## AN ABSTRACT OF THE THESIS OF

Josef Bodner for the degree of Master of Science in
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Title: Effect of Thinning and Fertilization on Wood Properties and Intra-Ring Characteristics in Young Douglas-fir

Redacted for Privacy
Abstract approved: ______________________
Dr. M. D. McKimmy

The purpose of this study was to determine if thinning, fertilization or a combination of thinning and fertilization had an effect on overall average specific gravity, modulus of elasticity, modulus of rupture, fiber length and intra-ring characteristics. Material for this experiment consisted of 7 trees randomly selected from each of two thinning/fertilization treatments and a control (unthinned and not fertilized) stand. Thus a total of 21 trees were involved. The trees were cut in the summer of 1982. Static bending tests were done on juvenile and mature wood from trees of all plots at the butt and at a height of 18 feet. Specific gravity and fiber length were also determined. The intra-ring parameters (earlywood width, latewood width, ring width, earlywood density, latewood density, ring density, minimum earlywood density, maximum latewood density, density range and percentage latewood) were determined by X-ray studies. Statistical analyses showed significant differences between treatments (thinning, or thinning/fertilization) in modulus of elasticity, modulus of rupture, fiber lengths and all the intra-ring parameters. Overall average specific gravity did not differ significantly among treatments but did between butt and top (18-foot height) wood values. Ring width and ring density seemed most influential on mechanical properties. Average modulus of elasticity for the samples tested were 10.6% (for the thinning/fertilization experiment) and 17.3% (for the thinning experiment) less than comparable values in the control plot. Average modulus of rupture for the samples tested were 6.3% (for the thinning/fertilization experiment) and 12.4% (for the thinning experiment) less than comparable values in the control plot. Age seemed to have the most influence on fiber length. Thinning treatments within the tree age-range of juvenile wood affected intra-ring parameters less than did such treatments in the age-range of mature wood. Fertilization by itself did not significantly increase tree growth (annual ring width).

# Effect of Thinning and Fertilization on Wood Properties and Intra-Ring Characteristics in Young Douglas-fir

by

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## INTRODUCTION

The forest manager is today looking for ways to improve the economics of forest production by increasing yields, reducing production costs, and improving quality. However, his success cannot be measured simply in terms of reduced costs per unit volume of production since the forester will need to satisfy the user that the timber he grows is an acceptable product (3).

Thinning and fertilization of forest stands are likely to be tried much more in forest management efforts to improve growth. Following thinning and fertilization, trees in the thinned areas show a response in diameter increment. This response is the result of improved growing space for the tree crowns, reduced competition for root soil moisture and nutrients, and better exposure of branches to lateral light (1, 6, 26).

The implications of such cultural practices for producing a greater wood supply are now well known and much research has been done on many tree species to measure the growth responses to intensive forest management. Relatively less research has been expended in the relationship of wood quality to increased rate of wood production. This study investigated the effect of forest stand thinning and fertilization on wood strength properties, fiber length and intra-ring parameters of Douglas-fir [*Pseudotsuga menziesii* var. *menziesii* (Mirb.) Franco].

# OBJECTIVES

The purpose of this investigation was to develop a technique that would allow precise measurement of intra-ring-parameters. The X-ray equipment available at Oregon State University needed to be improved and computerized in order to quantify the effects of cultural treatments on annual growth characteristics. The objectives of this project were:

1. To determine the effect of forest stand thinning and fertilization on average specific gravity, ring width, earlywood width, latewood width, density range, minimum earlywood density, maximum latewood density, ring density, and percentage of latewood, earlywood density, and latewood density.
2. To measure the influence of thinning and fertilization on mechanical strength properties and fiber length.

# LITERATURE REVIEW

## Effect of Thinning and Fertilization on Forest Stand Yield and Growth

A forest stand is thinned to redistribute growth potential to the best trees in the stand and to utilize all the merchantable material produced during the rotation (39). Many researchers have found that thinning young forest stands significantly increase growth rate and wood volume produced. Tappeiner *et al*. (43) found that Douglas-fir stands respond to precommercial thinning by substantially increasing diameter growth and maintaining high volume growth. Furthermore, they found young, rapidly growing thinned Douglas-fir can be profitable and can increase returns compared to unthinned stands. They concluded that lighter thinnings can yield higher volume and more value in a longer rotation than initially heavy thinnings.

Parker *et al*. (27) reported on the effect of fertilization and thinning of Douglas-fir wood. They analyzed trees showing a pronounced radial increment response to fertilization and thinning. This study found that thinning had a more sustained or continued increase on growth rate than did fertilizing.

Staebler (40) discussed the evidence of shock following thinning. Shock is simply failure of the tree to respond to thinning (presumably in diameter growth). He found that the effect of shock seems to have seldom if ever been measured in quantitative terms. The trees analyzed in this particular study showed a reduction in height growth in the first season after thinning.

Wahlenberg (44) found that diameter growth was the first tree dimension to respond in a thinned white pine stand. Reukema (33) reported that in Douglas-fir, thinning caused an increase in growth up to 25 percent when compared to unthinned stands. The increase in growth achieved by thinning is due to a combination of improved growth of residual trees and removal of less efficient trees. This growth pattern was also shown by Reukema and Pienaar (35) and Reukema and Bruce (34).

Brix (4) found in a 24-year-old Douglas-fir stand that trees fertilized showed a significant increae (51 percent) in diameter over that of the control stand. He mentioned that an increase in leaf area will only benefit growth if the amount of leaves and their distribution is sufficient for optimum utilization of available light. Therefore, nitrogen fertilization is generally very effective in improving growth in combination with stand thinning.

Lee (10) studied a 25-year-old Douglas-fir stand which was thinned and fertilized. He found that the benefits of thinning were not only in increased net yields on a per unit area basis and in tree size but also in climination of loss from mortality. He further reported that fertilizer treatment resulted only in short-term increase in yield per unit area.

Worthington _et al_. (46) studied a young Douglas-fir stand with different cutting intensities. They found that the average annual increment during the first period after thinning (2 years) was practically identical for thinned and unthinned compartments. During the second period (4-7 years after thinning), however, the thinned stand grew 211 cubic feet compared with 190 for the unthinned.

Schmidtling (36) concludes that cultural treatments strongly affected height, d.b.h., basal area, and volume in a stand of southern pine. Response to the addition of fertilizer was drastic. Though fertilizer was applied only once, the effects were still apparent after 9 years, with growth rates still diverging slightly.

Hamilton (16) studied a 17-year-old Sitka spruce stand thinned at several intervals and intensities. He found that increases in mean diameter at breast height were closely related to increased thinning intensities.

Wiley (46) et al. studied a 23-year-old precomercially thinned Douglas-fir stand. The thinned plots produced larger trees and more merchantable volume than unthinned plots with greater numbers of trees. The 24-year-old unthinned stands had 1,800 trees per acre at age 17, averaged 4.8 inches in d.b.h. and had 1,927 cubic feet merchantable volume per acre. This was 2.4 inches smaller in average d.b.h. and 1,034 cubic feet less in volume per acre than stands thinned at age 14 to 600 trees per acre. The thinned stands had 54 percent more volume at age 24 than the unthinned stands.

Myers (25) studied three Douglas-fir stands of different ages with different thinning intensities. He reported that growth did not differ much among any of the thinned stands but he also found that thinning stimulated diameter growth, especially in the younger stands.

## Effect of Accelerated Growth on Wood Quality

A forester modifies growth in a variety of ways but most commonly by spacing, and by fertilizer application. His primary objective is to enhance rates of growth but he should be aware of the consequences of his actions on wood quality. Of special importance are those properties which affect technical performance and thus commercial acceptance. Well documented differences have been observed between the quality of wood from regenerated forests and virgin forests (3). Now the industry is beginning to see harvest of the man-made forest and in the future, the forest will have trees grown from genetically improved stock from "super" trees, or perhaps even from tissue culture of selected clonal material (2).

Brazier (3) reported that the net result of fast growth is a large central cylinder consisting of a high volume of wood with wide juvenile growth rings relatively low in latewood and low in specific gravity. McKinnell and Radman (23) reported that six-year-old radiata pine on a nutrient-deficient site responded to potash treatment by enhanced yield of up to 50 percent over 6 years, but the wood had a mean density of 11 percent below that of untreated plots, due largely to an increase in amounts of earlywood. In an earlier study of 7-year-old *Pinus radiata*, the same workers found that enhanced growth, mainly following application of phosphates, resulted in a reduction of percent latewood and lower minimum earlywood density.

Polge (30) found that phosphate teatments on 7-year-old maritime pine resulted in density reductions of up to 7.4 percent with the percentage of dense wood in the rings significantly lower in treated compared with untreated stems. He also observed that maximum latewood densities were reduced more than minimum earlywood levels, thus reducing within-ring density variation and giving a more uniform texture.

In Douglas-fir, Erickson and Harrison (13) found that heavy thinning followed by fertilizer application each year for 9 years resulted in an immediate production of low density wood, with lower percent latewood, and a small decrease in tracheid length. In another study on Douglas-fir, Resler et al. (32) suggested there may be a difference in response between dominant and co-dominant trees. McKimmy (24) studied a 46-year-old Douglas-fir stand and found percent latewood, growth rate, age, seed source and plantations had a large effect on specific gravity. He also pointed out that density of juvenile wood was unreliable for predicting density of mature wood.

Smith (38) reported on the effect of fertilization and thinning of Douglas-fir. He found that specific gravity was closely correlated with percent latewood, and that specific gravity was higher in slowly grown wood at a given percentage of latewood.

Knigge (19) studied the density differences in stems caused by different growth conditions in the natural growing area of Douglas-fir. He reported that specific gravity decreased with increasing ring width and increased with incresing height of the tree. He concluded that in the first decades of wood formation density is mainly influenced by annual ring width; later, however, it is influenced by age.

Hapla (17) studied the effect of spacing on wood properties of Douglas-fir. He concluded that the mean ring width increased with the size of the spacing and that the mean latewood width increased absolutely with growing space. This increase, however, was negligibly in a growing space of 4 $m^2$.

Parker et al. (27) reported on the effect of fertilization and thinning of Douglas-fir. They found that thinning promoted higher latewood density and significantly increased ring width at breast height. Erickson and Lambert (14) analyzed a fertilizer/thinning study of Douglas-fir. Their findings indicated specific gravity was the same in thinned and control plots and there was a relationship between specific gravity and summerwood percentage. Furthermore, they found that thinning caused some tendency toward reduced cellulose content compared to the wood formed before thinning.

Megraw and Nearn (22) reported from another fertilizer/thinning study that thinning affected the within-ring, individual fiber densities. The overall ring specific gravity was not significantly changed by the fertilizer/thinning treatments. Treatments did cause a prolongation of lower average density across a growth ring.

Pechman and Wutz (28) studied a thinned and fertilized spruce stand. They found that when ring width increased from 1.5 to 3 mm, mainly in response to nitrogen application, specific gravity fell from 0.47 to 0.41 due to an increase in earlywood production, a more gradual transition from earlywood to latewood, and thinner walls in the latewood.

Sutton and Harris (42) studied the effect of heavy thinning on radiata pine. They concluded that despite the rapid increase in radial growth among heavily thinned trees, there was no evidence of any corresponding change in mean wood density. Shepard (37) looked at the effect of fertilization on red spruce. He reported that fertilization did not significantly affect specific gravity at breast height. All fertilizer treatments applied caused a 4 to 5 percent decrease in specific gravity at the base of the crown when compared to a stand with no fertilization.

Schmidtling (36) studied southern pine stands being thinned and fertilized. He concuded that cultural treatments did not affect summerwood content in a consistent manner, and differences among treatments were not significant. The increased growth rate following the more intensive treatments did not greatly affect summerwood percentage in the trees being studied. He even found that specific gravity was highest in the more intensive cultural treatment. He further reported that specific gravity was not clearly related to summerwood content on a treatment basis. The same findings are reported by Cown (9). He also found that in young radiata pine the wood properties were not markedly altered by thinning. Specific gravity did not change and the tracheid length was only very slightly reduced.

Sastry (41) reported a general decrease in specific gravity, percent latewood and mean treacheid length in wood of three Douglas-fir trees after they were fertilized. Fertilization of four Douglas-fir trees from 38 to 45 years of age caused a 74 percent increase in volume, a 10 percent decrease in specific gravity, and a slight increase in pulp yield per unit weight of wood.

Clark (7) found no close relationship between ring width and specific gravity in fast-grown Douglas-fir. He also reported that in his particular study no relationship between specific gravity and number of rings from the pith were found.

Brazier (3) recommended that heavy thinning should be avoided, and uneven spacing of thinning which favors one-sided growth of the crown, for example, some forms of line thinning, can be expected to yield localized compression wood and an irregular stem form.

Johnson (198) studied the wood quality of Douglas-fir thinned at different intensities. Her findings indicated a decrease of overall average mature wood MOR and MOE values. Further, she found that mature wood specific gravity from plots thinned at constant cutting intensity was significantly higher than from sample plots thinned at varying cutting intensities. She concluded that specific gravity and growth rate were the most important independent variables in MOR and MOE regressions. Similar results were also shown by Knigge (19).

Drow (11) reported that second growth, coast-type Douglas-fir had an average specific gravity of 0.43. His samples ranged from 4,500 to 10,000 psi in modulus of rupture while modulus of elasticity ranged from 900,000 to 2,000,000 psi and specific gravity varied from 0.32 to 0.54.

Galligan (15) made some interesting observations about small logs. He mentioned that most of our technology in sawing, drying, and grading lumber has been developed from large old-growth logs. In today's harvest of small logs, there is a higher percentage of two kinds of abnormal wood, namely, compression wood and juvenile wood. The specific gravity of juvenile wood is lower than normal wood and the fibril angle is higher than normal wood. In tests conducted on Douglas-fir lumber he found it some pieces as much as 50 percent below accepted strength values. He concluded that the American Institute of Timber Construction accepts only very limited amounts of juvenile and compression wood at the present time in glulam material. Due to these requirements he expressed doubts that Douglas-fir lumber will be able to maintain its present market for the laminated beam industry.

## REGULATION OF GROWTH AND PHOTOSYNTHESIS

The forest manager implements procedures that act directly on tree growth. He seeks to stimulate growth by improving the photosynthetic efficiency of the crown, either directly by providing space for its further growth or indirectly through the roots by improving the physical structure or nutrient status of the soil.

Well proven statistical models, like DFSIM at Oregon State University, were developed in order to forecast volume growth of stands, depending on site quality and type of treatment. These models can be incorporated into economic simulations which select optimum management regimes. The central discussion of such density models deals with the effect of density (trees per unit area) on growth (10). As tree size affects selling prices and logging costs, forest managers who want to select the economic optimum seek for an optimizing framework and a growth model that increases diameter growth as thinning intensity increases (5).

Most of these thinning models are based on the relative density index (a stand is supposed to support a certain number of trees at a given average diameter). This is well known as the 1.5 power law or self-thinning rule. Further assumptions are made by the fact that canopy leaf area is directly related to photosynthesis, but only to a certain point as the photosynthetic efficiency of a tree is evaluated by the simple equation: [Photosynthesis minus Respiration]. As trees develop larger crowns their photosynthetic efficiency drops since respiration is increasing inversely proportional to photosynthesis.

In other words, the larger the crown of a tree the less efficient the tree becomes.

Photosynthesis is directly related to illumination. Thinning is a proven way to improve illumination in a forest stand. Figure 1 shows the illumination in an unthinned and a thinned stand over a period of one day. By increasing illumination so drastically one changes the functions of the hormones regulating growth, like auxin and gibberelic acids which results in the production of wood with different density values.

A brief review of the literature concerned with the effect of thinning and fertilization on wood quality shows that growth rate tends to increase after thinning and the effect of fertilization is more pronounced after thinning. Wood specific gravity tends to decrease after both thinning and fertilization. Only two reports (22, 27) analyzed intra-ring density parameters.

This study was designed to sample enough trees to statistically evaluate the effect of thinning and fertilization on intra-ring density parameters and to establish correlations between intra-ring density parameters and mechanical properties of wood.

