EFFECTS OF POTASSIUM FERTILIZER ON THE WOOD DENSITY AND RELATED ANATOMICAL CHARACTERISTICS OF RED PINE WOOD

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INTRODUCTION

The past few decades have seen an increasing use of commercial fertilizers by land managers to replenish deficient soil nutrients in an attempt to increase the productivity of the forest stand.

Red pine (*Pinus resinosa* Ait.) from a 16-year-old plantation growing on a site known to be potassium deficient, exhibited a characteristically poor growth in height and diameter (10). When part of the area was treated with a potassium fertilizer, the trees in these fertilized plots showed marked response in foliage color, vigor, and significantly increased diameter and height growth, when compared to trees from unfertilized plots (11). This response continued for a period of at least twenty years after treatment.

The object of the present study was to attempt to determine whether this increased external growth rate of the fertilized trees was accompanied by changes in wood density and anatomical characteristics that could be interpreted as improvements in wood quality.

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REVIEW OF LITERATURE

An extensive review by Mustanaja and Leaf (17) points out that most research with forest fertilization up to the time of their writing concerned primarily tree growth and volume increase and only incidentally with anatomical changes in the xylem. It has only been during the last decade in North America that there has been an increased interest in the interaction effects between tree fertilization and the anatomical character of the wood produced in these trees. Therefore, the literature in this particular area is limited; and only a few investigations have been reported.

Tracheid Length.--Bissett (4), working with stems from *Pinus pinaster* Ait. trees, found a marked decrease in the length of latewood tracheids after application of superphosphate to the stands; and at the same time the total number of cells in the radial file within the growth ring increased. Zobel et al., (24) compared the wood of loblolly pine (*Pinus taeda* L.) which was formed seven years before fertilization with wood formed seven years after. Heavy rates of fertilization (i.e., three consecutive years of a high-level application of nitrogen (N), phosphorus (P), and potassium (K)--160-80-80- lb., respectively) caused a decrease in tracheid length and an increase in diameter growth. In an intense study by Posey (20), who fertilized loblolly pine with treatments of N, P, and K, results were reported that potassium had no detectable effect upon growth rate or wood properties. Nitrogen caused the greatest differences in wood properties and growth rate, although N with P gave slightly greater response than N without P. He concluded that the average tree response to fertilization was an increase in growth rate and a decrease in tracheid length.

Tracheid Wall Thickness and Diameters.--One of the first extensive studies of changes in wood characteristics due to varying fertilization treatments was reported by Pechman and Wutz (19) who studied the influences of different fertilizers on the wood properties of Norway spruce (*Picea excelsa* Link.) and on Scot's Pine (*Pinus sylvestris* L.). They reported that fertilization of a 56-year-old spruce stand with lime, phosphate, and calcium-ammonium nitrate for three consecutive years resulted in an increased radial growth and thinner tracheid walls in the latewood; while fertilization with N, P, and K of a pine stand over 200 years old resulted in thinner cell walls in both earlywood and latewood tracheids.

The effect of ammonium nitrate and superphosphate fertilizers on 9-year-old plantation grown slash pine (*Pinus elliottii* Engeln.) was was reported by Williams and Hamilton (22) and revealed no significant differences in wall thickness of earlywood tracheids associated with fertilization treatments.

Posey (20) reported that in most all instances the radial double-wall thickness of the fertilized trees was below the average of the check trees. Tangential tracheid diameter failed to show any differences after the several fertilizing treatments.

A review by Klem (12) of the more important results of wood quality associated with fertilized trees, concludes that the tangential tracheid diameter is less likely to be influenced by growth rate than is the radial diameter and that as the result of fertilization radial tracheid diameter increases in the latewood.

Percentage of Latewood.--The majority of investigators are in agreement on the effects of fertilization on latewood percentage. Pechman and Wutz (19), Williams and Hamilton (22), and Posey (20) all report conditions of rapid growth after fertilization with an increase in the proportion of earlywood and a commensurate decrease in the proportion of latewood.

The results of work by Sastry (21), who investigated the effects of fertilizer application on wood properties of Douglas fir (*Pseudotsuga menziesii* (Merb.) Franco.), showed a 16-50 percent increase in the radial width of increments and a corresponding decrease in latewood percentage.

Wood Density.--Density change resulting from fertilization is one characteristic that has been investigated over a period of years. The early work of Erickson and Lambert (6), which analyzed the combined effect of fertilization and/or thinning on 30-year-old Douglas fir, showed significant decreases in overall density due to fertilization.

Zobel's (24) preliminary study of loblolly pine showed that trees fertilized at age 16 produced wood of considerably lower density than unfertilized trees otherwise similar in age and treatment.

Posey's work (20) showed that the average tree responded to fertilization with a decrease in density. The trees with an initial higher density, longer tracheids, and thick radial cell walls showed more reduction (percent) than did those trees with initially low density or thin radial walls and short tracheids.

As Klem's review pointsout (12), it has been established by numerous researchers that up to 50 percent of the variation in wood density is directly related to the variation in latewood percentage, which in turn is related to the number of earlywood cells produced in a given growth increment. He concludes that experiments have shown that some trees, depending on their growing conditions before fertilization, will respond differently to a fertilization treatment. Trees that were originally extremely slow growing had an increase in density after fertilization, while medium to fast growth trees before treatment showed a decrease in wood density after treatment.

It can be realized from study of the available literature that knowledge of the effects of fertilization on various wood characteristics is somewhat limited. The majority of the investigators agree that fertilization does have an effect on wood characteristics, but to what extent and in relation to which characteristics seems to be a major cause of disagreement. There is general agreement on certain obvious effects: 1) an increase in width of growth increments; 2) a decrease in tracheid length; 3) a general decrease in latewood percentage accompanied by a corresponding decrease in wood density.

MATERIALS AND METHODS

The wood samples used in this investigation were obtained from a potassium deficient outwash plain on the Pack Forest, near Warrensburg, New York. Ten 36-year-old red pine trees were selected for study. These trees were all of dominant or co-dominant crown class as determined at the time of cutting and were made up of five trees randomly selected from a plot that had been treated with potassium fertilizer (plot G) and five randomly selected from a control plot (plot K). Insofar as is apparent. the fertilizer treatment constitutes the sole difference between these plots (see Table 1).

Single internodes were selected from comparable zones in each of the trees. The internode chosen for each group was taken as representative of maximum tracheid length for the entire height of the tree, which Denwoodie (5) reports as occurring at a distance between 20 and 40 percent of the total height from the ground. Also, consideration was given to the time of fertilization so that the internode from the fertilized trees was of wood produced entirely after treatment had occurred. Therefore, the internodes closest to 25 percent of the height from the root collar were chosen to satisfy both conditions; i.e., 22nd internode from the apex for each of the fertilized trees and 25th internode from the apex for each of the controls.

For each stem sampled, a cross-sectional disc, 1 1/4 inches thick, was taken approximately midway between nodes (See Figure 1). Two adjacent strips, approximately 1/2 inches wide, were cut on each side of a diametrical line drawn through the pith of these dics. Each strip was labeled as to tree number, internode number, and north direction.

One strip was used for measurements of earlywood and latewood cell counts from pith to bark, earlywood and latewood ring widths measured in millimeters, density measurements, latewood percentage determination, double-cell wall thickness measurements, cell-lumen diameter measurements, and total tracheid diameters, all were taken in the radial direction. The other diametrical strip was dissected into earlywood and latewood segments, macerated, and used for tracheid length measurements.

Determination of Tracheid Lengths.--Chips were taken from each individual ring, segregating earlywood from latewood, placed in labeled vials according to tree and individual ring number, and then macerated according to Franklin's Method (7). An Eberbach Micro-projector was used for the actual tracheid length measurements. Fifty randomized measurements were made from each earlywood and latewood sample in each ring. Care was exercised to choose only unbroken fibers.

Determination of Cell Counts.--The number of cells for the latewood and earlywood zones, the total number of cells from the pith, and the total number of cells in the growth increment were counted in a radial file from bark to pith on the cross-sectional base of the diametrical strip from each disc. These counts were made by a traveling light microscope, with a calibrated-traveling eyepiece using incident lighting. Mork's Rule (16) was used for distinguishing between earlywood and latewood zones.

Cell Size Determination.--The double-cell wall thickness of the tracheids, in the radial direction, was measured from thin microtomed sections taken from each diametrical strip. Ten measurements were made for both earlywood and latewood zones in each individual ring. Because of the relatively thin sections, a light microscope employing transmitted light could be used for more accurate measurements up to a hundredth of a micron.

Cell-lumen diameters and total cell diameters were also measured in the radial direction from these microtomed sections. Ten measurements were taken from each zone of maximum latewood tracheid length and minimum earlywood tracheid length within each individual ring, again using the light microscope with transmitted light and a calibrated traveling eyepiece.

Determination of Ring and Age Measurements.--The measurements for ring widths of both earlywood and latewood zones, total ring widths, and the distance of the zone from the pith were measured on the cross-section of the diametrical section with the traveling-incident light microsope. The rings were numbered (number one being at the bark) consecutively till the pith was reached, and the age was considered to be the total number of rings in the particular internode.

Determination of Percentage of Latewood.--Two methods for determining latewood percentage were employed in the present study. One involved counting the actual number of latewood cells in a particular ring and dividing this figure by the total cells in that ring. The second method involved dividing the width of that latewood zone, measured in millimeters, by the total width of that particular ring. Data was taken from each ring of all ten diametrical strips.

Determination of Wood Density by Beta-Ray Absorption.--Wood density, especially in relatively thin sections, may be measured with a high degree of accuracy by the use of beta-rays (15). Such a system was built and used for the current study. A detailed explanation of the beta-ray absorption technique used can be found in the original manuscript (9). In brief, the technique consists of passing thin radial microtomed sections (100 pm) of wood through a narrow beam of beta-rays. By graphically recording the modulation of the beam arising from density changes in successive locations in the sample, the variation of density across the growth increment is obtained (see Figure 2). The three main constituents that make up wood density; namely, actual wood substance, amount of water present in the wood, and the amount of extractives that are present were all taken into consideration during this technique. The extractives were removed, a close control was kept on the amount of water present in the wood which left the actual wood substance present as the only variable. Therefore, as the beta-rays that pass through the wood sample, they are absorbed according to the variation in wood substance across the growth increment. A graphic output of the beta rays that do pass through the specimen can be interpreted in terms of wood density variation when calibrated to a standard sample of known density. Figure 3 depicts a typical output graph. The operating standards, i.e., feed rate of the specimen, chart recorder speed, and operating voltage were also controlled quite closely.

TREATMENT OF DATA

Data Reduction.--The relationship of the various anatomical and wood properties between the fertilized and control trees was determined principally by regression analysis, using a computer for the basic calculations and in plotting the results. The standard "F" test and correlation coefficients were used to determine the significance of the regression equations and trends of the data.

Inter-comparisons.--A variation of the chi-square test for testing similarities between curves suggested by Freese (8) was employed for examining the pairs of regression equations. This method uses the chi-square distribution to compare the accuracy of a new method against a standard one, calculationg chi-square by means of a hypothesized variance. These tests were applied separately to each pair of earlywood regressions, fertilized and control, and each pair of latewood regressions for the individual characteristic under investigation.

DISCUSSION OF RESULTS

Tracheid Characteristics

Tracheid Length.--The well established pattern (5, 18) of increasing tracheid length as the distance from the pith increases was observed in this material. The data for each individual tree, plotted as single graphs, gives a pattern showing a rapid increase at first and then a more gradual increase as the tree grows older (Figure 4). This trend is in agreement with most other reports. When regression lines describing the changes in tracheid length were fitted to the pooled data of 110 rings (5 trees) for fertilized and 125 rings (5 trees) for control, straight line relationships were found to show the best fit (Figure 5).

All graphs presented in this discussion are regression lines, which were fitted to the independently pooled data for each group and represent the most significant trend found.

It is apparent from Figure 5 that fertilization was accompanied by a decrease in the average tracheid length for both earlywood and latewood tracheids. This decrease can be contributed to the increased radial growth rate of the fertilized trees. Fertilization caused an increase in growth with an average increase in tree diameter of approximately one inch which represents an increase of about 20 percent in diameter at d.b.h. (see Table 1). The increased growth rate results in an increase rate of pseudotransverse direction(see Figure 6) in Cambial initials, i.e., a reversion to the juvenile condition. A high rate of frequency of these divisions, combined with a high rate of survival of all new cambial initials, results in relatively short new cambial initials which in turn produce short tracheids (14). The addition of this increased amount of short tracheids in the increment reduces the average length of the tracheids.

Radial Double-Cell Wall Thickness.--Variations in tracheid wall thickness occur throughout the life of the tree. Earlywood and latewood tracheids present the most conspicuous differences, but there are also pronounced changes associated with age. It is a well established pattern that tracheid wall thickness in conifers, and particularly pines, increases with increasing age outward from the pith (18). This pattern is primarily evident in latewood tracheids; and although wall thickness of earlywood tracheids also varies, the variations are much reduced.

As can be observed from Figure 7, the radial double-cell wall thickness increases as the radial distance from the pith increases. Throughout this discussion, cell refers to a longitudinal tracheid of the xylem, Knowing that tracheid lengths also increase as the radial distance from the pith increases (Figure 5), the results shown in Figure 8 of increasing double-cell wall thickness as tracheid length increases are what is expected.

If the earlywood and latewood tissue systems are examined separately (Figures 7 and 8), it is apparent that in the latewood there is an approximate 20 percent decrease in radial-cell wall thickness of the fertilized material as compared to the control. This result corrobotates findings of other workers investigating similar systems (19, 20, 24). However, the increase of approximately 100 percent in the double-cell wall thickness of the earlywood of the fertilized material as compared to the control is in disagreement with these same authors, One possible explanation for this increase stems from a discussion by Larson (13). He suggests that the varying thickness of cell walls can be related to the photosynthetic process and net available assimilates resulting from photosynthesis.

During the spring, at the beginning of earlywood production the competition for available assimilates is very severe, The newly activated growth centers, i.e., tip and branch elongation points and new needle production use the majority of available assimilates. In the present investigation the control trees, with very poor crown development, have very little, if any, reserve assimilates from the previous year. Therefore, almost all new assimilates produced must be used for tip elongation and new needle production. This in turn leaves very little assimilates available for the developing earlywood cell wall. The result is that the S2 layer of the cell wall is poorly developed, and a thin wall is produced.

