AN ABSTRACT OF THE THESIS OF

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Title: Branch Diameter and Wood Density of Young Western Hemlock (Tsuga heterophylla (Raf.) Sarg.) Grown at Several Spacings.

Abstract approved: Signature redacted for privacy.
John C. Tappeiner, II

Branch diameter and wood density were measured in 29- and 38-year old western hemlock (Tsuga heterophylla (Raf.) Sarg.) thinning trials. Spacings ranged from 4 to 21.8 feet.

Branch diameter increased with spacing, but not to excessive sizes. Even at the widest spacings, the largest branches were under two inches in diameter. At current rotation lengths of 40 to 60 years, western hemlock stands can be grown at any of the spacings measured in this study without concern that increased knot size will have a large impact upon log grades as currently defined.

Wood density was negatively correlated to radial growth rate in samples composed of rings 20-24 from pith. An increase

in average ring width from 2 mm to 8 mm resulted in average wood density dropping from .47 to .37 g/cc. The primary reason for the decrease in wood density was an increase in the proportion of earlywood with higher rates of growth. Earlywood density decreased somewhat at higher growth rates, but latewood density was not related to growth rate.

BRANCH DIAMETER AND WOOD DENSITY OF YOUNG WESTERN HEMLOCK (*Tsuga heterophylla* (Raf.) Sarg.) GROWN AT SEVERAL SPACINGS

by

Jeffrey D. DeBell

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I. INTRODUCTION

A. BACKGROUND

Control of tree spacing is a major means through which foresters can influence the quantity and quality of wood production (Daniel et al. 1979). Most of the available data on spacing, however, deals with its effects on tree growth and stand volume production. Effects of tree spacing on characteristics or "quality" of the wood produced are not as well understood. A better understanding of these relationships is required so that both quantity and quality can be considered in approaches to maximizing stand value.

Western hemlock is a major commercial species, constituting 25% of the total softwood growing stock in western Oregon, Washington, British Columbia and Alaska (Beswick 1976). Western hemlock wood is used for both construction and finish lumber, veneer for core stock, and pulp and paper. From the mid-1970's to mid-1980's, hemlock accounted for more than 20% of the total lumber production and 50% of the volume used by the paper industry in Oregon and Washington (Cahill 1984); during the 1980's, it accounted for over 37% of all softwood log exports from Oregon and Washington (Warren 1991).

Despite the importance of western hemlock, little information is available concerning the effects of tree spacing on wood quality in this species.

Wood quality can be defined as the suitability of wood for a particular end use (Briggs and Smith 1986). Factors affecting wood quality include: density, uniformity, proportion of heartwood, fiber length, occurrence of juvenile and/or reaction wood, cellular composition, size and distribution of knots, grain orientation and chemical composition (Haygreen and Bowyer 1989).

This thesis is composed of two studies, one on branch diameter, the other on wood density. Knot (and therefore branch) diameter is critical to log and lumber grades; and density of wood is "its single most important physical characteristic" (Haygreen and Bowyer 1989).

B. LITERATURE REVIEW

1. The Effect of Spacing on Branch Diameter

Knot diameter is a critical factor affecting quality of most solid wood products. Knots affect both the strength and the appearance of wood. As a result, their occurrence is a primary factor in determining log and lumber grades (Haygreen and Bowyer 1989). Because knots are the direct result of branching patterns, studies of branch characteristics are useful in assessing the effects of silvicultural practices upon knots.

No studies of branch size in western hemlock have been published. In an unpublished paper, however, Smith (1977) has reported on branch diameters in a 20-year-old western hemlock spacing trial. Tree spacing ranged from 3x3 to 15x15 feet, and maximum branch diameter increased from 0.44 to 1.25 inches over this range.

Studies of other conifers have generally found that branch size increases with spacing. Grah (1961) found that average branch size increased from .27 to 1.98 inches at spacings from 4 to 20 feet in 20- to 40-year-old natural stands of Douglas-fir. Eversole (1955), working in a 27-year-old Douglas-fir spacing trial, reported that branch diameter increased from .36 to .73 inches at spacings of 4 to 12 feet, while height to live crown decreased from 19.5 to 6.7 feet over the same range. In lodgepole pine stands, branches on trees grown at lower initial densities remain alive longer and reach greater diameters than branches of trees grown at higher densities (Ballard and Long 1988).

Recent studies relating wood quality to silvicultural practices have used some form of branch size index, rather than average branch size. These indices recognize that the largest knot, rather than the average knot, causes reductions in log and lumber grades (NLRAG 1982; WWPA 1988). For example, Bier (1986) used the average of the diameters of the largest branch in each quadrant of a log. Ballard and Long (1988) used the average diameter of the five largest knots per 5 m log. And Whiteside et al (1977) measured the largest branch per quadrant per 1.2 m length, and averaged the 16 measurements for each 4.8 m log.

In summary, branch size has generally been found to increase with spacing. Recent studies of branch size have used an index of the largest branches rather than average branch diameter.

2. The Effect of Radial Growth Rate on Wood Density

Wood density is the single most important physical characteristic of wood; wood strength and stiffness, pulp yield, and caloric content are all closely correlated to wood density (Haygreen and Bowyer 1989).

Before further discussion of wood density, a point of terminology should be recognized. The terms density and specific gravity are often used interchangeably in the literature. Although they refer to the same wood property, these terms have precise and different meanings. Density is defined as mass per unit of volume. It can be measured using green weight and green volume, dry weight and green volume, or weight and volume at a specified moisture content. Specific gravity is defined as the ratio of the density of wood (always based on ovendry weight and volume at a specified moisture content) to the density of water at 4 degrees C (Haygreen and Bowyer 1989).

There is a common and persistent perception that more rapid rates of growth result in reduced wood density in conifers. This issue has been debated extensively, and the list of studies on the subject stretches back into the 19th century (Spurr and Hsuing 1954).

One pitfall in wood density research has been the difficulty of separating the different factors which may influence density. Researchers working with pines have concluded that there is an inherent increase in density with age from the pith (Turnbull and Duplessis 1946). Usually ring width decreases in the same direction. As Larson (1969) has pointed out, many scientists studying the effect of growth rate on wood density have failed to separate age effects from growth rate effects. According to Megraw (1985), when age is taken into consideration, many studies have shown that wood density and growth rate are unrelated.

However, many of the researchers who conclude that wood density is unrelated to growth rate are those who work with species which have a distinct transition between earlywood and latewood, such as the hard pines or Douglas-fir. Studies on the spruces, which have a gradual transition from earlywood to latewood, suggest that, at any given age, growth rate does influence wood density (Brazier 1970). Also, the spruces do not always exhibit the pattern of inherent density increase from pith to bark which has been established for the hard pines (Keith 1961). It is possible that conclusions from studies of abrupt transition species do not apply to gradual transition species. In hardwoods, for instance, it is well established that the relationship of growth rate to wood density is quite different between ring-porous and diffuse-porous species (Haygreen and Bowyer 1989). Western hemlock is described by Panshin and deZeeuw (1980) as having a "more or less gradual" transition from earlywood to latewood.

Wood density in western hemlock seems to be highest immediately adjacent to the pith, drops off abruptly over the first 10 or so rings, then remains fairly level or increases slowly (Wellwood and Smith 1962; Megraw 1986). Krahmer

(1966) reported the same type of pattern, but wrote that the extent of the zone of higher density wood "appeared to be independent of age and included growth rings within a radius of about two inches of the pith." The strong pattern of wood density increase with age from the pith reported for the hard pines apparently does not occur in western hemlock. The reason for the high density immediately around the pith in western hemlock is not established. However, Mergen (1958) demonstrated that the drooping leader in eastern hemlock (Tsuga canadensis (L.) Carr.) results in the formation of compression wood around the pith. Compression wood is higher in density than normal wood (Haygreen and Bowyer 1989). Since western hemlock also has a drooping leader, a similar relationship is possible. Aside from the high density region surrounding the pith, no juvenile wood zone has been defined for western hemlock.

Two studies of the relationship between wood density and growth rate in western hemlock indicated that more rapid growth results in reduced wood density. Krahmer (1966) measured specific gravity in wood samples from outside the high density zone adjacent to the pith. He found that the effect of ring width was highly significant, accounting for about 23% of the variation in specific gravity. Although ring age is not separated from ring width in the study, ring age does not seem to have a strong effect on wood density in western hemlock outside of the high density zone. Wellwood (1960) measured specific gravity of western hemlock wood from 60-year old stands, and reported that rate of growth was highly significant in its effect on specific gravity. He used wedge-shaped samples cut from cross-sectional disks. This technique allows rings to be sampled in proportion to their volume, and all samples are of the same average ring age.

Smith (1980) investigated the effect of spacing on percentage latewood in 20-year-old western hemlock stands. He reported that latewood percentage changed little with rings from the pith, and decreased with increasing ring width.

This review of wood density literature can be summarized as follows:

1) Ring age must be taken into account when assessing the effect of growth rate on wood density.

2) Western hemlock, a gradual transition wood, does not appear to follow the pattern of radial density variation reported for abrupt transition species such as the hard pines.

3) Studies of western hemlock indicate that wood density and latewood percentage decrease with increasing growth rate.

C. OBJECTIVE

The objective of this study is to examine effects of stand spacing on branch diameter and wood density in 29- and 38-year-old western hemlock (*Tsuga heterophylla* (Raf.) Sarg) stands which had been thinned at age 11 or 12 to nominal square spacings ranging from 4 to 21.8 feet. Although some information on wood density and branch diameter in western hemlock has been published, little of this information has come from managed stands. This study will provide detailed information on branch diameter and wood density variation in carefully managed stands of western hemlock. Specific objectives are as follows:

1) to determine the effect of tree spacing on branch diameter.
2) to determine the effect of tree spacing on wood density for wood at the same number of rings from the pith.
3) to determine the effect of radial growth rate on wood density for wood at the same number of rings from the pith.

II. METHODS

A. STUDY SITES AND TREE SELECTION

Data for this study were collected at two sites, both western hemlock spacing trials, in July 1989. One trial is located on the Cascade Head Experimental Forest, near Lincoln City, Oregon. The other is located near Clallam Bay, Washington. A detailed description of these sites can be found in Hoyer and Swanzy (1986). Selected characteristics are provided in Table 1.

The Cascade Head trial was installed in 1963, when the stand was twelve years old. Nine plots were established, including one control (unthinned) plot, and two plots at each of the following nominal square spacings (in feet): 8, 12, 16 and 20. Data for this study were collected on all nine plots.

The Clallam Bay trial was installed in 1971, when the stand was eleven years old. Although ten treatments were established in all, only five of the treatments were selected for measurement in this study. Treatments were selected to correspond to the treatments at the Cascade Head trial. Data for this study were collected from two plots at each of the following nominal square spacings (in feet): 4, 9.2, 12.3, 17.6, and 21.8.

CHARACTERISTIC	CASCADE HEAD	CLALLAM BAY
Longitude Latitude	123° 53' 45° 24'	124° 15' 48° 15'
Soils	Astoria silty clay or clay loam	Ozette silt loam
Average Site Index (ft.) (50-yr base by Wiley 1978)	106	122
Stand Age		
at treatment	12	11
at current measurement	38	29
Spacings (ft.)	control, 8, 12, 16, 20	4, 9.2, 12.3 17.6, 21.8
Mean DBH at 12' spacing (in.)	12.2 (in 1988)	11.3 (in 1989)

Table 1. Selected site and stand characteristics of Cascade Head and Clallam Bay thinning trials. From data on file at the Washington State Department of Natural Resources, Forest Land Management Center, Olympia, WA.

On each plot, three trees were selected for sampling. Trees were selected so that each plot would be represented by a dominant, a codominant and an intermediate individual. This was done so that data would be collected from all crown classes within a spacing. Crown class designation was based on tree diameter relative to diameter distribution on the plot. The extreme largest and smallest individuals were excluded from consideration. Within a crown class on a plot, selection of the individual to be sampled was random.

B. GENERAL TREE MEASUREMENTS

Because these trials were established by thinning rather than planting, actual spacing could be quite different from nominal spacing for any individual. For this reason, actual spacing was measured for each study tree. To measure actual spacing, the area surrounding the tree was randomly divided into quadrants. Distance to the nearest tree in each quadrant was measured to the nearest foot. The four distances were averaged to get a value for actual square spacing for each individual. On widely spaced plots where ingrowth occurred, choices sometimes had to be made on whether to measure the distance to a very close, usually ingrowth tree, or the longer distance to the closest original smaller plot tree. These decisions were made on a case by case basis, and involved a subjective judgement about how much influence the smaller tree had on the tree being sampled.

Diameter at breast height was recorded for each measurement tree. Additionally, diameter data at age 29 (1980 measurements) for Cascade Head trees were provided by the Washington Department of Natural Resources. Combining current measurements at Clallam Bay with 1980 measurements at Cascade Head provided diameter data at age 29 for both sites. This was used as a common basis upon which to evaluate the relationship of branch size to tree diameter. The branches measured at Clallam Bay were dead at age 29. Although the branches were measured at age 38 for the Cascade Head trees, it is assumed that these branches were dead at age 29 as well. So the comparison is branch diameter at age 29 versus tree diameter at age 29 for both sites.

C. BRANCH MEASUREMENTS

The branch portion of the study was measured in English units. This was done to allow easier discussion of effects of knot size on log grades, which are defined in English units. Branch diameter was measured on the first sixteen foot log above a one-foot stump. Each study tree was randomly divided into four quadrants. These quadrants did not necessarily correspond to those used in the actual spacing measurements. In each quadrant, the diameter of the largest branch was measured to the nearest 1/10 inch using calipers. The measurement was taken just beyond the collar where the branch joins the bole. The four measurements were averaged to obtain a branch size index for each log, following Bier (1986).

Simple linear regression was used to examine relationships of branch size index to spacing and tree diameter; analysis of variance was used to test the significance of the regression models.

D. CORE MEASUREMENTS

Two 5 mm diameter increment cores were extracted at breast height from each sample tree. The cores were taken at right angles to each other; otherwise orientation was random.

In the laboratory, each core was passed through a laboratory saw to produce a strip, 1.5 mm thick (along the grain) and 5 mm wide, from pith to bark. Resin was removed by a three-stage extraction in a distilling apparatus. First, a 2:1 toluene and ethanol solution was cycled for 48 hours, followed by pure ethanol for another 48 hours. Water was cycled for a final 24 hours to remove the ethanol.

After extraction, the strips were stored for one week in the x-ray densitometry room to allow them to air dry to an equilibrium moisture content of 9%.

After the week of drying, the strips were scanned in an x-ray densitometer as described by Hoag and McKimmy (1988). The densitometer measures the intensity of x-rays passing through a specimen and relates those measurements to wood density, using an attenuation coefficient for the species being scanned. The procedure used to determine the attenuation coefficient is described in Appendix A.

For each ring scanned, the densitometer calculated earlywood width and density, latewood width and density, total ring width and density, and percent latewood. The earlywood/latewood trigger, which is the density that the computer uses to separate earlywood from latewood, was set at 0.5 g/cc.

