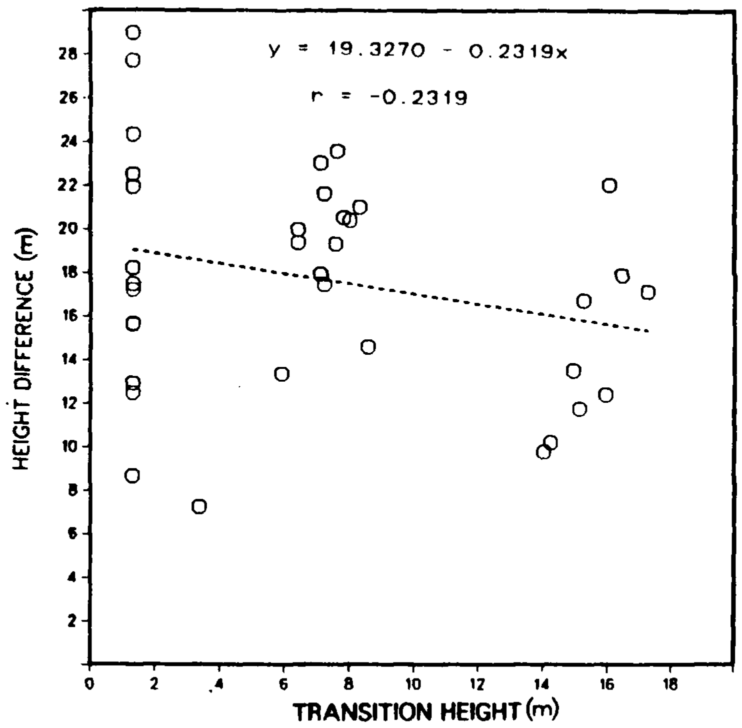


Figure 12b. Scatter and height prediction model for the difference between total height and juvenile - mature wood transition height over juvenile - mature wood transition height.

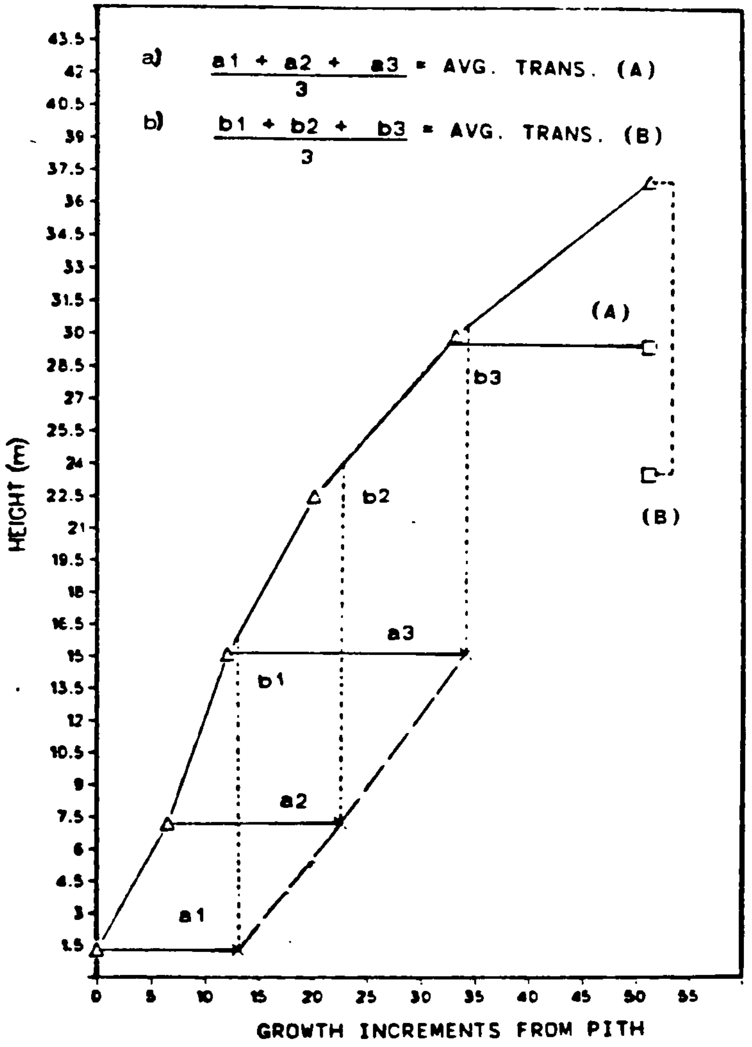


Figure 13. Graphical representation of: a) estimation of the average transition height A; and b) estimation of the average transition height height B over number of growth increments from pith at breast height.

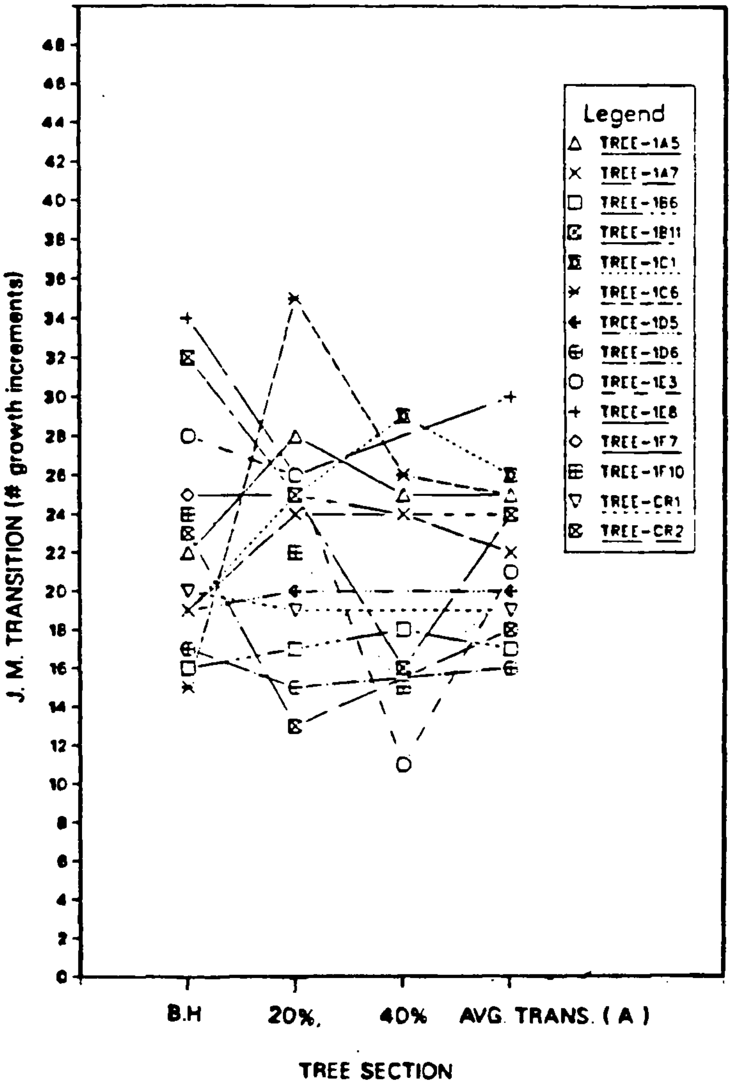


Figure 14. Scatter plot of juvenile - mature (J. M.) wood transition number of growth increments over tree sections and overall section averages, i.e. average transition age A.

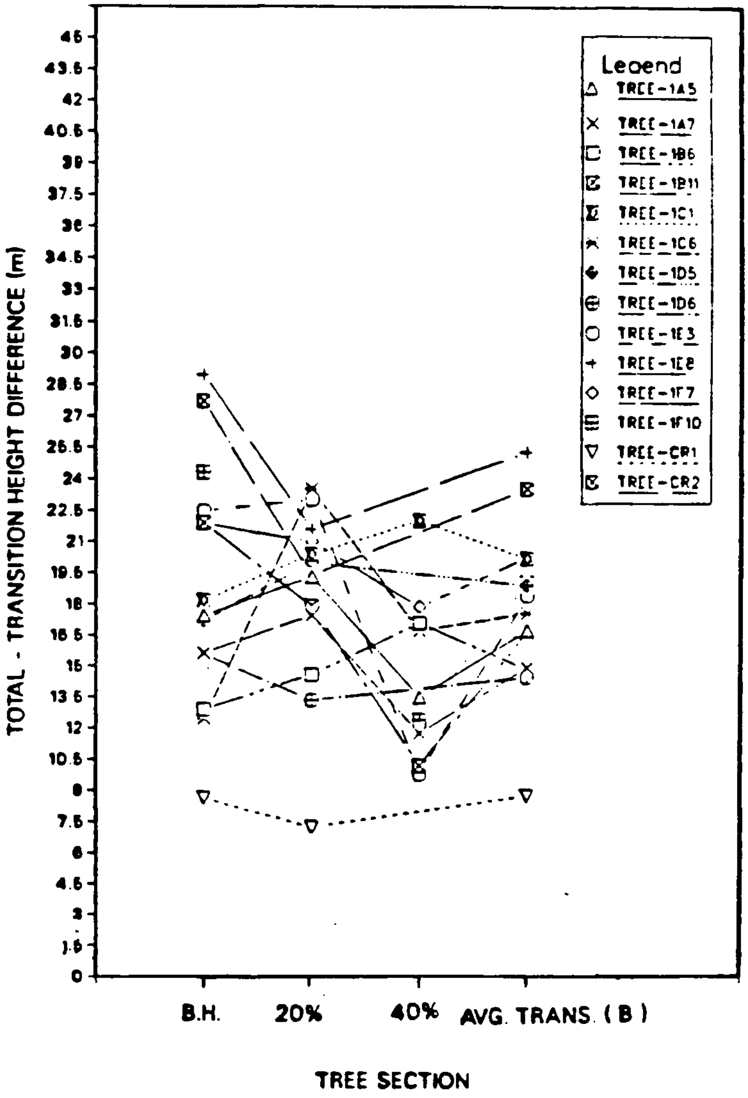


Figure 15. Scatter plot of height differences among total and transition heights over tree sections and overall section averages, i.e. average transition height B.

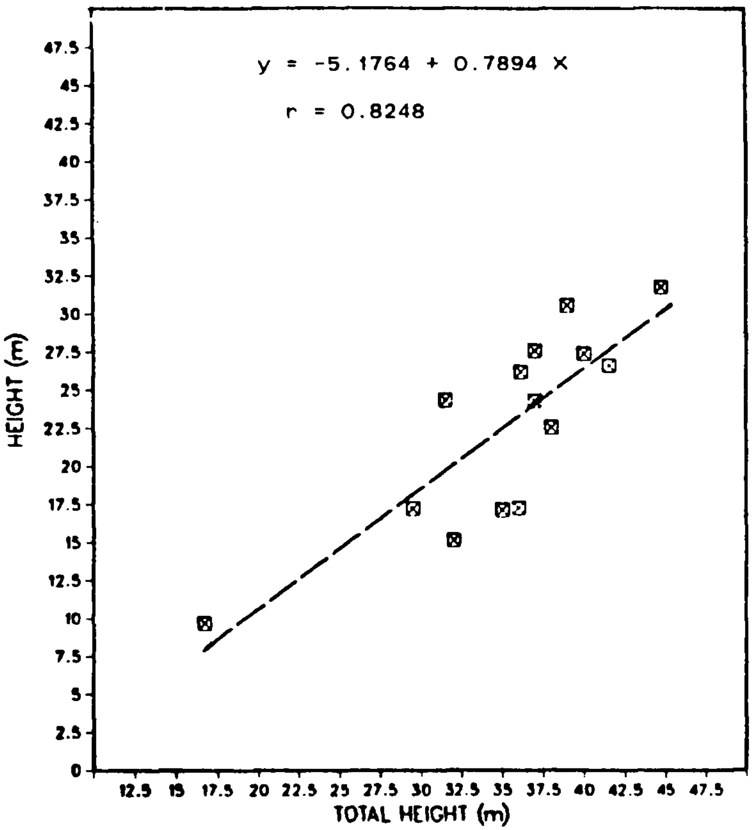


Figure 16a. Scatter plot and height prediction model for average transition height A over total height.

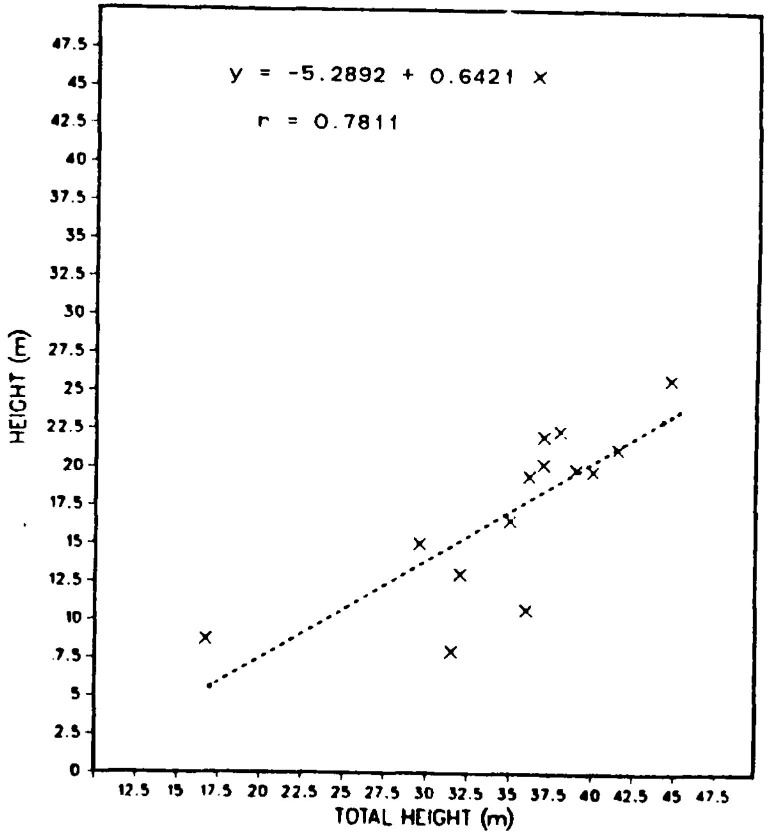


Figure 16b. Scatter plot and height prediction model for average transition height B over total height.

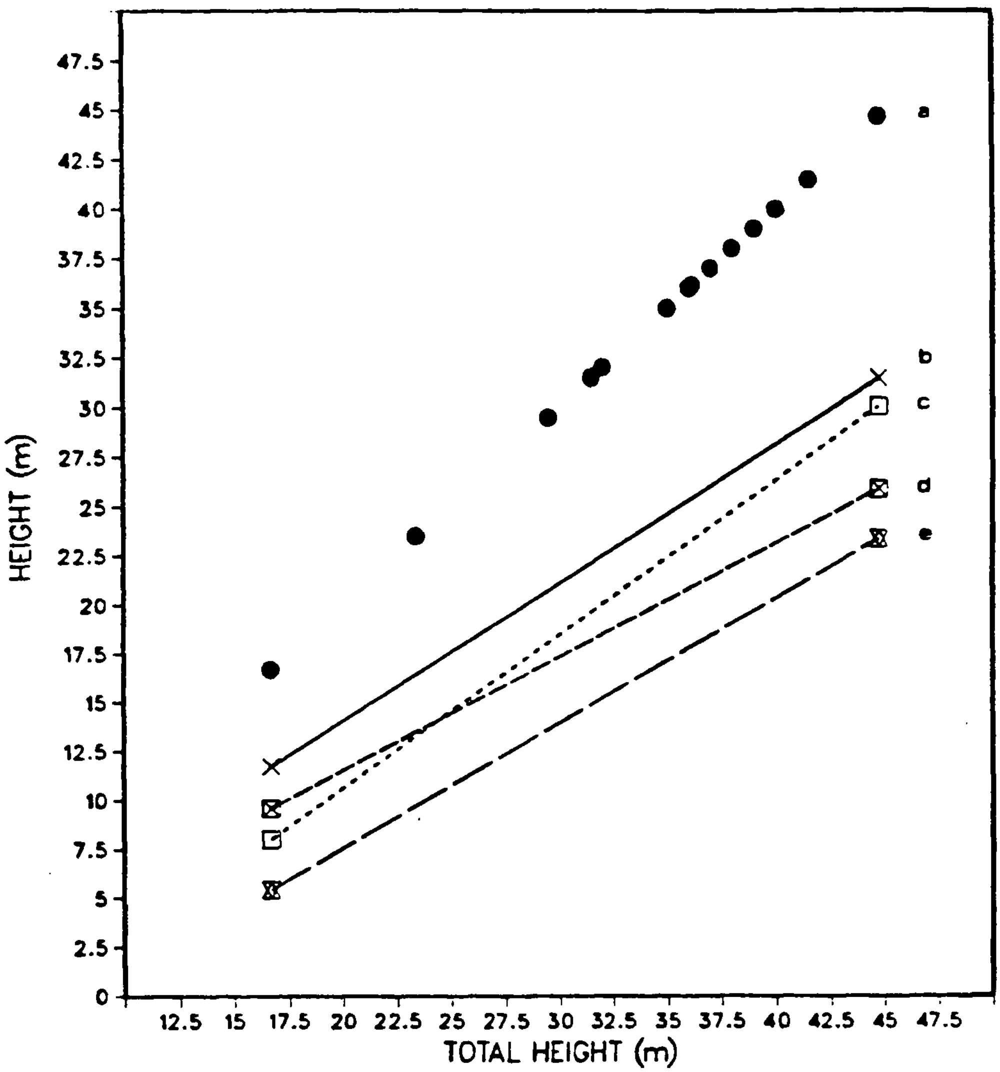


Figure 17. Scatter plot of a) total tree height, and height prediction models over total height for: b) average crown height; c) average transition height A; d) live crown base height; and e) average transition height B.

