QUANTITATIVE ANATOMICAL CHARACTERISTICS OF PLANTATION GROWN LOBLOLLY PINE (PINUS TAEDA L.) AND COTTONWOOD (POPULUS DELTOIDES Bart. ex Marsh.) AND THEIR RELATIONSHIPS TO MECHANICAL PROPERTIES

by

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INTRODUCTION

It can be safely stated without any misgivings that the future of our timber resource is no longer centered on the so called virgin forests. In the United States, in particular, the timber resource available to consumers has undergone a significant change, progressing from virgin forests to regrowth forests (perhaps third and fourth regrowths) and finally to the present era of entirely man planted forests (Bendsten 1974). In many parts of the world today, the trends have been very similar. The last couple of decades has witnessed this change in forestry policies of different countries - policy of growing trees from genetically improved seed stock. Incidentally, the wood using industry in many parts of the world has commenced harvesting of these man planted forests.

Successful planting of trees cannot be regarded as an end to itself, but rather a means to an end. The forester is still confronted with the task of improving certain wood characteristcs of these trees being planted. It seems not undesirable therefore to provide the forester with relevant information on the anatomical structure of such woods being grown. It is believed such knowledge will enable him to eventually influence the type of trees being planted in terms of improving the quality of the wood. For example, Larson (1962) shared this same belief when he described wood quality as representing a complex of anatomical and structural features of wood that could be studied independently in terms of various cell dimensions or cell wall physical or chemical properties. Considering the fact that the properties of any piece of wood are dependent almost entirely on its structure and chemical composition, the importance of the knowledge regarding the anatomical structure of the growing tree cannot be overemphasized (Dadswell et al 1959).

Moreover, as wood is a product of a complex biological system, the tree, the material constituent will no doubt be highly variable. It is perhaps not an unusual phenomenon for its anatomical structure and properties to vary from species to species, from tree to tree of same species, and even from one part of a single tree to the other. This structure of wood has often been used as a basis for identification by considering the qualitative shape, size, and distribution of the various anatomical elements. Similarly, scientists have also demonstrated that property differences are closely related to structure at both macroscopic and microscopic levels (Kellogg and Ifju 1962, Ifju 1969). It is probably a logical speculation that the utility of a piece of wood for a specific application is dependent upon its properties which, in turn, are influenced by structure.

A thorough knowledge of the anatomical imformation on trees being planted is not only important to the forester but equally valuable to those concerned with the utilization of the harvested trees. Wood being a product of the cambium, one would perhaps expect the resultant quality of the wood to be interdependent in all its manifestations (Larson 1962). Studying the anatomical structural features of wood independently is perhaps a positive direction to providing adequate anatomical information to the individual concerned with the management of forests and the utilization of forest products.

LITERATURE REVIEW

Influence of Growth Conditions on Wood Properties

Dadswell (1958) provided an excellent discussion on wood structure variations occuring during tree growth and their influence on wood properties. He pointed out that the changes in structure and properties in the wood formed during the early years of the trees' life can influence the utilization of young trees, thinnings, and tops from plantaions and regrowth forests. Citing one of his early studies (Greenhill and Dadswell 1940) he showed how density can increase with distance from the pith especially in plantation grown materials and also in many trees grown under natural conditions for both softwood and hardwoods.

Zobel et al (1961) reported on a study of the effects of a high level and moderated level fertilization on the wood properties of loblolly pine. Their findings indicated that heavy rates of fertilization resulted in wood of considerably lower specific gravity. They also noted the fertilizers to have caused a trend for shorter tracheid. Van Buijtenen (1969) examined various aspects of forestry operations as they affect wood quality. Major factors of forest management he considered as useful for controlling wood properties included: choice of site and species, genetic improvement, silvicultural practices and modern harvesting methods.

Yao (1970) investigated the influence of growth rate on specific gravity and other selected properties of loblolly pine. It was manifested in his results that, in general, significant relationships existed between specific gravity and number of rings per inch for growth rates ranging from approximately 3 to 8 rings per inch. He also found the specific gravity of specimens having the same number of rings per inch to vary according to height; i.e. specific gravity decrease with increase in height. Isebrands and Hunt (1975) evaluated the growth and wood properties of ten-year-old Japanese larch trees selected for rapid growth and grown under intensive management. They found the species to exhibit rapid juvenile growth with diameter and height averaging 15.7cm and 9.2m, respectively, in ten years. It was noted that the whole-ring specific gravity decreased for several years after fertilization and then increased. This, they believed was influenced by the presence of large amounts of transition wood and low latewood percent.

Thor and Core (1977) estimated the relative importance of soil-site characteristics, irrigation, and fertilization on the radial growth, specific gravity, extractives and fiber length of yellow-poplar. They sampled both natural stands and plantations in order to estimate the variation due to factors such as competition, unequal spacing, and the uneven-aged regeneration associated with poorly stocked natural stands. Site factors were found to account for only a small percentage of the variation in specific gravity, extractives, and fiber length in a natural forest. However, in plantation, 60 per cent of the variation in wood properties was found to be associated with a combination of site factors.

Foster and Thor (1979) studied the natural variation in specific gravity, fiber length and total extractives of American sycamore. A comparison of 12 upland and 12 bottomland trees revealed only small differences between sites' specific gravity of extracted and unextracted wood. However, they found bottomland trees to have longer fibers than those from upland trees.

It can be seen from the forgoing review that most of the published works have centered primarily on the specific gravity, fiber length and those properties most important in the manufacture of pulp and paper. There has been limited number of papers published in the literature on the mechanical properties of plantation grown woods. Olson et al (1947) reported on what has been considered the most comprehensive study of mechanical properties of rapid-grown plantation woods (Bendtsen 1978). They tested the standard 2-inch small, clear specimens and compared their results with published data for similar tests on natural forest trees. It was found in general, that the plantation grown trees were lower in both mechanical properties and specific gravity. For example, among the seven softwoods examined, the largest differences were noted for red pine: average modulus of rupture (MOR) of plantation material was about 32 percent lower, modulus of elasticity (MOE) about 39 percent lower, and compression parallel to grain 48 percent lower than forest material.

In Bendtsen's review (1978), a study by Boone and Chudnoff (1972) was cited. Boone and Chudnoff examined the compression wood formation and other characteristics of plantation grown Caribbean pine (Pinus caribaea). They found bending strength and stiffness to be less than 50 percent of published values for forest trees of the same species. Bower et al (1976), who later worked with the same species but on a 5-year-old material, also noted lower strengths. They found bending strength of 2-inch specimens tested to be about 35 percent of published values for natural forest trees, and stiffness was about 26 percent of published values.

Anatomical Measurements

In the characterization of anatomical features of wood, previous works have included many different types of measurements. Since the physical properties of a material depend on the properties of its parts, it can be conjectured that an analysis of the material's structure should enable physical behaviour of the whole to be predicted from those of its parts (Steele et al 1976). It is perhaps not surprising that previous workers have included several different measurements in characterizing the anatomical properties of the wood material. The fiber properties most often measured include fiber length, cell diameter, lumen diameter, cell wall thickness and fibril angle. Such cell characteristics have been used in the past for evaluating the enviromental or hereditary influences or to correlate structure with properties (Gofas and Tsoumis 1975). For example, Tsoumis (1974) found the proportional area of cell walls in a cross section to be related to specific gravity, which was also used to determine cell wall density by Kellogg and Wangaard (1969).

Numerous reports have been published on the various methods previously employed in wood cell structure measurements. Green and Worall (1964) developed a photometric scanning method for measuring wood anatomical characteristics such as ring width, the cross-sectional dimensions of tracheids and percent earlywood and latewood. They reported high correlations between wall thickness as determined by scanning procedures to that determined by micrometric measurement of fiber walls, a more time-consuming and tedious procedure. In the same year, Smith and Miller (1964) described another technique of using a dual-linear traversing micrometer to obtain a fairly precise estimate of wall thickness and cell diameter. The advantage of using this technique is that the combined widths of the double cell walls between lumens may be accumulated on one scale and the combined widths of the lumens on the other. Their method also has several other advantages, such as the simplicity of the preparation of the sample material and the ease of obtaining measurements of actual cell wall thickness and void volume. They also reported the practicability of estimating the relative amounts of fibrous, vascular, and parenchyma tissues. Smith (1965), when applying the dual-linear traversing technique to isolated earlywood and latewood of Douglas fir, obtained a high degree of correlation between specific gravity values calculated from cell measurements and actual determinations (by the maximum-moisture method after extraction with alcohol-benzene).

Kaeser and Boyce (1965) reported a technique of using an integrating stage micrometer on a compound microscope to determine the ratio of wall thickness to lumen diameter of hardwood species. Their procedure allowed simultaneous accumulation of six values in a single traverse, which reduces appreciably the time needed for the operator when information was required for several kinds of elements. Knigge and Schulz (1961) used the Zeiss particle-size analyzer for measuring cell lumen width, particularly for vessels. They remarked that the data could be summarized automatically either as a simple frequency distribution curve or as a cumulative distribution curve

A dot count method for estimating amounts of cell wall material in transverse sections using a transparent acetate sheet superimposed on a projected image was reported by Ladell (1959). He took point samples at random on a transverse sections and recorded the data whether the points fell on cell wall or on lumen. The proportion of points falling on cell walls gave him the percentage of cell wall material in the area sampled. His method was considered fast, easy to use and probably more accurate than direct measurements. Britt (1965) made similar counts of the number of fibers per square millimeter. He was able to determine the fiber coarseness in wood based on both these counts and the specific gravity. A similar technique based on counts per unit area, was employed by Ifju and Labosky (1972). They obtained the transverse cell wall dimensions by calculations from tracheid counts per unit area on stained cross sections. Tracheids enclosed in a given unit area were counted and the average cross-sectional dimensions of individual tracheids calculated.

Exley (1967) described another method of determining the cross-sectional dimensions of fibers. His method was not based on the number of feature counts per unit area. He equiped a vertically illuminated microscope with image shearing eyepiece . In this eyepiece, he shared the optical image into two components -one red, one green, by rotating a control knob. Both components of the shared image moved away simultaneouly, and by an equal amount, from the point of zero shear. A dimension was measured by shearing the images from coincidence until the edges of the two components just touched each other. The rotation of the control knob from the point of zero shear gave the measurement required, subject to a scale factor determined by the power of the objective lens. Use of the eyepiece also enabled measurements of each cell to be made rapidly.

Quirk (1975) reported another technique for estimating the average cross-sectional cell wall area of wood directly on the intact of the specimen. He used an integrating eyepiece to superimpose a dot grid pattern on the surface of intact wood specimens. He obtained an efficient and precise estimate of the amount of wall area as well as the proportion of tissue types in wood sample. Quirk and Smith (1975) later compared the technique described previously by the senior author using the dual linear method for estimating cross-sectional dimensions of tracheids. They found either technique to be reliable for estimating anatomical parameters. Quirk (1981) described a semiautomated recording technique of measuring wood cell dimensions. The new measuring device comprises of a sonic digitizing unit that allows large volumes of highly precise anatomical measurements to be made rapidly. Bendtsen et al (1981) in a recent study, applied the technique described by Smith and Miller (1964) and experimented with by Smith (1965) to measure the cross section and cell wall dimensions on the transverse sections of their test specimens.

Studies centering on the measurements of lengths of fibers have also been reported over the years. Bethel (1941) reviewed some of the pioneering works dating as far back as 1872. In his study of the effect of position within the bole upon fiber length of loblolly pine, he determined fiber length via the use of a microprojector. The length of the projected fiber image was recorded rather than the length of the fiber itself by calibrating the screen and reading each measurement directly. Ladell (1959) reported a nonmaceration cell tip method for evaluation of both within-ring variation of fiber length and fiber length at ring boundaries. With his method he reported a minimum variability associated with intra-ring extension growth so that better determinations could be made of variation among trees. Wilcox et al (1964) reported on improved optics that increased magnifications for measuring the short hardwood fibers. The ampliscope developed at the Institute of Forest Genetics, Gulfport Miss. was used in their study (Wilcox et al 1964).

Reck (1965) described a method of microprojection of macerated fibers and the curvimeter map tracer measurement of their length. He considered his methods to be expedient for extensive measurements using automatic recording devices for multi-length categories. Similar to Reck's study was the work reported by Wheeler and associates (1966). They measured tracheid length of loblolly pine using a Rayoscope with a 10-power eye piece and a 2.2-power objective to project tracheid images on a concentric circular measuring disk calibrated to 0.1mm. The procedure enabled them to measure tracheid length by interpolation to the nearest 0.05mm. Ifju and Labosky (1972) also determined the trachid length from tracheid images projected through a light microscope onto such a calibrated target.

Taylor (1975) described another technique of determining fiber length. He estimated the fiber length by measuring a representative number of whole fibers randomly selected from the macerated sample. His technique was a combination of the "Bulls-eye Target" method suggested by Wilson (1967) and the method of unbiased fiber selection proposed by Hart and Swindel (1967). In the following year, Taylor (1976) also reported a study on fiber length variation within growth rings of certain angiosperms, where he employed the above technique to estimate the fiber length. Taylor (1977) also used this same technique to determine the average fiber length when he investigated property variation within stems of selected hardwoods growing in the mid-south.

Quantitative Measurements of Anatomical Elements

The foregoing review of past studies on the various methods employed in anatomical measurements has not only included the conventional direct measurement techniques but also included early attempts of assessing anatomical wood elements quatitatively. Some of these works that have been the subject of quantitative microscopy comprised those by Ladell (1953), Kellogg and Ifju (1962), Britt (1965), Scallan and Green (1973), Quirk (1975), and Quirk and Smith (1975). It should be remarked however, that some of these earlier attempts failed to obtain the calculations of all the important parameters necessary for the complete quantitative characterization of the structures studied.

As mentioned earlier, wood, a product of a biological system, can be expected to be variable materially, both in its structure and properties. The anatomical structure of wood has served as the principal method of identification (Panshin and de Zeeuw 1970). Some of the structural characteristics considered in the identification keys such as the shapes, sizes, and distributions of the various anatomical constituents, are said to seldomly proffer a quantitative assessment of the anatomical elements (Steele et al 1976). Moreover, special skills and long trainning are required for a successful use of the identification keys in order to accomplish the desired consistency in making a series of subjective two-way decisions as to the size, distribution and shape of the anatomical elements. One may perhaps wonder if conventional identification techniques are truely material characterization as they fail to provide numerical assessments of wood structure.

It is believed that quantitative assessment of the anatomical elements is rather imperative for relating physical and mechanical properties of wood to its anatomy. In other words, numerical assessments of wood structure will be needed for predicting properties and performance in various applications or processes.

An indirect technique of obtaining size values of various elements is the application of stereological principles to section images of wood. Quantitative assessment of wood microstructure by principles of stereology centers on the application of geometrical-statistical techniques and equations to three dimensional structral quantities. This type of quantitative analysis has been termed "stereology" (Underwood 1970). But Han Elias (1962) once defined stereology as a "science which deals with a body of methods for the explorations of three-dimensional space, when only two-dimensional sections through solid bodies or their projections on a surface are available". Thus, stereology is an extrapolation from two to three-dimensional space.

In the interim, several branches of science have developed sophisticated mathematical methods to quantify the structure of their respective materials (Steele et al 1976). Fields of science, such as medicine, petrology, metallurgy, mineralogy, geology and ceramics have been involved in studying the microstructural properties of their respective materials. For example, in medicine the internal structure of cells, tissues and organs is being quantitatively investigated of which the data obtained have been successfully applied to quantitatively correlate structure and properties (Nasroun 1978). Similar investigations have also been carried out in recent years in the field of Wood Technology where efforts were expended to quantitatively characterize numerically the geometrical aspects of wood microstructure.

Steele et al (1976) tested the practicability of using stereology as a tool for characterizing wood microstructural elements and wood identification. Stereological measurements were obtained on the transverse sections of five species of North American hardwoods, some closely related others widely different. Their findings unraveled certain subtle differences in the species examined. They were able to describe the structural characteristics of the species quantitatively which otherwise would have been impossible by the conventional anatomy. Chimelo (1978), also experimented with this techique on some Brazillian tropical hardwoods. He used the stereological approach to obtain anatomical measurements. He attempted to relate some parameters measured to the specific gravity. He found that up to 40 per cent of the variation in specific gravity could be explained by anatomical parameters.

Nasroun (1978) in a similar study, quantitatively characterized the structure of seven Sudanese tropical hardwoods and also related these structral properties to the qualities of pulp and paper obtained. He found the stereological technique to provide a quick and accurate way of quantifying wood structure. Beery (1979) also employed the stereological techique to study the relationship between transverse tensile properties and anatomical structure of eight North American hardwood species. Some of the anatomical elements measured such as the ray size (or ray area), vessel and fiber diameters were found to be highly correrelated to most of the tensile properties investigated.

Recently, Chimelo (1980) again applied stereological techniques to the characterization of the microstructure of another set of tropical hardwoods from Brazil. Like Nasroun (1978), he also attempted relating the stereological structural parameters to the properties of the species studied. Again, he found the stereological procedures expedient and effective both for characterizing the anatomical structure of the tropical species and as a diagnostic tools in wood identification.

Anatomical Structure - Property Relationships

The relationship between physical and mechanical properties and anatomical structure of wood has been intensively researched in many studies. In most of these studies, either the proportions of certain cell types were related to a given property or the size and even number of elements per unit area have formed the basis for explainig variations in mechanical properties. From the results of all these reported works, the general consensus has been that relationships do in fact exist between the structural elements of wood and its physical and mechanical properties.

A review of the early studies on the anatomical structure and property relationships is worthwhile. Meyer (1922) studied the ray proportions in some American woods and related them to certain mechanical properties. He found hardness and modulus of rupture (MOR) to increase as ray volume increased, but conversely, the compression parallel to grain decreased with increase in ray volume. In a similar work, Clarke (1933) found compression strength parallel to grain (green condition) of English ash to be positively correlated with specific gravity and percent latewood. This same property was found by Berkely (1934) to be influenced by ray volume and resin canal volume for southern pine.

Schniewind (1959) examining the tensile strength perpendicular to grain of California black oak, developed equations for maximum stress and modulus of elasticity (MOE). Anatomical parameters related to these properties were, principally the proportions of earlywood, latewood, and the rays. He further propounded that the differences between radial and tangential properties of black oak could be attributed to the high radial strength and stiffness of rays. He concluded however, that gross anatomical structure, ray alignment in particular, was the primary, if not the sole, cause of the anisotropy of the wood properties.

Kellogg(1960) reported on the effect of repeated loading on tensile properties of wood. He concluded that at the gross structural level, the slope of grain, fibrillar orientation, and percent of the ray volume were the most important factors. Similarly, Preston (1960), studying the anisotropy in the microscopic and submicroscopic structure of wood, reported that the differences in wood properties whether between species, between individuals in a species or within one individual tree depend greatly on the nature and distribution of vessels and on their proportions relative to the fibers. Kellogg and Ifju (1962) investigating the influence of specific gravity and certain other factors on the tensile properties of wood, found specific gravity as the single factor of greatest importance. In relating this factor linearly to both tensile and modulus of elasticity, very high percentages of variation were accounted for. Bodig (1965) also studied the stress-strain relationship in transverse compression as influenced by the anatomy of two softwood and two hardwood species. He found the first failure in radial compression to be located in the weakest springwood layer of the specimen. It was also manifested in his study that ring porous and diffuse porous woods behaved differently with respect to maximum compressive strength, and that the differences could be related to the amount of latewood material present. As one would expect, the earlywood zone was reported as the region of initial failure in radial compression. He concluded that the direction of loading within a species can be more important than the differences between species of similar anatomical characteristics in the classification of stress strain curves.

Specific gravity which is a measure of the amount of cell wall material present in a unit volume of wood, has been considered the most important single physical property of wood that can influence other properties and uses. Bodig and Troxell (1965) reported increase in shear strength with increasing specific gravity. Bendtsen (1966) tested twenty four second-growth trees and found about 20 to 25 percent lower mechanical properties than those trees from virgin material. He attributed the observed properties, at least partially, to specific gravity differences.

Kennedy (1968) examined the transverse compression of nine species and reported the specific gravity and ring orientation as having the greatest influence on the proportional limit stress and modulus of elasticity (MOE). Ifju (1969) also studied six southern pine trees each representing a different species. He reported highly significant correlations between strength properties and specific gravity. In a study of loblolly pine growth increments by Ifju and Labosky (1972), a significant trend of specific gravity was reported. They inferred that the positive trend of specific gravity of wood across the ring from early- to latewood might indicate major differences of pulping and papermaking properties of wood within growth rings. Similarly, Bodig and Goodman (1973) investigating the elastic properties of wood reported a relationship between both the modulus of elasticity (MOE), and shear modulus (G), with density.

Beery (1979) investigated the relationship between transverse tensile properties and anatomical structure of eight hardwoods. He observed relationships between specific gravity and strength properties studied. Correlations between tensile properties and anatomical parameters were reported. For example, he found the species with large rays to have consistently higher radial and tangential specific MOE values than the species with small rays. This is perhaps indicative that large rays may be stiffer both along their length and across their width.

Recently, Chimelo (1980) reported good relationships between the density and some mechanical properties of some Brazilian hardwoods. He developed prediction equations using density alone as a property predictor for estimating strength.

OBJECTIVES

The purpose of this study was to provide a quantitative characterization of the anatomical properties of two different woods that have grown under intensive forest management and to relate anatomy to certain mechanical properties. Specific objectives of the study included the following:

(1). To determine the relative proportion of the various anatomical elements in loblolly pine and cottonwood trees:

 (a). in loblolly pine: tracheids, ray cells, and resin canals.

 (b). in cottonwood: vessels, fibers, and parenchyma ray cells.

(2). To determine the mean diameters and variation of the anatomical elements in the woods studied.

(3). To relate cell size distribution parameters and their variations to modulus of rupture (MOR), modulus of elasticity (MOE), maximum crushing strength parallel to grain and specific gravity values obtained from minispecimen tests.

(4). To construct regression models for predicting physical and mechanical properties from the anatomical variables of the species studied.

MATERIALS, METHODS AND PROCEDURES.

MATERIALS

The test material was obtained from six trees of loblolly pine (*Pinus taeda* L.) and six trees of cottonwood (*Populus deltoides* Bart. ex Marsh.). The pine trees came from a Weyerhauser Company plantation, the cottonwood trees were obtained from an arboretum on the outskirts of Madison, Wisconsin. The trees were chosen for straightness of bole and absence of discernable defects. Each tree was felled and a 6-to 8-foot bolt from about two feet above the ground was selected and delivered to Forest Products Laboratory at Madison, Wisconsin where they were wrapped in plastic and stored in a cold room (36^{0} F). The stored bolts remained in a green moisture content condition (well above fiber saturation point). They remained there approximately three months before being cut into test specimens.

It should be remarked that the ensuing methods and procedures reported on physical and mechanical tests are as provided by the U. S. Forest Products Laboratory in Madison, Wisconsin, where these tests were determined.

METHODS AND PROCEDURES.

Specimen Preparation.

Planks from which small specimen were to be made were cut from each log on a small sawmill. First, the desired side of a tree was chosen, then the log was mounted on the sawmill carriage and opened so as to expose the pith. This was accomplished by sawing very thin boards from the log and slighty reorienting the log between cuts so that a surface approximately parallel to the pith was exposed. Since the pith within a tree "wanders" quite a bit along the length of a log, considerable effort was required to obtain a suitable length of exposed pith. The log was then rotated 90 degrees and a 3-inch, radially oriented (quarter-sawn) plank was removed. From each plank a 3-foot length as free from small knots and other defects as possible was selected. The short planks were smoothed on a jointer and planer to obtain quarter-sawn boards having a maximum number of growth rings oriented as nearly perpendicular to the tree radius as possible. Due to normal non-uniformity of growth, not all growth rings were perfectly oriented within the boards. Also due to small irregularities in growth and knots, the small specimens produced for testing did not all come from the same height in all trees.

Subsequent machining produced one-inch square specimens taken sequentially from the pith outward for standard ASTM strength tests and 1/8-inch thick sheets from which individual growth ring specimens were produced. Bending and compression parallel to the grain specimens were prepared from each growth ring so that data on modulus of rupture (MOR), modulus of elasticity (MOE), maximum crushing strength parallel to the grain (C_{11}) and specific gravity (SG) could be obtained from both small individual rings and from end-matched ASTM specimens.

Individual growth ring specimen preparation was aided by use of a small table saw with a one-inch diameter saw blade mounted on a high speed engraving tool commonly used by hobbyists.

By use of a magnifier and a fine scale, the width of each growth ring was measured to the nearest 0.01-inch and the saw fence set so that the center (mid-length) of each specimen most accurately represented the ring width. Even with these very short specimens (1-1/2 to 2-1/4 inches) the growth zones were not straight. The saw kerf was approximately 1/32 inch thick. The cutting procedure, coupled with ring variability in width and straightness, produced specimens which were not perfect, complete growth rings in cross-section, but it resulted in rectangular beams and columns which could reasonably represent any change in measured properties along a tree radius at a given height in a tree. Attempts to side or end-match specimens of very small size introduced other inconsistencies which overshadowed those associated with the loss of wood due to saw kerf removal.

The planks, 1/8-inch thick sheets and the standard ASTM test specimens were kept wet and cold at all times prior to testing. They were stored in plastic bags in a cold room, each bag contained sufficient five percent solution of sodium pentachlorophenate to keep the wood surface saturated to preclude fungal or bactarial attack. The specimens were removed from the bags just prior to testing so that the outermost wood fibers could not dry during testing to increase wood strength during the several minutes it took to perform bending or compression tests. Specimens for the stereological characterization of the anatomical properties were removed from the bending test specimens near the point of failure. They were also stored in plastic bags containing five percent solution of sodium pentachlorophenate pending further preparations for anatomical studies.

Stereological Characterization of Anatomical Properties.

Materials received at Virginia Tech. from the U. S. Forest Products Laboratory Madison, Wisconsin, for anatomical characterization were prepared for microtoming. Transverse wood sections were microtomed from individual rings of each tree for both cottonwood and loblolly pine. Wood sections microtomed (approximately 20 μm thick) were stained in Safranin-O and mounted permanently on slides for subsequent stereological measurements. Slides prepared were diligently labelled and proper records maintained. A minimum of three wood sections was mounted with permount on each slide for each growth ring.

Since certain basic measurements are often required repeatedly in all quantitative stereological works, it will suffice to expatiate on those employed to characterize wood microstructure in this study. The basic stereological measurements performed were: the simple point count (P_P), intersection count (P_L), intercept count (N_L), and feature count (N_A). Point counting (P_P) is the fraction of grid points falling on the anatomical element of interest. In other words, application of a grid of points to sectional images allows the number and hence, the fraction of points lying over each type of microconstituent to be measured. Figure 1 demostrates this point counting measurement of a photomicrograph of a transverse view of a wood structure. Each point count represents a random statistic which is unbiased estimator of the area fraction (A_A) and volume fraction (V_V) (Underwood 1970). By averaging a set of random applications of a point counting grid, quantitative data concerning the amount of each element within a desired statistical confidence can be provided.

Intersection counting (P_L) is the number of point intersections with boundaries generated per unit length of test line. This measurement is an unbiased statistical estimator of half the surface (cell boundary) area per unit volume (DeHoff and Rhines 1968). Intercept counting (N_L), another important measurement frequently required in quantitative sterreology, is similar to the intersection counting. N_L is defined as the number of interceptions of features of microstructure per unit length of the test line. Feature count (N_A) is the number of objects or features in a certain area of microstruture.

The stereological measurements dilated above were made on transverse sections only. Images of the transverse sections were projected through a microscope onto a 16-point 10cm x 10cm grid square (overall size of 30cm x 30cm). Magnification of the transverse section image on the grid square was chosen for each growth ring such that the size of the largest longitudinal elements, namely that of vessels is approximately equal to the grid spacing. The projected images were also oriented such that the grid lines were parallel and perpendicular to the rays. In order to assess anatomical variations across the growth increments, the sampling grids were positioned strategically so that changes in cell sizes from earlywood to latewood could be determined (Figure 1). Each strategic position represented a sampling zone. A total of five sampling zones was measured within each growth ring. Each grid placement within a zone region was replicated three times. This amounted to fifteen grid positions for each growth ring.

With a 10-digit blood-cell counter, the following stereological counting data were tabulated and recorded for each anatomical element:

1. Point counting (P_p) - for cottonwood: vessel, fibers, and ray parenchyma; for loblolly pine: tracheids, ray cells and resin canals.

2. Intercept counting (N_L)- with direction perpendicular to the rays- the number of intercepts of grid lines with vessels, fibers, tracheids, ray parenchyma cells, and resin canals. With direction parallel to rays- the number of intercepts of grid lines with vessels, fibers, tracheids, and resin canals. Interception density in the tangential direction ($N_{L(T)}$) was calculated from countings with direction perpendicular to the rays, while the same density in the radial direction ($N_{L(R)}$) was obtained from countings with direction parallel to the rays.

3. Feature counting (N_A) - measured the number of anatomical elements within each grid area.

Mathematical Computations and Derivations of Anatomical Parameters.

Methods of computing some basic stereological parameters primarily from the previously mentioned countings have been developed and applied by previous workers (Underwood 1970, Steele et al 1976, Ifju and Chimelo 1989, Nasroun 1978, Beery 1979, and Chimelo 1980). The following are some of the computations and derivations used in this study:

1. Volume fraction (V_V)- could be estimated from the simple point count, areal analysis or lineal analysis because of the following fundamental relationship:

$$\overline{P_P} \doteq \overline{L_L} \doteq \overline{A_A} \doteq \overline{V_V} \qquad [1]$$

where $\overline{P_P}$ is the average of several randomly applied point fractions.

2. Average cell diameter- could be obtained from N_L and N_A counts as manifested in the following equation:

$$\text{Average Cell diameter } (\overline{d}) = \frac{\overline{N_L}}{\overline{N_A}} \qquad [2]$$

3. The second moment of distribution (M_2)- could be computed for the different cell types as follow:

$$M_2 = d^2 = \frac{4\overline{P_P}}{\pi \overline{N_A}} \qquad [3]$$

4. The mean cord intercept length and the mean free path of some anatomical elements could also be calculated from the P_p and N_L counts as follow:

$$\overline{\lambda}_{MCI} = \frac{\overline{P}_P}{\overline{N}_L} \qquad [4]$$

$$\overline{\lambda}_{MFP} = \frac{1-\overline{P}_P}{\overline{N}_L} \qquad [5]$$

where MCI = average chord length,

MFP = mean free path between features, and

$\overline{N}_L$ = interception count.

5. Double cell wall thickness (DCWT)- could be calculated from the following equation:

$$DCWT = \frac{\overline{N}_L}{\overline{N}_A} - \sqrt{\frac{4\ \overline{P}_{P(LUMEN)}}{\pi\ \overline{N}_A}} \qquad [6]$$

6. Fiber density Index- the ratio of the cell wall to the lumen could also be computed as follow:

$$\text{Fiber density Index} = \frac{\overline{P}_{P(CELL\ WALL)}}{\overline{P}_{p(LUMEN)}} \qquad [7]$$

7. Transverse vessel shape factor (VSF)- could be obtained from the following stereological measurements:

$$VSF = \frac{\overline{d}_{V(T)}}{\overline{d}_{V(R)}} \qquad [8]$$

Physical and Mechanical Testing Procedures

Strength Properties

The bending and compression parallel to grain specimens were 1/8-inch thick. The bending specimens had a 1.75-inch span length (14:1 span ratio) and a 2.25-inch overall length. Beam width was, of course, equal to the width of the growth ring less about one saw kerf thickness. The compression specimens were 1-1/4 inches long. For any growth increment of 1/8-inch or greater this produced a specimen with a length-to-dimension ratio of 10 or less, resulting in a "short" column and an anticipated crushing along the grain type of failure. A few specimens had growth increments less than 1/8-inch wide and approached the "intermediate" column range. In some cases the increments were quite small, making excision of a single ring impossible or impractical. Where this was the case, two contiguous increments were cut and tested as one specimen. This occured usually where one of the two increments was less than about 1/10-inch. Narrow ringed bending specimens were coupled with a neighbouring ring for testing in a simlar manner.

All specimens were tested on an Instron Universal testing machine. For the bending specimens the beam span was 1.75 inches, beam depth was 1/8-inch and beam width equalled ring width except for those few cases where ring width was very small. Machine head speed was 0.02 inches per minute, chosen so that the duration of the test was between two and ten minutes. The beams were center-loaded; the load head and the beam supports each had a 3/16-inch radius. The beam supports were free to rotate, but did not have rollers attached; preliminary tests indicated that very short spans gave consistent results with relatively low variability without roller supports. A piece of teflon was taped to the top surface of each beam support in lieu of rollers. Data from load-deflection graphs obtained during tests were used to calculate modulus of rupture (MOR), and modulus of elasticity (MOE) values for each specimenn. Specimen dimensions were also recorded.

For the compression parallel to grain tests the 1.25-inch long specimens were held lightly between small metal blocks restrained by a rubber band, providing lateral support to ensure that a true, vertical, axial load was imposed. Load speed was 0.005 inches per minute. Specimen dimensions were also recorded and load-deflection graphs were obtained. Compression parallel to the grain values were calculated.

Specific Gravity

Physical measurement with dial micrometers of bending and compression parallel to grain specimens in the oven-dry state after testing provided specific gravity data on every growth ring. Dimensions were measured to the nearest 0.001-inch, weights were taken to the nearest 0.001 gram. Green and oven-dry weights were also recorded to ascertain that all specimens were above fiber saturation point at time of test.

Statistical Analysis and Data Processing

Anatomical Measurements' Data

Anatomical measurements for the two types of wood studied were separately processed. For each type, measurements from all six trees were combined for statistical analysis. The Statistical Analysis System (1979) procedures were employed throughout the data processing and analysis. Since measurements were replicated as mentioned earlier, the first approach was to compute the means for these measured quantities on a zonal basis within each ring. The means of the basic stereological measurements (P_P, N_L, and N_A) were then related to the structural quantities as given in the equations described previously. Subsequent statistical analyses were based on these anatomical parameters.

It was desired to investigate variation of the anatomical parameters both within and among the growth rings. SAS PROC MEAN was employed to proffer information on the variation of the anatomical elements over the growing periods of each type of wood. In order to examine the influence of age on the anatomical elements, SAS PROC GLM was used. Information on the percentage of variation that could be accounted for by the age of trees was obtained. Similar analysis was carried out to examine the effect of age on the anaatomical elements within the growth ring.

Physical and Mechanical Property Data

Like the anatomical measurements, similar statistical analytical approach was given to the physical and mechanical properties' data. Since only one measurement was obtained for each growth ring, the variation of the properties among the growth ring was analyzed. SAS PROC MEAN provided average values of six trees for each type of wood. Regression analysis procedure was used for subsequent data analyses.

Anatomy - Physical and Mechanical Property Relationships

It was also desired to relate quantitative anatomical measurements to the physical and mechanical properties. For this analysis, statistical regression procedure was used.

RESULTS AND DISCUSSIONS

In this study the anatomical structures of the two species investigated were expressed in quantitative terms. The numerical values generated were derived from simple counting measurements. They included size distribution parameters of individual anatomical elements as viewed on cross-sections. These parameters were determined both in terms of within growth ring variability and in terms of changes from pith to bark within plantation-grown lobolly pine and cottonwood. These anatomical characters were then related to mechanical properties in bending and compression.

1. Loblolly pine

(a) Anatomical Characterization

Loblolly pine, as all coniferous species, has a relatively simple structure. It's anatomy consists mostly of tracheids (95%), ray cells and resin canals associated with epithelial cells.

The volume fraction of the three major anatomical elements, tracheids, ray cells and resin canals are shown in Table 1. The average values were calculated for each individual growth increment and where applicable, the volume fractions of the lumen and wall portions of these elements were determined separately.

Volume fraction of tracheids varied from 92.9% to 98.5%. These results were expected on the basis of the knowledge of the anatomy of this species (Koch 1972). There appears to be a slight trend in tracheid volume fraction as shown in Table 1. Growth rings laid down during the first few years by the sample trees showed somewhat lower values in tracheid volume fraction than in later years. However, this trend could not be proved to be statistically significant.

When tracheid wall and lumen area fractions were examined separately significant trends from pith to bark were found. These relationships are shown in Figure 2 and 3. Tracheid wall area fraction increased from pith to bark from approximately 0.33 to a high of 0.52 in ring near the periphery of the 6 sample trees. This trend appeared to be linear in relation to ring number with an R^2 value of 0.558. The regression model calculated relating tracheid wall fraction to ring number is shown in Figure 2 as well as in Table 2.

Tracheid lumen area fraction showed a trend opposite to that of tracheid walls. Figure 3 shows this relationship. The regression equation and associated statistics are also given in Figure 3 as well as in Table 3. The opposite trends in the change of wall and lumen fractions indicate that wall to lumen ratios increase as the tree gets older. However, this conclusion would only hold if the average cell sizes remain relatively constant.

The volume or area fractions of ray cells and resin canals showed no apparent relationship to ring number. This is either an inherent characteristic of the loblolly pine trees studied or the point counting measurements were not sensitive enough to depict a trend that might have existed.

The total cell wall fraction in sample trees are also shown in Table 1. This quantitative parameter is related to specific gravity. If the density of the cell wall material is known, the product of cell wall fraction and cell wall specific gravity should give the value of specific gravity. In this study the cell wall specific gravity was not known because the measurements were made using microscope slides in which the cell walls must have been in some swollen state having density values between 1.017 (green) and 1.5 (ovendry). A trend from pith to bark may be seen in cell wall fraction. In general, the total cell wall fraction is shown to be lower for growth increments near the pith than for those closer to the bark

An estimate of the cell wall specific gravity (G_{cw}) can be made by recalling that the green volume specific gravity (G_g) is equal to the product of the wall fraction (F_{cw}) and the specific gravity (G_{cw}) of the cell wall. Thus, since F_{cw} and G_g are known for each growth ring (Tables 1 and 7), estimated values of G_{cw} were calculated for each growth ring as the ratio G_g/F_{cw}. Since two values of G_g are given for each growth ring (Table 7) the mean was used in each case.

The mean value of G_{cw} for all growth rings was 1.192 with a standard deviation of 0.107. This falls within the range expected (1.017) and 1.5). Apparently the cell wall volume in the mounted slides was somewhat less than midway between the green and oven dry volumes. This idicates that during mounting procedure the cell wall volume decreased somewhat from the original swollen condition of the green wood.

Within-growth-ring variation of tracheid wall and lumen fractions are shown in Table 3 as well as in Figures 4 and 5. In addition, the regression equations relating these two anatomical variables to position within the growth ring are given in Table 4. These results were expected as it is well known that in hard pines, such as loblolly pine, tracheid walls are substantially thicker in latewood than in earlywood.

The number density values of anatomical elements are given in Table 5 as related to ring number. The number of intercepted elements per unit length of test lines are not meaningful in terms of quantitative assessment of the structures involved. However, these values were later used in the calculations of size distribution parameters.

The number of tracheids per square millimeter may be looked upon as size related parameters by themselves. In fact, the number of tracheids divided into 1 mm^2 gives the average cross-sectional area of a single tracheid if the area occupied by other elements, such as rays and resin canals, is first subtracted from the 1 mm^2 test area.

There is a trend that might be discerned in the number of tracheids. The regression equation relating number of tracheid per unit cross-sectional area to ring number is given in Table 2 and shown graphically in Figure 6. It may be seen in Figure 6 that the number of tracheids decreases from pith to bark. This result was expected since as trees mature they produce larger cells than they did in earlier years. The larger the tracheids, the smaller their number per unit area assuming that the other fractional area occupied by the anatomical elements do not change significantly. However, this assumption may not hold since the number of resin canals per mm^2 decreased from pith to bark (Figure 7, Table 2).

The number of tracheids per mm^2 within growth increments and in terms of ring numbers are shown in Figure 8. First, it should be noted that the number of tracheids per mm^2 increases from early- to latewood across growth increments. This was expected as the cross-sectional area of individual latewood tracheid is smaller in latewood than in earlywood. Second, the general trend of the decrease of tracheid number density from pith to bark in all five incremental zones is apparent. This indicates that at all stages of growth during the growing season the age of the tree has its influence on tracheid size development.

Intra-increment variation in tracheid number density is shown in Figure 9. This figure was based on the combined data including all growth rings of all the sample trees. The regression model relating number of tracheids per mm^2 to relative position within growth rings is given in Table 4. The high value of R^2 (0.708) indicates a strong relationship between tracheid number density and relative incremental position.

Table 6 shows three size distribution parameters for tracheids as function of ring number. Tracheid diameters were determined in both the radial and tangential directions. Both of these diameters appear to increase in growth rings from pith to bark. Although, the increases with ring number is not particularly great they do significantly affect the mean area of tracheid cross-sections. This result is in good agreement with the previously mentioned tracheid number density variation as a function of ring number.

Within-growth ring variation of tracheid diameters is given in Table 3. These intra-increment values are also shown in Figure 10. The figure shows that the maximum radial tracheid diameter is produced by the tree after reaching an age between 16 and 20 years. In addition, in the earlywood zones the radial tracheid diameters reach a maximum in each age zone. Within-ring variation in tangential diameter of tracheid showed no significant trend. This was expected from the well known anatomy of conifers. Tracheids, laid down in radial rows remain of the same tangential dimension but their radial diameters decrease towards the end of the growing season.

Tracheid density index value are also shown in Table 6 as well as in Figure 11. The regression model fitted to these data is given in Table 2. Tracheid density index is a variable often used by scientists in paper research. It is the ratio between cell wall and cell lumen area fractions. In this study, this density index changed from a low of 0.344 to a high of 2.306. In general, the trend was an increase in this parameter from pith to bark indicating that as loblolly pine trees mature they produce denser tracheids.

The means of the squares of tracheid diameters are also shown in Table 6. These values are not the squares of the mean diameters but the means of the squares of the diameters. For that reason, they may be used as indicators of the variability of the tracheid diameters just as conventional standard deviations are used. In this parameter, which may be called the second moment of size distribution, there apperars to be no consistent and significant change from pith to bark. This may indicate that tracheid diameter variations within growth rings is independent of the age of the tree.

Intra-increment variation in tracheid density index is given in Table 3 and the corresponding regression equation in Table 4. When the data were organized in 5-year growth intervals the results are illustrated in Figure 12. It is interesting to see that the greatest tracheid density is not reached at the very end of the growing season. The early latewood zones contain tracheids with the highest density values. It is also noteworthy to mention that while tracheid density decreases slightly from pith to bark in the earlywood zones, it increases significantly in the transition and the two latewood zones. This seems to indicate that an anatomically quite different wood is produced by the tree in its mature age than during the juvenile years.

(b) Physical and Mechanical Properties

Physical and mechanical properties were determined for each growth ring separately by the U.S. Forest Products Laboratory in Madison, Wisconsin. The results are shown in Table 7. In all properties listed in Table 7 there is an increase from pith to bark.

Modulus of rupture almost trippled within the 24 years for which the sample trees were analyzed. Modulus of elasticity in bending showed a greater change from pith to bark. These results confirm previous knowledge that in southern pines mature wood has superior physical and mechanical properties as compared to juvenile wood. Figures 13 and 14 are graphical representations of changes in flexural properties of loblolly pine wood excised as individual growth rings from pith to bark.