Difficulties were encountered in obtaining cores suitable for analysis. Some of the cores, especially those from very slow-growing trees, separated between annual rings and disintegrated in the saw. Due to the eccentric shape of hemlock boles, many of the cores missed the pith, and the innermost rings were bored at some angle off the perpendicular. This made accurate scanning of inner ring widths more difficult. In addition, the outer rings broke off from some cores. Because of these difficulties, only the best core from each tree was selected for analysis. Cores where neither the pith nor the current year's ring could be identified were discarded. In a some cases, both cores from a sample tree were discarded. The final sample consisted of 17 cores from Cascade Head and 20 cores from Clallam Bay. Of the nine trees from the three control plots, only two were represented with usable cores; otherwise, usable cores were distributed fairly evenly among spacings.

Since many of the cores did not include the pith, ring age was estimated by counting back from the current year's ring, which could be identified with certainty. This introduced some error into ring age data, since the year each tree reached breast height was not known with certainty. However, it eliminated variability between rings of the same estimated age due to differing climatic conditions; on the same site, all rings of a given estimated age were formed during the same growing season. In this study, rings will be referred to by their estimated age from the pith.

Rings 20 to 24 were selected for analysis, for several reasons. First, rings older than 24 were not available from Clallam Bay, as these trees were in the 25th growing season at breast height when the cores were extracted. Second, this section presumably was outside of any zone of juvenile wood which might exist in western hemlock. And third, the effect of spacing on diameter growth was most pronounced after age 20, providing a wider range of growth rates.

Data for all five rings in each sample were combined; this provided a five-year sample and allowed all comparisons to be made on wood of approximately the same number of rings from the pith. Earlywood widths, latewood widths, and ring widths were averaged for each sample. Earlywood density, latewood density and whole ring density were calculated for each sample using an average of individual ring densities weighted by the corresponding widths. Latewood percent was calculated by dividing average latewood width by average ring width.

Simple linear regression was used to examine relationships between nominal spacing, growth rate, earlywood and latewood widths, and ring density. Analysis of variance was used to test the significance of the regression models.

III. RESULTS

A. THE EFFECT OF SPACING ON BRANCH DIAMETER

There were no significant differences (alpha=.05) in branch diameter between the two study sites, so the data were combined.

Only one of the 228 individual branches measured in this study exceeded two inches in diameter; even at spacings wider than 16 feet, 84% of the branches were under 1.5 inches (Figure 1). Only two of the branches were still alive at this measurement. Both were on the same tree at the 12.3 foot spacing at Clallam Bay.

Branch size index (average of 4 largest branches) increased with nominal spacing (Figure 2). Because nominal spacing differed from actual spacing, branch size index was plotted against actual spacing (Figure 3); this improved the relationship slightly. This model was highly significant ($p<.00001$), and explained 48% of the variation in branch size index.

To help evaluate the tradeoffs between branch diameter and growth rate, branch size index was plotted against DBH at age 29 (Figure 4). This relationship was linear, and explained

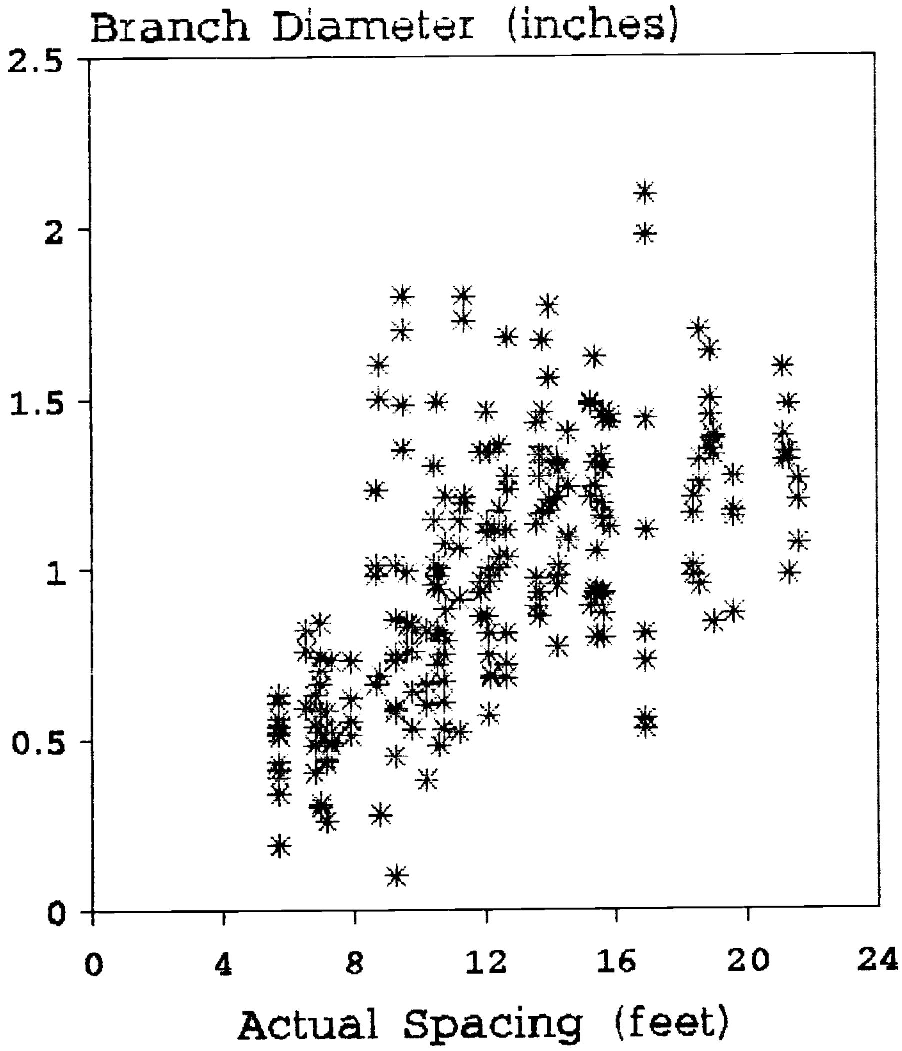

Figure 1. Individual branch diameters (4 per tree) vs.actual spacing. From thirty 29-year-old western hemlock trees at Clallam Bay, WA and twenty-seven 38-year-old western hemlock trees at Cascade Head, OR.

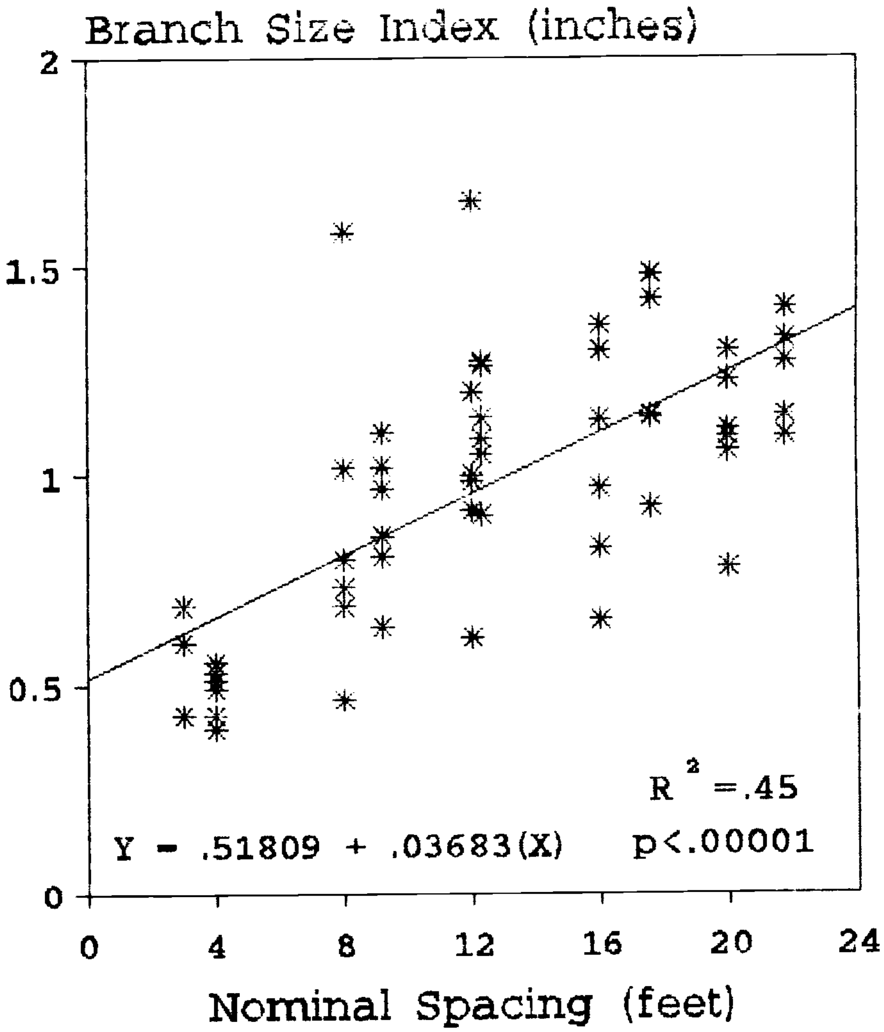

Figure 2. Branch size index vs. nominal spacing. From thirty 29-year-old western hemlock trees at Clallam Bay, WA and twenty-seven 38-year-old western hemlock trees at Cascade Head, OR.

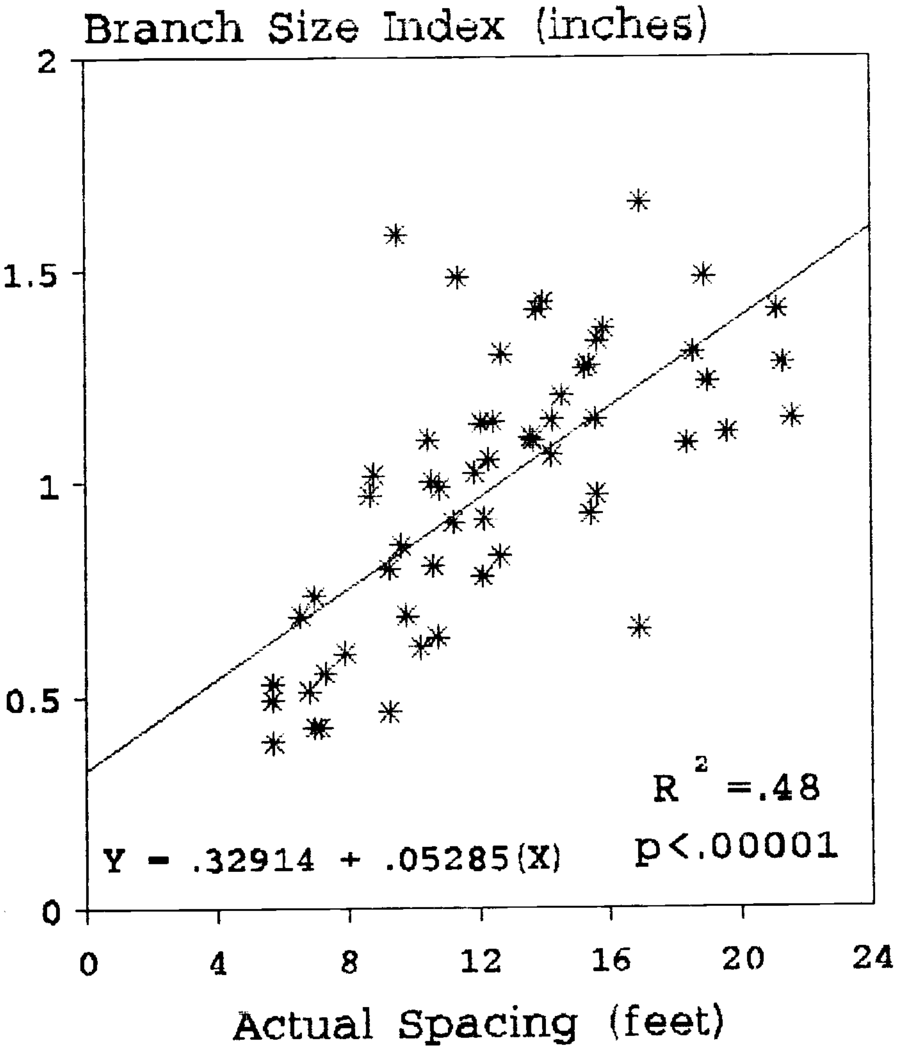

Figure 3. Branch size index vs. actual spacing. From thirty 29-year-old western hemlock trees at Clallam Bay, WA and twenty-seven 38-year-old western hemlock trees at Cascade Head, OR.

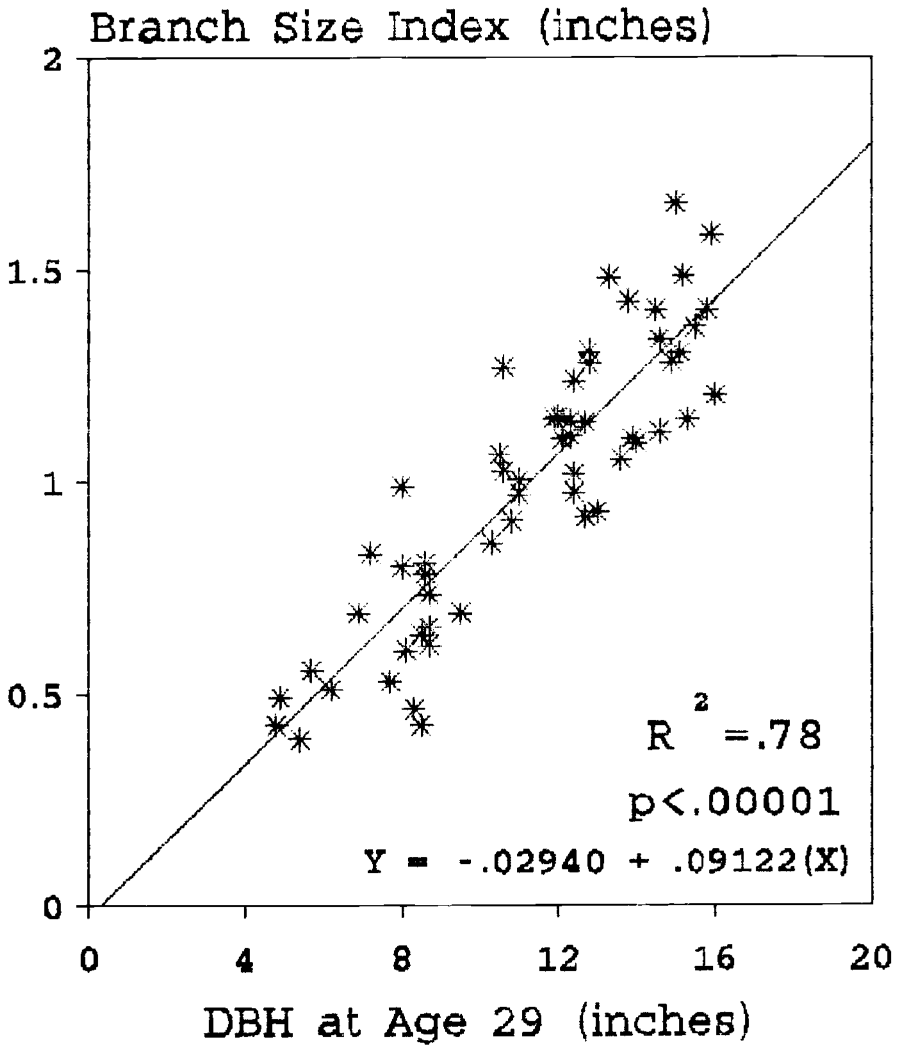

Figure 4. Branch size index vs. tree diameter at breast height at age 29. From thirty 29-year-old western hemlock trees at Clallam Bay, WA and twenty-seven 38-year-old western hemlock trees at Cascade Head, OR.