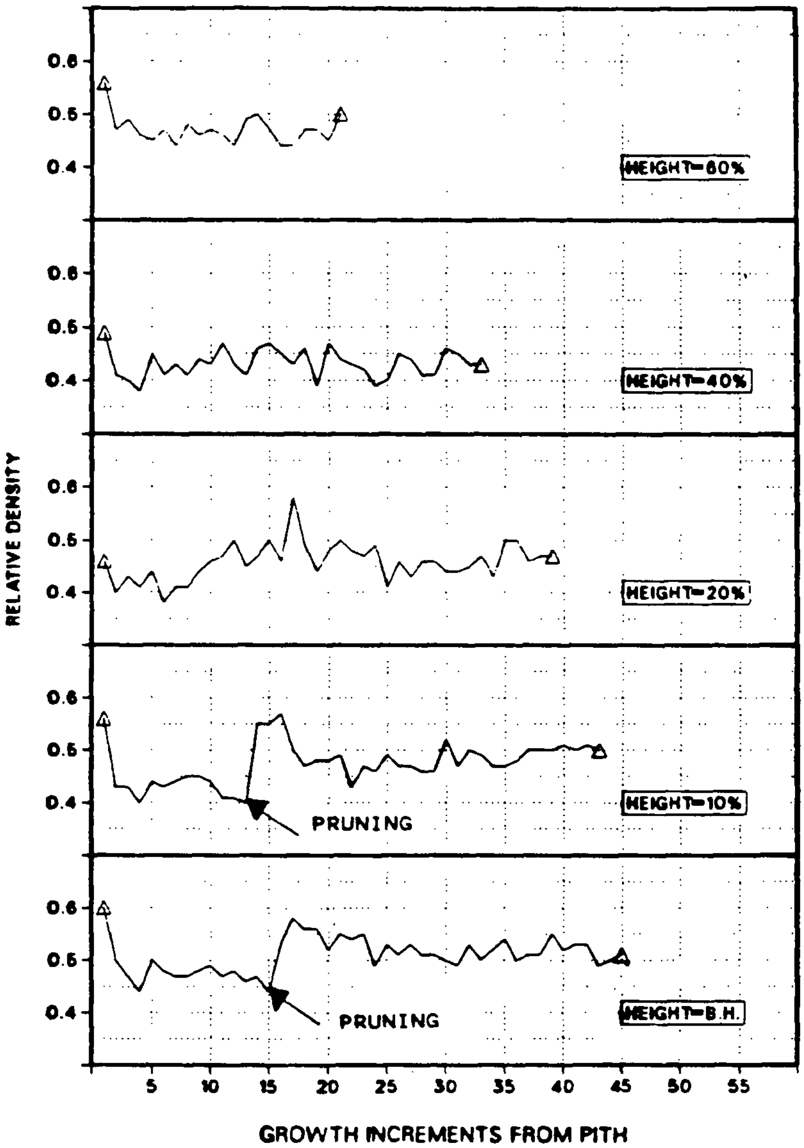


Figure 19. Pith to bark relative density profiles for pruned tree RF3.

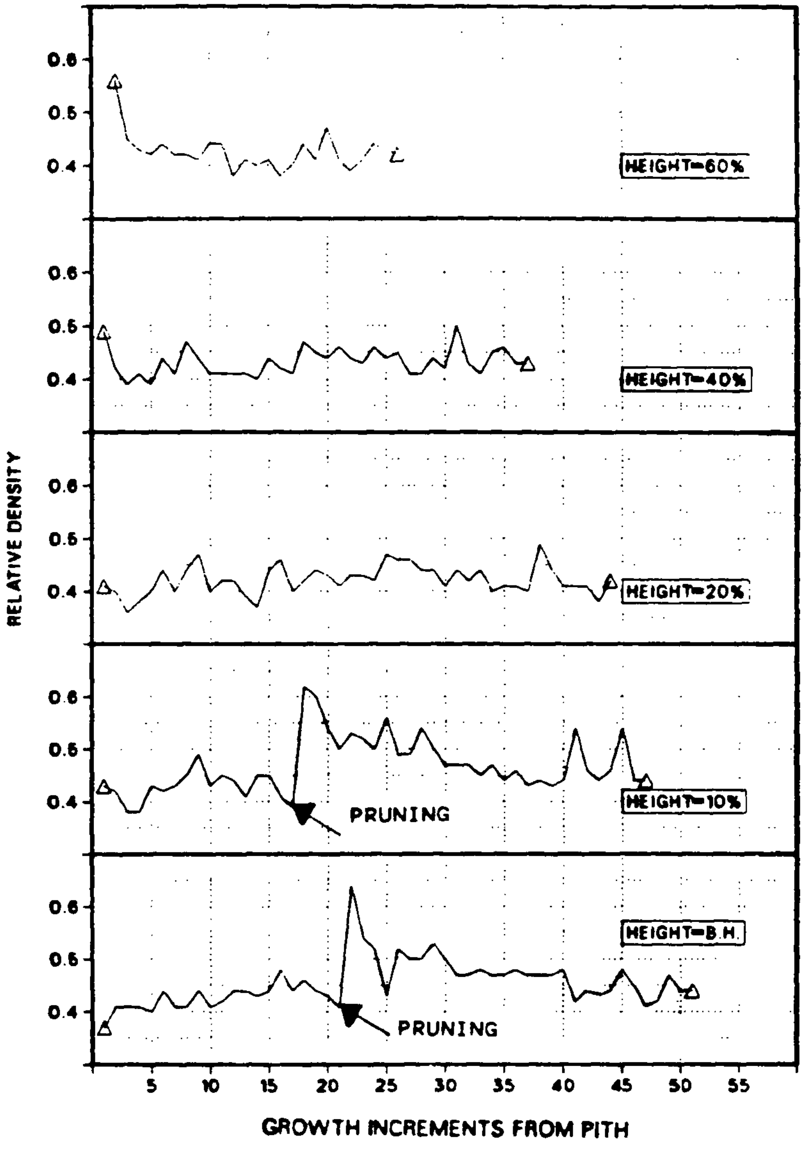


Figure 18. Pith to bark relative density profiles for pruned tree RF2.

Appendix 1. Average Crown Height Estimation Procedure

1. The length of each branch (BL) was plotted against the vertical distance from the terminal leader to the base of the branch (L) to observe the actual shape of each sampled crown (Appendix 1a).
2. The length of each branch (BL) was plotted against the transformed vertical distance from the terminal leader to the base of the branch (Appendix 1b):

$$\ln [(L/c) + 1]$$

where:

ln = natural logarithm

L = distance from the terminal leader to the branch base or crown length

c = coefficient that describes the curvature of the crown profile (estimated for Douglas-fir as 6.1 by Mitchell (1975))

3. The slope of each crown, or regression coefficient (b) values that relate branch growth to height growth were estimated using the following regression equation:

$$BL = bd \, [\, \ln (L/c) + 1 \,] \qquad (1)$$

where:

BL = branch length

b = regression coefficient that relates branch growth to height growth

d = coefficient that compensates for branch crooks (estimated for Douglas-fir as 0.975, by Mitchell (1975))

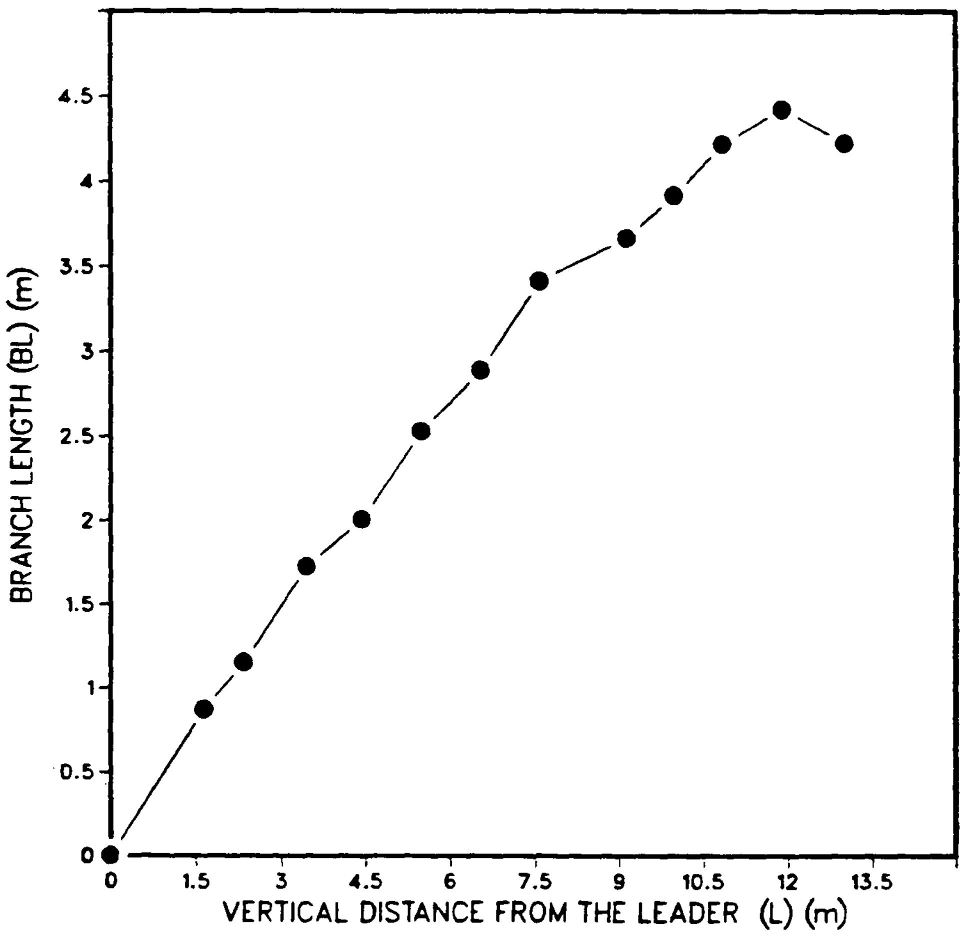
4. The average crown radius, which represented the maximum branch length (BL), was utilized to estimate the distance from the terminal leader to the crown base using Equation 1 and solving for L (Appendix 1c) as follows:

$$L = c \, (\, e^{BL/(bd)} - 1 \,)$$

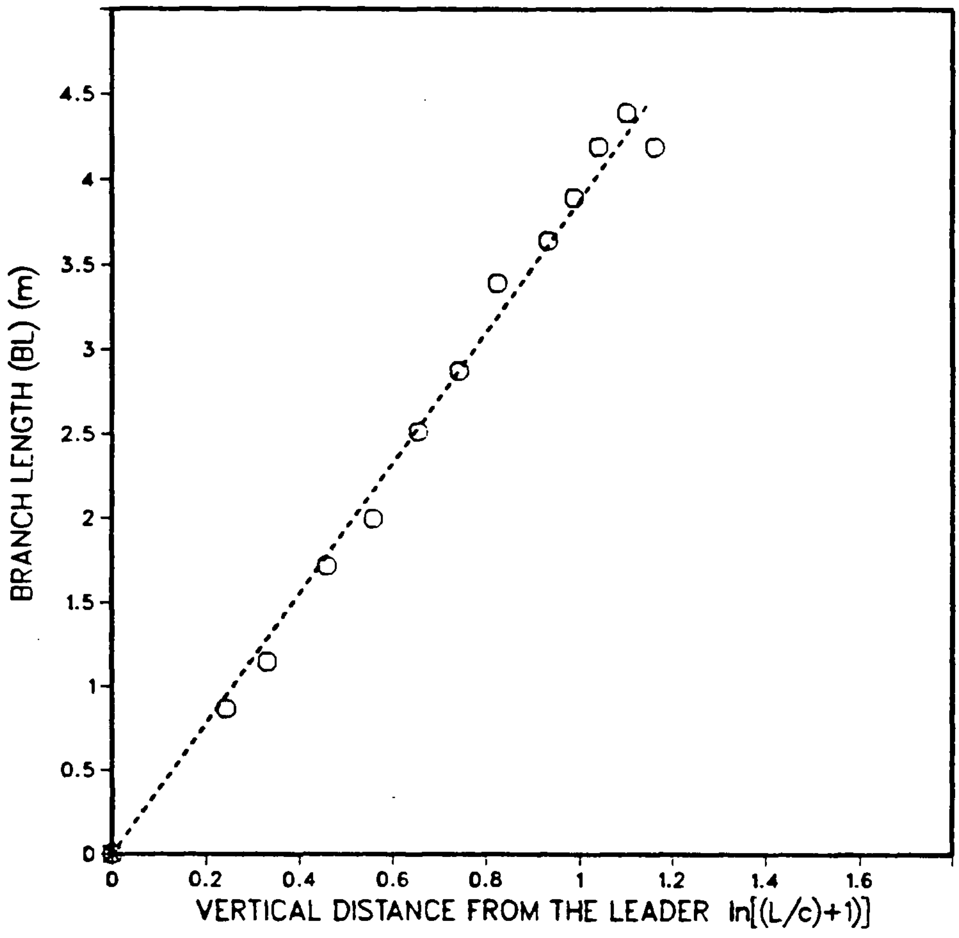
where:

e = 2.71828

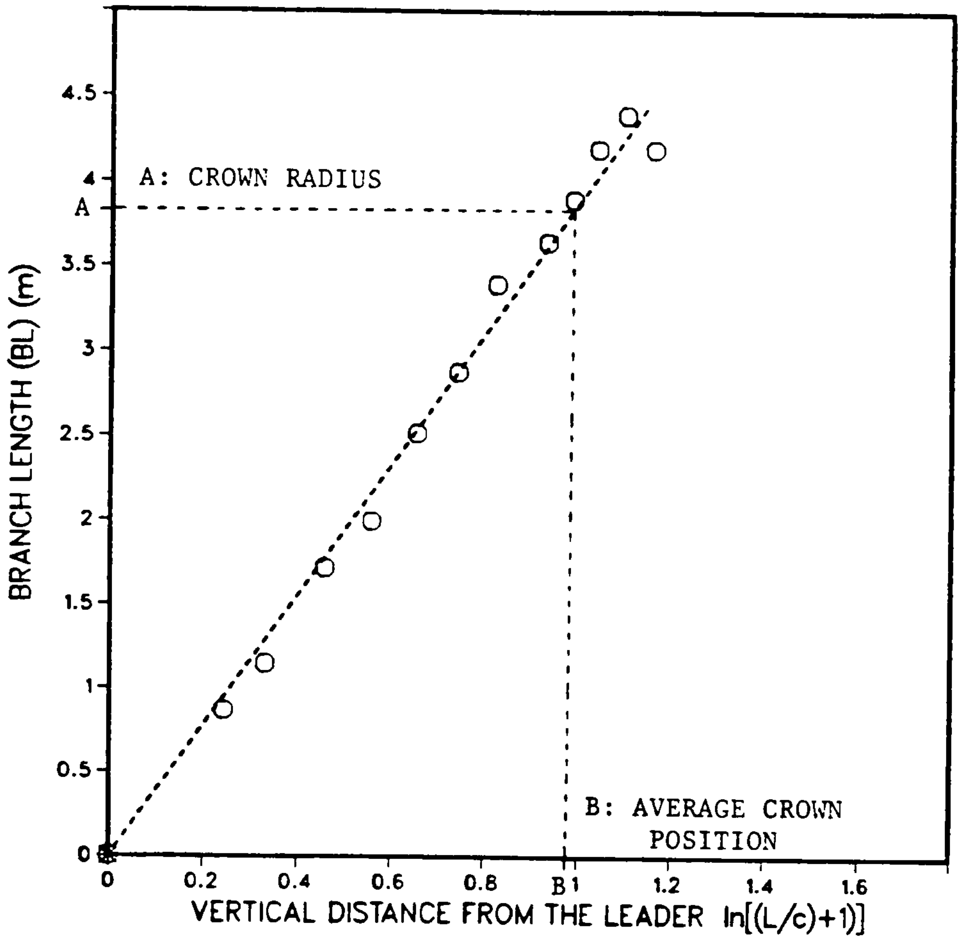
5. Average crown height was calculated by subtracting L from the total tree height (Table 3).



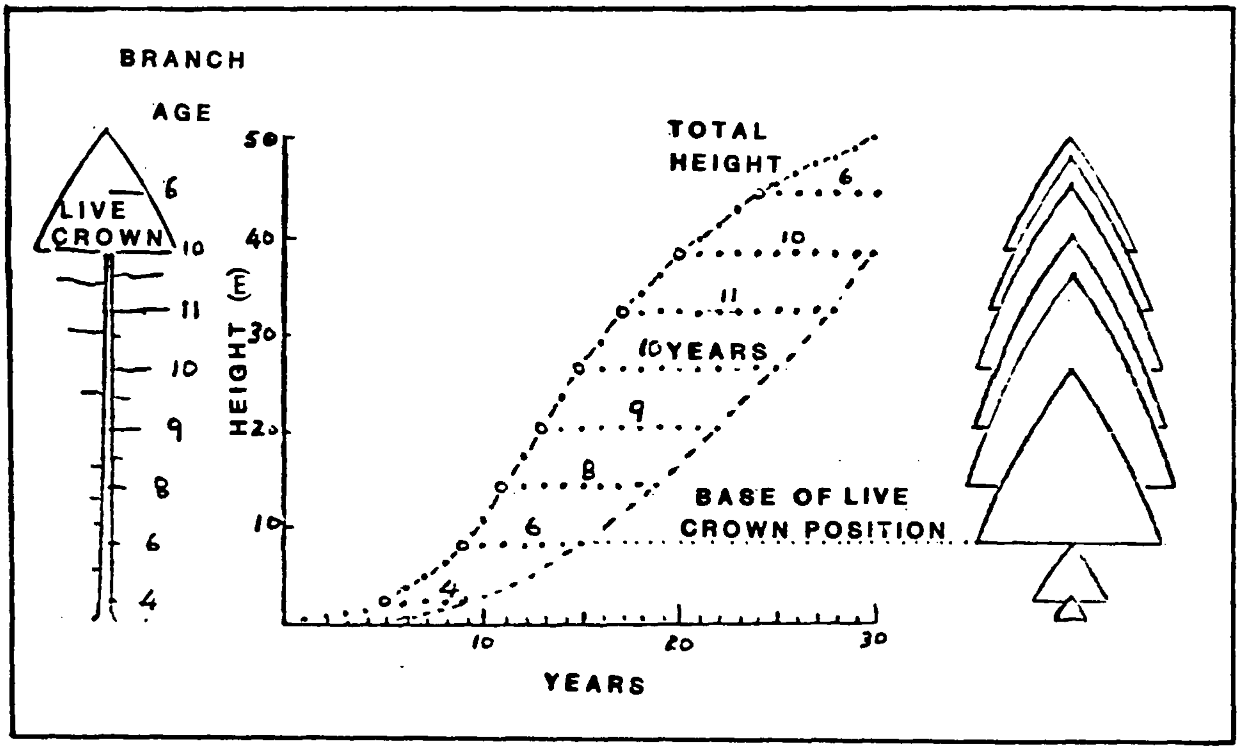
Appendix 1a. Relationship between total branch length (BL) and the vertical distance from the leader (L) for Sample Tree 1A5.



Appendix 1b. Relationship between total branch length (BL) and the transformed vertical distance from the leader ln [(L/c)+1] for Sample Tree 1A5 .



Appendix 1c. Average crown height position determination for sample tree 1A5.



Appendix 2. Relationship between total height and branch age to estimate base of live crown positions at young ages.

Appendix 3. Summary of X-Ray Densitometric Analysis Procedure

1. After air drying, the wood sample strips were mounted and glued between two mounting sticks.
2. The mounted samples were reduced to a uniform thickness of two mm using a specially designed twin blade circular saw.
3. Identification characters were then written on the mounts adjacent to the wood samples using an x-ray opaque lead based paint.
4. The wood samples were extracted by immersion in a solution of 1:2 alcohol benzene for 30 minutes and then air dried at room temperature.
5. A portion of the core mounting stick was removed to measure the angle between the longitudinal tracheids and the long axis of the sample surface. This angle was measured with a goniometer in the eyepiece of a low power stereoscopic microscope.
6. The wood samples along with calibration wedges were placed on fine grained, high resolution, single emulsion x-ray films. The calibration wedges, made of Douglas-fir wood blocks of known relative density, were utilized in the conversion of film density into wood relative density data.