Maximum crushing strength showed relatively smaller changes compared to flexural properties (Table 7). However, it is still more than doubled from the early juvenile period to mature age of the sample trees. The regression equation given in Table 2 and shown diagramatically in Figure 15 is highly significant as indicated by the R^2 value of 0.727.

Specific gravity appeared to change the least with age (Table 7). However, the increase from pith to bark was statistically significant. The regression equation relating specific gravity to ring number is given in Table 2 and shown in Figure 16.

(c). Inter-relations Between Properties and Anatomy

Specific gravity has long been used as the most important single variable affecting strength properties of wood. In this study it was demonstrated that while specific gravity changes only slightly, mechanical properties, in some cases, increase almost ten fold (MOE) from pith to bark. This should indicate that certain other factors, such as microstructural variations, not accounted for by specific gravity alone, may play a major role in determining strength properties as the tree matures. Therefore, an analysis was undertaken to determine what influence certain anatomical factors may have on the development of some mechanical properties of plantation-grown loblolly pine.

The statistical analysis selected was to maximize the R^2 value for the relationships between strength properties and anatomical variables. At the outset all anatomical variables were included. Then the contribution of each variable was tested and those having minimal value in affecting the relationship were eliminated. Using this successive elimination procedure the following anatomical parameters were selected for the regression models of all physical and mechanical propeties. These were:

X_1: average number of resin canals /mm^2

X_2: tracheid density index

X_3: mean radial diameter of tracheids (mm)

The best correlation including the above three independent variables was obtained for modulus of rupture (MOR) as shown in Table 8. Close to 87% of the variation in MOR could be accounted for by the three anatomical parameters. It should be noted that the regression models in Table 8 are not truely linear models because the dependent variables are used in the logarithmic (natural) form. The MOR-anatomy relationship is also shown in Figure 17. It is conveniently manifested in the figure that with increasing tracheid density index MOR increases. This is expected as this index is closely related to wood density but it is perhaps a more meaningful expression of the amount of cell wall material in this case than specific gravity would be. Tracheid density index is based only on tracheids and not on any other wood tissue and when axial stresses are acting, such as those in bending, the tracheids are the most important elements resisting those stresses.

The positive contribution of the radial diameter of tracheids to MOR is more difficult to explain. It has been reported (Pillow et al 1959) that southern pine trees produce larger tracheids, both longer and of larger diameter, in their mature age than during their juvenile years. It is also known that there exists a relationship between tracheid length and fibril angle in the secondary walls of tracheids; the longer the tracheids the steeper the fibril angle. On the other hand, fibril angle has been shown to influence axial strength properties; the steeper the angle the stronger the wood. Thus, an increase in tracheid diameter may be considered an indicator of longer tracheids which, in turn, are associated with steeper fibril angle. Tracheid diameter is therefore only indirectly related to strength through fiber length and fibrillar orientation. Thus, the larger the diameter the stronger the wood.

It is also shown in Figure 17 that the number of resin canals is inversely related to MOR. This apparent relationship is due to the fact that the resin canal concentration decreased from the pith outward, and the two really important factors i.e., specific gravity and mean fibril angle also change from pith to bark. Thus, as in this case of tracheid diameters discussed above, the apparent change in strength with change in resin canal concentration is really a function of the associated change in fibril angle. The effect of specific gravity is discussed later.

The regression equations relating modulus of elasticity (MOE) and maximum crushing strength to the three anatomical parameters are also given in Table 8 and corresponding diagrams are shown in Figures 18 and 19, respectively. These relationships are quite similar to that for MOR (Figure 17), therefore, the explanations given above should hold for these two properties as well. The only exception may be MOE. This mechanical property is not related to failure. However, it is conceivable that elastic deformation may be influenced by the weak tissues associated with resin canals.

The influence of the three anatomical variables on specific gravity is shown in Figure 20 and the corresponding regression equation is given in Table 8. It is apparent from the table that the lowest coefficient of determination ($R^2 = 0.776$) was obtained for this relationship. Apparently, specific gravity is not very highly dependent on the type of tissue the wood is comprised of. It is, by definition, the measure of the amount of wood substance present in a unit volume of wood, and not, to any degree, related to what type of cells that material is part of.

(d) Specific Strength Property-Anatomy Relationships

As indicated earlier, the specific gravity of wood, a measure of the relative amount of solid cell wall material, has been considered the best index for predicting strength properties. Therefore, it was attempted in this study to examine the correlation that might exist between strength properties and specific gravity of plantation grown loblolly pine. Table 9 contains coefficients for the regressions obtained for this analysis. The regression equations given for MOR, MOE, and crushing strength parallel to grain in the table (Table 9) are highly significant as manifested by the corresponding R^2 values. Figures 21 through 23 graphically illustrate the highly significant linear relationships that exist between specific gravity and strength properties of plantation grown loblolly pine. It should be noted that the above trends are consistent with previous knowledge of the relationship between specific gravity and strength properties.

It has been demonstrated that the effectiveness of wood in resisting any particular form of applied force is a function not only of the total amount of the wall material, but that of the proportion of the cell wall components found in a given piece. Also the amount of extractives in the cell lumen may have influence on strength (Panshin and deZeeuw 1980). In order to remove the effect of specific gravity on strength properties, specific strength values were calculated. Specific strength is thus a ratio of strength to specific gravity. Considering the highly significant linear relationships that were found between specific gravity and strength properties, it was justified to examine what anatomical parameters beside specific gravity may account for the variation in the strength properties of plantation grown loblolly pine.

Table 10 contains the results of specific strength versus anatomy analyses. The multiple regression procedure employed for this analysis was similar to that discussed earlier, i.e. to maximize the R^2 value for the relationship between specific strength properties and anatomical variables not closely related to specific gravity. Again, a limit of three independent variables, was imposed for each of the three prediction equations as contained in Table 10. These variables for loblolly pine were:

X_1 : average number of resin canal per mm square
X_2 : mean square values of tracheid diameters
X_3 : tangential and radial diameter ratios of tracheid

The prediction equations as shown in Table 10 accounted for between 84 and 94 percent of the variation in the specific strength properties of the sample trees of loblolly pine. These prediction models are diagramatically illustrated in Figures 24 through 26. It is evident by comparing these figures with Figures 17-19, that the apparent effect of resin canal concentration is considerably reduced when the effect of specific gravity is accounted for by plotting specific strength. Further reduction in the apparent effect of resin canal concentration would be expected if associated changes in fibril angle from pith to bark were also considered. The small remaining direct effect of resin canal concentration may be due to stress concentration in their vicinity.

The means of the squares of tracheid diameters contribute positively to the prediction models. It should be borne in mind that this anatomical parameter is only indicative of the variability of the tracheid diameters. It was noted earlier in the discussion that this parameter showed no consistent and significant change from pith to bark. This fact is likely to negate any plausible explanations that may be advanced for the positive relationship between specific strength properties and the means of the squares of tracheid diameters.

The ratio of tangential and radial diameter of tracheid was calculated by dividing tangential tracheid diameter by radial diameter. Resulting values of this parameter were found to be positively related to the specific strength properties of plantation grown loblolly pine. Discussion on the tangential and radial diameters of tracheid has shown that both diameters increase in growth rings from pith to bark. The resulting ratio of the two diameters is not expected to relatively increase in growth increments from pith to bark in the same manner. However, the increase in this parameter might have been that either of the two diameters could have increased faster or slower than the other. Assuming this is the case it may be logical to present the same explanation given in the discussion of the positive relationship between the radial diameter of tracheid and strength properties. In other words, based on the explanation given earlier, it could be inferred that tangential and radial diameter ratio of tracheid is therefore only indirectly related to specific strength through fiber length and fibrillar orientation.

The foregoing discussions have demonstrated the strong relationship between strength properties and specific gravity. The significance of anatomical parameters in explaining variations in strength properties of plantation grown loblolly pine after the removal of specific gravity influence, was also discussed. It was equally of interest in this study to examine how much of the total variation in strength properties could be explained by combining specific gravity with the anatomical parameters. For this purpose the strength properties of interest were regressed on specific gravity combined with the same anatomical variables used in earlier multiple regression analyses. Table 11 lists the newly constructed models with their coefficients, using up to four independent variables.

It is evinced in Table 11 that as much as 92-97 percent of total variation in the strength properties of plantation grown loblolly pine could be accounted for by a combination of specific gravity and three anatomical parameters. Modulus of rupture (MOR) had up to 96 percent of its total variations accounted for by the new model, with all prediction variables contributing significantly to the model. A high R^2 value of 0.94 was obtained for modulus of elasticity (MOE), with all but one prediction variables contributing significantly to the model. Maximum crushing strength parallel to the grain also showed a similar trend with a high R^2 value of about 0.92.

It may be noted that in all three models the contributing effect of specific gravity factor has been highly significant at the 1 percent probability level. This is in corroboration of the general knowledge that specific gravity can be a good index for predicting strength properties of wood.

2. Cottonwood

(a) Anatomical Characterization

Cottonwood, a diffuse porous hardwood species, has an anatomical structure more complex than that of the coniferous loblolly pine. Its anatomical elements have differentiated to perform specific functions in the xylem tissue. As a result, longitudinal elements are classified into vessels, parenchyma cells, and fibers. Its ray cells are all the parenchyma type. In cottonwood, longitudinal parenchyma cells are sparse and cannot be readily distinguished from fibers under the microscope. Therefore, on cross sections only three anatomical elements, vessels, "fibers" and ray parenchyma were identified. All longitudinal parenchyma cells were lumped into the general category of "fibers".

Table 12 summarizes the results of the point count measurements which served is estimates of the volume fractions of the three types of elements, including their lumens and wall, in the cottonwood xylem tissues. The total fractional area occupied by vessels shows a general increase within growth rings as the tree matured. This increase is even more apparent for vessel lumens as depicted in Figure 27 where the vessel lumen area fraction is plotted against ring number as counted from pith to bark. The corresponding simple regression is given in Table 13. This relationship indicates that as the tree matures, it produces anatomical elements, especially vessels, larger in size than those laid down during the juvenile stages of development. However, this is only true if the number of vessels per unit area remains constant or decreases from pith to bark.

Indeed there was a decrease in the number of vessels per unit area in the sample trees from pith to bark. This result may be seen in Table 14 where the number density of vessels decreased from 158 per square millimeter in the ring closest to the pith to 54 in the increment next to the bark. The decrease of the number of vessels as the trees matured was found highly significant (Table 13, Figure 28). Therefore, it can be safely concluded that the vessels produced by the cambium during the mature age of the trees were significantly larger than those laid down during the juvenile years.

Table 12 also shows the changes in the lumen wall fractional areas for fibers. While the total area occupied by fibers remained relatively constant over the life of the 26-year-old trees, the lumen and wall fractions showed opposite trends. Fiber lumen area fraction showed a slight trend of increase, but the wall fraction decreased. This shows again that mature trees produced somewhat larger fibers than they did during the juvenile stages of growth. This conclusion is further substantiated in Table 14 where the number of fibers per unit area is given. The number density of fibers decreased from pith to bark. The simple regression showing this decrease of the number of fibers is given in Table 13 and shown diagramatically in Figure 29.

Ray parenchyma cells showed no trend as the sample trees matured. This may be seen in Tables 12 and 14. In Table 14 a slight decrease of the number of rays per unit area, shown as number of rays intersected per unit length of perpendicular lines, showed a slight but statistically non-significant decrease.

Within-growth-ring variations of area fractions and number densities of the three major anatomical elements are given in Table 15. The mean values of vessel lumen area fractions and number of vessels per unit area show opposite trends from the beginning to the end of the increments. An analysis of variance (ANOVA) was performed to determine whether or not these trends were statistically significant. The results of ANOVA test (Table 16) shows that indeed variations in these inatomical characteristics within growth increments are highly significant. In order to ascertain which growth zones within the rings were truly different from others, a Duncan's multiple range test was applied. In Table 15 those mean values of vessel lumen area and vessel number density that are not significantly different from one another according to the Duncan's test are connected with a solid line.

It is of interest to note that both area fraction and number density of vessels are significantly different in the late latewood from those in the earlier growth zones. This is in direct violation of the definition of diffuse porous hardwoods. Diffuse porous wood should have vessels or pores of uniform size and number throughout the growth ring. Cottonwood, which is classified as "diffuse porous" should conform to the above definition. It is apparent from the results of this study that the sample trees did not strictly fulfil the requirements of a diffuse porous wood.

An attempt was made to see whether or not the above inconsistency could be observed at all ages of the sample trees. Figure 30 shows the result of this analysis. It may be seen in the figure that in all age zones the latewood portions show higher values in vessel number density than in earlier growth zones. However, the greatest differences occured during the first ten years of the sample trees. At the more mature age zones the sample cottonwood trees developed xylem more closely assumed the classical diffuse porous structure.

The number of fibers per unit area increased from earlywood to latewood as well (Table 15). An ANOVA test procedure indicated that only the latewood portion was significantly different from the earlier growth zones (Table 15 and 16). When the sample material was divided into age periods again the largest difference in the number of fibers per unit area was found during the earlier years, although all age groups showed a larger number density of fibers toward the ends of the growth increments (Figure 31).

Size parameters of the three major anatomical elements in the sample cottonwood trees were calculated from stereological counts. Table 17 shows these parameters for vessels listed from pith to bark. Radial and tangential diameters show an increase from the earlier to the later years of the life of the trees. However, while radial diameters increased from 51 µm to 106 µm, tangential diameters only changed from 41 to 74 µm. It should be noted that in all parts of the sample trees the vessels had a shape elongated in the radial direction. This was expected on the basis of the knowledge of the anatomy of cottonwood. However, the highly siginificant increase of vessel diameter with age has not been reported in the literature. Figure 32 and 33 show these relationships. The linear regression equations corresponding to these relationships are listed in Table 13. The observation that mature trees grow larger vessels has been discussed earlier. Diameter changes with age are further indications of that trend.

Vessel shape factors were calculated by dividing the mean tangential diameter by that of radial diameter in each growth increments (Table 17). As mentioned earlier, all such ratios showed that cottonwood vessels were changing in the radial direction resulting in vessel shape factors smaller than one. However, as the trees matured the vessels tended to become isodiametrical in shape. This trend was analyzed statistically and found to be highly significant, although the R^2 value calculated for this relationship was only 0.334 (Table 13). The scatter of points around the regression line, shown in Figure 34 shows clearly the trend and variation of individual points around the line.

Within-growth-ring variation in both radial and tangential diameters of vessels are given in Table 15. It should be noted that both vessel diameters decreased from earlywood to latewood. This trend was found to be highly significant when tested by ANOVA (Table 16). However, a Duncan's multiple range test showed that only in the latewood were vessel diameters significantly smaller than those in earlier growth zones. This indicates that cottonwood produces smaller vessels during the end of the growing season when growth slows down. Here, again the question may be asked whether or not plantation grown cottonwood studied in this research is truly diffuse porous.

Figures 35 and 36 show the within-growth-ring variation of vessel diameters for the sample trees for which the increments were stratified in 5-year groups. These figures show that at each 5-year growth interval the late latewood zones contained smaller vessels than the earlier growth zones. The greatest relative difference may be observed during the most juvenile portion of the trees studied.

Vessel shape factor increases slightly from 0.708 to 0.779 from earlywood to latewood (Table 15). However, this trend was significant only at the 95 % level of probability as shown in Table 16. The Duncan's multiple range test at the 0.01 alpha level also showed that the differences were not large enough to clearly separate any single growth zone from the others. Nevertheless, the trend was towards a more isodiametric shape of the vessels from earlywood to latewood.

The means of the squares of the vessel diameters were calculated to assess the variability of vessel diameters. This variable, often called the second moment of size distribution, may be used as an estimate of variation around the arithemetic mean diameters. The larger the diameter square ($\overline{d^2}$), the greater the variation.

The second moment of vessel diameter distribution increased from a low value of 2.613 $10^{-3}\mu m^2$ in ring No. 1 to a high of 9.048 $10^{-3}\mu m^2$ in ring No. 23, indicating that the sample trees produced vessels of greater size variation in their mature stages than during their juvenile stages of growth.

The mean cord intercept of and mean free distance between vessels in both the tangential and radial directions are also given in Table 17. The mean cord intercept is another measure of vessel size closely related but always smaller than the corresponding diameter. This variable is equal to the diameter only if the shape of the anotomical element in question assumes a rectangular shape. It may be easily derived that the mean cord intercept of a feature is two-thirds of the diameter if the feature is circular. Nevertheless, the relationship between these two size distribution parameters is close enough to follow the same trend as may be seen in Table 17.

The mean free path is a measure of the average distance between vessels measured on a random line superimposed on a cross-section and oriented in the tangential or radial direction. It may be seen in Table 17 that the radial mean free path between vessels increased slightly from juvenile wood to mature wood but the tangential counterpart remained relatively constant.

Table 18 contains the stereological parameters calculated for fibers in cottonwood growth increments. Both radial and tangential diameters increased in growth rings from juvenile wood to mature wood. This trend again indicates that trees produce larger cells, including fibers, as they reach maturation. The changes in radial and tangential diameters from pith to bark in the sample trees are shown diagramatically in Figures 37 and 38, respectively. The corresponding regression equations with their statistics are given in Table 13. As may be seen, these trends are highly significant with R^2 values of 0.630 for radial and 0.578 for tangential fiber diameters. It may be of interest to note that the general shape of fibers throughout the sample material was found to be somewhat elongated in the radial direction. However, a shape factor for fibers, similar to that shown earlier for vessels was not calculated.

Within-growth-ring variations in fiber diameters are shown in Table 15. Both radial and tangential diameters decreased slightly from earlywood to latewood. ANOVA analysis showed that these trends were highly significant (Table 16). The Duncan's multiple range test at the 0.01 alpha level also clearly separated the five incremental growth zones in terms of fiber diameters (Table 15). The same general trend may be seen in Figures 39 and 40, where within-increment radial and tangential variations in fiber diameters are shown, respectively.

The second moments of fiber diameter distributions are listed in Table 18. Just as noted earlier for vessels, fiber diameter variations within growth rings increased from juvenile wood to mature wood.

Double cell wall thickness of fibers did not show any consistent trend for the sample cottonwood trees (Table 18). However, fiber density index, the ratio between cell wall area and cell lumen area, decreased from juvenile wood to mature wood. This trend may be seen in Table 18 and Figure 41. Although the regression was found to be highly significant (Table 13), the scatter of points around the regression line and the R^2 value of 0.272 indicate that the relationship was not particularly consistent (Figure 41).

Within-growth-ring variation in fiber density index is shown in Table 15. ANOVA analysis procedure gave a non-significant F value for this variable (Table 16) and, therefore, a Duncan's multiple range test could not separate the five growth zones in terms of fiber density index. The same conclusion may be drawn from Figure 42 where within-increment averages of fiber density index is separately shown for 5-year growth intervals.

The only variable for rays that showed a significant relationship to age was that of the mean tangential distance between rays. As shown in Figure 43 and Table 13 mean tangential distance between rays increased as the sample trees matured.

(b) Physical and Mechanical Properties

Table 19 is a summary of the results of the physical and mechanical properties determined for individual growth increments of the sample cottonwood trees. It may be noted in the table that all mechanical properties increase with age. Strictly, differences occured in modulus of rupture (MOR) in bending showing an increase from 17982 kPa for ring No. 1 to 37860 kPa for ring No. 24 in the mature zone. Modulus of elasticity (MOE) increased almost six fold from juvenile wood to mature wood. When the data were analyzed using a regression technique, highly significant statistics were obtained as shown in Table 13. The R^2 value for the MOR vs. ring number relationship was 0.616 and for MOE vs. ring number was 0.890. These high values of the coefficients of determination indicate that high percentage of the variation in flexural properties could be accounted for by the location of the test material within the sample trees. The influence of age or ring number on the bending properties is shown in Figures 44 and 45. These Figures show no evidence of a levelling off of MOR and MOE within the 26 years included in this study for the sample trees.

Compression parallel to the grain also increased as the sample trees matured. The differences in this property were not as drastic as those in bending. The minimum vahue was observed for the ring closest to the pith, 9136 kPa and the maximum was reached in the 24th ring, 17168 kPa (Table 19). This influence of tree age to maximum crushing strength was shown by the 0.853 R^2 value in Table 13. The corresponding linear regression is shown diagramatically in Figure 46. Here again no evidence may be seen of any levelling off of crushing strength at age 26, suggesting that had the trees been let to grow further, they might have produced wood of even higher compressive strength.

Specific gravity showed the least consistent change from juvenile wood to mature wood. This may be observed in Table 19 and also in Table 13 where the R^2 value for the specific gravity versus ring number relationship is shown to be only 0.300. Also, the scatter of points around the regression line as shown in Figure 47 indicats a low level of association between specific gravity and age of cottonwood trees. It may be concluded from these results that wood characteristics other than those affecting specific gravity may determine strength properties of plantation grown cottonwood trees.

(c) Inter-Relationships Between Physical and Mechanical Properties and Anatomy

As mensioned earlier in the discussion of anatomy-property inter-relationships for loblolly pine, a multiple regression analysis was performed relating mechanical properties to the three most important anatomical variables by maximizing R^2. The three most important independent variabhes thus selected turned out to be (1) the average number of fibers per unit area, (2) the radial diameter of fibers, and (3) the fiber density index. These anatomical variables, all related to fibers, suggest that the most important anatomical elements determining strength are the fibers in cottonwood.

Cottonwood has a complex anatomical structure compared to loblolly pine. Therefore, it presents a more difficult task in relating the structure to strength. This may be seen in Table 20 where the multiple regression equations are listed with their appropriate statistics. For example, MOR related to the three fiber properties has a coefficient of determination of only 0.396, indicating that slightly less than 40% of the variation in MOR may be explainable by fiber properties alone. The corresponding Figure 48 depicts diagramatically the dependence of MOR on fiber properties. It should be noted that this relationship is non linear as its solution results in the natural logarithm of the dependent variable MOR.

The multiple regression relating MOE to fiber properties is significantly better than that calculated for MOR. The R^2 value for this regression, as shown in Table 20 is 0.686 indicating that almost 70 % of the variation is explainable on the basis of fiber properties. The question may be raised why is MOE more closely related to fiber properties than MOR. The answer may lie in the difference in nature between MOR and MOE. While MOE is the measure of the unit deflection as a response to bending stress within the proportional limit, MOR is closely related to failure. If fibers have the major responsibiliy of resisting stresses in cottonwood, they may not govern the failure mechanism. Failure is often influenced in wood by the presence of certain discontinuities in the specimens. These may be elements other than fibers, such as vessels, rays, or axial parenchyma cell. Such discontinuities produce localized stress concentration and initiate failure. At these locations fiber or fiber bundles may be subjected to stresses significantly higher than those calculated by averaging the load over the whole cross-section. Localized conglomeration of weak tissues, such as vessels or rays, may produce stress concentrations, thereby reducing maximum stress values. But they are not effective in influencing stiffness or MOE. The graphical representation of the MOE-anatomy relationship is shown in Figure 49.

Over 55% of the variation in maximum crushing strength could be explained by fiber properties (Table 20). The regression model is shown in Figure 50.

(d) Specific Strength Property-Anatomy Relationships

Results of the simple linear regression analyses used to explore the relationship between specific gravity and strength properties, are contained in Table 21. It is evident from the table that specific gravity is significantly correlated with the three mechanical properties of plantation grown cottonwood. It may be noted that the coefficients of determination (R^2) obtained for cottonwood in the relationships are in general, lower than those obtained for loblolly pine. This is expected as the anatomical elements that influence specific gravity are more complex in cottonwood than in loblolly pine. Figures 51 through 53 are graphical illustrations of these relationships.

The significant relationship found between strength properties and specific gravity of plantation grown cottonwood prompted further analysis to explore the source of variation in mechanical properties after removing the effect of specific gravity. As in loblolly pine, specific strength properties were calculated for cottonwood. Using the multiple regression analysis procedure, up to three independent anatomical parameters, not closely related to specific gravity, were employed in the analyses. Each of the specific MOR, specific MOE, and specific crushing strength parallel to grain was regressed on the anatomical parameters. These independent anatomical variables selected for cottonwood were as follows:

X_1 : radial diameter of fibers (mm)

X_2 : vessel shape factor

X_3 : tangential diameter of vessel (mm)

The coefficients of determination and equations relating specific strength properties to the above anatomical varaiables are listed in Table 22. It may be noted from the table that over 60 percent of the variation in specific MOR of plantation grown cottonwood was explainable by anatomical parameters not related to specific gravity. In the equation for the specific modulus of rupture (Table 22), only the contributory effect of the tangential diameter of vessel was significant at the 0.01 level, while the two other variables contributed inversely to the model at the significant level of 0.05. The graphical representation of this model is shown in Figure 54.

Over 80 percent of the variation in specific MOE was accounted for by the three anatomical variables in the model. Of the three prediction variables, the contributory effect of radial diameter of fibers was the only one found significant at the 5 percent probability level. The other two variables contributed significantly to the model at the 0.01 alpha level. Figure 55 is the diagramatic illustration of this model for predicting specific MOE of plantation grown cottonwood.

The model for predicting specific maximum crushing strength parallel to grain was significant at the 0.01 alpha level with a corresponding high R^2 value of approximately 0.86. The radial diameter of fibers was a negative factor in the model and of no contributory significance at the 5 percent probability level. The second parameter in the equation, vessel shape factor, was also inversely related to the specific crushing strength, but only at the 0.05 alpha level. Only the third parameter, tangential diameter of vessels, was a positive factor in the model, contributing significantly at the 0.01 alpha level. Figure 56 provides graphical illustration of the model for predicting specific maximum crushing strength parallel to grain of sample trees of plantation grown cottonwood.

It should be noted in Table 22 that two of the prediction variables, radial diameter of fibers and vessel shape factor, have consistently contributed negatively to each of the specific strength property models. Conversely, the third parameter in the model, tangential diameter of vessels, as shown in the table was consistently positive.

A similar analysis made for loblolly pine, to examine how much of the total variation in strength properties could be explained by specific gravity combined with anatomical variables, was also carried out for cottonwood. Table 23 gives the multiple regression coefficients obtained from regressing each of MOR, MOE and maximum crushing strength parallel to grain on specific gravity combined with three other anatomical variables. The three anatomical variables in each of the new models were the same ones used for predicting specific strength properties.

It is evident from Table 23 that addition of specific gravity to the new models significantly improved the R^2 values (Table 22 and 23). The three strength properties, MOR, MOE, and maximum crushing strength parallel to the grain, had 82-92 percent of their variations accounted for by the new models. The effect of specific gravity factor was highly significant in all the three models. Modulus of rupture (MOR) had an R^2 value of about 0.82 while as much as 88 percent of total variation in modulus of elasticity (MOE) could be accounted for by specific gravity and three anatomical parameters unrelated to specific gravity. As high as 92 percent of the total variation in maximum crushing strength parallel to the grain of plantation grown cottonwood was explained by combined specific gravity and anatomical parameters.

The inference that may be drawn here is that, certain other factors, such as anatomical parameters, not closely related to specific gravity, may be playing a major role in determining strength properties of plantation grown woods of loblolly pine and cottonwood. In other words, it may be concluded from these results that wood characteristics other than those related to specific gravity may determine strength properties of plantation grown loblolly pine and cottonwood trees.

CONCLUSIONS

Based on the results obtained in this study, the following conclusions may be drawn:

1. Quantitative wood anatomy based on the principles of stereology was demonstrated to be a useful tool for characterizing the structure of conifers and diffuse porous hardwood species.

2. Tracheid lumen and wall area fractions of plantation grown loblolly pine showed significant decrease and increase respectively from pith to bark. Trends by the two fractions were in direct opposite to one another. Within-growth-ring variation of tracheid lumen and wall fractions also showed significant patterns similar to the among ring variations. Tracheid lumen fraction decreased from earlywood to latewood regions, while tracheid wall fraction increased. This was not unexpected for the fact that in hard pines, thin walled tracheids are laid down first, followed by the thicker walled tracheid in the latewood region of growth increments.

3. Number of tracheids per unit cross-sectional area decreased significantly from pith to bark. Within-growth-increment

variation of tracheid number density showed a positive trend. Tracheid number density increased from early- to latewood across growth increments indicating that the cross-sectional area of individual latewood tracheids is smaller in latewood than in earlywood.

4. Both radial and tangential diameters of tracheids increased in growth rings from pith to bark. The maximum radial diameter of tracheid within growth increments was produced in the latter age of the sample trees.

5. Tracheid density index changed significantly from pith to bark. The intra-incremental variation showed that the greatest tracheid density index was reached at the early latewood region.

6. The total fractional area occupied by vessels in plantation grown cottonwood increased as the trees matured. However, the number of vessels per unit area in the sample trees decreased from pith to bark.

7. The fractional area occupied by fiber lumen and wall showed opposite trends. Fiber lumen area fraction slightly increased, while wall fraction decreased. The number density of fibers showed significant decrease from pith to bark.

Conversely, within-ring variation of fiber number density showed an increase from early- to latewood.

8. There were significant differences noted in both area fraction and number density of vessels from the earlywood to those in the latewood. This is in direct contradiction with the definition of diffuse porous in which cottonwood is classified.

9. Radial and tangential diameter of cottonwood vessels and fibers increased from pith to bark. Vessel shape factor also showed a slight increase from early- to latewood within-growth increments.

10. The fiber density index of plantation grown cottonwood decreased from juvenile wood to mature wood.

11. Average physical and mechanical properties of both loblolly pine and cottonwood showed significant increases from pith to bark.

12 Physical and mechanical properties and their variations in loblolly pine and cottonwood were found to be highly correlated with changes in anatomical structure during the life of the sample trees.

13. Multiple regression models constructed for predicting physical and mechanical properties in loblolly pine, using up to three anatomical parameters as independent variables, accounted for as much as 76-87% of total variations.

14 Anatomical parameters selected for predicting strength properties in cottonwood were all related to fiber properties. However, the overall predictive power of the models in cottonwood was less than that in loblolly pine. Total variations accounted for by the fiber properties as independent variables ranged from less than 40% to about 70%.

15 It may also be concluded from this study that wood characteristics other than those related to specific gravity may determine specific strength properties of plantation grown loblolly pine and cottonwood trees.

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TABLES

Table 1 Means (X) and standard deviations (SD) of point counts (volume fractions) for cell types of loblolly pine (*Pinus taeda*)

Growth Ring	Tracheids Lumen (%) X	Tracheids Lumen (%) SD	Tracheids Wall (%) X	Tracheids Wall (%) SD	Tracheids Total	Ray cells Lumen (%) X	Ray cells Lumen (%) SD	Ray cells Wall (%) X	Ray cells Wall (%) SD	Ray cells Total	Resin Canal (%) X	Resin Canal (%) SD	Total Cellwall Fraction (%)
1	58.8	10.8	34.5	11.7	93.3	5.8	5.8	0.5	1.3	6.3	0.4	1.3	35.0
2	56.1	14.7	37.7	13.1	93.8	4.0	3.4	1.7	2.5	5.7	0.5	1.5	39.4
3	57.2	16.9	37.7	15.5	94.9	2.0	3.5	1.5	2.7	3.5	1.6	2.3	39.2
4	62.4	17.9	33.2	16.7	95.6	2.0	4.3	0.8	1.8	2.8	1.6	2.5	34.0
5	56.8	15.9	39.4	14.5	96.2	3.0	3.9	-	-	3.0	0.8	2.1	39.4
6	53.1	18.3	42.5	18.7	95.6	2.5	3.5	0.8	1.9	3.3	1.1	2.8	43.3
7	52.2	18.0	43.7	17.2	95.9	3.1	5.4	0.3	0.9	3.4	0.7	2.1	44.0
8	53.6	21.0	43.1	21.2	96.7	2.0	3.0	0.5	1.1	2.5	0.8	2.6	43.6
9	55.6	21.0	40.4	19.7	96.0	1.5	2.6	1.2	2.1	2.7	1.3	3.6	41.6
10	56.7	21.6	39.0	20.0	95.7	2.0	2.6	1.6	2.7	3.6	0.7	2.7	40.6
11	48.8	22.9	47.5	21.5	96.3	3.1	4.4	0.4	1.0	3.5	0.2	1.1	47.9
12	51.0	22.5	46.1	21.1	97.1	2.2	3.5	0.5	1.4	2.7	0.2	1.5	46.6
13	53.7	21.0	43.3	21.4	97.0	3.0	4.4	-	-	3.0	-	-	43.0
14	53.1	22.9	45.0	23.0	98.1	1.5	3.1	0.1	0.3	1.6	0.3	1.0	45.1
15	51.6	22.2	46.9	22.1	98.5	0.8	1.8	0.1	0.5	1.3	0.6	1.7	47.0
16	55.0	20.8	42.6	20.8	97.6	1.4	2.1	0.6	1.6	2.0	0.4	1.4	43.2
17	49.4	25.1	43.5	22.5	92.9	2.9	3.8	1.8	2.8	4.7	2.4	4.0	45.3
18	52.0	26.5	46.4	26.5	98.4	1.1	3.0	0.2	0.5	1.3	0.3	1.1	46.6
19	51.2	23.4	45.5	21.5	96.7	1.8	2.9	0.8	1.6	2.6	0.7	2.1	46.3
20	51.7	23.3	44.7	22.4	96.4	2.4	3.9	0.6	1.6	3.0	0.6	1.7	45.3
21	52.9	23.8	44.5	23.3	97.4	1.7	2.8	0.2	0.8	1.9	0.7	2.2	44.7
22	51.6	21.8	44.7	21.0	96.3	3.0	3.8	0.5	1.5	3.5	0.2	0.7	45.2
23	52.6	22.5	44.3	22.6	96.9	2.0	3.0	0.6	1.9	2.6	0.5	1.6	44.9
24	48.1	21.8	49.2	22.2	97.3	1.9	3.1	0.3	0.9	2.2	0.5	1.3	49.5
25	50.8	20.5	45.3	18.8	96.1	3.3	5.0	0.1	0.7	3.4	0.5	1.1	45.4
26	51.9	18.8	45.3	19.6	97.2	1.7	2.8	0.5	1.2	2.2	0.6	1.9	45.8
27	49.4	22.9	48.3	22.5	97.7	1.7	3.1	0.3	1.1	2.0	0.3	1.2	48.6
28	49.2	25.1	48.3	24.5	97.5	1.9	3.6	0.1	0.5	2.0	0.5	2.0	48.4
29	53.6	22.6	44.2	22.3	97.8	1.7	2.8	0.4	1.4	2.1	0.1	0.7	44.6
30	53.1	24.2	42.9	22.1	96.0	1.9	3.6	0.8	2.0	2.7	1.3	3.9	43.7
31	46.7	26.9	51.7	27.3	98.4	0.8	1.8	-	-	0.8	0.8	1.8	51.7

Each mean is based on 90 stereological measurements.

Table 2 Variation of certain anatomical, physical and mechanical properties of loblolly pine (<u>Pinus taeda</u>) from pith to bark

Property (Y)	b_0	b_1	Coeff. of determination R^2	Std.error of estimate Sy.x
Tracheid lumen area	0.568** (0.0091)	-0.249E-02** (0.497E-03)	0.4639**	0.0247
Tracheid wall area	0.381** (0.010)	0.339E-02** (0.560E-03)	0.5583**	0.0270
Number of tracheids per mm square	1260** (32)	-11.078** (1.781)	0.5715**	88.698
Number of resin canal per mm square	0.717** (0.103)	-0.021** (0.005)	0.3269**	0.2801
Tracheid density index	0.672** (0.031)	0.010** (0.001)	0.5335**	0.086
Transverse mean free path of ray parenchyma	0.238** (0.013)	0.347E-02** (0.716E-03)	0.4474**	0.0356
Modulus of rupture (kPa)	36093** (4316)	1930.74** (243.16)	0.6924**	11527
Modulus of elasticity (MPa)	3730** (603)	346.693** (33.995)	0.7878**	1611
Max. compression parallel to grain (kPa)	14471** (1345)	661.548** (78.074)	0.7267**	3542
Specific gravity (g/cm^3)	0.435** (0.016)	0.562E-02** (0.920E-03)	0.5799**	0.0417

$Y = b_0 + b_1X_1$

where:

X_1: ring number from pith to bark

** Significant at the 1 percent probability level

* Significant at the 5 percent probability level

The standard error for the regression coefficient is shown in parenthesis below each coefficient.

Table 3 Means (X) and standard deviations (SD) of point counts (volume fractions) and derived stereological parameters for cell types with-in growth rings of loblolly pine (<u>Pinus taeda</u>)

Property	Relative position within growth increment (%)									
	10		30		50		70		90	
	X	SD	X	SD	X	SD	X	SD	X	SD
Tracheid lumen area fraction	0.743	0.090	0.734	0.091	0.503	0.113	0.318	0.112	0.350	0.127
Tracheid wall area fraction	0.229	0.086	0.238	0.088	0.453	0.107	0.643	0.118	0.611	0.130
Number of tracheids per mm^2	776	213	819	200	1103	183	1333	212	1403	261
Radial tracheid diameter (mm)	0.033	0.007	0.031	0.007	0.020	0.004	0.015	0.003	0.014	0.002
Tangential tracheid diameter (mm)	0.026	0.006	0.025	0.006	0.021	0.004	0.020	0.004	0.020	0.003
Ratio of tang/rad diameter	0.803	0.102	0.827	0.097	1.108	0.175	1.402	0.309	1.446	0.262
Tracheid density index	0.328	0.174	0.345	0.177	1.003	0.499	2.437	1.337	2.127	1.212

Each mean is based on 167 values

Table 4 Variation of certain anatomical properties with-in-growth increments of loblolly pine (<u>Pinus</u> <u>taeda</u>)

Property (Y)	b_0	b_1	Coeff. of determination R^2	Std error of estimate Sy.x
Tracheid lumen area fraction	0.833** (0.014)	-0.607E-02** (0.257E-03)	0.7843**	0.0907
Tracheid wall area fraction	0.142** (0.015)	0.588E-02** (0.263E-03)	0.7653**	0.0928
Tracheid density index	-0.149^{ns} (0.098)	0.025** (0.002)	0.5998**	0.6016
Radial diameter of tracheid (mm)	0.036** (0.0006)	-0.266E-03** (0.104E-04)	0.8089**	0.0036
Tangential diam of tracheid (mm)	0.026** (0.0004)	-8.31E-05** (0.82E-05)	0.4043**	0.0028
Ratio of tang/ rad diam of tracheid	0.651** (0.024)	0.919E-02** (0.426E-03)	0.7523**	0.1501
Number of tracheids per mm^2	641** (26.297)	-8.834** (0.457)	0.7088**	161.200

$Y = b_0 + b_1X_1$
where:

X_1: relative position winthin growth increments (10%, 30%, 50%, 70%, and 90%)

** Significant at the 1 percent probability level

* Significant at the 5 percent probability level

ns Not significant at the 5 percent probability level

The standard error for the regression coefficient is shown in parenthesis below each coefficient.

Table 5 Means (X) and standard deviations (SD) of lineal and areal feature counts of tracheids, ray cells and resin canals for loblolly pine (*Pinus taeda*)

Growth Ring	Number of Tracheids per mm				No of Ray Cells per mm (Tangential)		Number of Resin Canal per mm				Number of Tracheid per mm square		Number of Resin Canals per mm square	
	(Tang) mm^{-1}		(Rad) mm^{-1}		mm^{-1}		(Tang) mm^{-1}		(Rad) mm^{-1}		mm^{-2}		mm^{-2}	
	X	SD	X	SD	X	SD	X	SD	X	SD	X 3	SD	X 4	SD
1	26.8	4.8	25.5	4.6	5.5	1.4	0.05	0.18	0.04	0.10	1592	257	0.38	1.10
2	26.9	4.2	24.1	4.9	4.7	1.6	0.07	0.19	0.07	0.21	1228	339	1.14	2.76
3	27.0	4.5	25.4	3.2	4.4	1.5	0.16	0.24	0.15	0.25	1207	271	1.36	2.42
4	27.7	4.9	25.7	4.4	4.2	1.6	0.13	0.21	0.11	0.16	1168	324	1.05	2.05
5	24.5	4.2	23.4	5.2	4.5	2.1	0.03	0.12	0.04	0.13	1161	281	0.38	1.12
6	24.4	4.3	23.8	5.1	3.4	1.1	0.05	0.22	0.09	0.23	1206	296	0.64	1.55
7	23.5	5.3	23.8	4.3	3.3	1.8	0.05	0.18	0.06	0.17	1169	287	0.63	1.44
8	23.9	4.6	23.1	4.4	3.6	1.6	0.06	0.20	0.05	0.18	1187	343	0.61	1.45
9	23.8	6.0	23.6	4.3	3.5	1.1	0.07	0.24	0.06	0.19	1105	282	0.44	1.31
10	22.4	5.7	22.6	4.2	3.2	1.4	0.03	0.16	0.03	0.16	1157	326	0.27	1.51
11	21.7	4.4	23.4	4.2	3.6	1.3	0.01	0.10	0.02	0.10	1206	320	0.13	0.75
12	20.9	4.0	23.1	5.0	3.5	1.5	0.01	0.05	0.01	0.05	1095	311	-	-
13	21.0	3.5	24.0	5.6	3.4	1.3	-	-	-	-	1112	345	-	-
14	20.5	3.6	23.2	4.8	3.8	1.3	0.01	0.06	0.01	0.06	1063	323	0.10	0.56
15	20.4	3.1	23.4	5.7	3.0	1.3	0.02	0.10	0.04	0.14	1065	329	0.30	0.98
16	21.5	4.5	25.1	6.3	2.6	1.5	0.02	0.11	0.02	0.11	1043	322	0.15	0.68
17	19.6	4.8	21.6	3.6	3.1	1.2	0.14	0.22	0.18	0.28	937	288	0.77	1.60
18	19.0	4.0	22.0	4.8	2.8	1.5	0.02	0.11	0.02	0.11	927	340	0.23	0.84
19	19.8	4.0	22.7	5.2	3.3	1.5	0.04	0.11	0.04	0.14	954	284	0.45	1.38
20	20.7	4.0	23.5	5.4	2.9	1.5	0.02	0.07	0.04	0.14	965	294	0.31	1.00
21	20.3	3.4	23.3	5.0	3.0	1.5	0.05	0.17	0.04	0.15	1017	336	0.29	0.92
22	21.1	4.0	23.8	5.6	3.1	1.1	0.01	0.04	0.01	0.02	1024	293	0.11	0.63
23	20.0	3.7	23.3	5.3	3.4	1.4	0.01	0.05	0.01	0.06	973	292	0.12	0.44
24	20.3	4.4	22.7	5.2	2.9	1.6	0.02	0.06	0.03	0.08	926	303	0.36	0.94
25	20.6	3.3	23.2	5.2	3.6	1.9	0.03	0.09	0.01	0.05	966	312	0.26	1.07
26	20.7	3.8	24.0	4.9	3.0	1.3	0.02	0.07	0.03	0.10	1029	300	0.17	0.67
27	20.6	3.2	23.3	5.7	2.8	1.3	0.03	0.17	0.01	0.08	1076	379	0.22	0.99
28	20.5	3.6	22.6	5.1	2.6	1.4	0.04	0.19	0.03	0.15	1031	329	0.17	0.97
29	20.2	2.9	22.7	5.7	3.1	1.4	0.01	0.08	0.01	0.08	983	366	0.08	0.48
30	23.3	2.1	27.6	7.8	3.7	1.8	0.09	0.32	-	-	1004	320	0.52	1.65
31	21.5	3.7	25.4	6.4	2.9	0.9	0.03	0.08	-	-	985	316	-	-

Each mean is based on 90 stereological measurements.