On the other hand, the fertilized trees have vigorously growing crowns, resulting in a reserve of assimilates from the previous year, For this reason the axial elongation proceeds very rapidly, and the new needles reach maturity much more quickly than in the control trees. As a result, the photosynthesis from the new leaves appears sooner than in the control group; and more net assimilates are available for cell wall production. This in turn results in an earlywood cell wall which is thicker in fertilized trees than in the control trees.

The decrease in radial double-cell wall thickness of the latewood tracheids discussed earlier could possibly be explained along reverse lines. Latewood cells are produced by the cambium at the end of the growing season, a period of decreasing photosynthesis production. This decrease in available assimilates must be distributed over the development of a larger number of cell walls. The increase of total cells in the latewood zone as seen from Figure 9 would mean a greater total cell wall area that must share the net assimilates.

Tracheid Diameter.--As is observed from Figures 7 and 10, the earlywood of the fertilized material when compared to the control has thicker cell walls and increased radial cell lumen diameters. These results add up to an overall larger diameter earlywood tracheid produced by the fertilized tree as seen in Figure 11.

No measurements were made in the tangential direction in the present investigation. However, results from other studies reveal that there is a slight increase in the tangential dimensions associated with distance from the pith and also as the result of fertilization (14, 20).

When comparing the same features of the latewood tracheids, the control material has the thicker cell wall (Figure 7), the larger radial cell lumen diameter (Figure 10), and thus the overall larger diameter latewood tracheid (Figure 11).

It is also clear from Figure 10 that the radial cell lumen diameter of the earlywood increases with increasing age but decreases slightly in latewood. However, total radial tracheid diameter (Figure 11) for the earlywood zones both show an increase for about 15 years and then a decrease towards the bark, while the latewood shows an increase with increasing age.

LATEWOOD PERCENTAGE

Variability in coniferous woods can, in part, be accounted for by the separation of the growth rings into earlywood and latewood zones (13). The percentage of latewood is a widely used index of the proportionate division of the growth increment in measurement of wood quality. Even though the earlywood and latewood zones each display individual characteristics, fluctuations in cell diameter and wall thickness caused by variable growth conditions make these zones at times difficult to determine.

For the most part it is agreed that the percentage of latewood in conifers varies directly from the pith to the bark in the radial direction (18). The graphic trends for red pine used in the current study (Figures 12 and 13) conform to this well established relationship.

The fertilized trees with their accelerated growth rate have been shown to have wider growth increments than those of the control group (Figure 14) with the greater percentage of increase in the earlywood (Figures 9 and 15).

If the number of cells or width of earlywood zone increases at a greater rate than the corresponding latewood zone, then the latewood percentage which is a ratio of these two components must decrease. This seems to be the situation in the fertilized where a decrease in the latewood percentage is evident when compared to the control trees at the same age (Figure 13).

Also evident from Figure 12 and 13 is the similarity between the two graphs. Apparently, there is little differentiation between age (number of rings from the pith) and distance from the pith when compared to percentage of latewood.

WOOD DENSITY

Wood density is a complex variable. It is determined by several growth and physiological factors which themselves can be quite variable. Density of the wood is affected by anatomical characteristics, i.e., cell wall thickness, cell diameters, percent latewood and cell length. The chemical composition of wood, i.e., such as percent of holocellulose, percent of lignin, and also the amount of infiltrates that are present may have some affect on wood density (23). The present study was confined to the anatomical factors affecting wood density.

Density Variation with Age and Distance from Pith.--Density determinations were made for each earlywood and latewood zone directly from the maximum and minimum points on the density curve for the particular increment. The results are presented as two separate groups of regressions, i.e., the latewood, control and fertilized, as one group; and the earlywood, control and fertilized as another. In all cases, unless otherwise stated these regressions of the density trends represent the densities of earlywood and latewood zones independently and not the density of the entire ring.

It is apparent from Figures 16 and 17 that for all cases the density of the fertilized trees decreases from the pith outward for approximately 14 years and then begins to increase toward the bark. This is characteristic of a large group of conifer woods (18). For density compared to age, Figure 16, this trend is evident in all cases except for the latewood control, where the results show a steady decrease from pith outward. Both the earlywood and latewood control show a steady decrease in density when compared to distance from the pith (Figure 17). In both cases there is a greater decrease in density for the fertilized trees. Figure 18 shows the relationship of wood density and cells per zone. In both earlywood and latewood the fertilized trees show a lower density.

Density Variance with Tracheid Characteristics.--A comparison between density and tracheid characteristics that contribute to wood density leads to the observation of a variety of trends.

Figure 19 shows a general decrease in wood density for all cases as the cell wall thickness increases. The earlywood fertilized group shows a much sharper decrease in density when compared to the control.

Figure 20 relates radial cell lumen diameter with wood density. The data reveal an increase in latewood density and a decrease in earlywood density with increased radial cell lumen diameter.

The trend in Figure 21 is for a decrease in density for the latewood of the fertilized trees and for both the earlywood groups as radial tracheid diameter increases while an increase in density is evident with increasing tracheid diameter for latewood control.

Figure 22, relating density to tracheid length, indicates a decreasing density with increasing tracheid length. From Figure 8 we saw that the longer tracheids are associated with a thicker radial double-cell wall so it would seem that the results in Figure 22 are just reversed. However, it has been shown in the past (5, 20) that longer tracheids also have a larger radial cell lumen diameter compared to shorter tracheids. Therefore, it seems that the radial cell lumen diameter is a greater factor than double-cell wall thickness in controlling wood density.

It becomes apparent after carefully studying Figures 19-22 that density changes in the earlywood zone follow a more uniform pattern than is the case for density changes in the latewood zone. It is also apparent that earlywood density is a function of radial tracheid diameter with the controlling factor being that of cell lumen diameter rather than wall thickness or tracheid length. For the latewood, wall thickness seems to be a more important factor in the control of wood density than tracheid lumen radial diameter.

In comparing Figures 11 and 16 (see Figure 23) it can be seen that the lowest earlywood density in both control and fertilized trees coincides approximately with the largest earlywood tracheid diameters. It can also be noted that fertilization has resulted in larger earlywood tracheid diameters and a corresponding lower earlywood density when compared to that of the control groups. From these same figures, the latewood tracheid diameters of the fertilized trees are less than that of the control and concomitantly the latewood density of the fertilized trees is slightly less than that of the control.

Density Variations with Latewood Percentage.--Figure 24 relates mean density, i.e., the average of the earlywood and latewood density, to latewood percentage. For the control group no significant trend of the data comparing wood density to latewood percentage could be found. The fertilized material, however, showed a slightly lower density for any given value of latewood percentage and an increase in density with increase in latewood percentage.

SUMMARY AND CONCLUSIONS

An investigation was conducted to determine the effects of correcting potassium deficiency in red pine (*Pinus resinosa* Ait.) on wood density and several related anatomical characteristics. The modifications induced by fertilization were studied as changes in the characteristic patterns of earlywood and latewood from the pith to the bark.

The wood samples studied were taken from 36-year-old red pine plantations growing on an outwash plain on the Pack Forest, near Warrensburg, New York. Two blocks in the plantation were sampled. These represented identical sites except for the fact that one was deficient in potassium, and the contrasting area had been fertilized by broadcast of potassium at 200 pounds per acre twenty years prior to sampling.

Five dominant trees were sampled in each plot by cutting discs from the trunk, at approximately one-fourth the total height. Thus, the internodes selected represent wood formation entirely influenced by either one of the levels of potassium in the site. Two adjacent diametrical strips were cut from each disc. One diametrical strip was used for tracheid length measurements, while the other was used for various radial tracheid dimensions, cell counts, ring widths, and wood density measurements. Earlywood and latewood data were segregated for all measurements, A continuous record of wood density from pith to bark was made from 100 um radial sections using a beta-ray absorption technique.

Data reduction and regression analysis were performed on the IBM 1620 II computer to determine the relationship within and among the various properties investigated. A variation of the chi-square test was employed for determining similarities of data for individual properties between the two groups.

The data indicated that treatment with potassium fertilizer produced an average increase in diameter of approximately one inch over that of similar trees from potassium deficient sites. Concomitant with this increased radial growth, a decrease in average tracheid length across the growth increment was apparent in the fertilized trees, most probably resulting from an increased rate of pseudotransverse divisions in the cambium. This accelerated growth rate was reflected in both the earlywood and latewood zones by increased radial widths and number of cells.

The response to fertilization as measured by wood properties, resulted in significant decreases in latewood radial double-cell wall thickness, latewood radial tracheid diameter, and percentage of latewood. In contrast, significant increases were found in earlywood wall thickness and earlywood tracheid diameter. Density of the wood in both earlywood and latewood was shown to be decreased by treatment of the site with potassium. The density changes were shown to be related to changes in tracheid dimension.

Correlations among the wood characteristics revealed the following relationships, significant at the five percent level. As age or distance from the pith increased: tracheid length, radial double-cell wall thickness, earlywood cell lumen diameter, radial tracheid diameter, and latewood percentage increased; total ring width, number of cells per zone, width of zone, latewood cell lumen diameter, and total cells per ring decreased. Earlywood and latewood density both revealed significant parabolic trends from pith to bark, with minimum values at about the mid point in the radius. As tracheid length increased, radial double-cell wall thickness increased and wood density decreased in both earlywood and latewood systems. As wood density increased, number of cells per zone, total cells per ring, latewood cell lumen diameter, and latewood percentage increased. Decreases in wood density were inversely related to radial wall thickness of the fertilized trees, earlywood cell lumen diameters, and earlywood tracheid diameters. There appeared to be little or no relationship between latewood density and latewood radial tracheid diameter.

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Table 1.--Plot data and diameter breast height for the red pine trees used in the investigation.

Plot Data

	Plot K	Plot G
Planted	1930	1930
Treatment		
Year	--	1946
Type	--	KCL
Rate	--	200 lb/acre
Grade	--	Analytical reagent
Method	--	Broadcast
Thinning	25% cut in 1961	25% cut in 1961
Cut	Nov. 1966	Nov. 1966

Diameter Breast Height

Fertilized		Control	
Tree No.	D.B.H.	Tree No.	D.B.H.
600	5.2"	655	4.5"
611	6.4	666	4.4
622	5.2	677	4.3
633	5.6	688	4.6
644	5.1	699	4.7

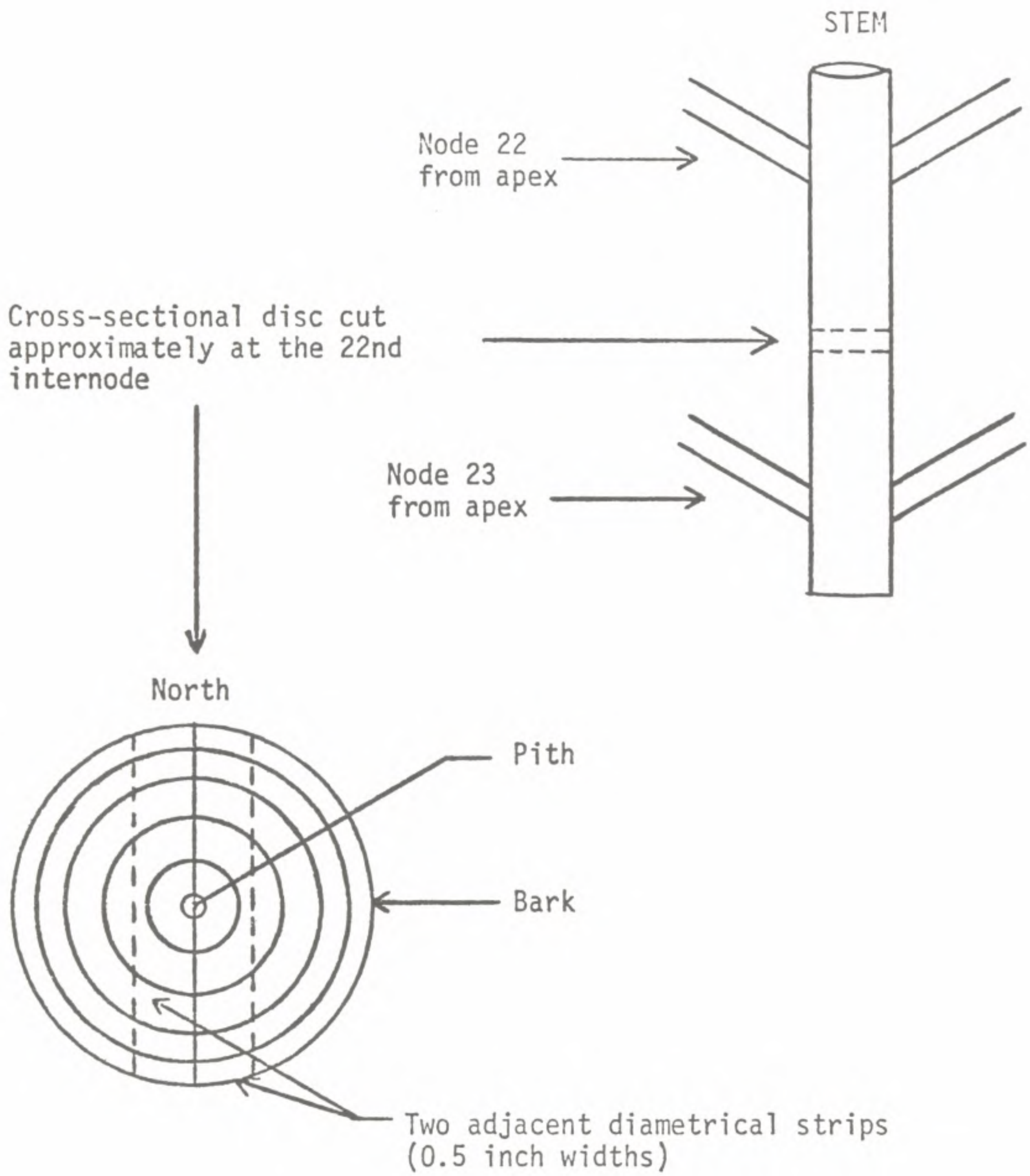


Figure 1. Schematic diagram of sampling and initial sub-division of the fertilized stems. Control stems were sampled in a similar manner at the 25th internode.