7. Radiographs were then made by exposing the wood samples, calibration wedges and x-ray films on a moving collimated x-ray scanning machine oriented according to the angle of the longitudinal tracheids.
8. The radiographs were developed in specially designed film processing tanks containing separate solutions of developer, stop bath indicator and fixer with hardener. The tanks were placed in a temperature controlled waterjacket. The length of time and temperature at which the radiographs were exposed to the chemicals was determined according to the chemical manufacturer's instructions.
9. The developed radiographs were examined on a light table under a low power stereoscopic microscope. The pith date and the corresponding growth increment calendar years were marked, in decades, on the films.
10. The radiographs were placed on a computerized scanning densitometer that converted the wood sample image on the film into growth increment width and relative density data, measured at 0.01 mm and 0.05 mm steps along the radius of the wood sample, respectively.
11. The data obtained from the densitometer were stored on magnetic tapes for further processing and summarizing. Forintek Canada Corporation's data acquisition Tree Ring Input Program (TRIP) was used to obtain the average relative density of each growth increment.

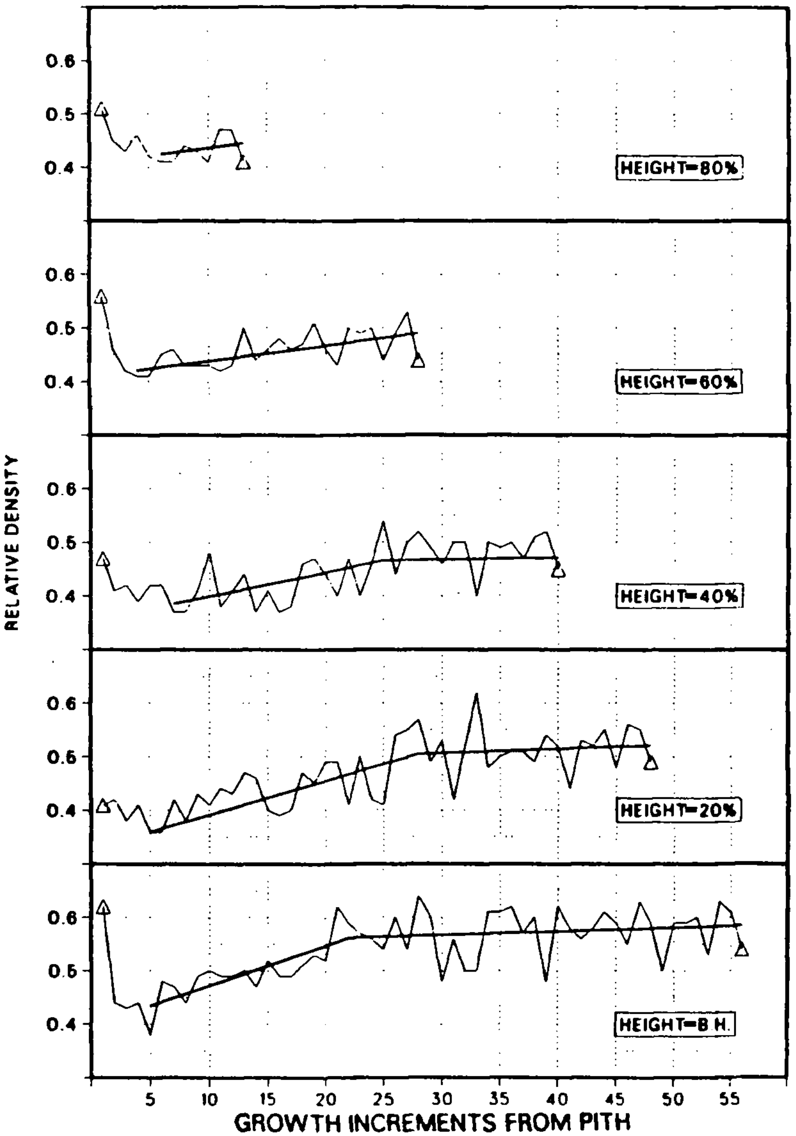
Appendix 4. Fortran program to determine residual sum of squares using non-linear optimization routines for segmented regression models.

Listing of FAST

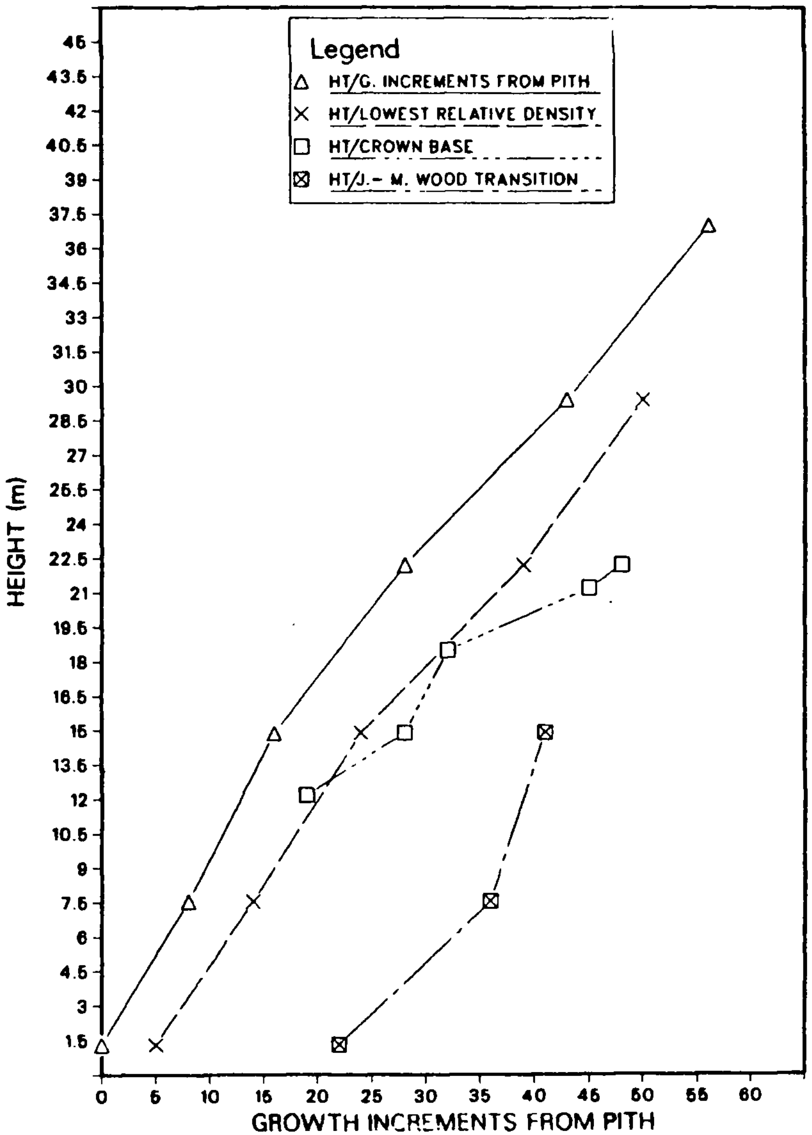
```
$R *FTN SCARDS=DAVID.S SPRINT=-C
R -LOAD+NA:NLMON
ASSIGN 1=1A53RD(8)
CALL GETDAT
IN P
.41025,.35647E-2,20,.49241E-2:
PR F
EX SIMPLX
1
200,10
1.E-05
EX FNMIN
200
10,1.E-11
STOP
SET COST=ON
```

Listing of ...+DAVID.S

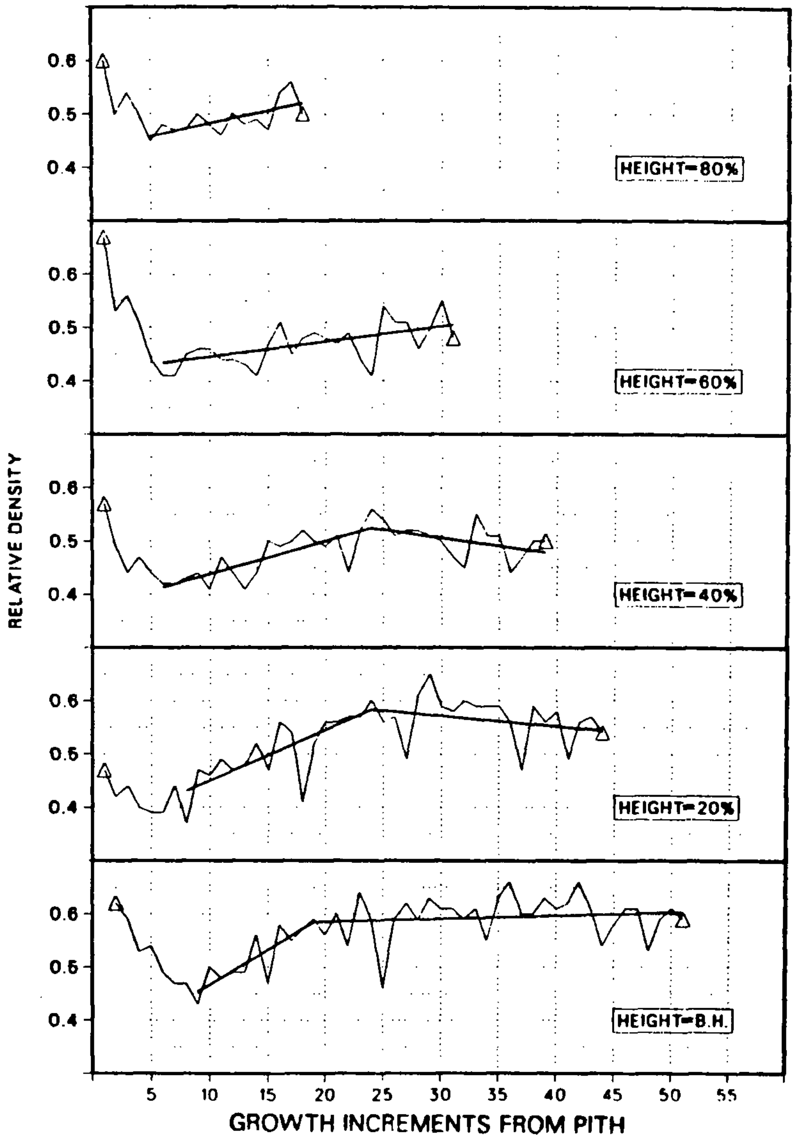
```
          FUNCTION XDFUNC(X,N)
          IMPLICIT REAL*8(A-H,O-Z)
          COMMON /SHARE/POINTS(2,100),NDAT
          REAL*8 X(N)
          XDFUNC=0.0
          DO 100 I=1,NDAT
          IF(POINTS(1,I).GT.X(3))XDFUNC=XDFUNC+(POINTS(2,I)-
         1   (X(1)+X(2)*X(3)+X(4)*(POINTS(1,I)-X(3))))**2
          IF(POINTS(1,I).LE.X(3))XDFUNC=XDFUNC+(POINTS(2,I)-
         1   (X(1)+X(2)*POINTS(1,I)))**2
    100   CONTINUE
          RETURN
          END
C
C
C
          SUBROUTINE GETDAT
          IMPLICIT REAL*8(A-H,O-Z)
          COMMON /SHARE/POINTS(2,100),NDAT
          DO 100 I=1,100
          READ(1,200,END=500)POINTS(1,I),POINTS(2,I)
    200   FORMAT(T6,F2.0,F11.7)
          WRITE(6,200)POINTS(1,I),POINTS(2,I)
          NDAT=I
    100   CONTINUE
    500   RETURN
          END
```



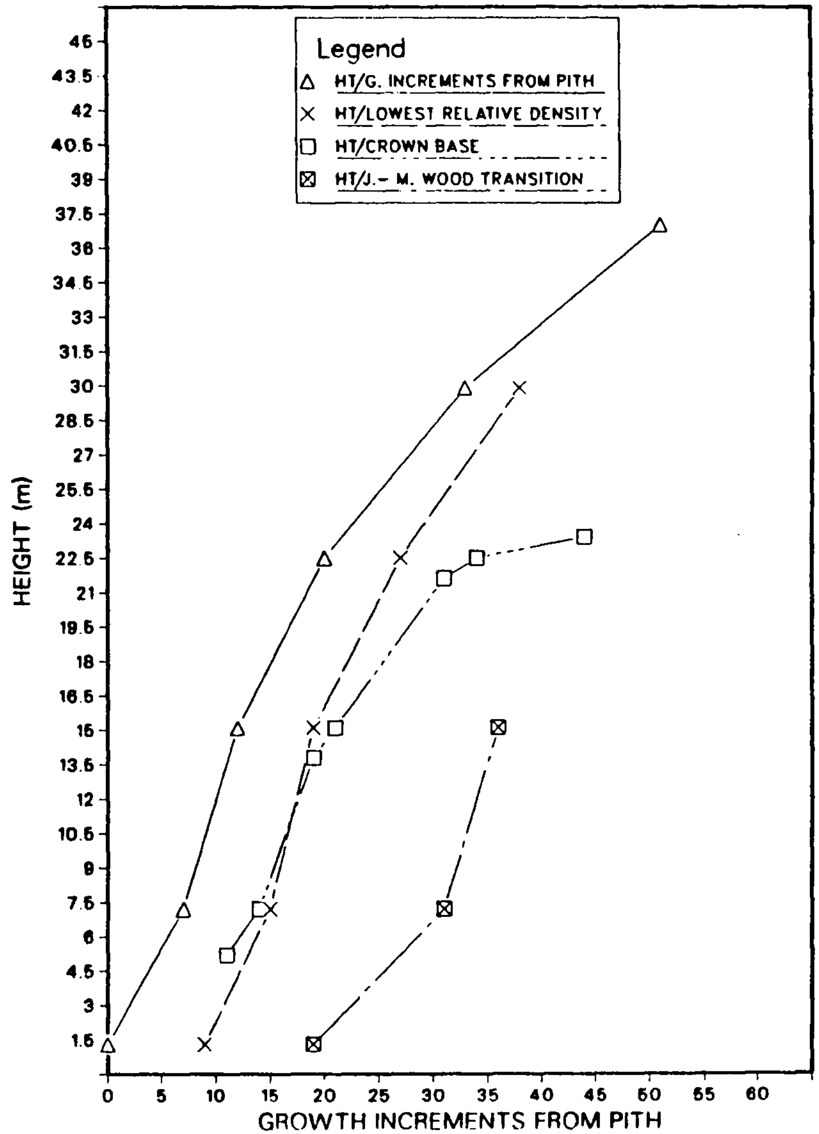
Appendix 5. a) Tree 1A5. Simple and segmented linear regression models on pith to bark relative density profiles.



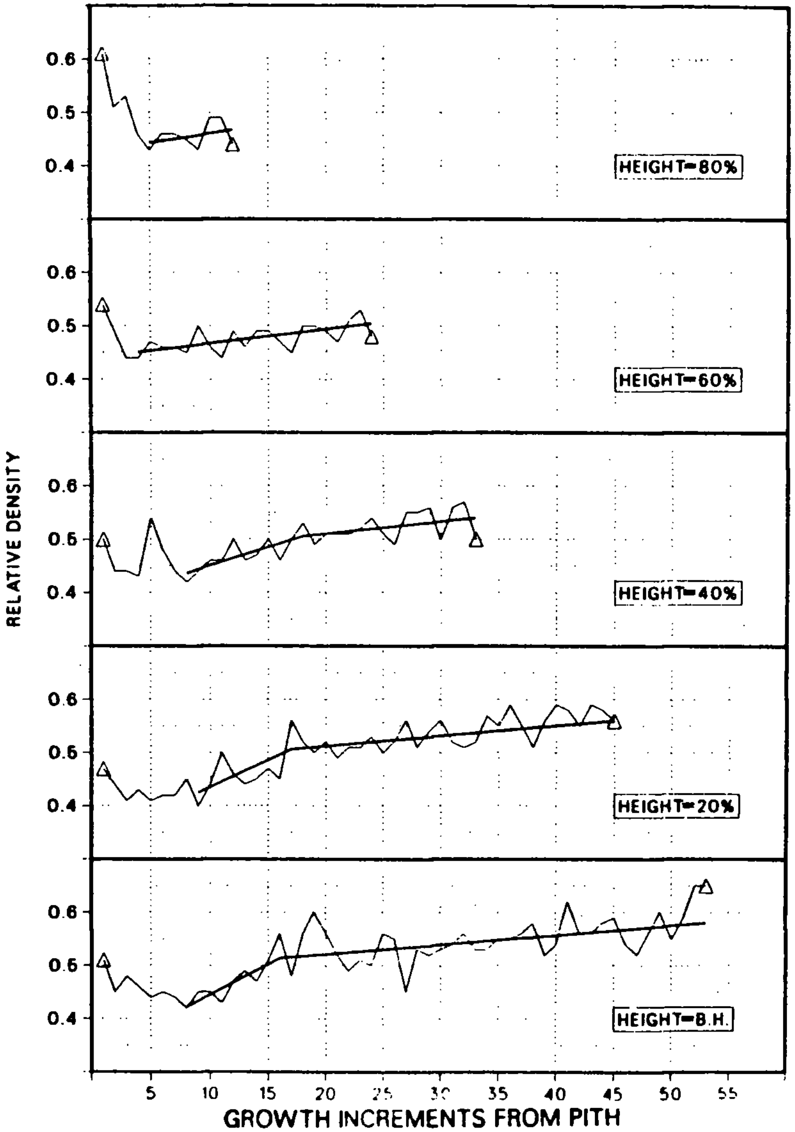
Appendix 5. b) Tree 1A5. Relationships between total tree height, lowest relative density height, crown base height and juvenile - mature wood transition over number of growth increments from pith at breast height.