Table 6 Means (X) and standard deviation (SD) of important derived stereological parameters for cell types of loblolly pine (*Pinus taeda*)

Growth Ring	Tracheid Diameter (Radial) µm X	SD	(Tangential) µm X	SD	Diameter Square 10^{-3} x μm^2 X	SD	Tracheid Density Index X	SD
1	17	3	16	2	0.762	0.119	0.642	0.344
2	23	7	20	6	1.054	0.336	0.805	0.572
3	24	6	22	4	1.053	0.257	0.852	0.703
4	26	8	23	4	1.118	0.305	0.683	0.597
5	22	7	20	3	1.120	0.292	0.832	0.548
6	22	7	20	3	1.063	0.247	1.076	0.901
7	22	8	21	5	1.107	0.285	1.096	0.855
8	23	9	20	4	1.125	0.327	1.172	1.122
9	24	10	22	6	1.182	0.331	1.106	1.014
10	22	9	20	4	1.150	0.365	0.987	0.892
11	20	7	20	3	1.109	0.324	1.508	1.289
12	21	8	22	4	1.230	0.367	1.561	1.802
13	21	8	22	3	1.220	0.393	1.166	1.031
14	22	9	22	4	1.290	0.410	1.394	1.533
15	22	10	23	6	1.300	0.453	1.461	1.177
16	23	9	25	5	1.300	0.391	1.101	0.964
17	24	11	25	8	1.390	0.478	1.507	1.440
18	25	13	25	7	1.550	0.615	1.576	1.524
19	24	12	25	8	1.430	0.520	1.402	1.274
20	24	11	26	6	1.410	0.490	1.406	1.459
21	23	10	24	5	1.360	0.461	1.319	1.193
22	23	9	24	4	1.300	0.387	1.376	1.532
23	23	9	25	4	1.390	0.447	1.335	1.285
24	25	10	26	5	1.470	0.439	1.538	1.271
25	24	10	25	5	1.420	0.511	1.335	1.309
26	23	10	24	4	1.310	0.416	1.179	0.941
27	22	9	23	5	1.300	0.453	1.557	1.430
28	23	10	23	5	1.340	0.453	1.722	1.694
29	24	11	25	6	1.460	0.549	1.264	1.128
30	26	9	27	3	1.350	0.480	1.175	0.993
31	25	11	26	2	1.379	0.132	2.065	2.306

Each mean is based on 30 values.

Table 7 Averages (X) and standard deviations (SD) of physical and mechanical properties of plantation loblolly pine (<u>Pinus taeda</u>) in the green condition

Growth Ring	Modulus of Rupture (kPa)		Modulus of Elasticity (MPa)		Max Compressive Strength (kPa)		Specific Gravity* Compresion (g/cm^3)		Specific Gravity* Bending (g/cm^3)	
	X 7	SD	X 8	SD	X 9	SD	X 10	SD	X	SD
1	29186	5502	1997	522	14371	2937	0.414	0.033	0.429	0.047
2	29266	5060	2027	549	12954	2068	0.383	0.025	0.378	0.014
3	26215	2667	2023	514	11148	1262	0.399	0.027	0.396	0.025
4	30162	4495	2389	955	12229	1641	0.402	0.040	0.415	0.041
5	38867	6038	3608	1315	15320	2158	0.442	0.035	0.432	0.027
6	37831	5874	3545	1254	14491	2730	0.422	0.057	0.430	0.070
7	44576	5702	4424	1655	17582	3020	0.466	0.046	0.477	0.026
8	46097	9770	4647	2127	20096	3737	0.500	0.085	0.509	0.076
9	59698	8239	6233	1250	21972	3294	0.514	0.042	0.526	0.078
10	67705	7412	7753	2356	23615	1758	0.530	0.044	0.543	0.058
11	66088	6792	6840	1338	26049	1227	0.569	0.045	0.596	0.061
12	78486	11142	9878	2065	26852	3585	0.558	0.033	0.592	0.044
13	89869	16272	11073	2880	28359	1441	0.577	0.066	0.659	0.070
14	77369	14251	10140	2461	28176	1923	0.572	0.042	0.575	0.042
15	67095	-	7509	-	29152	2495	0.548	0.016	0.511	-
16	85156	9866	11211	1145	28547	1316	0.581	0.019	0.584	0.041
17	69571	8700	10072	723	30159	41	0.557	0.029	0.530	0.044
18	84160	5116	9788	465	27970	3847	0.550	0.021	0.565	0.033
19	73466	8536	9528	972	23176	3626	0.531	0.041	0.525	0.029
20	78610	8480	10299	1399	28828	1662	0.550	0.019	0.561	0.057
21	67657	4617	8627	1868	28969	2454	0.556	0.051	0.527	0.055
22	74017	2089	9235	1086	25512	1841	0.523	0.022	0.547	0.028
23	87291	1696	11303	2490	32840	3309	0.602	0.044	0.571	0.043
24	86836	11859	12434	2935	30993	3399	0.569	0.033	0.593	0.040
25	82540	12562	10308	2023	31772	1558	0.544	0.014	0.560	0.019
26	81699	5238	11164	1844	29389	2220	0.557	0.037	0.572	0.034
27	82096	2758	10263	1392	30238	1482	0.530	0.013	0.528	0.001
28	75657	11004	10834	1829	29200	3240	0.547	0.041	0.547	0.044
29	82815	-	11390	-	-	-	-	-	-	-
30	80492	-	12569	-	28117	-	0.585	-	0.600	-
31	-	-	-	-	-	-	-	-	-	-

* Specific gravity values are based upon oven-dry weight and ovendry volume.

Each value represents an average of six specimens at most.

Table 8 Multiple linear regression coefficients of physical and mechanical properties on anatomical characteristics of loblolly pine (Pinus taeda)

Equation[a]	b_0	b_1	b_2	b_3	Coefficient of determination (R^2)	Standard error of estimate (Sy.x)
Modulus of Rupture (kPa)						
	8.178** (0.498)	-0.913** (1.117)	1.330** (0.286)	103.596** (23.282)	0.8675**	0.148
Modulus of Elasticity (MPa)						
	3.813** (0.804)	-0.339** (0.189)	2.265** (0.462)	181.336** (37.592)	0.8551**	0.239

(a). ln $Y = b_0 + b_1X_1 + b_2X_2 + b_3X_3$
where:
Y : predicted property
X_1 : average number of resin canal per mm square
X_2 : tracheid density index
X_3 : radial diameter of tracheid

** Significant at the 1 percent probability level
* Significant at the 5 percent probability level
ns Not significant at the 5 percent probability level
The standard error is shown in parenthesis below each coefficient

Table 8 Continued

Equation$^{(a)}$	b_o	b_1	b_2	b_3	Coefficient of determination (R^2)	Standard error of estimate (Sy.x)
Maximum Crushing Strength parallel to grain (kPa)						
	8.016^{**} (0.496)	-0.641^{**} (0.120)	1.299^{**} (0.286)	60.154^{*} (23.420)	0.8158^{**}	0.147
Specific gravity (g/cm^3)						
	-1.441^{**} (0.221)	-0.286^{**} (0.053)	0.420^{**} (0.128)	26.882^{*} (10.461)	0.7757^{**}	0.065

(a). $\ln Y = b_o + b_1X_1 + b_2X_2 + b_3X_3$
where:
Y : predicted property
X_1 : average number of resin canal per mm square
X_2 : tracheid density index
X_3 : radial diameter of tracheid

** Significant at the 1 percent probability level
* Significant at the 5 percent probability level
ns Not significant at the 5 percent probability level
The standard error is shown in parenthesis below each coefficient

Table 9 Relationship between strength properties and specific gravity for loblolly pine (Pinus taeda)

Property (Y)	b_0	b_1	Coeff. of determination R^2	Std error of estimate Sy.x
Modulus of rupture, MOR (kPa)	-79964** (11484)	275814** (21607)	0.8578**	7884
Modulus of elasticity, MOE (MPa)	-15492** (2303)	44544** (4333)	0.7965**	1581
Max. compression parall. to grain (kPa)	-27403** (3380)	99603** (6451)	0.8982**	2161

$Y = b_0 + b_1 X_1$.

where:

X_1: specific gravity

** Significant at the 1 percent probability level

* Significant at the 5 percent probability level

ns Not significant at the 5 percent probability level

The standard error for the regression coefficient is shown in parenthesis below each coefficient.

Table 10 Multiple linear regression coefficients of specific mechanical properties on anatomical characteristics of loblolly pine (<u>Pinus taeda</u>)

Equation$^{(a)}$ b_o	b_1	b_2	b_3	Coefficient of determination (R^2)	Standard Error of Estimate (Sy.x)
Specific Modulus of Rupture (kPa)					
9.843^{**}	-0.297^{**}	1006.580^{**}	0.745^{*}	0.9375^{**}	0.0692
(0.259)	(0.059)	(176.249)	(0.340)		
Specific Modulus of Elasticity (MPa)					
5.759^{**}	-0.409^{**}	1777.870^{**}	1.740^{*}	0.9232^{**}	0.1387
(0.519)	(0.119)	(352.830)	(0.681)		

(a). $\ln Y = b_o + b_1X_1 + b_2X_2 + b_3X_3$
where:

Y : predicted property

X_1 : average number of resin canal per mm square

X_2 : diameter square of tracheid

X_3 : tangential and radial diameter ratio of tracheid

** Significant at the 1 percent probability level
* Siginficant at the 5 percent probability level
ns Not significant at the 5 percent probability level
The standard error is shown in parenthesis below each coefficient

Table 10 Continued

Equation[(a)] b_0	b_1	b_2	b_3	Coefficient of determination (R^2)	Standard Error of Estimate (Sy.x)
Specific Maximum Crushing Strength parallel to grain (kPa)					
9.338** (0.323)	-0.217** (0.074)	524.673* (219.785)	0.807ns (0.424)	0.8355**	0.0864

(a). $\ln\ Y = b_0 + b_1X_1 + b_2X_2 + b_3X_3$
where:
Y : predicted property
X_1 : average number of resin canal per mm square
X_2 : diameter square of tracheid
X_3 : tangential and radial diameter ratio of tracheid
** Significant at the 1 percent probability level
* Siginficant at the 5 percent probability level
ns Not significant at the 5 percent probability level
The standard error is shown in parenthesis below each coefficient

Table 11 Multiple linear regression coefficients of strength properties on specific gravity and anatomical characteristics of loblolly pine (*Pinus taeda*)

Equation$^{(a)}$ b_o	b_1	b_2	b_3	b_4	Coefficient of determination (R^2)	Standard Error of Estimate (Sy.x)
Modulus of Rupture (kPa)						
-106516** (15874)	130395** (24083)	-9810* (4207)	4.7E07** (1.1E07)	50123* (21935)	0.9650**	4148
Modulus of Elasticity (MPa)						
-26626** (3570)	22129* (5417)	133^{ns} (946)	7.4E06** (2.3E06)	13402* (4934)	0.9370**	933

(a). $Y = b_0 + b_1X_1 + b_2X_2 + b_3X_3 + b_4X_4$
where:

Y : predicted property

X_1 : specific gravity

X_2 : average number of resin canal per mm square

X_3 : diameter square of tracheid

X_4 : tangential and radial diameter ratio of tracheid

** Significant at the 1 percent probability level
* Siginficant at the 5 percent probability level
ns Not significant at the 5 percent probability level
The standard error is shown in parenthesis below each coefficient

Table 11 Continued

Equation[(a)] b_o	b_1	b_2	b_3	b_4	Coefficient of determination (R^2)	Standard Error of Estimate (Sy.x)
Maximum Crushing Strength parallel to grain (kPa)						
-31429^{**} (7429)	63681^{**} (15506)	-1757^{ns} (1954)	$9.1E06^{ns}$ (5.2E06)	12126^{ns} (11291)	0.9242^{**}	1977

(a). $Y = b_o + b_1X_1 + b_2X_2 + b_3X_3 + b_4X_4$
where:

Y : predicted property

X_1 : specific gravity

X_2 : average number of resin canal per mm square

X_3 : diameter square of tracheid

X_4 : tangential and radial diameter ratio of tracheid

** Significant at the 1 percent probability level
* Siginficant at the 5 percent probability level

ns Not significant at the 5 percent probability level

The standard error is shown in parenthesis below each coefficient

Table 12 Means (X) and standard deviations (SD) of point counts (volume fractions) for cell types of cottonwood (Populus deltoides)

Growth Ring	Vessels					Fibers					Ray Parenchyma					Total Cellwall Fraction (%)
	Lumen (%)		Wall (%)		Total	Lumen (%)		Wall (%)		Total	Lumen (%)		Wall (%)		Total	
	X	SD	X	SD		X	SD	X	SD		X	SD	X	SD		
1	22.6	5.5	4.5	2.8	26.9	39.6	11.2	28.0	11.0	67.6	3.5	2.4	2.0	2.9	5.5	34.3
2	26.8	10.2	5.4	4.1	32.2	36.3	9.3	27.4	8.2	63.7	2.8	2.1	1.3	2.2	4.1	34.1
3	24.5	9.2	3.5	2.5	28.0	39.3	10.0	29.3	8.8	68.6	2.4	2.7	1.0	2.2	3.4	33.8
4	25.5	10.3	4.2	3.8	29.7	37.1	10.5	27.0	6.6	64.1	3.7	3.2	2.5	2.8	6.2	33.7
5	24.9	7.7	4.7	3.1	29.6	39.5	9.6	27.2	8.9	66.7	2.8	3.0	0.9	1.3	3.7	32.8
6	28.5	8.3	4.5	2.9	33.0	34.8	11.8	26.7	8.4	61.5	4.2	2.9	1.3	2.2	5.5	32.5
7	25.4	9.1	3.2	2.4	28.6	37.5	11.3	28.0	11.2	65.5	4.1	3.7	1.8	2.9	5.9	33.0
8	26.6	7.2	3.5	2.6	30.1	39.3	8.1	25.0	8.7	64.3	3.4	3.4	2.2	2.8	5.6	30.7
9	26.8	8.6	4.0	3.2	30.8	36.3	9.1	25.0	7.2	61.3	4.5	3.5	3.0	4.2	7.5	32.0
10	28.2	8.8	4.2	3.5	32.4	41.6	13.1	20.9	7.1	62.5	3.1	2.8	2.0	2.7	5.1	27.1
11	25.0	6.6	4.0	2.9	29.0	42.0	10.2	23.6	9.1	65.6	3.3	2.6	2.1	3.1	5.4	29.7
12	26.8	8.8	3.5	2.9	30.3	43.4	12.2	20.4	10.5	63.8	4.0	3.4	1.9	2.2	5.9	25.8
13	30.0	7.8	2.8	2.2	32.8	42.1	11.1	21.1	9.5	63.2	2.0	2.2	2.0	2.4	4.0	25.9
14	29.5	6.3	5.6	4.7	35.1	38.8	11.0	21.6	9.1	60.4	2.4	2.2	2.1	2.2	4.5	29.3
15	26.3	7.1	3.2	2.4	29.5	39.8	7.8	24.7	6.6	64.5	4.5	4.2	1.5	2.2	6.0	29.4
16	24.3	7.8	3.8	3.5	28.1	38.5	9.4	26.8	10.3	65.3	4.0	3.0	2.6	3.1	6.6	33.2
17	32.5	7.4	4.9	3.4	37.4	34.0	7.6	23.2	10.8	57.2	2.7	2.3	2.7	3.3	5.4	30.8
18	28.6	7.3	4.5	2.6	33.1	35.2	8.5	26.5	10.3	61.7	2.6	2.8	2.6	2.1	5.2	33.6
19	34.6	9.1	3.7	2.8	38.3	35.4	9.0	22.0	8.7	57.4	2.6	2.1	1.7	2.4	4.3	27.4
20	31.3	9.2	3.3	2.3	34.6	35.7	6.7	26.5	7.8	62.2	2.3	3.0	0.9	1.6	3.2	30.7
21	31.7	10.5	3.3	3.0	35.0	39.3	11.3	21.6	9.5	60.9	2.4	2.8	1.7	2.2	4.1	26.6
22	31.6	9.4	2.2	1.8	33.8	40.0	6.1	22.0	6.6	62.0	2.4	2.4	1.8	2.7	4.2	26.0
23	39.8	11.6	2.9	2.5	42.7	31.8	6.5	23.0	9.2	54.8	1.4	1.6	1.1	1.9	2.5	27.0
24	35.4	10.4	3.7	3.1	39.1	37.6	13.7	19.9	9.4	57.5	2.6	2.4	0.8	1.5	3.4	24.4
25	30.7	7.3	4.2	3.0	34.9	39.8	10.9	19.8	9.8	59.6	2.9	3.3	2.6	3.6	5.5	26.6
26	29.2	8.5	3.8	1.9	33.0	47.7	10.6	15.0	8.4	62.7	2.0	1.3	2.3	3.0	4.3	21.1

Each mean value is based on 90 stereological observations

Table 13 Variation of certain anatomical, physical and mechanical properties of cottonwood (Populus deltoides) from pith to bark

Property (Y)	b_0	b_1	Coeff. of determination R^2	Stand. error of est. Sy.x
Vessel lumen area	0.236** (0.011)	0.383E-03** (0.708E-3)	0.5497**	0.0271
Number of vessel per mm square	128.376** (6.423)	-3.351** (0.415)	0.7300**	15.9075
Number of fibers per mm square	4116.290** (117.537)	-79.170** (7.610)	0.8184**	291.057
Transverse mean free path of ray parenchyma	0.069** (0.181E-02)	0.126E-02** (0.117E-03)	0.8292**	0.0044
Tangential diameter of vessel (mm)	0.0389** (0.132E-02)	0.128E-02** (0.859E-04)	0.9033**	0.0032
Radial diameter of fiber (mm)	0.0116** (0.352E-03)	0.145E-03** (0.228E-04)	0.6301**	0.0008
Tangential diameter of fiber (mm)	0.0085** (0.239E-03)	8.902E-05** (0.155E-04)	0.5786**	0.593E-03
Vessel shape factor	0.788** (0.0148)	-0.0033** (0.961E-03)	0.3338**	0.0367
Fiber density index	0.735** (0.0408)	-0.0079** (0.264E-02)	0.2719**	0.1010

$Y = b_0 + b_1 X_1$
where:

X_1: ring number from pith to bark

** Significant at the 1 percent probability level

* Significant at the 5 percent probability level

The standard error for the regression coefficient is in parenthesis below each coefficient

Table 13 Continued

Property (Y)	b_0	b_1	Coeff. of determination R^2	Stand. error of est. Sy.x
Modulus of rupture (MOR-kPa)	22490^{**} (1347)	541^{**} (87)	0.6159^{**}	3336
Modulus of elasticity (MOE-MPa)	1316^{**} (189)	171^{**} (12)	0.8904^{**}	468
Max. copression parallel to grain (kPa)	8551^{**} (430)	328^{**} (27)	0.8528^{**}	1065
Specific gravity (g/cm)	0.339^{**} (0.682E-02)	$0.141E-02^{**}$ (0.441E-03)	0.3001^{**}	0.0169
Radial diameter of vessel (mm)	0.0486^{**} (0.176E-02)	$0.205E-02^{**}$ (0.114E-03)	0.9307^{**}	0.0043

$Y = b_0 + b_1X_1$

where:

X_1: ring number from pith to bark

** Significant at the 1 percent probability level

* Significant at the 5 percent probability level

The standard error for the regression coefficient is in parenthesis below each coefficient

Table14 Means (X) and standard deviations (SD) of lineal and feature counts of vessels, fibers and ray parenchyma for Cottonwood (Populus deltoides)

Growth Ring	Number of Vessels per mm (Tang) mm^{-1} X	SD	Number of Vessels per mm (Radial) mm^{-1} X	SD	Number of Fibers per mm (Tang) mm^{-1} X	SD	Number of Fibers per mm (Radial) mm^{-1} X	SD	Number of Ray Parenchyma per mm (Tangential) mm^{-1} X	SD	Number of Vessels per mm square mm^{-2} X	SD	Number of Fibers per mm square mm^{-2} X	SD
1	7.2	1.2	6.1	1.4	51	6	37	7	15	2	158	70	4466	1624
2	7.2	3.2	5.7	1.5	47	7	37	7	13	2	154	64	4800	1824
3	6.5	1.5	5.1	1.2	49	5	38	7	13	2	127	62	4243	1315
4	6.4	1.7	4.8	1.7	46	6	33	6	13	3	107	41	3827	1007
5	6.8	1.5	5.1	1.6	44	4	32	6	13	2	127	73	3611	956
6	6.5	1.2	5.0	1.5	41	5	29	5	13	2	115	47	3370	1142
7	5.4	0.9	4.1	1.0	43	6	29	6	12	2	85	31	3098	752
8	6.1	1.4	4.5	1.2	42	6	30	6	12	2	88	31	3200	825
9	5.6	1.1	4.2	1.1	40	8	27	6	12	1	77	26	3076	730
10	6.2	1.8	4.5	1.3	43	6	29	7	12	1	86	37	3237	730
11	5.6	1.1	3.9	1.1	42	6	30	5	11	1	74	22	3061	716
12	5.5	1.1	4.0	0.9	41	5	29	7	11	1	70	22	2914	659
13	5.4	1.1	4.1	1.1	38	4	28	5	11	1	66	21	2711	580
14	5.6	0.8	4.2	0.8	38	6	30	6	10	1	72	20	2905	648
15	5.0	1.1	3.8	1.0	40	6	29	6	10	1	62	18	2971	719
16	4.7	0.7	3.6	0.8	41	6	28	6	11	1	58	16	2776	553
17	5.5	0.8	4.3	0.9	36	5	23	5	11	1	70	20	2748	729
18	5.3	0.8	4.4	2.7	38	6	27	5	10	1	66	21	2809	662
19	6.3	1.1	4.6	1.0	36	5	25	6	10	1	73	20	2679	621
20	5.8	1.0	4.0	1.0	35	4	25	5	11	1	64	16	2462	571
21	5.5	1.1	3.7	0.8	38	6	26	5	11	2	57	19	2449	576
22	5.5	1.0	3.6	0.7	36	5	25	4	10	1	57	17	2305	525
23	6.2	1.3	4.5	1.0	31	5	21	4	9	2	65	22	2282	682
24	5.7	0.9	4.2	0.8	33	4	23	5	10	1	60	13	2443	622
25	5.3	0.9	3.9	0.8	36	6	25	6	10	1	58	14	2467	550
26	5.5	1.0	3.6	0.8	37	4	27	5	10	1	54	19	2311	308

Each mean is based on 90 stereological observations

Table 15 Duncan's Multiple Range Tests for structural elements within growth increment of cottonwood (<u>Populus</u> <u>deltoides</u>)

Sructural Element	Percent relative position within growth increments (from earlywood to latewood) 10	30	50	70	90
	(MEAN)*	(MEAN)*	(MEAN)*	(MEAN)*	(MEAN)*
Vessel lumen area fraction	0.321	0.297	0.297	0.285	0.238
Number of vessel per mm square	83	68	72	81	112
Number of fiber per mm square	2706	2884	2930	2119	3597
Fiber density index	0.647	0.602	0.600	0.622	0.704
Tangential diameter of vessel (mm)	0.058	0.063	0.063	0.058	0.046
Radial diameter of vessel (mm)	0.083	0.086	0.084	0.078	0.060
Tangential diameter of fiber (mm)	0.011	0.010	0.009	0.009	0.008
Radial diameter of fiber (mm)	0.014	0.014	0.014	0.013	0.012
Vessel shape factor	0.708	0.730	0.752	0.754	0.779
Double cellwall thickness(mm)	0.0012	0.0008	0.0009	0.0006	0.0002

* Means joined by the same line are not significantly different

Each mean is based on 130 values

Table 16 Results of one-way ANOVA for structural elements within growth increments of cottonwood (Populus deltoides)

Factor	F-statistic	Significance of test
Vessel lumen area fraction	9.67	**
Number of vessels per mm square	7.61	**
Number of fibers per mm square	6.29	**
Fiber density index	1.93	NS
Tangential diameter of vessel	8.88	**
Radial diameter of vessel	10.35	**
Tangential diameter of fiber	7.87	**
Radial diameter of fiber	7.62	**
Vessel shape factor	2.95	*
Double cellwall thickness	5.06	**

** Significant at 1 percent level
* Significant at 5 percent level
NS Not significant

Table 17 Means (X) and standard deviations (SD) of important stereological parameters for vessels in cottonwood (*Populus deltoides*)

Growth Ring	Mean Diameter (Rad)		Mean Diameter (Tang)		Diameter Square		Mean Cord Intercept (Rad)		Mean Cord Intercept (Tang)		Mean Free Path (Rad)		Mean Free Path (Tang)		Vessel Shape Factor	
	µm		µm		10^{-3} x µm^2		µm		µm		µm		µm			
	X	SD	X	SD	X	SD	X	SD	X	SD	X	SD	X	SD	X	SD
1	51	16	42	10	2.613	1.4	47	17	38	11	126	32	105	21	0.852	0.124
2	52	16	41	13	3.239	2.1	57	21	45	16	129	50	100	35	0.789	0.124
3	56	14	43	13	3.156	1.2	55	11	43	11	154	63	117	36	0.796	0.183
4	63	12	47	12	3.794	1.3	62	13	46	14	172	90	120	48	0.756	0.190
5	64	33	47	16	3.799	2.0	60	20	44	13	155	75	109	37	0.756	0.177
6	61	16	46	12	4.107	1.6	69	23	51	17	153	81	107	31	0.779	0.226
7	69	20	53	17	4.829	2.2	68	18	52	15	184	69	136	34	0.782	0.185
8	74	18	53	13	4.929	2.2	71	24	50	14	168	56	120	37	0.753	0.227
9	77	17	56	13	5.538	2.1	75	19	55	15	184	87	128	34	0.747	0.169
10	78	20	57	17	5.552	2.4	75	19	54	14	169	75	120	42	0.739	0.150
11	79	14	54	13	5.338	1.8	76	14	51	12	204	91	131	35	0.689	0.138
12	84	19	60	17	6.114	2.5	77	21	55	14	190	84	130	36	0.725	0.146
13	88	20	64	14	6.822	2.1	81	16	59	10	178	64	129	42	0.754	0.156
14	81	17	61	12	6.691	2.2	84	18	63	13	158	35	119	26	0.766	0.141
15	85	17	64	16	6.508	2.1	79	19	59	13	200	91	147	47	0.776	0.183
16	85	18	65	17	6.642	2.7	78	20	59	17	209	61	155	38	0.770	0.170
17	87	21	63	13	7.344	2.2	90	23	64	11	153	44	110	26	0.750	0.175
18	85	21	66	28	6.979	2.6	85	26	62	13	181	73	129	30	0.805	0.352
19	89	18	65	15	7.114	2.2	84	16	61	11	142	46	101	27	0.733	0.112
20	93	19	65	15	7.319	2.6	86	20	60	14	172	60	117	30	0.712	0.150
21	102	23	70	19	8.444	2.9	92	21	64	16	187	86	125	38	0.702	0.161
22	101	21	67	14	8.125	3.0	92	26	61	18	188	55	123	30	0.665	0.097
23	101	19	74	18	9.048	3.1	95	24	69	16	132	49	96	28	0.752	0.187
24	98	20	72	15	8.561	2.6	92	23	67	16	155	62	111	36	0.749	0.149
25	95	21	70	16	8.818	2.9	91	23	66	20	174	47	126	32	0.747	0.170
26	106	32	70	18	8.457	3.0	92	19	60	13	199	67	127	37	0.661	0.138

Each mean is based on 30 values

Table 18 Averages (X) and standard deviations (SD) of important stereological parameters for fibers in cottonwood (<u>Populus deltoides</u>)

Growth Ring	Mean Diameter (Radial)		(Tangential)		Diameter Square		Double Wall Wall Thickness		Fiber Density Index	
	μm		μm		$10^{-3} x$ μm^2		μm			
	X	SD	X	SD	X	SD	X	SD	X	SD
1	13.0	5.1	9.3	3.3	0.216	0.074	1.9	2.7	0.830	0.496
2	11.4	4.3	9.2	3.9	0.190	0.065	1.0	2.7	0.785	0.267
3	12.4	2.8	9.8	3.4	0.220	0.057	1.2	1.4	0.821	0.371
4	12.8	2.5	9.3	2.5	0.223	0.054	1.6	1.5	0.816	0.395
5	13.1	3.5	9.7	3.2	0.253	0.079	1.0	1.9	0.766	0.387
6	13.4	3.6	10.3	5.6	0.257	0.087	1.6	2.5	0.895	0.512
7	14.8	3.4	9.9	2.6	0.283	0.069	2.2	1.5	0.923	0.723
8	14.0	3.0	9.8	2.6	0.276	0.092	1.5	2.1	0.679	0.300
9	13.4	2.4	9.2	2.2	0.263	0.058	1.0	1.7	0.750	0.327
10	13.8	2.5	9.5	2.6	0.259	0.078	0.9	2.6	0.623	0.484
11	14.4	3.0	10.6	3.1	0.289	0.082	1.0	2.0	0.658	0.486
12	14.7	2.7	10.4	3.0	0.292	0.072	0.8	1.8	0.578	0.448
13	14.5	2.9	10.7	3.0	0.308	0.074	0.3	2.0	0.570	0.359
14	13.8	3.0	10.7	2.8	0.275	0.062	0.8	2.4	0.647	0.376
15	14.1	2.5	10.2	3.3	0.289	0.068	0.9	1.9	0.661	0.275
16	15.0	1.9	10.3	2.2	0.309	0.060	1.7	1.8	0.812	0.581
17	14.0	3.8	10.1	3.5	0.282	0.078	1.2	2.7	0.764	0.456
18	14.2	2.2	10.1	2.4	0.292	0.064	1.4	1.8	0.845	0.457
19	13.8	2.5	9.7	2.4	0.282	0.054	0.8	1.8	0.687	0.359
20	15.2	3.2	10.5	2.5	0.334	0.069	1.4	2.7	0.790	0.349
21	16.4	3.3	11.3	2.7	0.329	0.076	2.0	2.0	0.665	0.492
22	16.1	2.6	11.5	2.0	0.353	0.063	1.1	2.2	0.564	0.190
23	14.4	3.2	10.0	2.6	0.321	0.024	0.8	2.0	0.756	0.351
24	14.2	3.1	10.2	3.1	0.308	0.065	0.2	2.4	0.648	0.409
25	15.2	2.9	10.6	2.2	0.321	0.077	0.8	2.8	0.589	0.445
26	16.3	1.8	12.0	2.1	0.349	0.058	0.1	1.9	0.355	0.250

Each mean is based on 30 values

Table 19 Averages (X) and standard deviations (SD) of physical and mechanical properties of plantation cottonwood (*Populus deltoides*) in the green condition.

Growth Ring	Modulus of Rupture (kPa)		Modulus of Elasticity (MPa)		Max Compressive Strength (kPa)		Specific Gravity* Compression (g/cm^3)		Specific Gravity* Bending (g/cm^3)	
	X	SD	X	SD	X	SD	X	SD	X	SD
1	17982	-	958	-	9136	648	0.366	0.028	0.317	0.012
2	32186	5198	2594	288	11445	1027	0.370	0.018	0.361	0.009
3	27876	6612	2300	691	11020	1379	0.367	0.031	0.356	0.027
4	24663	6474	2045	552	10027	1482	0.340	0.025	0.337	0.028
5	25503	4951	2234	467	10336	1434	0.346	0.024	0.340	0.026
6	22661	5020	2037	515	9204	1868	0.312	0.049	0.312	0.048
7	23450	2699	2423	481	9601	952	0.328	0.022	0.332	0.024
8	27706	6879	2673	1045	10556	1875	0.347	0.028	0.348	0.030
9	25595	4199	2680	563	10842	1737	0.332	0.021	0.328	0.012
10	26924	5323	2826	622	11670	1855	0.359	0.017	0.348	0.019
11	27880	4958	3127	895	11388	1744	0.342	0.016	0.336	0.015
12	28610	5591	3384	1280	11463	1585	0.359	0.019	0.343	0.022
13	25695	4302	2923	605	12004	1778	0.340	0.020	0.328	0.013
14	26391	4268	2864	780	12031	2158	0.343	0.030	0.336	0.021
15	29393	6136	3556	1042	12521	2406	0.350	0.023	0.341	0.027
16	30862	6067	4136	1295	12100	2137	0.357	0.023	0.343	0.029
17	33782	7067	4544	1180	14569	2751	0.356	0.028	0.357	0.026
18	37354	6322	4813	1372	16072	2454	0.377	0.024	0.368	0.023
19	37343	5660	5468	1427	16734	2055	0.382	0.018	0.370	0.019
20	37043	6529	5500	1319	16234	2123	0.379	0.024	0.373	0.018
21	33013	6516	4884	1457	16434	2231	0.391	0.021	0.375	0.010
22	29508	7239	4323	1089	15454	2399	0.376	0.016	0.372	0.021
23	35735	8191	5451	1393	16299	2848	0.378	0.024	0.363	0.030
24	37860	7279	5659	1468	17168	1848	0.388	0.020	0.375	0.015
25	34178	6378	5186	1189	16258	1295	0.375	0.023	0.363	0.021
26	35570	7047	5774	1583	16065	1578	0.352	0.023	0.336	0.034

* Specific gravity values are based upon oven-dry weight and ovendry volume.

Each value represents an average of six specimens at most

Table 20 Multiple linear regression coefficients of physical and mechanical properties on anatomical characteristics of cottonwood (<u>Populus deltoides</u>)

Equation(a)				Coefficient of determination (R^2)	Standard Error of Estimate (Sy.x)
b_o	b_1	b_2	b_3		
Modulus of Rupture (kPa)					
12.00^{**}	$-27.82E-05^{**}$	-63.35^{ns}	-0.020^{ns}	0.3956^{*}	0.1528
(1.053)	(98.65E-06)	(51.28)	(0.33)		
Modulus of Elasticity (MPa)					
11.25^{**}	$-66.84E-05^{**}$	-77.56^{ns}	-0.069^{ns}	0.6861^{**}	0.2582
(1.78)	(16.66E-05)	(86.64)	(0.56)		

(a). ln $Y = b_o + b_1X_1 + b_2X_2 + b_3X_3$
where:

Y : predicted property

X_1 : average number of fibers per unit area (mm^2)

X_2 : radial diameter of fiber (mm)

X_3 : fiber density index

** Significant at the 1 percent probability level

* Siginficant at the 5 percent probability level

ns Not significant at the 5 percent probability level

The standard error is shown in parenthesis below each coefficient

Table 20 Continued

Equation[(a)]	b_0	b_1	b_2	b_3	Coefficient of determination (R^2)	Standard Error of Estimate (Sy.x)
Maximum Crushing Strength parallel to grain (kPa)						
	11.0^{**}	$-30.10E-05^{**}$	-42.24^{ns}	-0.098^{ns}	0.5570^{**}	0.1488
	(1.025)	(96.07E-06)	(49.94)	(0.32)		

(a). ln $Y = b_0 + b_1X_1 + b_2X_2 + b_3X_3$
where:

Y : predicted property

X_1 : average number of fibers per unit area (mm^2)

X_2 : radial diameter of fiber (mm)

X_3 : fiber density index

** Significant at the 1 percent probability level

* Siginficant at the 5 percent probability level

ns Not significant at the 5 percent probability level

The standard error is shown in parenthesis below each coefficient

Table 21 Relationship between strength properties and specific gravity for cottonwood (Populus deltoides)

Property (Y)	b_o	b_1	Coeff. of determination R^2	Std error of estimate Sy.x
Modulus of rupture, MOR (kPa)	-52864** (11669)	236920** (33669)	0.6770**	3060
Modulus of elasticity, MOE (MPa)	-15622** (3703)	55176** (10599)	0.5303**	971
Max. compression parall. to grain (kPa)	-25232** (6375)	106517** (17741)	0.6003**	1755

$Y = b_o + b_1X_1$

where:

X_1: specific gravity

** Significant at the 1 percent probability level

* Significant at the 5 percent probability level

ns Not significant at the 5 percent probability level

The standard error for the regression coefficient is shown in parenthesis below each coefficient.

Table 22 Multiple linear regression coefficients of specific strength properties on anatomical characteristics of cottonwood (Populus deltoides)

Equation$^{(a)}$ b_o	b_1	b_2	b_3	Coefficient of determination (R^2)	Standard Error of Estimate (Sy.x)
Specific Modulus of Rupture (kPa)					
12.339^{**} (0.643)	-69.621^{*} (25.895)	-1.216^{*} (0.580)	15.120^{**} (2.843)	0.6546^{**}	0.0901
Specific Modulus of Elasticity (MPa)					
10.542^{**} (1.160)	-81.310^{ns} (46.691)	-3.115^{**} (1.046)	36.358^{**} (5.126)	0.8514^{**}	0.1625
Specific Maximum Crushing Strength Parallel to Grain (kPa)					
10.770^{**} (0.531)	-39.008^{ns} (21.364)	-0.979^{*} (0.479)	17.110^{**} (2.345)	0.8568^{**}	0.0689

(a). $\ln\ Y = b_o + b_1X_1 + b_2X_2 + b_3X_3$

where:

Y : predicted property

X_1 : radial diameter of fibers (mm)

X_2 : vessel shape factor

X_3 : tangential diameter of vessel (mm)

** Significant at the 1 percent probability level

* Siginficant at the 5 percent probability level

ns Not significant at the 5 percent probability level

The standard error is shown in parenthesis below each coefficient

Table 23 Multiple linear regression coefficients of strength properties on specific gravity and anatomical characteristics of cottonwood (<u>Populus deltoides</u>)

Equation $^{(a)}$					Coefficient of determination (R^2)	Standard Error of Estimate (Sy.x)
b_o	b_1	b_2	b_3	b_4		
Modulus of Rupture (kPa)						
-10865^{ns}	151893^{**}	$-1.3E06^{ns}$	-17102^{ns}	336431^{**}	0.8185^{**}	2451
(24360)	(34523)	(7.6E05)	(16621)	(94419)		
Modulus of Elasticity (MPa)						
-5415^{ns}	24971^{**}	-99125^{ns}	-4935^{ns}	94912^{**}	0.8790^{**}	526
(5234)	(7418)	(164608)	(3571)	(20288)		
Maximum Crushing Strength Parallel to Grain (kPa)						
-8716^{ns}	63719^{**}	$-2.7E05^{ns}$	-9948^{ns}	174739^{**}	0.9180^{**}	849
(7412)	(10314)	(2.5E05)	(5504)	(31508)		

(a). $Y = b_o + b_1X_1 + b_2X_2 + b_3X_3 + b_4X_4$
where:
Y : predicted property
X_1 : specific gravity
X_2 : radial diameter of fiber (mm)
X_3 : vessel shape factor
X_4 : tangential diameter of vessel (mm)

** Significant at the 1 percent probability level
* Siginficant at the 5 percent probability level
ns Not significant at the 5 percent probability level
The standard error is shown in parenthesis below each coefficient

FIGURES

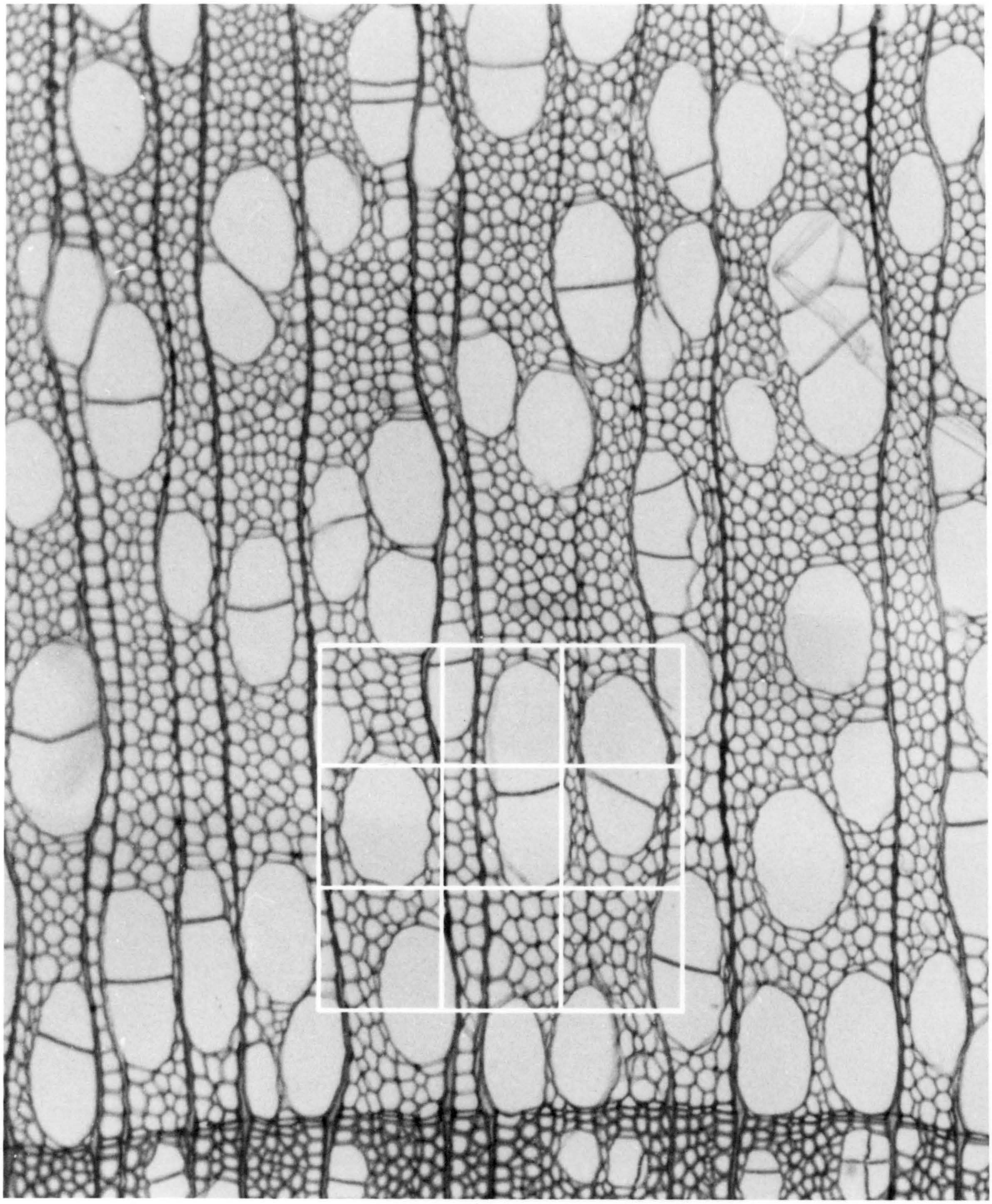


Fig. 1. Sampling grid superimposed on transverse section of plantation grown cottonwood for stereological measurements. Grid was positioned in the earlywood zone of the growth increment.