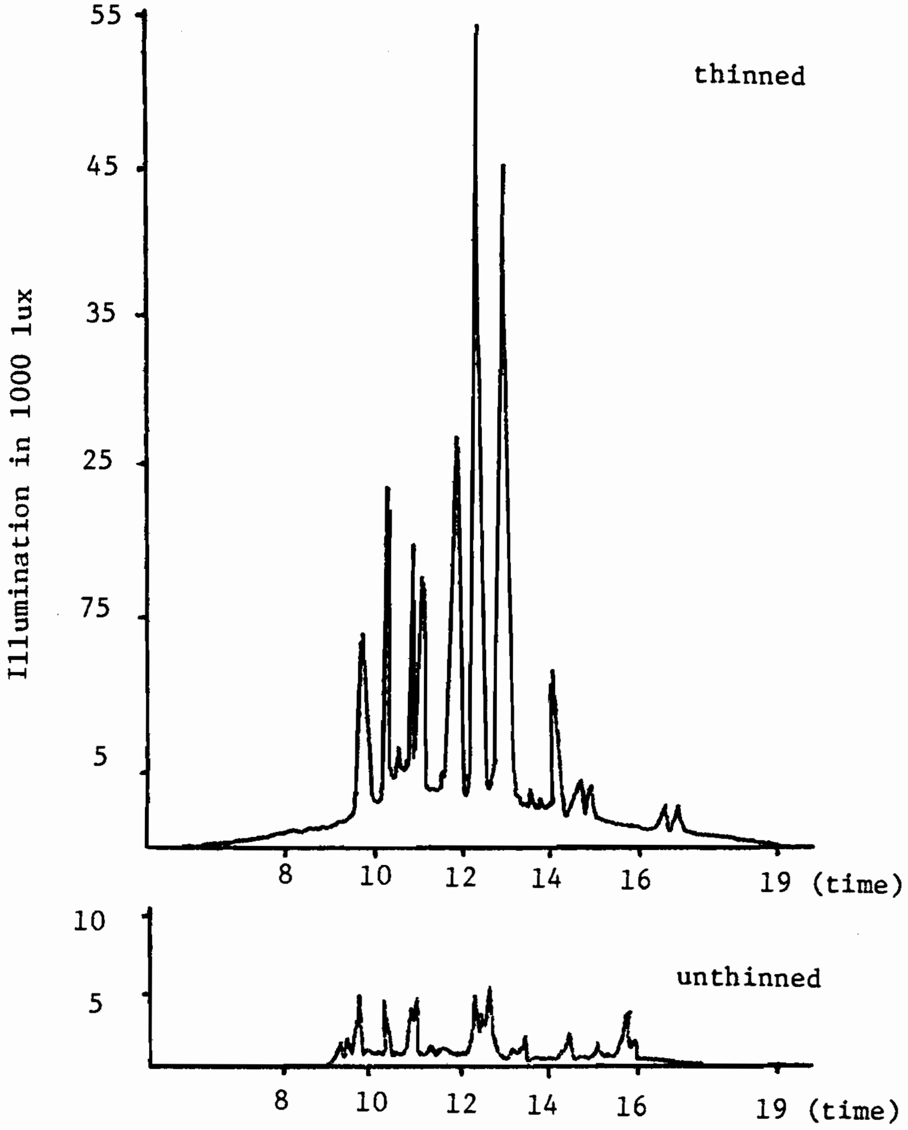

Figure 1. Illumination at the ground over a period of one day in a spruce stand ( 21) .

# PROCEDURE

## Material

Material for this experiment consisted of 7 trees randomly selected from each of 2 thinning treatments and a control (unthinned) stand. Thus a total of 21 trees were collected. The lack of thinning experiments forced us to select one group of 7 trees which were 6 years older than the other 14 trees.

Unthinned control trees and trees from a thinned/fertilized plot (a total of 14 trees) were obtained from hill lands a few miles northeast of Sweet Home, Oregon. Seven trees were obtained from the Oregon State University (OSU) School Forest (Dunn Forest) approximately 10 miles northwest of Corvallis, Oregon.

Both the control stand (C) and the fertilized and thinned stand in the Sweet Home area (Hill Forest) were 42 years-old while the thinned stand in the OSU Dunn Forest was 48 years-old. Further information on the stands sampled are summarized below:

1. C = Control stand, 42 years old, Sweet Home area, natural reforestation, no treatment at all. The soil is of the Dixonville soil series. This is supposed to be a well drained soil. Available water capacity is from 4.5 to 11 inches. The slope aspect is W. Elevation, 800-900 ft.; site index, 110.
2. F = Fertilized and thinned, 42 years old, Sweet Home area, natural reforestation. Soil, site index A, and elevation like in C, approximately 650 trees/acre.

Treatments: 1959 - precommercial thinning to 10 x 10 spacing.

1959 - fertilized, 200 p/acre, 40% U.B.N.

1966 - fertilized, 200 p/acre, 45% U.B.N.

1978 - individual light thinning, 500 BF/acre removed.

1979 - fertilized, 200 p/acre 45% U.B.N.

3. S = Thinned stand, 48 years old, Berry-Creek, School Forest, natural reforestation, elevation 500-600 ft., site index 120. The soil consists of well-drained, moderately deep soils that formed in colluvium. The permeability is moderately slow to slow. The slope aspect is E.

Treatments: 1960 - thinned from 700 trees/acre to 330 trees/acre.

1970 - thinned from 330 trees/acre to 300 trees/acre.

1975 - thinned from 300 trees/acre to 160 trees/acre.

Only dominant trees in the control stand were felled because of the desire to select only trees likely to reach harvestable age and the necessity to obtain logs of sufficient size to obtain lumber for the grade recovery study. In the Hill Forest and Dunn Forest, the forest manager selected codominant trees that would best thin the stands.

## Static Bending Sample Preparation and Testing

From each of the 21 felled trees left on the ground, bolts approximately two-feet long were selected at the butt and at a height of 16-18 feet above the stump. All bolts were labeled and taken to the Forest Research Laboratory at Oregon State University for preparation and testing. The remaining 14-foot butt logs were transported to a mill for sawing into lumber. The lumber from these trees is presently at the Oregon State University Forest Research Laboratory and will be used for a grade recovery study in the future.

Twelve static bending samples were cut from each bolt. Six of these samples were from juvenile wood and 6 were from mature wood. Each bending sample was cut to a 1" x 1" x 16" size, attempting to keep the growth rings parallel to one edge while avoiding knots and compression wood. The bending samples were placed in a standard room (temperature 70°F; relative humidity 70%) for four weeks to equilibrate in moisture content before testing.

The bending specimens were tested on the Instron Universal Testing Machine following ASTM procedure D-141 for solid wood testing under the following conditions:

| | |
|---|---|
| Sample size | 1" x 1" x 16" |
| Span | 14" |
| Crosshead speed | 0.1 cm/min. |
| Loading block diameter | 3" |

The samples were placed in the machine and loaded until maximum load (rupture) was reached. The slope of the elastic portion of the load-deflection curve, the maximum load, and the load at proportional limit were obtained from the load-deflection charts. From these values the modulus of elasticity (MOE), and modulus of rupture (MOR) were calculated using the following formulas:

$$\text{MOE} = \frac{(\text{load at proportional limit})(\text{length}^3)}{4\ (\text{deflection})(\text{width})(\text{depth}^3)}$$

$$\text{MOR} = \frac{1.5\ (\text{maximum load})(\text{length})}{(\text{width})(\text{depth}^2)}$$

For convenience, psi units were converted into metric units using $kg/cm^2$.

## Fiber Preparation and Measurement

Four trees from each treatment were randomly chosen for fiber measurements. Earlywood and latewood portions of annual-rings representing control, thinning and/or fertilization were selected for maceration. Specimens were also taken from the samples used for static bending tests. The samples were allowed to stand in hoods for 3 hours in a mixture of 35 ml. water, 12 drops of acetic acid, and 2.0 g of sodium chlorite. The staining method in this particular preparation was proposed by R. M. Echols (12). The separated fibers were washed thoroughly with several changes of water and retained in distilled water. Generous amounts of fibers were placed in a watch glass. One percent Chlorozol Black E stain was added to the material until it was completely covered. The fibers were allowed to remain in the stain for about two hours. Afterwards the stained fibers were washed in two or three changes of distilled water and placed on a slide. About 5 drops of a PVA mixture (Elmer's Glue) was applied, the fibers were teased apart, and distributed uniformly over the slide. The slides were then placed on a warming table. After a few minutes the slides started to clear and about 30 minutes later could be handled. From each slide 8 fibers were randomly chosen and measured in length on a microscope-slide-viewer.

## X-Ray Density Analysis

The development of X-ray densitometry of wood samples has greatly improved quality evaluation. The pioneer work in this particular area was done by Polge (30, 31). In an attempt to measure wood density, Polge developed for his doctoral thesis a method of wood density measurements that employed the use of X-rays. The technique provided an indirect method by which the density of wood could be measured continuously across a growth ring or along a piece of wood. Since development, the technique has been modified by several organizations, and the main impetus in this study was to computerize the densitometer process and to develop a set of intra-ring parameters which should provide some information about density changes in trees that have been thinned and/or fertilized. The X-ray generator and the X-ray scanning machine used in this study were built by R. M. Echols.

## Preparation of Samples

The same trees randomly chosen for fiber measurements provided specimens for the X-ray studies. Cross sections from each of the 4 trees from each treatment were sawn 2-feet above the butt and at a height of 18 feet. The samples were conditioned to a moisture content of 12%. From the cross sections the actual specimens were sawn out at a constant thickness of 4.45 mm and 2 cm in width with a very fine circular saw. This method produced specimens with a smooth surface and a uniform thickness required for accurate determination of density. Care was taken to orientate the specimens as perpendicular to the fiber axis of the trees as possible in order to attain perpendicular orientation of the growth rings to the longitudinal axis of the samples. This is very important in order to avoid blurring of the earlywood-latewood boundaries in the subsequent X-ray negatives. Samples at a moisture content of 12% were used because it was difficult to maintain oven-dry conditions during X-ray exposure. The specimens remained in the 12% constant relative humidity room. A desicator was used to transport the samples from the Forest Research Laboratory to the X-ray Laboratory in order to keep moisture content at 12%.

## Preparation of Calibration Wedges

Most laboratories use pulp or cellulose acetate for their calibrtion of their X-ray equipment in wood density studies. The lack of uniformity and shadowed X-ray negatives forced me to use a wood calibration wedge, consisting of 5 different species with different density values (Figure 2). The following species were used: balsa, cottonwood, birch, hickory and mahagony. Before the calibration wedge was constructed specific gravity of each of the species used was determined by the gravimetric method, with molten paraffin covering the wood. The specimens were conditioned to a moisture content of 12%, mounted and sawn out to dimensions similar to the wood samples. The calibration wedge remained in the constant humidity room until used.

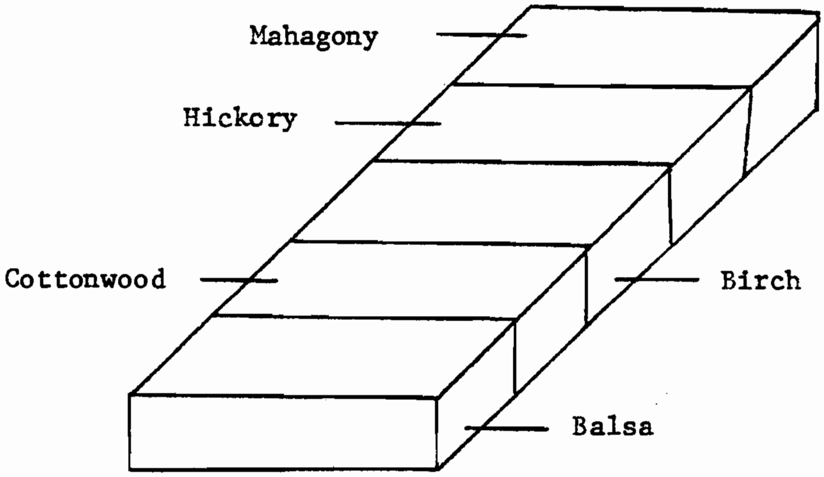

Figure 2. Calibration wedge used in each x-ray exposure .

## Procedure in X-ray Analyses

The X-ray density system consists of the following parts: X-ray generator, X-ray film development, X-ray densitometer, voltmeter, digital computer, printer (Figure 3).

1. The X-ray calibration wedges with the tree ring samples were placed on X-ray film along the anticipated densitometer-scan line. The adjustable shelf for the film is directly beneath the X-ray generator. Exposure distance is adjustable up to a distance of 30 cm. The collimated X-rays (60 KVp, 6 m.A.) were passed over the stationary film at a constant speed.
2. Uniform X-ray film development is required to assure the accurate measurement of intra-ring parameters. The Eastman Kodak Co. recommended use of a special film (Industrial AA X-ray Film). The film-processing tanks were placed in a temperature-controlled waterjacket.
3. The developed negatives (Figure 4) were scanned on a densitometer, the output of which was coupled to a computer (digital MINC 11) making 32 readings per mm. The calibration portion of the negative was scanned first giving the raw stepwedge data for each particular negative (Table 1). The areas between the steps were avoided and approximately 110 measurements were made on the different species for each density step. Following measurement of the step wedge all annual rings of a tree radius were scanned, giving some 4,000-6,000 individual voltage values for each particular radius.

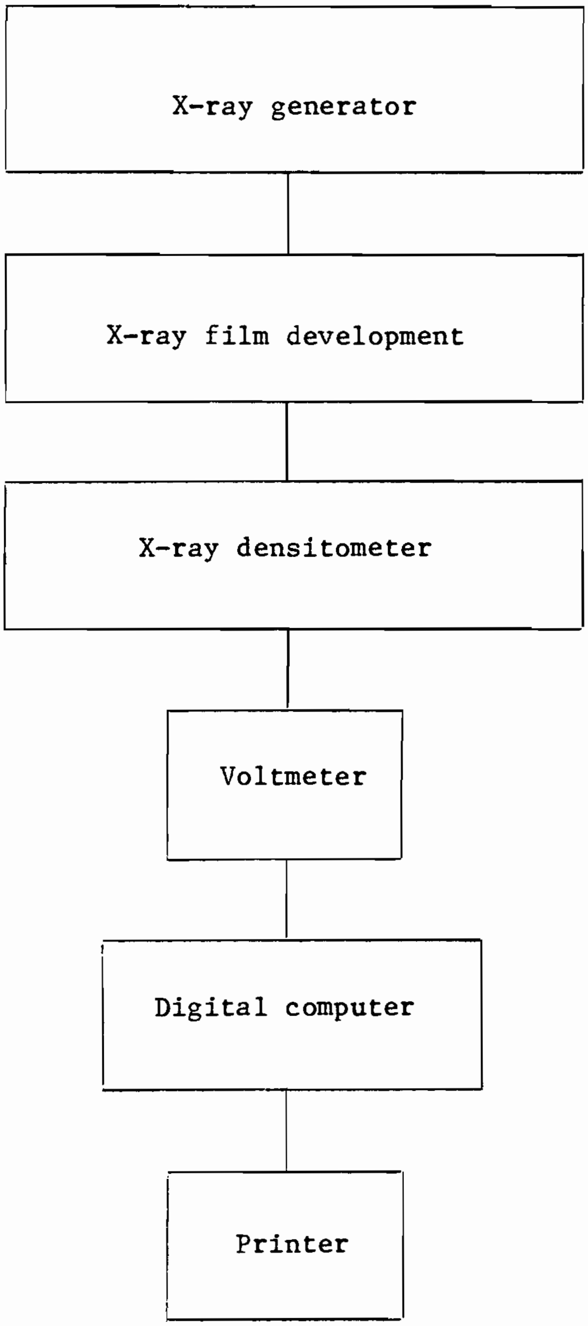

Figure 3. Flow chart of X-ray densitometer system used for analyzing intra-ring parameters.

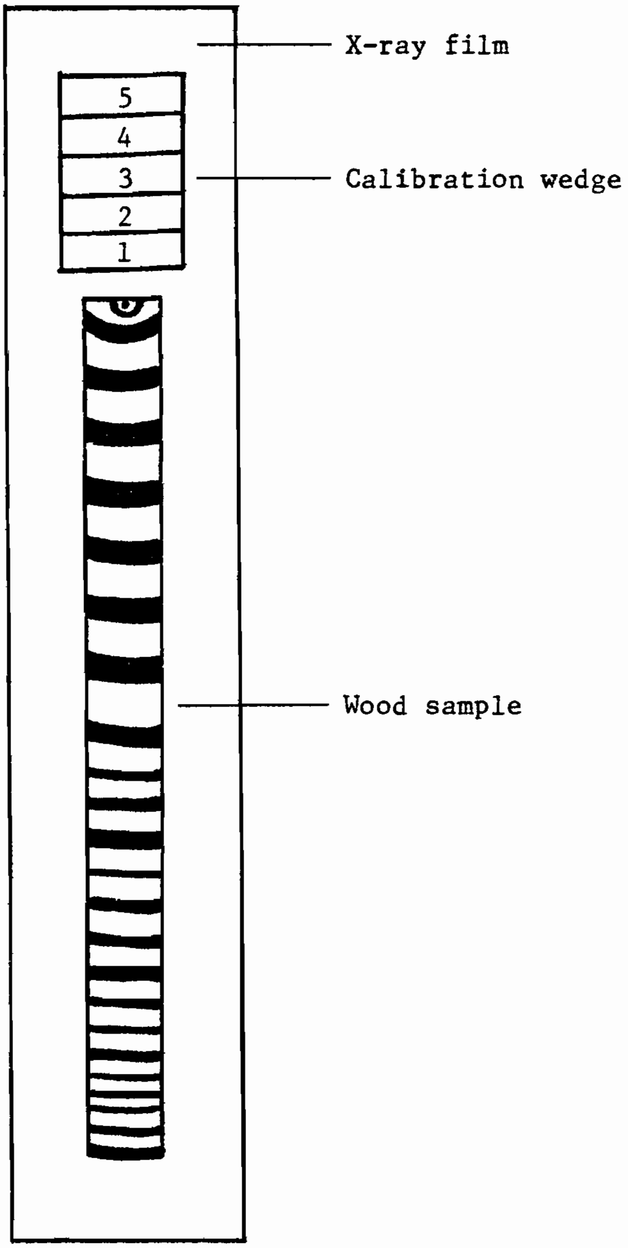

Figure 4. Exposed X-ray negative of calibration wedge and tree radius.