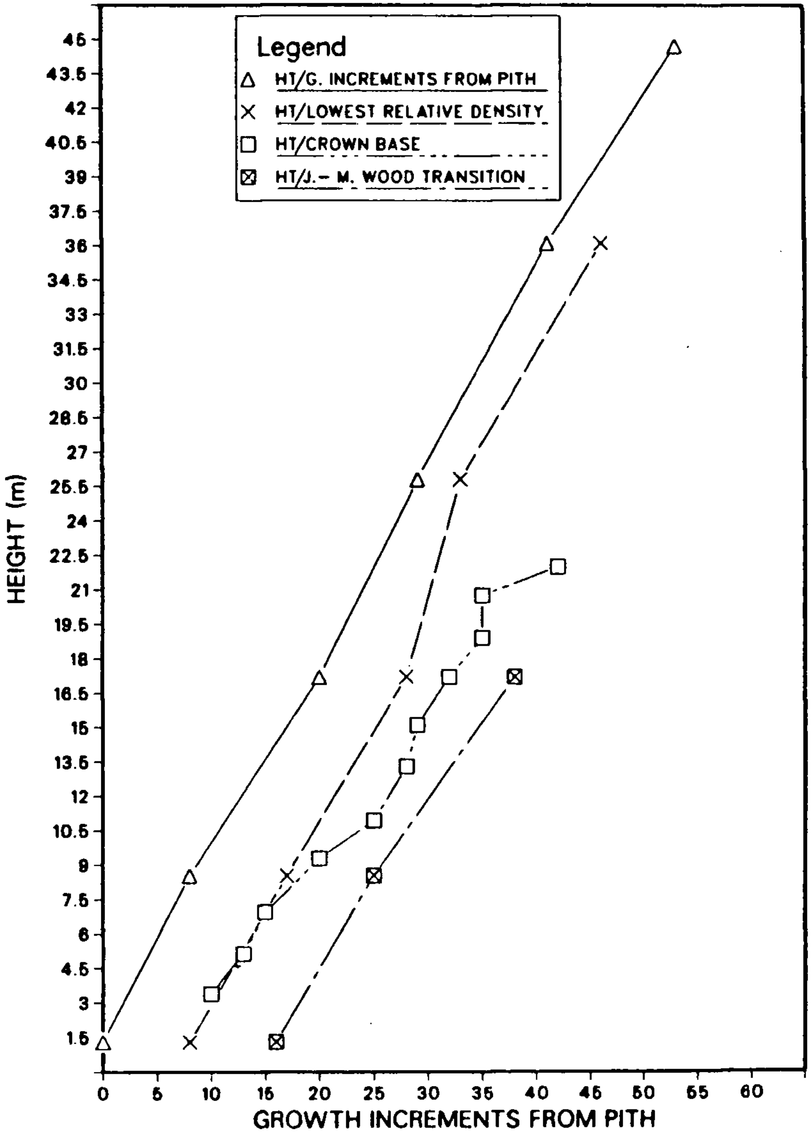
Appendix 6. a) Tree 1A7. Simple and segmented linear regression models on pith to bark relative density profiles.



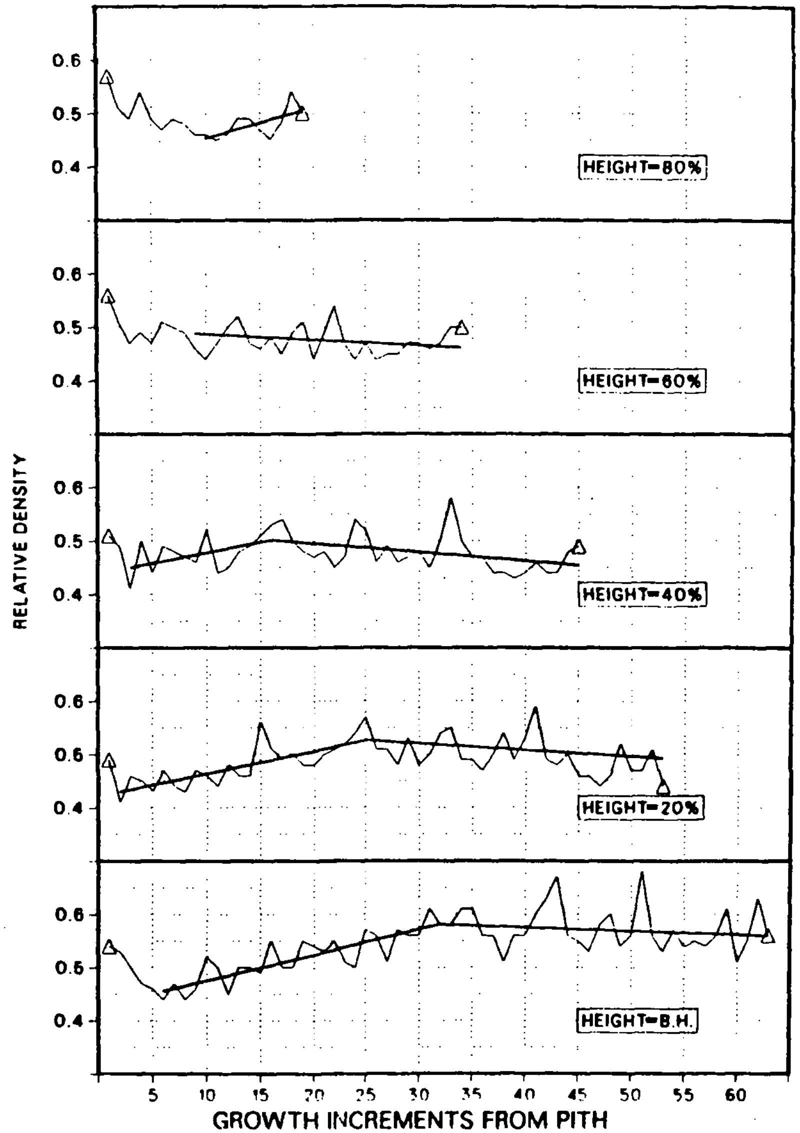
Appendix 6. b) Tree 1A7. Relationships between total tree height, lowest relative density height, crown base height and juvenile - mature wood transition over number of growth increments from pith at breast height.



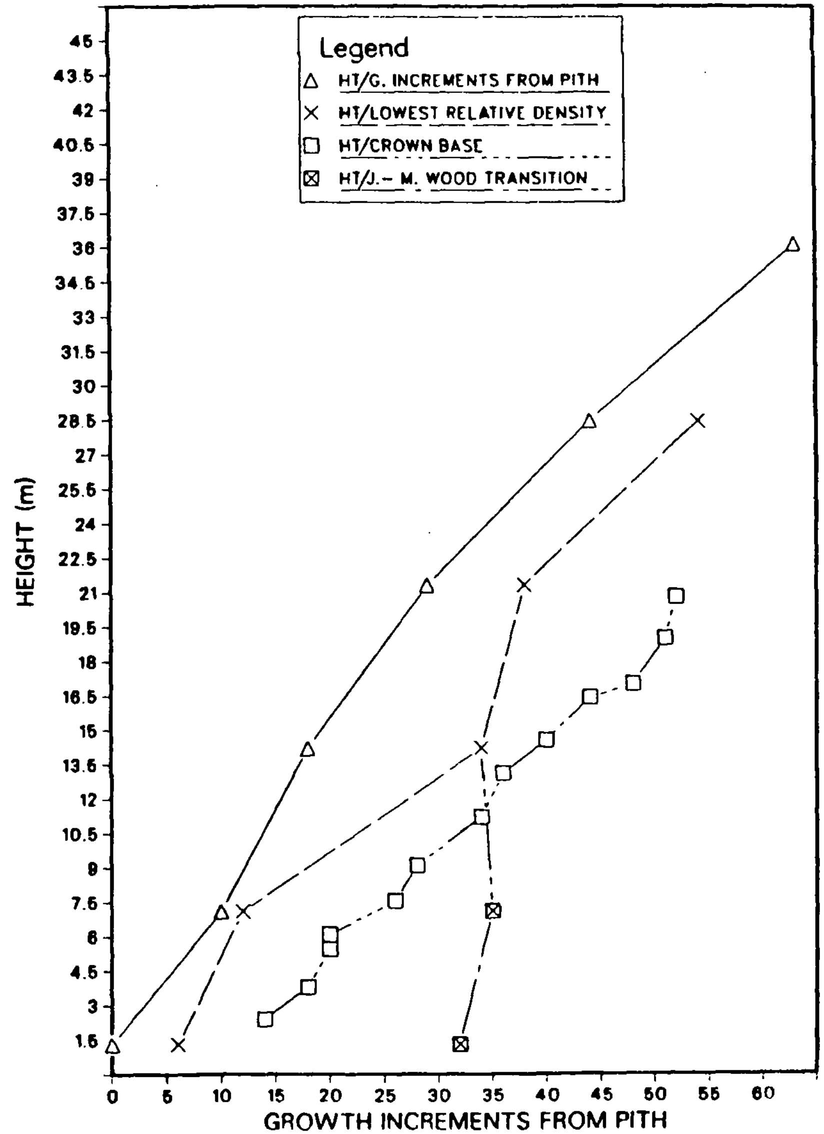
Appendix 7. a) Tree 1B6. Simple and segmented linear regression models on pith to bark relative density profiles.



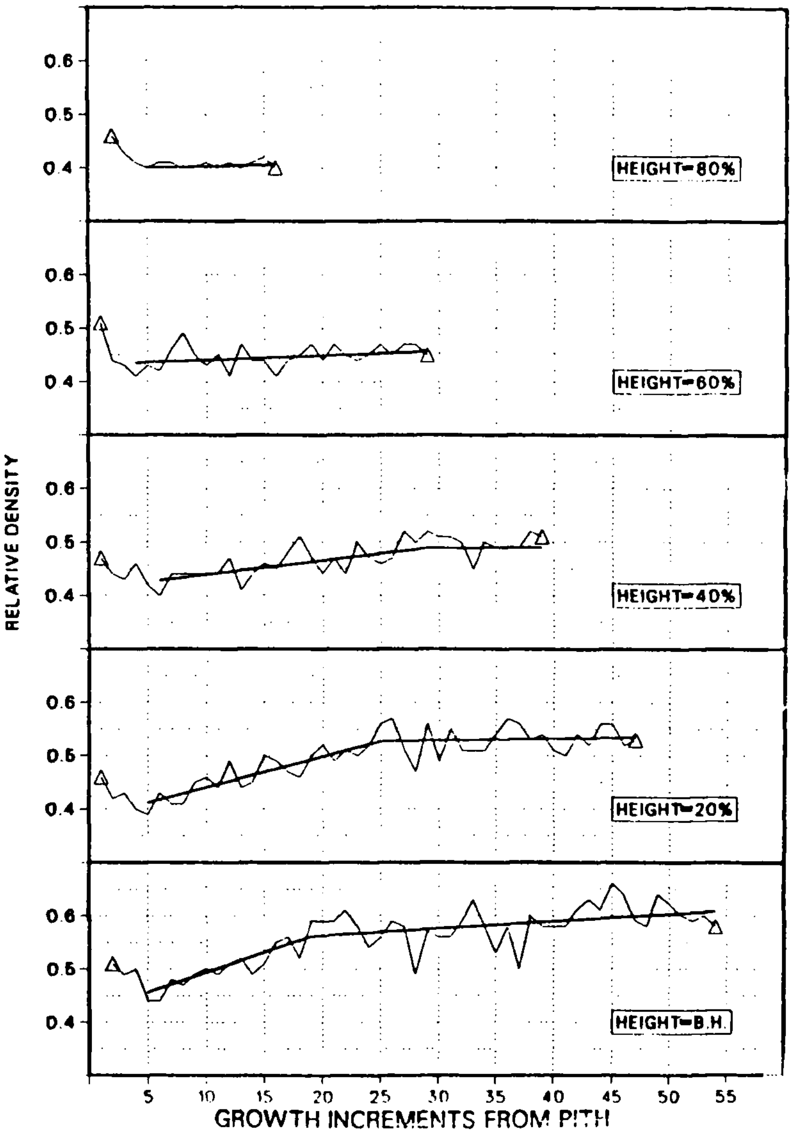
Appendix 7. b) Tree 1B6. Relationships between total tree height, lowest relative density height, crown base height and juvenile - mature wood transition over number of growth increments from pith at breast height.



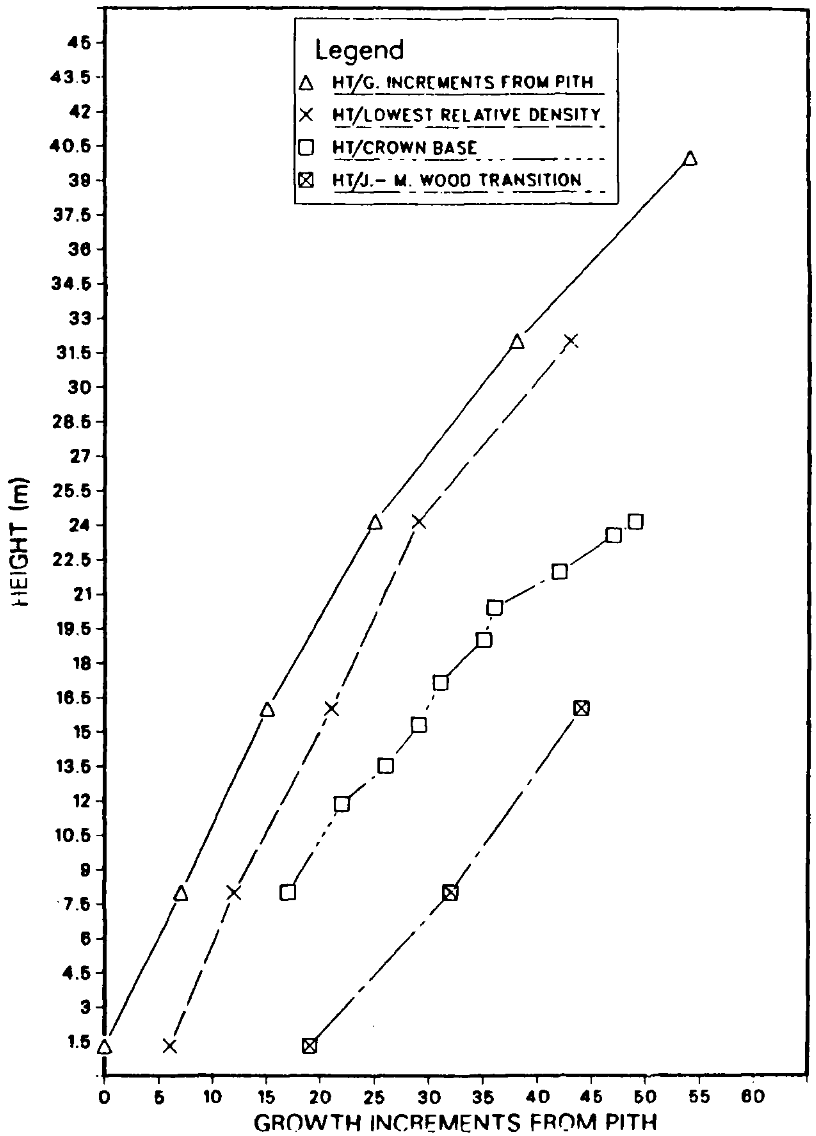
Appendix 8. a) Tree 1B11. Simple and segmented linear regression models on pith to bark relative density profiles.



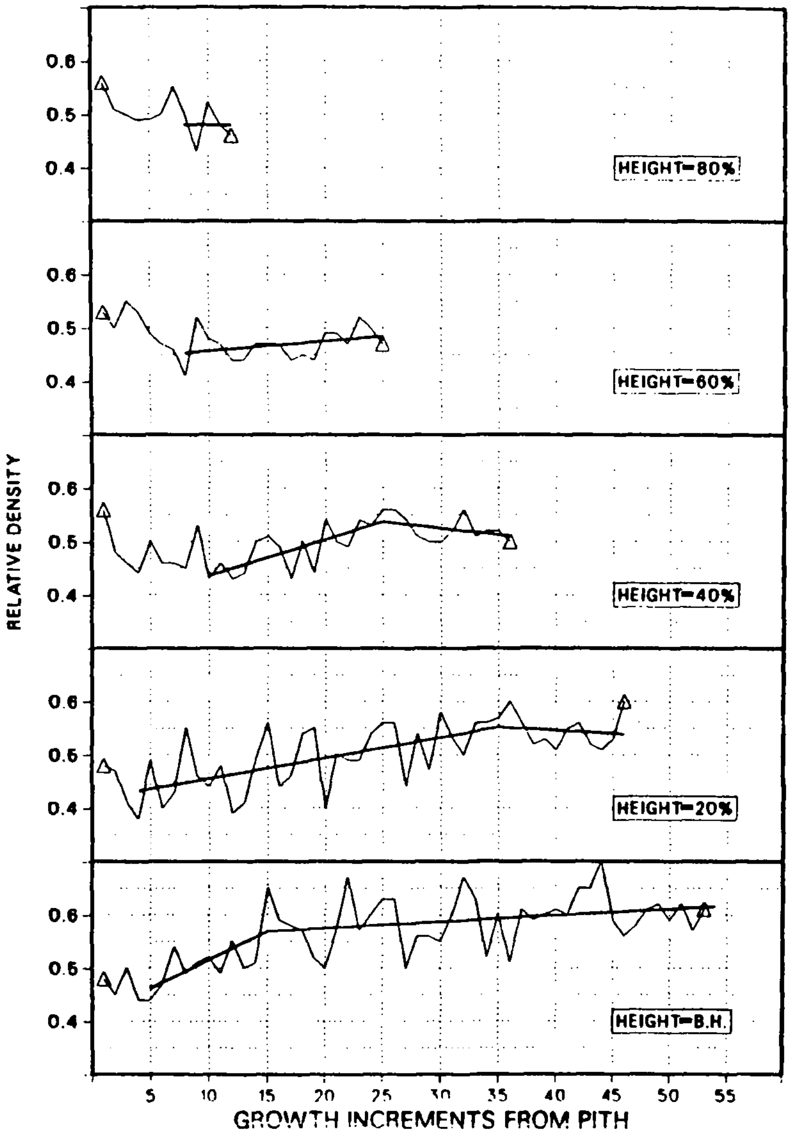
Appendix 8. b) Tree 1B11. Relationships between total tree height, lowest relative density height, crown base height and juvenile - mature wood transition over number of growth increments from pith at breast height.



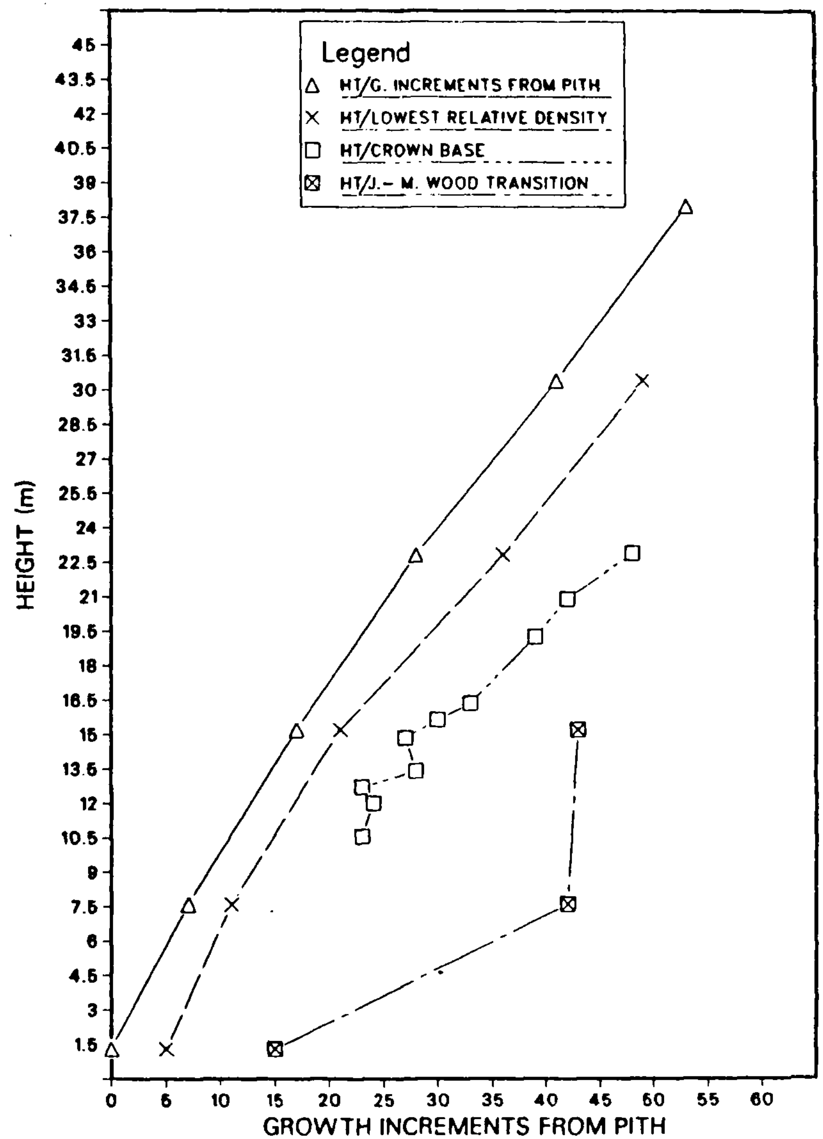
Appendix 9. a) Tree 1C1. Simple and segmented linear regression models on pith to bark relative density profiles.