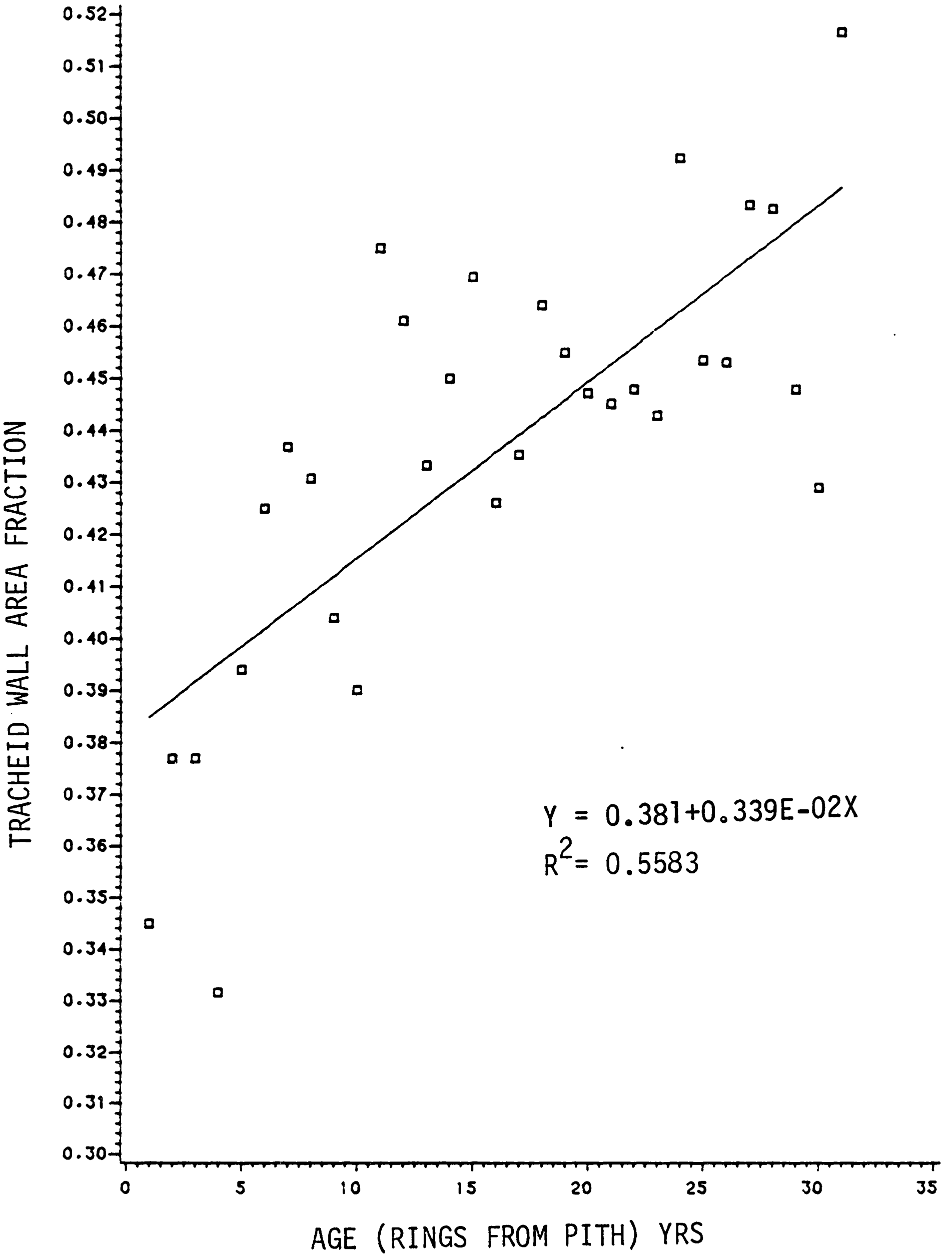


Fig 2 The relationship between tracheid wall area fraction (Y) and age (X) of plantation grown loblolly pine (*Pinus taeda*)

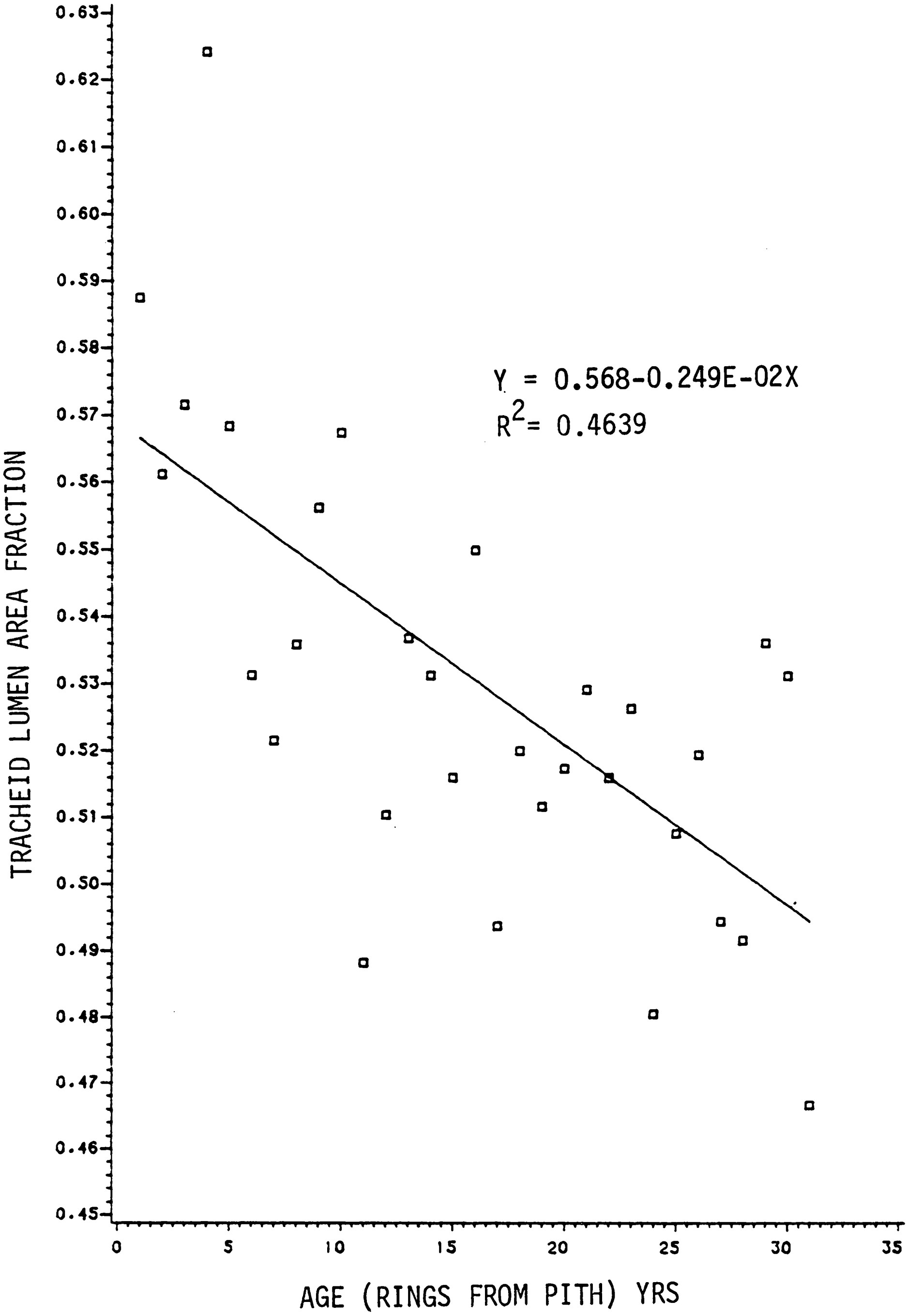


Fig 3 The relationship between tracheid lumen area fraction (Y) and age (X) of plantation grown loblolly pine (*Pinus taeda*)

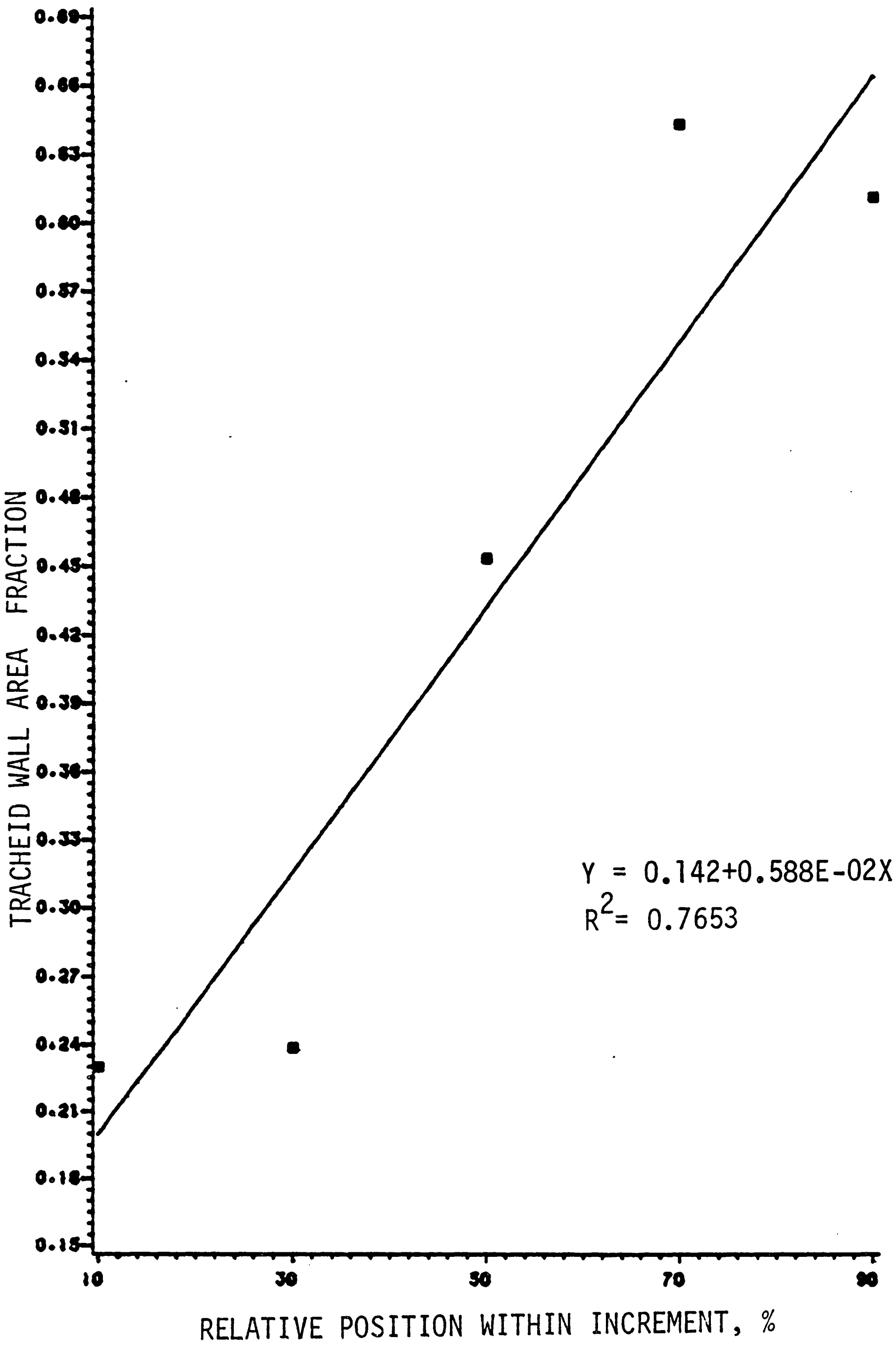


Fig 4 The relationship between tracheid wall area fraction (Y) and their relative position within increment (X) of plantation grown loblolly pine (<u>Pinus taeda</u>)

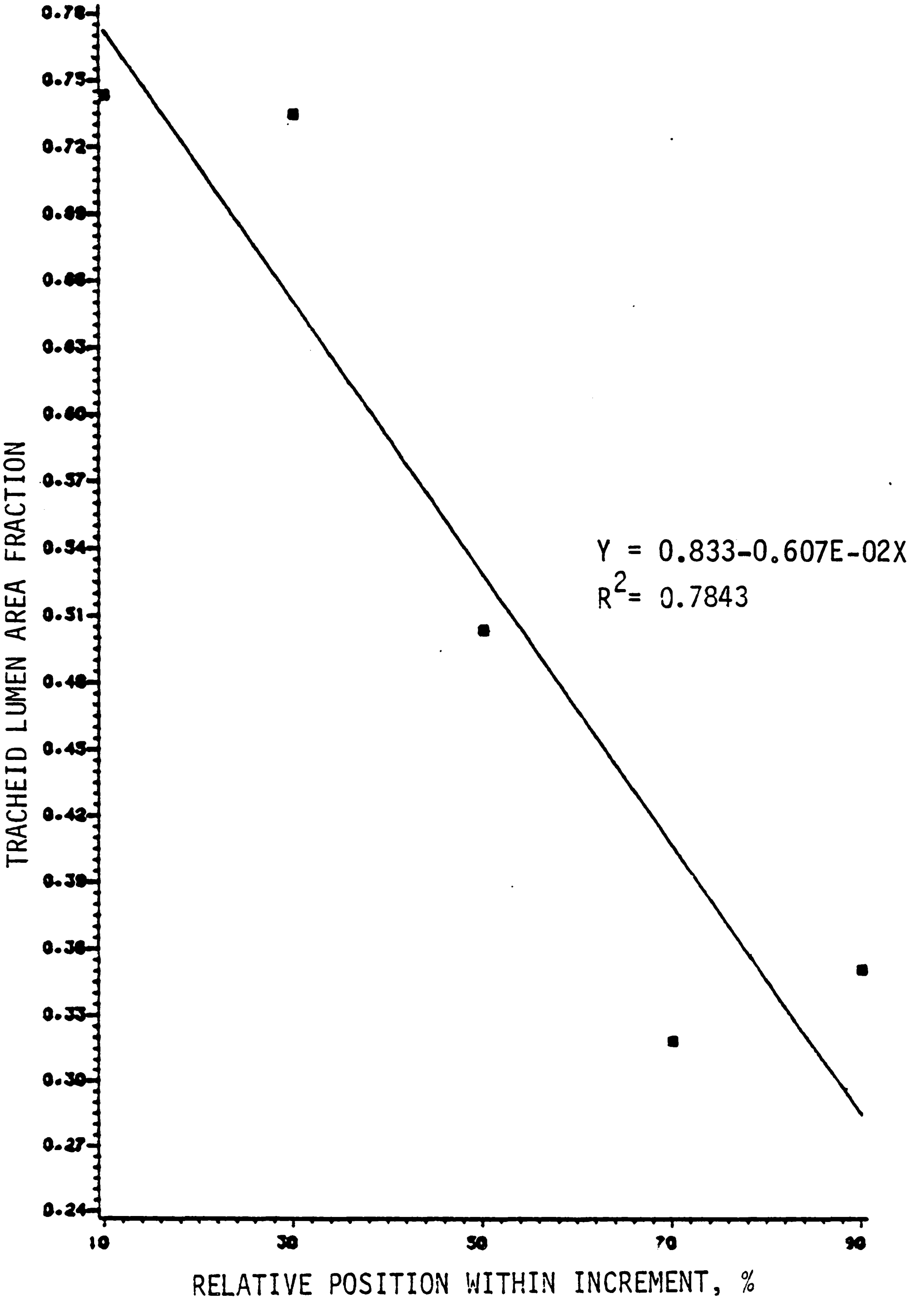


Fig 5 The relationship between tracheid lumen area fraction and their relative position within increment of plantation grown loblolly pine (Pinus taeda)

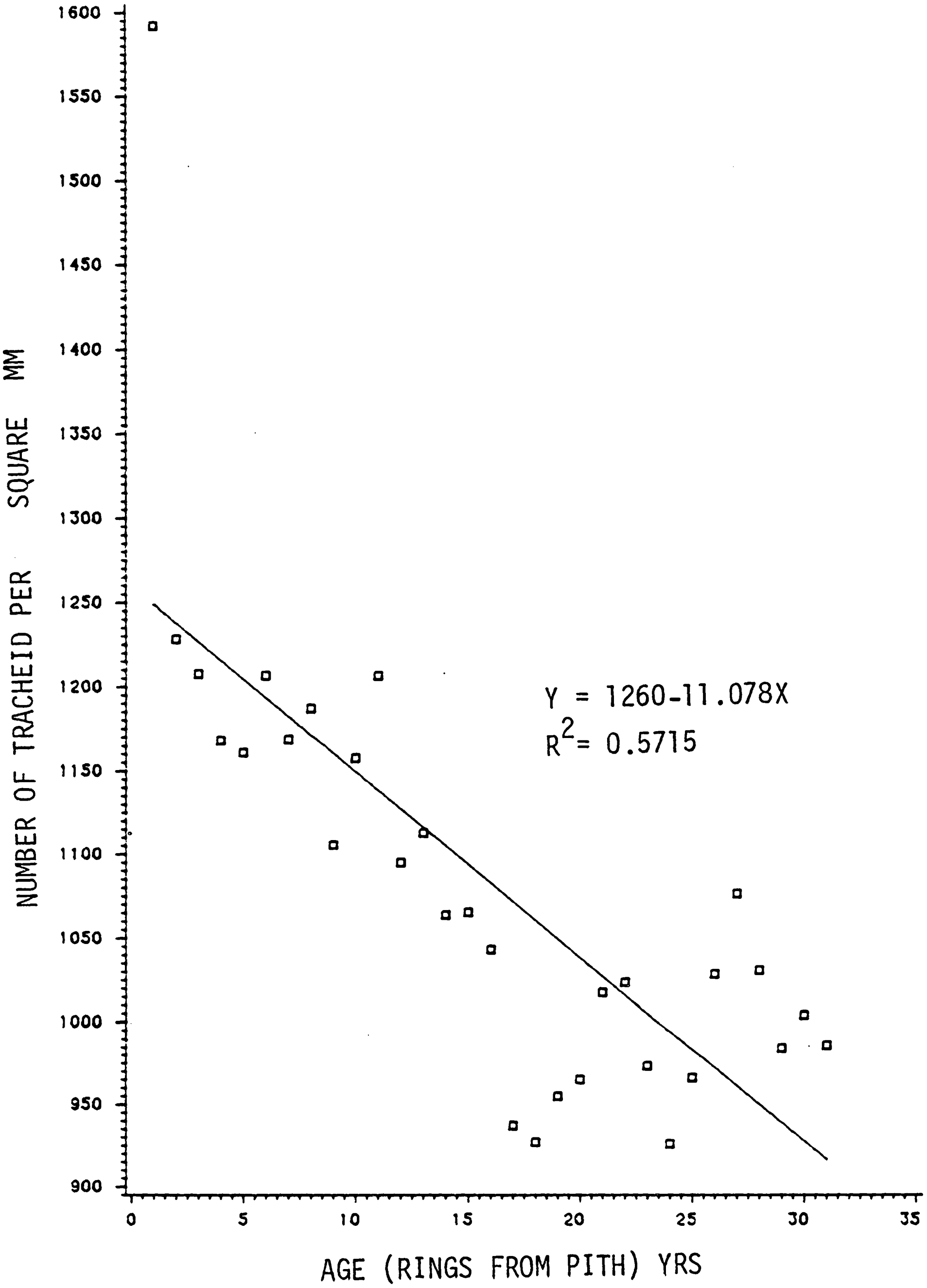


Fig 6 The relationship between number of tracheid per millimeter square (Y) and age (X) of plantation grown loblolly pine (<u>Pinus taeda</u>)

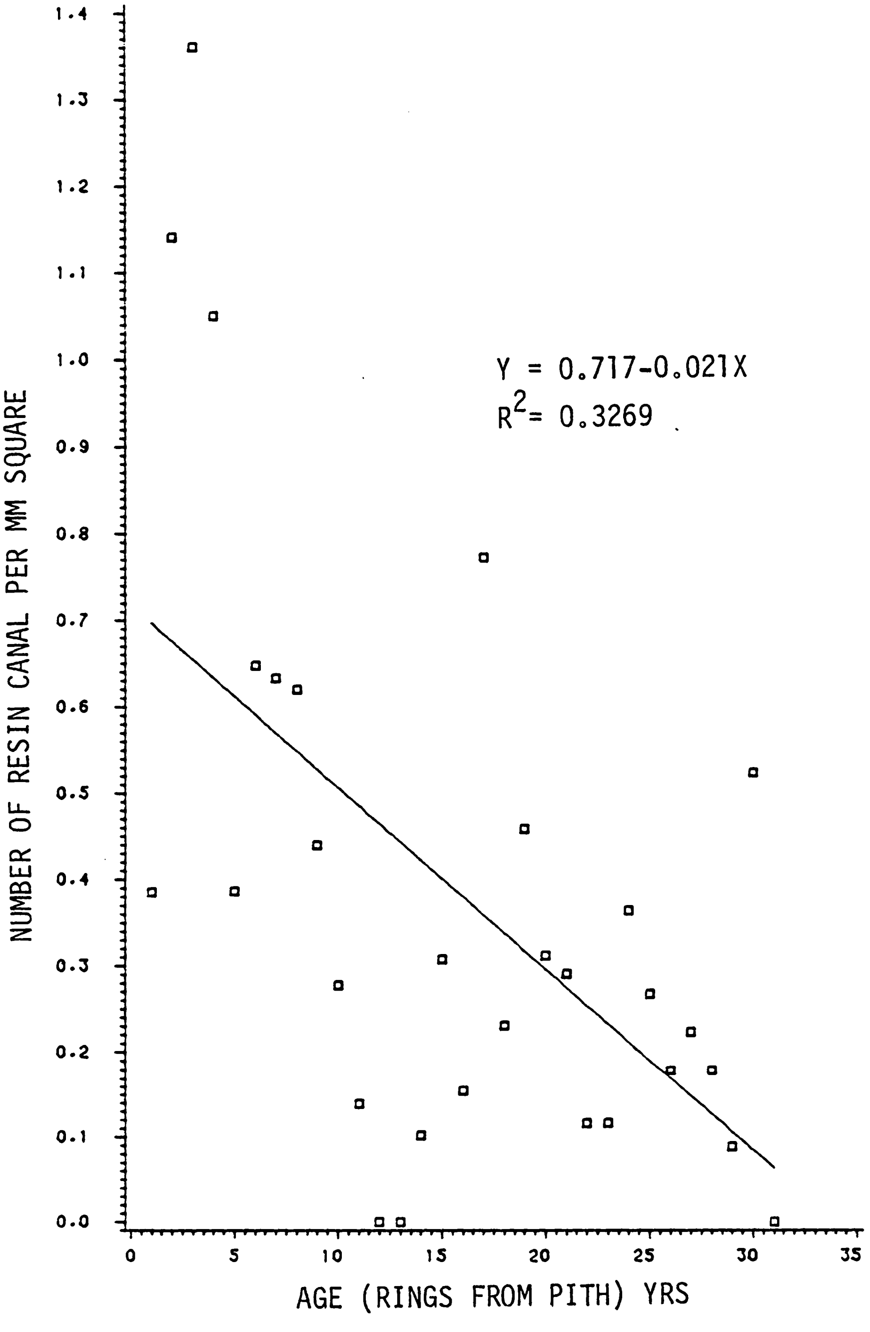


Fig 7 The relationship between number of resin canal per millimeter square (Y) and age (X) of plantation grown loblolly pine (*Pinus taeda*)

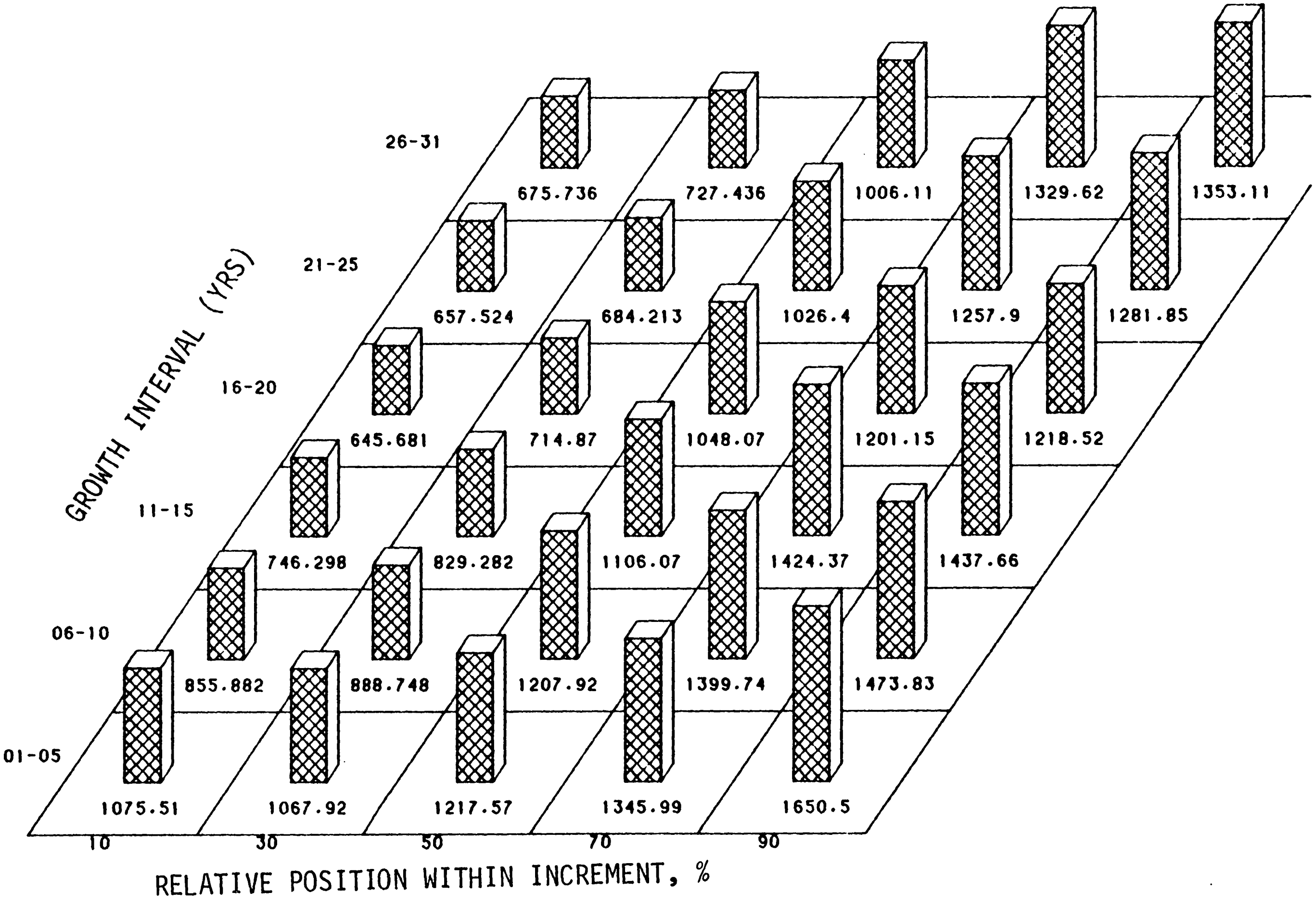


Fig 8 Within-stem variation of the number of tracheid per millimeter square at 5-year growth intervals in plantation grown loblolly pine (*Pinus taeda*)

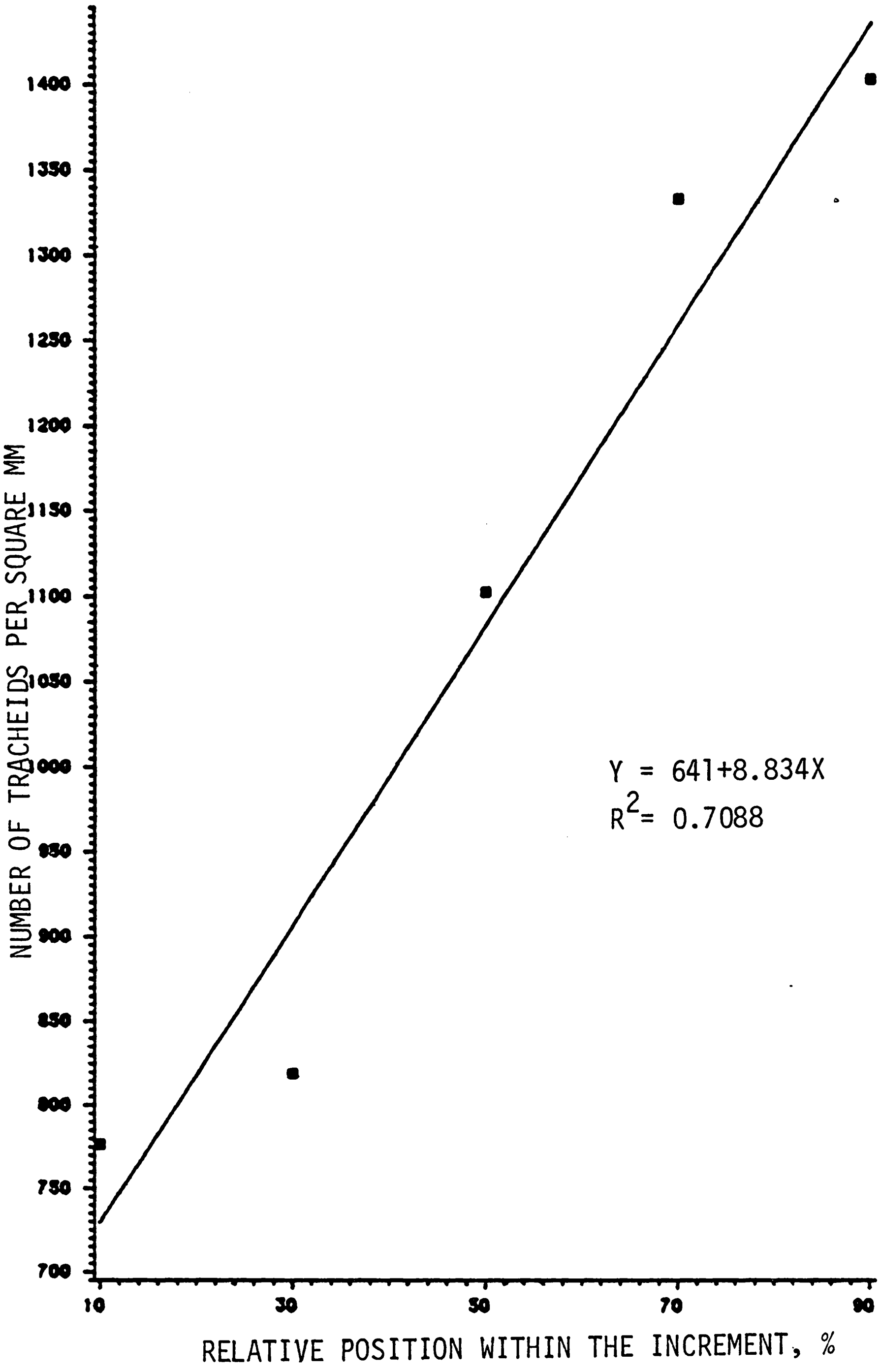


Fig 9 The relationship between number of tracheids per mm^2 (Y) and their relative position within increment (X) of plantation grown loblolly pine (Pinus taeda)

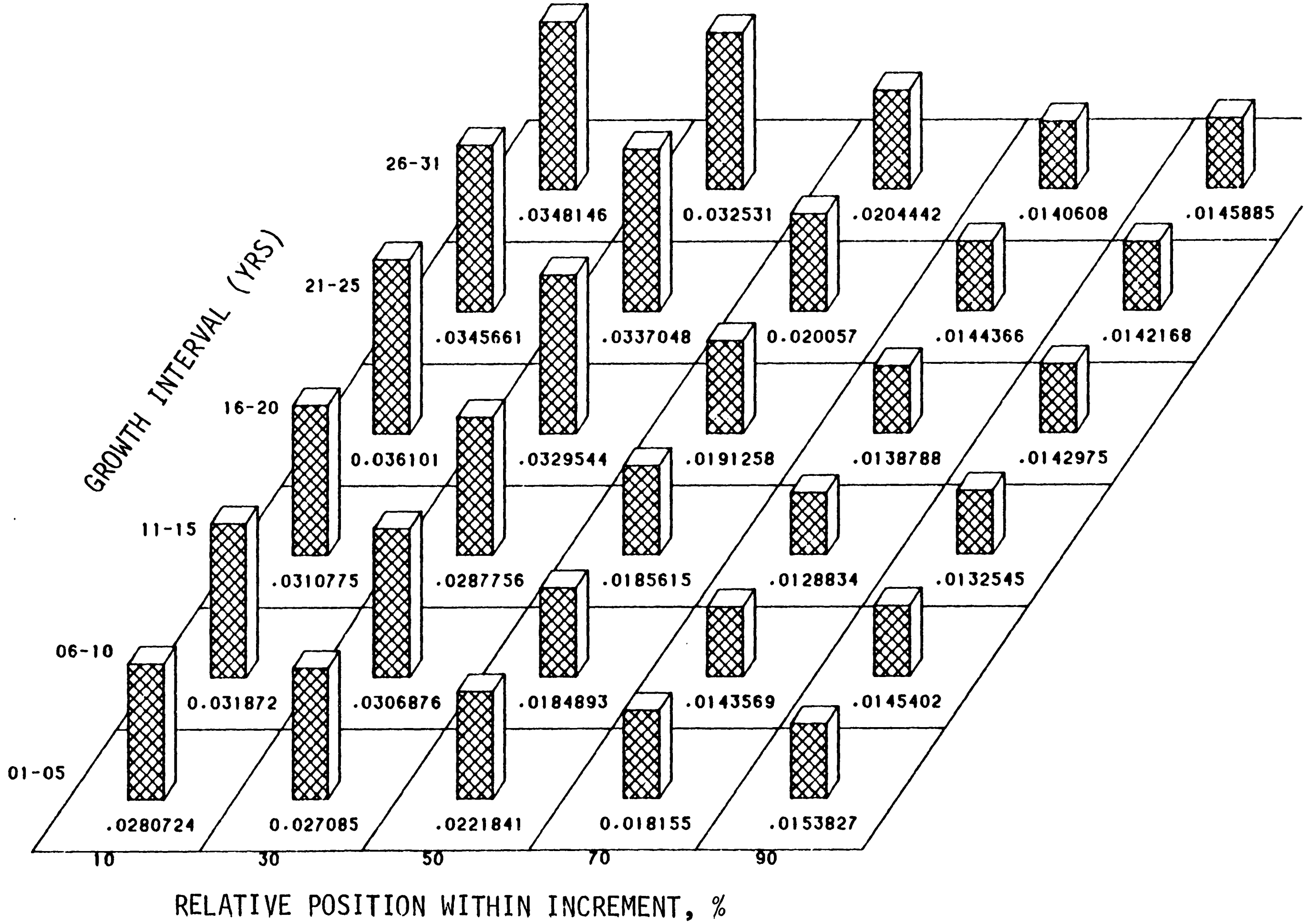


Fig 10 Within-stem variation of radial diameter of tracheid (mm) at 5-year growth intervals in plantation grown loblolly pine (*Pinus taeda*)

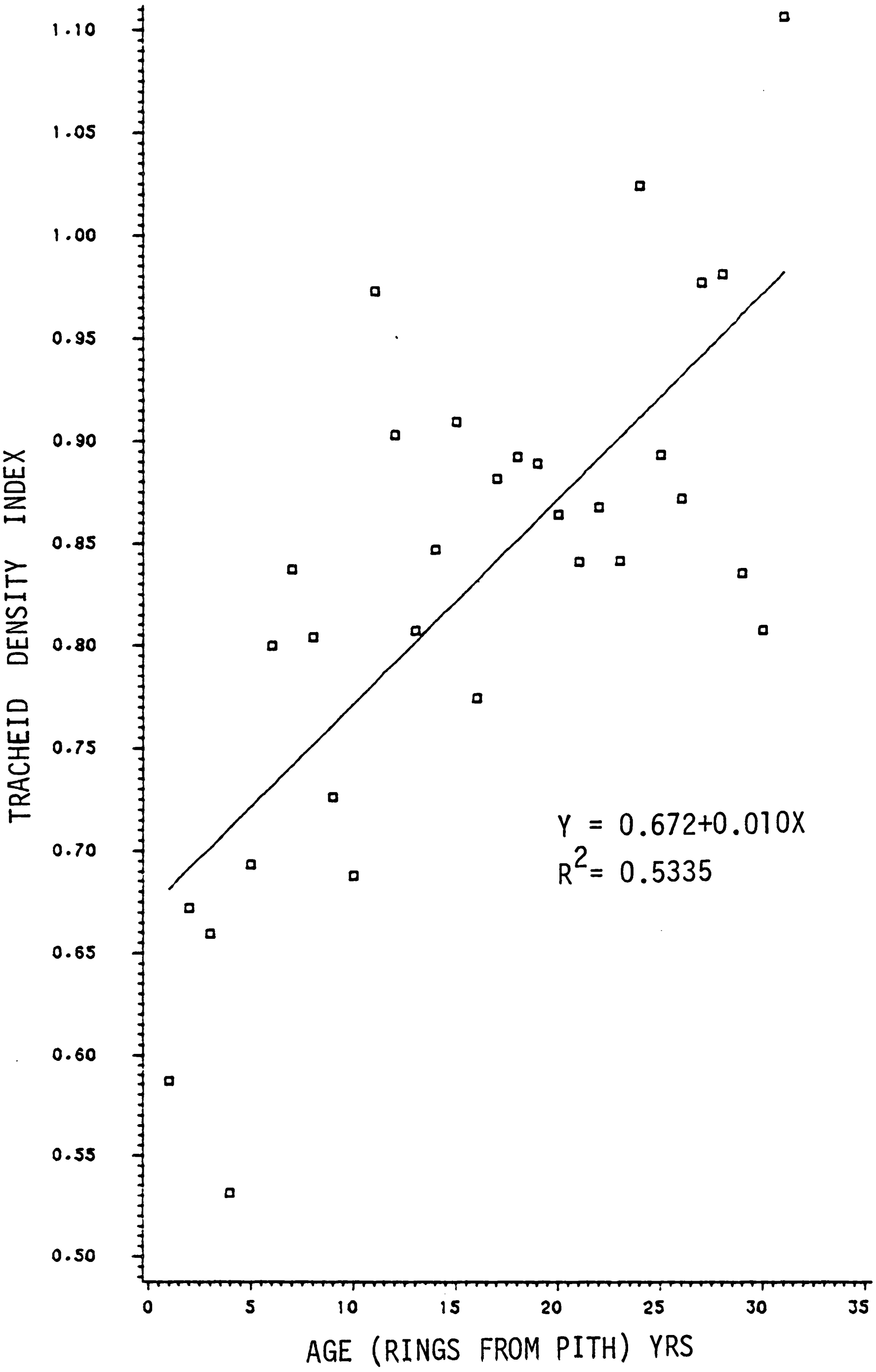


Fig 11 The relationship between tracheid density index (Y) and age (X) of plantation grown loblolly pine (<u>Pinus taeda</u>)

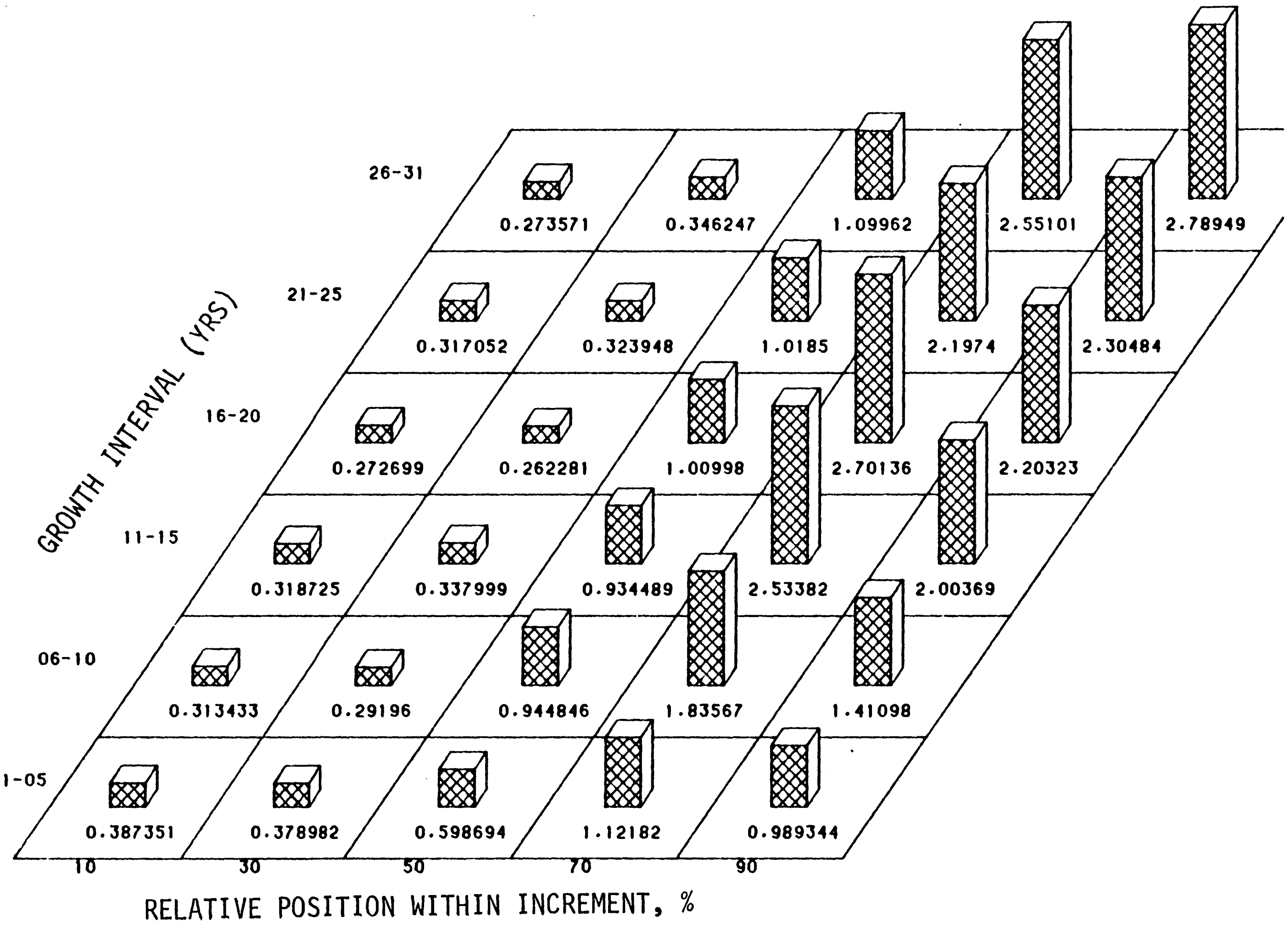


Fig 12 Within-stem variation of tracheid density index at 5-year growth intervals in plantation grown loblolly pine (Pinus taeda)