Table 1. Calibration wedge voltage readings for one negative showing demarcation between density steps.

| | | | | |
|---|---|---|---|---|
| -0.315000 | -0.330000 | -0.365000 | -0.365000 | -0.355000 |
| -0.372500 | -0.360000 | -0.392500 | -0.382500 | -0.350000 |
| -0.322500 | -0.347500 | -0.327500 | -0.082500 | -0.080000 |
| -0.127500 | -0.140000 | -0.147500 | -0.160000 | -0.155000 |
| -0.157500 | -0.162500 | -0.145000 | -0.137500 | -0.160000 |
| -0.127500 | -0.197500 | -0.165000 | -0.165000 | -0.152500 |
| -0.102500 | -0.125000 | -0.250000 | -0.357500 | -0.282500 |
| -0.335000 | -0.275000 | -0.387500 | -0.235000 | -0.355000 |
| -0.317500 | -0.450000 | -0.342500 | -0.347500 | -0.355000 |
| -0.420000 | -0.395000 | -0.370000 | -0.447500 | -0.332500 |
| -0.437500 | -0.395000 | -0.485000 | 0.130000 | 0.097500 |
| 0.080000 | 0.065000 | 0.087500 | 0.087500 | 0.090000 |
| 0.070000 | 0.102500 | 0.102500 | 0.067500 | 0.090000 |
| 0.100000 | 0.102500 | 0.105000 | 0.107500 | 0.095000 |
| 0.072500 | 0.305000 | 0.360000 | 0.352500 | 0.362500 |
| 0.337500 | 0.327500 | 0.342500 | 0.377500 | 0.347500 |
| 0.340000 | 0.330000 | 0.330000 | 0.360000 | 0.332500 |
| 0.340000 | 0.310000 | 0.312500 | 0.315000 | 0.330000 |
| 0.327500 | 0.367500 | 0.330000 | 0.420000 | 0.432500 |
| 0.440000 | 0.432500 | 0.422500 | 0.420000 | 0.420000 |

4. After all the readings on a cross section had been completed the voltage values were converted to density values and a data file for the regression program (third degree) workfile was set up. The voltage values for the different species of the calibration wedge were regressed against the density values previously determined. This establishes the relationship between film density and wood density.
5. After the system was calibrated, so that voltage output from the densitometer can be converted to wood density values, the next step was to convert the voltage values according to the regression analyses from the calibration wedge. The absolute density values represented the basic density data for calculation on intra-ring parameters. Calc (W) determined ring width, earlywood width, latewood width, Calc (D) determined earlywood density, latewood density, ring density; Calc (M) determined minimum earlywood density, maximum latewood density, density range.

The programs used in the on-line computer for data acquisition were developed in cooperation with Johan Forrer from the University of Stellenbosch, South Africa. Figure 6 summarizes the software used to analyze intra-ring parameters from the negatives of cross sections of tree radii exposed to X-rays.

6. Each annual ring scanned was analyzed by the program as follows:

   Ten intra-ring parameters were claculated according to a preselected earlywood-latewood boundary level based on the average density of the whole tree radius (Figure 5). The intra-ring characteristics calculated were (Table 2):

1. Ring width (RW)
2. Earlywood width (EW)
3. Latewood width (LW)
4. Mean ring density (RD)
5. Earlywood density (ED)
6. Latewood density (LD)
7. Minimum earlywood density (MED)
8. Maximum latewood density (MLD)
9. Density range (DR)
10. Percentage of latewood (PL)

The system can be very precise and accurate. This precision, however, depends to a large extent on the care taken in sample preparation, densitometer operations and on the quality of the electronic and mechanical components of the system, especially the film development which can be a constant source of errors. Relatively good quality wood samples are required and considerable time and care are needed for sample preparation. The ring-width boundary, which affects most of the ring parameters, could be improved by finding a more precise way of determining the boundary between earlywood and latewood.

A "Inter-Laboratory Standardization Survey" carried out all over the world (8) did not make very clear which criteria are needed to identify an annual ring. Thus, the following question still must be answered. Where does an annual ring start and where does it end in the data matrix? This question is significant because factors such as

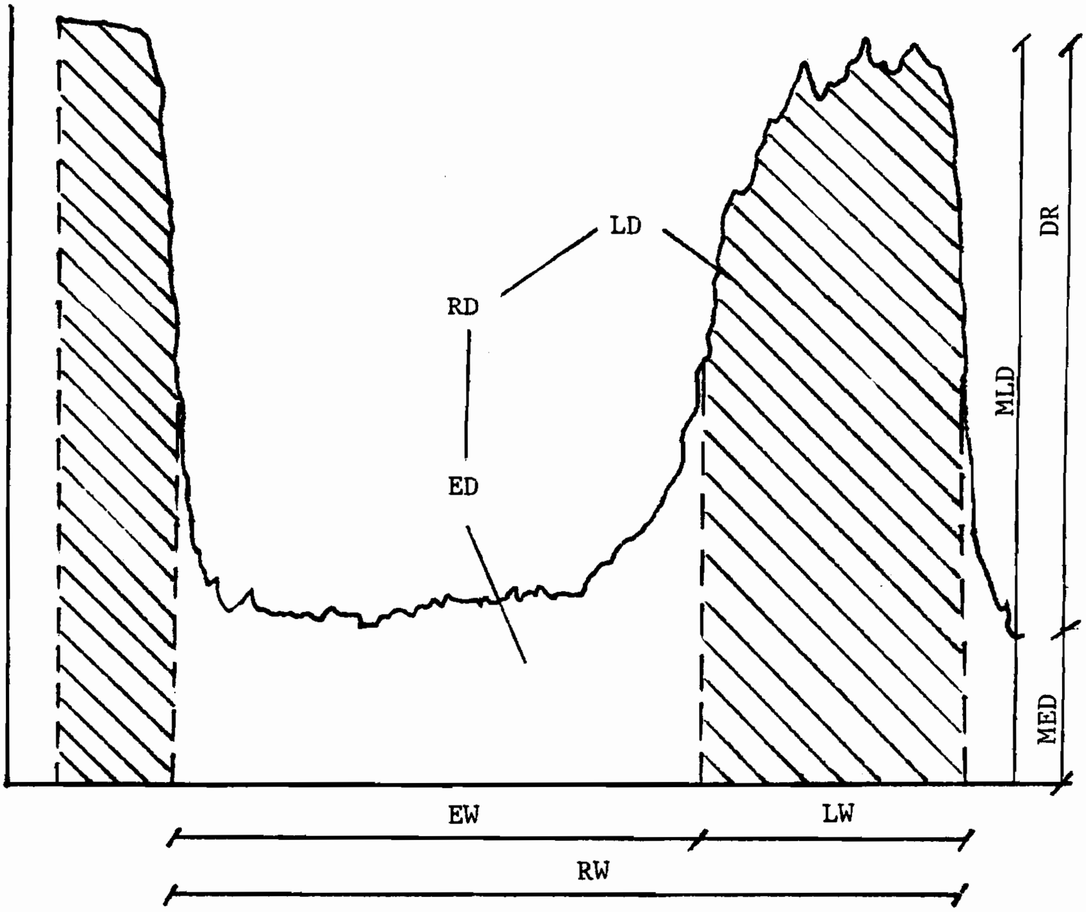

Figure 5. Density variation across an annual ring and some intra-ring parameters. See explanation of variables on page 26.

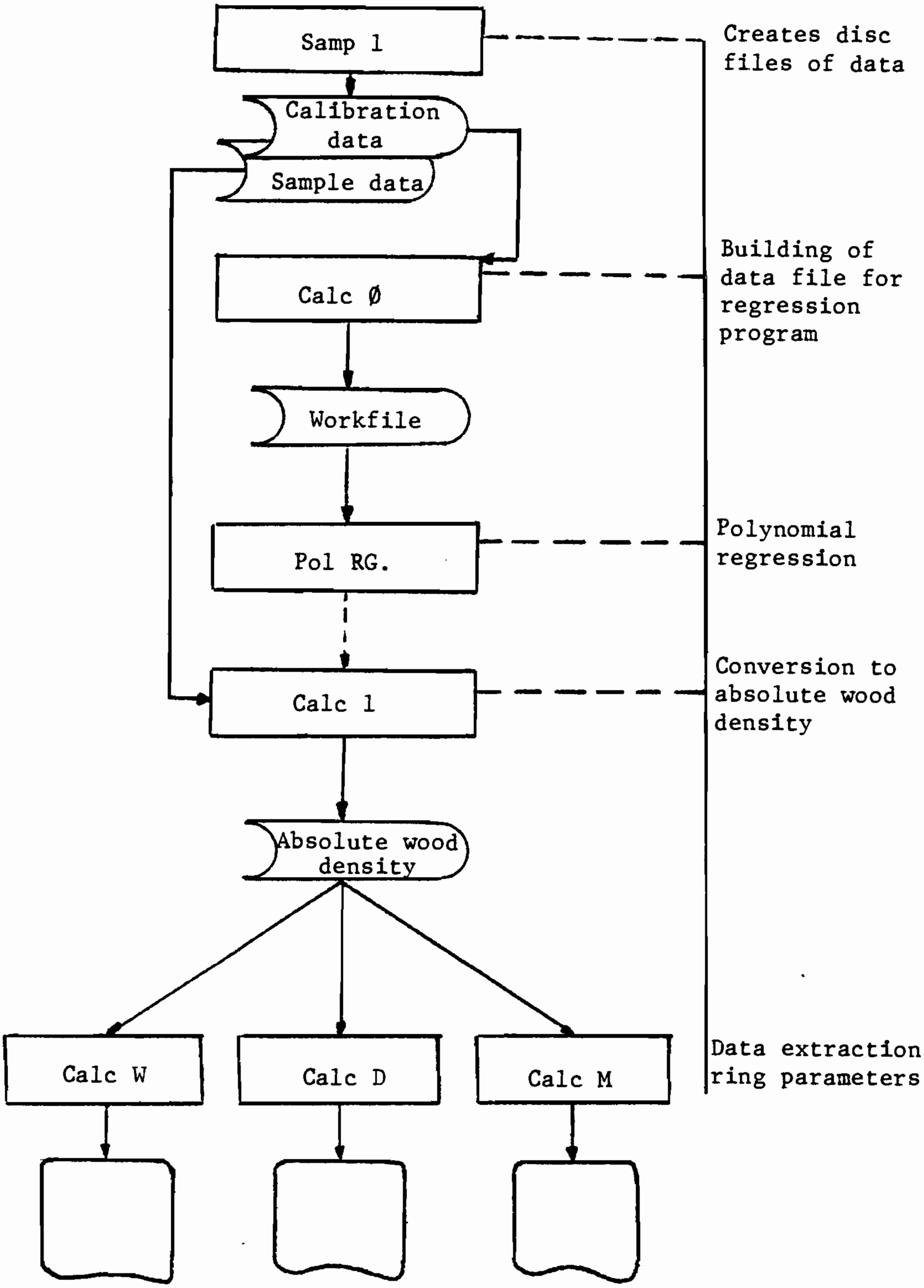

Figure 6. Summary of software used for X-ray analysis of wood quality.

Table 2. Intra-ring parameters for one particular tree radius.

| | EW | LW | RW | ED | LD | RD | MED | MLD | DR |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.127 | 2.251 | 2.378 | 0.535 | 0.493 | 0.495 | 0.418 | 0.565 | 0.147 |
| 2 | 2.061 | 2.473 | 4.533 | 0.337 | 0.473 | 0.411 | 0.281 | 0.568 | 0.287 |
| 3 | 3.107 | 2.061 | 5.168 | 0.332 | 0.500 | 0.399 | 0.278 | 0.607 | 0.329 |
| 4 | 4.153 | 2.061 | 6.214 | 0.308 | 0.536 | 0.383 | 0.237 | 0.657 | 0.420 |
| 5 | 4.153 | 1.744 | 5.897 | 0.328 | 0.515 | 0.383 | 0.278 | 0.670 | 0.392 |
| 6 | 4.343 | 1.617 | 5.960 | 0.293 | 0.476 | 0.343 | 0.220 | 0.520 | 0.300 |
| 7 | 4.058 | 1.268 | 5.326 | 0.233 | 0.470 | 0.289 | 0.150 | 0.548 | 0.398 |
| 8 | 3.234 | 1.585 | 4.819 | 0.216 | 0.533 | 0.320 | 0.117 | 0.679 | 0.562 |
| 9 | 3.012 | 1.870 | 4.882 | 0.284 | 0.530 | 0.379 | 0.210 | 0.693 | 0.483 |
| 10 | 3.297 | 1.649 | 4.946 | 0.289 | 0.557 | 0.378 | 0.230 | 0.670 | 0.440 |
| 11 | 2.314 | 1.902 | 4.216 | 0.288 | 0.531 | 0.398 | 0.233 | 0.642 | 0.408 |
| 12 | 2.822 | 2.187 | 5.009 | 0.307 | 0.595 | 0.433 | 0.207 | 0.793 | 0.587 |
| 13 | 2.980 | 1.997 | 4.977 | 0.326 | 0.570 | 0.424 | 0.284 | 0.738 | 0.454 |
| 14 | 2.758 | 2.092 | 4.850 | 0.327 | 0.560 | 0.427 | 0.252 | 0.644 | 0.392 |
| 15 | 3.265 | 2.156 | 5.421 | 0.282 | 0.501 | 0.369 | 0.210 | 0.599 | 0.389 |
| 16 | 3.614 | 1.839 | 5.453 | 0.274 | 0.503 | 0.351 | 0.185 | 0.591 | 0.406 |
| 17 | 2.726 | 1.332 | 4.058 | 0.282 | 0.594 | 0.384 | 0.220 | 0.745 | 0.525 |
| 18 | 2.156 | 1.458 | 3.614 | 0.298 | 0.554 | 0.401 | 0.249 | 0.687 | 0.438 |
| 19 | 2.283 | 1.332 | 3.614 | 0.300 | 0.577 | 0.402 | 0.233 | 0.682 | 0.448 |
| 20 | 1.522 | 1.332 | 2.853 | 0.315 | 0.542 | 0.421 | 0.252 | 0.634 | 0.382 |
| 21 | 1.427 | 1.395 | 2.822 | 0.324 | 0.646 | 0.483 | 0.281 | 0.875 | 0.594 |
| 22 | 0.824 | 1.268 | 2.092 | 0.373 | 0.514 | 0.458 | 0.327 | 0.725 | 0.398 |
| 23 | 1.205 | 0.888 | 2.092 | 0.339 | 0.517 | 0.414 | 0.295 | 0.632 | 0.337 |
| 24 | 1.014 | 1.014 | 2.029 | 0.348 | 0.563 | 0.456 | 0.297 | 0.721 | 0.424 |
| 25 | 0.507 | 0.159 | 0.666 | 0.372 | 0.448 | 0.390 | 0.307 | 0.385 | 0.077 |
| 26 | 0.190 | 0.793 | 0.983 | 0.483 | 0.519 | 0.512 | 0.372 | 0.627 | 0.255 |
| 27 | 0.666 | 0.634 | 1.300 | 0.339 | 0.504 | 0.419 | 0.240 | 0.618 | 0.378 |

mean ring density, ring width, earlywood/latewood width and percentages are all affected by the density value selected to differentiate earlywood from latewood. Most research laboratories use a threshold value of 0.5 g/cm$^2$ to separate earlywood from latewood.

One way to improve the X-ray densitometric system is to use the direct scanning method. In the direct scanning method the amount of radiation passing through the wood sample is recorded by a photomultiplier sensor rather than a radiographic film. In this way most of the errors associated with the film process are eliminated.

Another factor affecting the intra-ring parameters is the difficult decision as to where to start and where to end with the scanning process. This affects the accuracy of the first annual-ring near the pith and the last annual-ring near the bark.

## Statistical Analysis

The data were statistically analyzed using the SIPS program at Oregon State University. An analysis of variance was performed using a Randomized Block Design. The analysis tested differences of the following variables: OSG (overall average specific gravity), MOEJ (modulus of elasticity, juvenile wood, kg/cm$^2$), MOEM (modulus of elasticity, mature wood, kg/cm$^2$), MORJ (modulus of rupture, juvenile wood, kg/cm$^2$), and MORM (modulus of rupture, mature wood, kg/cm$^2$). It was desired to examine whether differences of the variables (variables explained in Table 3) were due to the main effects of position and treatment (POS*TRM), treatment (TRM) or position (POS).