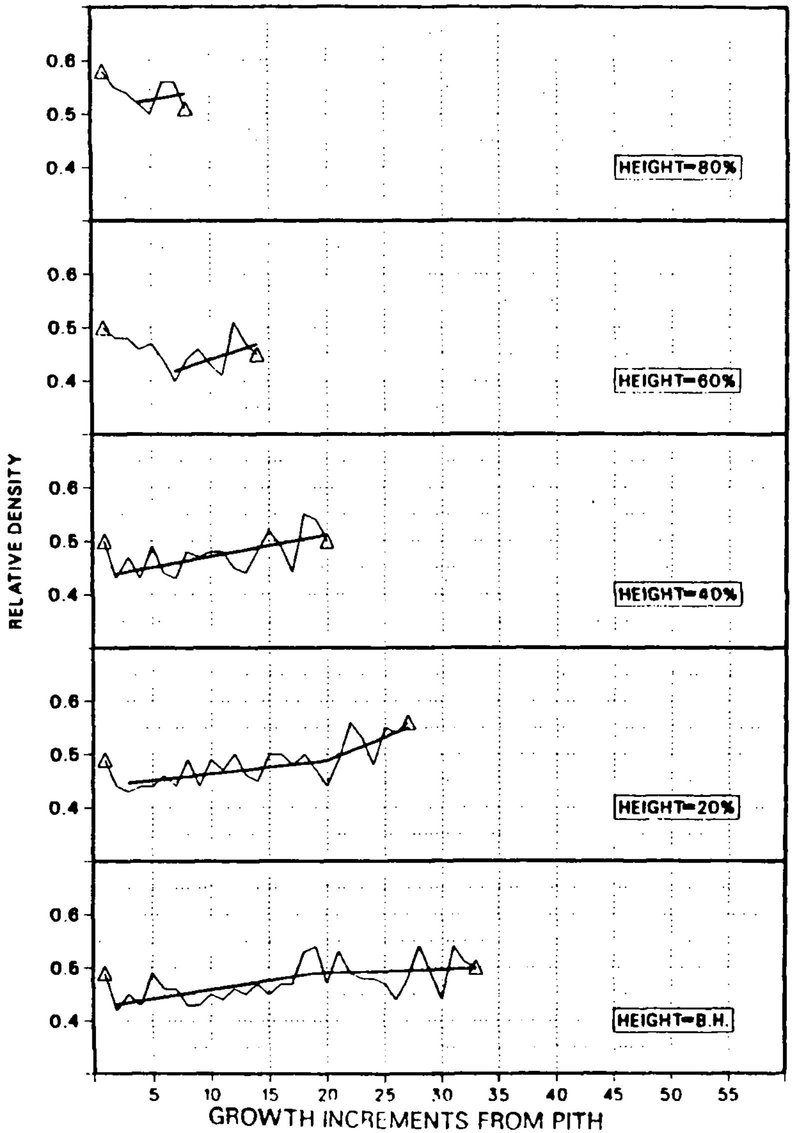
Appendix 9. b) Tree 1C1. Relationships between total tree height, lowest relative density height, crown base height and juvenile - mature wood transition over number of growth increments from pith at breast height.



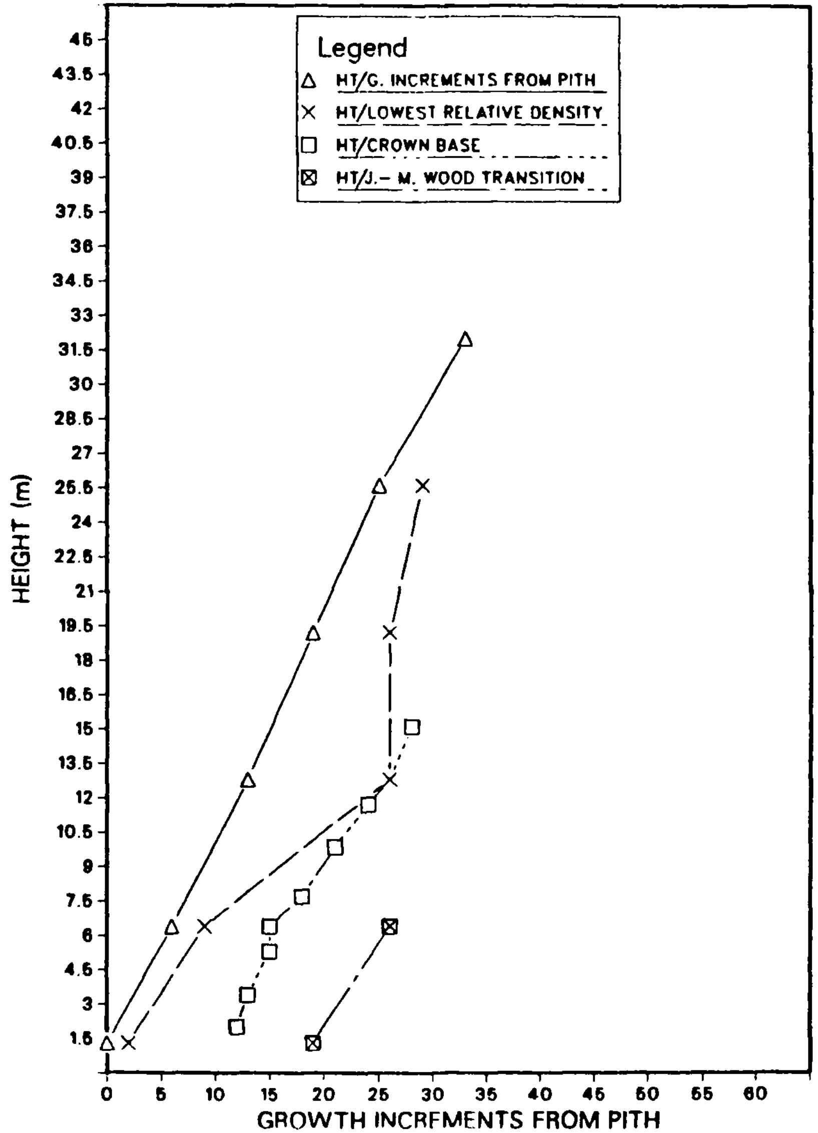
Appendix 10. a) Tree 1C6. Simple and segmented linear regression models on pith to bark relative density profiles.



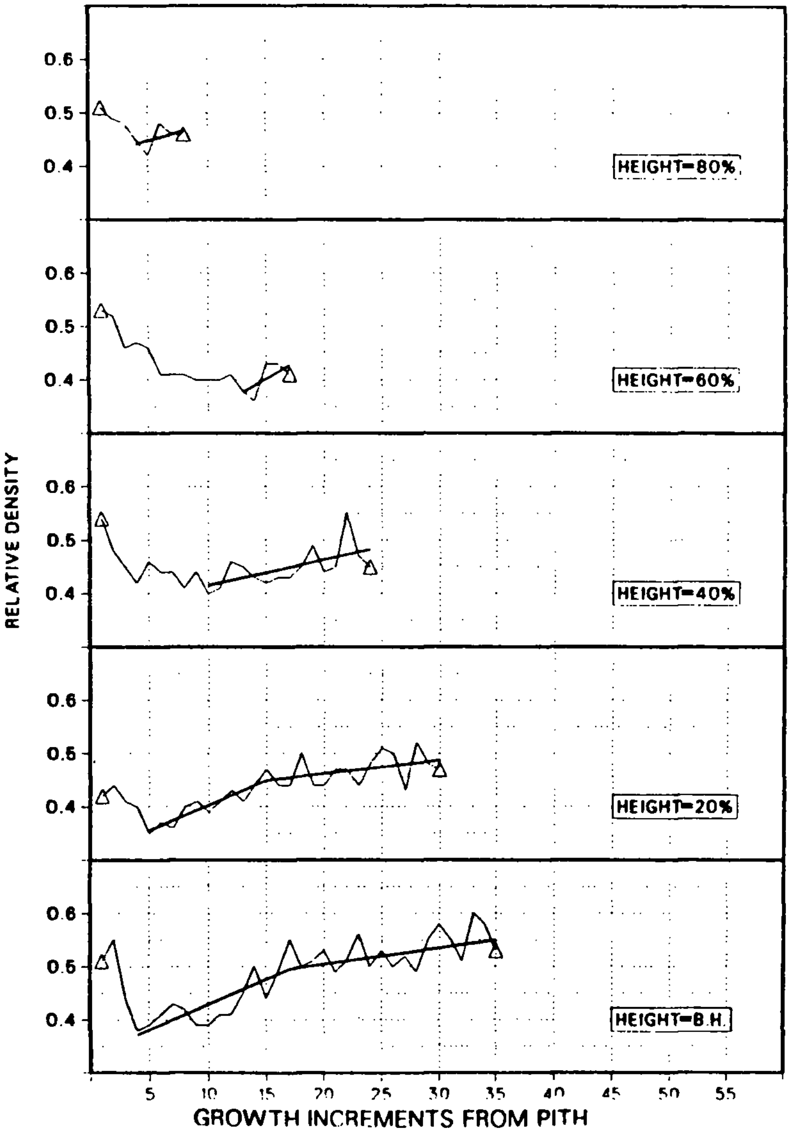
Appendix 10. b) Tree 1C6. Relationships between total tree height, lowest relative density height, crown base height and juvenile - mature wood transition over number of growth increments from pith at breast height.



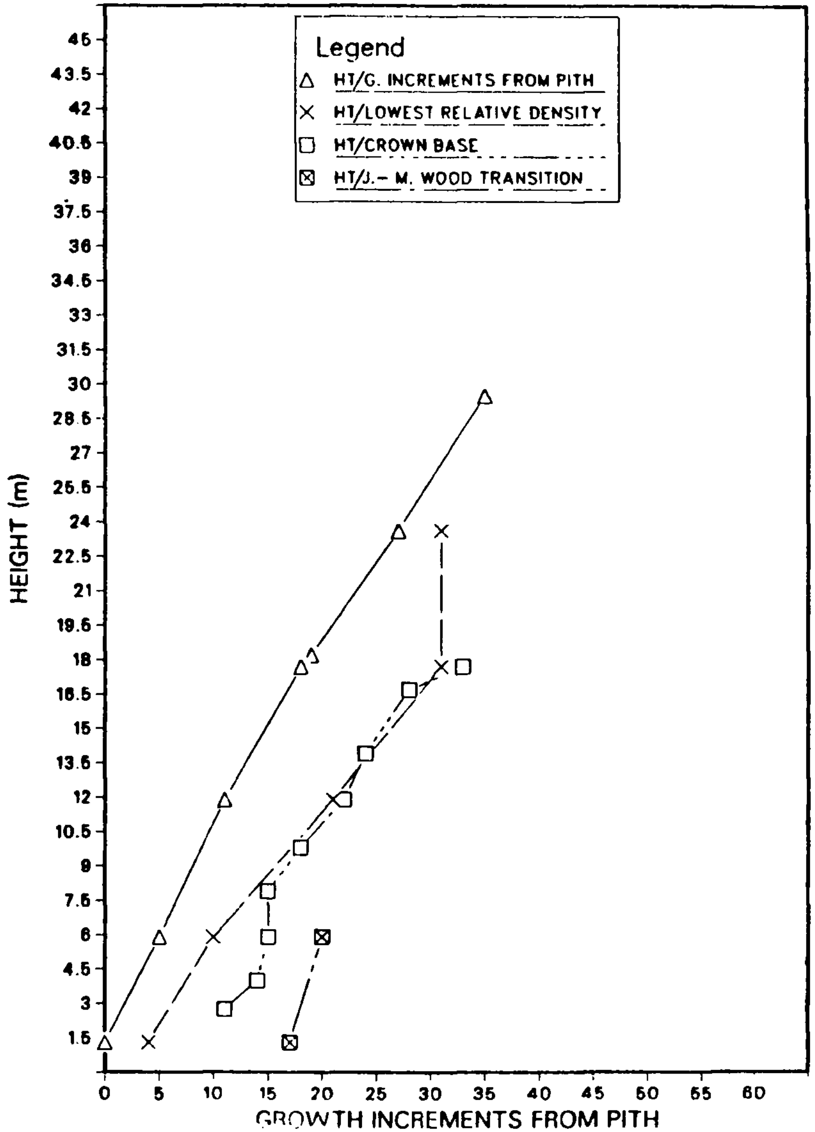
Appendix 11. a) Tree 1D5. Simple and segmented linear regression models on pith to bark relative density profiles.



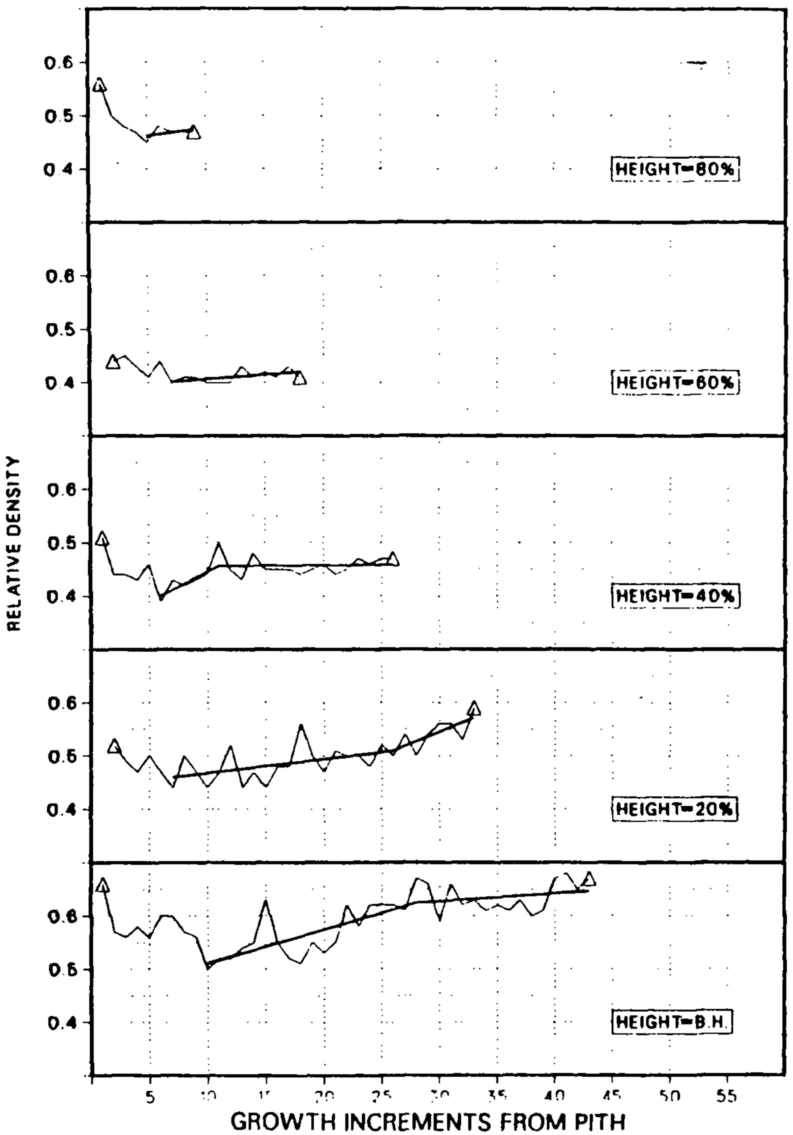
Appendix 11. b) Tree 1D5. Relationships between total tree height, lowest relative density height, crown base height and juvenile - mature wood transition over number of growth increments from pith at breast height.



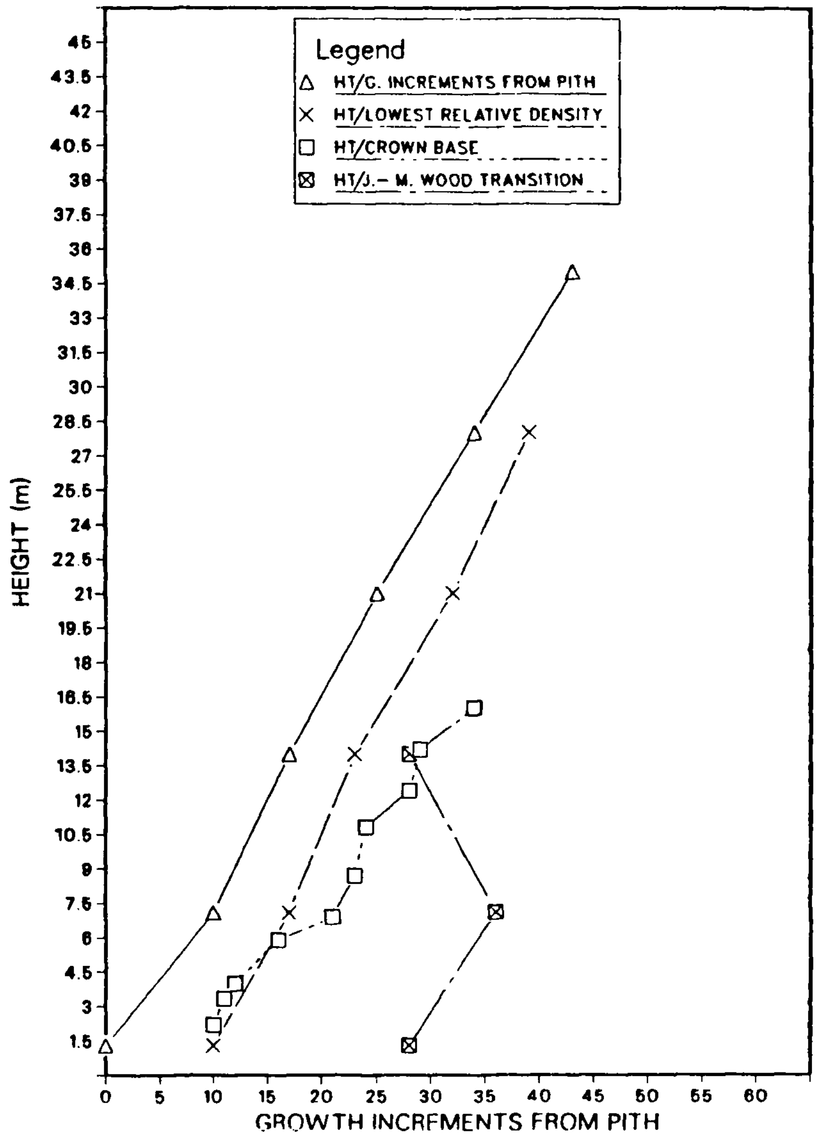
Appendix 12. a) Tree 1D6. Simple and segmented linear regression models on pith to bark relative density profiles.