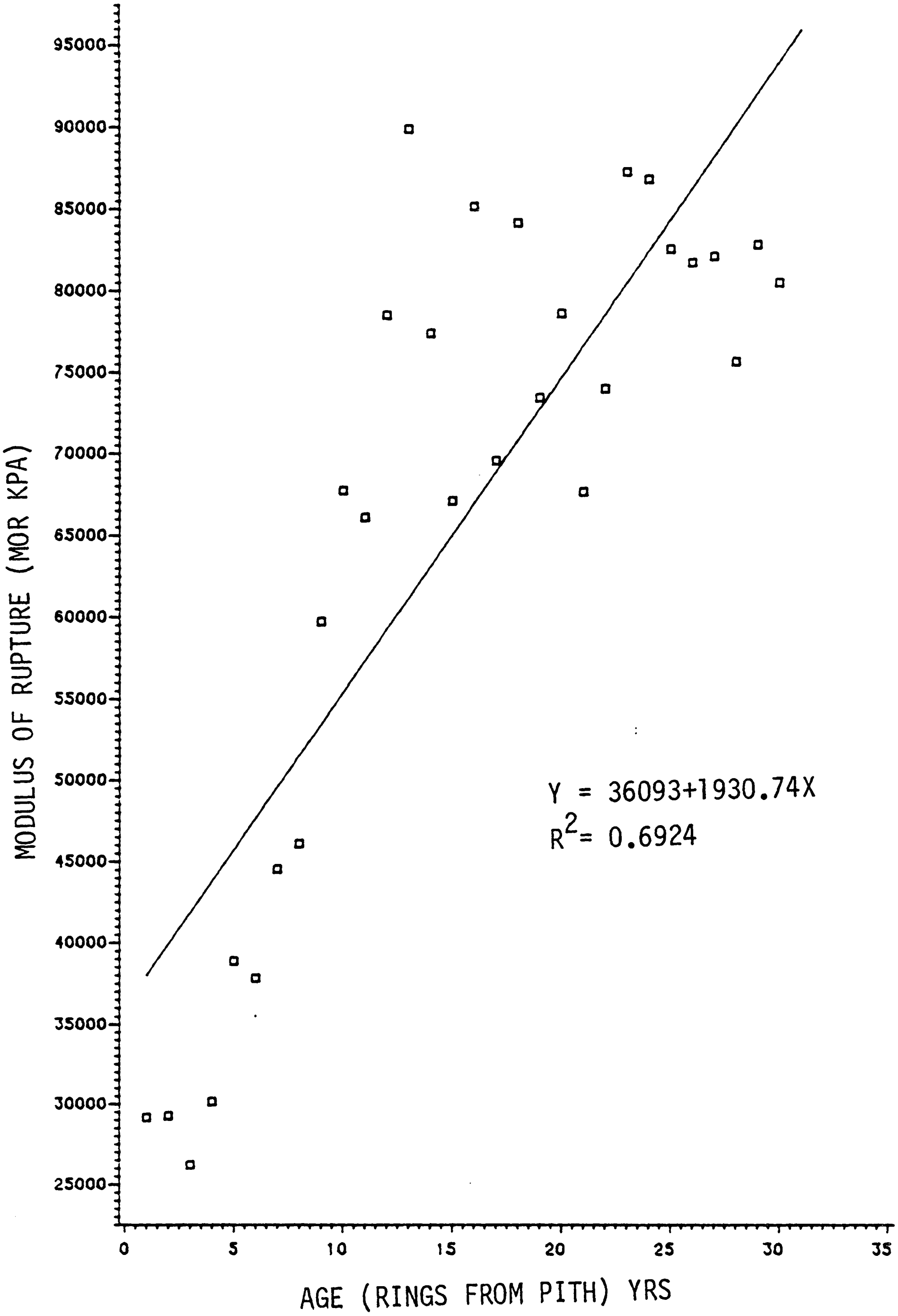


Fig 13 The relationship between modulus of rupture (Y) and age (X) of plantation grown loblolly pine (*Pinus taeda*)

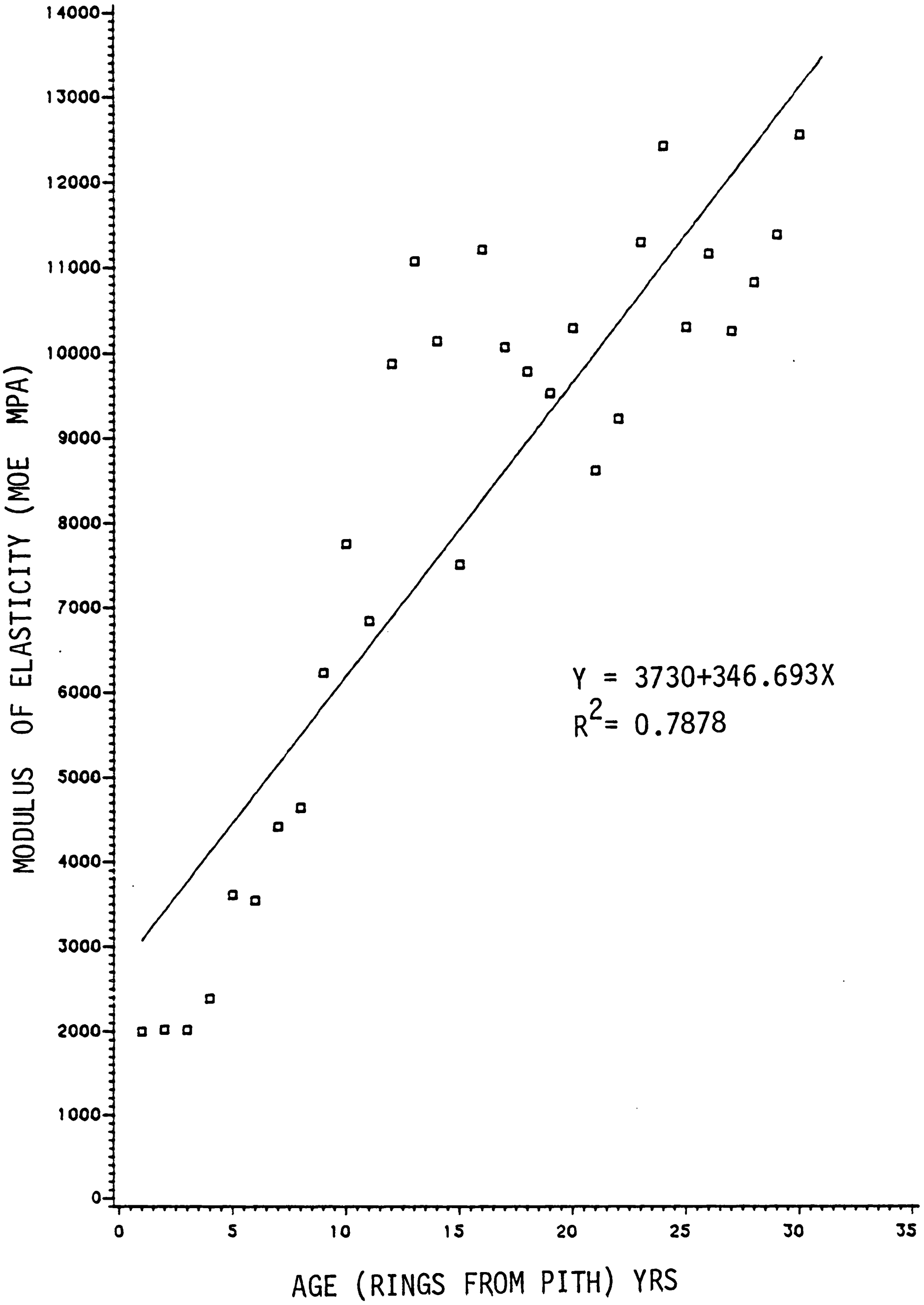


Fig 14 The relationship between modulus of elasticity (Y) and age (X) of plantation grown loblolly pine (Pinus taeda)

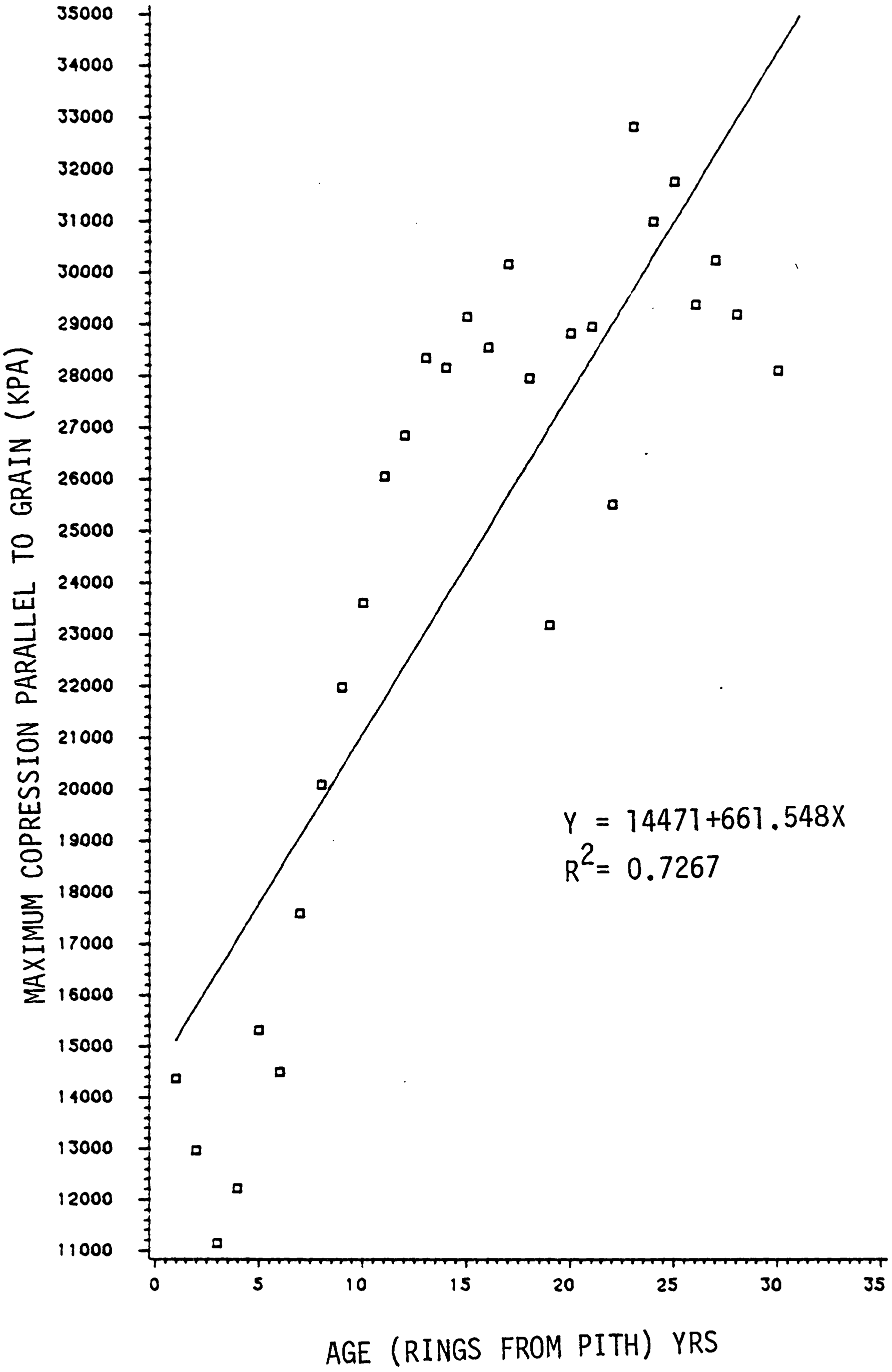


Fig 15 The relationship between maximum compression parallel to grain (Y) and age (X) of plantation grown loblolly pine (<u>Pinus taeda</u>)

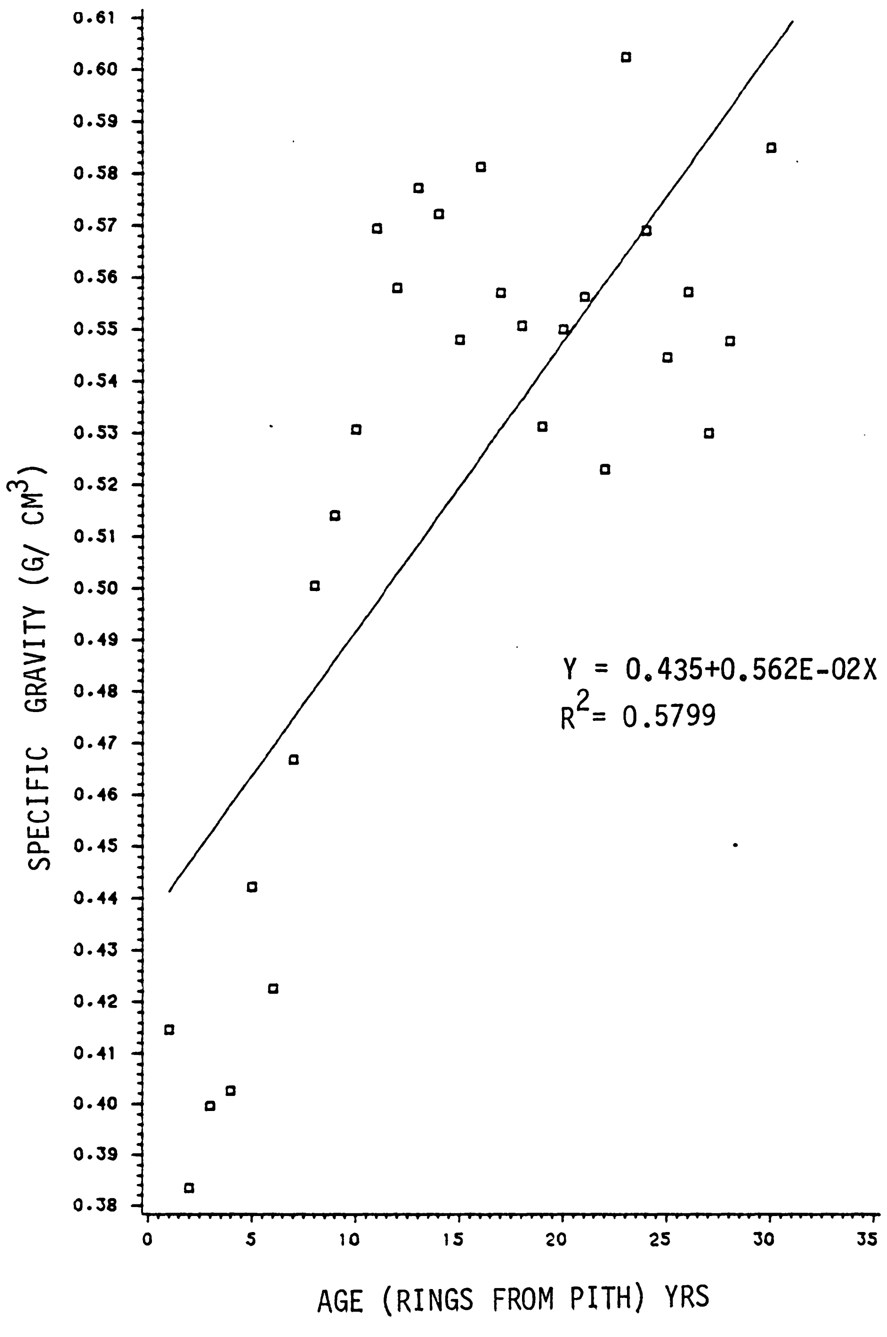


Fig 16 The relationship between specific gravity (Y) and age (X) of plantation grown loblolly pine (*Pinus taeda*)

Fig. 17 Relationship between modulus of rupture and number of resin canals per unit area, tracheid density index and radial diameter of tracheid in loblolly pine (*Pinus taeda*) as given in Table 8.

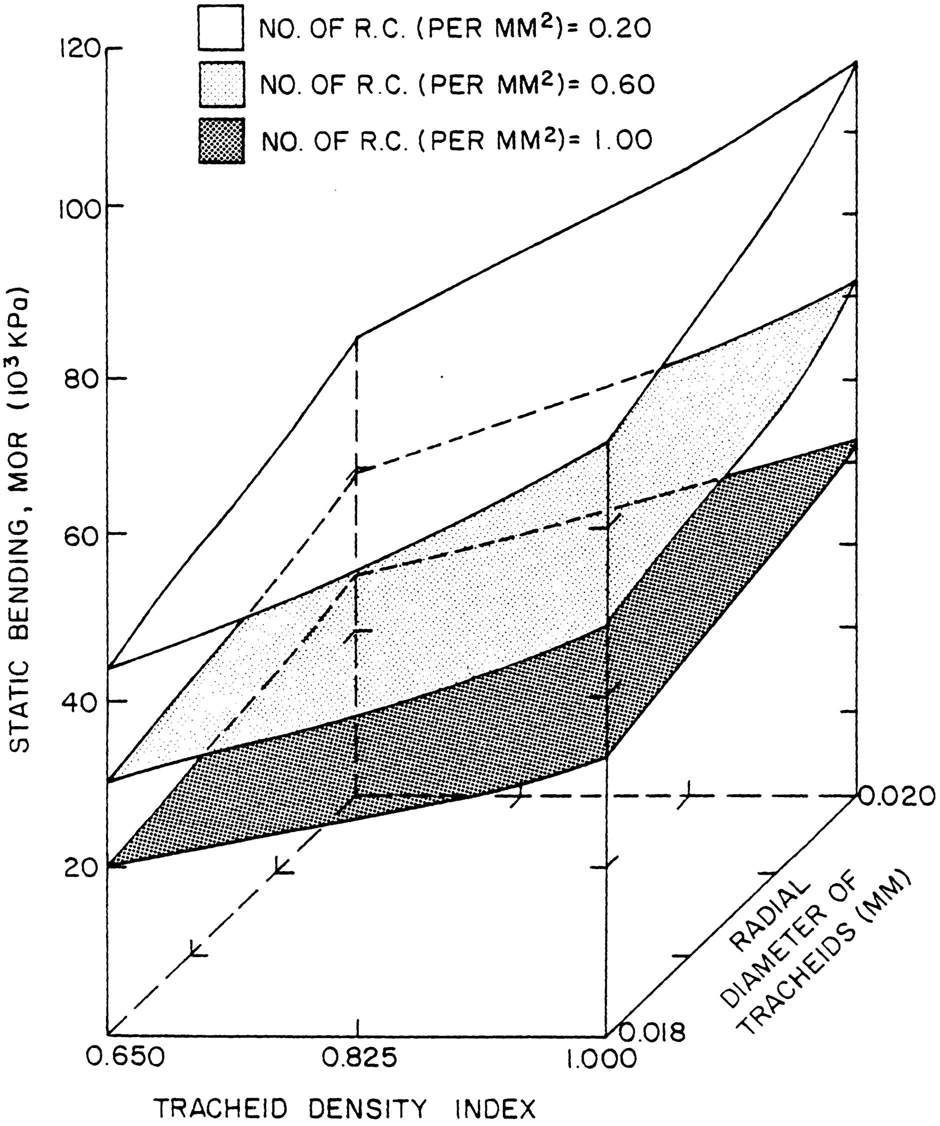

NO. OF R.C. (PER MM²)= 0.20
NO. OF R.C. (PER MM²)= 0.60
NO. OF R.C. (PER MM²)= 1.00
STATIC BENDING, MOR (10³ KPa)
120
100
80
60
40
20
0.650
0.825
1.000
TRACHEID DENSITY INDEX
0.018
0.020
RADIAL DIAMETER OF TRACHEIDS (MM)

Fig. 18 Relationship between modulus of elasticity and number of resin canals per unit area, tracheid density index and radial diameter of tracheid in loblolly pine (*Pinus taeda*) as given in Table 8.

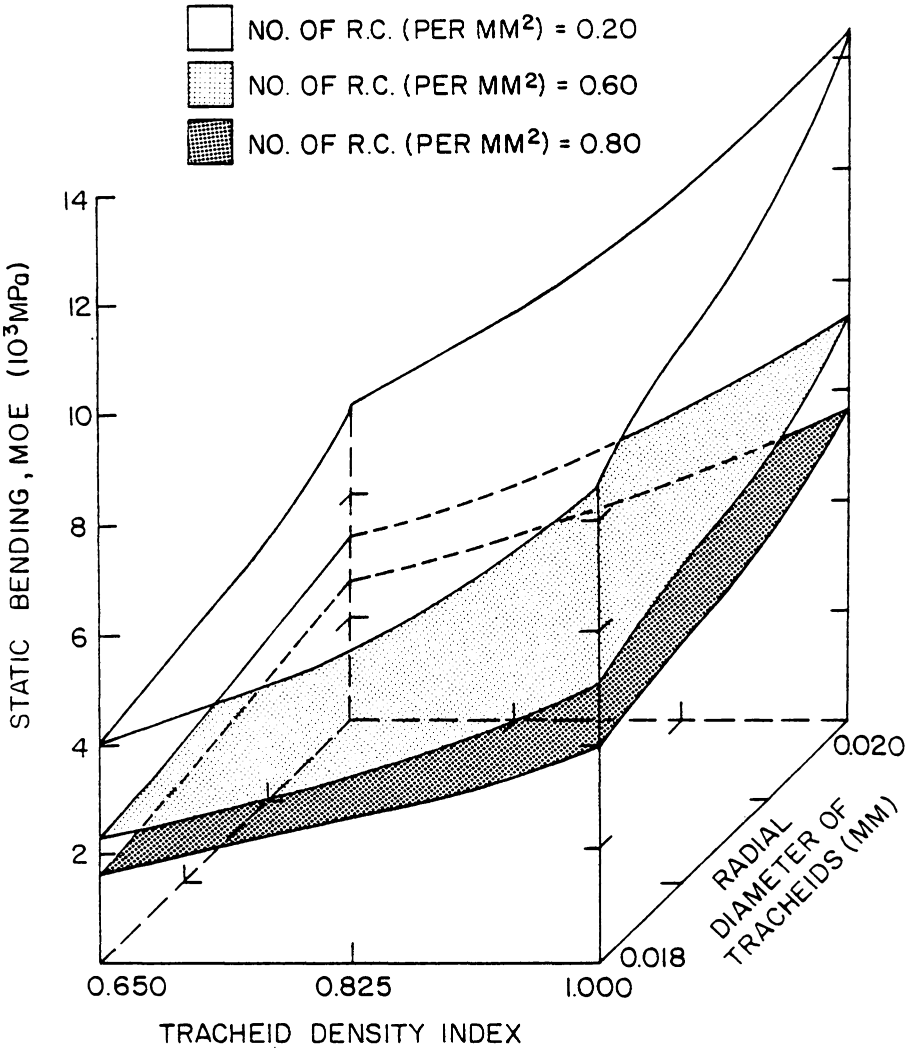

NO. OF R.C. (PER MM^2) = 0.20
NO. OF R.C. (PER MM^2) = 0.60
NO. OF R.C. (PER MM^2) = 0.80
STATIC BENDING, MOE (10^3MPa)
14
12
10
8
6
4
2
0.650
0.825
1.000
TRACHEID DENSITY INDEX
0.018
0.020
RADIAL DIAMETER OF TRACHEIDS (MM)

Fig. 19 Relationship between maximum crushing strength parallel to grain and number of resin canals per unit area, tracheid density index and radial diameter of tracheid in loblolly pine (Pinus taeda) as given in Table 8.

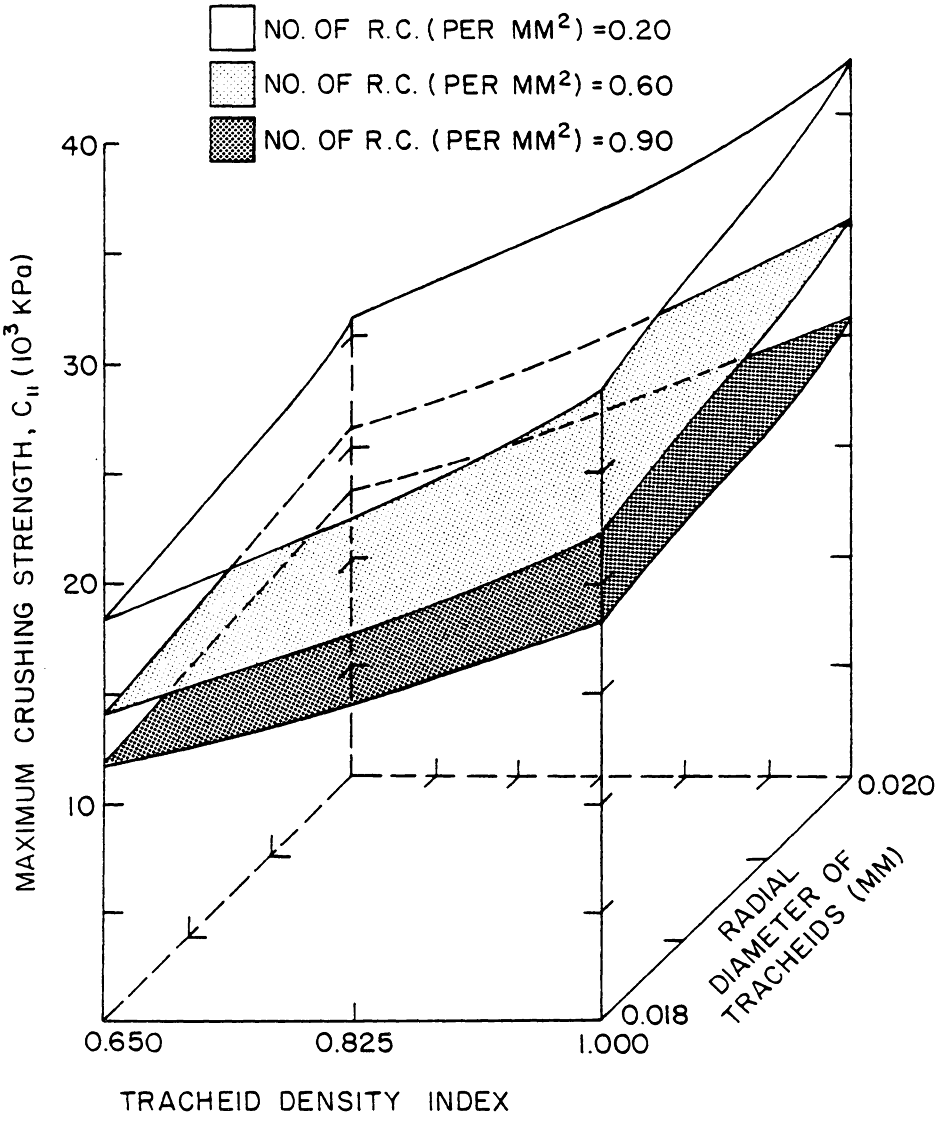
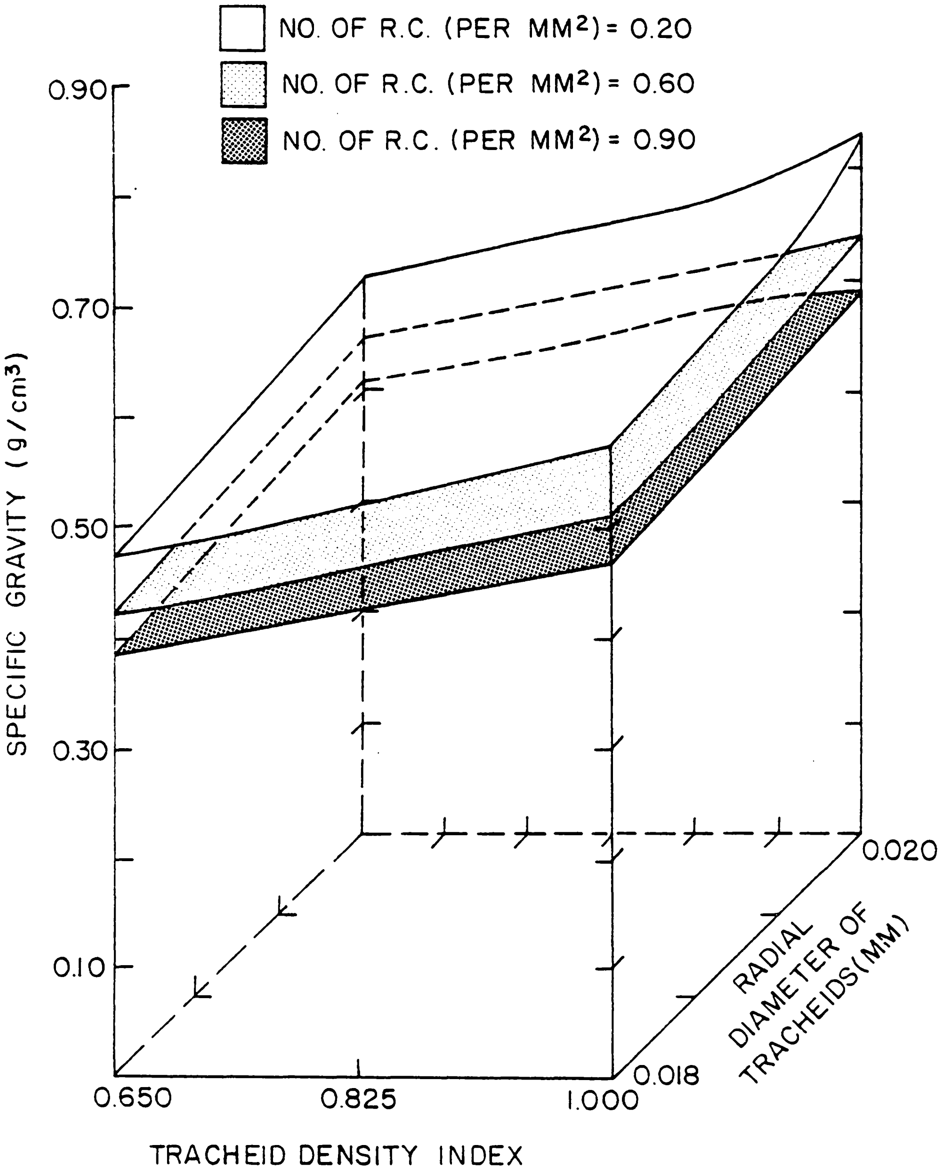

NO. OF R.C. (PER MM²) =0.20
NO. OF R.C. (PER MM²) =0.60
NO. OF R.C. (PER MM²) =0.90
MAXIMUM CRUSHING STRENGTH, C11 (10³ KPa)
40
30
20
10
0.650
0.825
1.000
TRACHEID DENSITY INDEX
0.018
0.020
RADIAL DIAMETER OF TRACHEIDS (MM)

Fig. 20 Relationship between specific gravity and number of resin canals per unit area, tracheid density index and radial diameter of tracheid in loblolly pine (*Pinus taeda*) as given in Table 8.


NO. OF R.C. (PER MM²) = 0.20
NO. OF R.C. (PER MM²) = 0.60
NO. OF R.C. (PER MM²) = 0.90
SPECIFIC GRAVITY (g/cm³)
0.90
0.70
0.50
0.30
0.10
0.650
0.825
1.000
TRACHEID DENSITY INDEX
0.018
0.020
RADIAL DIAMETER OF TRACHEIDS (MM)

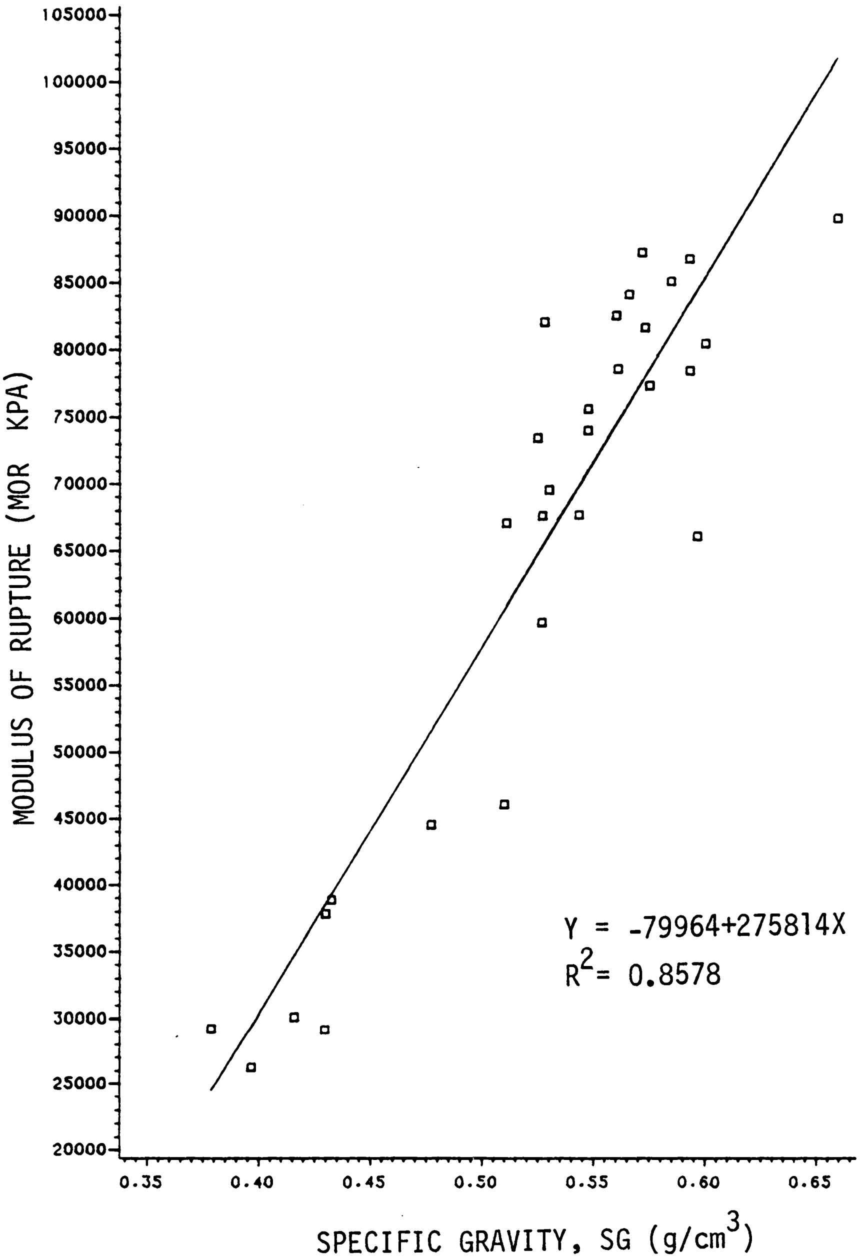


Fig. 21 The relationship between modulus of rupture (Y) and specific gravity (X) of plantation grown loblolly pine (<u>Pinus taeda</u>)

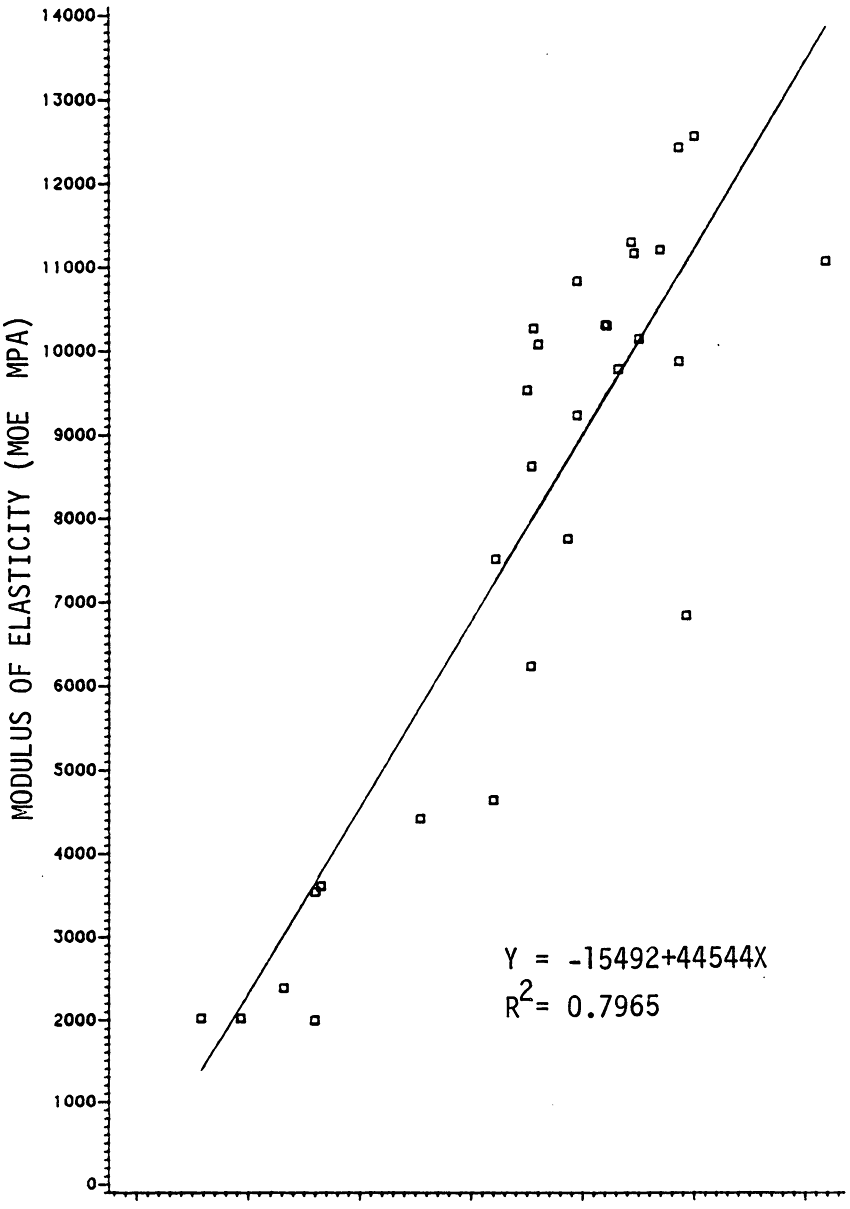


Fig. 22 The relationship between modulus of elasticity (Y) and specific gravity (X) of plantation grown loblolly pine (Pinus taeda)

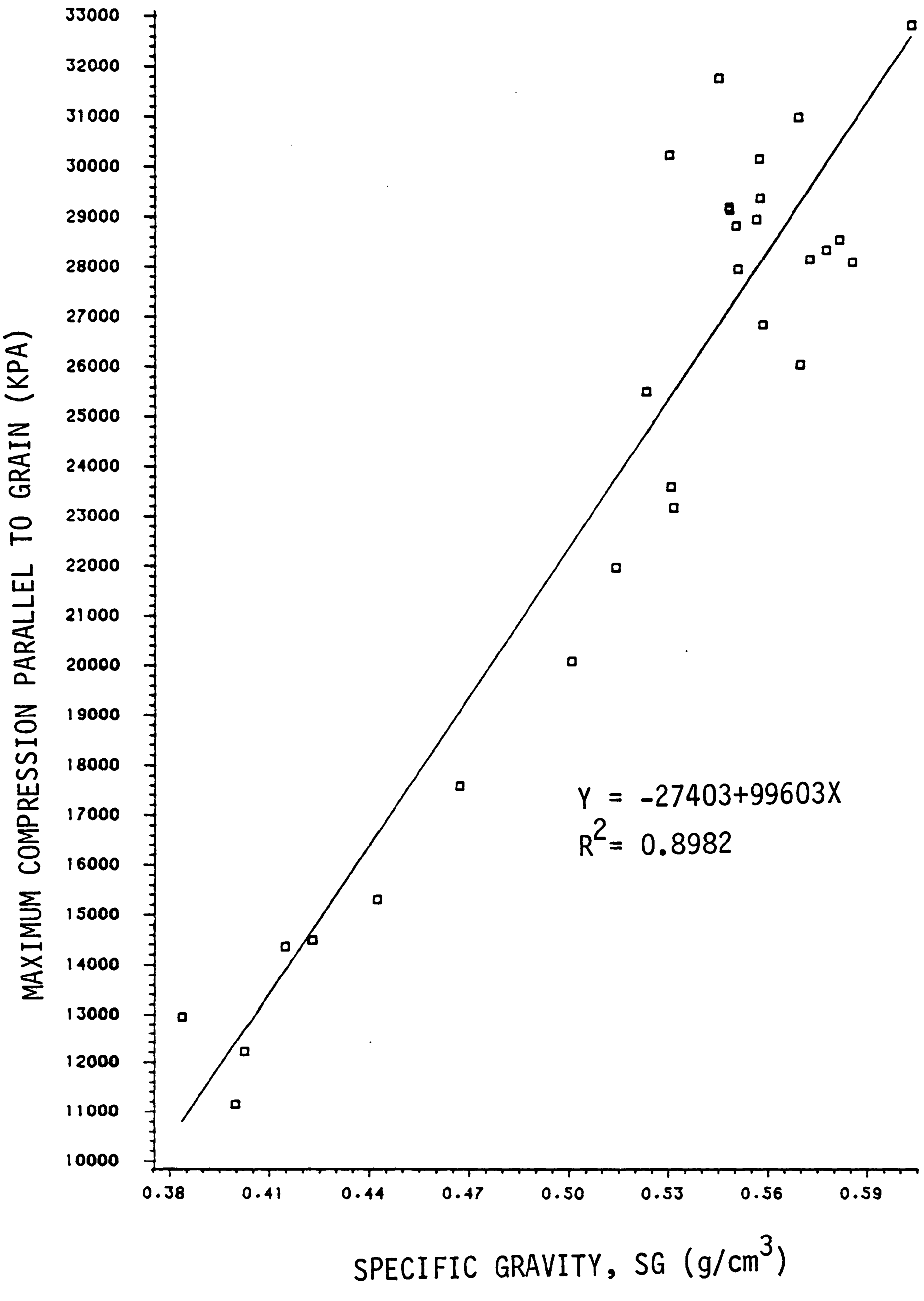


Fig. 23 The relationship between maximum compression parallel to grain (Y) and specific gravity (X) of plantation grown loblolly pine (*Pinus taeda*)

Fig. 24 Relationship between specific modulus of rupture and average number of resin canal per millimeter square, mean square values of tracheid diameters and tangential and radial diameter ratios of tracheid in loblolly pine (*Pinus taeda*) as given in Table 10.