The lack of thinning experiments available in Oregon for stands of the same age over the same time period, as mentioned before, forced the selection of treatment S (Dunn Forest) although that stand had a different age and time of thinning treatments than treatments C (control) and F (Hill Forest). This lack of experimental material permitted only the separate comparison of the control treatment C (Hill Forest) with treatment S (Dunn Forest) and the control (Hill Forest) with treatment F (Hill Forest) for intra-ring characteristics and fiber length studies. This is because annual ring characteristics are strongly influenced by environmental factors within one year of growth, e.g., temperature and precipitation. The analysis of variance (completely randomized design) performed on fiber length tested the differences of variables EFL (earlywood fiber length) and LFL (latewood fiber length). It was desired to examine whether the variation in the variables (variables explained in Tables 4 and 5) were due to the effects of treatment C/F and treatment C/S (KNDT), position (POS), kind of application - thinning/fertilization - (TRMT), (POS*TRMT), (POS*KNDT), (TRMT*KNDT) or (POS*TRMT*KNDT). Earlywood and latewood fiber lengths were considered separately. The analysis of variance (Randomized Block Design) on the intra-ring parameters tested differences among the variables of RW (ring width), ED (earlywood density), LD (latewood density), RD (ring density), MED (minimum earlywood density), MLD (Maximum latewood density), and PL (percentage of latewood). It was desired to determine whether differences in the variables (variables explained in Tables 6 and 7) were due to the main effects of treatment C/F and treatment C/S (KNDT*TRMT), treatments C/F and C/S (KNDT) or treatment (TRMT). The data used in these analyses were for 5 annual rings from the bottom of each tree. These annual

Table 3. Variables used in randomized block design statistical analyses.

TRM: Tratments (C, F, S)[1]

POS: Top/bottom (butt) wood indicator variable

OSG: Overall average specific gravity

MOEJ: Modulus of elasticity, juvenile wood, kg/cm$^2$

MOEM: Modulus of elasticity, mature wood, kg/cm$^2$

MORJ: Modulus of rupture, juvenile wood, kg/cm$^2$

MORM: Modulus of rupture, mature wood, kg/cm$^2$

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[1] See pages 14-15 for description.

Table 4. Variables used in completely randomized design statistical analysis for treatment C (control) and F (Hill Forest).

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TRMT: Treatment, 1959 - Thinning and fertilization
1966 - Fertilization
1979 - Thinning and fertilization

KNDT: Treatment C/F indicator variables

POS: Top/bottom indicator variables

EFL1*: Earlywood fiber length

LFL1: Latewood fiber length

---

*1 indicates treatments C and F .

Table 5. Variables used in completely randomized design statistical analysis for treatment C (control) and S (Dunn Forest).

---

TRMT: Treatment, 1960 - Thinning
1970 - Thinning
1975 - Thinning

KNDT: Treatment C/S indicator variables

POS: Top/bottom indicator variables

EFL2*: Earlywood fiber length

LFL2: Latewood fiber length

---

*2 indicates treatments C and S.

Table 6. Variables used in randomized block design statistical analysis of control (C) treatment and Hill Forest (F).

| | |
|---|---|
| TRMT: | Treatment, 1958-1962 - Thinning and fertilization<br>1965-1968 - Fertilization<br>1977-1981 - Thinning and fertilization |
| KNDT: | Treatment C/F indicator variable |
| RW1: | Ring width |
| ED1: | Earlywood density |
| LD1: | Latewood density |
| RD1: | Ring density |
| MED1: | Minumum earlywood density |
| MLD1: | Maximum latewood density |
| PL1: | Percentage of latewood |

Table 7. Variables used in randomized block design statistical analyses between control (C) treatment and Dunn Forest Treatment (S).

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TRMT: Treatment, 1959-1963 - Thinning
1969-1973 - Thinning
1974-1978 - Thinning

KNDT: Treatment C/S indicator variable

RW2: Ring width

ED2: Earlywood density

LD2: Latewood density

RD: Ring density

MED2: Minimum earlywood density

MLD2: Maximum latewood density

PL2: Percentage of latewood

---

rings included the year before, and the four years after the fertilization and thinning treatment.

In instances where analysis of variance using Randomized Block Design proved significant differences between applications, treatments and position, a test was carried out to determine homogeneity of variances followed by computation of the T-values.

Regressions were calculated using the computer command STEPWISE which adds variables one at a time, according to which variable has the highest F value until all variables are incorporated into the model. At addition of each variable the F value was tested to see if the variable just added was significant to the regression. MOEJ, MOEM, MORJ, MORM (see Table 3), and RD were used as dependent variables with ED, LW, RW, ED, LD, MED, and MLD as independent variables. These stepwise regression analyses were carried out separately for each of the individual treatments at the base of the tree.

In the report the term density and specific gravity are used interchangably although technically they are quite different in that density should be given mass per unit volume while specific gravity is a pure or dimensionless number. In the metric system, as used in this project, the numerical values of each term is the same.

# RESULTS

Analyses of variance using a Randomized Block Design showed that many of the intra-ring parameters and mechanical properties analyzed differed significantly in wood from the three different treatments. A highly significant difference (0.01 level)[1] in juvenile and mature wood modulus of elasticity (MOE) and mature wood modulus of rupture (MOR) was caused by one or more of the thinning treatments. Furthermore, there was a highly significant difference in overall average specific gravity and juvenile modulus of elasticity and a significant difference in the mature wood modulus of rupture between top and butt wood values (Table 8).

The juvenile wood modulus of elasticity means were highly significantly different between treatments C and S and between F and S in both positions. Furthermore, there was a highly significant difference in juvenile wood MOE between top and bottom means for all three treatments. The mature wood modulus of elasticity values differed significantly beween treatment C (control) and F (Hill Forest) in butt wood samples and were highly significantly different between treatment C and S. Similarly, mature wood at a height of 18 ft. differed significantly between treatments C and S as well as F and S.

The mean values for mature wood modulus of rupture from butt samples were highly significantly different between treatment C and S.

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[1] In this report statistically significant results are indicated as follows:

0.05 level at probability--"significantly different"
0.01 level at probability--"highly significantly different"

Table 8. F-values for mechanical properties associated with analysis of variance (randomized design).

| Variable | Source of variation | F-value |
|---|---|---|
| OSG:[1] | POS | 23.03** |
| | TRM | 1.60 |
| | POS*TRM | 0.40 |
| MOEJ: | POS | 28.17** |
| | TRM | 21.89** |
| | POS*TRM | 3.33* |
| MOEM: | POS | 0.43 |
| | TRM | 25.11** |
| | POS*TRM | 1.38 |
| MORJ: | POS | 2.98 |
| | TRM | 2.62 |
| | POS*TRM | 2.51 |
| MORM: | POS | 3.90* |
| | TRM | 4.39** |
| | POS*TRM | 0.39 |

[1] See Table 3 for description of variables.

*Significant (at 0.05 level).

**Significant (at 0.01 level).

The overall average specific gravity means differed significantly between bottom and top wood for treatment C and were highly significantly different between bottom and top wood in treatment S.

Statistical analyses of the fiber lengths associated with treatments C and F showed highly significant differences between one or more of the thinning/fertilization applications in 1958, 1966 and 1978/79 for both earlywood fibers and latewood fibers (Table 9). This is not surprising, since with increasing diameter and smaller rings, fibers tend to be longer. There was no statistical difference in fiber length between top and bottom wood.

The values associated with treatment C and S showed highly significant differences between one or more of the three thinning applications of 1960, 1970 and 1975 for both earlywood and latewood fiber lengths (Table 10). There was a highly significant difference in the earlywood fiber lengths between treatment C and S in the applications for 1960, but not in 1970 or 1975. Again, there were no statistical differences in fiber lengths between top and bottom wood.

The analyses of the intra-ring parameters associated with treatments C (control) and F (Hill Forest) showed the following results: Highly significant differences in ring width, earlywood density, ring density, minimum earlywood density and maximum latewood density were caused by one or more of the thinning/fertilizer applications and also between the treatments C and F.

Highly significant differences in percentage of latewood was caused by one or more of the thinning/fertilizer applications (Table 11). A summary of these results is shown in Figure 7. A significant difference in variable RW1 (ring width) was found between the control

Table 9. F-values for fiber length associated with analysis of variance (completely randomized design) - treatment C vs. F.

| Variable | Source of Variation | F-value |
|---|---|---|
| EFL1:[1] | POS | 0.15 |
| | KNDT | 3.17 |
| | TRMT | 14.06** |
| | POS*KNDT | 0.20 |
| | POS*TRMT | 3.16 |
| | KNDT*TRMT | 3.22 |
| | POS*KNDT*TRMT | 1.96 |
| LFL1: | POS | 3.88 |
| | KNDT | 3.01 |
| | TRMT | 38.41** |
| | POS*KNDT | 0.60 |
| | POS*TRMT | 1.59 |
| | KNDT*TRMT | 1.81 |
| | POS*KNDT*TRMT | 1.23 |

[1] See Table 4 for description of variables.

*Significant (at 0.05 level).

**Significant (at 0.01 level).

Table 10. F-values for fiber length associated with analysis of variance (completely randomized design) - treatment C vs. S.

| Variable | Source of variation | F-value |
|---|---|---|
| EFL2:[1] | POS | 0.55 |
| | KNDT | 16.71** |
| | TRMT | 48.65** |
| | POS*KNDT | 0.47 |
| | POS*TRMT | 1.87 |
| | KNDT*TRMT | 10.95** |
| | POS*KNDT*TRMT | 3.04 |
| LFL2: | POS | 0.99 |
| | KNDT | 4.98* |
| | TRMT | 42.69** |
| | POS*KNDT | 0.41 |
| | POS*TRMT | 2.77 |
| | KNDT*TRMT | 3.89* |
| | POS*KNDT*TRMT | 0.87 |

[1] See Table 5 for description of variables.

*Significant (at 0.05 level).

**Significant (at 0.01 level).

Table 11. F-values for intra-ring parameters associated with analysis of variance (randomized block design). C vs. F.

| Variable | Source of variation | F-value |
|---|---|---|
| RW1:[1] | KNDT | 17.97** |
| | TRMT | 66.79** |
| | KNDT*TRMT | 4.18* |
| ED1: | KNDT | 107.16** |
| | TRMT | 98.93** |
| | KNDT*TRMT | 26.37** |
| LD1: | KNDT | 30.27** |
| | TRMT | 17.90** |
| | KNDT*TRMT | 4.14* |
| RD1: | KNDT | 29.44** |
| | TRMT | 71.86** |
| | KNDT*TRMT | 11.61** |
| MED1: | KNDT | 142.22** |
| | TRMT | 84.81** |
| | KNDT*TRMT | 18.27** |
| MLD1: | KNDT | 26.07** |
| | TRMT | 12.51** |
| | KNDT*TRMT | 9.11** |
| PL1: | KNDT | 3.19 |
| | TRMT | 43.14** |
| | KNDT*TRMT | 4.20* |

[1] See Table 6 for description of variable.

*Significant (at 0.05 level).

**Significant (at 0.01 level).

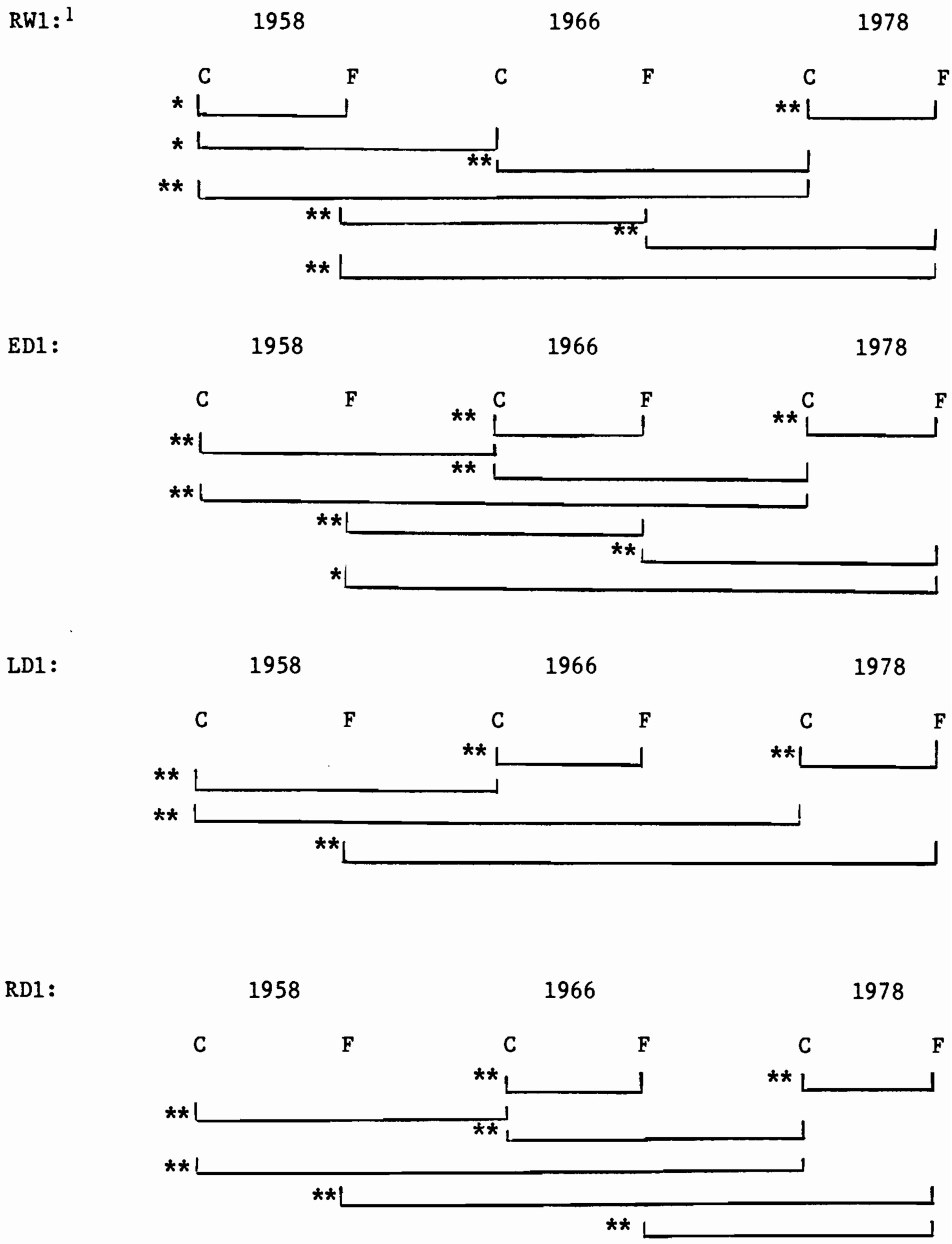
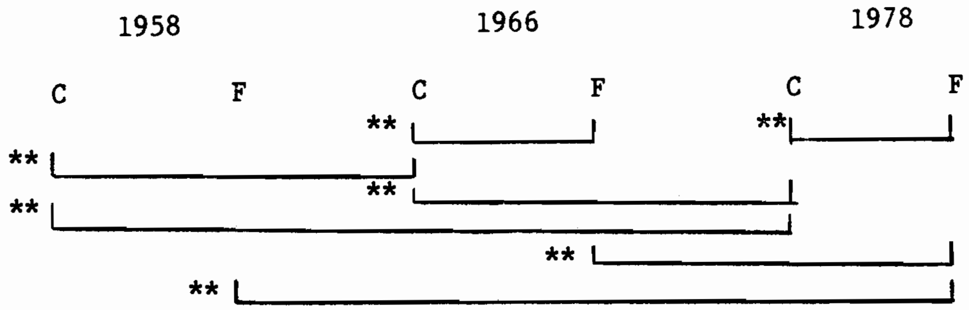


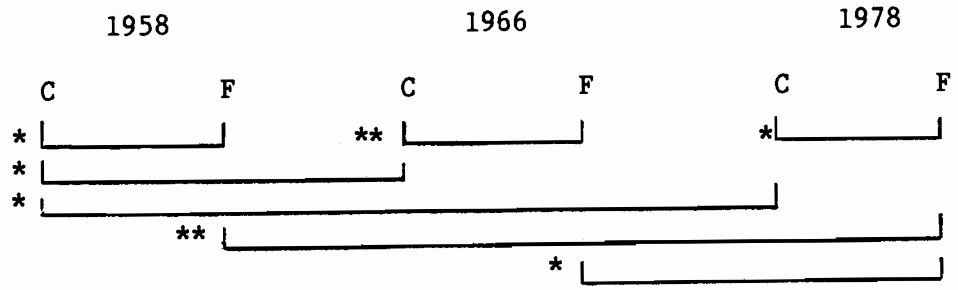
Figure 7. Summary of analyses on various intra-ring parameters as they relate to applications and treatments C (control) and F (Hill Forest).