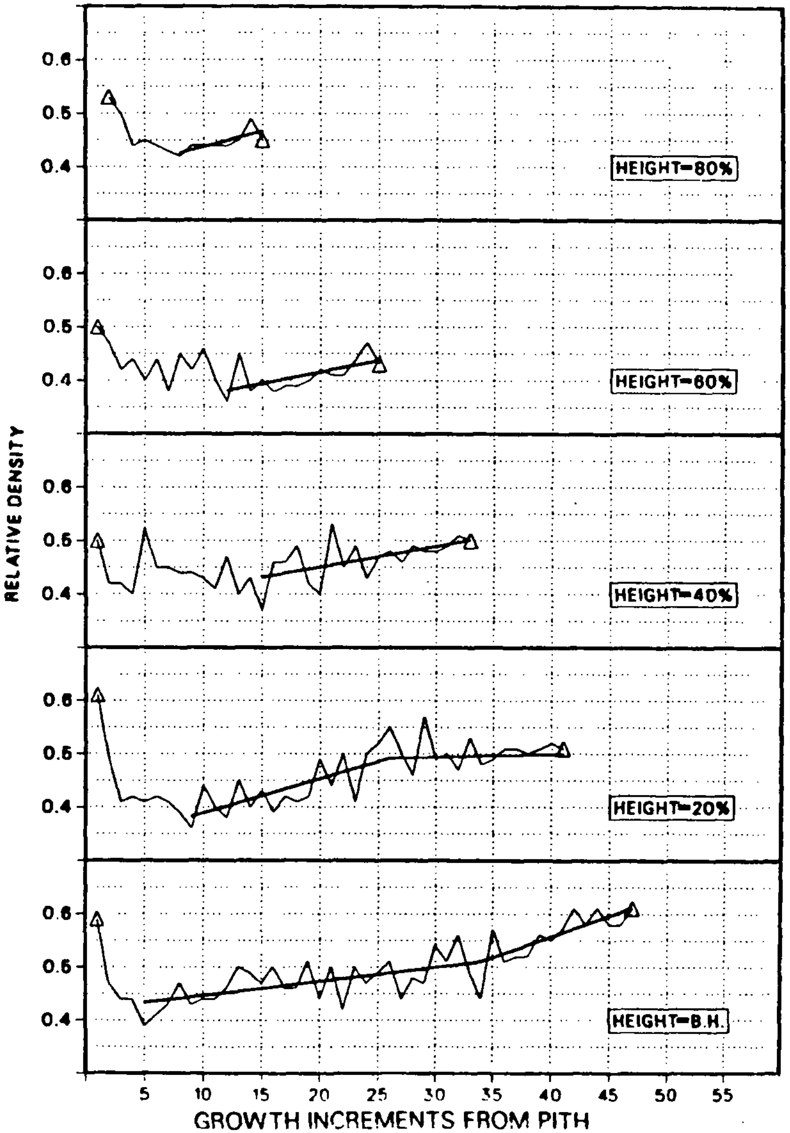
Appendix 12. b) Tree 1D6. Relationships between total tree height, lowest relative density height, crown base height and juvenile - mature wood transition over number of growth increments from pith at breast height.



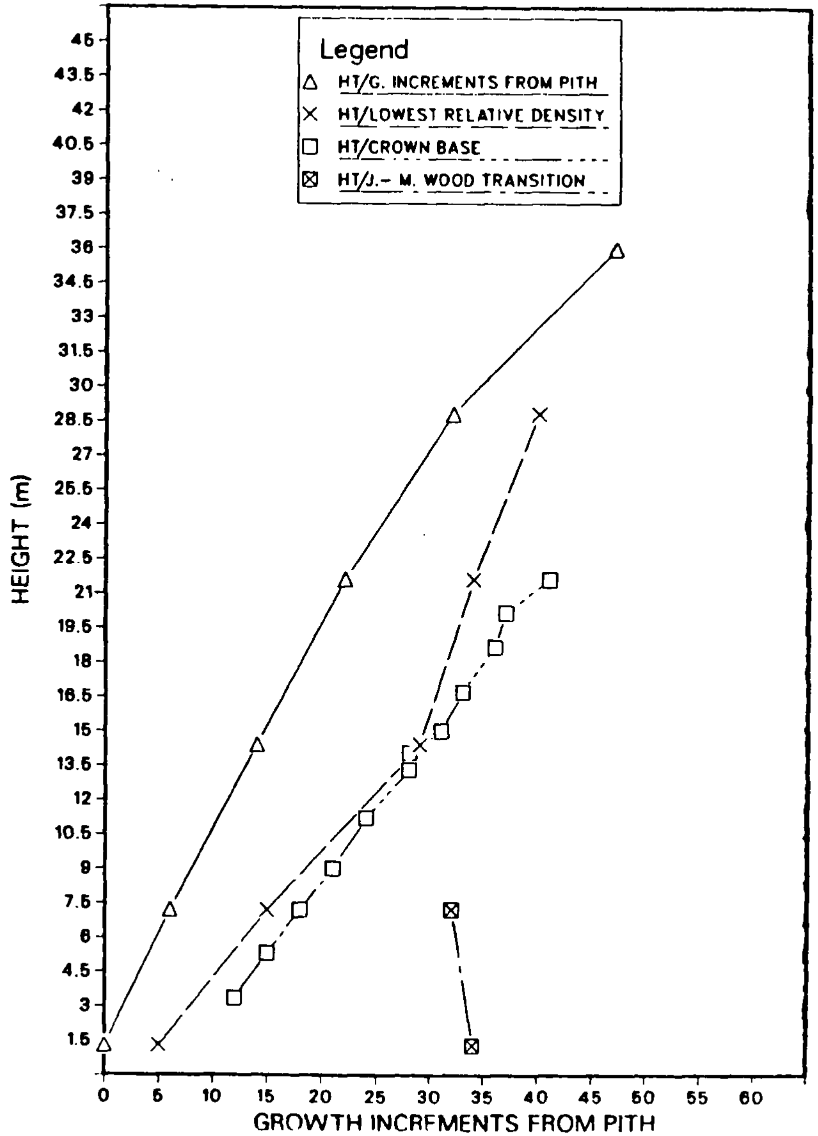
Appendix 13. a) Tree 1E3. Simple and segmented linear regression models on pith to bark relative density profiles.



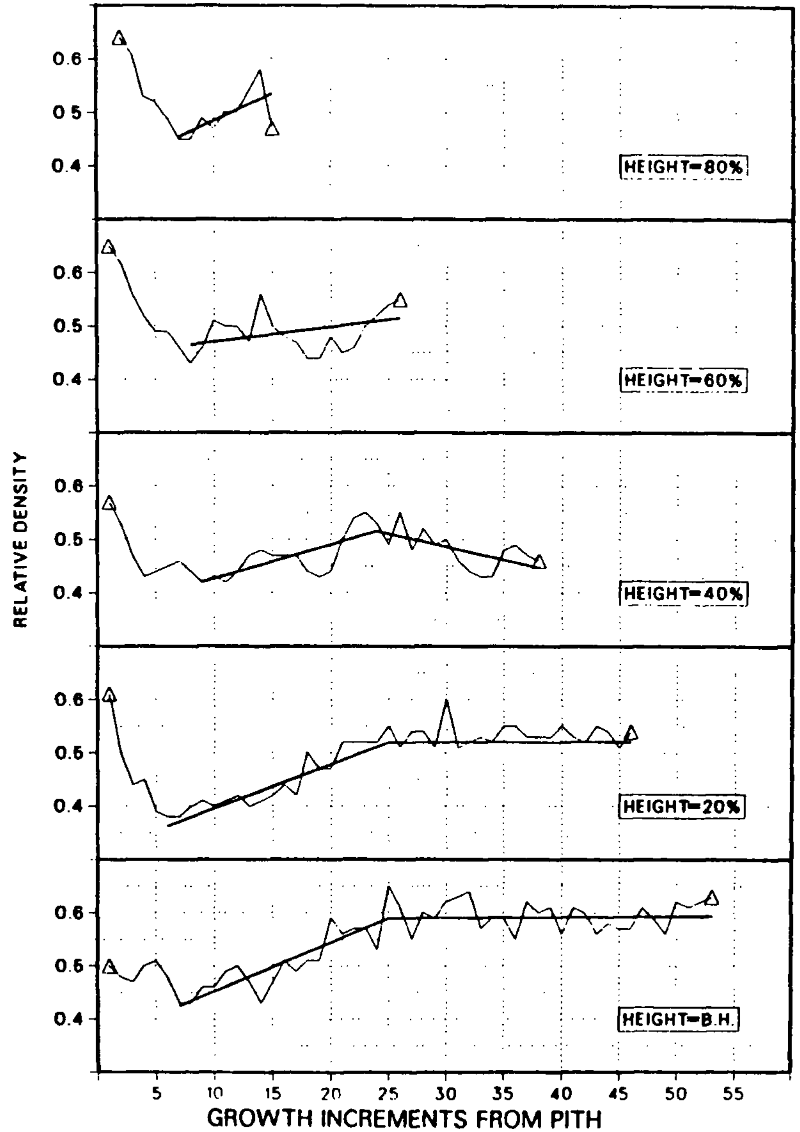
Appendix 13. b) Tree 1E3. Relationships between total tree height, lowest relative density height, crown base height and juvenile - mature wood transition over number of growth increments from pith at breast height.



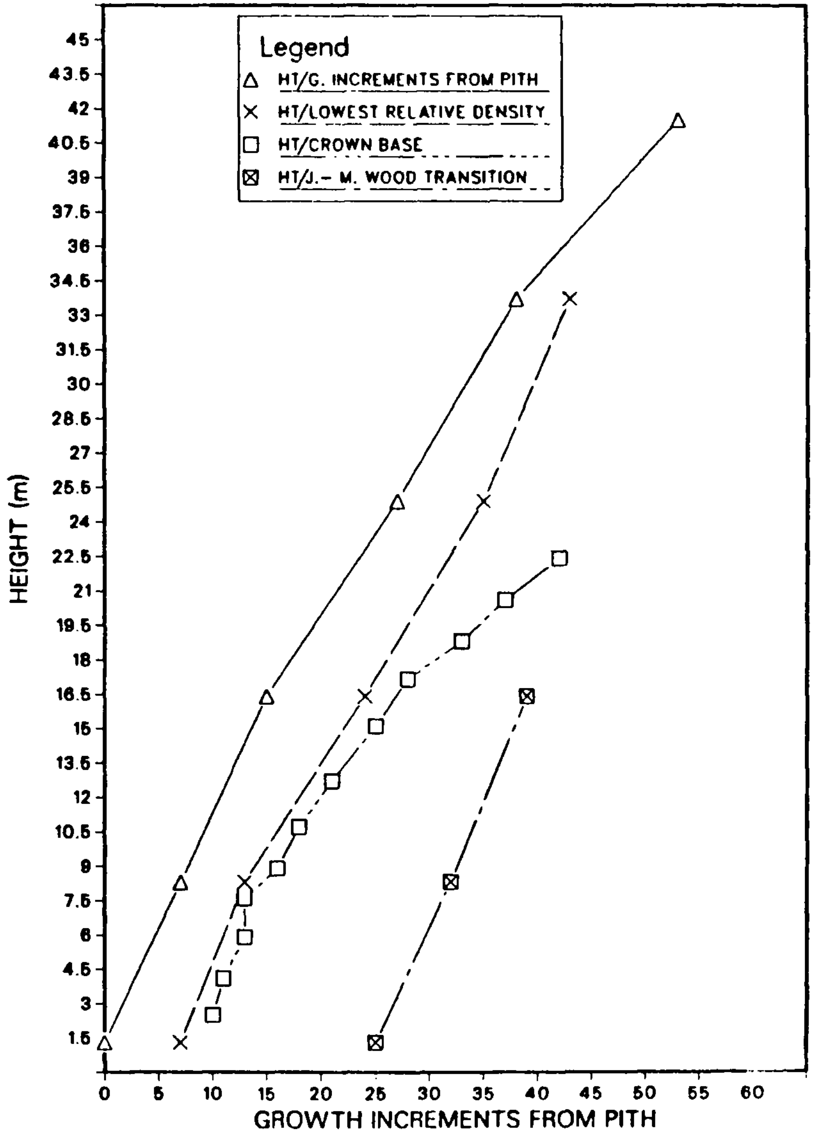
Appendix 14. a) Tree 1E8. Simple and segmented linear regression models on pith to bark relative density profiles.



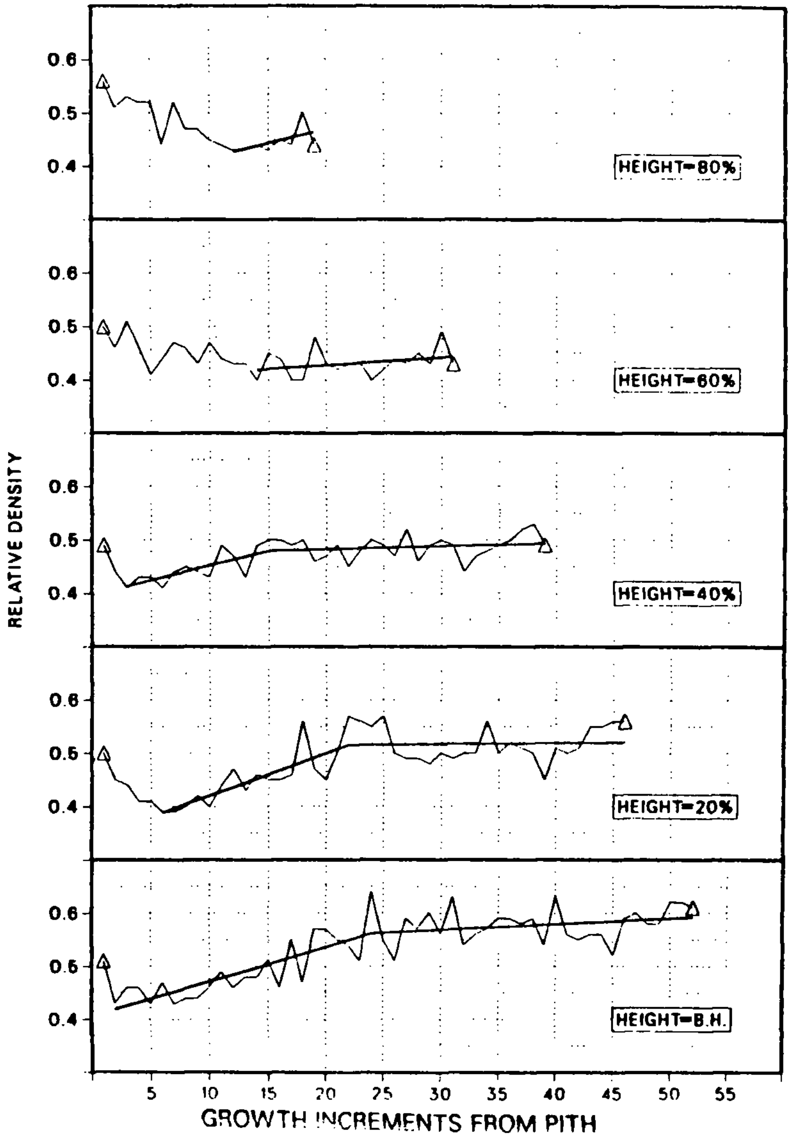
Appendix 14. b) Tree 1E8. Relationships between total tree height, lowest relative density height, crown base height and juvenile - mature wood transition over number of growth increments from pith at breast height.



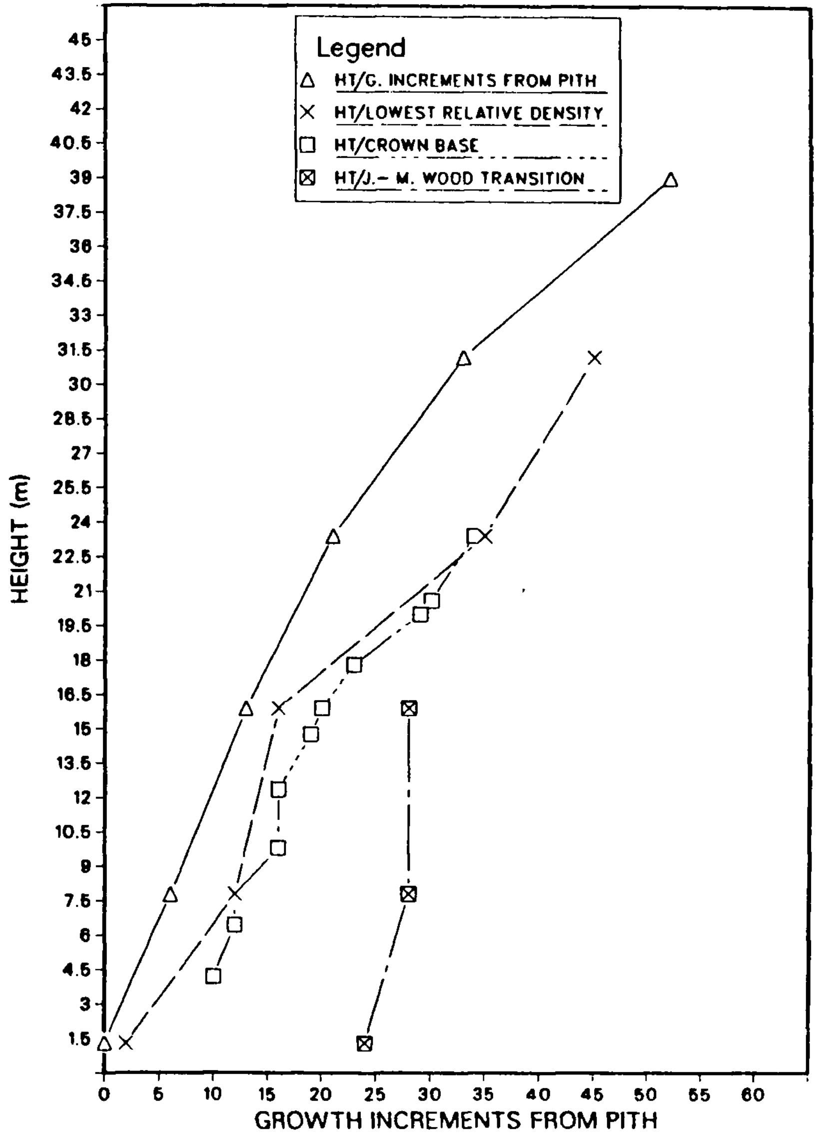
Appendix 15. a) Tree 1F7. Simple and segmented linear regression models on pith to bark relative density profiles.