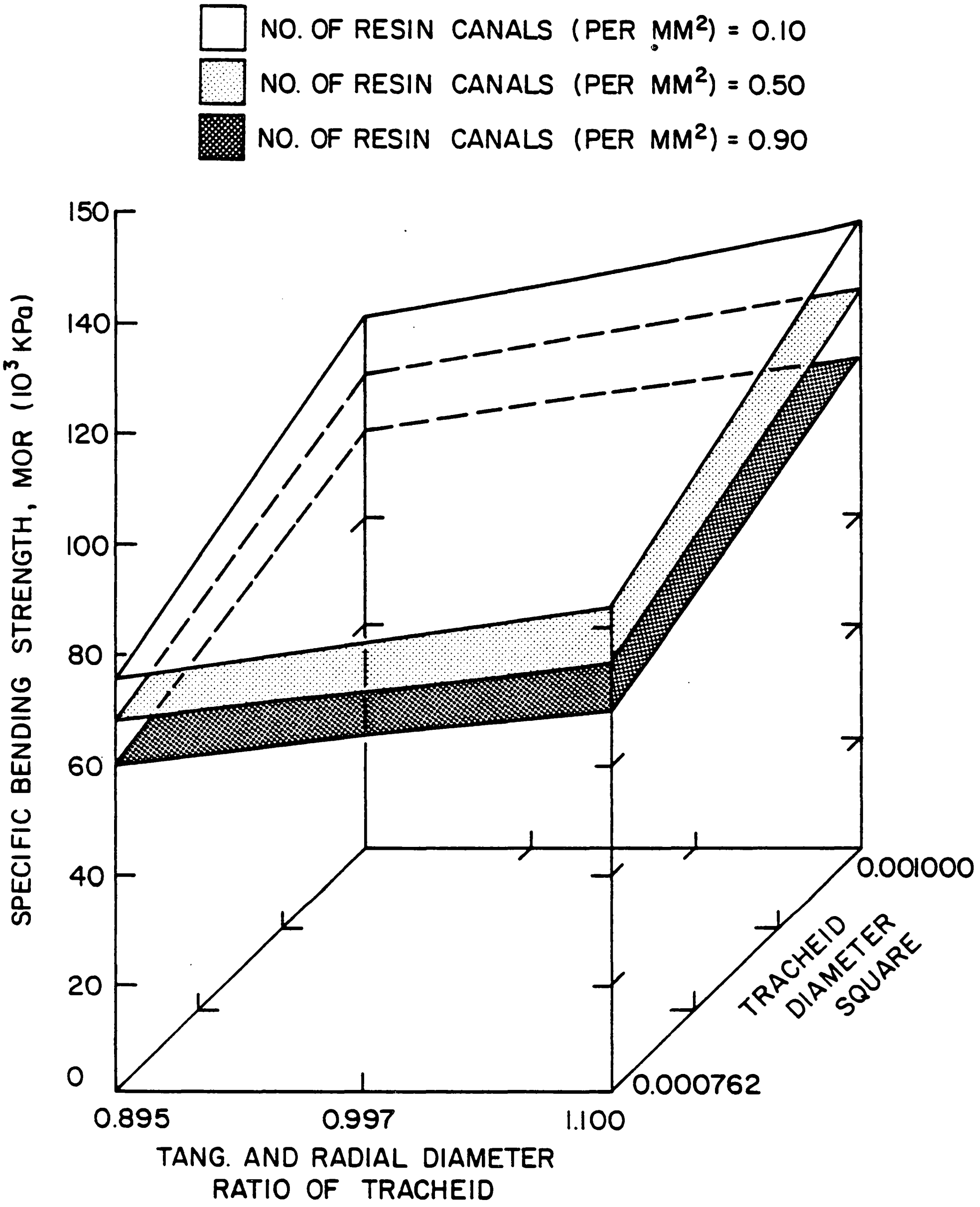

NO. OF RESIN CANALS (PER MM²) = 0.10
NO. OF RESIN CANALS (PER MM²) = 0.50
NO. OF RESIN CANALS (PER MM²) = 0.90
SPECIFIC BENDING STRENGTH, MOR (10³ KPa)
150
140
120
100
80
60
40
20
0
0.895
0.997
1.100
TANG. AND RADIAL DIAMETER RATIO OF TRACHEID
0.001000
TRACHEID DIAMETER SQUARE
0.000762

Fig. 25 Relationship between specific modulus of elasticity and average number of resin canal per millimeter square, mean square values of tracheid diameters and tangential and radial diameter ratios of tracheid in loblolly pine (<u>Pinus</u> <u>taeda</u>) as given in Table 10.

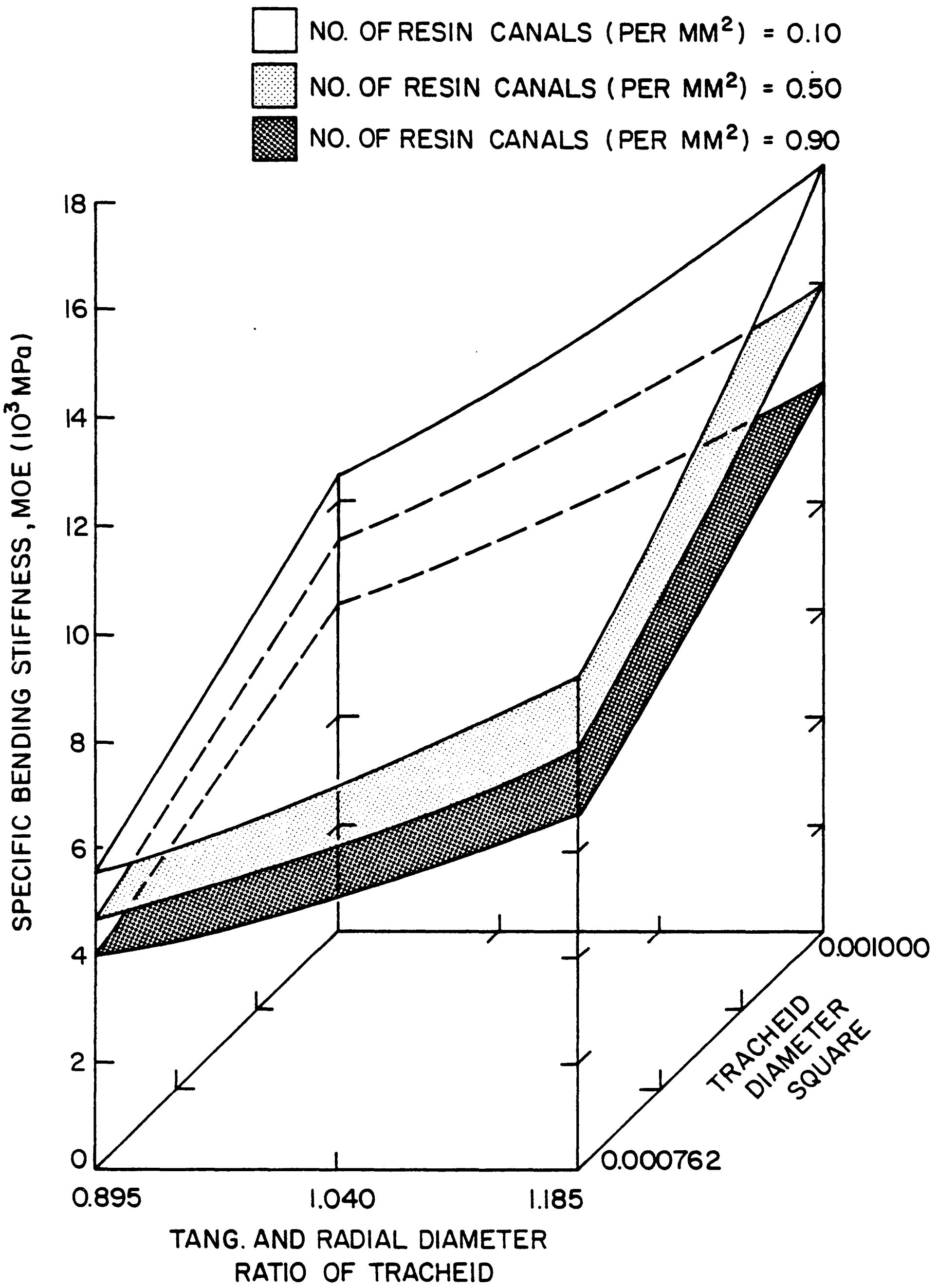
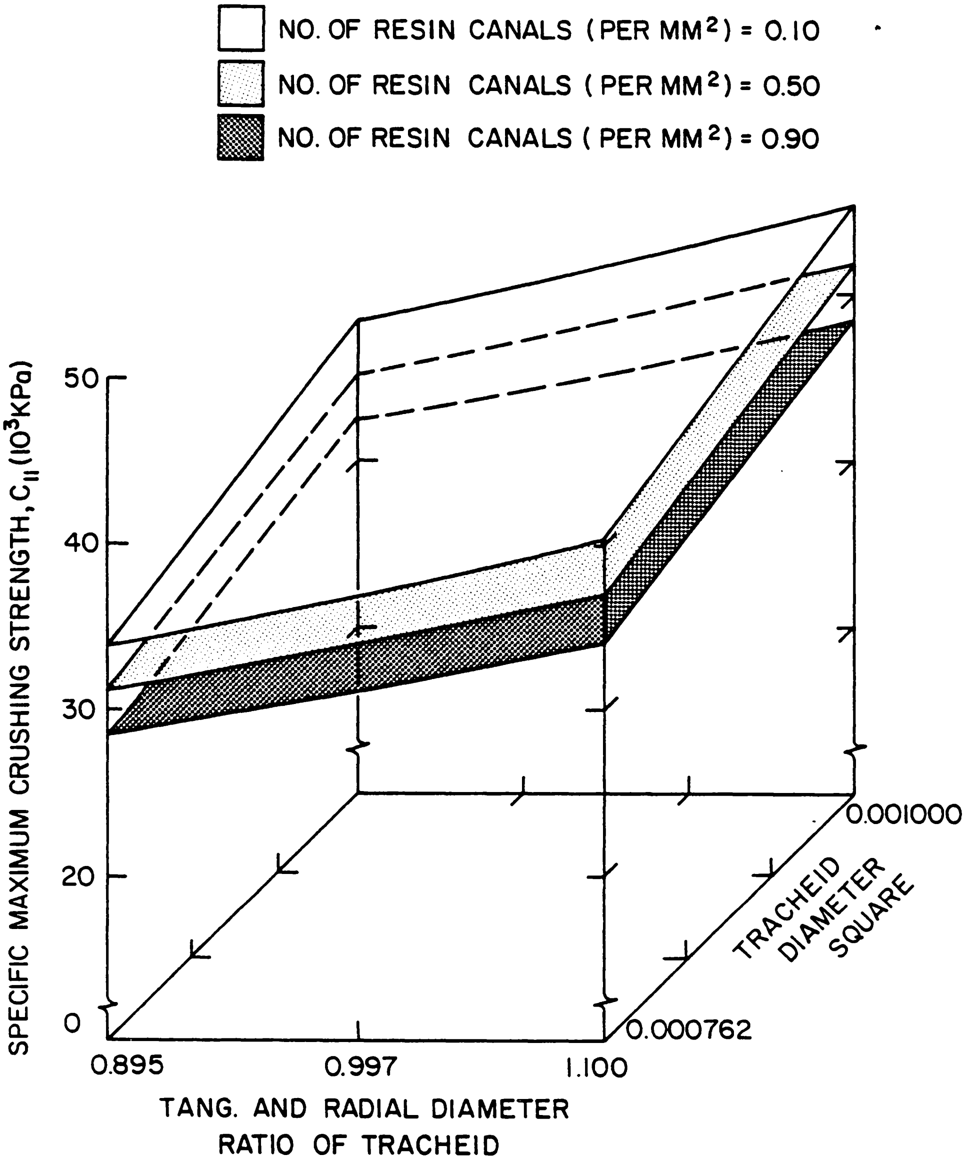

NO. OF RESIN CANALS (PER MM²) = 0.10
NO. OF RESIN CANALS (PER MM²) = 0.50
NO. OF RESIN CANALS (PER MM²) = 0.90
SPECIFIC BENDING STIFFNESS, MOE (10³ MPa)
18
16
14
12
10
8
6
4
2
0
0.895
1.040
1.185
TANG. AND RADIAL DIAMETER RATIO OF TRACHEID
0.000762
0.001000
TRACHEID DIAMETER SQUARE

Fig. 26 Relationship between specific maximum crushing strength parallel to grain and average number of resin canal per millimeter square, mean square values of tracheid diameters and tangential and radial diameter ratios of tracheid in loblolly pine (*Pinus taeda*) as given in Table 10.


NO. OF RESIN CANALS (PER MM²) = 0.10
NO. OF RESIN CANALS (PER MM²) = 0.50
NO. OF RESIN CANALS (PER MM²) = 0.90
SPECIFIC MAXIMUM CRUSHING STRENGTH, C11 (10³KPa)
50
40
30
20
0
0.895
0.997
1.100
TANG. AND RADIAL DIAMETER RATIO OF TRACHEID
0.001000
0.000762
TRACHEID DIAMETER SQUARE

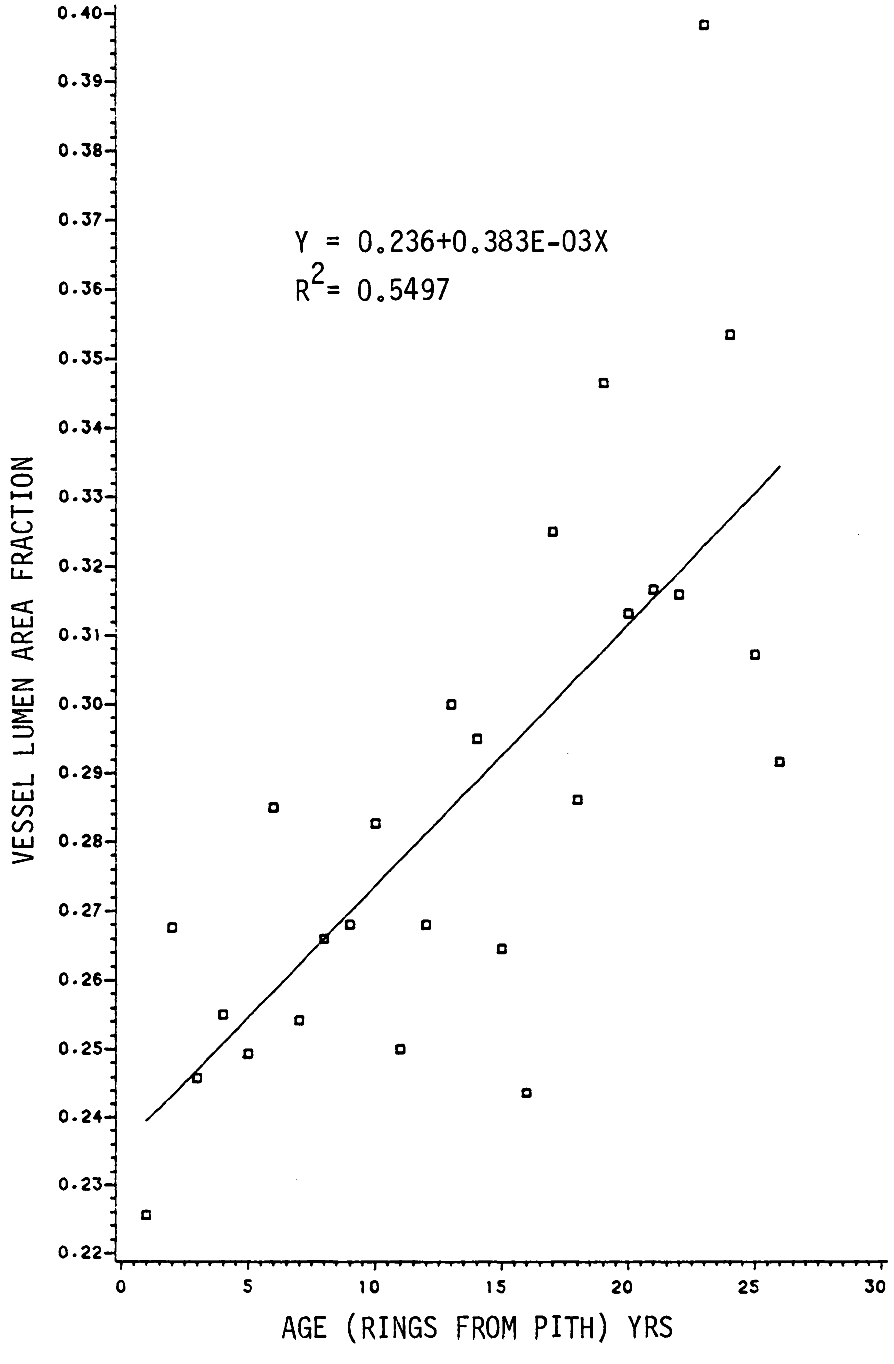


Fig 27 The relationship between vessel lumen area fraction (Y) and age (X) of plantation grown cottonwood (<u>Populus deltoides</u>)

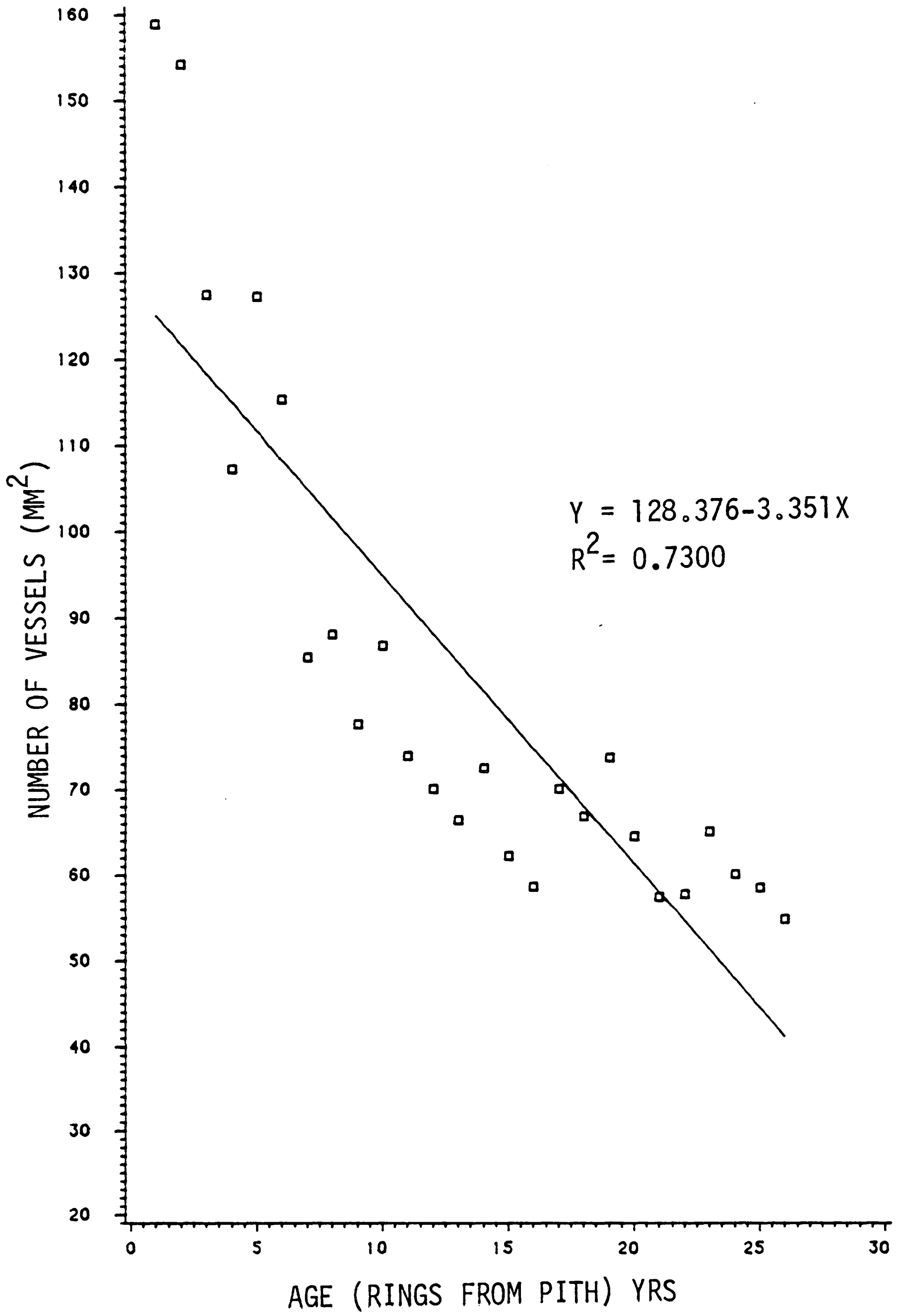


Fig 28 The relationship between number of vessels per millimeter square (Y) and age (X) of plantation grown cottonwood (*Populus deltoides*)

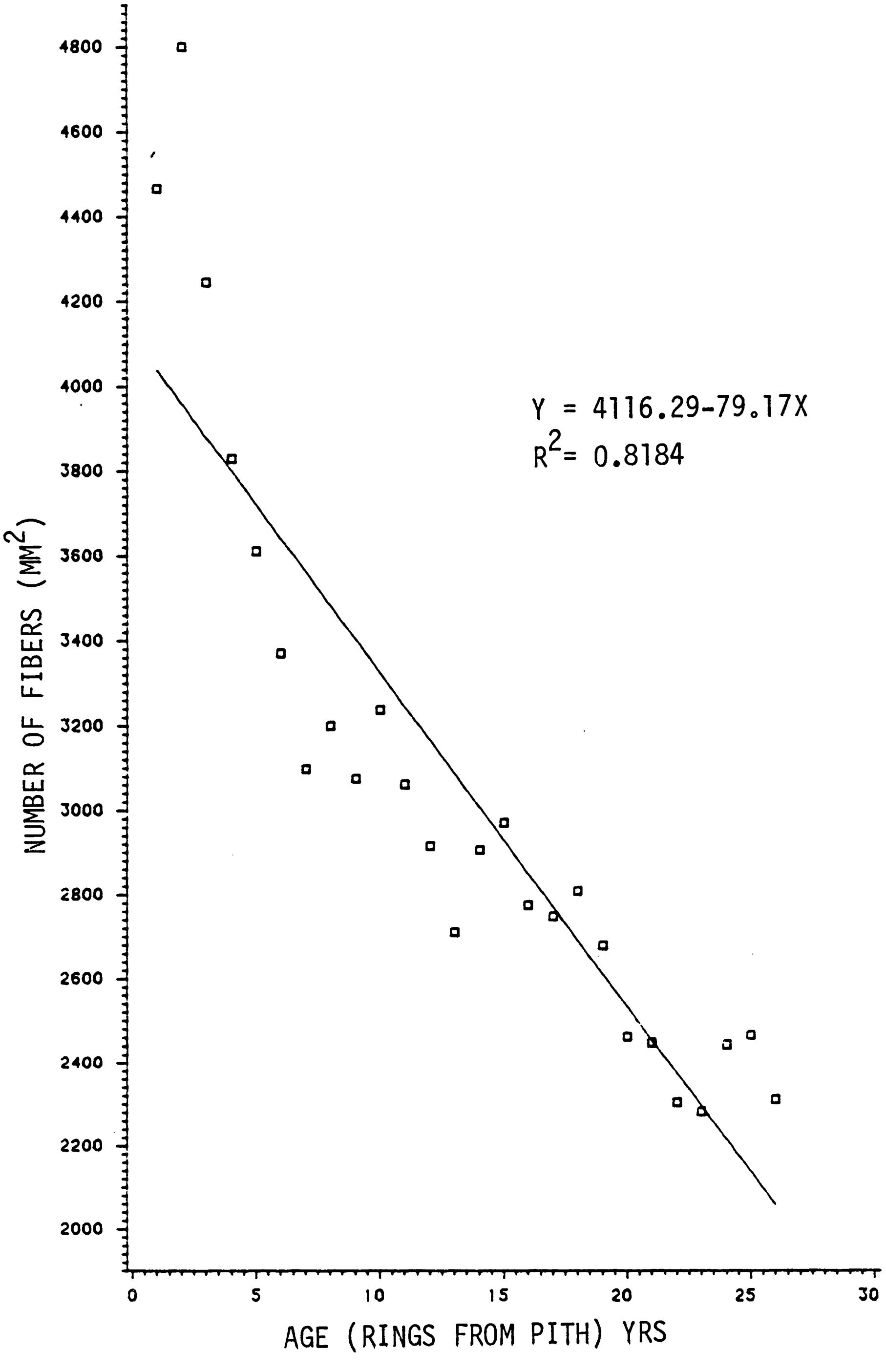


Fig 29 The relationship between number of fibers per millimeter square (Y) and age (X) of plantation grown cottonwood (Populus deltoides)

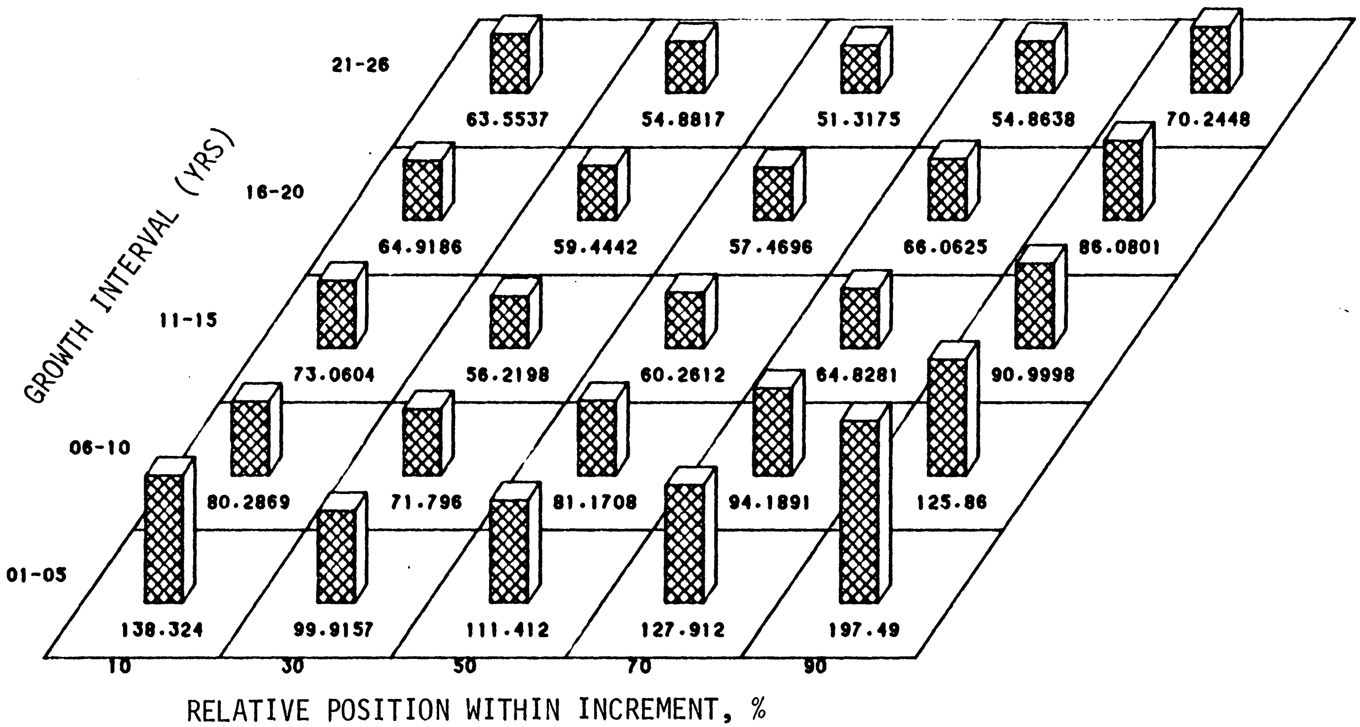


Fig 30 Within-stem variation of number of vessels per millimeter square (mm^2) at 5-year growth intervals in plantation grown cottonwood (Populus deltoides)

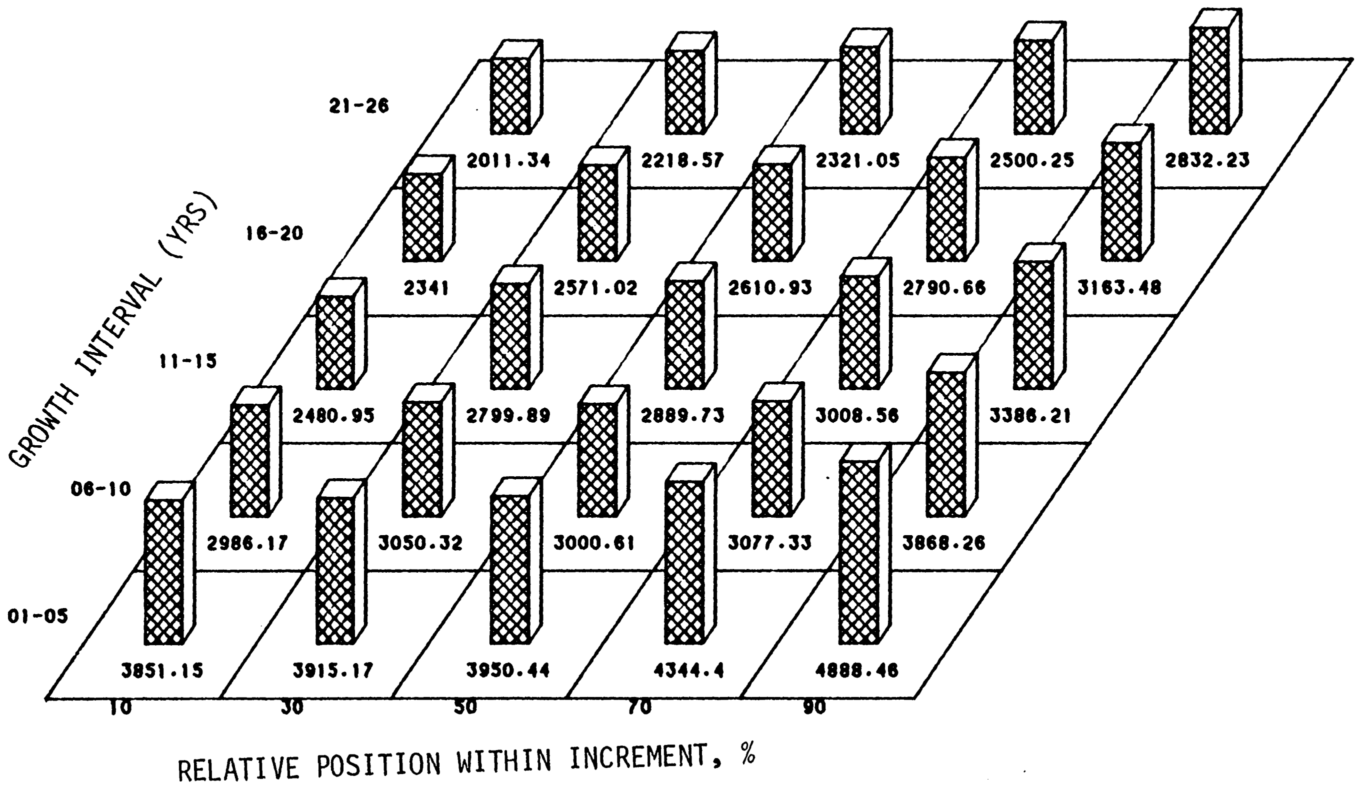


Fig 31 Within-stem variation of number of fibers per millimeter square (mm^2) at 5-year growth intervals in plantation grown cottonwood (*Populus deltoides*)

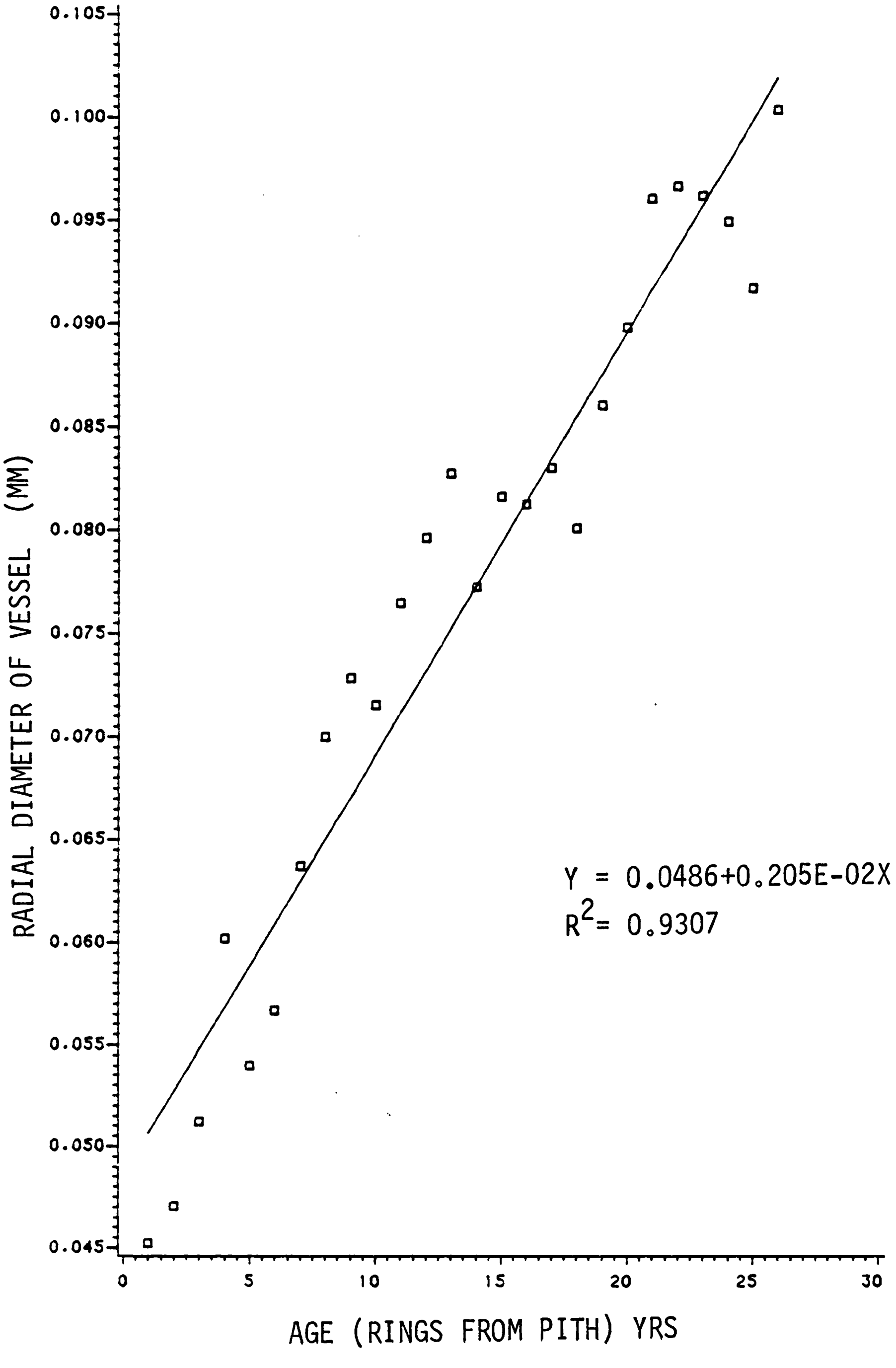


Fig 32 The relationship between radial diameter of vessel (Y) and age (X) of plantation grown cottonwood (<u>Populus deltoides</u>)

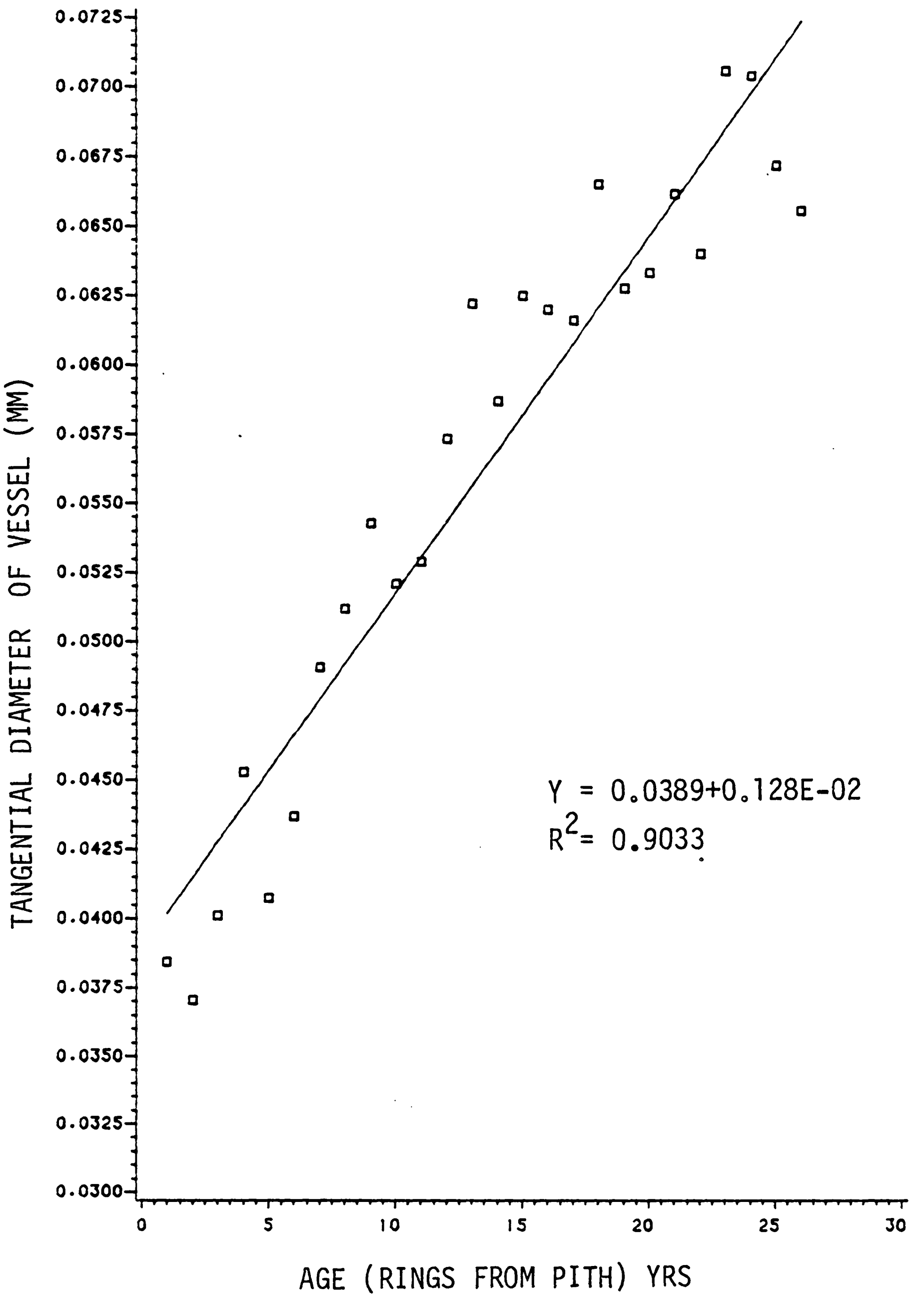


Fig 33 The relationship between tangential diameter of vessel (Y) and age (X) of plantation grown cottonwood (*Populus deltoides*)

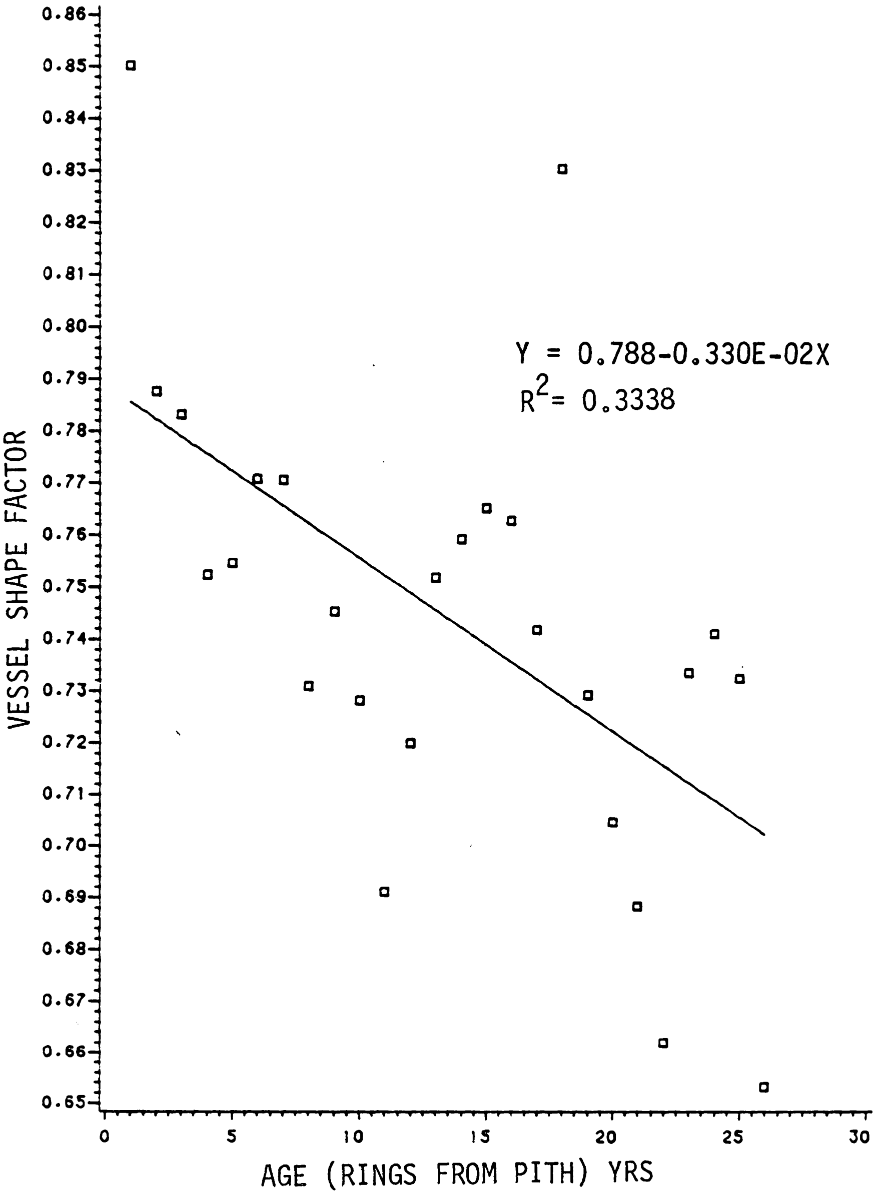


Fig 34 The relationship between vessel shape factor (Y) and age (X) of plantation grown cottonwood (*Populus deltoides*)