Figure 7 (continued)

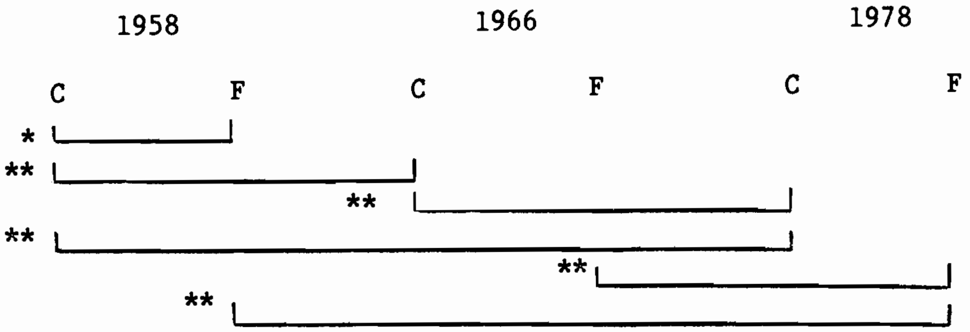
MED1:[1]



MLD1:



PL1:



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[1] See Table 6 for description of variable.

*Significant (at 0.05 level).

**Significant (at 0.01 level).

plot and the thinning/fertilization experiment of 1958 and a highly significant difference was found between the control plot and the thinning/fertilization experiment of 1978/79.

Fertilization by itself did not change ring width significantly. Furthermore, a highly significant difference in ring width was found in the control plots of 1958 and of 1978 as well as between 1966 and 1978. Treatment F showed highly significant differences in ring width between 1958 and 1966, between 1958 and 1978, and between 1966 and 1978.

The earlywood density (variable ED1) showed a highly significant difference between the control plot and the fertilization experiment of 1966 and between the control plot and the thinning/fertilization experiment of 1978/79. Earlywood density was highly significantly different between the control plots of 1958, of 1978 and between 1956 and 1978. Further, there was a highly significant difference in earlywood density between treatment F (Hill Forest) for 1958 vs. 1966 and for 1966 vs. 1978.

A highly significant difference in latewood density (variable LD1) was found between the control plot and the fertilization experiment of 1966 and between the control plot and the thinning/fertilization experiment of 1978/79. Latewood density (LD1) differed highly significantly between the control plot of 1958 vs. 1966 and for 1958 vs. 1978. Also, a highly significant difference was found between the thinning/fertilization experiment of 1958 and the thinning/fertilization experiment of 1978/79. No significant difference was found between the thinning/fertilization experiment of 1958 and the fertilization experiment of 1966.

Ring density (variable RD1) was highly significantly different between the control plot and the fertilization experiment of 1966 and between the control plot and the thinning/fertilization experiment of 1978/79. Ring width (RW1) showed significant differences between the control plots of 1958 vs. 1966 and for 1966 vs. 1978/79. Further, a highly significant difference was found between the control plots in 1958 and 1978. Treatment F showed a highly significant difference between the thinning/fertilization experiment of 1958 vs. 1978/79 and between the fertilization experiment of 1966 and the thinning/fertilization experiment of 1978/79.

A highly significant difference was found in the minimum earlywood density (variable MED1) between the control plot and the fertilization experiment of 1966 and between the control plot and the thinning/fertilization experiment (Hill Forest) of 1978/79. Minimum earlywood density (MED1) was highly significantly different between the control plots of 1958 and 1966, between 1958 and 1978 as well as between 1966 and 1978. Minimum earlywood density (MED1) in the fertilization experiment (F) showed a highly significant difference between the thinning/fertilization experiment of 1958 and the fertilization experiment of 1966, between the fertilization experiment in 1966 and the thinning/fertilization experiment in 1978 and between the thinning/fertilization experiments of 1958 and 1978. Appendix D gives the detailed data.

Maximum latewood density (MLD1) showed a highly significant difference between the control plot and the fertilization experiment (Hill Forest) of 1966 and a significant difference between the control plots of 1958 and 1966 and between those of 1958 and 1978. Maximum latewood density (MLD1) in plot F (Hill Forest) showed a highly significant difference between the thinning/fertilization experiment of 1958 and 1978 and a significant difference between the fertilization experiment of 1966 and the thinning/fertilization experiment of 1978. Appendix D gives the detailed data.

Percentage latewood (variable PL1) was significantly different between the control plot and the thinning/fertilization experiment of 1958 (Hill Forest). Percentage latewood (PL1) showed highly significant differences between the control plots of 1958 and 1966, between those of 1958 and 1978 and between those of 1966 and 1978. Further, there was a highly significant difference between the thinning/fertilization experiments of 1958 and 1978 and between the fertilization experiment of 1966 and the thinning/fertilization experiment of 1978 (Hill Forest). Appendix D gives the detailed data.

The analyses for the intra-ring parameters associated with the control treatment (C) and Dunn Forest thinning plot (S) showed the following results:

Ring width, earlywood density, ring density, minimum earlywood density and maximum latewood density were all highly significantly different between one or more of the three thinnings and also between the two treatments (thinned and unthinned). Latewood density was highly significantly different between one or more of the thinnings and significantly different between treatments C (control) and S (Dunn Forest). Percentage latewood was highly significantly different between one or more of the three applications (Table 12). The detailed results are shown in Figure 8.

Table 12. F-values associated with analysis of variance (randomized block design). C vs. S.

| Variable | Source of variation | F-value |
|---|---|---|
| RW2:[1] | KNDT | 11.13** |
| | TRMT | 85.74** |
| | KNDT*TRMT | 134.17** |
| ED2: | KNDT | 342.76** |
| | TRMT | 75.28** |
| | KNDT*TRMT | 26.91** |
| LD2: | KNDT | 5.92* |
| | TRMT | 14.33** |
| | KNDT*TRMT | 3.44* |
| RD2: | KNDT | 27.26** |
| | TRMT | 73.27** |
| | KNDT*TRMT | 8.97** |
| MED2: | KNDT | 297.93** |
| | TRMT | 56.30** |
| | KNDT*TRMT | 4.71* |
| MLD2: | KNDT | 19.70** |
| | TRMT | 19.74** |
| | KNDT*TRMT | 3.68* |
| PL2: | KNDT | 3.03 |
| | TRMT | 41.04** |
| | KNDT*TRMT | 4.98* |

[1] See Table 7 for description of variable.

*Significant (at 0.05 level).

**Significant (at 0.01 level).

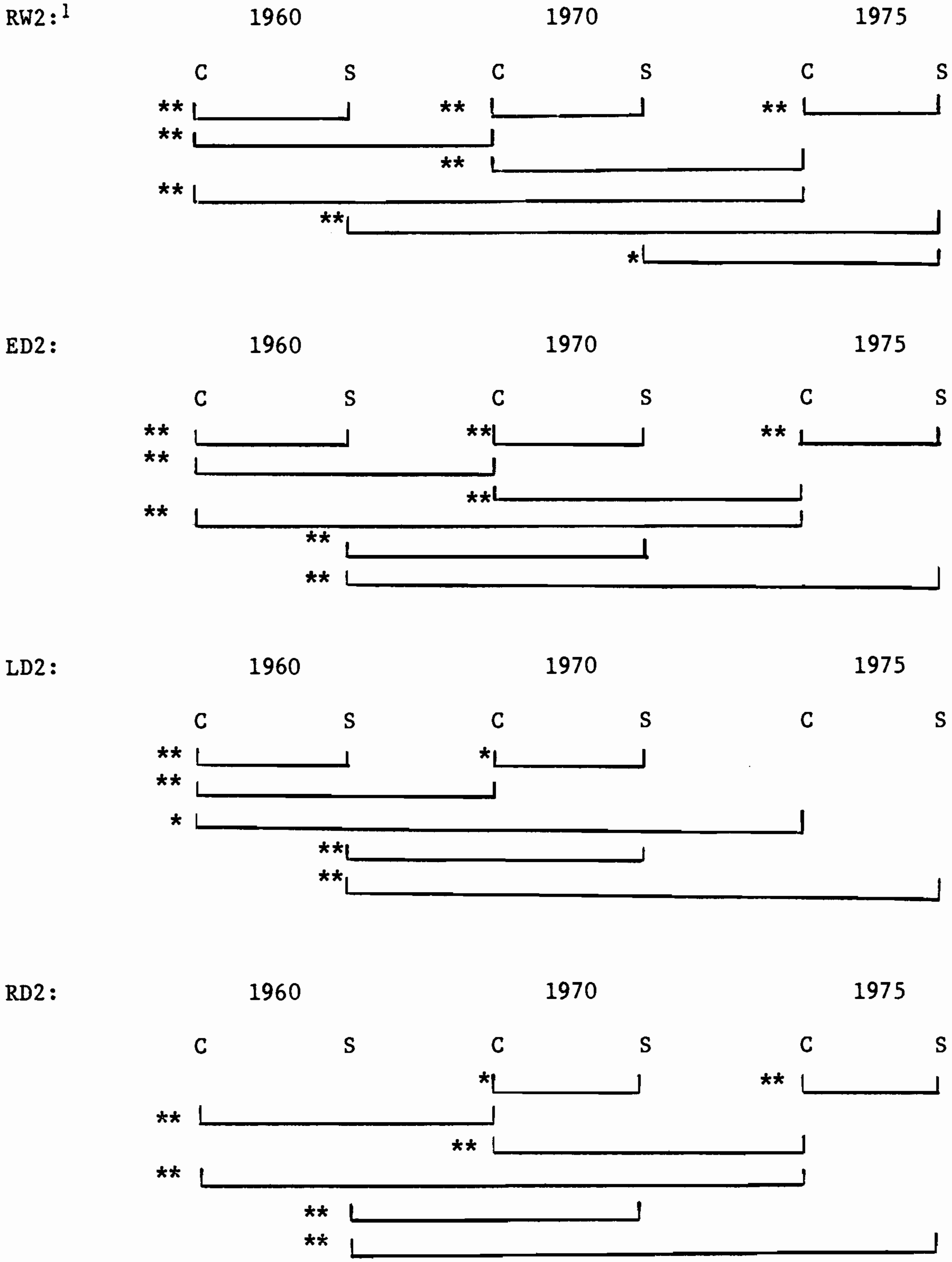
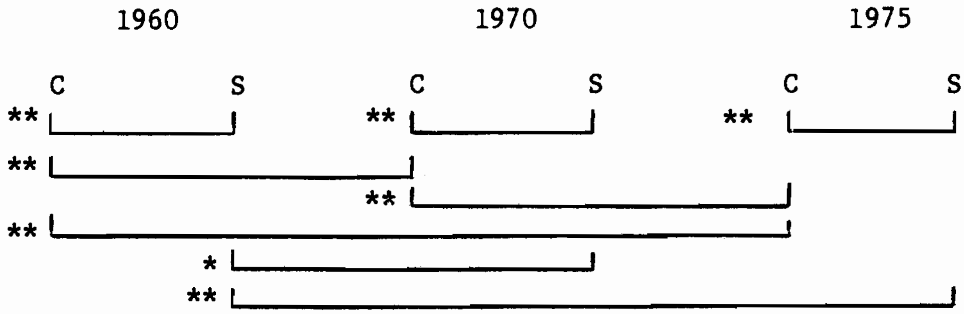


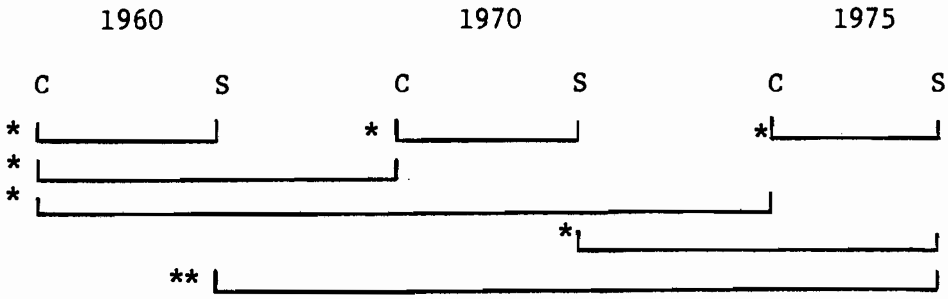
Figure 8. Summary of analyses of various intra-ring parameters as they relate to applications and treatments C and S.

Figure 8 (continued)

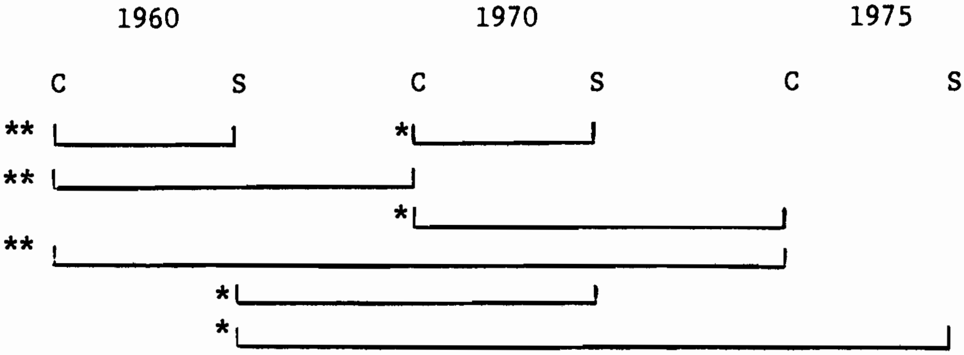
MED2:[1]



MLD2:



PL2:



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[1] See Table 7 for description of variables.

*Significant (at 0.05 level).

**Significant (at 0.01 level).

Ring width (variable RW2) was highly significantly different between the control plots and the thinning experiments of 1960, 1979 and 1975. Further, ring width was highly significantly different between the control plots of 1960 and 1979, between the control plots of 1960 and 1975 and between those of 1970 and 1975. Treatment S (Dunn Forest) proved ring width was highly significantly different in the Dunn Forest thinned stand between 1960 and 1975 and significantly different between 1970 and 1975. Appendix D gives the detailed data.

Earlywood density (variable ED2) showed a highly significant difference between the control plots and the thinning experiments of 1960, 1970 and 1975. Further, earlywood density was highly significantly different between the control plots of 1960 and 1970, between the control plots of 1970 and 1975 and those of 1960 and 1975. Treatment S (Dunn Forest) was highly significantly different between the thinning experiments of 1960 and 1970, between the thinning experiments of 1960 and 1975 but not between those of 1970 and 1975. Appendix D gives the detailed data.

Latewood density (variable LD2) was highly significantly different between the control plot and the thinning experiments of 1960 and 1970 (Dunn Forest) but not of 1975. Latewood density (LD2) was highly significantly different between the control plots of 1960 and 1970 and between those of 1960 and 1975. Further, there was a highly significant difference in latewood density between the thinning experiments of 1960 and 1970, between those of 1960 and 1975 but not between those of 1970 and 1975. Appendix D gives the detailed data.

Ring density (Variable RD2) showed a significant difference between the control plot and the thinning experiment (Dunn Forest) of

1970 and a highly significant difference between the control plot and the thinning experiment of 1975. Ring density (RD2) showed a highly significant difference between the control plot of 1960 and 1970, between the control plots of 1960 and 1975 and between those of 1970 and 1975. Ring density in the Dunn Forest thinning treatment (S) showed a highly significant difference between the thinning experiment of 1960 and 1975 and between those of 1960 and 1975 but not between those of 1970 and 1975. Appendix D gives the detailed data.

Minimum earlywood density (variable <u>MED2</u>) was highly significantly different between the control plots and the thinning experiments of 1960, 1970 and 1975. Further, minimum earlywood density (<u>MED2</u>) was higly significantly different between the control plots of 1960 and 1970, between those of 1960 and 1975 and between those of 1960 and 1975. Dunn Forest treatment showed a highly significant difference in minimum earlywood density between the thinning experiments of 1960 and 1975 and a significant difference between the thinning experiments of 1960 and 1970. Appendix D gives the detailed data.

Maximum latewood density (variable <u>MLD2</u>) showed a significant difference between the control plots and the thinning experiments (Dunn Forest) of 1960, 1970 as well as 1975. There was a significant difference between the control plots of 1960, 1970 and between those of 1960 and 1975. Dunn Forest (treatment S) showed there was a highly significant difference between the thinning experiments 1960 and 1975 and a significant difference between 1970 and 1975. Appendix D gives the detailed data.

Percentage latewood (variable <u>PL2</u>) was highly significantly different between the control plot and the thinning experiment of 1960 and was significantly different between the control plot and the thinning experiment of 1970. Percentage latewood (PL2) was highly significantly different between the control plots of 1960 and 1970, between the control plots of 1960 and 1975 and was significantly different between the control plots of 1970 and 1975. Further, there was a significant difference between the thinning experiments of 1970 and 1975 and between those of 1960 and 1975. Appendix D gives the detailed data.

The results of the stepwise regression analysis are in Table 13. The table shows the order in which the variables entered the model. For the control plot, minimum earlywood density, maximum latewood density, latewood width and earlywood density entered into the regression first; for the thinning/fertilization experiment (Hill Forest), earlywood density, latewood density, earlywood width and latewood width entered into the regression first; for the thinning experiment (Dunn Forest), maximum latewood density, earlywood density, earlywood width and latewood with entered the regression first.