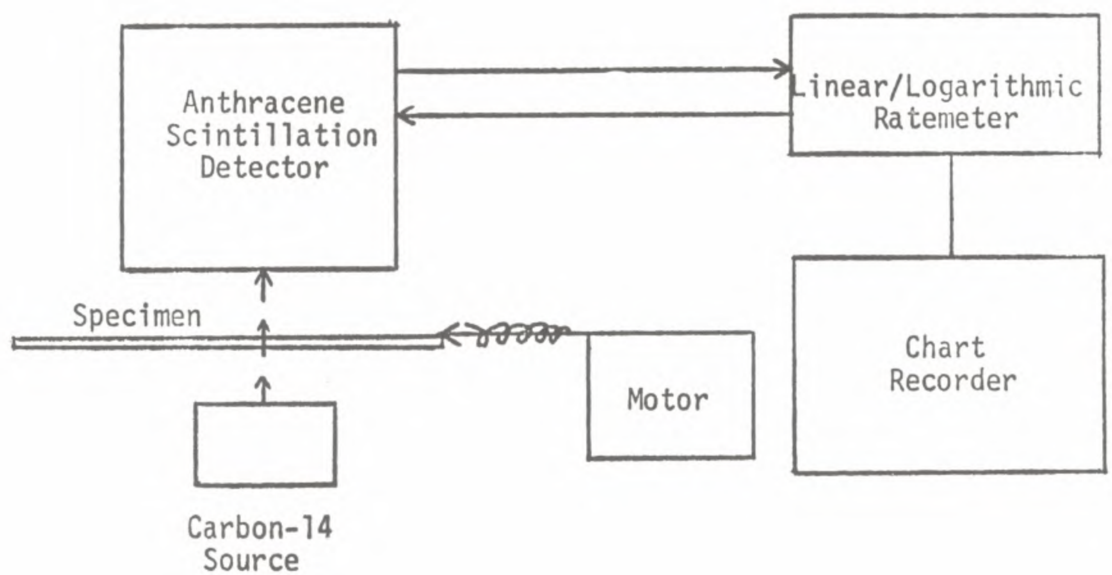
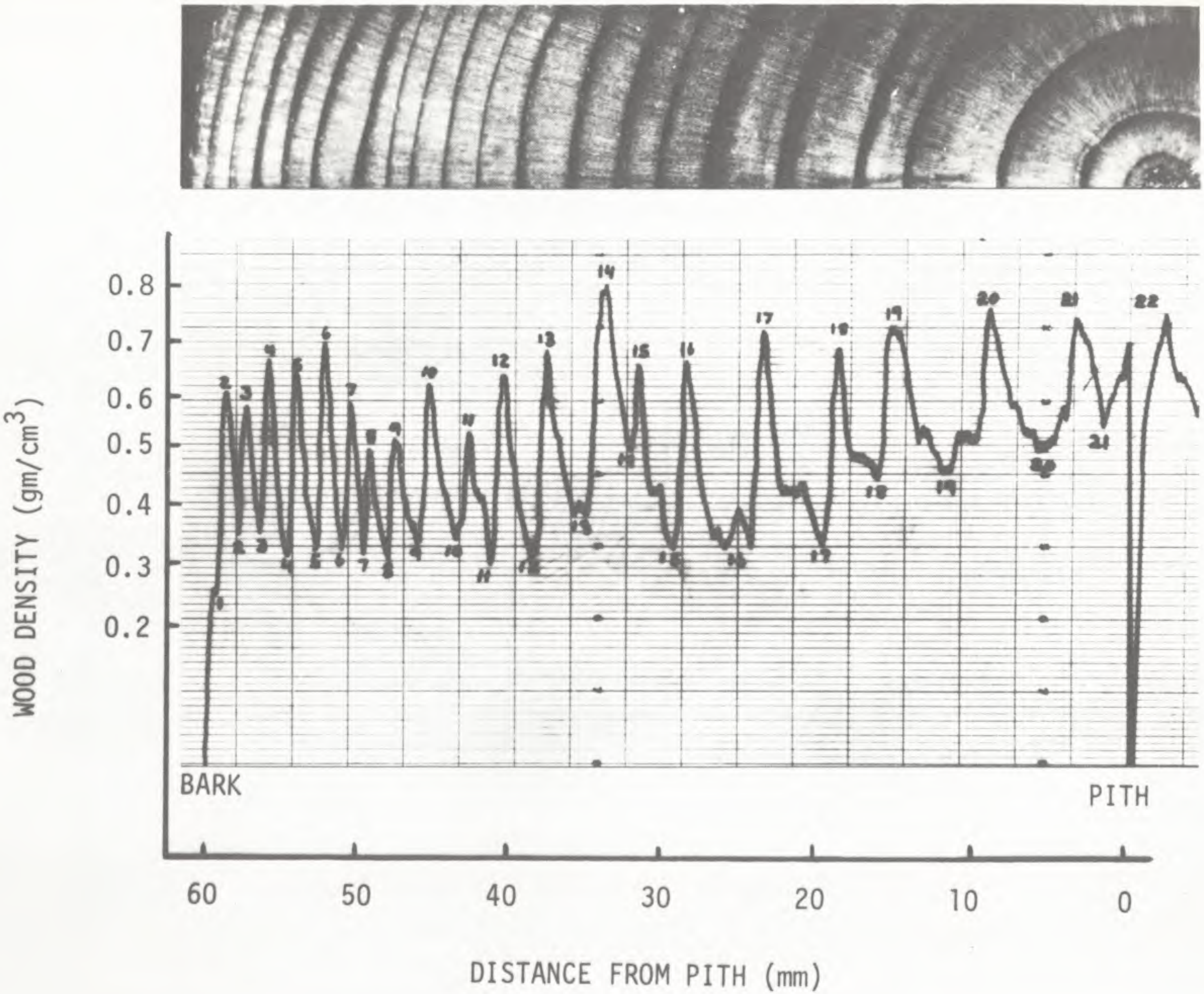


Figure 2 Schematic representation of the apparatus employed for the beta radiation absorption method of density determination.



WOOD DENSITY (gm/cm3)
0.8
0.7
0.6
0.5
0.4
0.3
0.2
BARK
PITH
60
50
40
30
20
10
0
DISTANCE FROM PITH (mm)

Figure 3 A typical recorder curve of radial wood density variation obtained by the beta radiation absorption technique. The low value for ring one (at bark) is probably due to the fact that this was the last material to be produced by the cambium and possibly had not matured by the time the tree was cut. The maximum and minimum points in each zone are labeled consecutively starting at the bark. This record represents a typical curve from a fertilized tree.

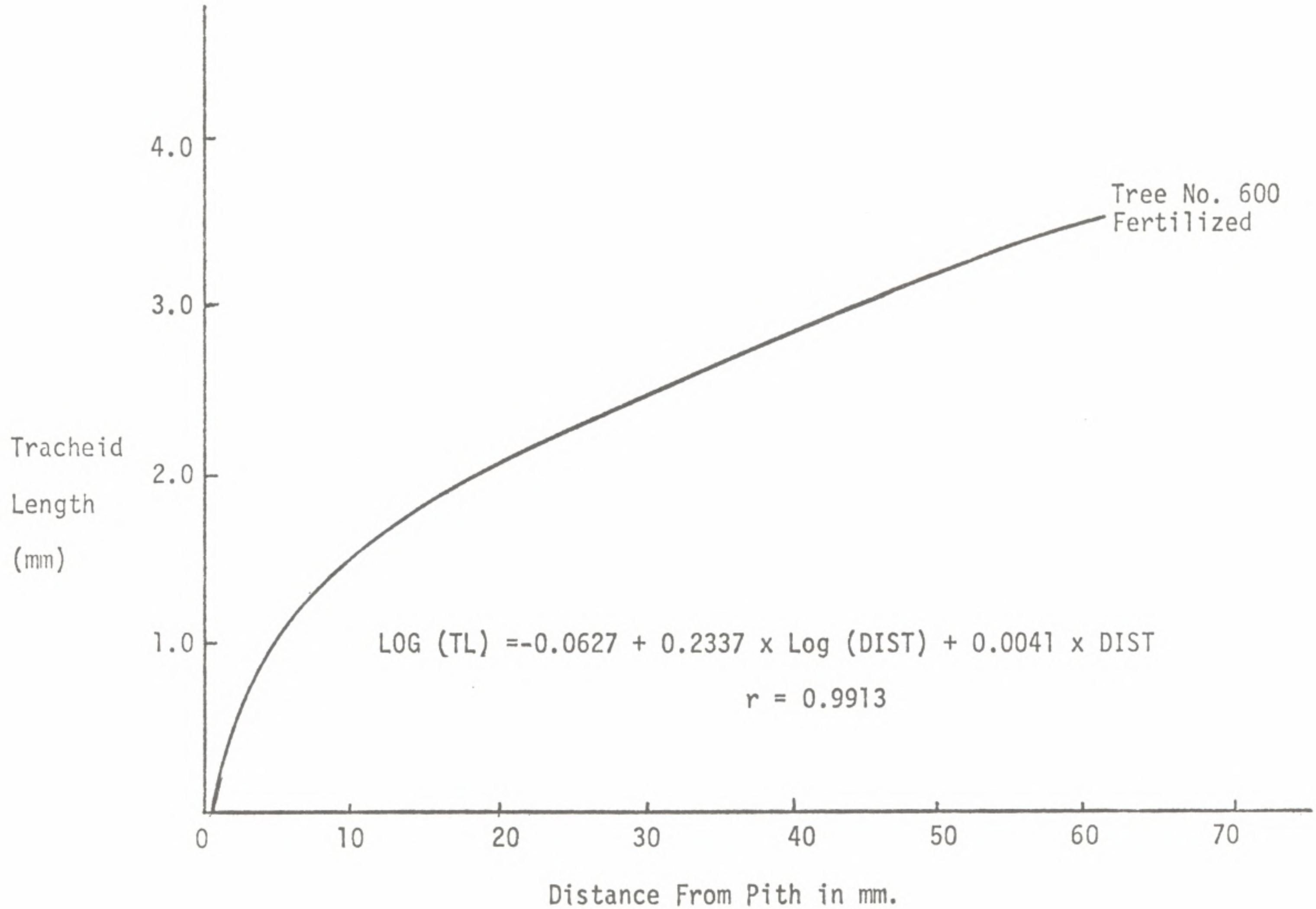


Figure 4 Relationship between tracheid length and distance from the pith of a single fertilized tree. This shows the initial rapid increase and then a more gradual increase trend in the later growth.

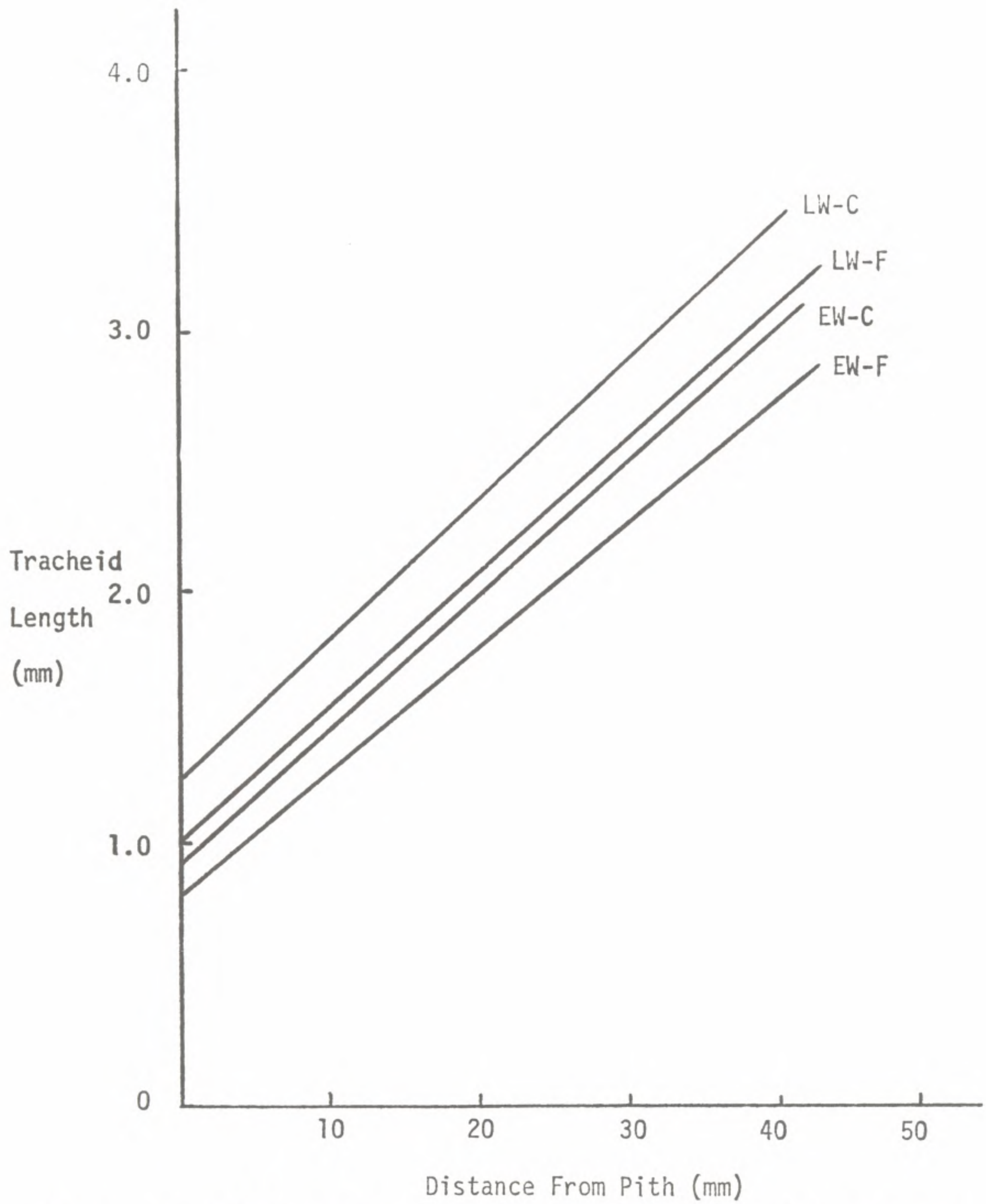
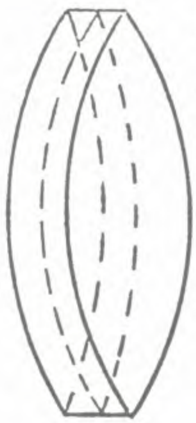


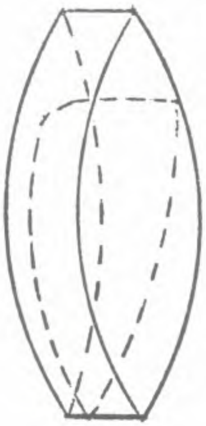
Figure 5 Relationship between tracheid length and distance from the pith both measured in mm.
Latewood - LW, Earlywood - EW,
Fertilized - F, Control - C.
These symbols will be used on all subsequent graphs.
Unless otherwise stated all plots are pooled data from the 5 trees in each group.