78% of the variation in branch size index.

B. THE EFFECT OF RADIAL GROWTH RATE ON WOOD DENSITY

There were no significant differences (alpha=.05) between the two sites in wood density, so the density data were combined.

There did not appear to be any relationship between nominal spacing and wood density (Figure 5). Because nominal spacing differed from actual spacing, wood density was plotted against actual spacing. Although the relationship is statistically significant at $p<.05$, the relationship is very weak, and of little practical significance (Figure 6).

Wood density was negatively correlated to ring width (Figure 7). The relationship was highly significant ($p=.00004$) and explained 39% of the variation in wood density.

There was no relationship between ring width and latewood density (Figure 8). Earlywood density appeared to decrease somewhat with wider ring widths, but the relationship was not strong (Figure 9).

Latewood percentage decreased with increasing ring width (Figure 10); ring width explained 48% of the variation in latewood percentage. Wood density was closely tied to latewood percentage (Figure 11); latewood percentage explained 88% of the variation in wood density.

Earlywood width was very closely related to ring width (Figure 12); latewood width was unrelated to ring width (Figure 13). Additionally, the magnitude of variation in latewood width (range 0.3 to 2.1 mm) was much less than that of earlywood width (range 0.6 to 7.8 mm).

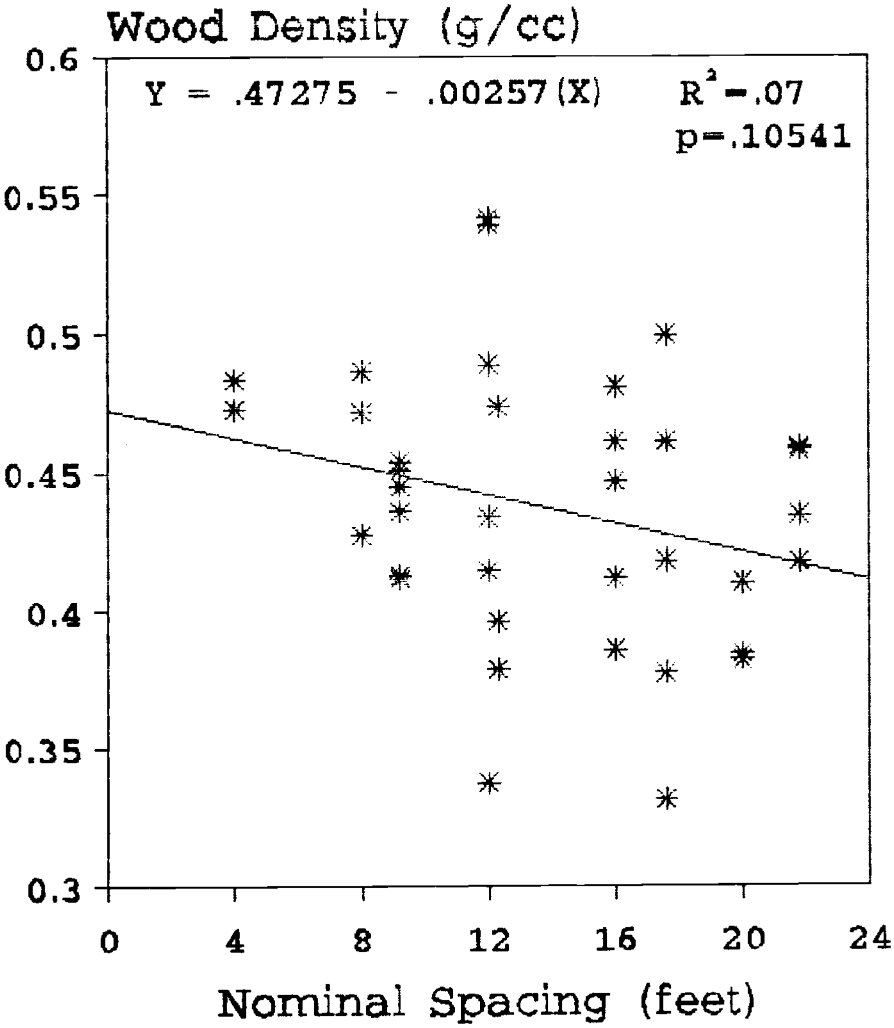

Figure 5. Wood density vs. nominal spacing for rings 20-24 from pith. From 20 increment cores taken at Clallam Bay, WA and 17 increment cores taken at Cascade Head, OR.

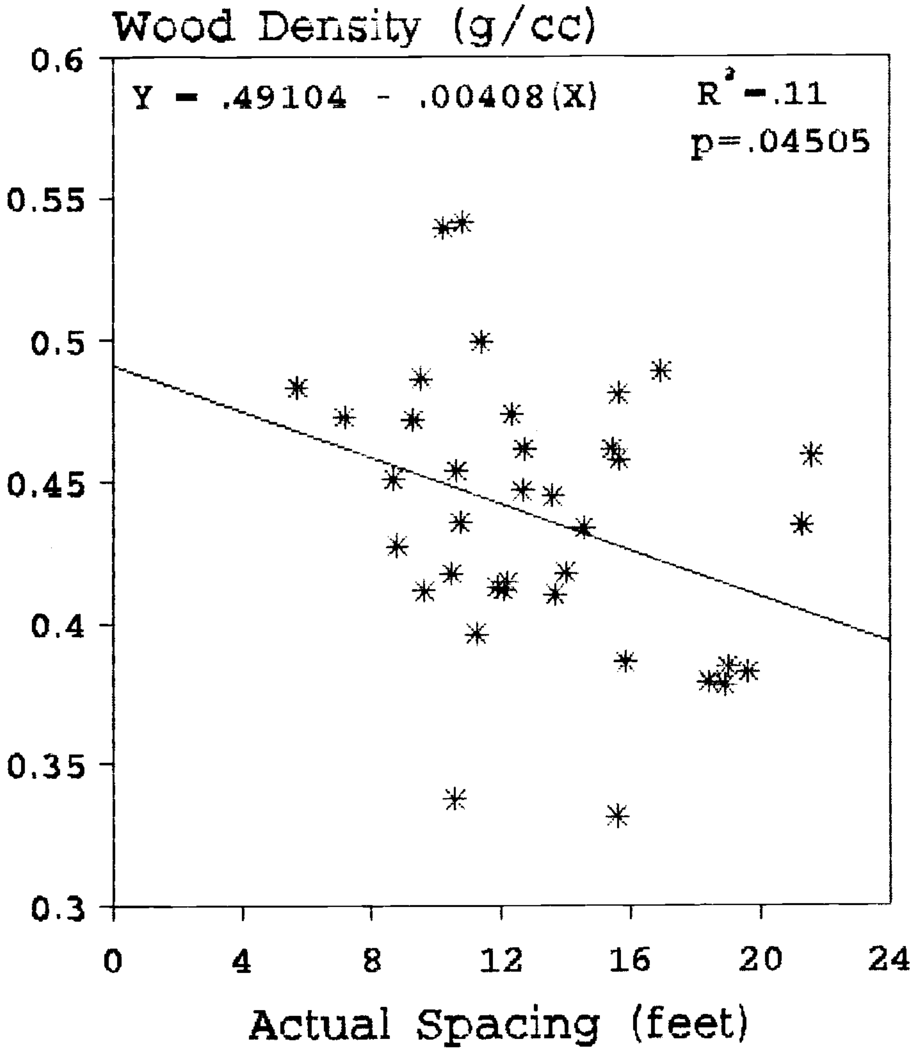

Figure 6. Wood density vs. actual spacing for rings 20-24 from pith. From 20 increment cores taken at Clallam Bay, WA and 17 increment cores taken at Cascade Head, OR.

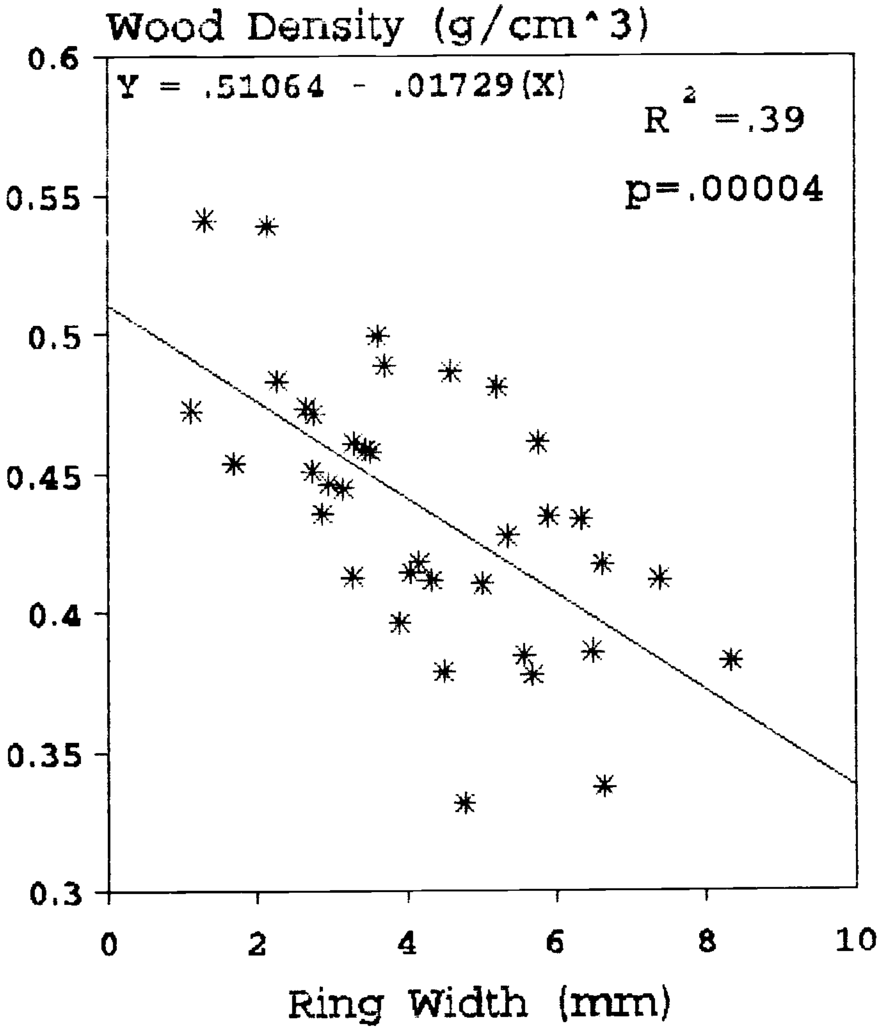

Figure 7. Average wood density vs. average ring width for rings 20-24 from pith. From 20 increment cores taken at Clallam Bay, WA and 17 increment cores taken at Cascade Head, OR.

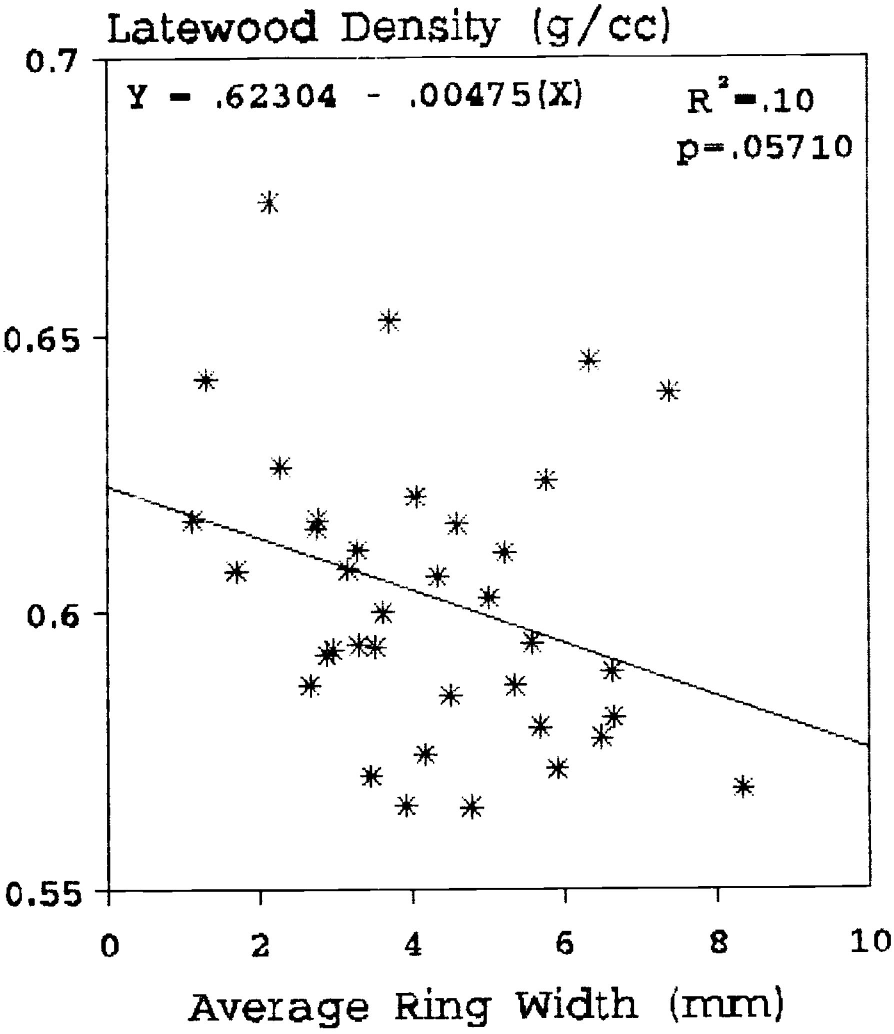

Figure 8. Average latewood density vs. average ring width for rings 20-24 from pith. From 20 increment cores taken at Clallam Bay, WA and 17 increment cores taken at Cascade Head, OR.