Table 13. Order of variables entered into regression model and associated F-values.

| Dependent variable ring density | Independent Variables in Entering Order[1]<br>F-value | | | | | | | $R^2$ at last significant entering order[2] |
|---|---|---|---|---|---|---|---|---|
| Control | MED<br>281.72** | MLD<br>176.22** | LW<br>122.60** | ED<br>91.21** | LD<br>67.41** | RW<br>51.50** | EW<br>47.80** | 0.965 |
| Hill Forest | ED<br>56.17** | LD<br>83.72** | EW<br>72.97** | LW<br>185.84** | MLD<br>221.61** | MED<br>261.41** | RW<br>89.30** | 0.9948 |
| Dunn Forest | MLD<br>268.97** | ED<br>324.62** | EW<br>242.58** | LW<br>253.11** | LD<br>229.68** | RW<br>193.17** | MED<br>157.06** | 0.9910 |

[1] See Tables 6 and 7 for explanation of variables.

[2] $R^2$ values at last significant entering variable.

*Significant (at 0.05 level).

**Highly significant (at 0.01 level).

# DISCUSSION

## Treatment Effects on Overall Specific Gravity

Overall average specific gravity did not differ significantly among treatments at the butt or at the 18 foot-height level. For individual treatments, average specific gravity of butt wood in the Hill Forest was 4.22% less than the control plot and the Dunn Forest treatment (S) was 8.24% less than the control plot. At 18 ft. height level average specific gravity of treatment F (Hill Forest) had slightly higher values than those of the control plot and 8.97% higher than treatment S (Dunn Forest). There was no significant difference (Hill Forest) in the overall average specific gravity between top and bottom wood, indicating that competition among the crowns at the 18-foot level was still very severe. In other words, at that height level, diameter growth was a secondary factor. The primary factor for the tree was still to increase growth in height which produced narrower growth rings with higher density. This relationship was verified by the fact (not mentioned in this thesis) that the average diameter of the Hill Forest trees at the 18-foot level was actually slightly smaller than the diameter of the control plot trees. In Dunn Forest (S) heavy thinning reduced competition for light, giving individual trees the opportunity to grow more in diameter and less in height. Appendix A summarizes the data.

The trees studied in this particular project were still young, indicating that the trend of reduction in overall specific gravity will continue if silvicultural practices should continue to be carried out. This observation can be studied further in the intra-ring parameter data. It is projected that by stimulating growth until harvest (about at the age of 100) overall specific gravity will further decrease and might result in a reduction below values stated in the grading rules. Figure 9 summarizes overall average specific gravity of all treatments. The detailed values are shown in Appendix A.

## Treatment Effects on Fiber Length

The Hill Forest thinning/fertilizer experiment caused a significant change in fiber length at neither the butt or at the 18-foot height. Fiber length increased significantly with increasing diameter. This change is most probably the result of increasing age. H. D. Erickson and A. T. Harrison reported that the influence of age was highly significant on tracheid length (13). The results (without statistical significance) showed a slight decrease of earlywood fiber length in treatment F (Hill Forest) when compared to fiber length in the control plot at both positions. However, fertilization of the Hill Forest (F) in 1966 increased latewood fiber length at the 18-foot level by 4% when compared to the control plot. The thinning/fertilization experiment in 1978/79 (Hill Forest) increased latewood fiber length at the 18-foot height level over the control plot.

The results were quite different in the Dunn Forest thinning study (S). The following results were obtained when comparing average fiber length of wood from log butts in the control plot and the Dunn Forest thinning experiment. Heavy thinning in 1960 greatly reduced earlywood fiber length (26.5%). This reduction was much smaller in the thinning treatment of 1975 (7.9%). There was no reduction in

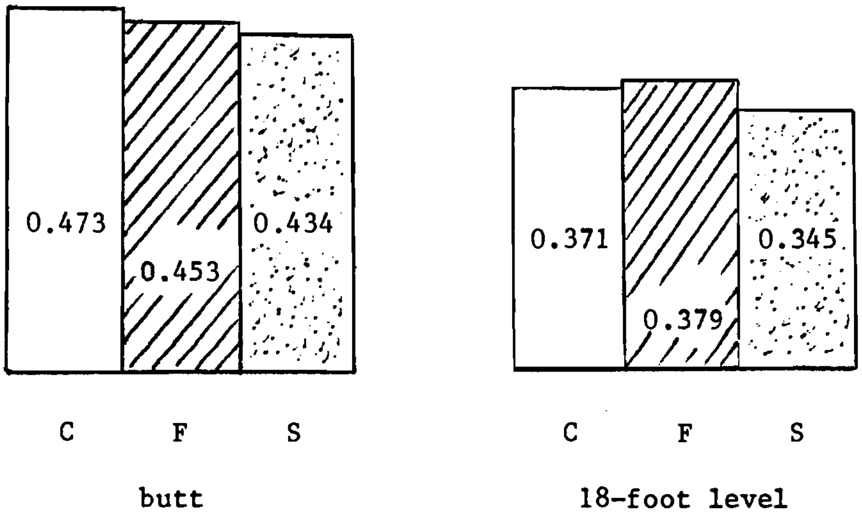

Figure 9. Overall specific gravity of treatments C (Control), F (Hill Forest) and S (Dunn Forest) in both positions.

length of earlywood fibers observed in the Dunn Forest thinning experiment of 1970.

A significant difference in latewood fiber length was found only between treatment C (control) and S (Dunn Forest) at the bottom of the trees. The Dunn Forest thinning experiment of 1960 and 1975 caused a significant decrease in fiber length. Light thinning did not reduce latewood fiber length significantly. Again, there was no statistical difference between top and bottom wood fiber length values. All values (Appendix B) indicate an increasing trend of fiber length with increasing diameter. Further, fiber length, in general, increases slightly with height.

## Treatment Effects on Modulus of Elasticity

Modulus of elasticity (MOE) values showed a significant difference among thinning treatments in the Dunn Forest. The reduction in juvenile wood modulus of elasticity for treatment F was 0.5% less than the control at the bottom of the trees and increased by 1.0% at a height of 18 feet. The similarity of overall average specific gravity and fiber length at a height of 18 feet is not surprising. Again, less growth in diameter and more growth in height of the trees seemed to be responsible for those results. This hypothesis is supported by the highly significant difference in average specific gravity and fiber length between butt and top values of treatment C (control) but only a significant difference for them in treatment F (Hill Forest).

The r value for juvenile MOE values and ring width in treatment C was 0.7388, and was 0.2380 in treatment F (Hill Forest). Mature wood MOE and ring width in treatment C had an r value of 0.3824 and those variables in treatment F had an r value of 0.3961. The r value for mature wood MOE values and ring density of treatment C was 0.3281 and that of treatment F (Hill Forest) was 0.2930. MOE of treatment S (Dunn Forest) correlated best with earlywood density, r value 0.943. The r value for juvenile wood MOE and earlywood density (Dunn Forest) was 0.734 and 0.6301 for mature wood MOE. The mature MOE values of treatment F (Hill Forest) was 10.6% less at the butt of the trees and 2.6% less at a height of 18 feet than the control plot. It should be mentioned that the thinning/fertilization experiment of 1978 probably did not have much of an influence on these MOE values.

Modulus of elasticity values for treatment S (Dunn Forest) decreased much more than those of treatment F. The juvenile wood modulus of elasticity at the bottom of the trees was 17.9% less than the control value while the wood at 18 feet was 17.6% less than the control value. The mature wood modulus of elasticity values of treatment S also showed a large decrease when compared with the control values. The mature wood MOE value at the bottom of the trees was 17.3% less than the control plot and was 14.4% less than the control at a height of 18 feet. The mature wood modulus of elasticity value of treatment S (Dunn Forest) was not significantly different between top and bottom wood. The average mature MOE values of treatment S were 10.2% less than Wood Handbook values for coast range Douglas-fir (45). The average MOE values for mature wood in treatment F (Hill Forest) was 3.9% less than the Wood Handbook values for coast range Douglas-fir. Figure 10 summarizes the results and Appendix C gives the detailed values of all the trees tested. It is expected that by stimulating growth until harvest, overall modulus of

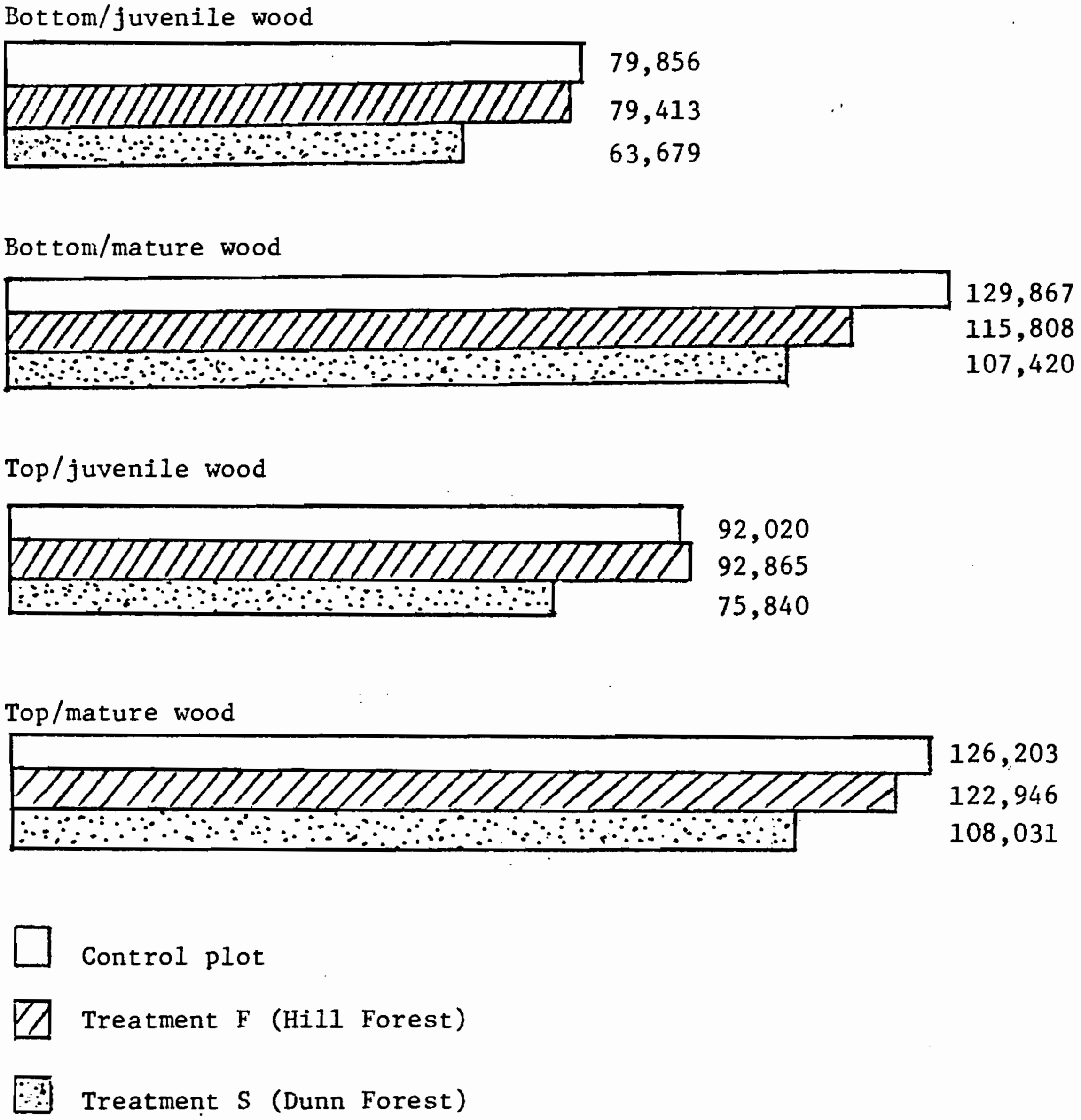

Figure 10. Modulus of elasticity values for treatments C (control), F (Hill Forest) and S (Dunn Forest) in kg/cm$^2$.

elasticity may further decrease and possibly result in values below those stated in the grading rules.

## Treatment Effects on Modulus of Rupture

The juvenile wood modulus of rupture (MORJ) was not significantly different between top and bottom wood values or within treatments. This differed from mature wood modulus of rupture (MORM) values. Juvenile wood modulus of rupture of treatment F was 8.6% less than control values at the bottom of the trees and was 4.9% more than control value at a height of 18 feet. Again, we find similarities to specific gravity, fiber length and MOE values. The mature wood modulus of rupture values of treatment F (Hill Forest) was 2.6% less at the bottom of the trees and 1.1% less at a height of 18 feet than the control plot. The correlation coefficients between juvenile wood MOR and ring density were 0.702 for the control plot and 0.116 for treatment F (Hill Forest). Mature wood MOR of treatment F correlated best with ring width with an r value of 0.642. The r value for juvenile wood MOR and ring width of treatment F (Hill Forest) was 0.697.

Modulus of rupture values of treatment S decreased much more than those of treatment F. The juvenile wood modulus of rupture at the bottom of the trees and at the 18-foot level were, respectively, 12.4% and 2.0% less than the values from the control plot. The mature wood modulus of rupture values also showed a decrease with values at the bottom of the trees and at 18 feet, respectively, 6.3% and 6.0% less than the values for the control plot. Juvenile wood modulus of rupture of treatment S (Dunn Forest) correlated best with maximum latewood density for an r value of 0.515 and mature wood modulus of rupture correlated best with ring width giving an r value of 0.567. Figure 11 summarizes these mechanical properties results and Appendix C gives the detailed values for all trees tested.

It appears that as more raw material for our lumber supply comes from small logs we might need to reconsider the stress and stiffness values for that material. My values verify the results found by Johnson (18) who found MOR and MOE values 28.2% (for mature wood MOE) and 14.5% (for mature wood MOR) less, respectively, than the Wood Handbook values. These results indicate that more mechanical testing should be conducted on wood from young trees to better establish stress and stiffness values for such material.

## Treatment Effects on Ring Width

Ring width of treatment F (Hill Forest) was affected by silvicultural practices. Figure 19 shows the decrease in ring width for the control plot. With increasing age, ring width slowed down constantly in treatment C (control) to a constant width of about 1.61 cm. The thinning/fertilization experiment in 1959 showed a significant difference in ring width compared to that of the control plot. Ring width decreased slightly after the thinning experiment in 1959 (0.09 mm), which could be interpreted as having a slight shock effect. From 1960 (one year after treatment) there was an increase in ring width up to 5.86 cm in 1962. The culmination point was reached in 1963, which indicates that thinning treatments like those employed last about 4 years, especially in this early stage of stand growth (trees about 20 years of age) where the crown growth of trees respond very rapidly to thinning.

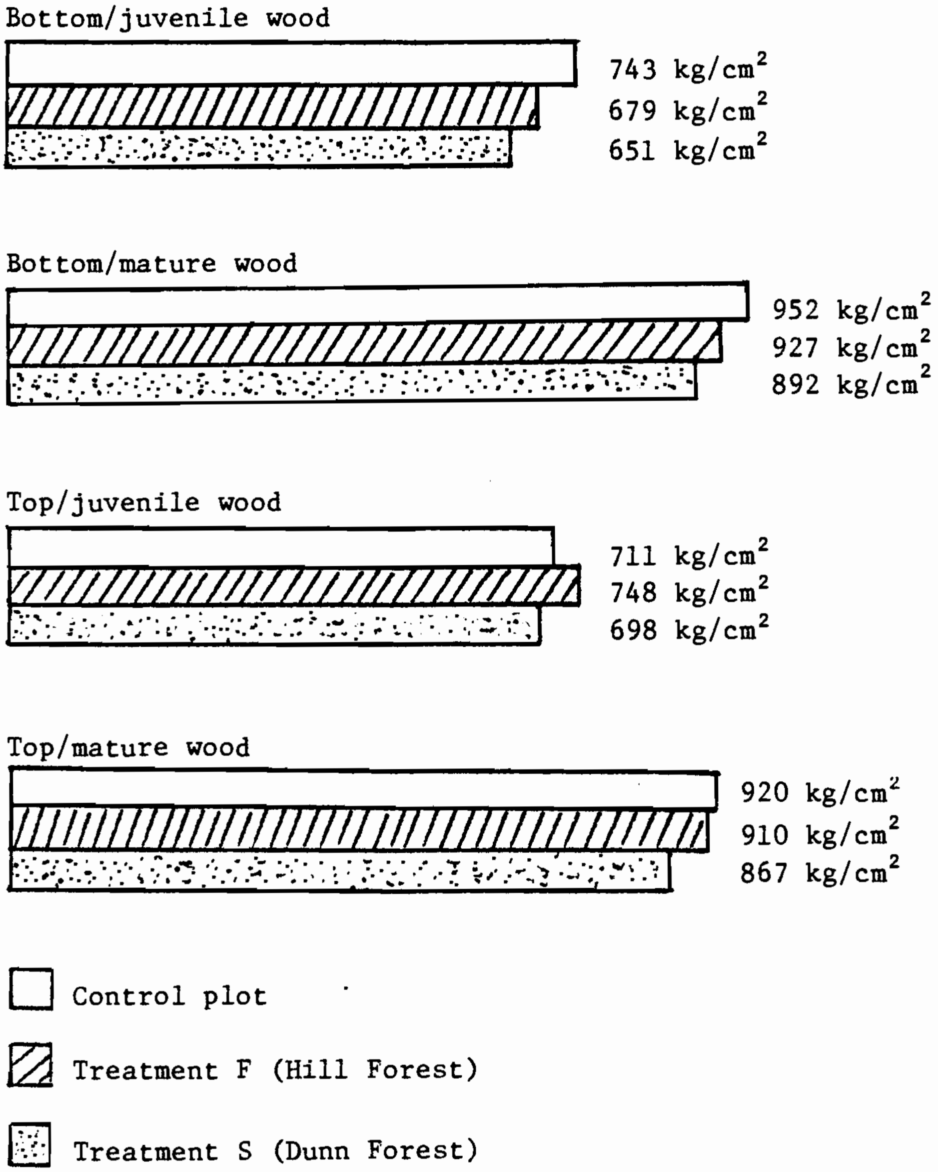

Figure 11. Modulus of rupture values for treatments C (control), F (Hill Forest) and S (Dunn Forest).