PERICLINAL DIVISIONS - tangential-longitudinal plane



True Periclinal

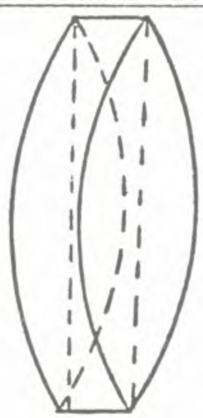
Major plane of division during growing season



Off-Center Periclinal

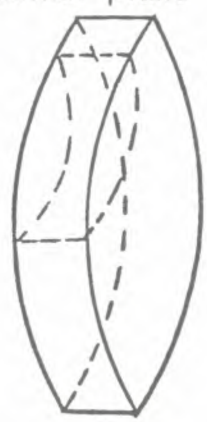
Shorter or longer cell can remain in cambium, if continually shorter cell, results in ray initial

ANTICLINAL DIVISIONS - radial-longitudinal plane



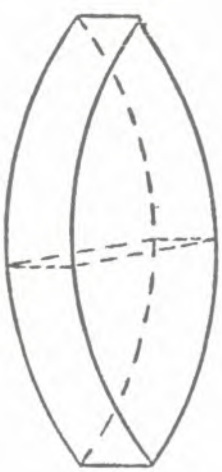
True Anticlinal

Commonly found in storied cambium; resulting cells tabular



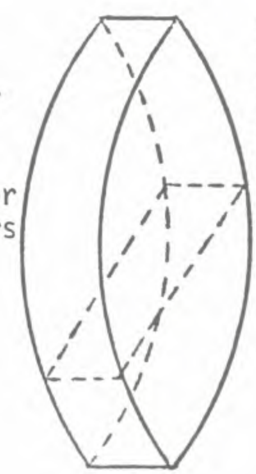
Off-the-side Anticlinal

Very uncommon; small cell may become ray initial



True Transverse

Wall perpendicular to long axis of fusiform initial, common division for increase in numbers of ray initials



Pseudotransverse

Oblique angle of wall may be very steep; major type of division towards end of growing season

Figure 6 Schematic drawings of the major planes of divisions which occur in cambial initials.

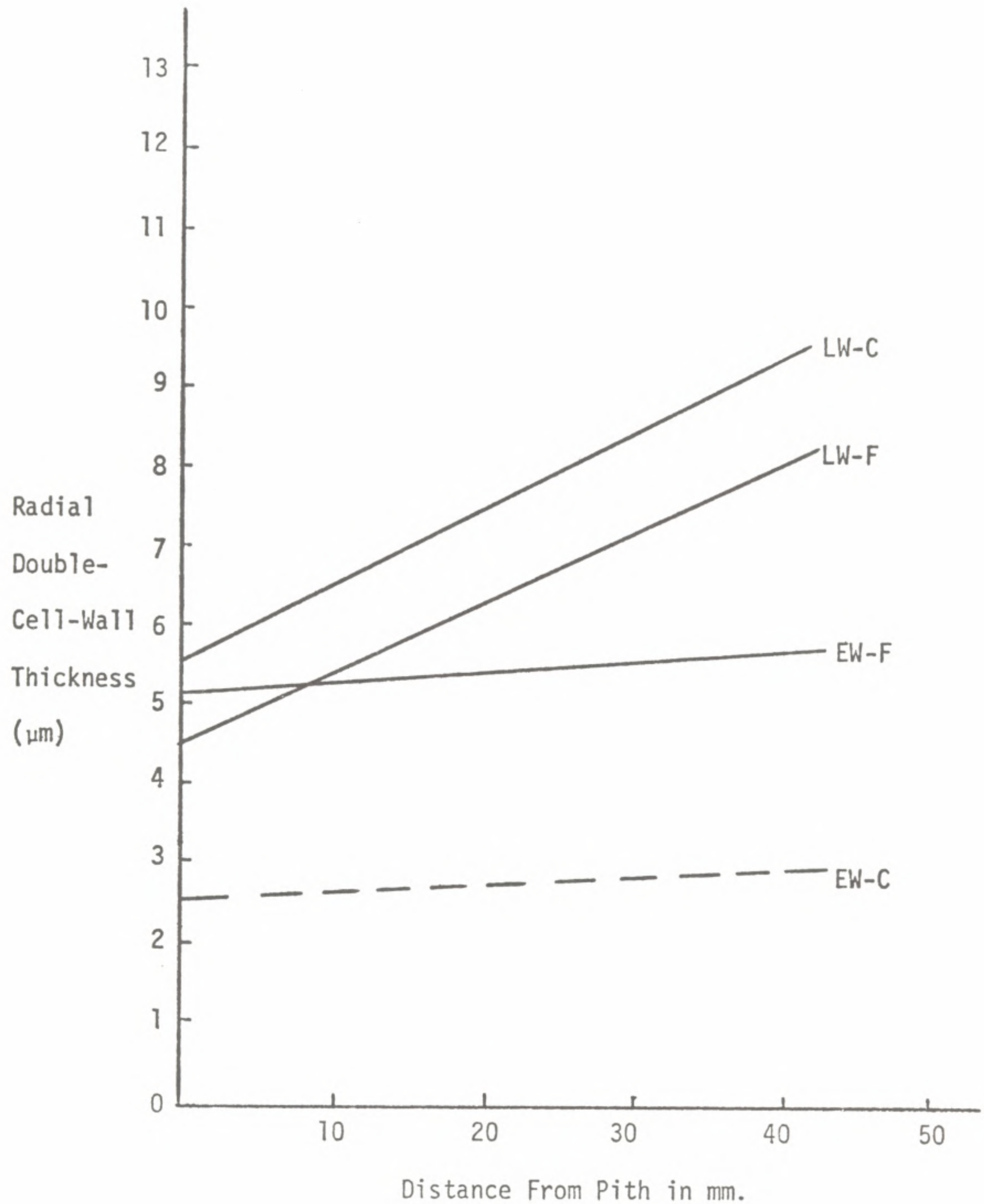


Figure 7 Relationship between double-cell-wall thickness (measured in the radial direction) and distance from the pith.
——— Significant at .05 probability level
- - - - - Significant at less than the .05 prob. level.
These symbols will be used in all subsequent graphs.

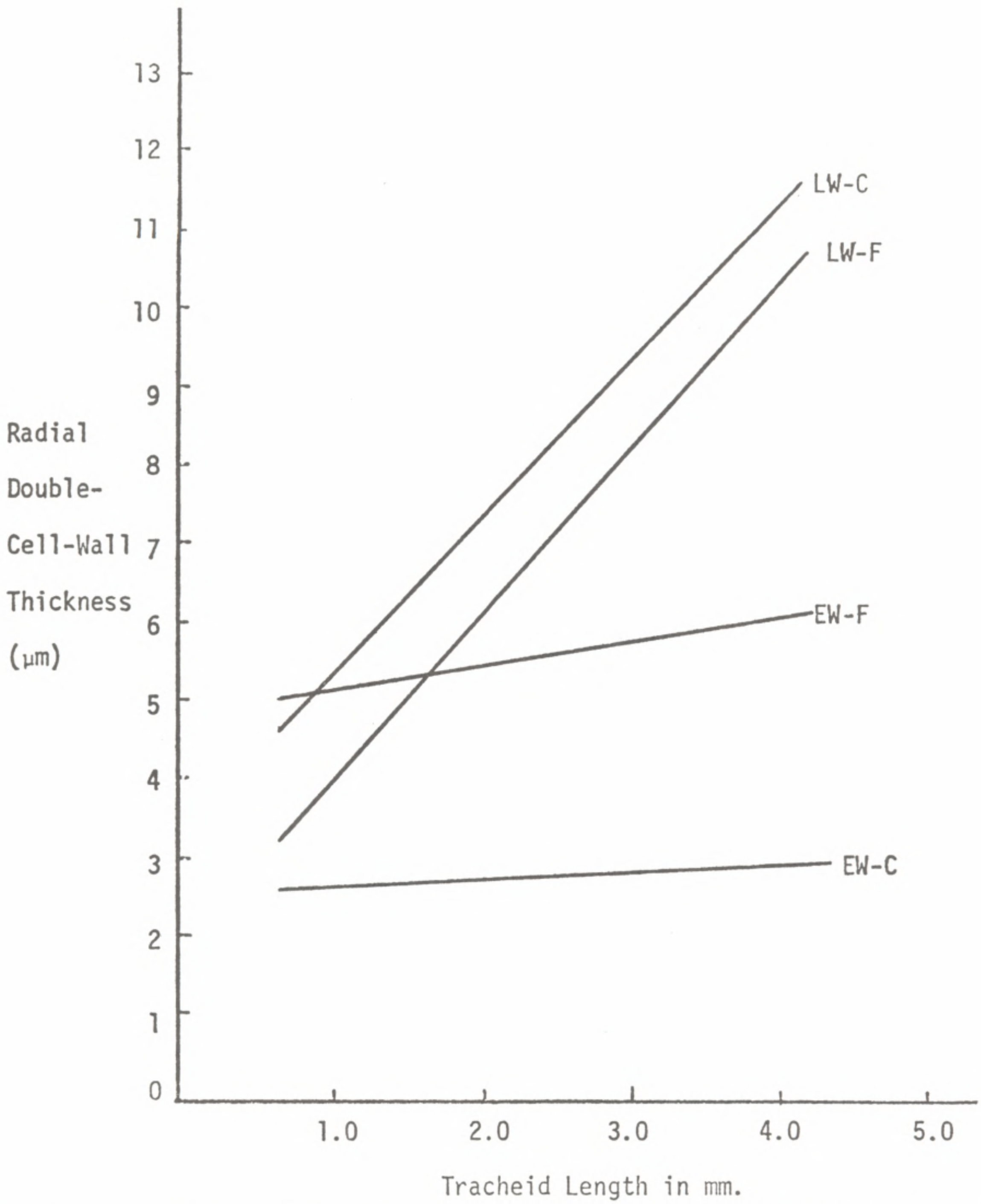


Figure 8 Relationship between radial double-cell-wall thickness and tracheid length.

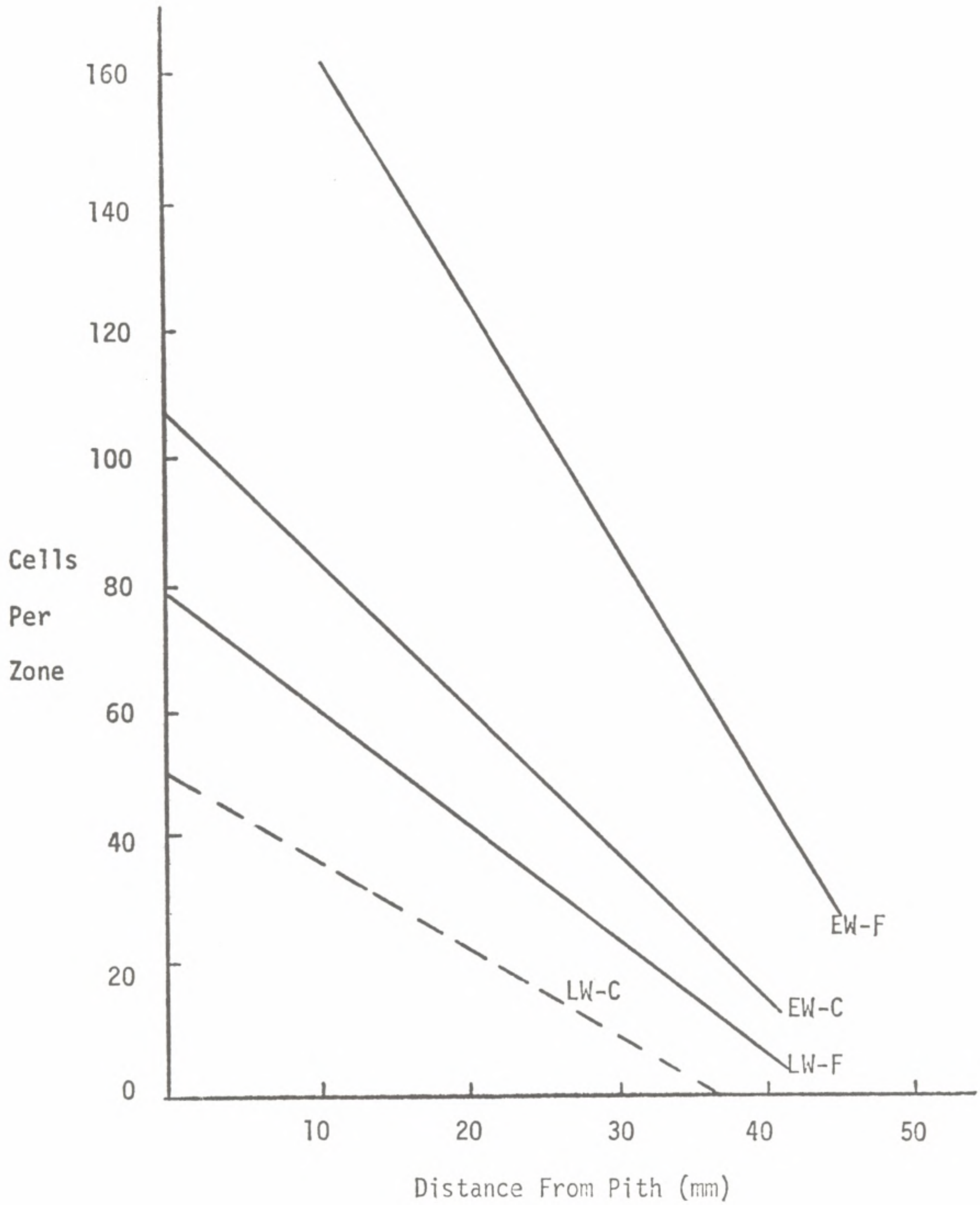


Figure 9 Relationship between cells per individual earlywood or latewood zone and distance from the pith.