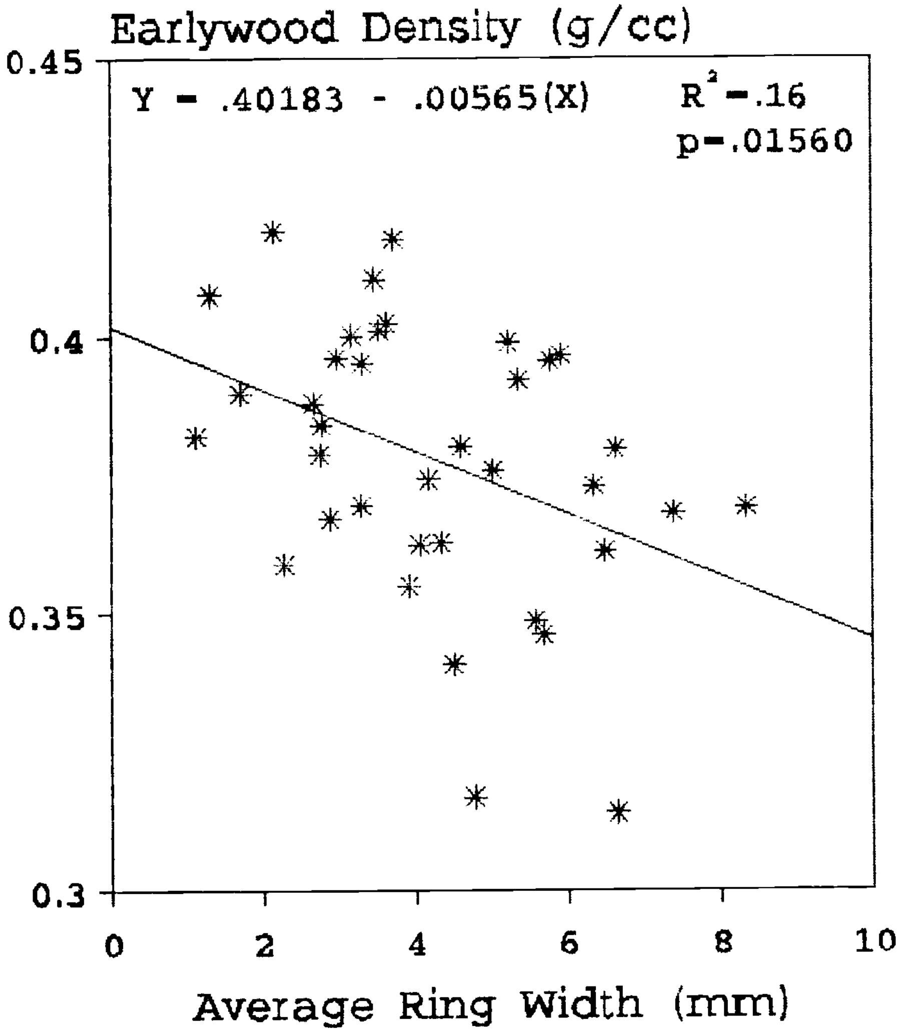

Figure 9. Average earlywood density vs. average ring width for rings 20-24 from pith. From 20 increment cores taken at Clallam Bay, WA and 17 increment cores taken at Cascade Head, OR.

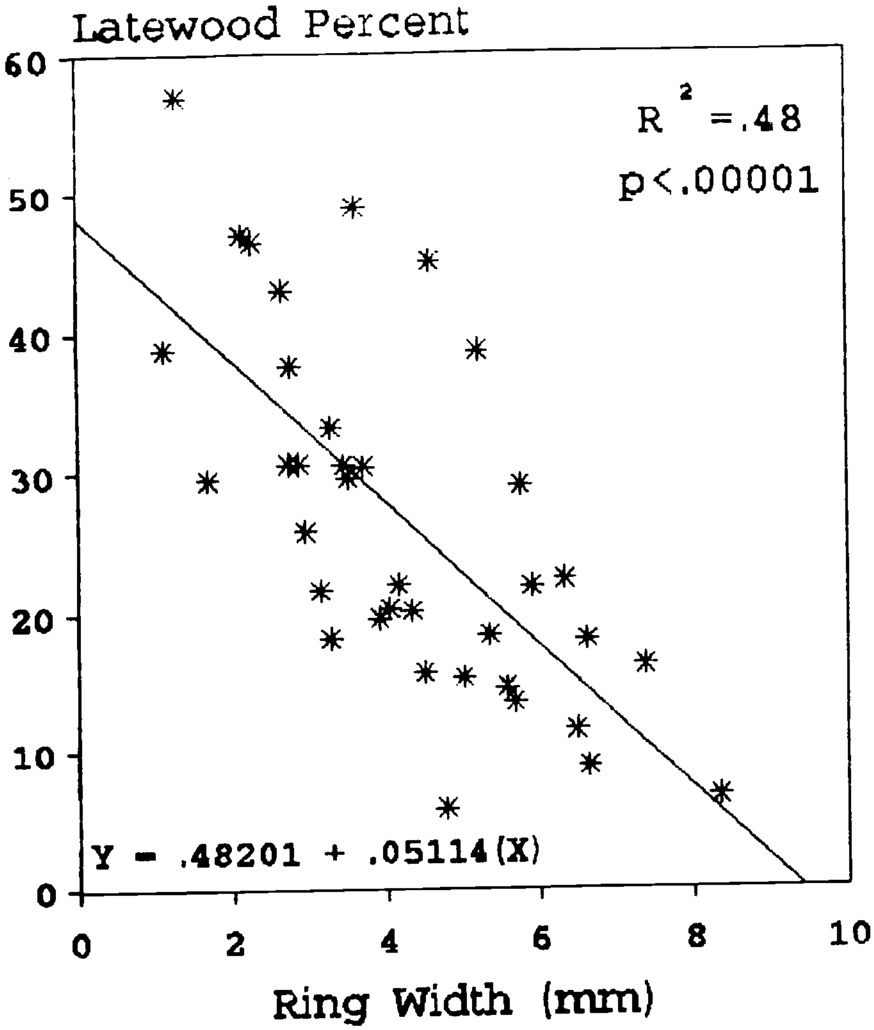

Figure 10. Average latewood percentage vs. average ring width for rings 20-24 from pith. From 20 increment cores taken at Clallam Bay, WA and 17 increment cores taken at Cascade Head, OR.

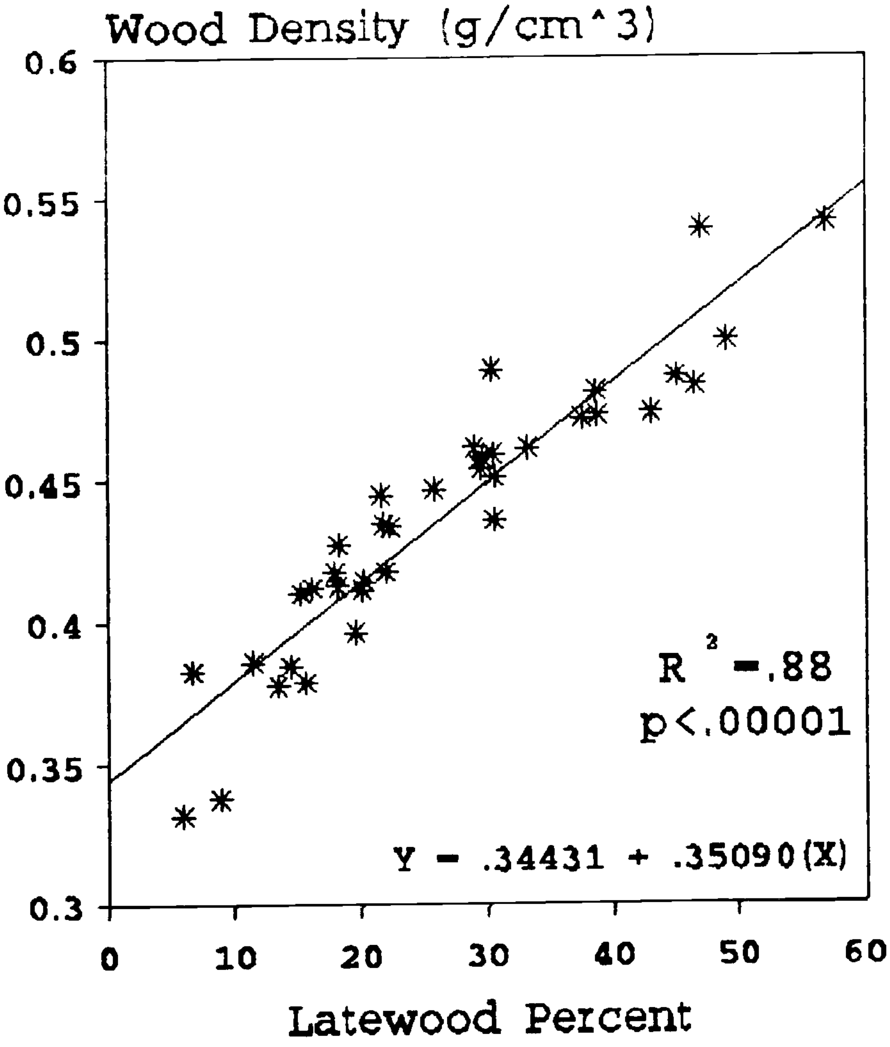

Figure 11. Average wood density vs. average latewood percentage for rings 20-24 from pith. From 20 increment cores taken at Clallam Bay, WA and 17 increment cores taken at Cascade Head, OR.

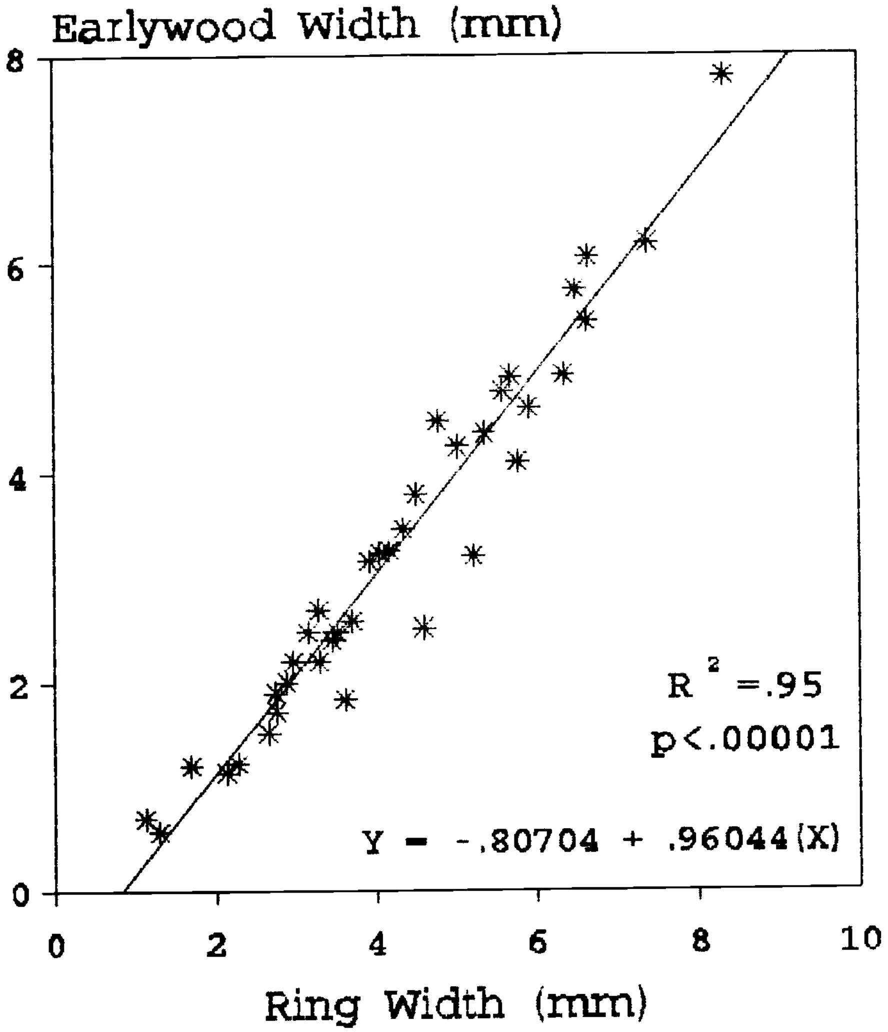

Figure 12. Average earlywood width vs. average ring width for rings 20-24 from pith. From 20 increment cores taken at Clallam Bay, WA and 17 increment cores taken at Cascade Head, OR.

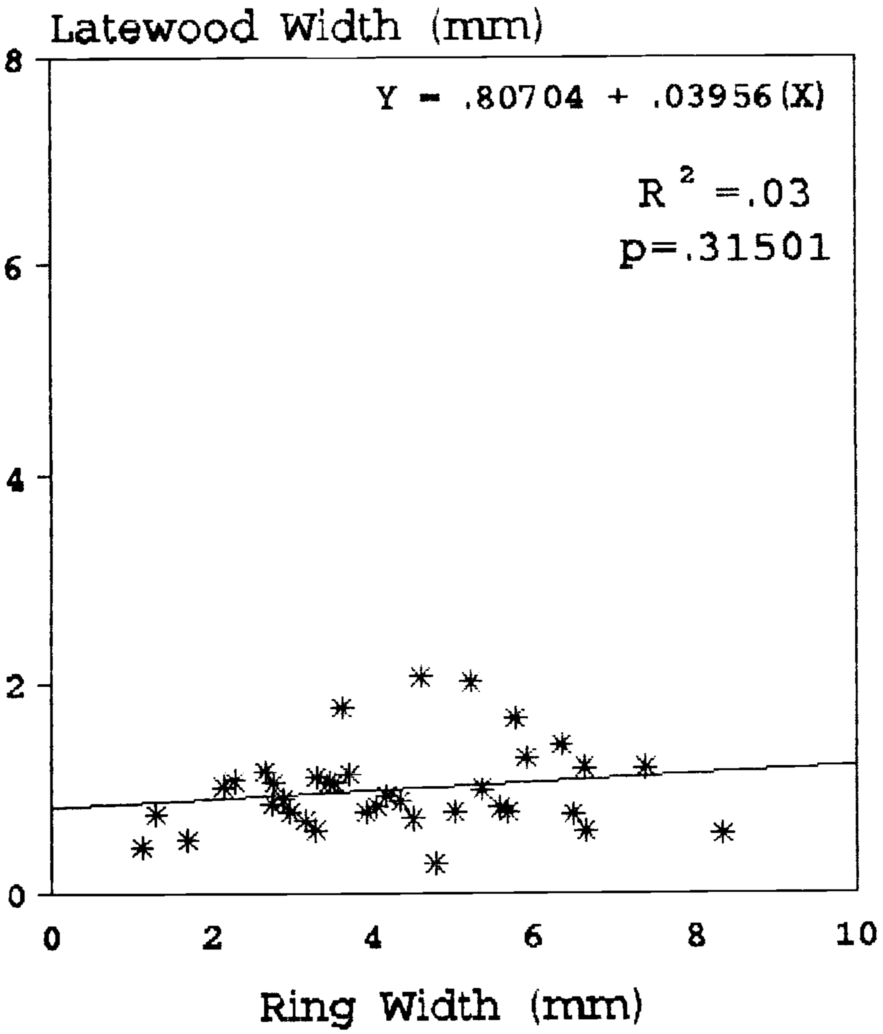

Figure 13. Average latewood width vs. average ring width for rings 20-24 from pith. From 20 increment cores taken at Clallam Bay, WA and 17 increment cores taken at Cascade Head, OR.

IV. DISCUSSION

A. THE EFFECT OF SPACING ON BRANCH DIAMETER

The findings of this study are consistent with the report of Smith (1977) that western hemlock branch diameter increased with spacing. Smith's method of measuring maxiumum knot size used the largest knot in each whorl, rather than the four largest per log, but his values for maximum branch size are quite comparable to those in this study.