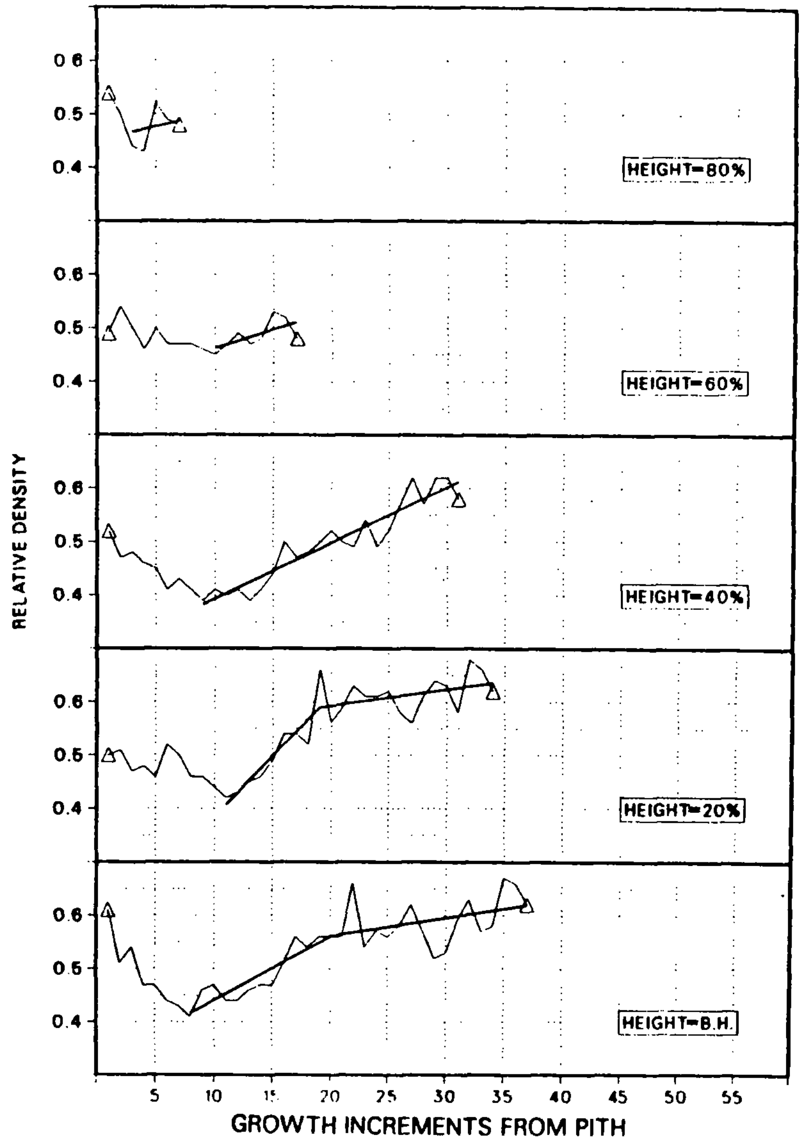
Appendix 15. b) Tree 1F7. Relationships between total tree height, lowest relative density height, crown base height and juvenile - mature wood transition over number of growth increments from pith at breast height.



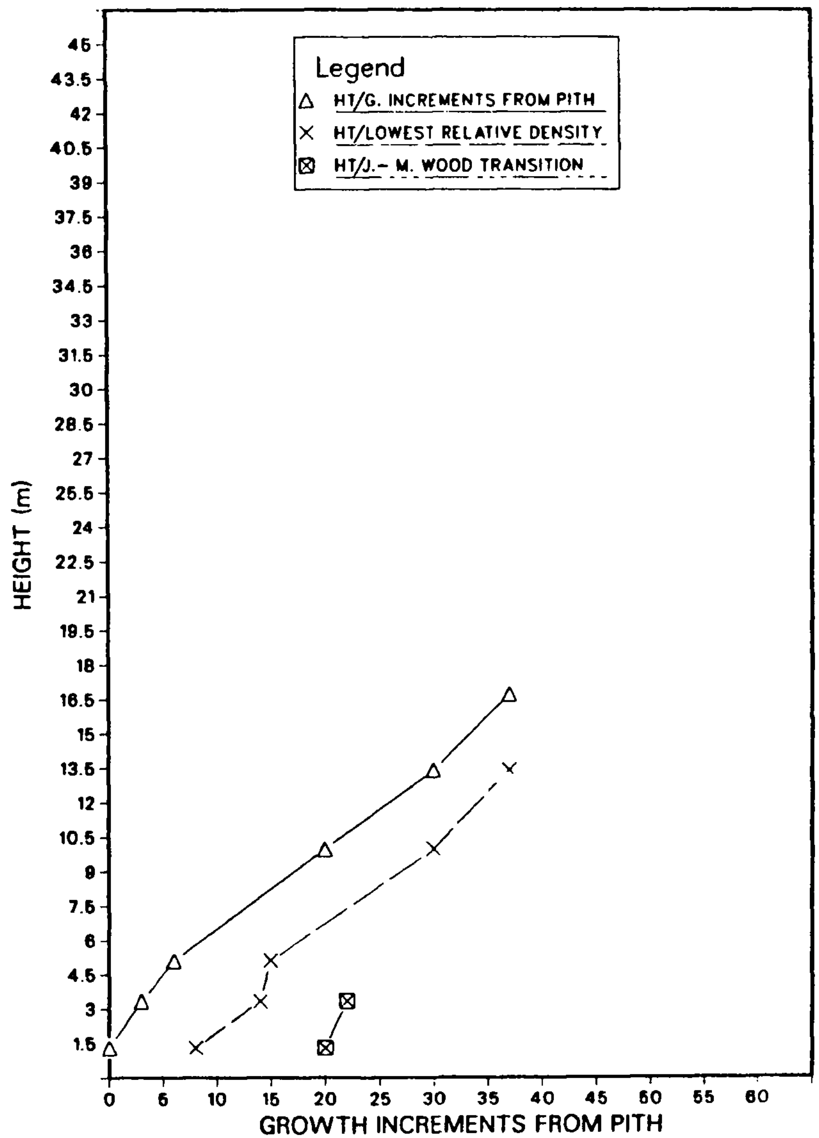
Appendix 16. a) Tree 1F10. Simple and segmented linear regression models on pith to bark relative density profiles.



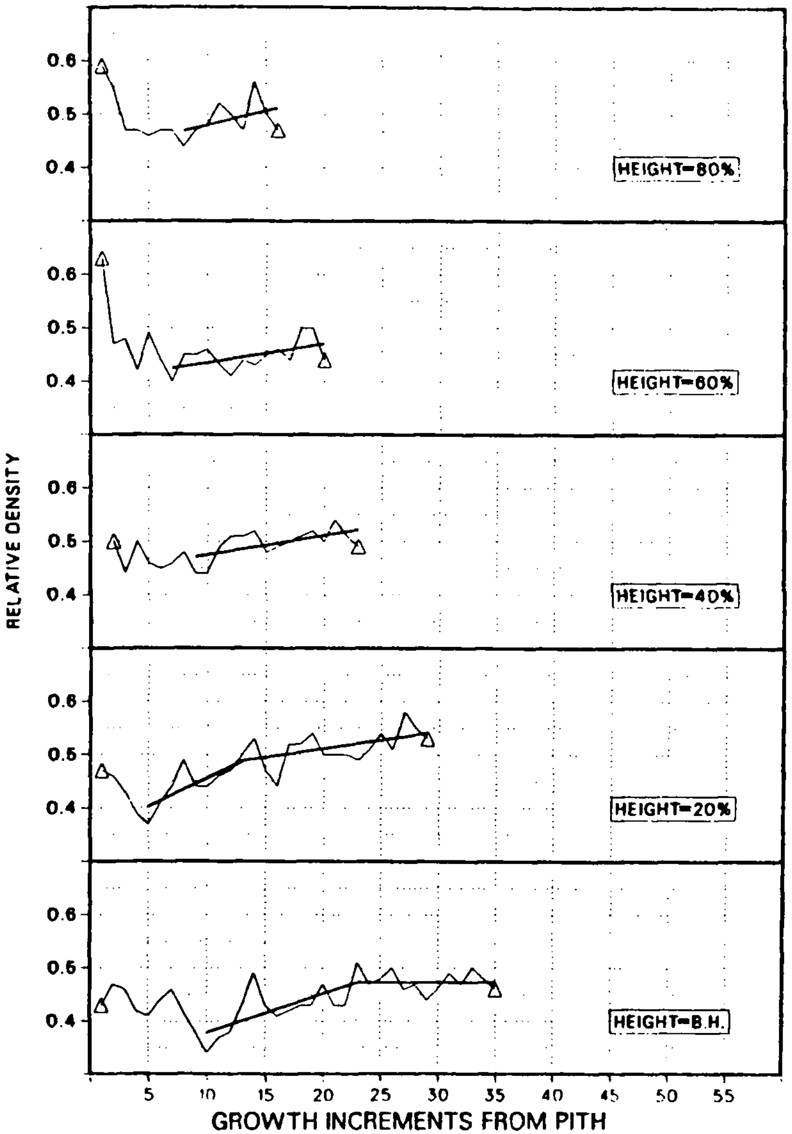
Appendix 16. b) Tree 1F10. Relationships between total tree height, lowest relative density height, crown base height and juvenile - mature wood transition over number of growth increments from pith at breast height.



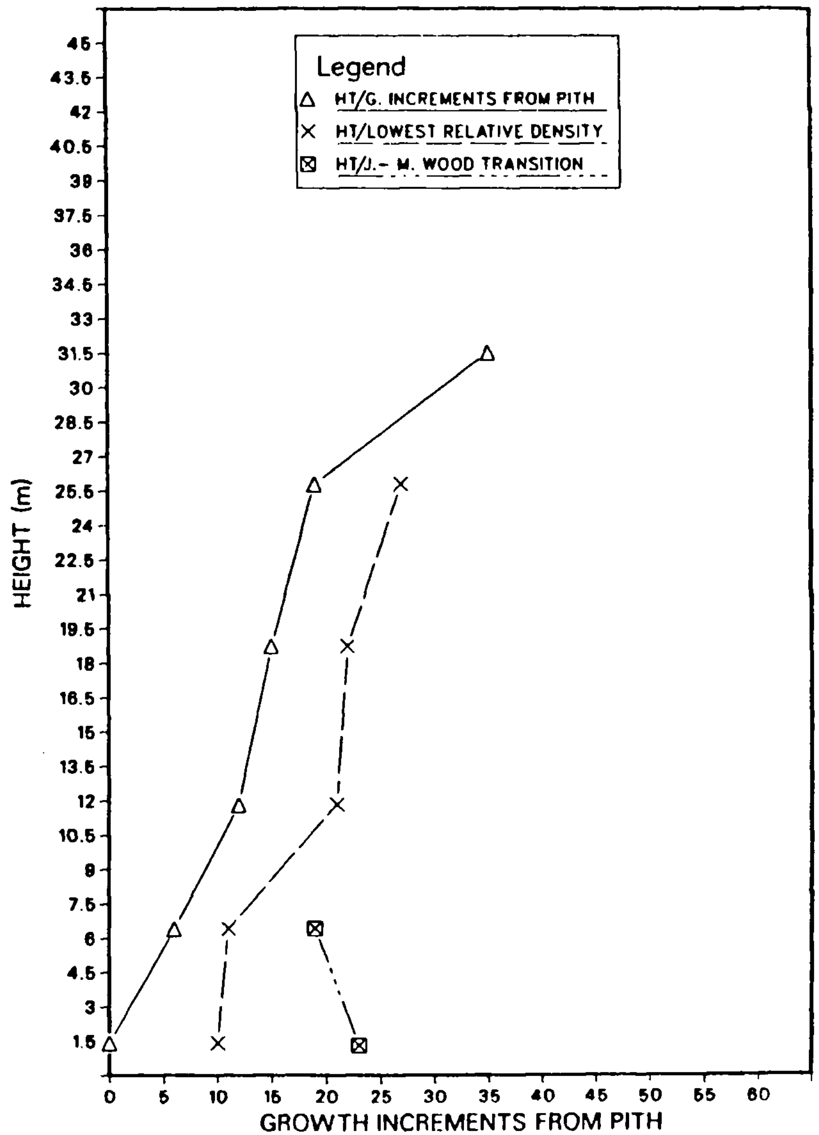
Appendix 17. a) Tree CR1. Simple and segmented linear regression models on pith to bark relative density profiles.



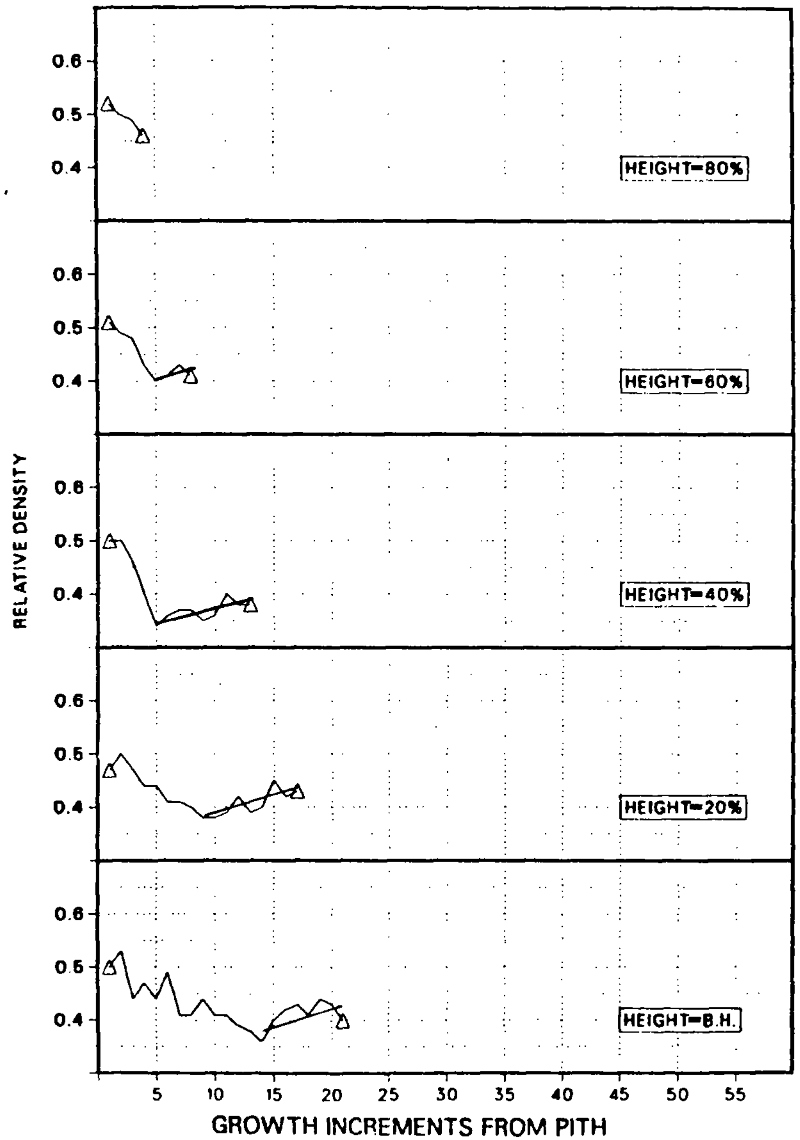
Appendix 17. b) Tree CR1. Relationships between total tree height, lowest relative density height, crown base height and juvenile - mature wood transition over number of growth increments from pith at breast height.



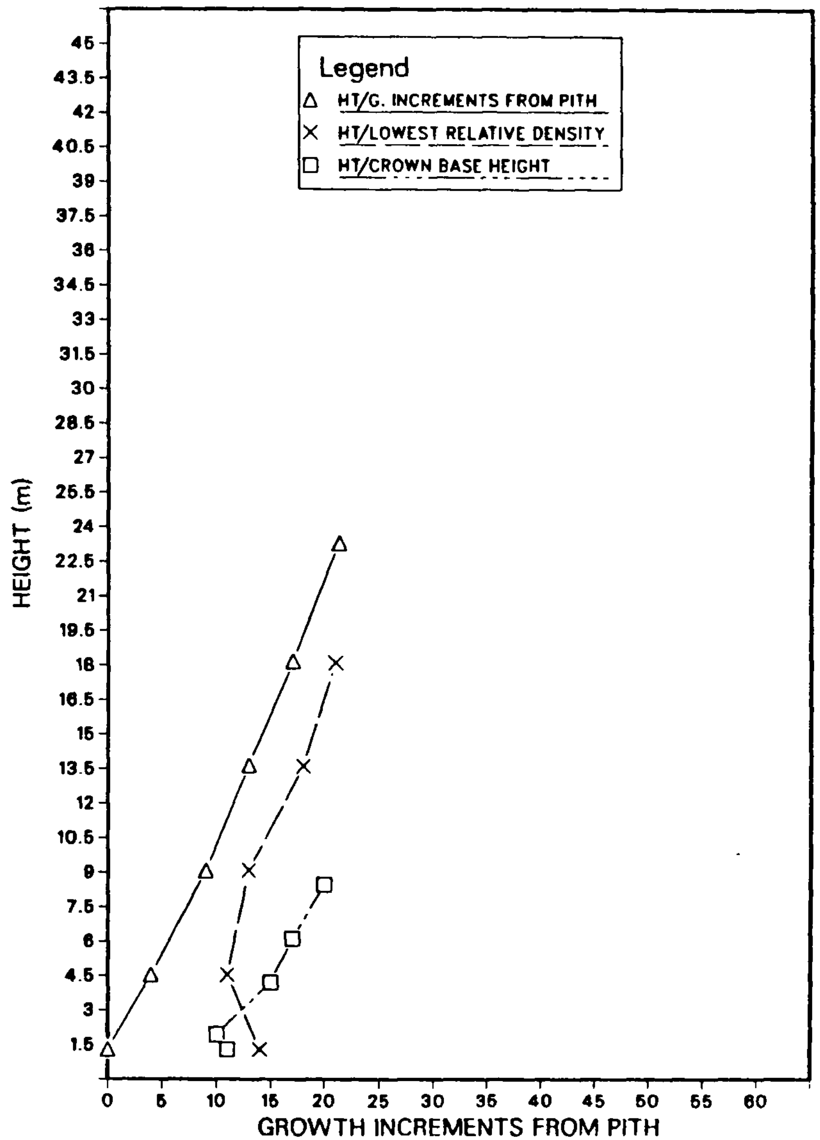
Appendix 18. a) Tree CR2. Simple and segmented linear regression models on pith to bark relative density profiles.