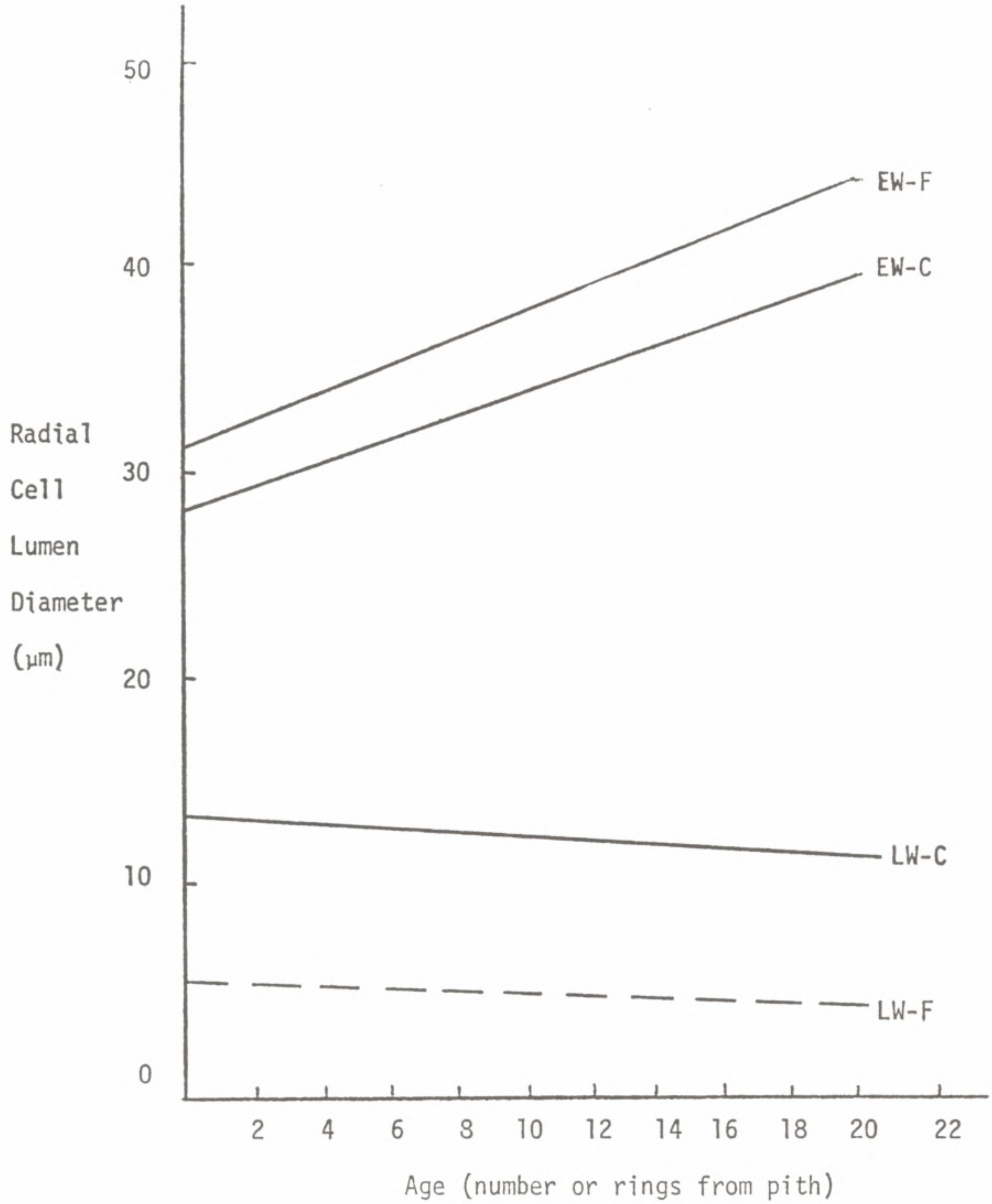


Figure 10 Relationship between tracheid lumen diameter measured in the radial direction and age expressed as number of rings from the pith.

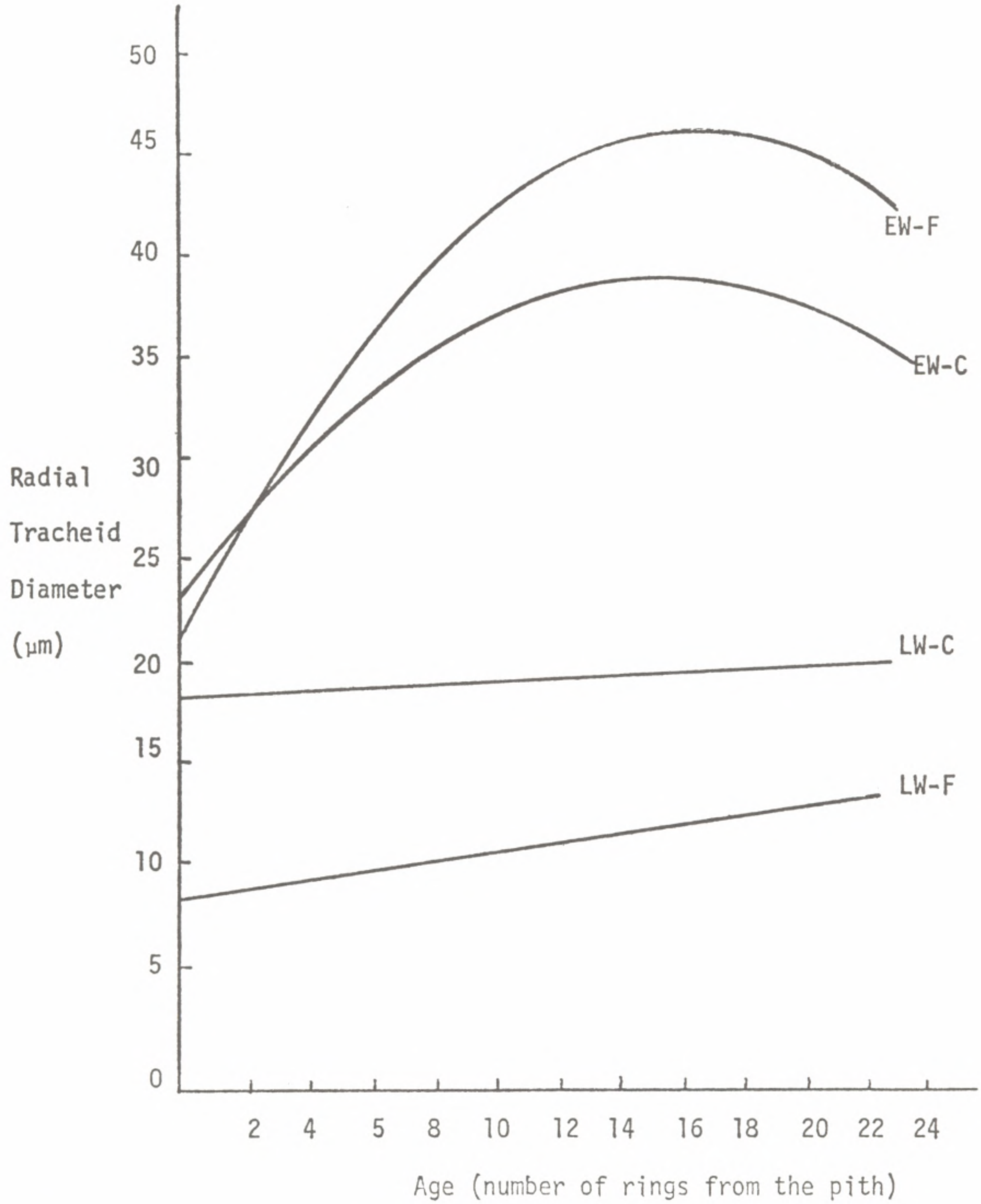


Figure 11 Relationship between radial tracheid diameter and age, expressed as number of rings from pith.

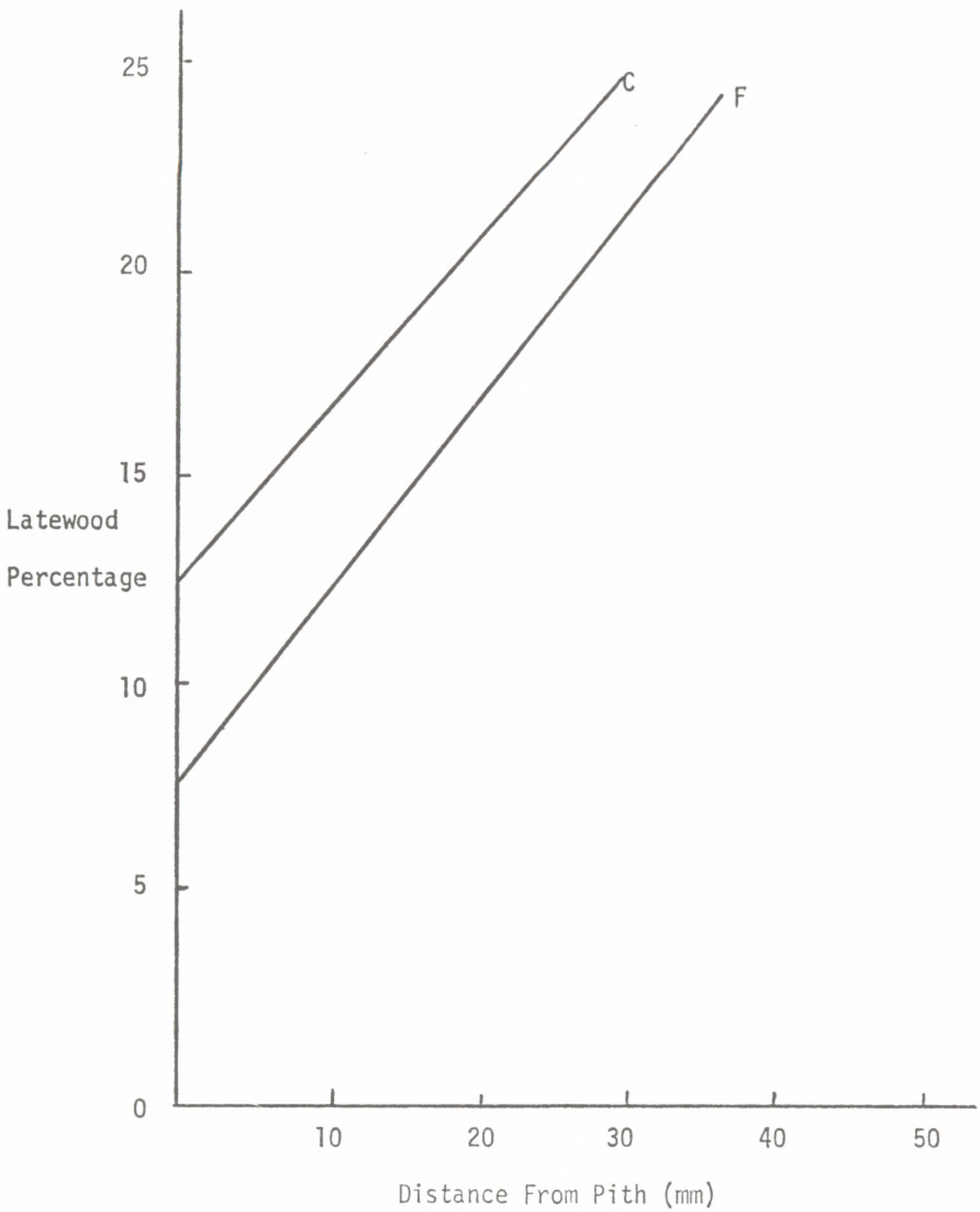


Figure 12 Relationship between latewood percentage and distance from pith. Latewood percentage was taken as the ratio of latewood cells to the total cells per growth increment.

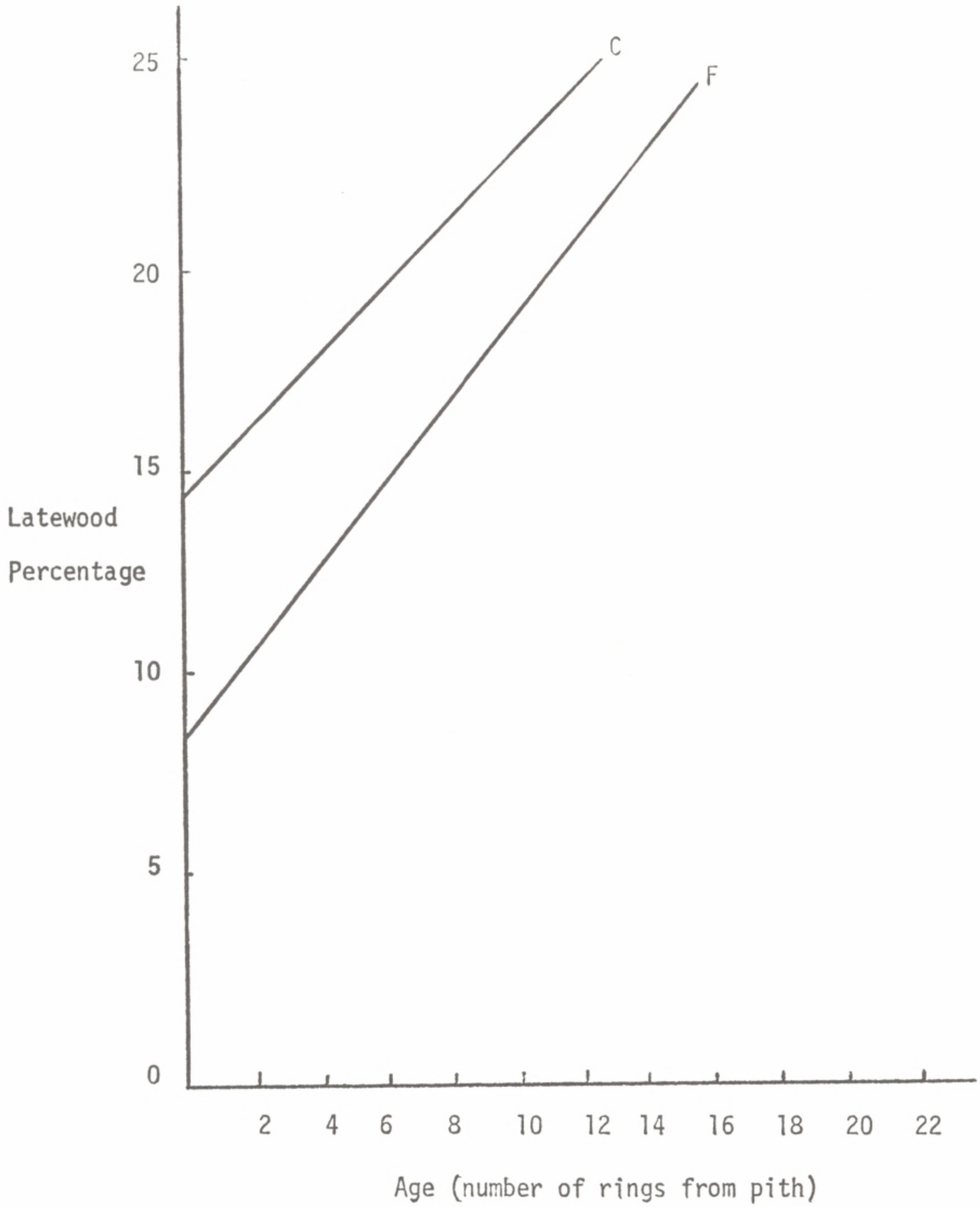


Figure 13 Relationship between latewood percentage and age.