The plots sampled in this study cover the range of spacings likely to be prescribed in young western hemlock stands. The data indicate that branch size will increase with spacing over this range, but will not become excessive. Even at spacings of 16 to 20 feet, relatively few branches exceeded 1.5 inches; nearly all were less than 2 inches in diameter. Essentially all the branches measured were dead, so the branch sizes measured are probably representative of the situation on the butt log even at harvest age. Also, because branch diameter was measured outside of the bark, actual knot size in the bole was overestimated. Therefore, knots in products made from these logs would be somewhat smaller than the branch size index suggests. The exact knot diameter will depend on location within the bole, since knot size decreases to zero at the pith.

Knots up to 2.5 inches are acceptable in the No. 2 Sawmill Western Hemlock grade (NLRAG 1982; Table 2), so even the branch diameters at the widest spacings should not disqualify logs for this grade. Large clear logs, such as Peeler Western Hemlock or No. 1 Sawmill Western Hemlock will not be produced at any spacing at current rotation lengths of 40 to 60 years; few logs, if any, would qualify for the Special Mill grade. Any spacing wide enough to allow logs to reach the diameters required by these grades would result in disqualifying knot diameters. So attempting to reduce knot size with tighter spacings is not likely to produce logs better than No. 2 Sawmill grade. Log grades in denser stands may actually be lower if the minimum 12-inch diameter requirement of the No. 2 Sawmill grade is not met; Figure 4 shows that reducing knot size requires a substantial decrease in tree diameter at age 29. It appears that, over the range of spacings considered in this study, log quality will be determined primarily by factors other than knot size, such as log diameter or amount of defect.

It is possible that log grades could change in the future. If this does occur, it should not change the conclusions of this study. The tradeoff will still be knot size vs. log diameter. Large diameter logs will remain less expensive to harvest, haul and manufacture. Unless a high premium is placed on small diameter logs with very small knots, the advantages of larger piece size should continue to outweigh the disadvantages of somewhat larger knots.

The effect of knots on end product grades varies with the product being considered. In lumber, knot size can reduce grade. However, as lumber width increases, so does maximum acceptable knot size (WWPA 1988; Figure 14). For the lumber grades shown in Figure 14, at widths of six to twelve inches, a 2-inch increase in board width allows a 0.5-inch increase in knot size. While wider spacings produce larger knots, they also produce larger diameter logs. Larger logs allow the manufacture of wider boards, which are generally the most valuable. Wider boards allow larger knots; so there is a balancing effect.

Although wider spacings will increase knot size, the effect on log and end product grades should be minimal. Foresters managing young western hemlock stands should be able to choose from the range of spacings considered in this study without concern that increased knot size will have a large impact upon stand value. For current rotation lengths of 40 to 60 years, it is probably more valuable to manipulate tree

Grade	Required Product Grade Recovery	Maximum Knot Size	Minimum Gross Diameter
Special Mill	65% of NET scale in Select Merchantable and better lumber <u>and</u> 100% of NET scale in veneer core and backs	1.5 inches; also, knots may not number more than an average of 1 per foot of log length	16"
Peeler Western Hemlock	50% of NET scale in Clear Face stock veneer <u>or</u> 50% of NET scale in B and Better lumber	None listed	24"
No. 1 Sawmill Western Hemlock	35% of NET scale in B and Better lumber	None listed	24"
No. 2 Sawmill Western Hemlock	65% of NET scale in Construction and Better lumber	2.5 inches	12"
No. 3 Sawmill Western Hemlock	33% of GROSS scale in Standard and Better lumber	3 inches	6"
No. 4 Sawmill Western Hemlock	NET scale at least 33% of GROSS scale, and at least 10 board feet	None listed	None listed

Table 2. Selected requirements of western hemlock log grades. Adapted from NLARG (1982).

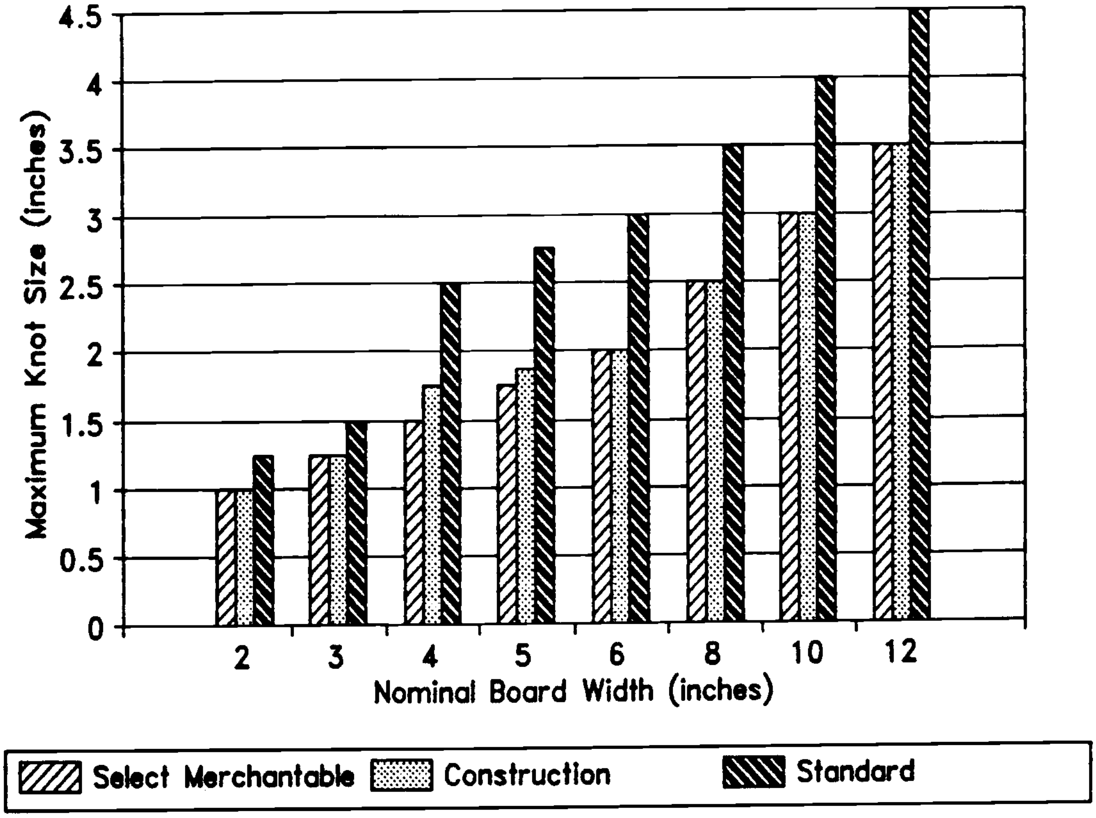

Figure 14. Effect of board width on maximum allowable knot diameters for three board grades. Based on WWPA (1988).

spacing to optimize tree size and stand volume production than to minimize knot size.

B. THE EFFECT OF RADIAL GROWTH RATE ON WOOD DENSITY

The lack of a strong relationship between tree spacing and wood density in this data (Figures 5 and 6) may due to the sampling method. Presumably, any effect of spacing on wood density would be due primarily to radial growth rate. So an analysis of the effect of tree spacing on wood density should concentrate on trees with radial growth rates representative of the spacings being studied. Because sample trees differed considerably in diameter within each spacing, they were not representative of the average growth rate at that spacing.

The sampling method was well suited to analyzing the effect of radial growth rate on wood density, since the sample included cores representing a wide range of growth rates from throughout the diameter distribution of the study areas. So the remainder of the discussion will focus on this question.

This study addresses the question of how wood density is related to growth rate, using material from stands where tree spacing has been controlled. The samples are all of the same approximate ring age. The x-ray densitometer allowed collection of detailed data on ring characteristics. Such detailed information from managed stands has not been published for hemlock.

The relationships of radial growth rate to ring characteristics are very similar to those described for sitka spruce by Brazier (1970). These relationships support the findings of Krahmer (1966) and Wellwood (1960) in finding that wood density decreased with higher rates of growth in western hemlock, and go a step farther in showing why the decrease in density occurs. And finally, the results are consistent with Smith's (1980) report that latewood percentage decreased with increasing growth rate in western hemlock.

The samples in this study cover a wide range of growth rates from managed second-growth stands of western hemlock. Over this range, wood density was negatively correlated with growth rate (Figure 7). It is not possible with the data in this study to evaluate the importance of this decrease to either total cellulose production or average wood density in a stand. However, Figure 15 gives an indication of the average density of wood produced at breast height at each spacing over three time periods. Growth rates in Figure 15 were calculated from average diameter data from the Cascade Head plots, supplied by the Washington State Department of

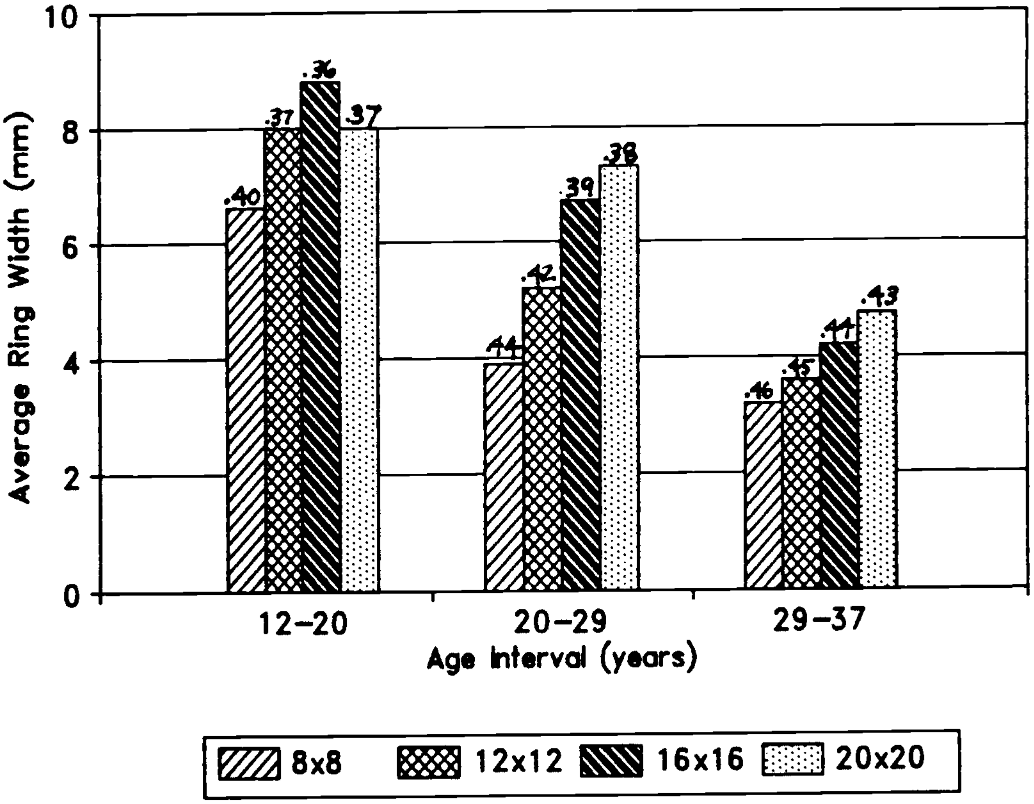

Figure 15. Predicted wood density produced at breast height for three time periods at four spacings.

Natural Resources. The wood densities in this figure are those predicted for the respective growth rate by the equation in Figure 7. Figure 15 applies only to wood at breast height, and is intended as a rough approximation of differences in average growth rate and possible density differences between spacings for three time periods.

The decrease in wood density with higher rates of growth must be caused by a decrease in one or more of the following ring characterics: 1) earlywood density, 2) latewood density, and/or 3) latewood percentage.

Ring width does not appear to influence latewood density (Figure 8). Earlywood density did decrease somewhat with wider ring widths, but the relationship is fairly weak (Figure 9). Also, the decrease in earlywood density is only about 0.05 g/cc over the range of ring widths studied, while ring density decreases about 0.15 g/cc over the same range. Latewood percentage drops sharply with increasing growth rate (Figure 10). And latewood percentage explains 88% of the variation in wood density (Figure 11). The data suggest that an increase in the proportion of earlywood is the primary reason that wood density decreases with increasing ring width. Reduced earlywood density may also be associated with wider rings, causing a further decrease in wood density.

The increase in the proportion of earlywood occurred because increases in ring width resulted in more earlywood being produced (Figure 12) with no corresponding increase in latewood width (Figure 13). This can be seen graphically in Figure 16.

Figure 16 is a model based on Figure 12. First, the regression line from Figure 12 was replotted, forming the earlywood portion of the graph. This line represents the average earlywood width over a range of ring widths. The latewood component of Figure 14 was added as the difference between earlywood width and ring width.

Despite the sharp drop in latewood percentage with increasing growth rate, 52% of the variation in latewood percentage remains unexplained (Figure 10). Some of the unexplained variation can be attributed to the fact that latewood width varies independently of growth rate. This independent variation in latewood width makes it difficult to accurately predict latewood percentage based on growth rate. When latewood is narrow in width, growth rate overestimates latewood percentage; with wider bands of latewood, growth rate underestimates latewood percentage.

Because wood density is so closely tied to latewood

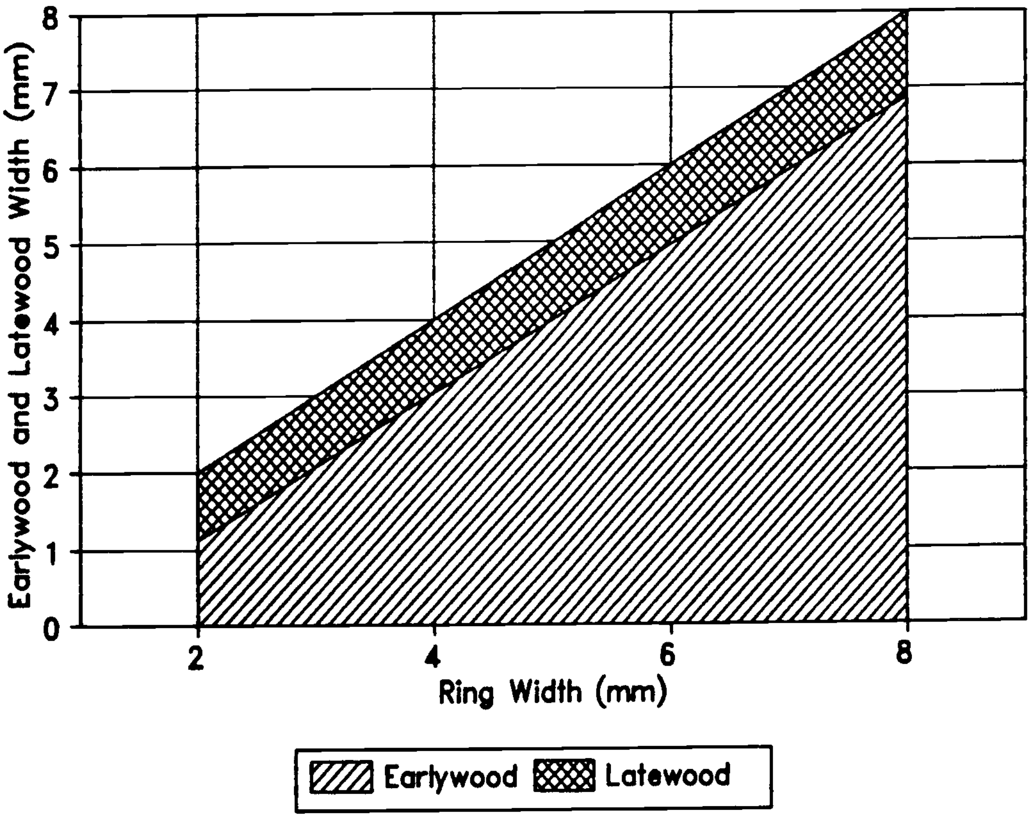

Figure 16. Predicted earlywood and latewood widths over a range of ring widths for western hemlock.

percentage (Figure 11), manipulation of latewood percentage is an important means by which wood density can be controlled in western hemlock. Latewood percentage could be increased by either of two strategies. The first strategy would be to reduce earlywood width by reducing radial growth rate. This could be accomplished through control of tree spacing, but reducing growth rate is usually considered undesirable. The other strategy would be to increase latewood width. At present, factors controlling latewood width in western hemlock are not understood. But, if latewood width is subject to silvicultural or genetic control, it would offer a means of increasing wood density without decreasing radial growth rate.