Appendix 18. b) Tree CR2. Relationships between total tree height, lowest relative density height, crown base height and juvenile - mature wood transition over number of growth increments from pith at breast height.



Appendix 19. a) Tree RF1. Simple and segmented linear regression models on pith to bark relative density profiles.



Appendix 19. b) Tree RF1. Relationships between total tree height, lowest relative density height and crown base height over number of growth increments from pith at breast height.

Appendix 20. Summary of relative density data.

a) Tree 1A5

Height (m)	Diameter (cm) I.B.	Diameter (cm) O.B.	Section Height	Number of Growth Increments Juv. Wood	Mat. Wood	Total Sect.	Relative Density: Juvenile Wood Mean	S.D.	Max.	Min.	Mature Wood Mean	S.D.	Max.	Min.	Total Mean	S.D.	Max.	Min.
1.30	46.8	40.3	B.H.	22	34	56	.496	.058	.620	.380	.572	.044	.640	.480	.542	.062	.640	.380
7.55	39.3	33.8	20%	28	19	47	.438	.054	.570	.360	.513	.044	.620	.420	.468	.063	.620	.360
14.90	34.1	29.5	40%	25	15	40	.422	.043	.540	.370	.483	.033	.520	.400	.445	.049	.540	.370
22.20	27.0	25.9	60%	28	-	28	.460	.038	.560	.400	-	-	-	-	.460	.038	.560	.400
29.40	19.5	18.7	80%	13	-	13	.440	.030	.510	.410	-	-	-	-	.440	.030	.510	.410

b) Tree 1A7

Height (m)	Diameter (cm) I.B.	Diameter (cm) O.B.	Section Height	Number of Growth Increments Juv. Wood	Mat. Wood	Total Sect.	Relative Density: Juvenile Wood Mean	S.D.	Max.	Min.	Mature Wood Mean	S.D.	Max.	Min.	Total Mean	S.D.	Max.	Min.
1.30	46.1	39.8	B.H.	19	32	51	.525	.052	.620	.430	.597	.040	.660	.460	.569	.057	.660	.430
7.20	41.7	37.3	20%	24	20	44	.482	.067	.600	.370	.567	.042	.650	.470	.520	.071	.650	.370
15.10	37.0	32.8	40%	24	15	39	.471	.046	.570	.400	.495	.042	.550	.380	.480	.045	.570	.380
22.50	30.7	26.5	60%	31	-	31	.479	.054	.670	.410	-	-	-	-	.479	.054	.670	.410
29.90	17.6	16.1	80%	18	-	18	.499	.038	.600	.450	-	-	-	-	.499	.038	.600	.450

Appendix 20. Summary of relative density data (cont.).

c) Tree 1B6

Height (m)	Diameter (cm) I.B.	Diameter (cm) O.B.	Section Height	Number of Growth Increments Juv. Wood	Mat. Wood	Total Sect.	Relative Density Juvenile Wood Mean	S.D.	Max.	Min.	Mature Wood Mean	S.D.	Max.	Min.	Total Mean	S.D.	Max.	Min.
1.30	49.2	40.0	B.H.	16	37	53	.467	.035	.560	.420	.551	.042	.650	.450	.520	.055	.650	.420
8.55	39.5	36.5	20%	17	28	45	.448	.038	.560	.400	.539	.030	.590	.490	.504	.055	.590	.400
17.20	33.5	31.5	40%	18	14	32	.470	.034	.540	.420	.526	.027	.570	.490	.495	.042	.570	.420
25.80	25.6	24.5	60%	24	-	24	.478	.027	.540	.440	-	-	-	-	.478	.027	.540	.440
36.10	14.5	13.3	80%	12	-	12	.479	.052	.610	.420	-	-	-	-	.479	.052	.610	.420

d) Tree 1B11

Height (m)	Diameter (cm) I.B.	Diameter (cm) O.B.	Section Height	Number of Growth Increments Juv. Wood	Mat. Wood	Total Sect.	Relative Density Juvenile Wood Mean	S.D.	Max.	Min.	Mature Wood Mean	S.D.	Max.	Min.	Total Mean	S.D.	Max.	Min.
1.30	49.1	43.5	B.H.	32	25	63	.515	.044	.610	.430	.572	.041	.680	.510	.543	.057	.680	.430
7.10	41.8	37.7	20%	25	28	53	.480	.039	.570	.410	.496	.034	.590	.440	.489	.037	.590	.410
14.20	36.5	32.0	40%	16	29	45	.479	.032	.530	.410	.477	.034	.580	.430	.478	.033	.580	.410
21.30	27.7	24.7	60%	29	-	29	.479	.031	.560	.430	-	-	-	-	.479	.031	.560	.430
28.45	15.8	14.0	80%	19	-	19	.488	.032	.570	.450	-	-	-	-	.488	.032	.570	.450

Appendix 20. Summary of relative density data (cont.).

e) Tree 1C1

Height (m)	Diameter (cm)		Section Height	Number of Growth Increments			Relative Density											
							Juvenile Wood				Mature Wood				Total			
	I.B.	O.B.		Juv. Wood	Mat. Wood	Total Sect.	Mean	S.D.	Max.	Min.	Mean	S.D.	Max.	Min.	Mean	S.D.	Max.	Min.
1.30	47.3	40.7	B.H.	19	35	54	.503	.037	.590	.440	.586	.035	.660	.490	.558	.053	.660	.440
8.00	40.1	36.2	20%	25	22	47	.464	.043	.560	.390	.530	.027	.570	.470	.490	.049	.570	.390
16.00	36.1	32.9	40%	29	10	39	.458	.030	.520	.400	.497	.019	.520	.450	.468	.032	.520	.400
24.15	29.8	25.9	60%	29	-	29	.448	.023	.510	.410	-	-	-	-	.448	.023	.510	.410
32.00	12.0	14.9	80%	15	-	15	.411	.015	.460	.400	-	-	-	-	.411	.015	.460	.400

f) Tree 1C6

Height (m)	Diameter (cm)		Section Height	Number of Growth Increments			Relative Density											
							Juvenile Wood				Mature Wood				Total			
	I.B.	O.B.		Juv. Wood	Mat. Wood	Total Sect.	Mean	S.D.	Max.	Min.	Mean	S.D.	Max.	Min.	Mean	S.D.	Max.	Min.
1.30	47.1	37.5	B.H.	15	38	53	.502	.052	.650	.440	.592	.046	.700	.500	.566	.062	.700	.440
7.60	39.8	34.2	20%	35	11	46	.489	.059	.580	.380	.544	.032	.600	.510	.502	.059	.600	.380
15.20	35.1	31.5	40%	26	10	36	.488	.043	.560	.430	.518	.019	.560	.500	.496	.040	.560	.430
22.80	29.0	26.7	60%	25	-	25	.478	.034	.550	.410	-	-	-	-	.478	.034	.550	.410
30.40	14.4	13.2	80%	12	-	12	.499	.035	.560	.430	-	-	-	-	.499	.035	.560	.430

Appendix 20. Summary of relative density data (cont.).

g) Tree 1D5

Height (m)	Diameter (cm) I.B.	Diameter (cm) O.B.	Section Height	Number of Growth Increments Juv. Wood	Mat. Wood	Total Sect.	Relative Density Juvenile Wood Mean	S.D.	Max.	Min.	Mature Wood Mean	S.D.	Max.	Min.	Total Mean	S.D.	Max.	Min.
1.30	45.5	26.8	B.H.	13	14	33	.462	.031	.540	.420	.490	.032	.540	.440	.474	.034	.540	.420
6.40	35.7	31.9	20%	20	7	27	.466	.026	.500	.430	.530	.032	.560	.480	.482	.039	.560	.430
12.80	27.6	25.9	40%	20	-	20	.475	.035	.550	.430	-	-	-	-	.475	.035	.550	.430
19.20	20.3	18.2	60%	14	-	14	.456	.034	.510	.390	-	-	-	-	.456	.034	.510	.390
25.60	11.3	10.1	80%	8	-	8	.540	.027	.580	.500	-	-	-	-	.540	.027	.580	.500

h) Tree 1D6

Height (m)	Diameter (cm) I.B.	Diameter (cm) O.B.	Section Height	Number of Growth Increments Juv. Wood	Mat. Wood	Total Sect.	Relative Density Juvenile Wood Mean	S.D.	Max.	Min.	Mature Wood Mean	S.D.	Max.	Min.	Total Mean	S.D.	Max.	Min.
1.30	43.2	38.5	B.H.	17	18	35	.445	.055	.550	.380	.530	.033	.600	.490	.488	.062	.600	.380
5.90	.384	34.3	20%	15	14	29	.407	.031	.470	.350	.468	.031	.520	.430	.437	.043	.520	.350
11.90	33.4	32.1	40%	23	-	23	.450	.037	.550	.400	-	-	-	-	.450	.037	.550	.400
17.70	25.8	23.4	60%	17	-	17	.428	.041	.530	.360	-	-	-	-	.428	.041	.530	.360
23.60	13.2	12.2	80%	8	-	8	.468	.027	.510	.420	-	-	-	-	.468	.027	.510	.420

Appendix 20. Summary of relative density data (cont.).

i) Tree 1E3

Height (m)	Diameter (cm)		Section Height	Number of Growth Increments			Relative Density											
							Juvenile Wood				Mature Wood				Total			
	I.B.	O.B.		Juv. Wood	Mat. Wood	Total Sect.	Mean	S.D.	Max.	Min.	Mean	S.D.	Max.	Min.	Mean	S.D.	Max.	Min.
1.30	39.4	37.6	B.H.	28	15	43	.574	.045	.670	.500	.634	.028	.680	.590	.595	.049	.680	.500
7.10	35.3	32.5	20%	26	6	32	.487	.030	.560	.440	.546	.031	.590	.500	.498	.038	.590	.440
14.00	31.3	28.5	40%	11	15	26	.444	.034	.510	.390	.454	.013	.480	.430	.450	.024	.510	.390
21.00	22.8	21.1	60%	17	-	17	.417	.017	.450	.400	-	-	-	-	.417	.017	.450	.400
28.00	12.8	11.4	80%	9	-	9	.483	.031	.560	.450	-	-	-	-	.483	.031	.560	.450

j) Tree 1E8

Height (m)	Diameter (cm)		Section Height	Number of Growth Increments			Relative Density											
							Juvenile Wood				Mature Wood				Total			
	I.B.	O.B.		Juv. Wood	Mat. Wood	Total Sect.	Mean	S.D.	Max.	Min.	Mean	S.D.	Max.	Min.	Mean	S.D.	Max.	Min.
1.30	68.2	57.1	B.H.	34	13	47	.472	.042	.590	.390	.527	.016	.570	.510	.487	.044	.590	.390
7.20	54.7	48.6	20%	26	15	41	.441	.057	.610	.360	.503	.026	.570	.460	.463	.057	.610	.360
14.40	45.4	40.5	40%	33	-	33	.456	.039	.530	.370	-	-	-	-	.456	.039	.530	.370
21.60	36.3	32.5	60%	25	-	25	.420	.034	.500	.360	-	-	-	-	.420	.034	.500	.360
28.80	21.3	19.7	80%	14	-	14	.454	.030	.530	.420	-	-	-	-	.454	.030	.530	.420

Appendix 20. Summary of relative density data (cont.).

k) Tree 1F7

Height (m)	Diameter (cm) I.B.	Diameter (cm) O.B.	Section Height	Number of Growth Increments Juv. Wood	Mat. Wood	Total Sect.	Relative Density Juvenile Wood Mean	S.D.	Max.	Min.	Mature Wood Mean	S.D.	Max.	Min.	Total Mean	S.D.	Max.	Min.
1.30	57.5	48.3	B.H.	25	28	53	.503	.053	.650	.430	.595	.025	.640	.550	.551	.061	.650	.430
8.30	47.3	44.0	20%	25	21	46	.454	.061	.610	.380	.533	.026	.600	.510	.490	.061	.610	.380
16.40	39.9	37.3	40%	24	14	38	.470	.043	.570	.420	.478	.033	.550	.430	.473	.040	.570	.420
24.90	30.9	26.8	60%	22	-	22	.497	.056	.650	.430	-	-	-	-	.497	.056	.650	.430
33.70	16.1	14.7	80%	14	-	14	.517	.058	.640	.450	-	-	-	-	.517	.058	.640	.450

l) Tree 1F10

Height (m)	Diameter (cm) I.B.	Diameter (cm) O.B.	Section Height	Number of Growth Increments Juv. Wood	Mat. Wood	Total Sect.	Relative Density Juvenile Wood Mean	S.D.	Max.	Min.	Mature Wood Mean	S.D.	Max.	Min.	Total Mean	S.D.	Max.	Min.
1.30	52.7	45.3	B.H.	24	28	52	.492	.054	.640	.430	.576	.030	.630	.510	.537	.060	.640	.430
7.80	41.5	36.4	20%	22	24	46	.450	.048	.570	.390	.517	.032	.570	.450	.485	.052	.570	.390
15.90	35.0	31.3	40%	15	24	39	.446	.028	.490	.410	.487	.021	.530	.440	.472	.030	.530	.410
23.40	28.0	23.9	60%	26	-	26	.495	.026	.550	.460	-	-	-	-	.495	.026	.550	.460
31.20	16.5	14.4	80%	19	-	19	.470	.042	.560	.430	-	-	-	-	.420	.042	.560	.430

Appendix 20. Summary of relative density data (cont.).

m) Tree CR1

Height (m)	Diameter (cm) I.B.	Diameter (cm) O.B.	Section Height	Number of Growth Increments Juv. Wood	Mat. Wood	Total Sect.	Juvenile Wood Mean	S.D.	Max.	Min.	Mature Wood Mean	S.D.	Max.	Min.	Total Mean	S.D.	Max.	Min.
1.30	22.1	20.0	B.H.	20	17	37	.491	.054	.610	.410	.590	.046	.670	.520	.536	.070	.670	.410
3.34	19.8	18.4	20%	19	15	34	.490	.054	.660	.420	.612	.034	.680	.560	.543	.076	.680	.420
5.10	18.0	16.8	40%	31	14	31	.486	.069	.620	.390	-	-	-	-	.486	.069	.620	.390
9.95	12.3	11.4	60%	17	-	17	.485	.025	.540	.450	-	-	-	-	.485	.025	.540	.450
13.38	6.3	5.7	80%	7	-	7	.485	.040	.540	.430	-	-	-	-	.485	.040	.540	.430

n) Tree CR2

Height (m)	Diameter (cm) I.B.	Diameter (cm) O.B.	Section Height	Number of Growth Increments Juv. Wood	Mat. Wood	Total Sect.	Juvenile Wood Mean	S.D.	Max.	Min.	Mature Wood Mean	S.D.	Max.	Min.	Total Mean	S.D.	Max.	Min.
1.40	42.4	38.4	B.H.	23	12	35	.428	.038	.510	.340	.473	.017	.500	.440	.444	.039	.510	.340
6.40	36.8	34.5	20%	13	16	29	.443	.037	.500	.370	.514	.032	.580	.440	.483	.049	.580	.370
11.80	33.6	31.7	40%	22	-	22	.488	.028	.540	.440	-	-	-	-	.488	.028	.540	.440
18.72	24.8	23.4	60%	20	-	20	.459	.048	.630	.400	-	-	-	-	.459	.048	.630	.400
25.77	10.7	10.0	80%	16	-	16	.493	.041	.590	.440	-	-	-	-	.493	.041	.590	.440

Appendix 20. Summary of relative density data (cont.).

o) Tree RF1

Height (m)	Diameter (cm) I.B.	Diameter (cm) O.B.	Section Height	Number of Growth Increments Juv. Wood	Mat. Wood	Total Sect.	Relative Density Juvenile Wood Mean	S.D.	Max.	Min.	Mature Wood Mean	S.D.	Max.	Min.	Total Mean	S.D.	Max.	Min.
1.30	28.3	26.0	B.H.	21	-	21	.429	.041	.530	.360	-	-	-	-	.429	.041	.530	.360
4.54	24.3	22.3	20%	17	-	17	.423	.035	.500	.380	-	-	-	-	.423	.035	.500	.380
9.00	20.6	18.6	40%	13	-	13	.398	.054	.500	.340	-	-	-	-	.398	.054	.500	.340
13.65	15.0	14.0	60%	8	-	8	.445	.042	.510	.400	-	-	-	-	.445	.042	.510	.400
18.16	7.4	0.6	80%	4	-	4	.492	.025	.520	.460	-	-	-	-	.492	.025	.520	.460

p) Tree RF2

Height (m)	Diameter (cm) I.B.	Diameter (cm) O.B.	Section Height	Number of Growth Increments Juv. Wood	Mat. Wood	Total Sect.	Relative Density Juvenile Wood Mean	S.D.	Max.	Min.	Mature Wood Mean	S.D.	Max.	Min.	Total Mean	S.D.	Max.	Min.
1.30	59.4	68.3	B.H.	21	30	51	.425	.021	.480	.370	.475	.045	.640	.410	.454	.045	.640	.370
3.80	51.6	61.0	10%	17	30	47	.427	.028	.490	.380	.489	.050	.620	.430	.466	.053	.620	.380
6.30	50.7	56.0	20%	44	-	44	.421	.027	.490	.360	-	-	-	-	.421	.027	.490	.360
12.30	44.4	50.3	40%	37	-	37	.432	.026	.500	.390	-	-	-	-	.432	.026	.500	.390
18.90	31.1	34.6	60%	26	-	26	.425	.035	.560	.380	-	-	-	-	.425	.035	.560	.380

Appendix 20. Summary of relative density data (cont.).

q) Tree RF3

Height (m)	Diameter (cm) I.B.	Diameter (cm) O.B.	Section Height	Number of Growth Increments Juv. Wood	Mat. Wood	Total Sect.	Relative Density: Juvenile Wood Mean	S.D.	Max.	Min.	Mature Wood Mean	S.D.	Max.	Min.	Total Mean	S.D.	Max.	Min.
1.30	37.5	44.0	B.H.	15	30	45	.482	.035	.600	.440	.523	.023	.580	.490	.509	.033	.600	.440
2.90	34.4	40.5	10%	13	30	43	.438	.039	.560	.400	.490	.029	.570	.430	.474	.040	.570	.400
4.35	32.0	36.8	20%	39	-	39	.458	.036	.580	.380	-	-	-	-	.458	.036	.580	.380
11.60	25.0	30.4	40%	33	-	33	.431	.026	.490	.380	-	-	-	-	.431	.026	.490	.380
17.75	17.0	19.6	60%	21	-	21	.470	.027	.560	.440	-	-	-	-	.470	.027	.560	.440