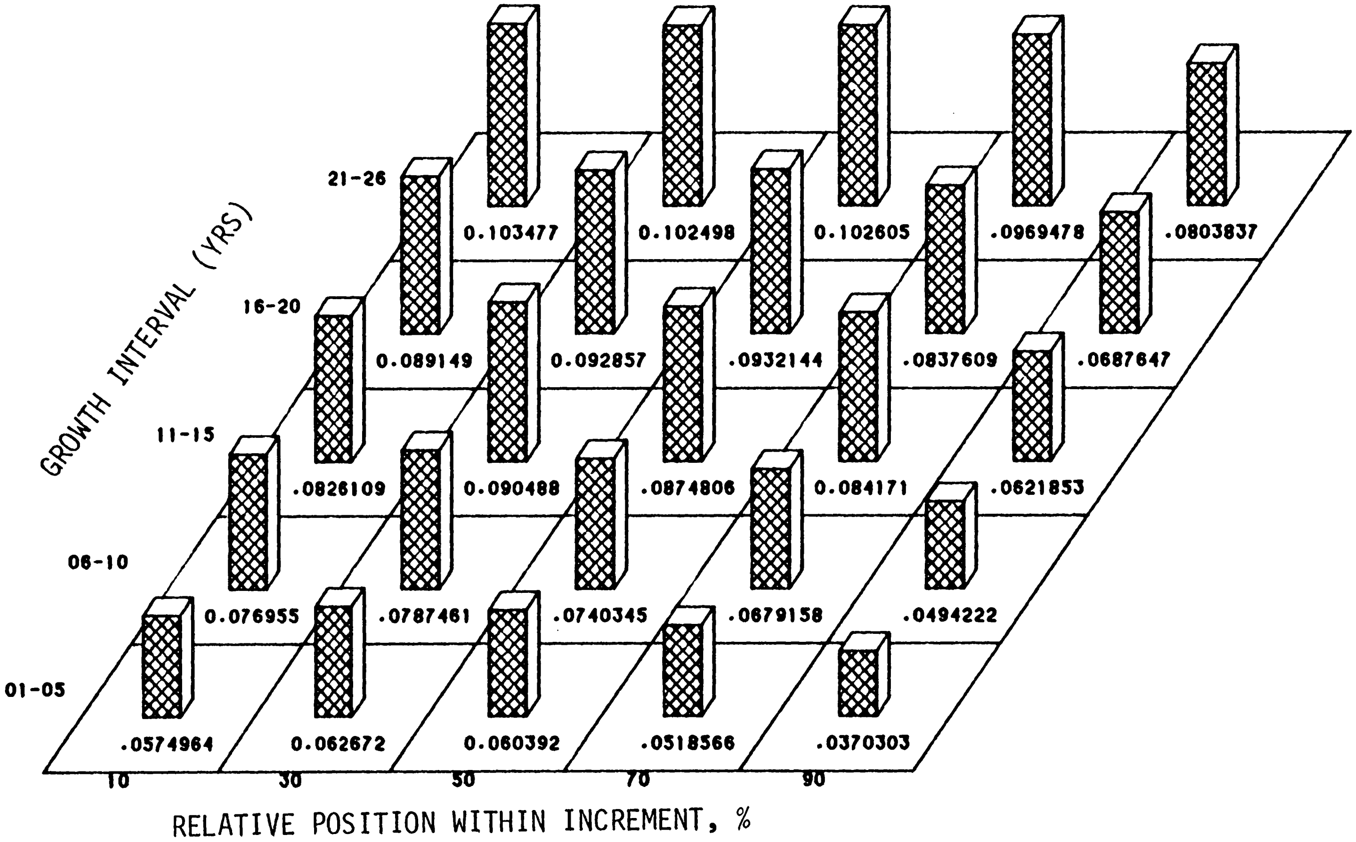


Fig 35 Within-stem variation of radial diameter of vessel (mm) at 5-year growth intervals in plantation grown cottonwood (*Populus deltoides*)

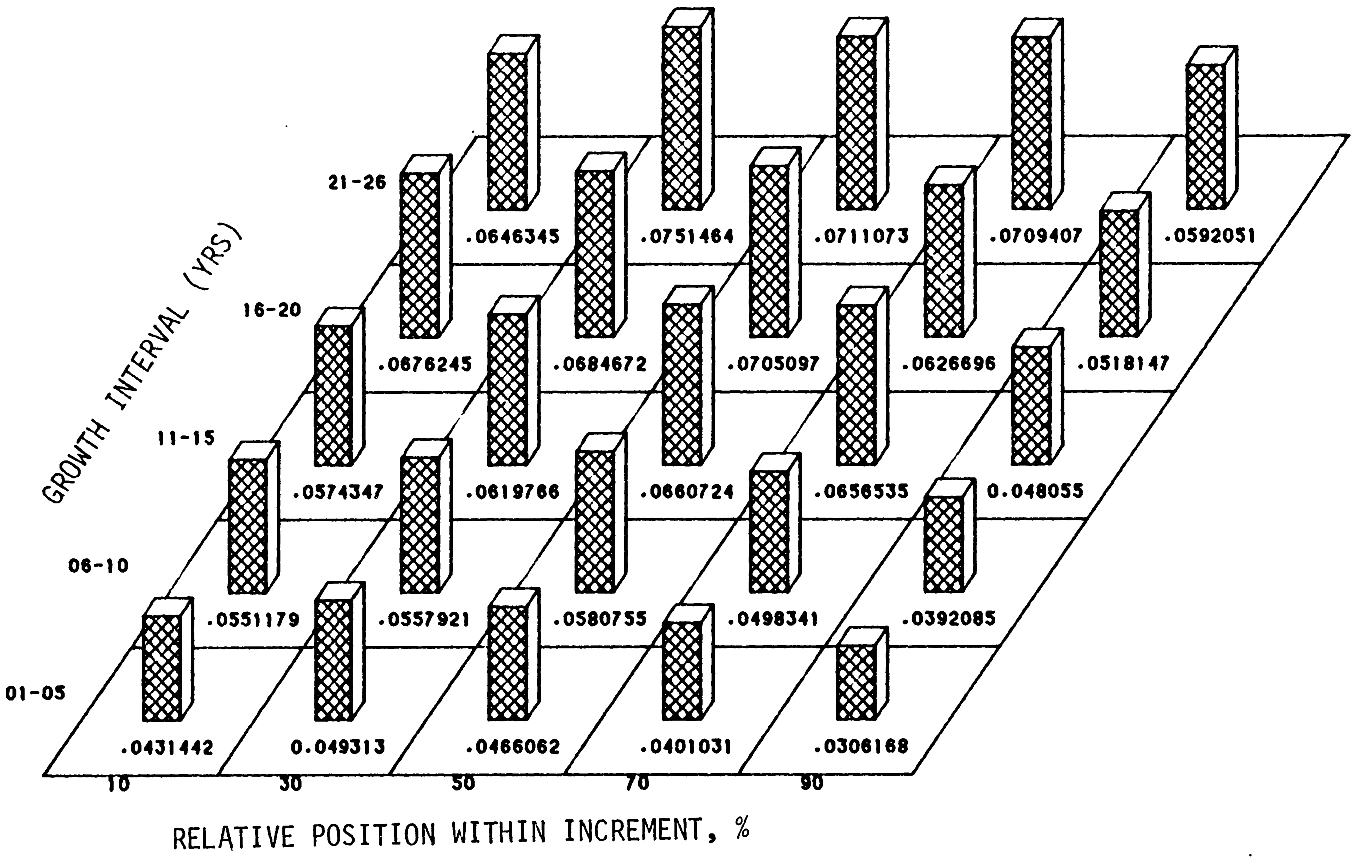


Fig 36 Within-stem variation of tangential diameter of vessel (mm) at 5-year growth intervals in plantation grown cottonwood (*Populus deltoides*)

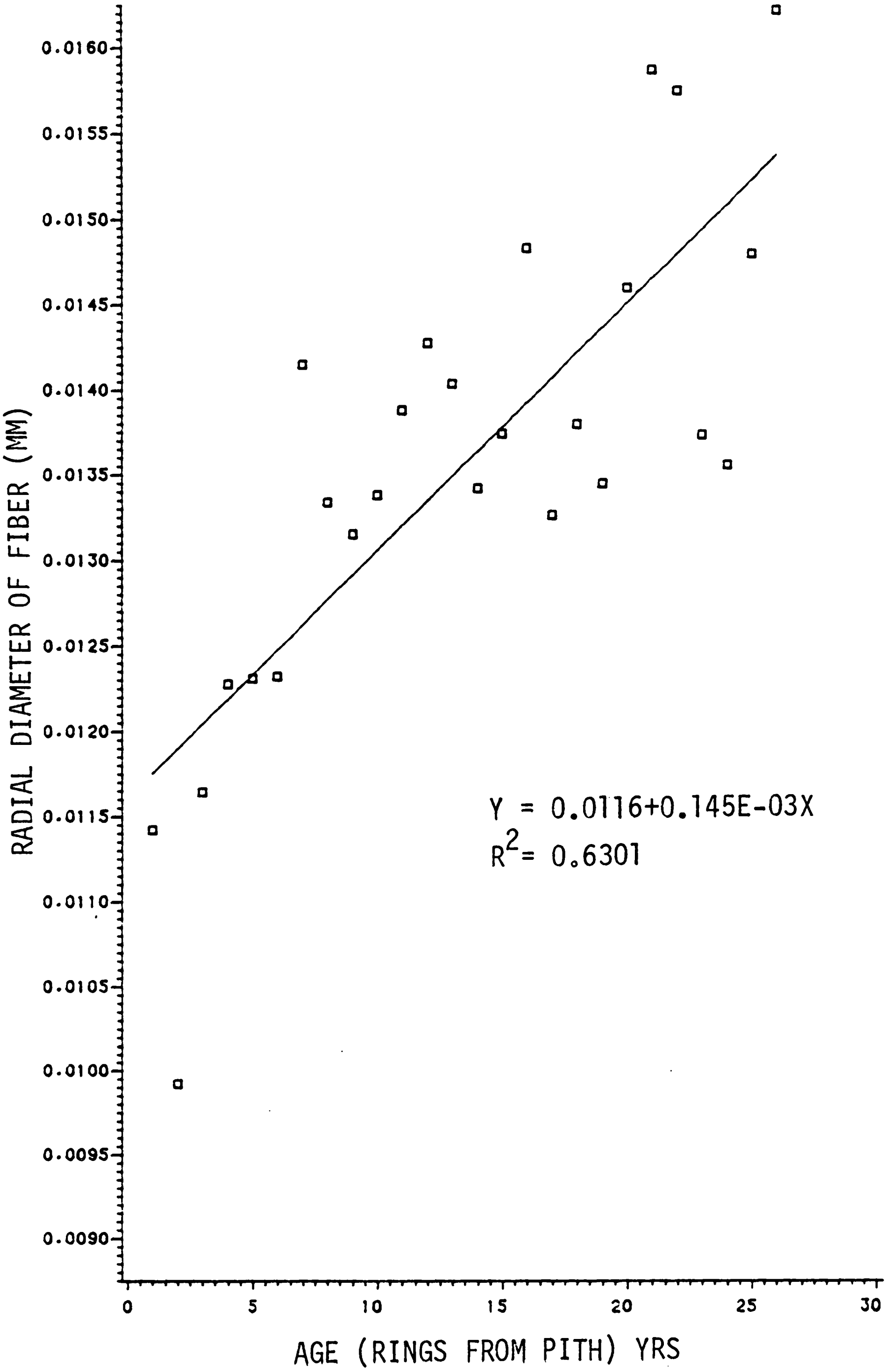


Fig 37 The relationship between radial diameter of fiber (Y) and age (X) of plantation grown cottonwood (*Populus deltoides*)

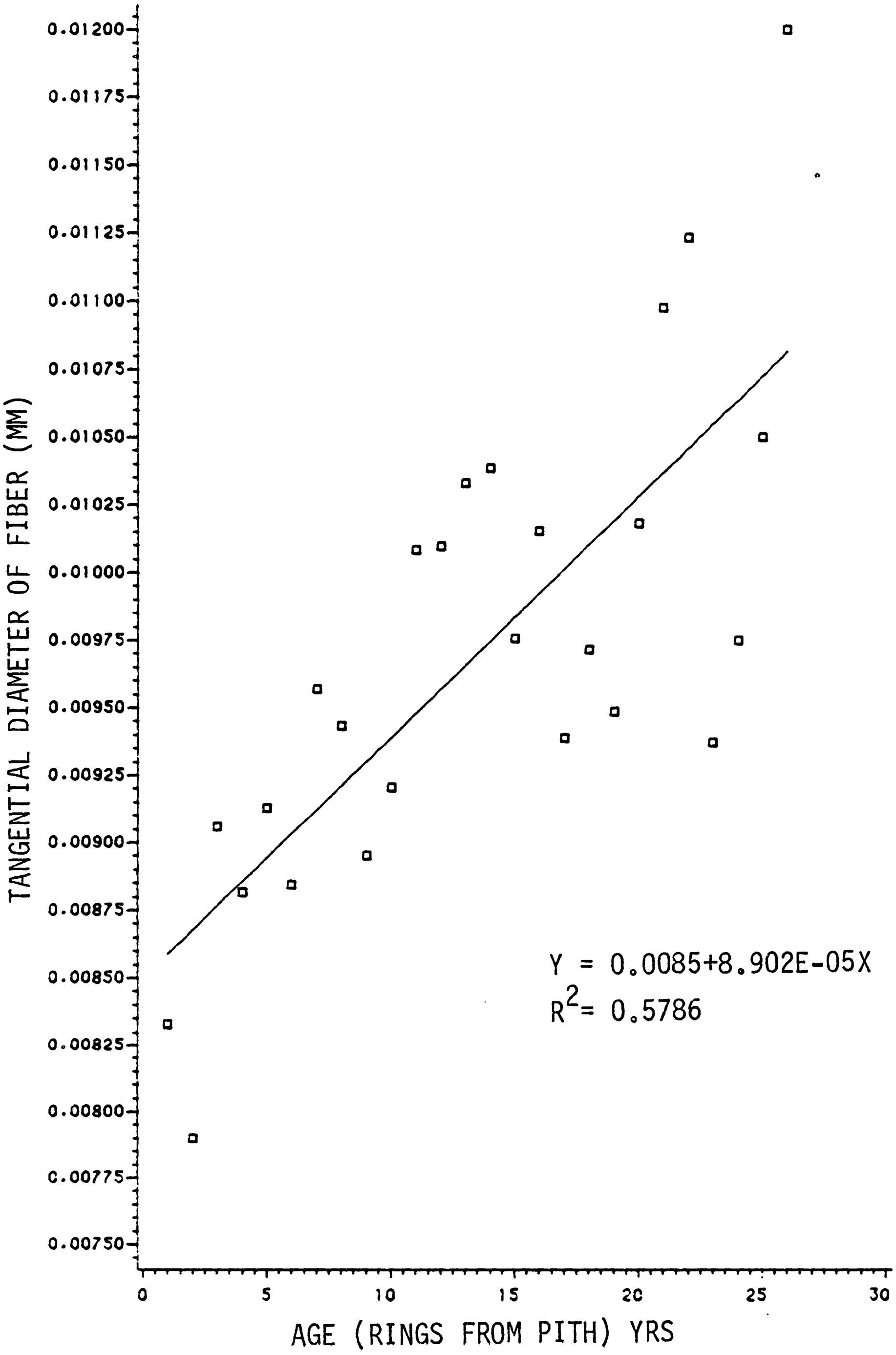


Fig 38 The relationship between tangential diameter of fiber (Y) and age (X) of plantation grown cottonwood (*Populus deltoides*)

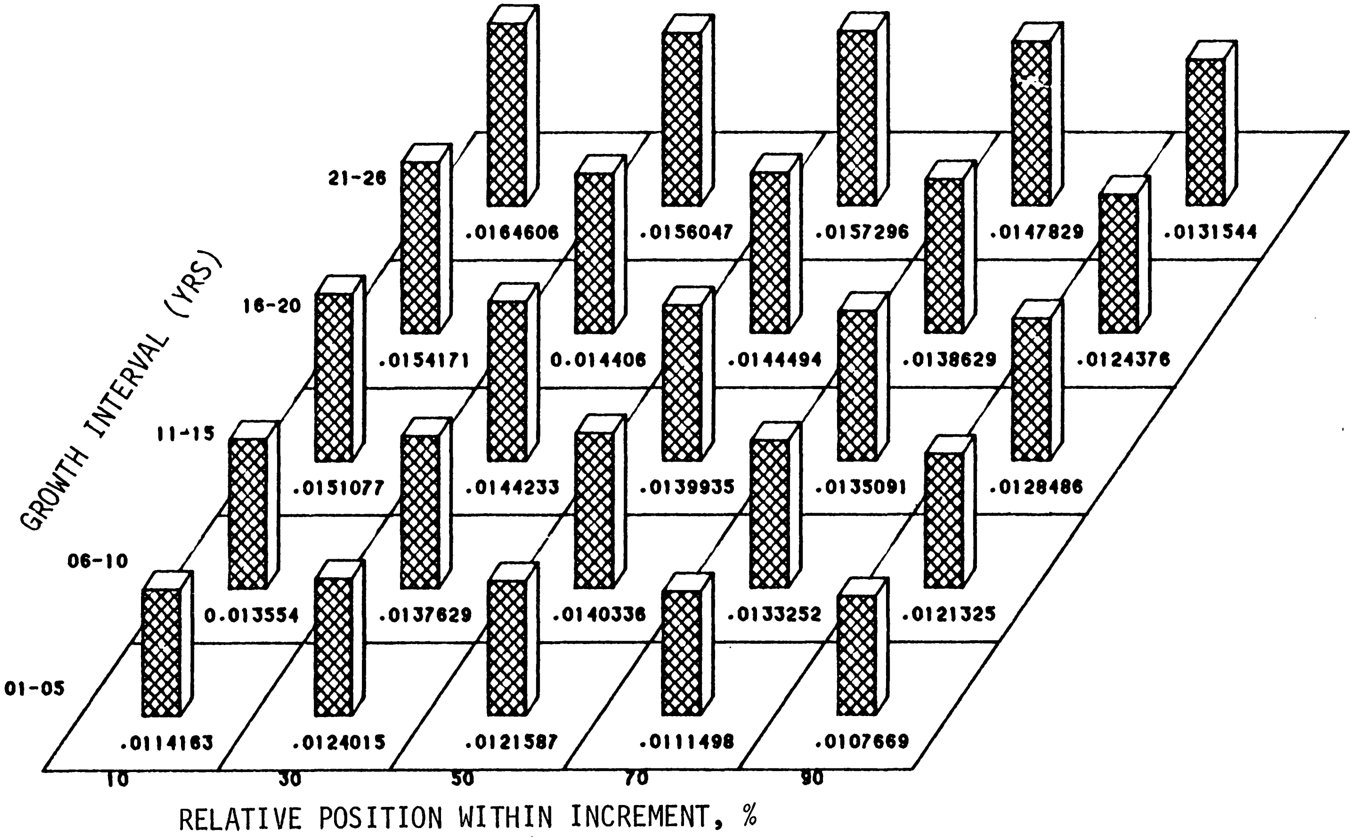


Fig 39 Within-stem variation of radial diameter of fibers (mm) at 5-year growth intervals in plantation grown cottonwood (<u>Populus deltoides</u>)

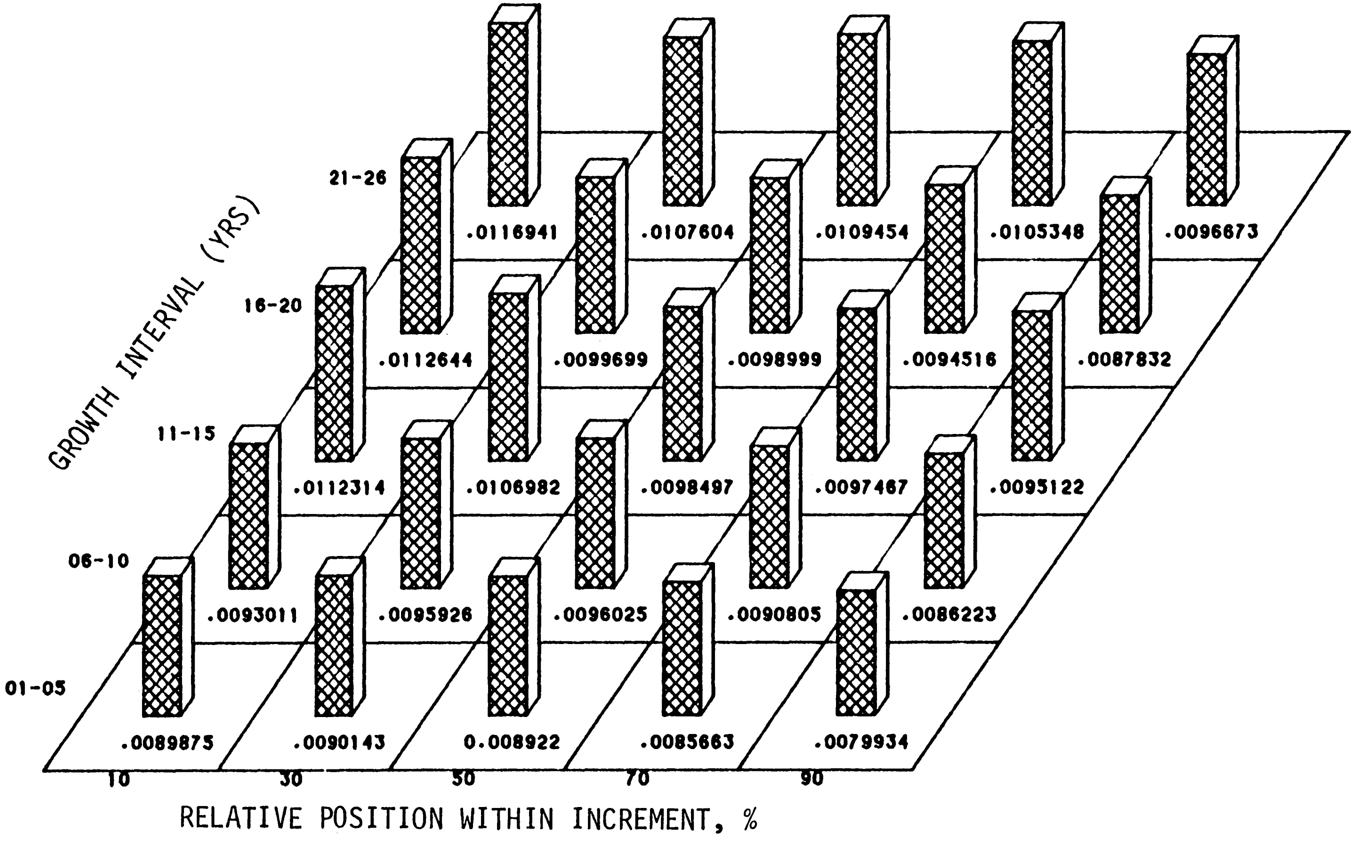


Fig40 Within-stem variation of tangential diameter of fibers (mm) at 5-year growth intervals in plantation grown cottonwood (<u>Populus deltoides</u>)

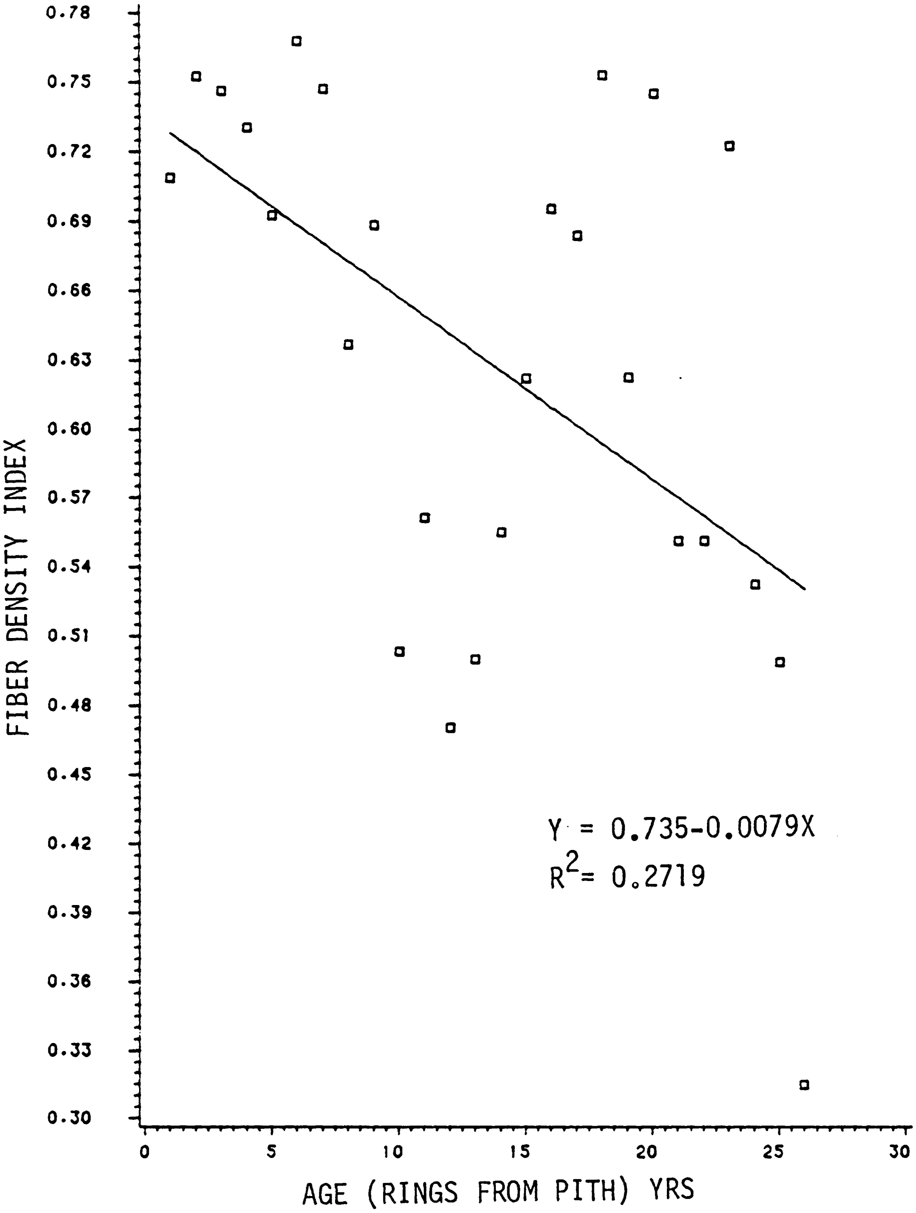


Fig 41 The relationship between fiber density index (Y) and age (X) of plantation grown cottonwood (*Populus deltoides*)

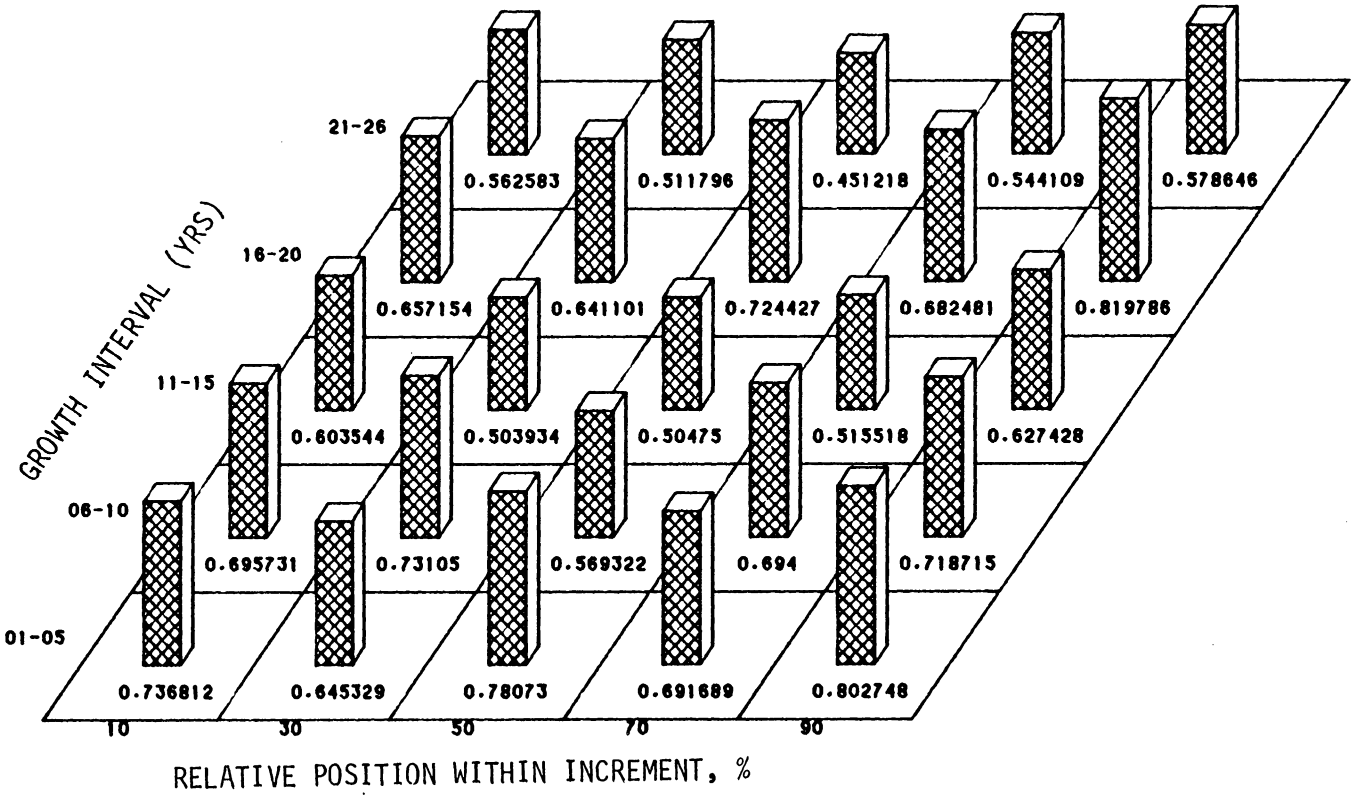


Fig 42 Within-stem variation of fiber density index at 5-year growth intervals in plantation grown cottonwood (Populus deltoides)

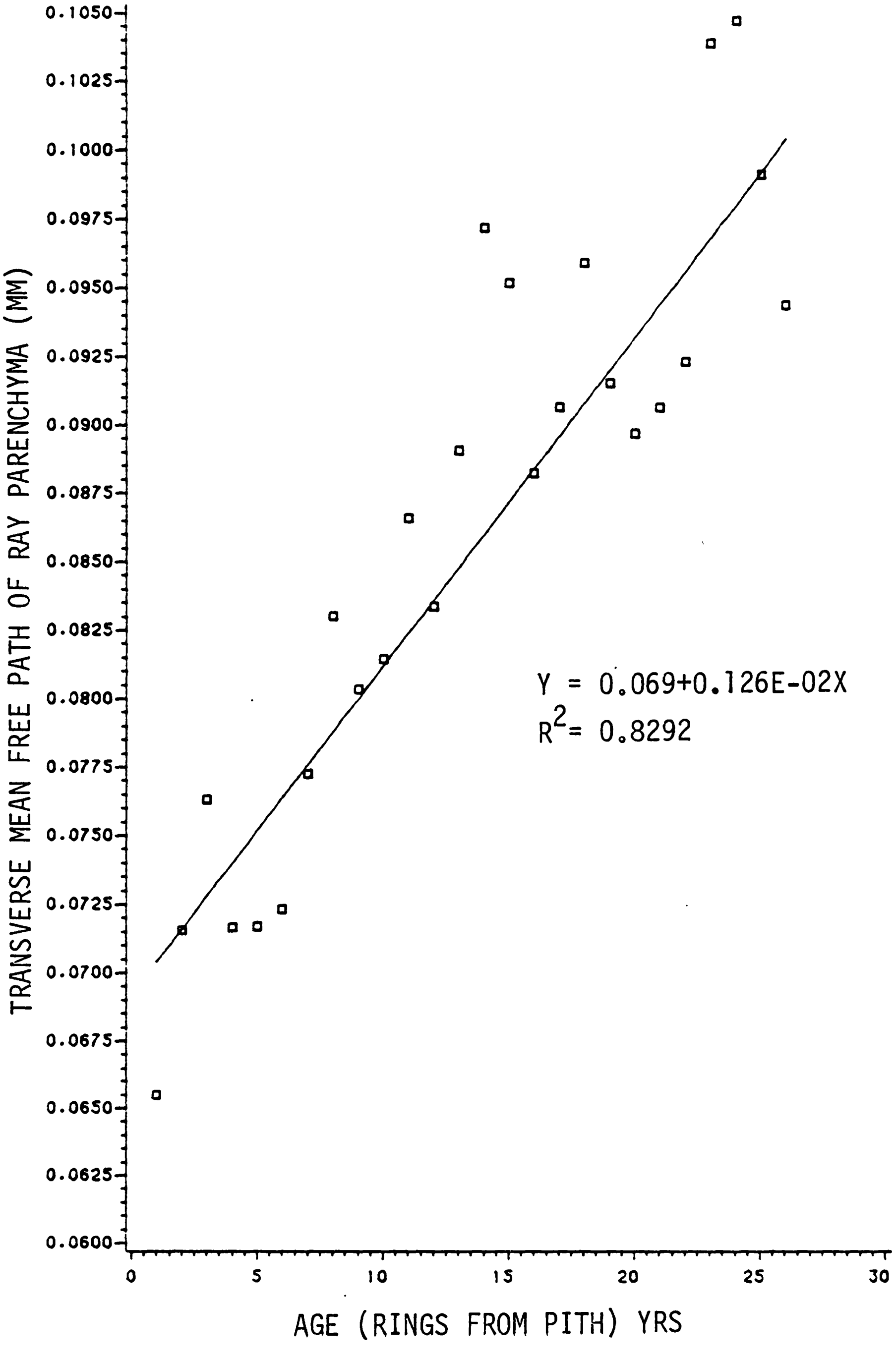


Fig 43 The relationship between transverse mean free path of ray parenchyma (Y) and age (X) of plantation grown cottonwood (*Populus deltoides*)

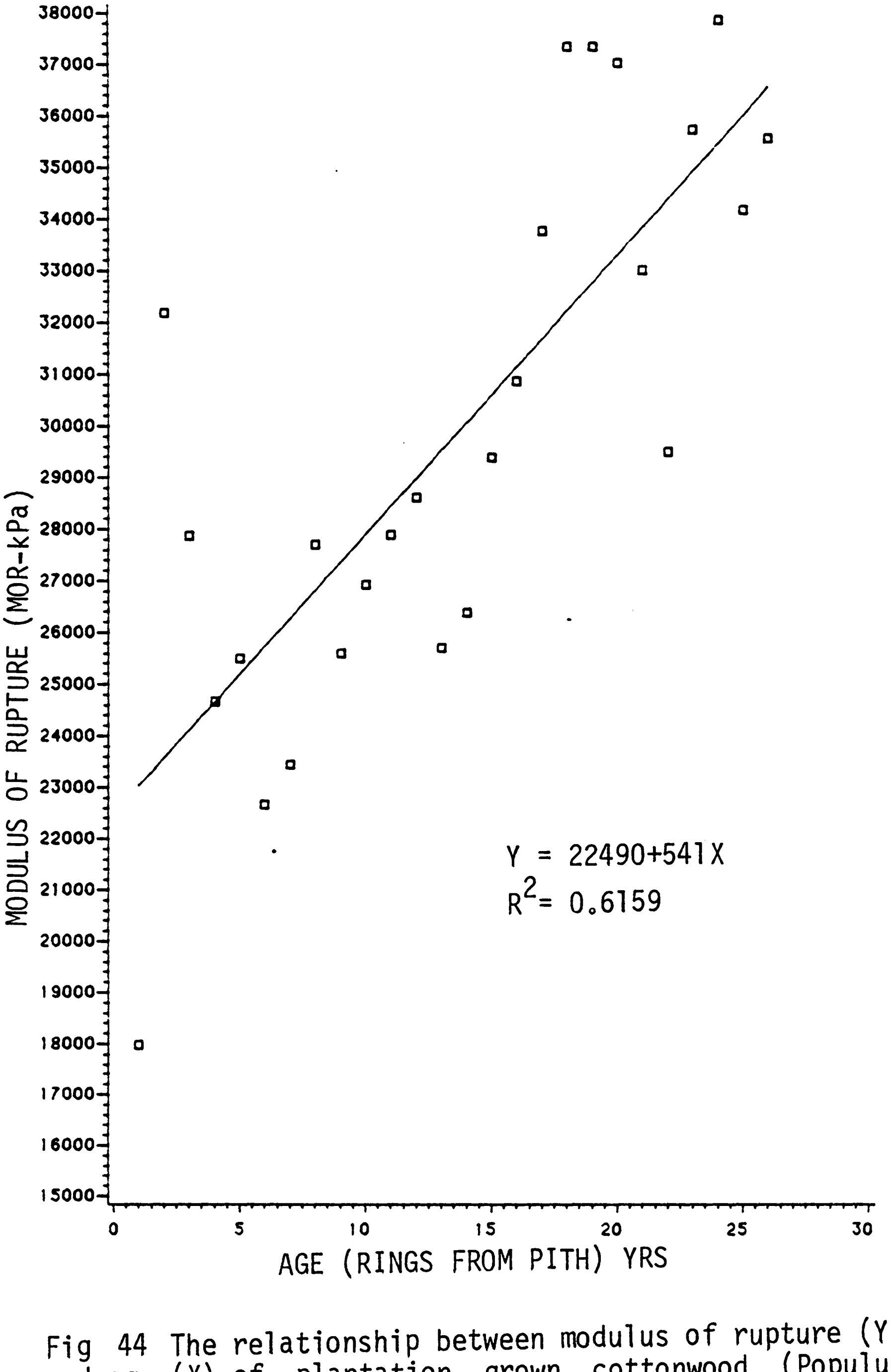


Fig 44 The relationship between modulus of rupture (Y) and age (X) of plantation grown cottonwood (Populus deltoides)

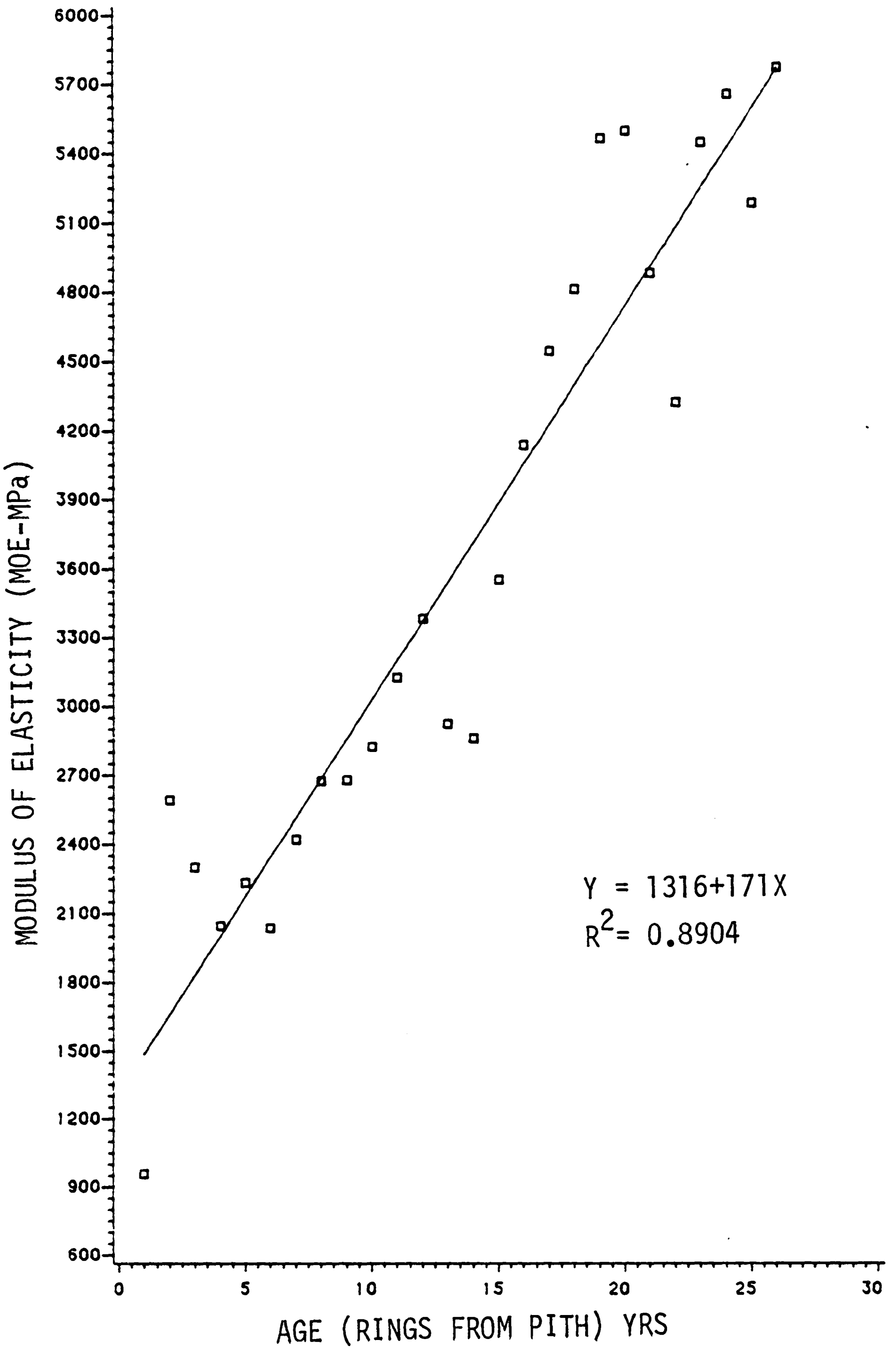


Fig 45 The relationship between modulus of elasticity (Y) and age (X) of plantation grown cottonwood (<u>Populus deltoides</u>)

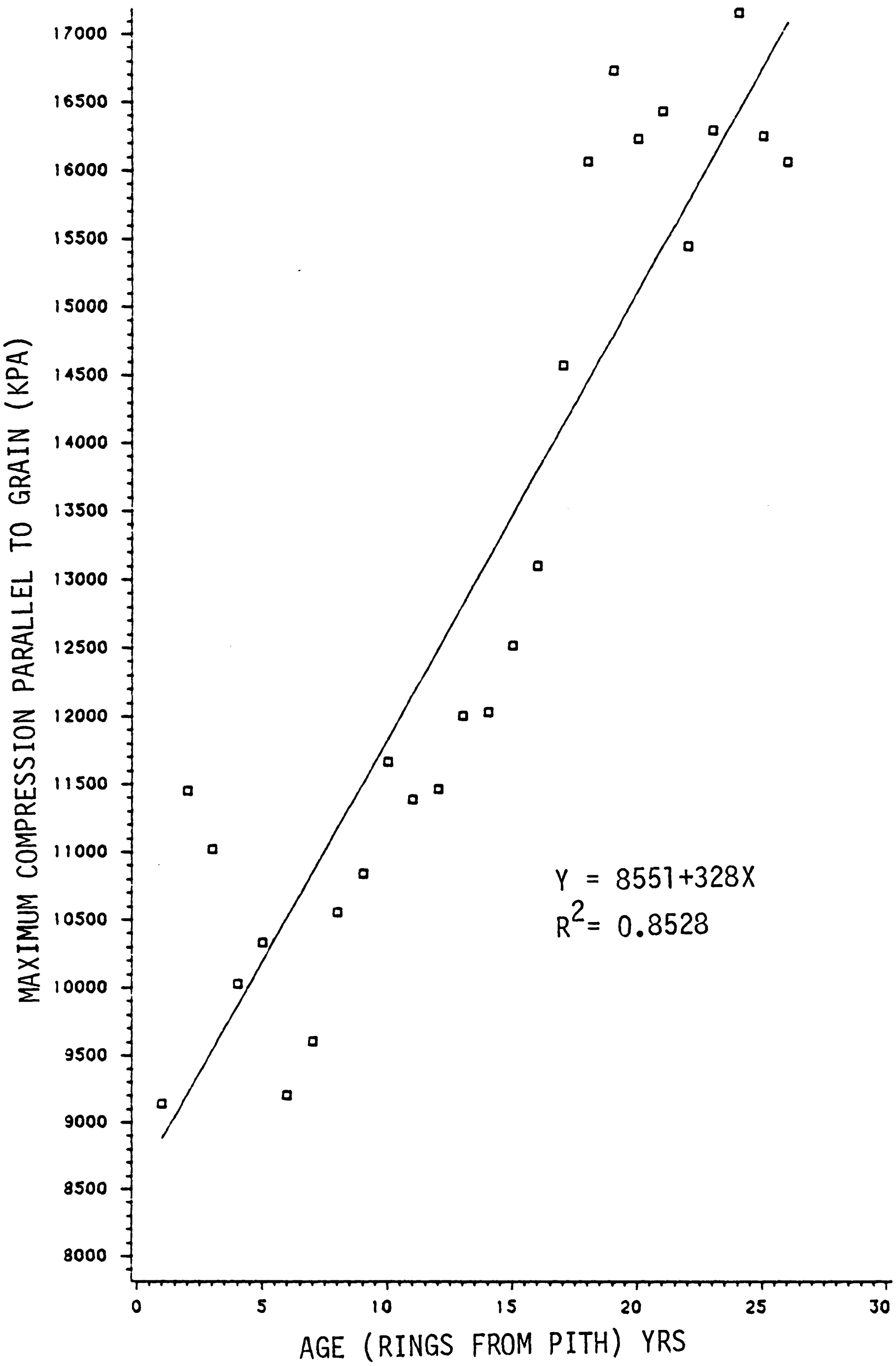


Fig 46 The relationship between maximum compression parallel to grain (Y) and age (X) of plantation grown cottonwood (*Populus deltoides*)

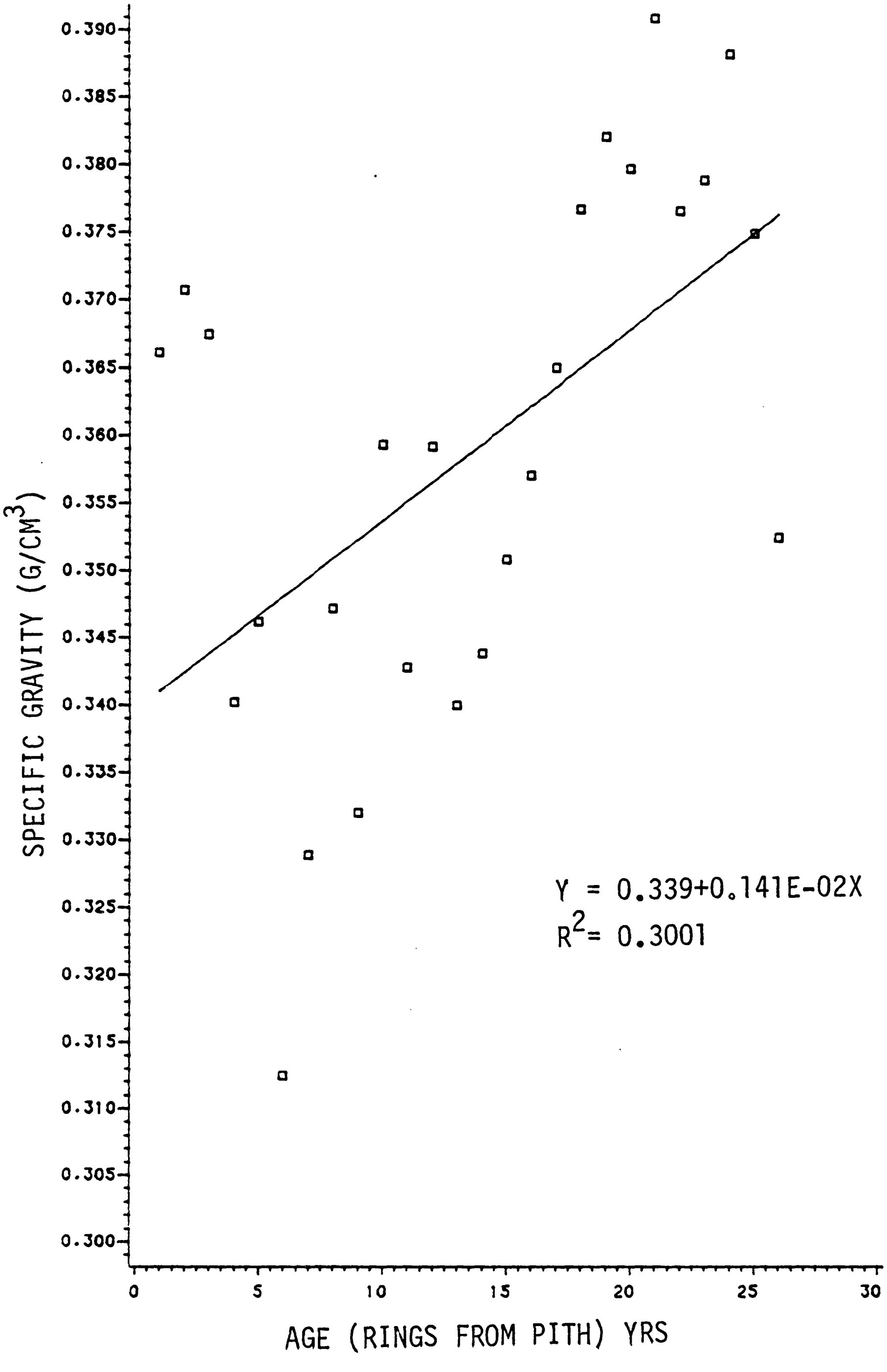


Fig 47 The relationship between specific gravity (Y) and age (X) of plantation grown cottonwood (_Populus deltoides_)

Fig. 48 Relationship between modulus of rupture and number of fibers per uint area, radial diameter of fiber and fiber density index in cottonwood (Populus deltoides) as given in Table 20.