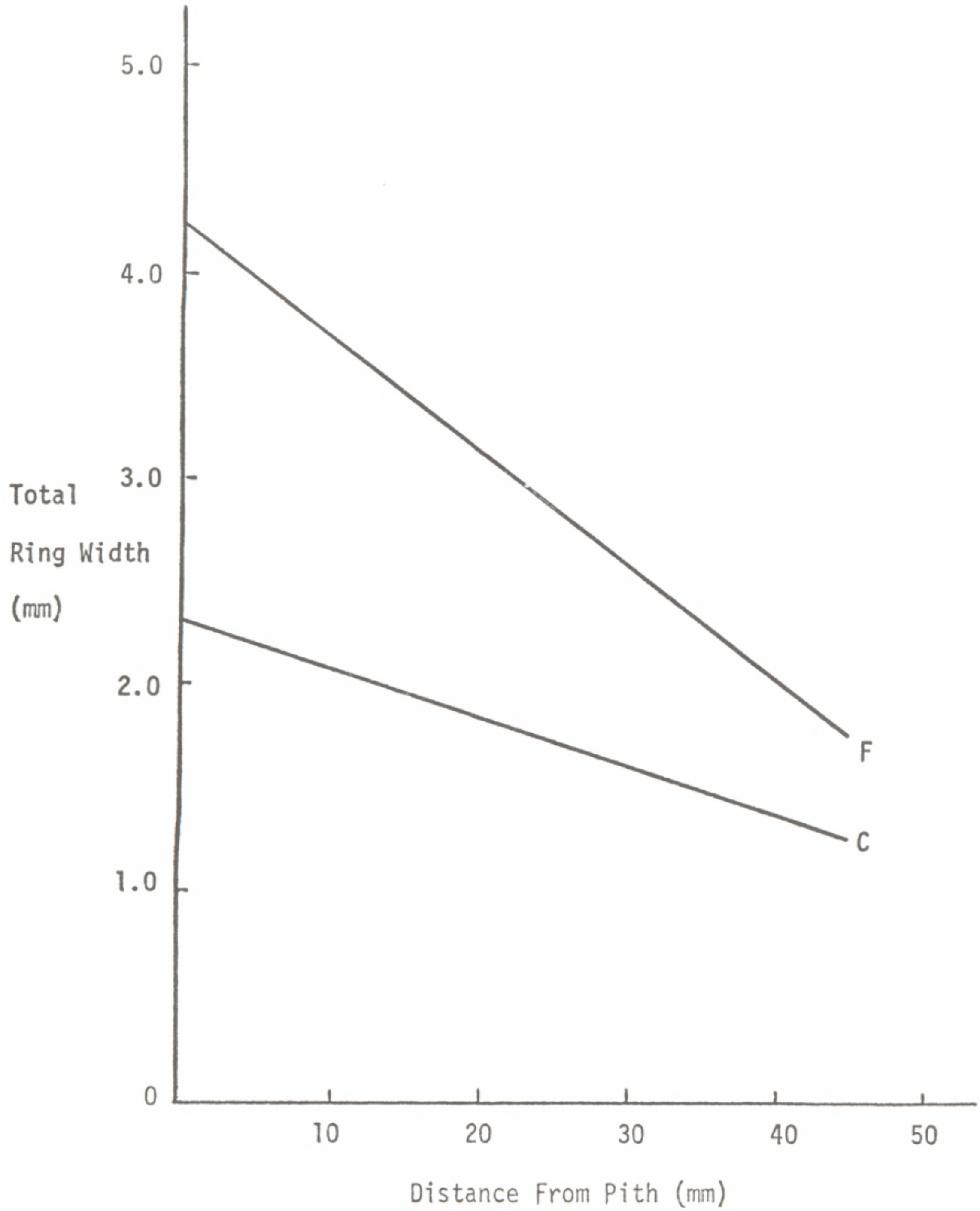


Figure 14 Relationship between total ring width and distance from pith.

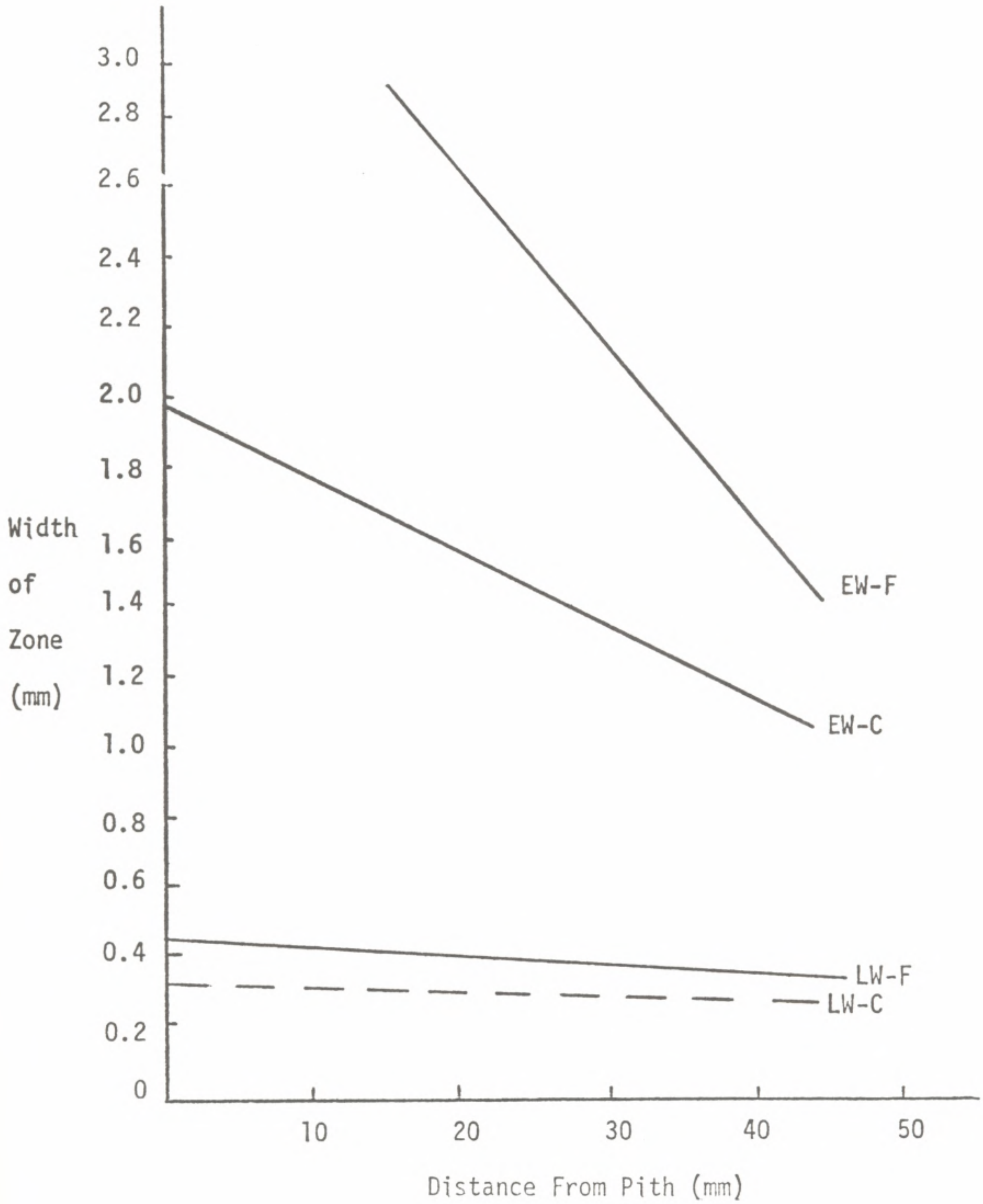


Figure 15 Relationship between width of individual earlywood or latewood zone and distance from the pith.

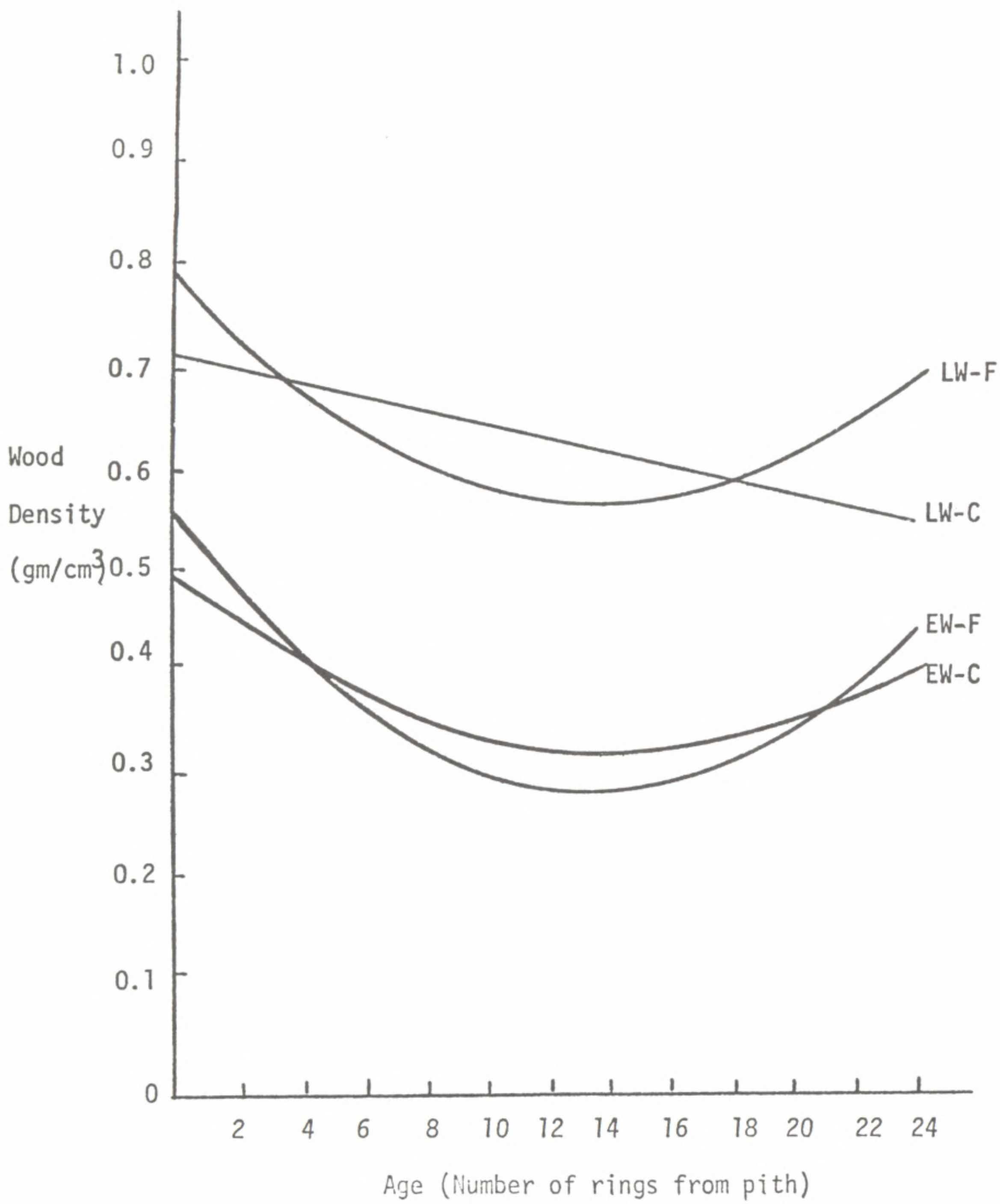


Figure 16 Relationship between wood density and age expressed as number of rings from the pith.

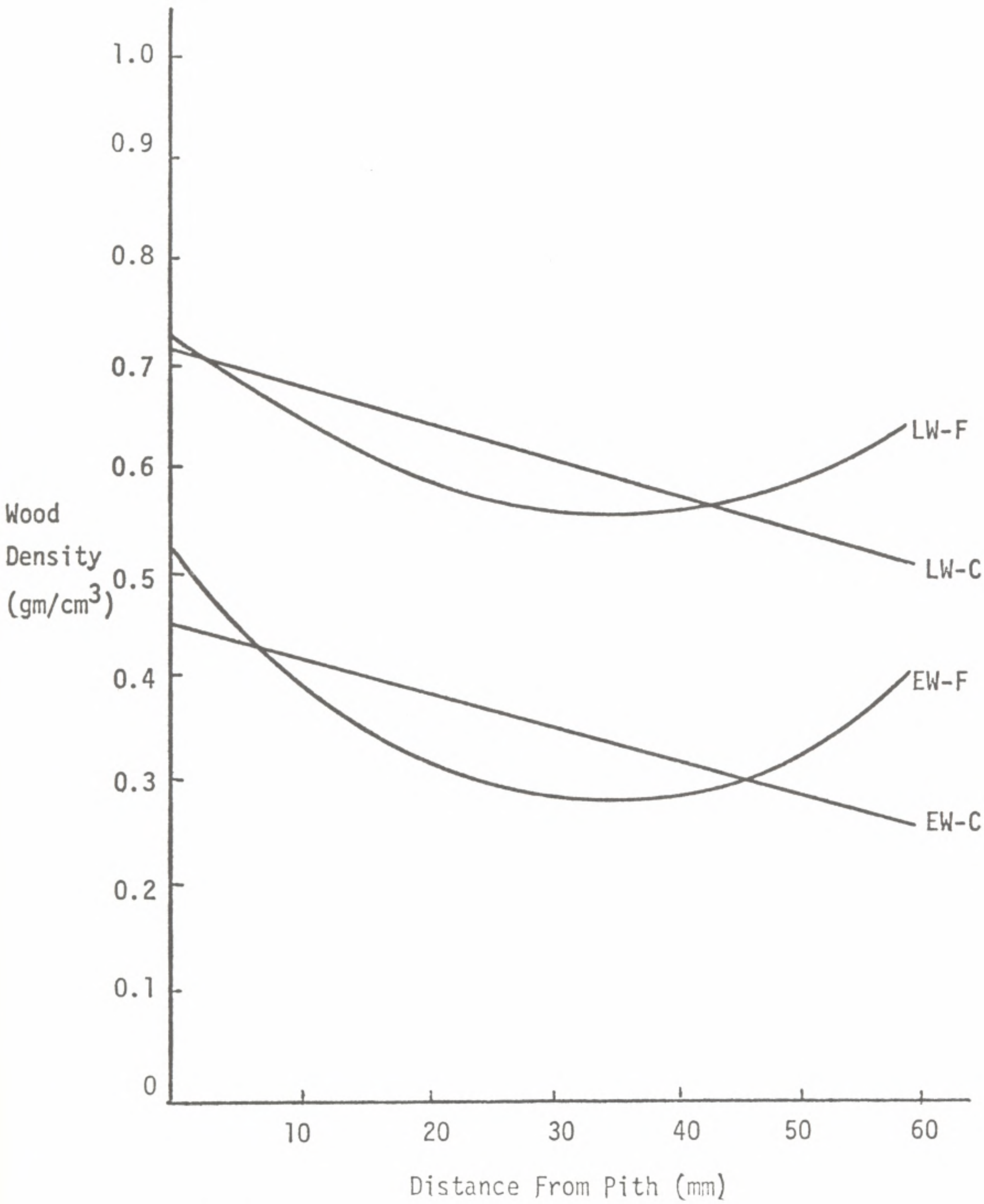


Figure 17 Relationship between wood density and distance from pith.