Wood density could also be increased without reducing growth rate by increasing earlywood and latewood densities. Of these two, earlywood density is the most important at higher rates of growth, because the majority of a wide ring is composed of earlywood. While the data do suggest some influence of ring width on earlywood density (Figure 9), most of the variation (84%) is due to some other factor. Wood density in the pines has been shown to be subject to a large degree of genetic control (Haygreen and Bowyer 1989). If the same is true of hemlock, genetic selection may be used to increase earlywood or latewood densities.

In summary, wood density decreased with higher rates of radial growth in western hemlock primarily because latewood percentage decreased. The decrease in latewood percentage occured because growth increases occur mostly in earlywood, with no corresponding increase in latewood width. A mild effect of growth rate on earlywood density was found, but growth rate did not affect latewood density.

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APPENDICES

APPENDIX A: Determining the Attenuation Coefficient

The attenuation coefficient is the number which relates intensity of x-rays passing through a specimen of wood to the density of that specimen. The procedure for determining that coefficient is outlined below.

1. Disks were cut from the tops of 10 western hemlock stumps in a recently thinned stand near Hebo, Oregon.

2. A 5mm thick by 5mm wide strip, from pith to bark, was cut from each disk using a table saw.

3. The strips were put through the extraction and drying process described in the "Methods" section.

4. After drying, the gravimetric density of each strip was calculated. The width and thickness were measured to the nearest 0.1 mm using digital calipers; the length was measured to the nearest millimeter with a ruler; the sample was weighed to the nearest .001 gram on a laboratory scale.

5. The strips were then scanned in the x-ray densitometer, using 0.732 as the attenuation coefficient, to calculate density. (0.732 was the coefficient currently entered in the densitometer, so it was used. An examination of the equation below shows that the exact number used at this point is not important; a change in the coefficient will be balanced by a change in the x-ray density.)

6. For each strip, a corrected attenuation coefficient was calculated by the following equation:

$$\text{Attenuation Coefficient} = \frac{.732 * (\text{x-ray density})}{\text{gravimetric density}}$$

7. The corrected attenuation coefficients from the ten strips were averaged. The average was 0.753, with a standard deviation of 0.009.

8. The attenuation coefficient used for this study was **0.753**.

APPENDIX B: Radial Profiles for Three Cores

In this appendix, radial profiles of three cores are presented.

All three cores show high latewood width, latewood percent and wood density near the pith. This is consistent with earlier reports, as discussed in the literature review. The fact that latewood widths are exceptionally high near the pith, with very little earlywood, may indicate the presence of compression wood.

Figures 22 to 24 suggest that as growth rate changes over time, most of the change is in earlywood width. This is consistent with the data presented in the "Results" section.

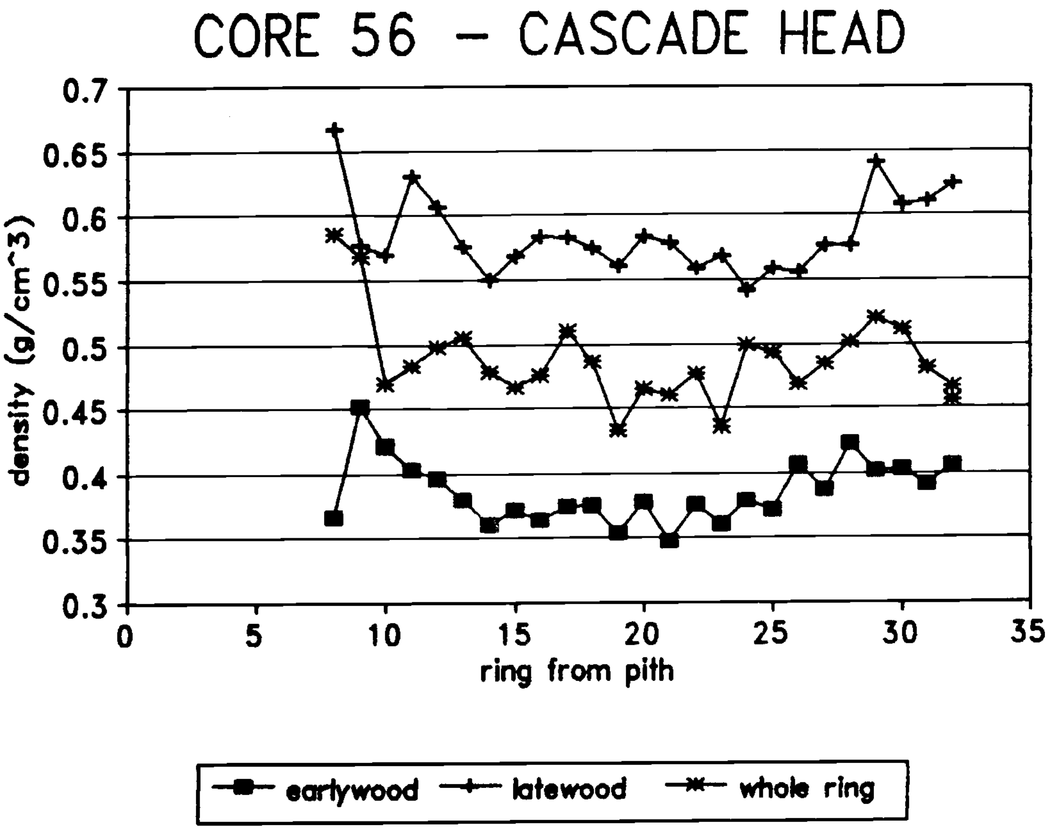

Figure B1. Radial density profile for core 56, from Cascade Head, Oregon.

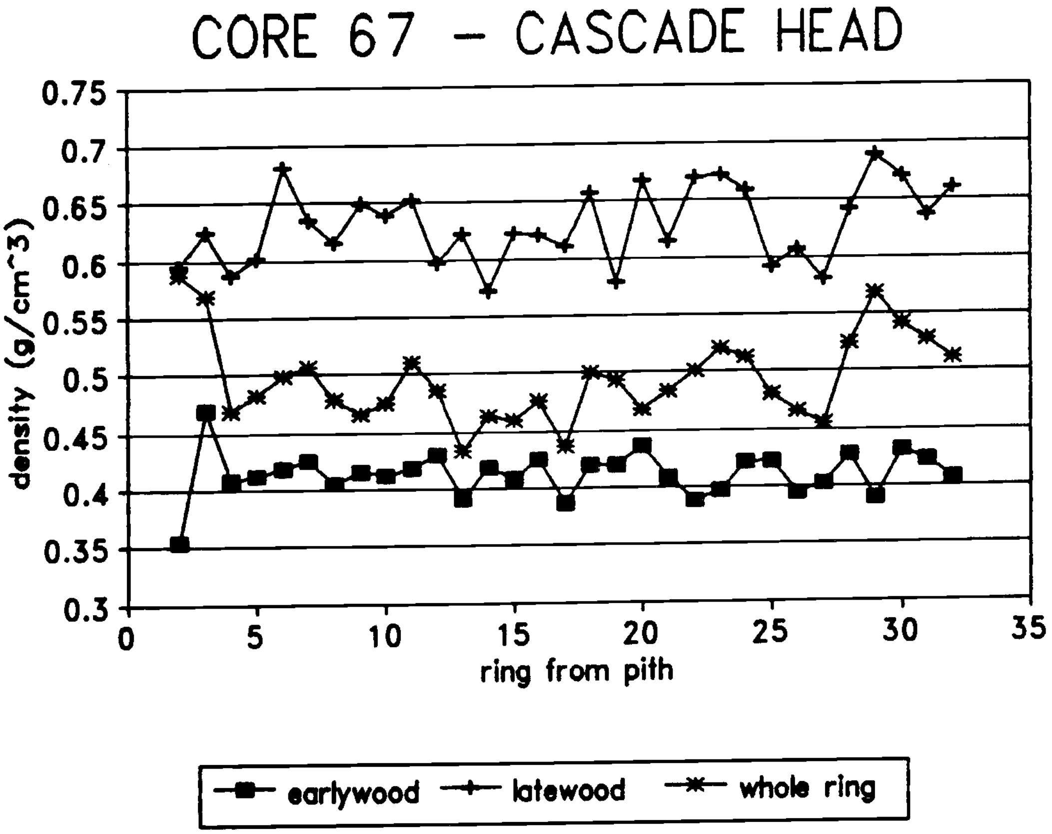

Figure B2. Radial density profile for core 67, from Cascade Head, Oregon.

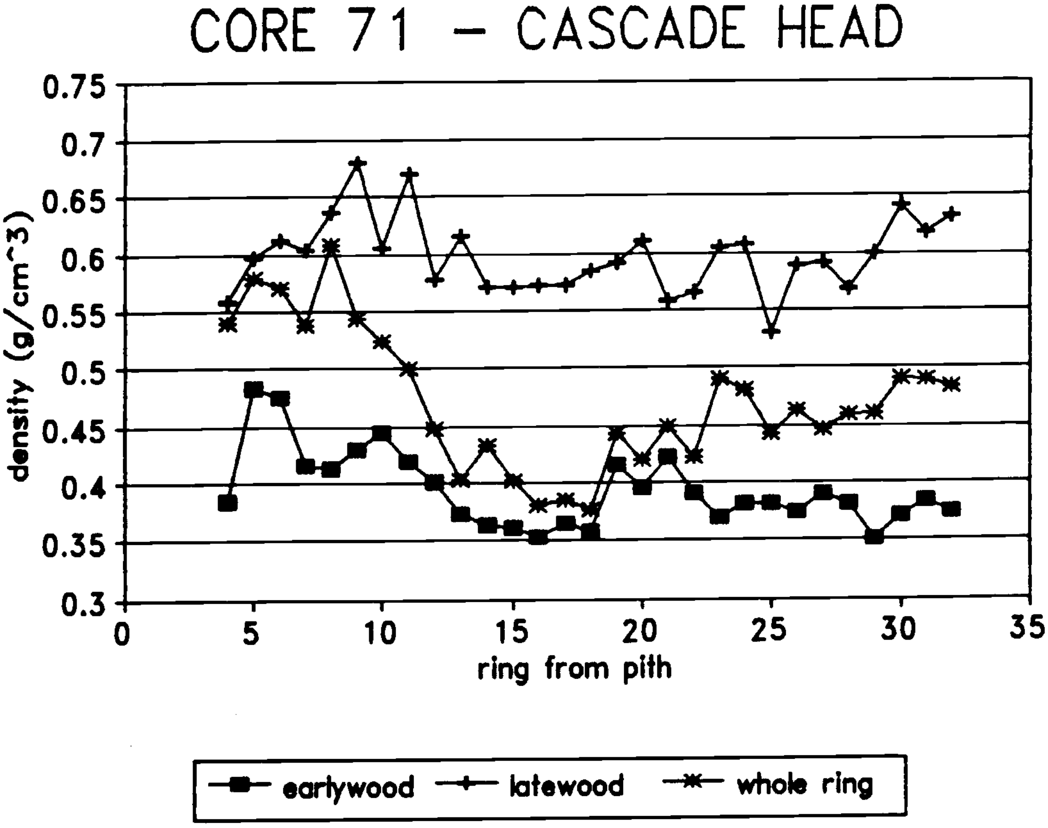

Figure B3. Radial density profile for core 71, from Cascade Head, Oregon.

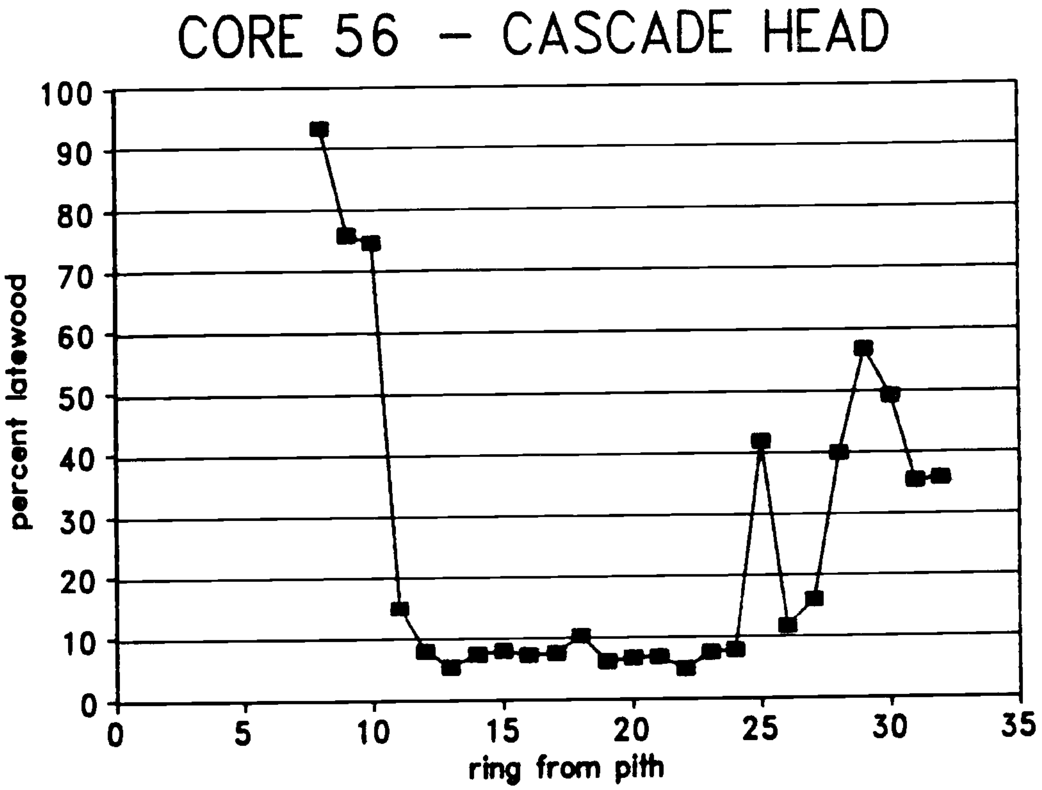

Figure B4. Radial latewood percent profile for core 56, from Cascade Head, Oregon.