The fertilization experiment of 1966 showed a quite different development. Here, ring width decreased similar to the values of the control plot. The experiment does not tell us though if this decrease in ring width would have occurred without fertilization, but it tells us that fertilization in this stage of stand development without thinning does not bring the results (for example, increased ring width) forest managers expect. This might be explained by the law of minimum from J. V. Liebing: When a process is conditioned as to its rapidity by a number of separate factors, the rate of the process is limited by the pace of the slowest factor. In this particular situation (the control plot) illumination was the minimum factor regulating growth.

The thinning/fertilization treatment (Hill Forest) of 1978/79 showed about the same ring width results as the 1959 treatment. Here, the increase in ring width is larger, from 2.11 cm in 1979 to 4.31 cm in 1981. The statistical analyses showed a highly significant difference in ring width for this particular growth pattern. One might explain this growth pattern by the time interval between thinning (1978) and fertilization (1979). The large increase in ring width between 1978 and 1981 (difference from the control plot of about 2.7 cm) giving us the same ring width as the juvenile wood samples at some 20 years ago. This sudden increase in rate of growth reduced all density parameters as will be discussed later. Figure 12 summarizes these results.

The thinning experiment of treatment S also affected ring width. Figure 13 also shows the downward trend of ring width in the control plot. The problem in comparing treatment S (Dunn Forest) with

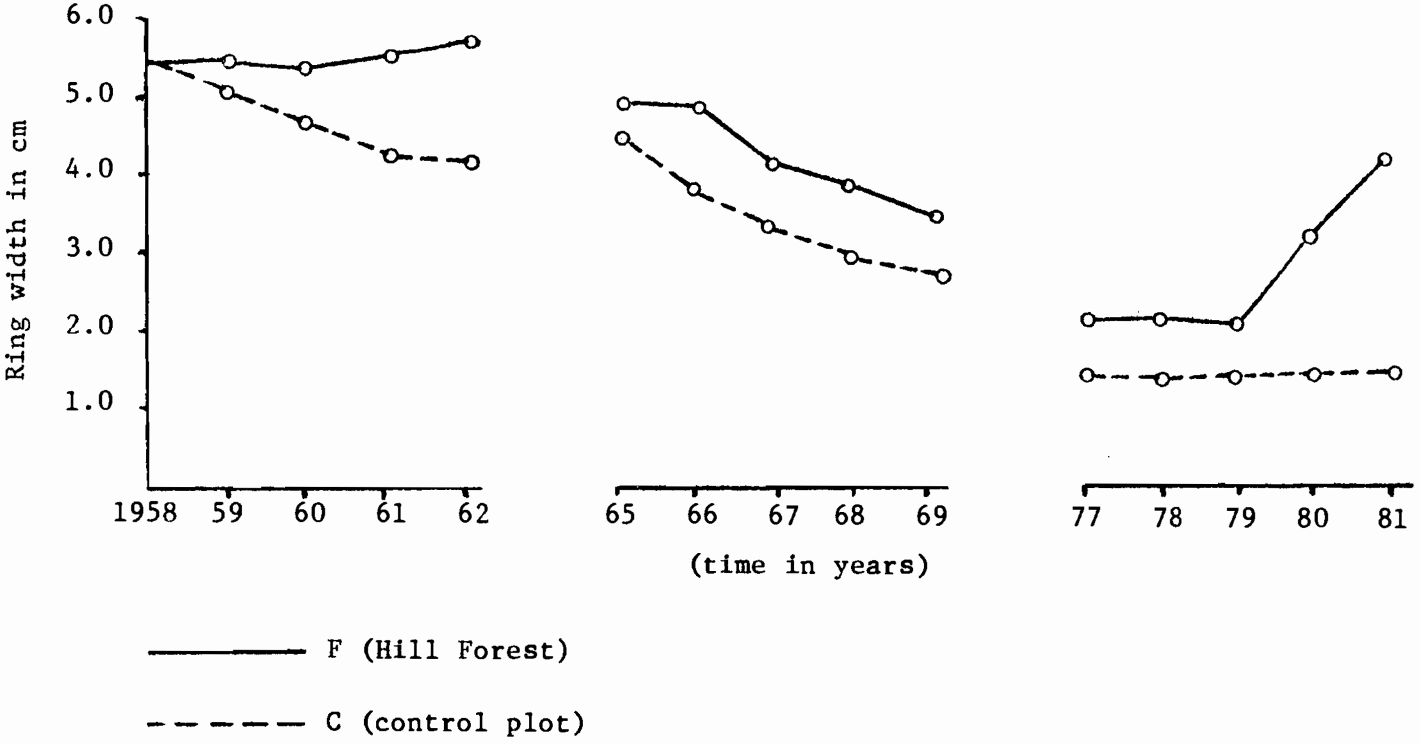

Figure 12. Ring width of treatment F (Hill Forest) and control plot C.

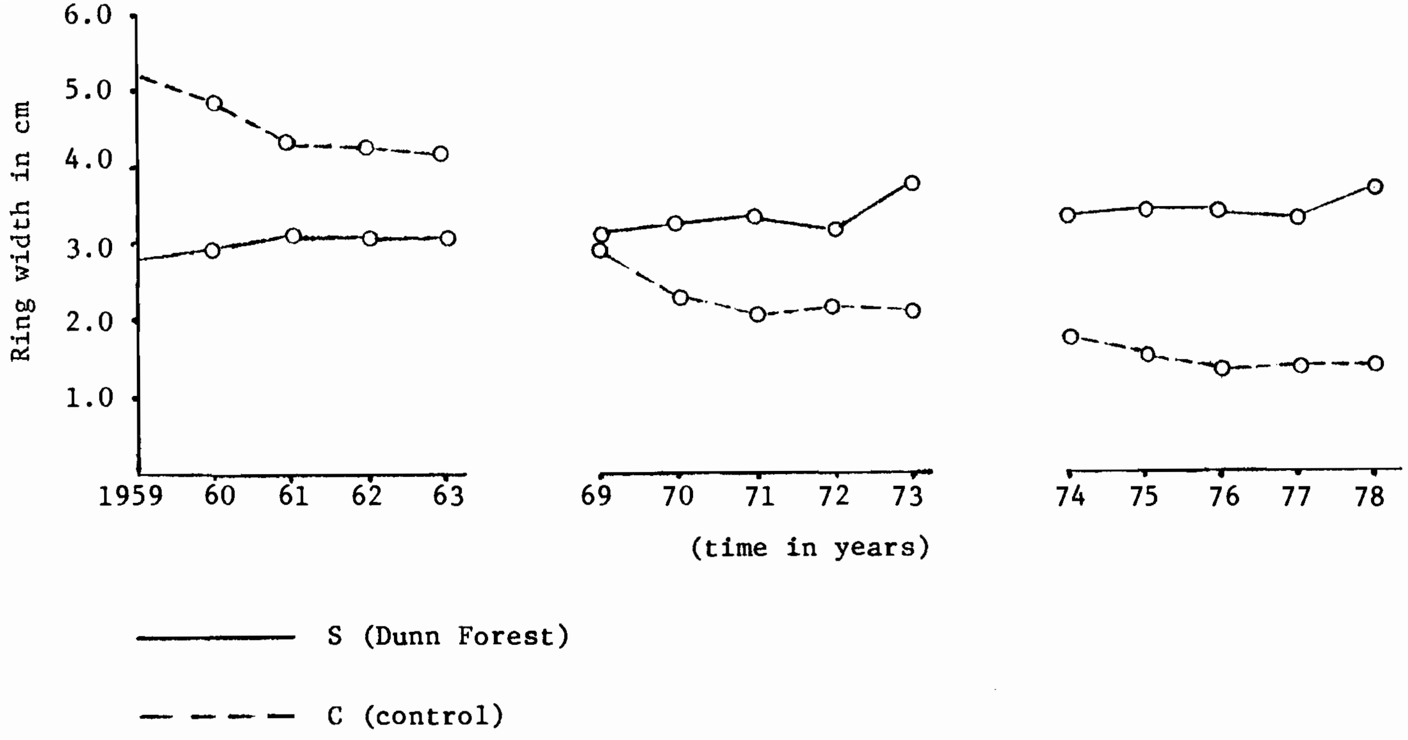

Figure 13. Ring width of treatment S (Dunn Forest) and control plot C.

treatment C is, as mentioned before, that the stands differ in age by about 6 years. Despite this disadvantage, it is still possible to find a general trend in the behavior of stand growth. Again, the general trend of decreasing ring width was found for the control plot up to a ring width of 1.41 cm in 1978. The relative large ring-width values for the control plot up to about 1966 can be explained because we are most probably looking at juvenile wood. Figure 13 reveals some data that is of general interest. All three thinning treatments actually increased ring width between the periods of the first treatment in 1960 and the third treatment in 1975. Further, there was a statistical difference between the second thinning treatment in 1970 and the third treatment in 1975.

From the knowledge we now have, we would expect a decrease in ring width with increasing tree age. The results of the three thinning experiments, however, were rather different. Thinning actually caused an increase in ring width, producing at least the same ring width as was produced 20 years earlier. This situation, as indicated earlier could have an adverse impact on meeting the requirements specified in the grading for lumber used in the laminated beam industry. In absolute terms, the average ring width in 1978 (assumed to be mature wood) was actually 67.7% higher for treatment S (Dunn Forest) than for the control plot. This difference would probably be even more if compared with a control plot of the same age. It is expected that this trend will continue with repeated thinning experiments, thus producing wider growth rings with lower density.

Thinning treatments very successfully shift the growth potential of a good site from many trees to fewer trees which will tend to reach harvestable age. Thus if the objective is to increase volume harvested various thinning treatments will fulfill that goal. However, if one considers the effect of such increased growth rate on strength properties of wood and intra-ring density parameters the forest manager should be cautious about attempting to obtain only maximum volume yield. As already indicated, the grading rules for high quality lumber going into laminated beams are very strict regarding rate of growth and density (percent latewood) requirements. Since Douglas-fir lumber constitutes around 80% of the lam stock produced, it will be undoubtedly difficult to supply that market as more raw material is supplied by small logs, many of which will come from thinned stands.

## Effect of Treatments on Earlywood Density

Much of the results, as mentioned in the description of the X-ray procedure, depends on the borderline set for earlywood/latewood differentiation. The fertilizer experiment of 1966 and the thinning/fertilization experiment (Hill Forest) of 1978/79 affected earlywood density significantly. This was not the case for the thinning/fertilization experiment of 1959. Figure 14 gives some additional details of the changes observed. Earlywood density of the control plot increased with age while the earlywood density values of treatment F stayed roughly at the same level or even decreased. After the thinning/fertilization experiment of 1959 earlywood density decreased from 0.35 g/cm$^3$ in 1958 to 0.33 g/cm$^3$ (not a significant difference) in 1959. This pattern is similar to the trend for ring width shown in Figure 12, but what is very interesting is that with a

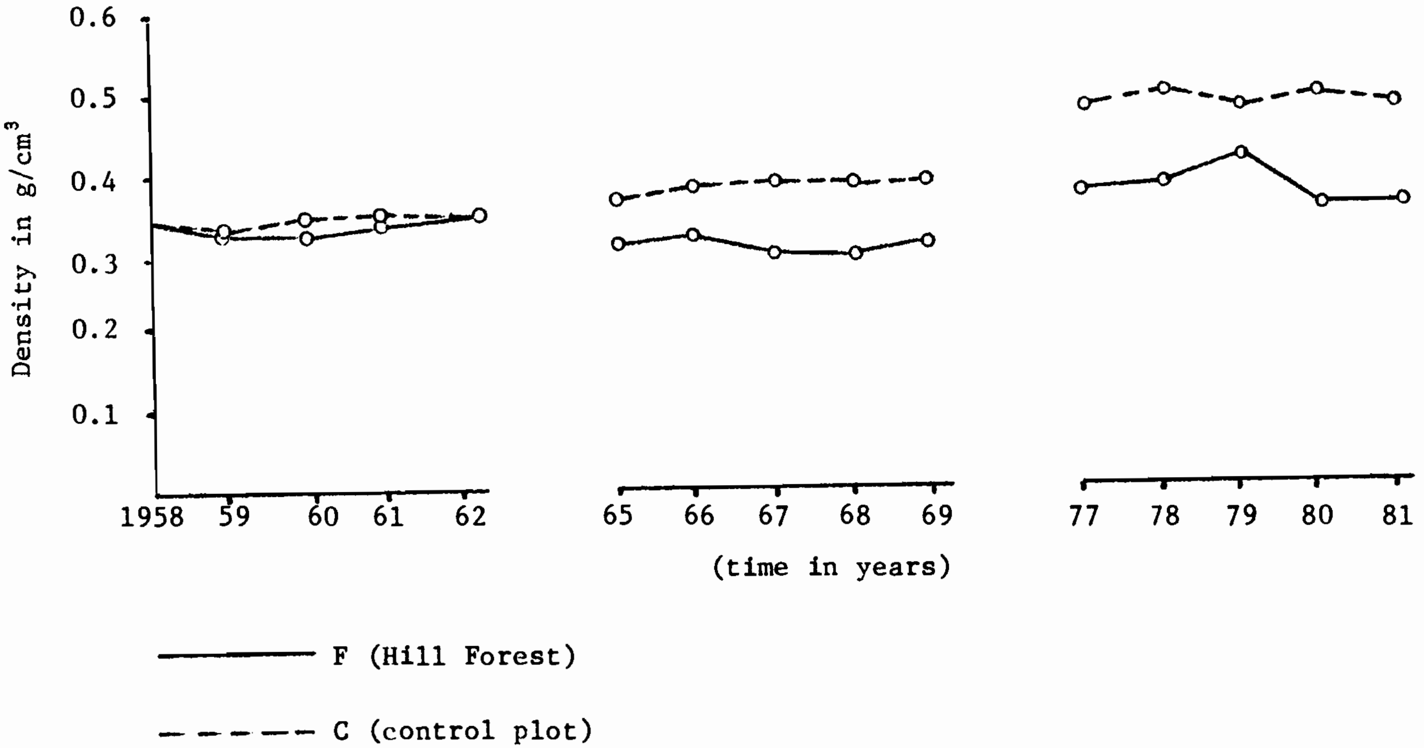

Figure 14. Earlywood density of treatment F (Hill Forest) and control plot C.

slight decrease in ring width (1959-1960) earlywood density also decreased. One would expect the opposite result.

Unexpected results were also true for the fertilization experiment of 1966. Although ring width decreased, earlywood density also decreased. This result supports the hypothesis that fertilization by itself decreases earlywood density, even though ring width decreases. This hypothesis is also supported by the fact that the percentage of latewood decreased with fertilization. In absolute values, average earlywood density decreased from 0.34 g/cm$^3$ in the 1958-1962 period to 0.30 g/cm$^3$ in the 1965-1969 period.

The strange results apply only to the samples selected. However, if fertilization alone really acts as I found, than fertilization is not recommended.

When fertilization is conducted along with thinning then some increase in growth rate occurs. However, ring density and intra-ring wood density values indicate that the values of fertilization is somewhat marginal. Thus, the increase in harvestable wood must be balanced against the possible adverse effect on wood quality.

The thinning/fertilization experiment of 1978/79 showed an increase in average earlywood density after the 1978 experiment from 0.39 g/cm$^3$ to 0.43 g/cm$^3$ and a sudden decrease to 0.35 g/cm$^3$ after fertilization in 1979. Again, these results are similar to those reported previously. Much of the explanation of these results can be attributed to environmental factors. Earlywood density correlated best with ring density with an r value of 0.901. There was a significant difference in earlywood density between the 1958-1962 and 1965-1969 periods as well as between the 1965-1969 and 1977-1981 periods in the control plot, indicating that earlywood density increased significantly with age.