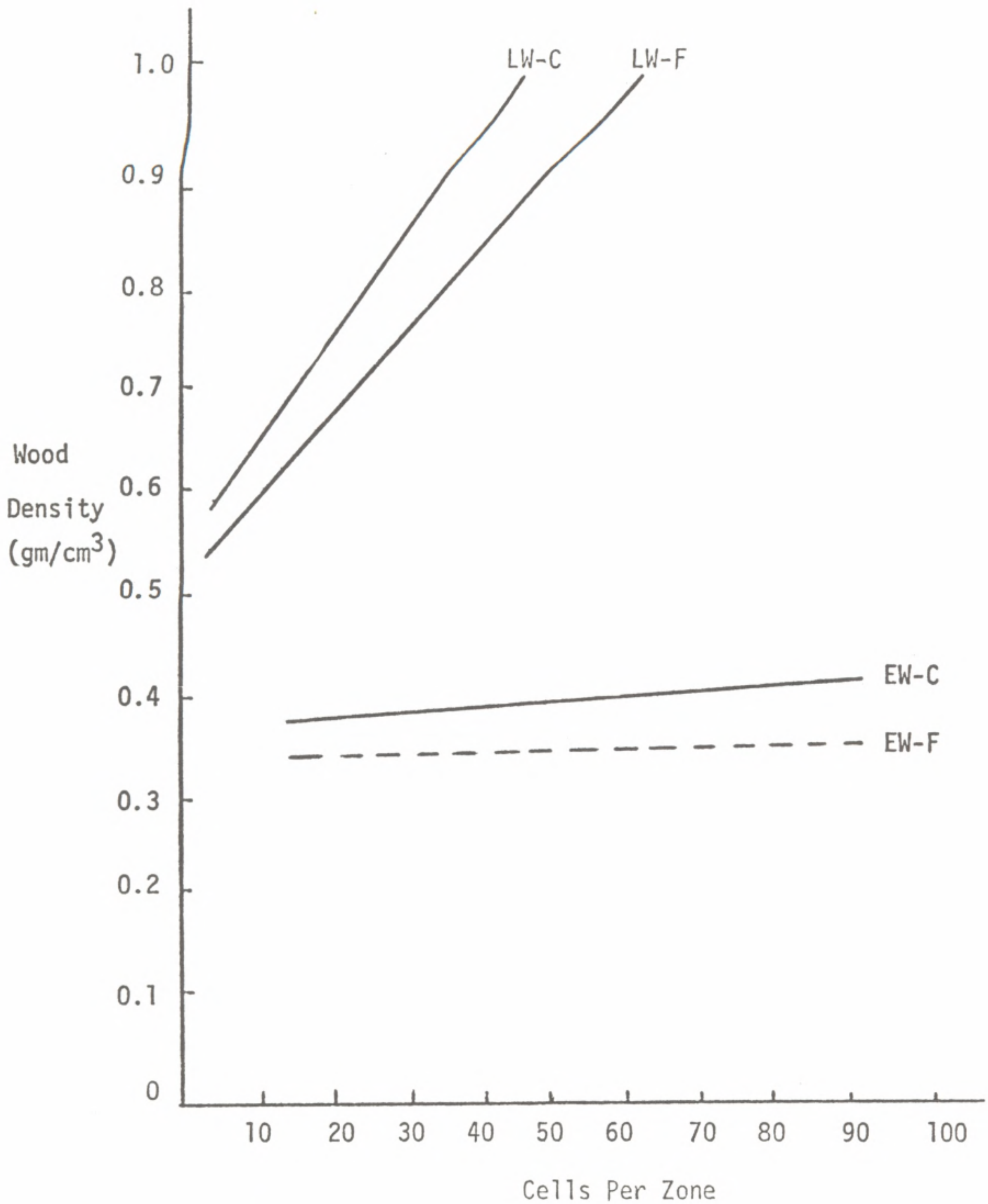


Figure 18 Relationship between wood density and cells per individual zone within the growth increment.

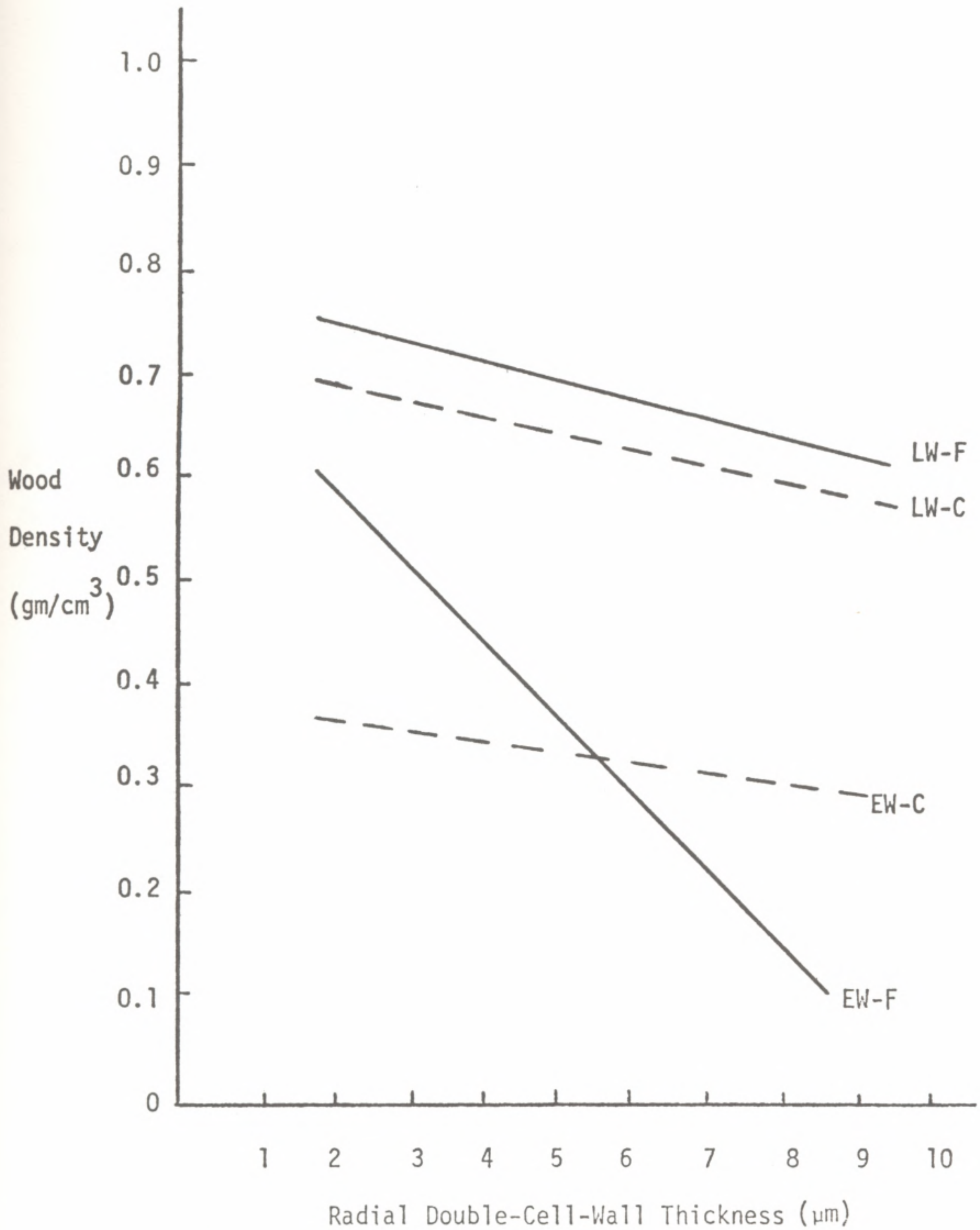


Figure 19 Relationship between wood density and radial double-cell-wall thickness of tracheids.

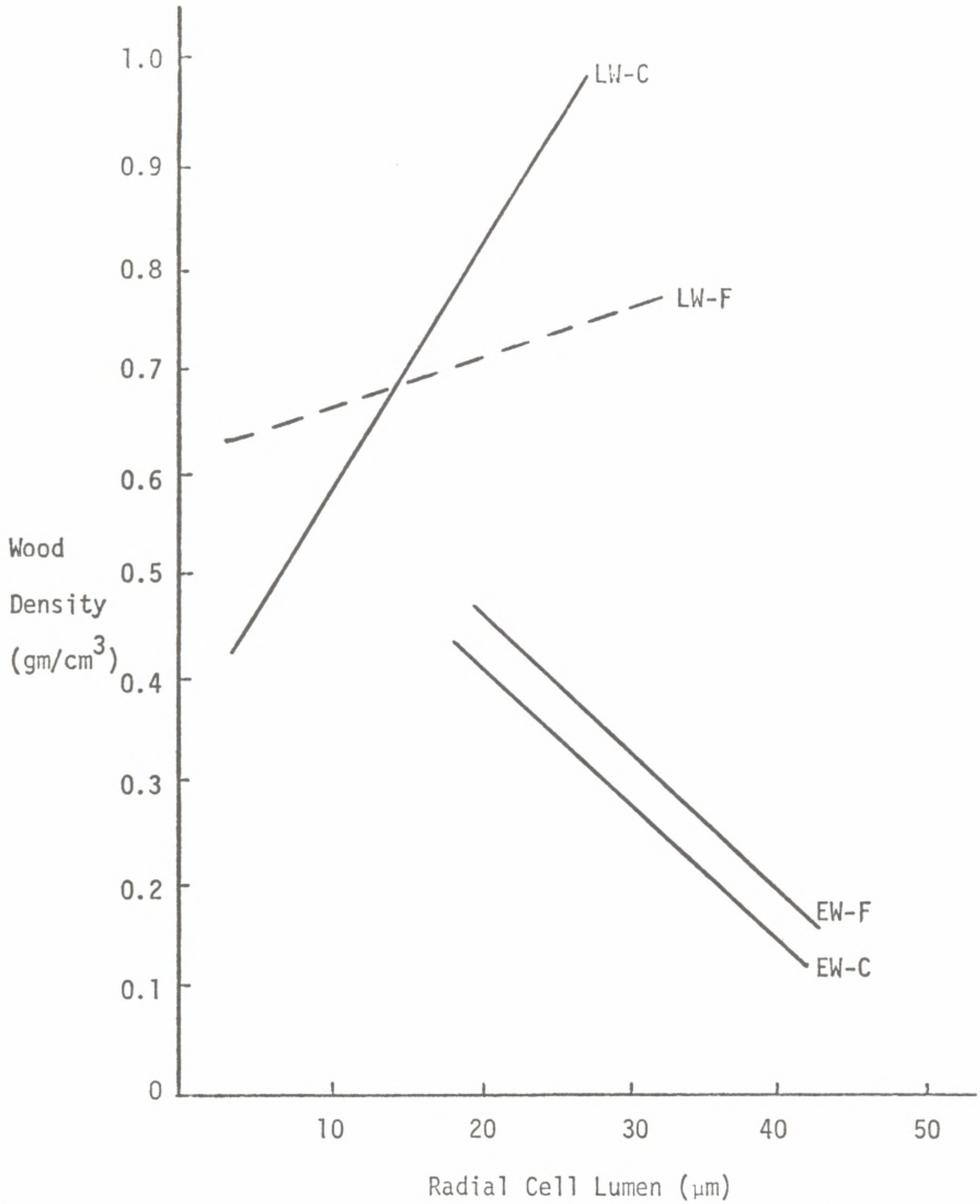


Figure 20 Relationship between wood density and radial cell lumen diameter of the tracheids.