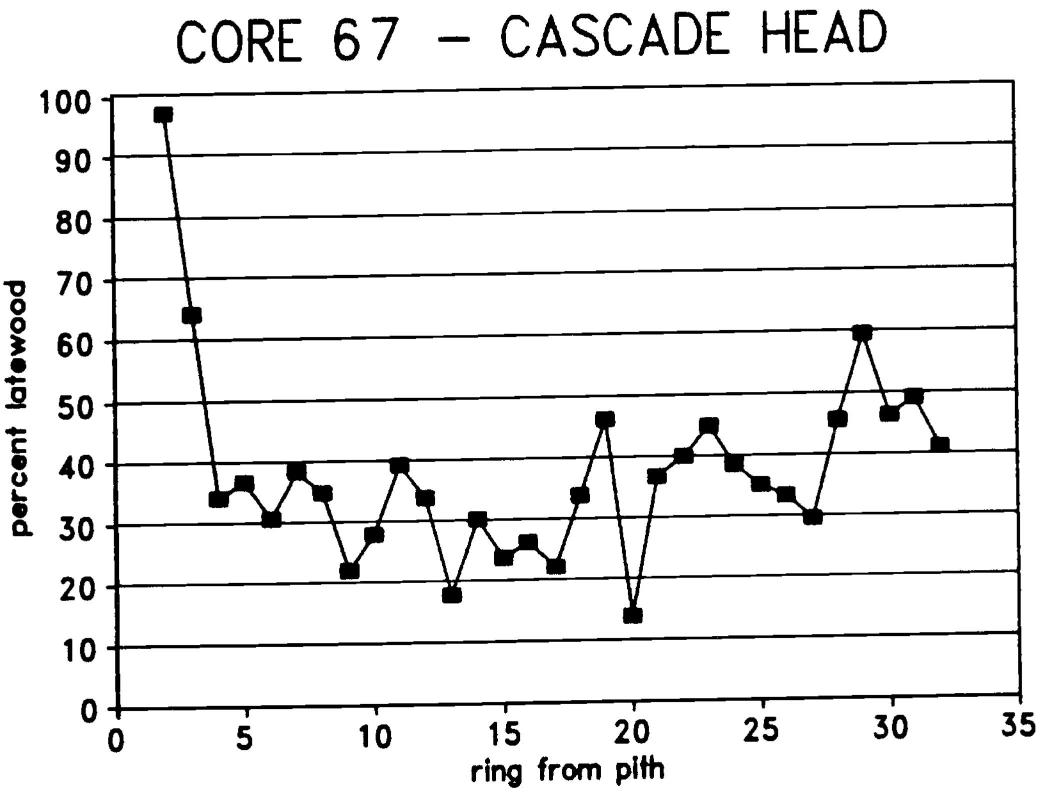

Figure B5. Radial latewood percent profile for core 67, from Cascade Head, Oregon.

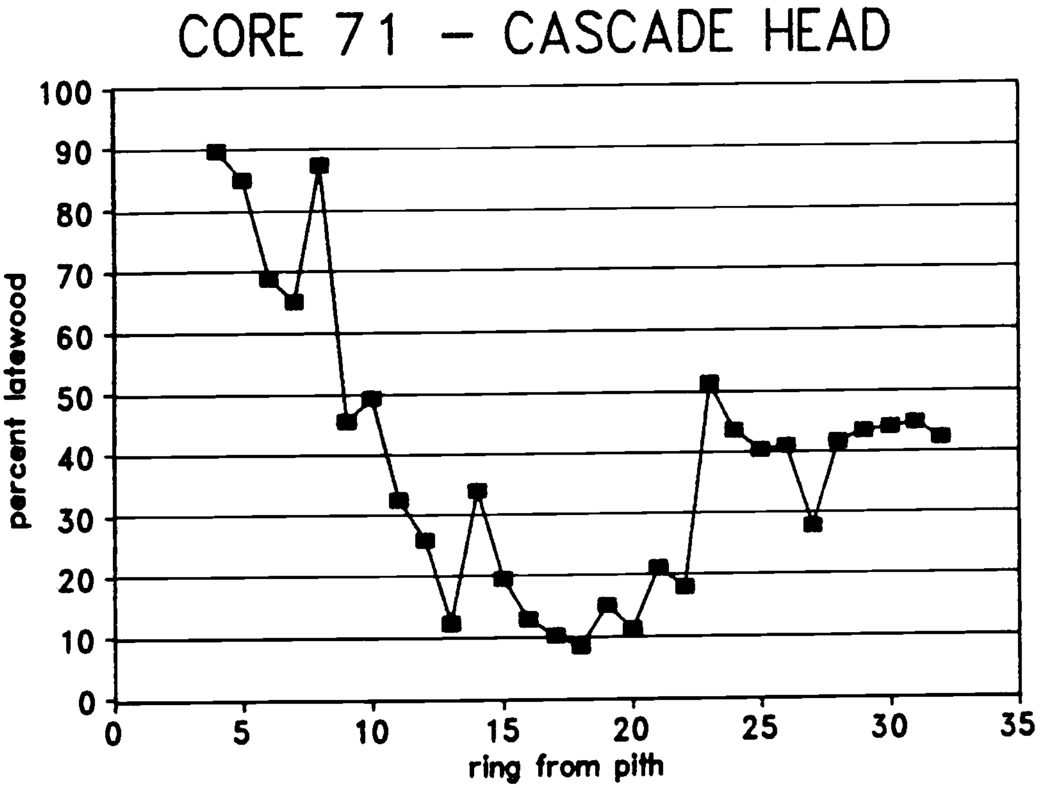

Figure B6. Radial latewood percent profile for core 71, from Cascade Head, Oregon.

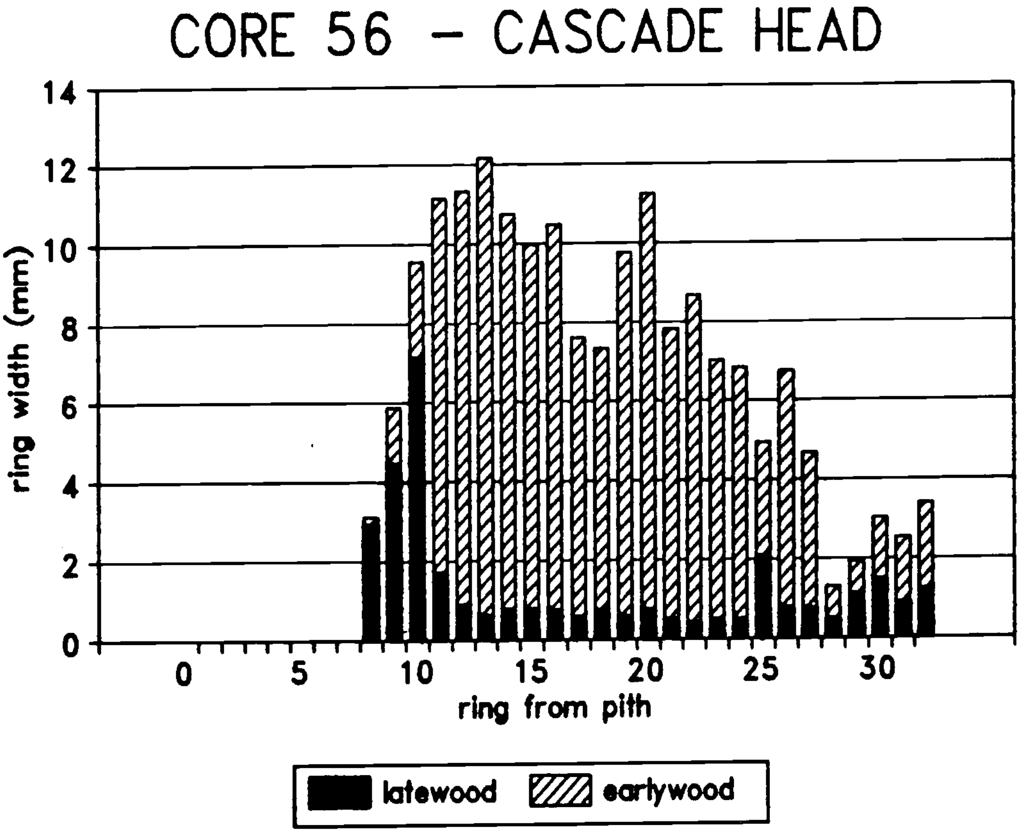

Figure B7. Radial ring width profile for core 56, from Cascade Head, Oregon.

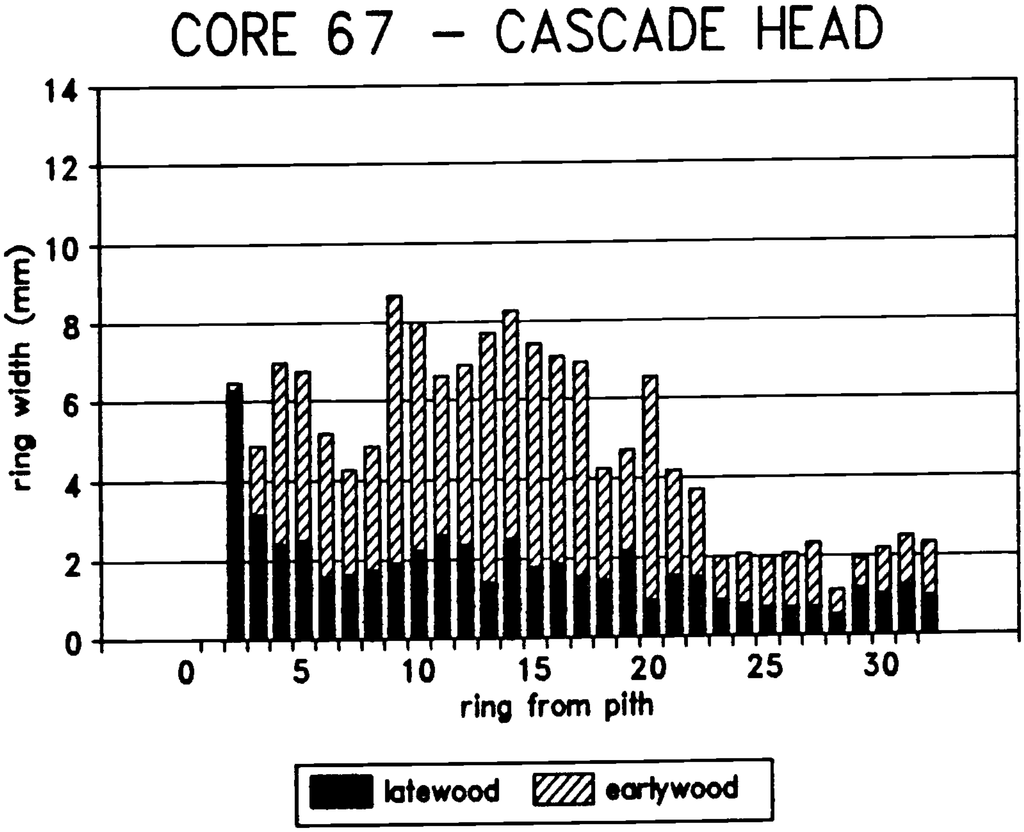

Figure B8. Radial ring width profile for core 67, from Cascade Head, Oregon.

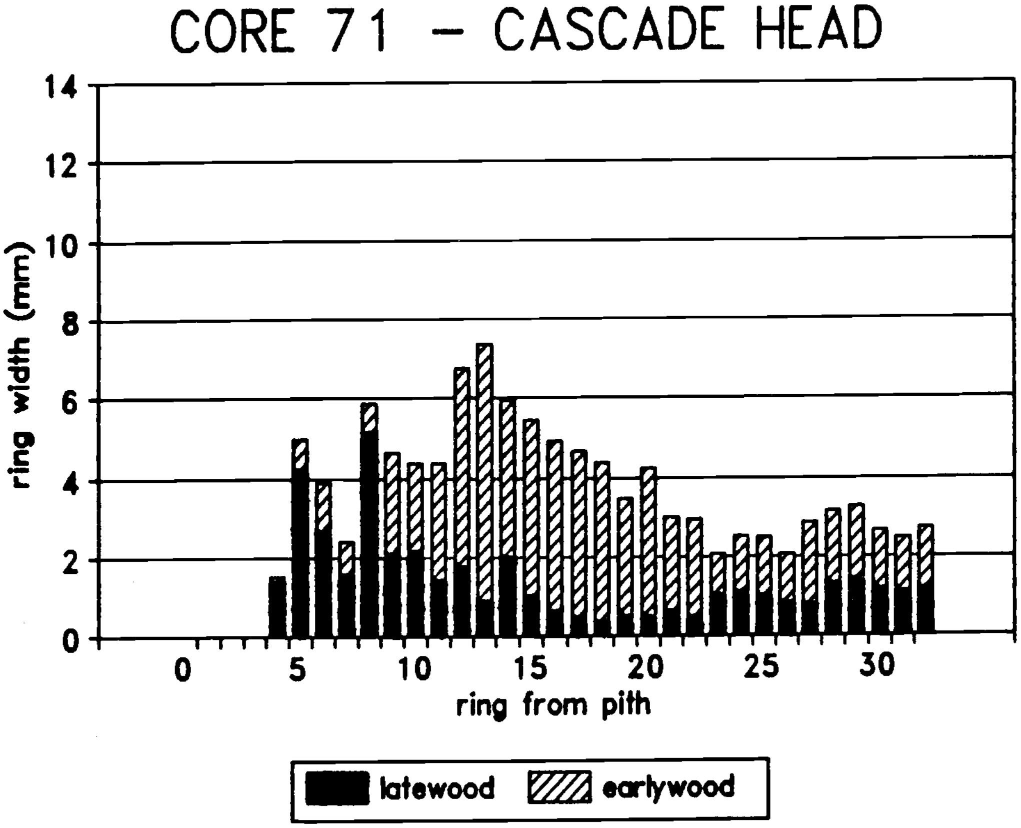

Figure B9. Radial ring width profile for core 71, from Cascade Head, Oregon.

APPENDIX C: Ring Width and Density Relationships in Rings 28-32 from Cascade Head Samples

The trees at Cascade Head were older than those at Clallam Bay. This allowed the ring width and density relationships discussed in this thesis to be checked using older rings. So the same relationships plotted in the "Results" section were replotted using data from rings 28-32 at Cascade Head.

The combination of reducing the number of cores in the sample from 37 to 17, and using rings further from the pith (which are usually narrower), resulted in a diminished range of growth rates. In this older sample, only two cores had ring width values greater than 4 mm. In contrast, the sample using rings 20-24 from both sites included 19 cores with ring width values between 4 mm and 9 mm.

The narrower range of growth rates in the smaller sample limits its usefulness in evaluating the relationships reported in the "Results" section of this thesis. However, since the data was available, it was included in this appendix.

The data are shown as scatter plots. As much as possible, the plots were kept at the same scale as the corresponding figures in the "Results" section. In some cases, though, the older rings included a wider range of values than the original sample. In these cases, the x and y axes were adjusted accordingly. The regression lines from the "Results" section were plotted over the scatter plots to see how the older data were distributed around these lines.