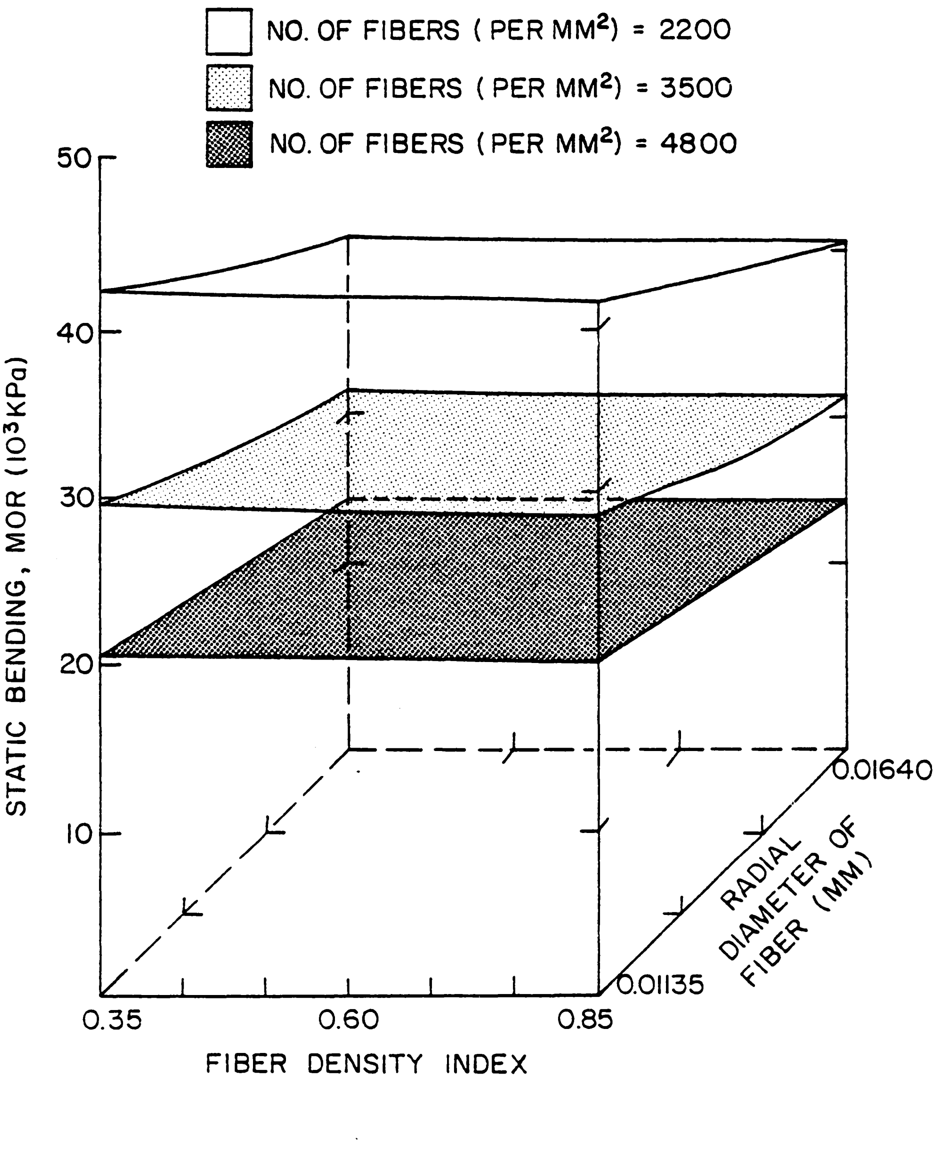

NO. OF FIBERS (PER MM²) = 2200
NO. OF FIBERS (PER MM²) = 3500
NO. OF FIBERS (PER MM²) = 4800
50
40
30
20
10
STATIC BENDING, MOR (10³KPa)
0.35
0.60
0.85
FIBER DENSITY INDEX
0.01135
0.01640
RADIAL DIAMETER OF FIBER (MM)

Fig. 49 Relationship between modulus of elasticity and number of fibers per unit area, radial diameter of fiber and fiber density index in cottonwood (Populus deltoides) as given in Table 20.

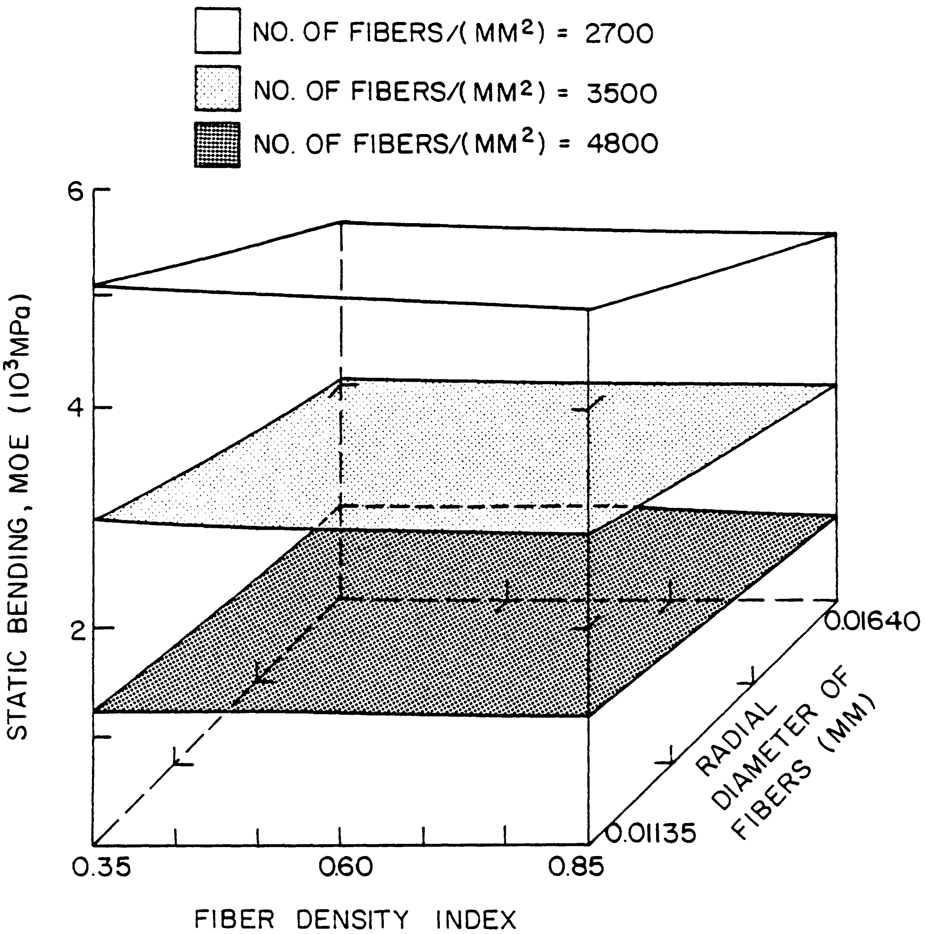
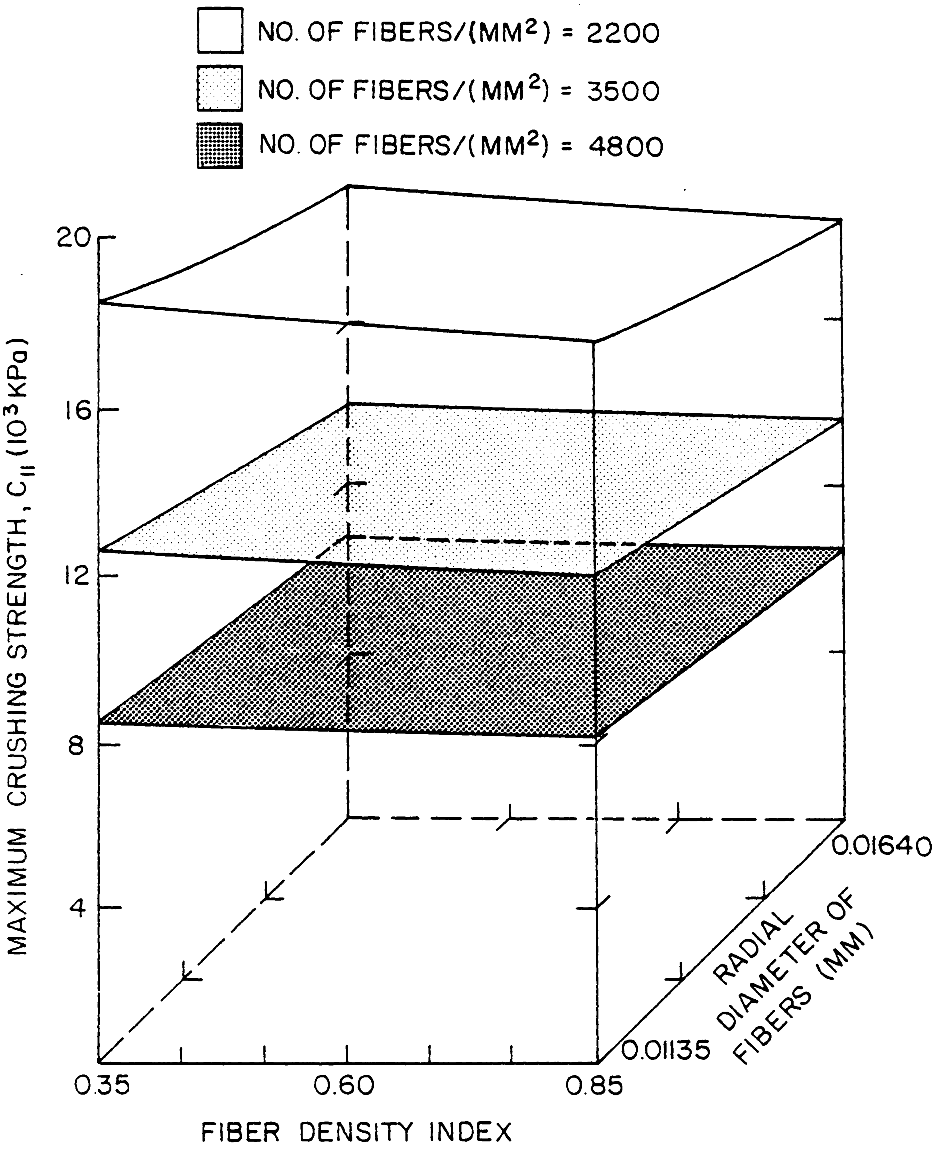

□ NO. OF FIBERS/(MM2) = 2700
░ NO. OF FIBERS/(MM2) = 3500
▓ NO. OF FIBERS/(MM2) = 4800
STATIC BENDING, MOE (10³MPa)
6
4
2
0.35
0.60
0.85
FIBER DENSITY INDEX
0.01135
0.01640
RADIAL DIAMETER OF FIBERS (MM)

Fig. 50 Relationship between maximum crushing strength parallel to grain and number of fibers per unit area, radial diameter of fiber and fiber density index in cottonwood (Populus deltoides) as given in Table 20.


NO. OF FIBERS/(MM^2) = 2200
NO. OF FIBERS/(MM^2) = 3500
NO. OF FIBERS/(MM^2) = 4800
MAXIMUM CRUSHING STRENGTH, C_{11} (10^3 KPa)
20
16
12
8
4
0.35
0.60
0.85
FIBER DENSITY INDEX
0.01135
0.01640
RADIAL DIAMETER OF FIBERS (MM)

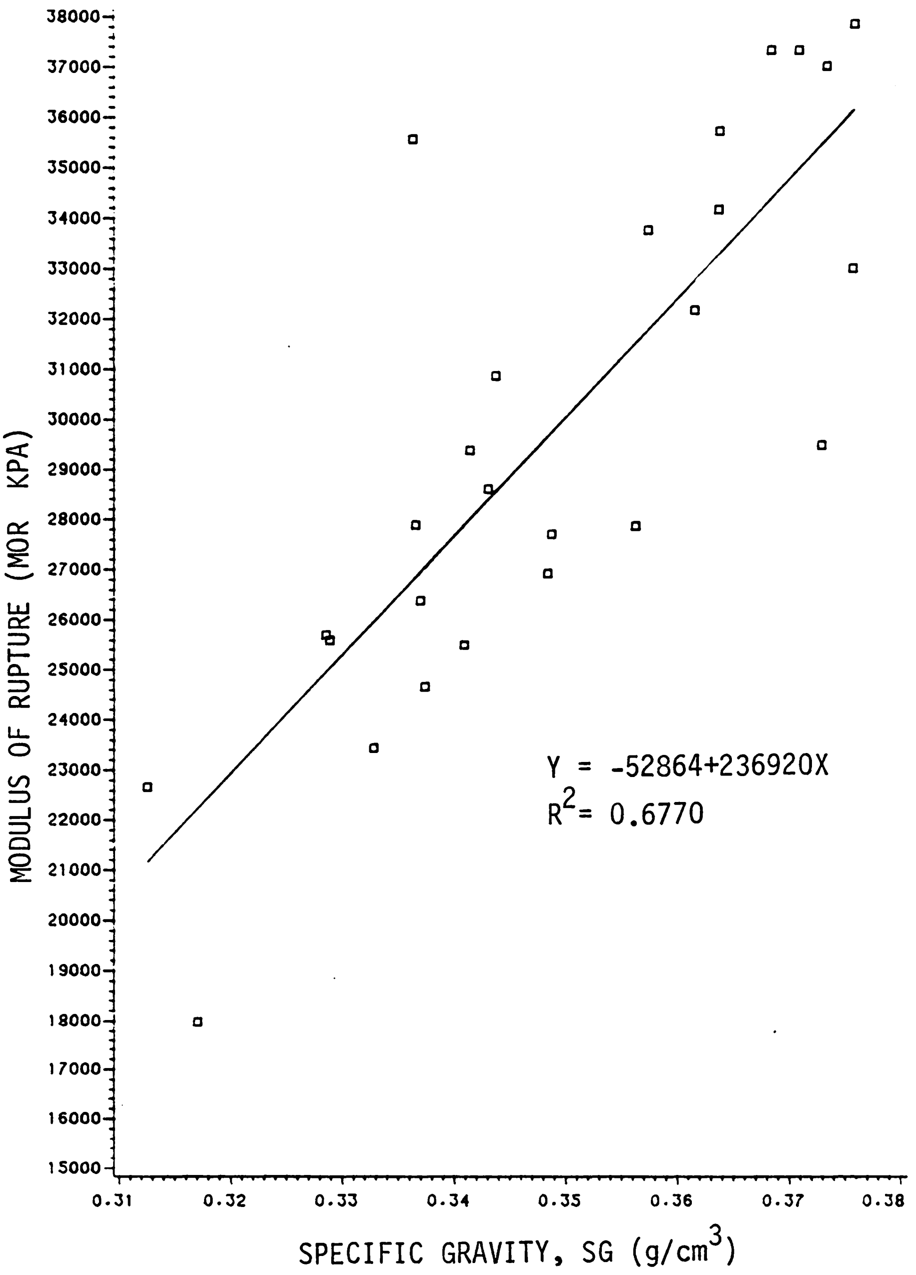


Fig. 51 The relationship between modulus of rupture (Y) and specific gravity (X) of plantation grown cottonwood (Populus deltoides)

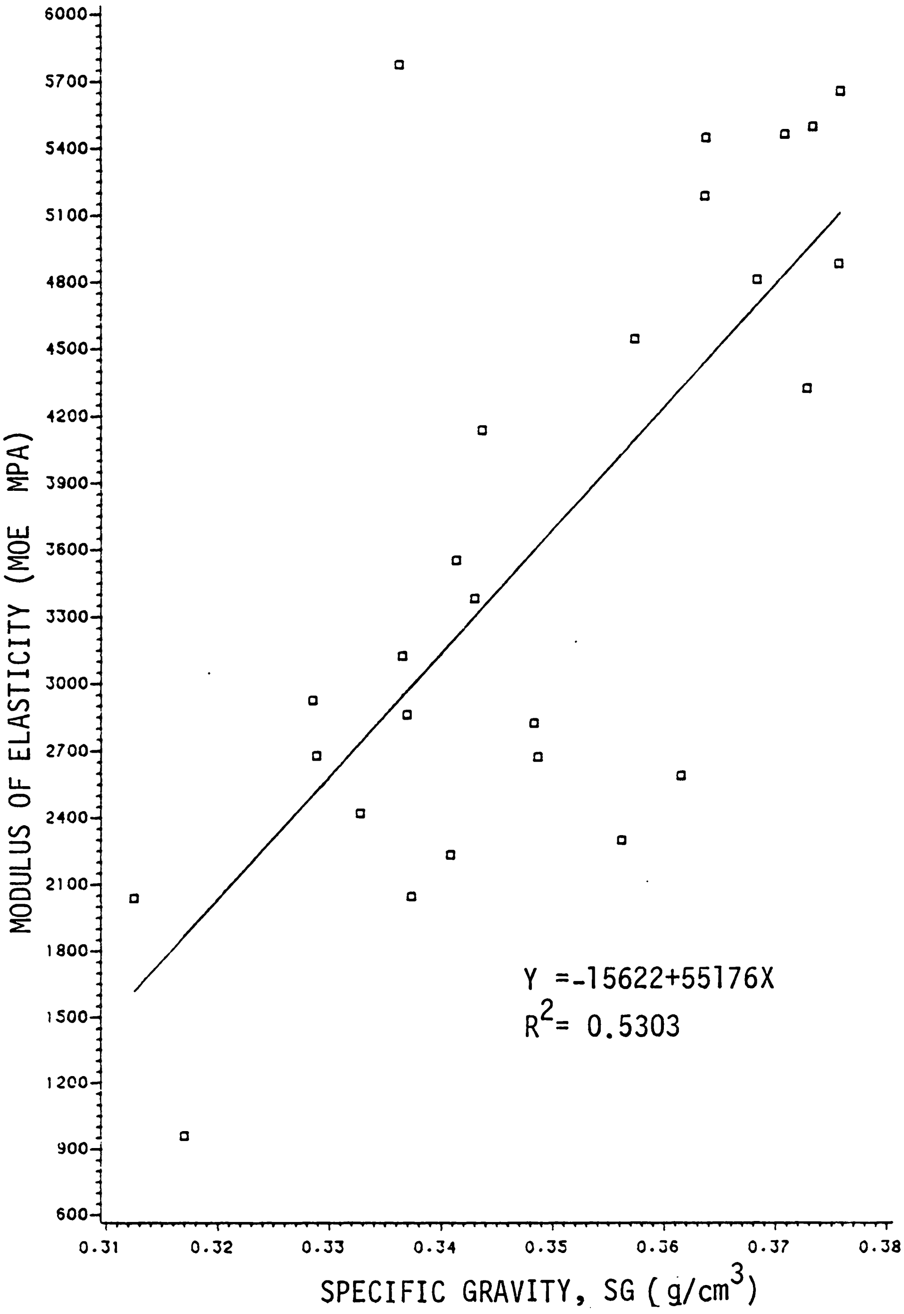


Fig. 52 The relationship between modulus of elasticity (Y) and specific gravity (X) of plantation grown cottonwood (Populus deltoides)

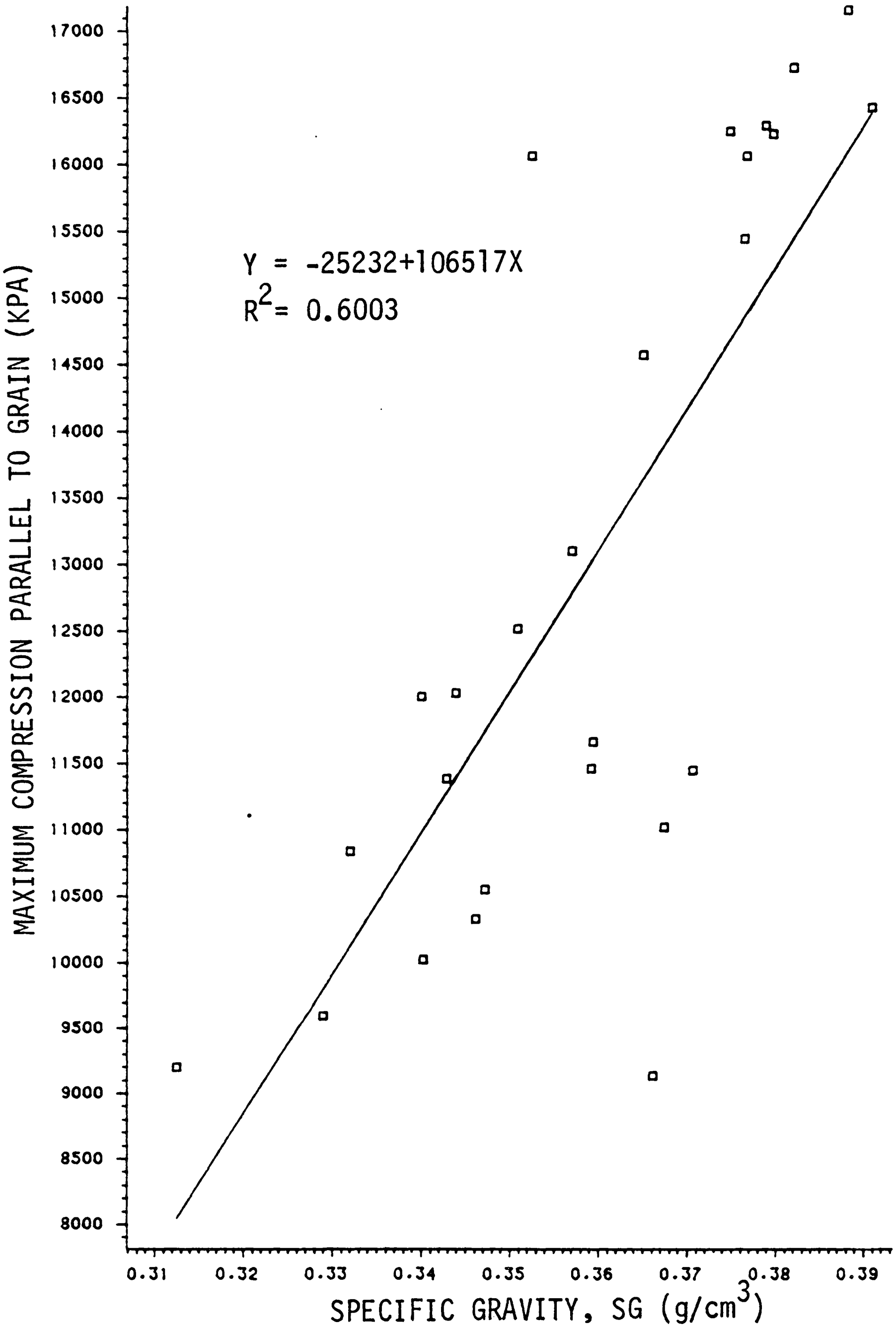


Fig.53 The relationship between maximum compression parallel to grain (Y) and specific gravity (X) of plantation grown cottonwood (Populus deltoides)

Fig. 54 Relationship between specific modulus of rupture and radial diameter of fiber, vessel shape factor, and tangential diameter of vessel in cottonwood (*Populus deltoides*) as given in Table 22.

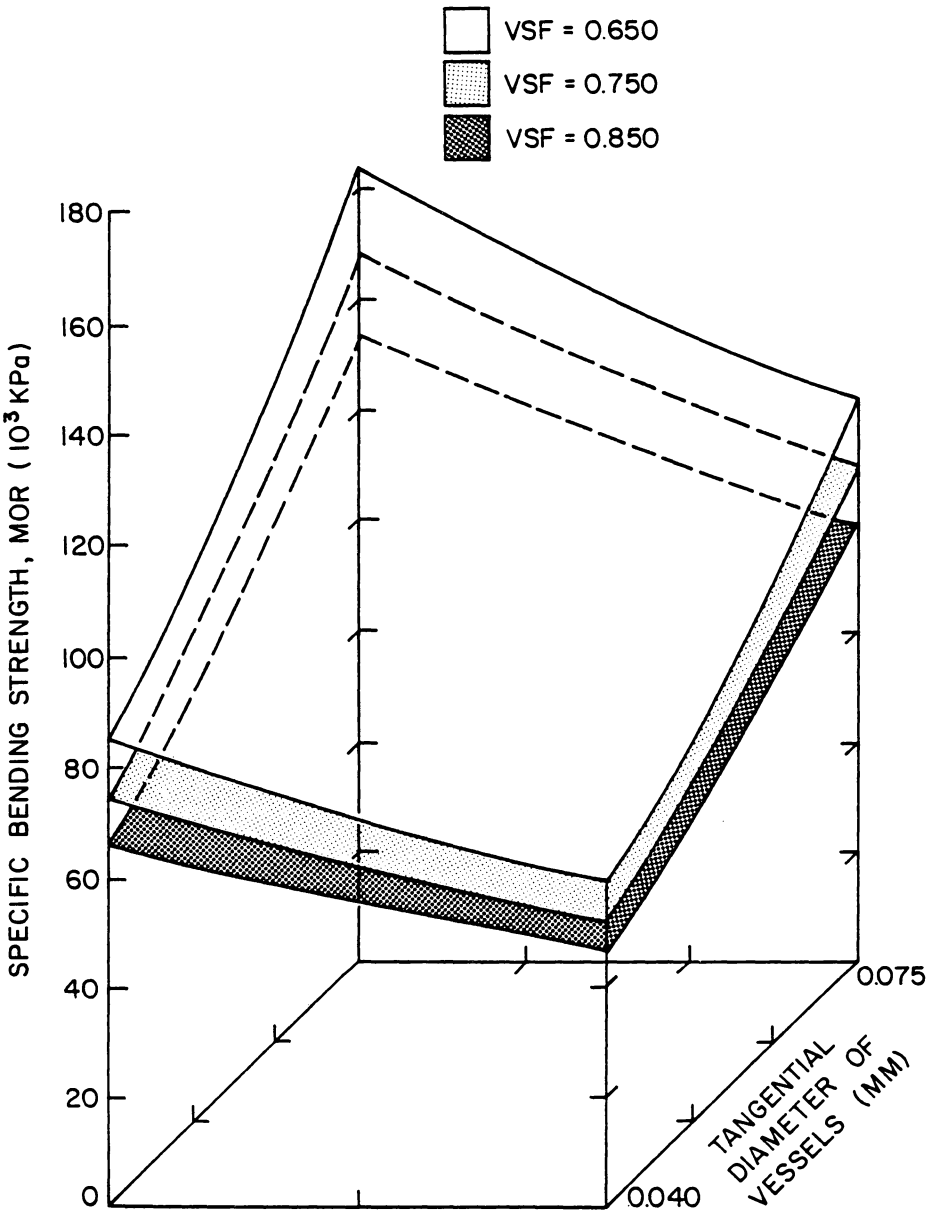

VSF = 0.650
VSF = 0.750
VSF = 0.850
SPECIFIC BENDING STRENGTH, MOR (10^3 KPa)
180
160
140
120
100
80
60
40
20
0
0.0115
0.0140
0.0165
RADIAL DIAMETER OF FIBER (MM)
0.040
0.075
TANGENTIAL DIAMETER OF VESSELS (MM)

Fig. 55 Relationship between specific modulus of elasticity and radial diameter of fiber, vessel shape factor, and tangential diameter of vessel in cottonwood (Populus deltoides) as given in Table 22.

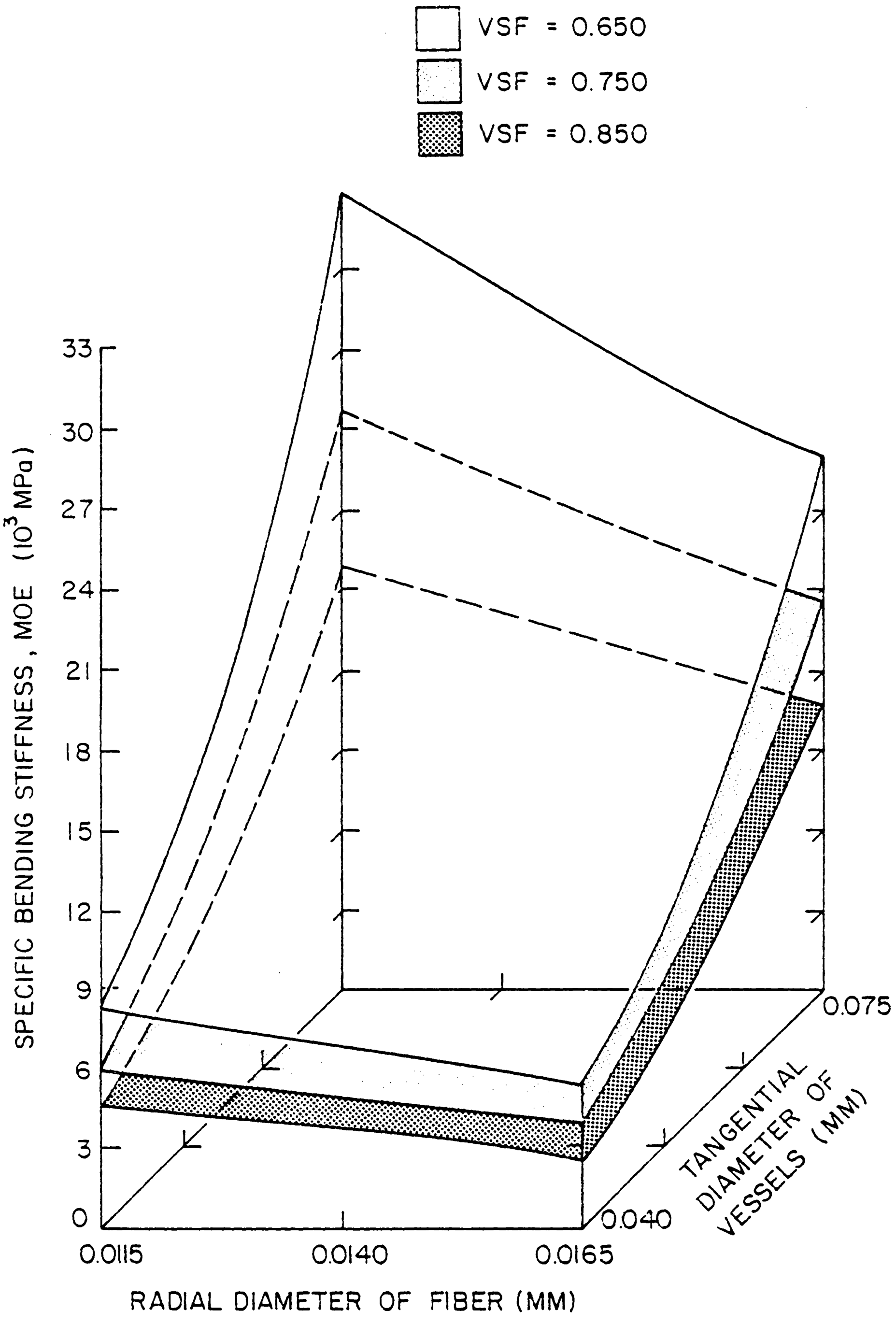
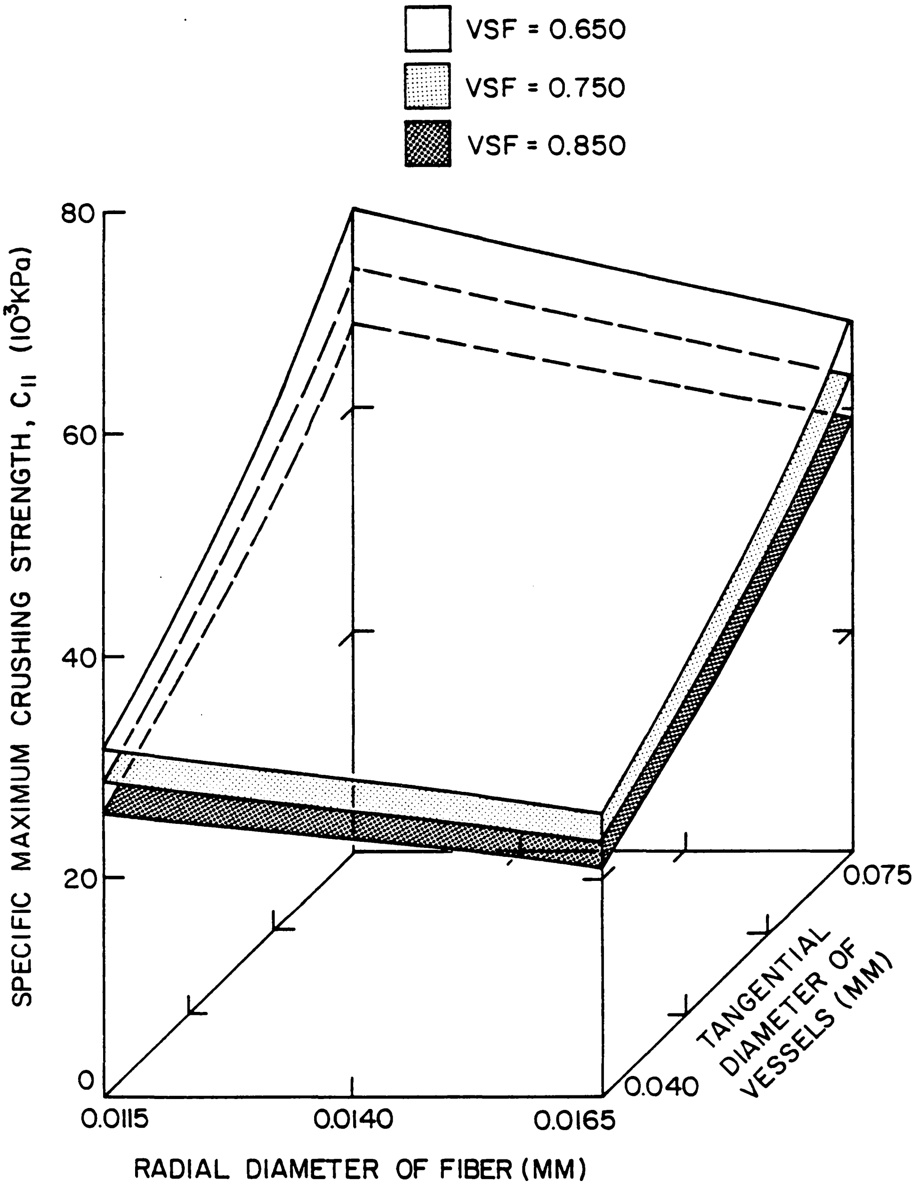

VSF = 0.650
VSF = 0.750
VSF = 0.850
SPECIFIC BENDING STIFFNESS, MOE (10^3 MPa)
33
30
27
24
21
18
15
12
9
6
3
0
0.0115
0.0140
0.0165
RADIAL DIAMETER OF FIBER (MM)
0.075
0.040
TANGENTIAL DIAMETER OF VESSELS (MM)

Fig. 56 Relationship between specific maximum crushing strength parallel to grain and radial diameter of fiber, vessel shape factor, and tangential diameter of vessel in cottonwood (*Populus deltoides*) as given in Table 22.


VSF = 0.650
VSF = 0.750
VSF = 0.850
SPECIFIC MAXIMUM CRUSHING STRENGTH, C_{11} (10^3KPa)
80
60
40
20
0
0.0115
0.0140
0.0165
RADIAL DIAMETER OF FIBER (MM)
0.040
0.075
TANGENTIAL DIAMETER OF VESSELS (MM)

QUANTITATIVE ANATOMICAL CHARACTERISTICS OF PLANTATION GROWN LOBLOLLY PINE (PINUS TAEDA L.) AND COTTONWOOD (POPULUS DELTOIDES Bart. ex Marsh.) AND THEIR RELATIONSHIPS TO MECHANICAL PROPERTIES

by

Musiliu Ade Onilude

ABSTRACT

The anatomical properties of loblolly pine (*Pinus taeda* L.) and cottonwood (*Populus deltoides* Bart. ex Marsh.), both from intensively managed woodlands, were quantitatively characterized using the principles of stereology. Physical and mechanical properties were also determined for each growth increment of six sample trees of both species. Anatomical parameters measured were correlated to certain mechanical properties.

The numerical values obtained for the anatomical properties were derived from simple counting measurements. They included size distribution parameters of individual anatomical elements as viewed on transverse sections. The parameters were determined both in terms of within growth ring variability and in terms of changes from pith to bark within the species studied.

Average mechanical properties of the two species were shown to increase significantly from pith to bark. In the regression models

constructed for predicting physical and mechanical properties, up to three anatomical variables were found to significantly account for the variation in the strength properties. Close to 87% of the variation in MOR and 86% in MOE could be accounted for by the three anatomical parameters in loblolly pine. About 82% of the variation in the crushing strength parallel to grain could be explained by the anatomical variables. The three anatomical parameters selected for predicting strength properties in cottonwood were all related to fibers, suggesting that the most important anatomical elements determining strength in cottonwood are the fibers. Overall predictability in cottonwood was not as good as in loblolly pine. Less than 40% of the variation in MOR could be explained by fiber properties alone, while almost 70% in MOE was accounted for. Over 55% of the variation in maximum compression strength parallel to grain could be explained by fiber properties alone.

About 84 to 94% of the variation in specific strength properties was accounted for by three anatomical variables unrelated to specific gravity in loblolly pine. Addition of specific gravity improved the model with R^2 values between 92-97%. In cottonwood, 65-85% of variation in specific strength properties was accounted for by three anatomical variables unrelated to specific gravity. The R^2 values also improved by addition of specific gravity (82-92%).