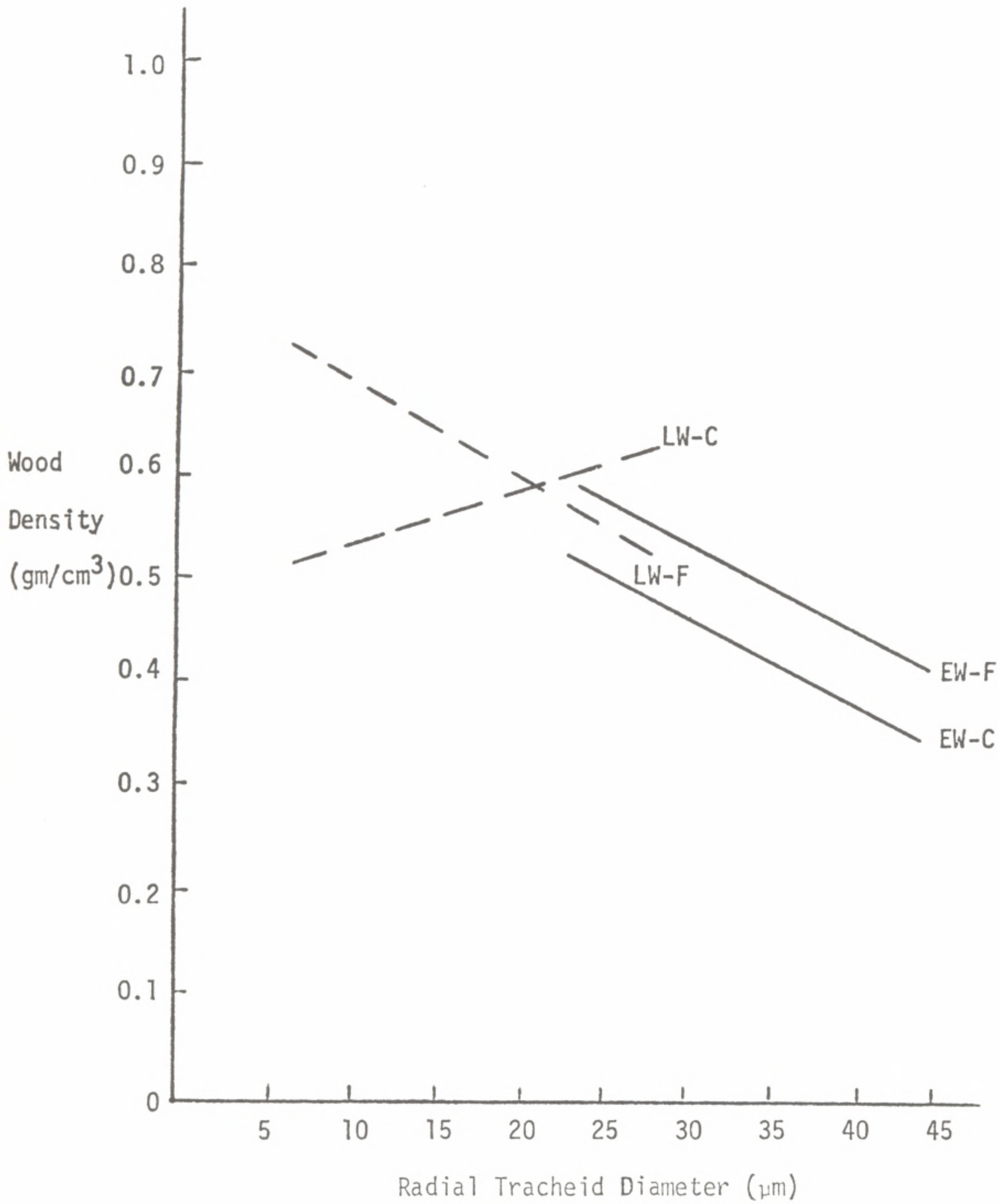


Figure 21 Relationship between wood density and total tracheid diameter measured in the radial direction.

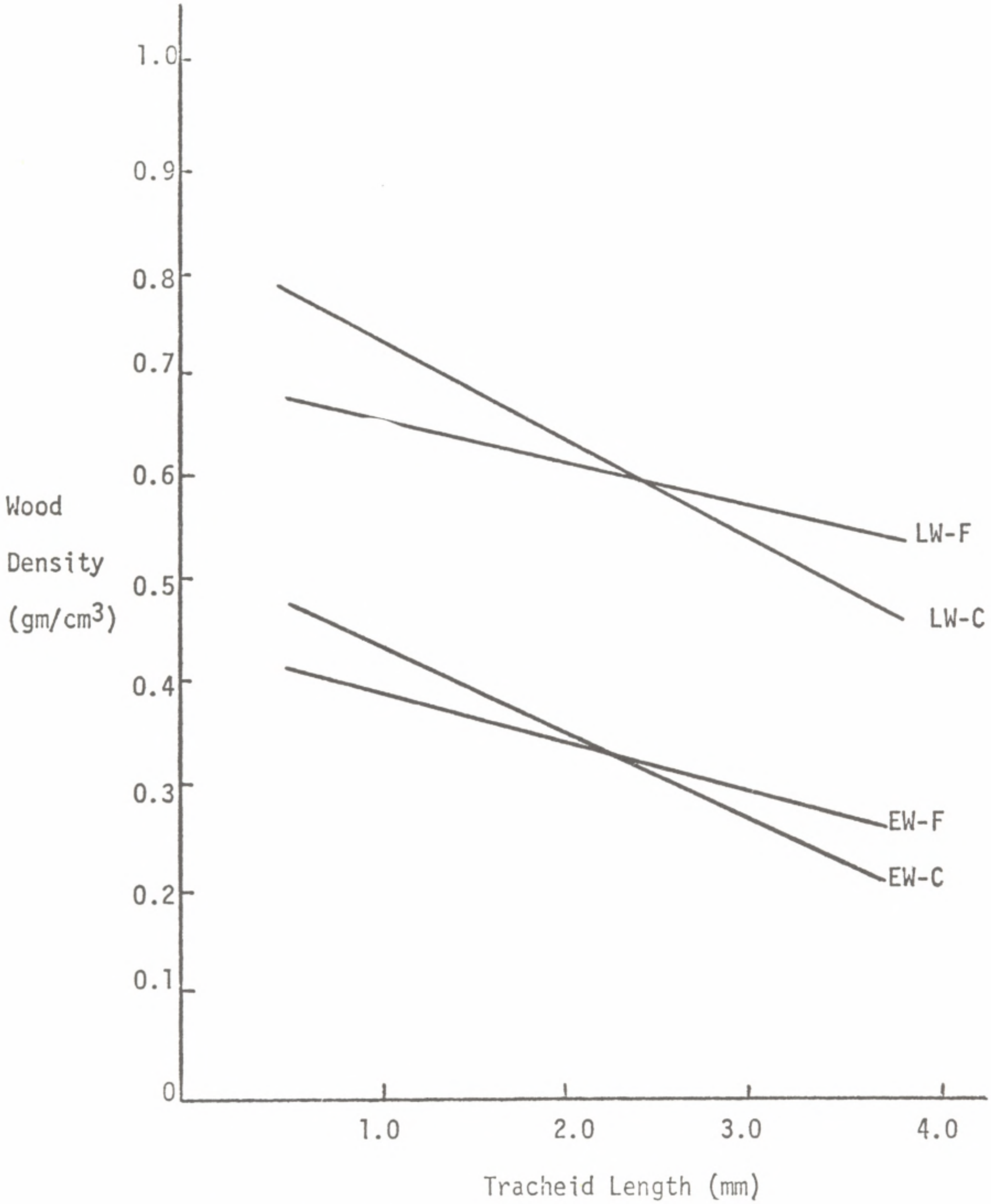


Figure 22 Relationship between wood density and tracheid length.

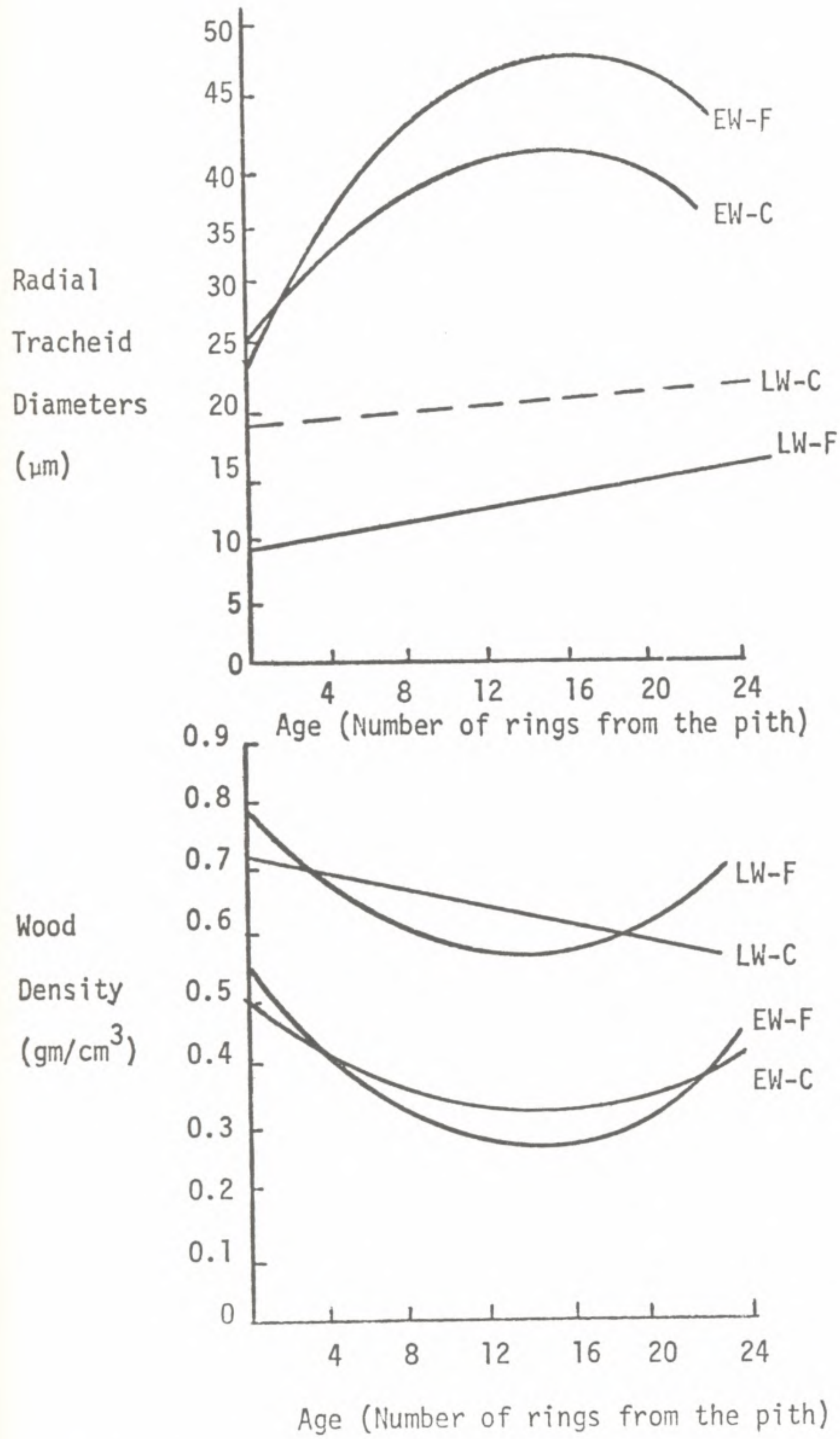


Figure 23 Relationship between total radial tracheid diameter and age (measured by rings from pith) compared to relationship between wood density and age or number of rings from the pith.

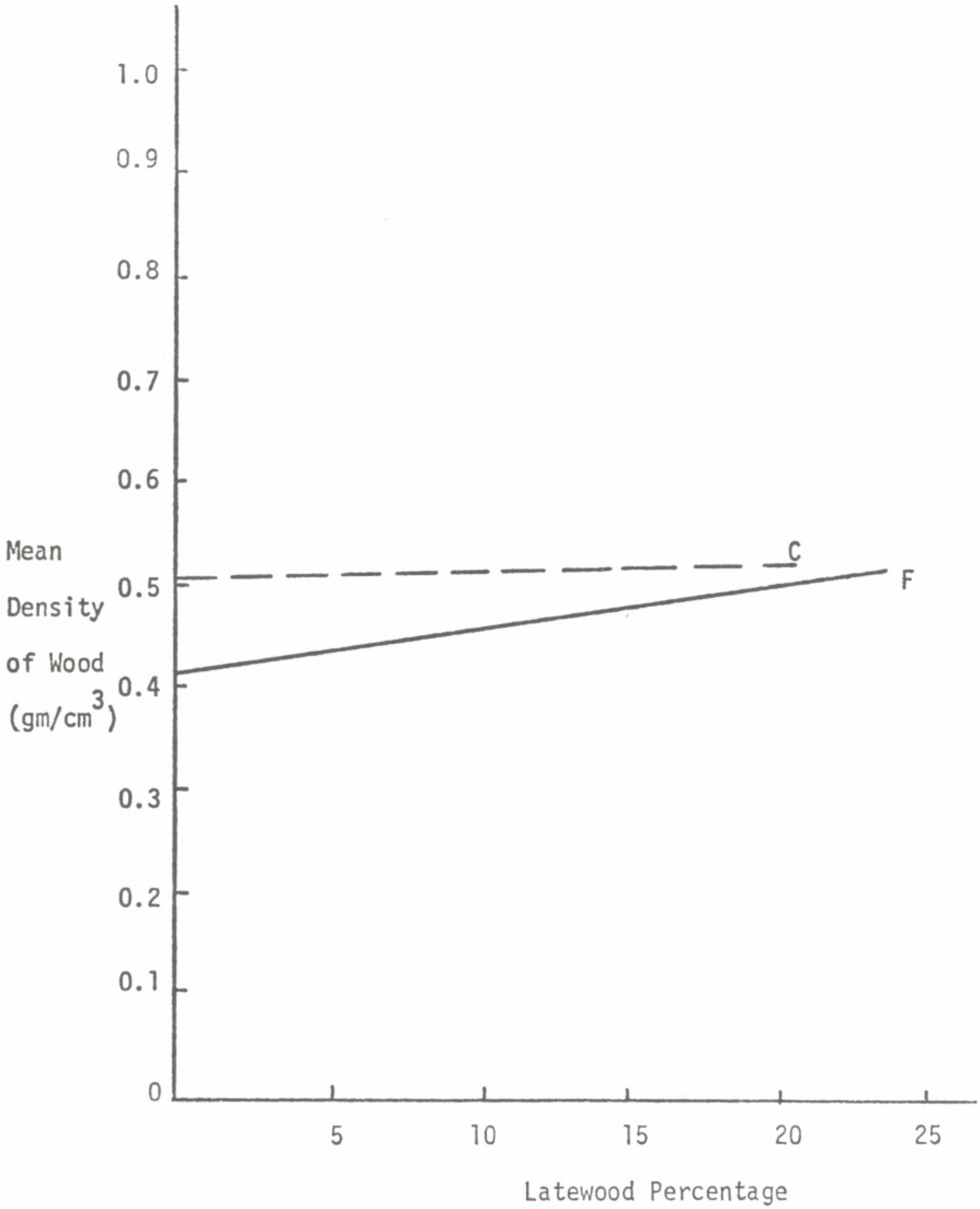


Figure 24 Relationship between wood density and latewood percentage The density is a weighted average for both earlywood and latewood zones.