As Figures 25 to 29 show, the regression lines established for rings 20-24 seem to be appropriate for rings 28-32. Although there are several data points which seem to be high in latewood percent and wood density, the values are not out of line considering the the amount of variation found in the younger rings. In any case, the relationships in the older rings are quite similar to those found in the younger rings.

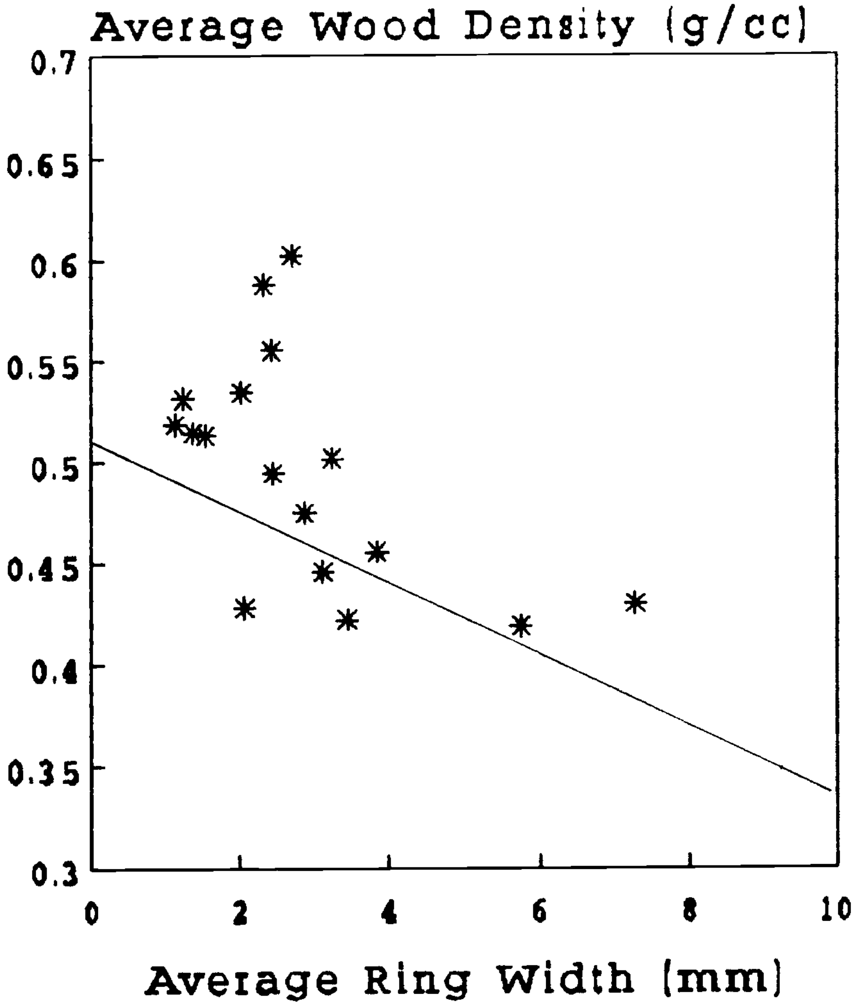

Figure C1. Wood density vs. ring width for rings 28-32 from pith. From 17 increment cores taken at Cascade Head, OR. The regression line plotted in this figure is from Figure 7.

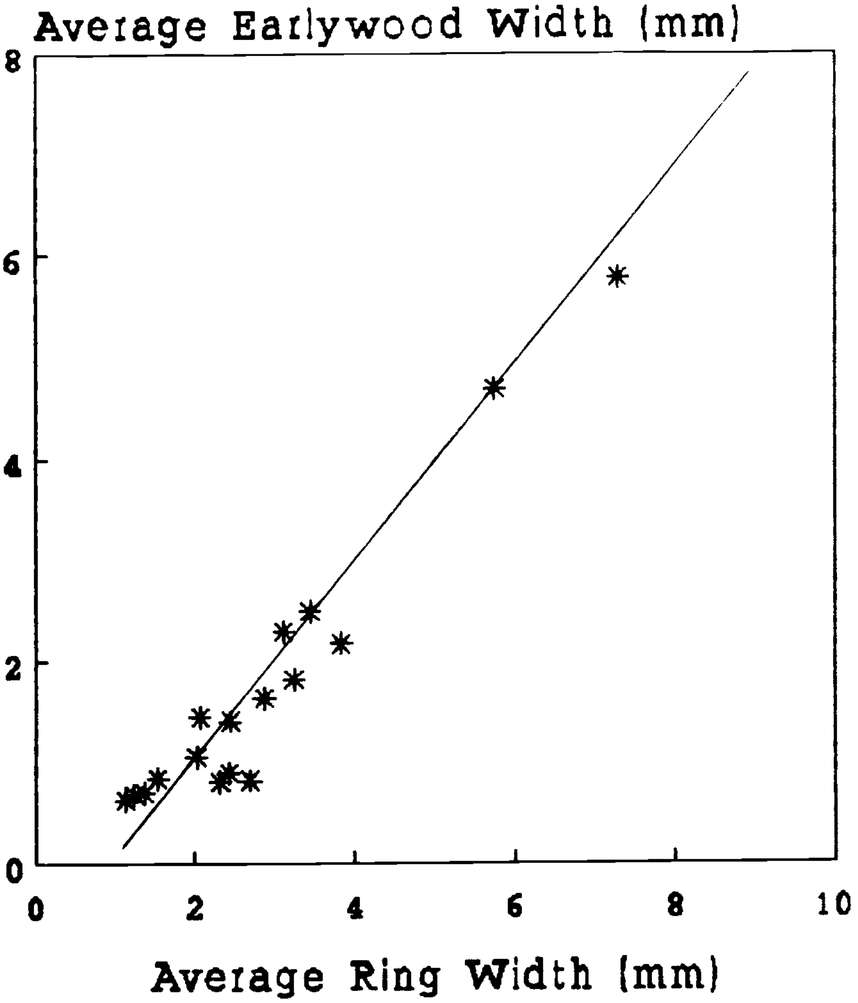

Figure C2. Earlywood width vs. ring width for rings 28-32 from pith. From 17 increment cores taken at Cascade Head, OR. The regression line plotted in this figure is from Figure 12.

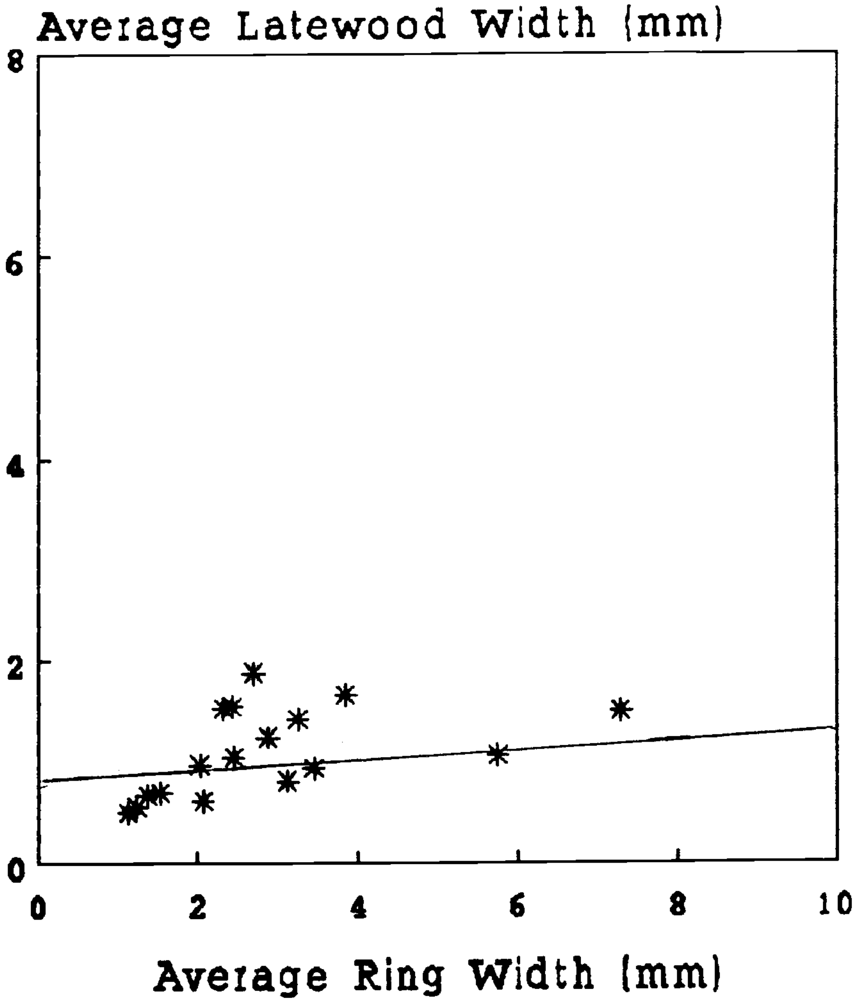

Figure C3. Latewood width vs. ring width for rings 28-32 from pith. From 17 increment cores taken at Cascade Head, OR. The regression line plotted in this figure is from Figure 13.

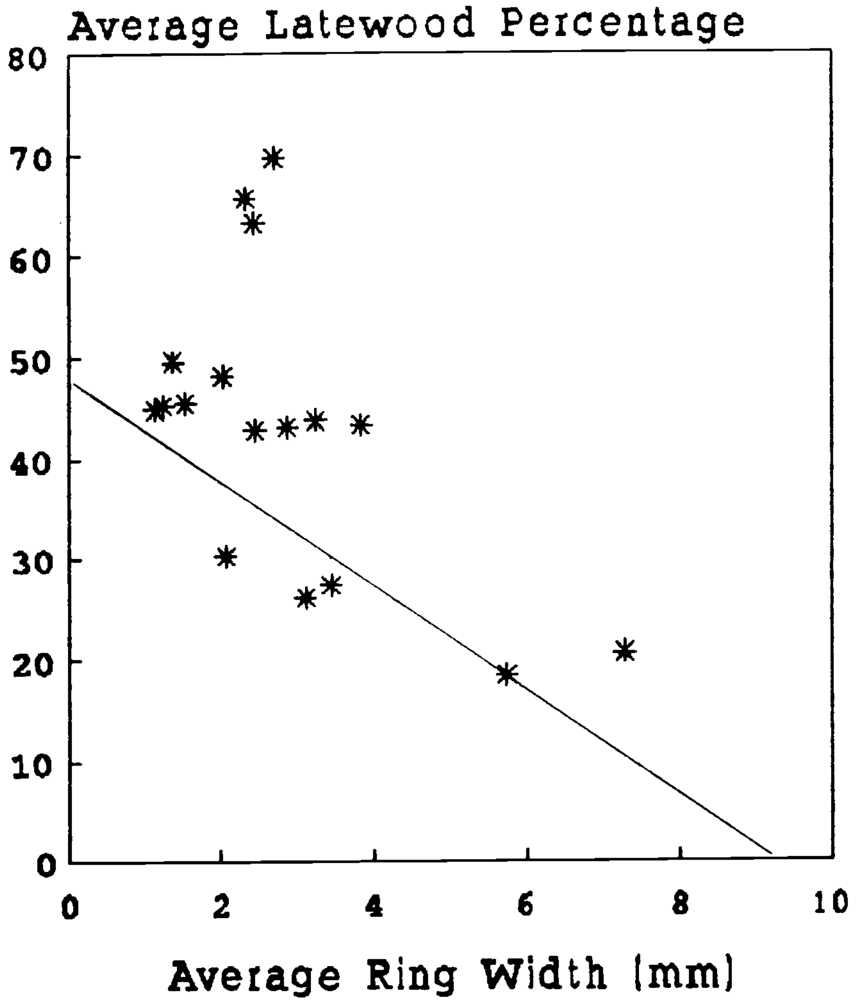

Figure C4. Latewood percentage vs. ring width for rings 28-32 from pith. From 17 increment cores taken at Cascade Head, OR. The regression line plotted in this figure is from Figure 10.

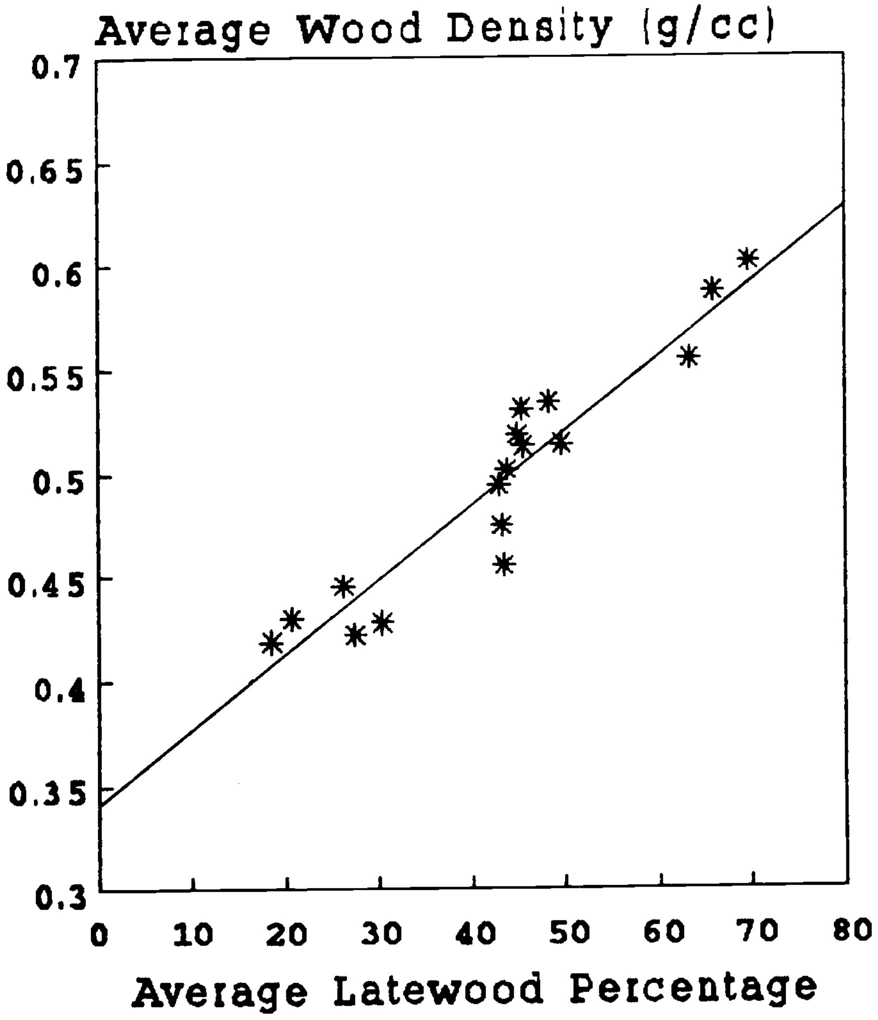

Figure C5. Wood density vs. latewood percentage for rings 28-32 from pith. From 17 increment cores taken at Cascade Head, OR. The regression line plotted in this figure is from Figure 11.