The thinning experiments of treatment S (Dunn Forest) also affected earlywood density. The statistical analyses showed there were significant differences between the thinning experiments of 1960, 1970, 1975 and the control plot. Figure 15 again shows the upward trend of earlywood density in the control plot. This increase of earlywood density corresponds to a reduction in ring width. Overall, a reduction in ring width of 20% in the control plot increases earlywood density by about 8%. On the other hand, an increase of ring width by 10%, after thinning decreases earlywood density by 8.8%. These results were not true for the fertilization experiment where a decrease in ring width by 18% caused a decrease in earlywood density by 9.8%.

After the first thinning experiment (Dunn Forest) of 1960, earlywood density decreased slightly from 0.29 g/cm$^3$ to 0.27 g/cm$^3$, only to recover again after two years and reached 0.30 g/cm$^3$ again in 1963. The thinning experiment of 1970 did not change earlywood density very much. There was a slight increase in earlywood density from 0.31 g/cm$^3$ in 1970 to 0.33 g/cm$^3$ in 1971, followed by a slight decrease in 1973 to 0.32 g/cm$^3$ and again an increase up to 0.34 g/cm$^3$ in 1973. The r value for earlywood density and ring density in treatment S (Dunn Forest) was 0.183. Ring density, as will be discussed later, correlated best with maximum latewood density. There were no significant differences between the earlywood density values of the second thinning experiment in 1970 and the third thinning experiment of 1975. In absolute values, earlywood density was the same for the

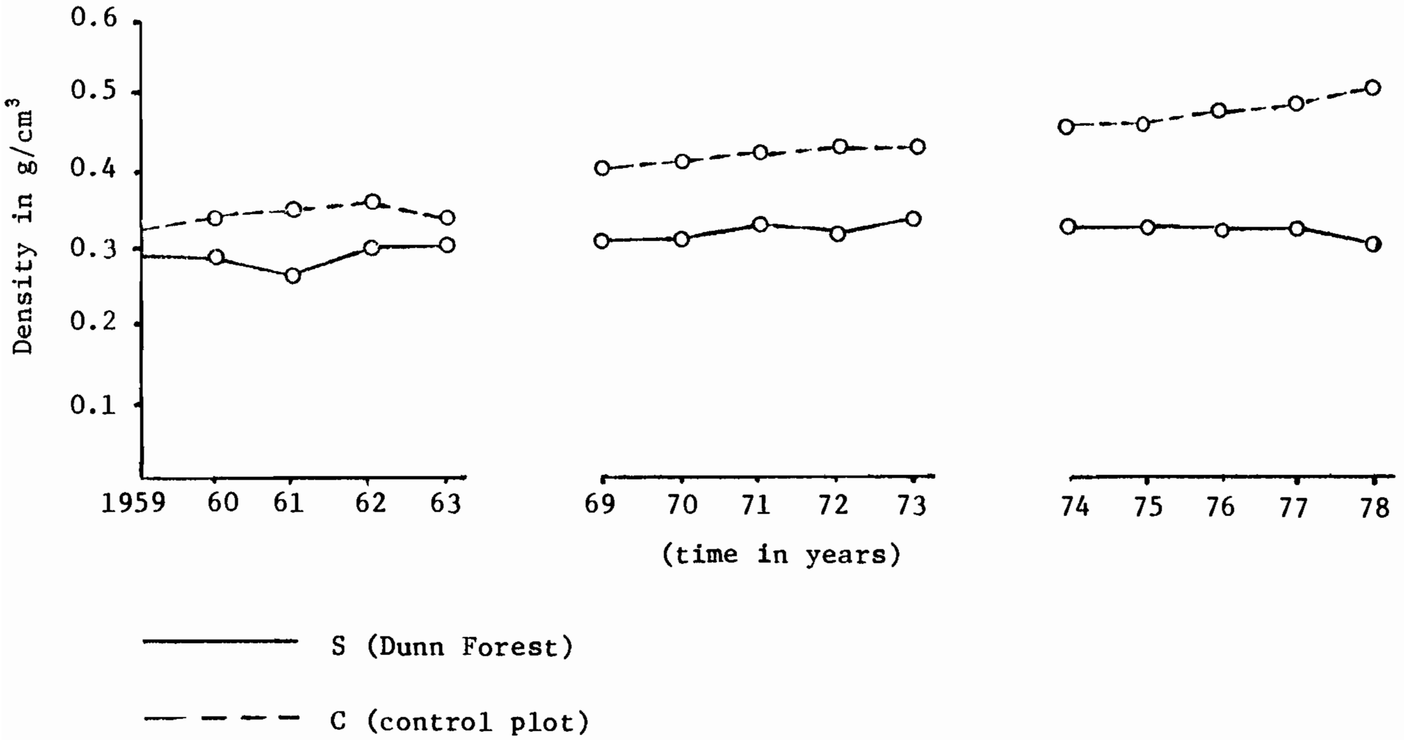

Figure 15. Earlywood density of treatment S (Dunn Forest) and control plot C.

periods 1969-1973 and 1974-1978, having a mean earlywood density of 0.32 g/cm$^3$. In comparing these results with those of the control plot, a reduction of 33% was found for the period 1974-1978. Further, this trend would be expected to continue if experiments should be extended. Overall, we should expect that earlywood density would stay roughly at the same level for treatment S (Dunn Forest).

## Effect of Treatments on Latewood Density

Latewood density of treatment F (Hill Forest) was influenced by silvicultural practices. Figure 16 shows the upward trend of latewood density in the control plot and some fluctuations caused by environmental factors. The statistical analyses showed a significant difference within the control plot between the 1959-1962 and 1964-1969 periods and between the 1959-1981 period. The fertilization treatment in 1966 and the thinning/fertilization experiment in 1978/79 affected latewood density significantly. This relationship did not occur in the thinning/fertilization experiment (Figure 16) of 1960. That thinning/fertilization treatment caused a slight decrease in latewood density only to recover in the following two years. While latewood density values of the control plot increased with age, those values for treatment F (Hill Forest) stayed around the same level. The statistical analyses showed only a significant difference between the thinning/fertilization experiment of 1978. The average latewood density of treatment F was 15% less than that of the control plot during the period of 1965-1969 and was 16% less than the control plot in the period 1977-1981.

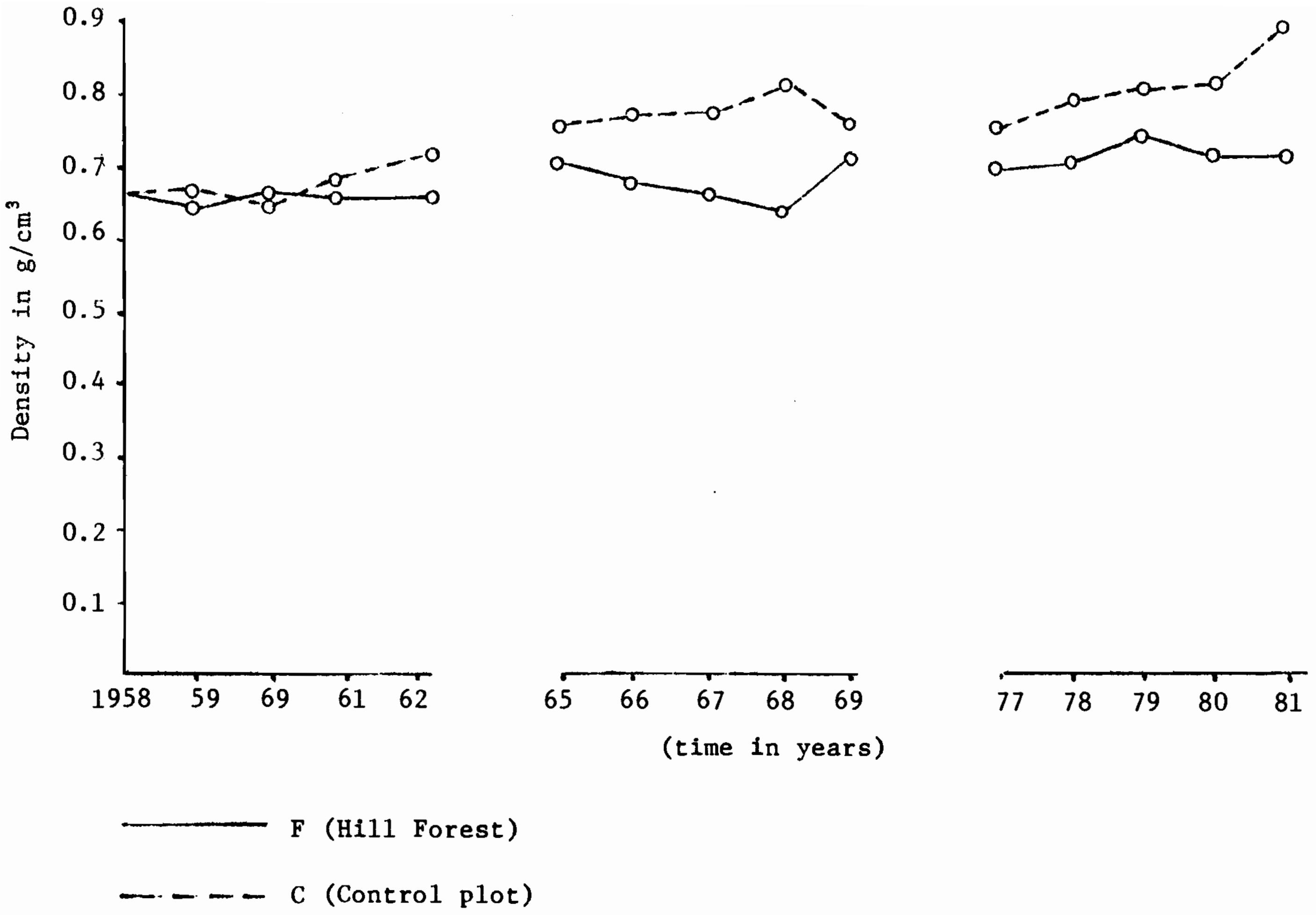

Figure 16. Latewood density of treatment F (Hill Forest) and control plot C.

Fertilization by itself caused a decrease in latewood density similar to the decrease in ring width. Only 4 years after fertilization latewood density had recovered. A decrease in ring width after fertilization in 1966 of about 20% is associated with a decrease in latewood density of about 10%. The thinning/fertilization treatment results in 1978/79 were different. There, a decrease of latewood density of about 5% is associated with an increase of ring width of about 10%. The r value for latewood density and ring density of treatment F (Hill Forest) was 0.347.

The results reported so far supports the hypothesis that fertilization by itself does not increase the magnitude of the intra-ring density parameters. Only a combination of thinning and fertilization increases growth while decreasing density values. The unusual behavior reported for tree growth after fertilization cannot be explained by the data collected in this work. Only a detailed analysis of rate of photosynthesis and ADP (adenosine diphoshate) could give a detailed answer to this phenomenon.

The thinning experiments of treatment S (Dunn Forest) also affected latewood density. The statistical analyses showed a significant difference between the thinning treatments of 1960, 1970 and those of the control plot. The 1975 treatment did not affect latewood density significantly. The statistical analyses showed a significant difference in the control plot between the period 1959-1963 and between the period 1969-1973 but not for those in the period 1969-1973 and the period 1974-1978. In absolute values latewood density was 0.91 g/cm$^3$ for the period 1959-1963, and was 0.80 g/cm$^3$ for the period 1969-1973 and 0.81 g/cm$^3$ for the period 1974-1978. Latewood density of the thinning experiments showed the following results. Within the first thinning experiment latewood ring density was on average 0.63 g/cm$^3$, 0.74 g/cm$^3$ for the second thinning experiment and 0.77 g/cm$^3$ for the third thinning experiment.

The first thinning experiment of 1960 did not reduce latewood density. Ring width remained roughly at the same level of 3.13 cm while latewood density increased by 4%. There were no abrupt changes in latewood density as in 1970. The second thinning treatment in 1970 caused a large decrease of latewood density by 11.5% from 1970 to 1971 only to recover again after one year. The r value for latewood density and ring density of treatment S (Dunn Forest) was 0.98. MED (minimum earlywood density), MLD (maximum latewood density), LW (latewood width) and EW (earlywood width) correlated best with ring density in treatment S (Dunn Forest). The thinning experiment of 1975 was not significantly different when comparing the control plot and the thinning experiment. Latewood density (Figure 17) decreased similar to the control plot by 9.13% until 1977.

Our data do not give an appropriate explanation for the decrease in latewood density with increase in tree age since latewood density in the control plot also decreased with tree age. But what we can learn from this observation is that with increasing tree age (production of mature wood) thinning/fertilization causes latewood density to remain roughly the same while latewood density of unthinned trees increase. This relationship does not hold for the juvenile latewood density from thinned stands where, though being significantly different from unthinned stands, juvenile latewood density still increased after thinning treatments.

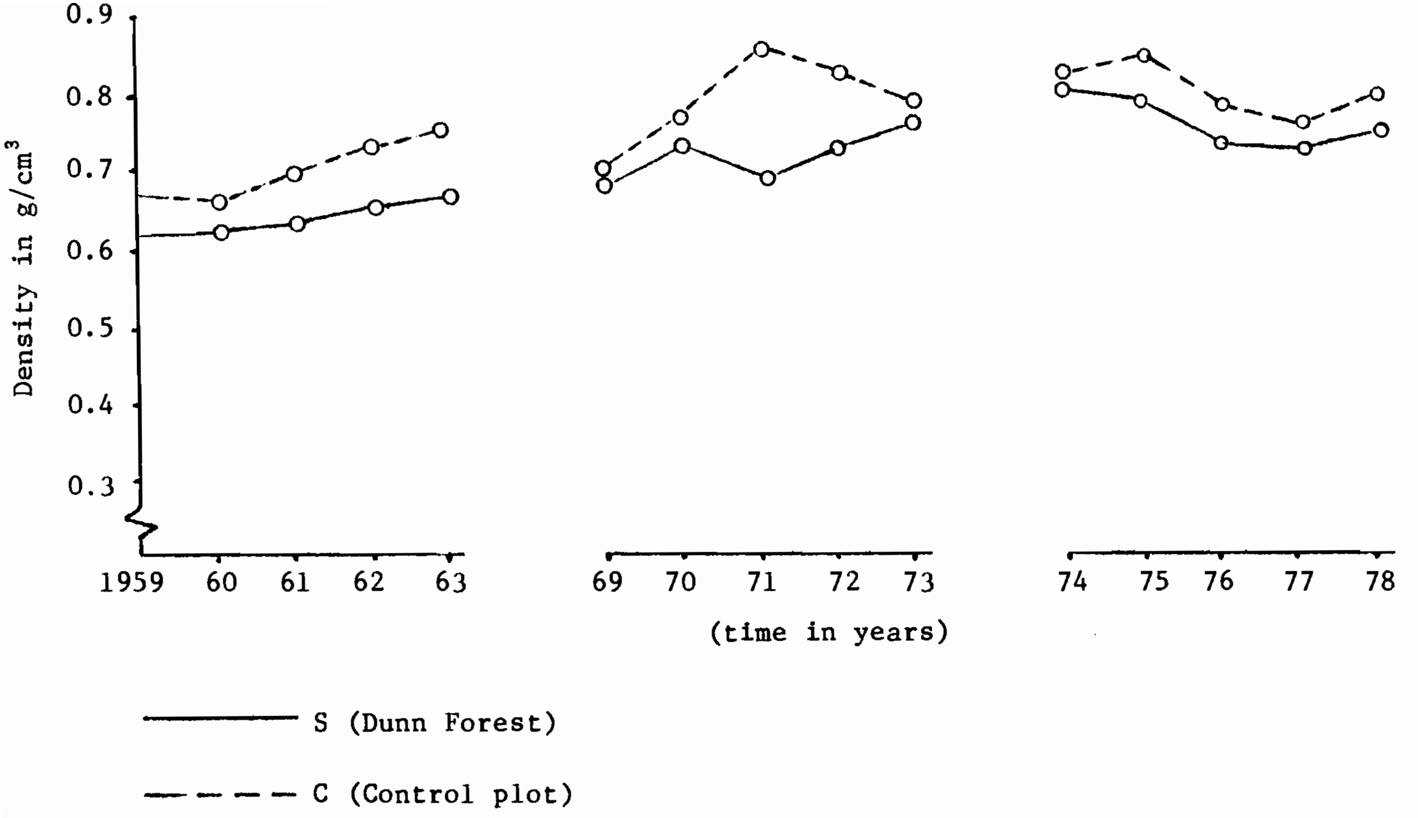

Figure 17. Latewood density of treatment S (Dunn Forest) and control plot C.

## Effect of Treatments on Ring Density

Ring density represents, besides ring width, one indication of wood quality. The r value for ring density and minimum earlywood density of the control plot was 0.972. Ring density of treatment F (Hill Forest) correlated best with earlywood density with an r value of 0.901. Ring density, a function of all the ring-parameters discussed in this particular X-ray project, varied with the age of the trees and environmental factors. Table 13 summarizes the results of the regression analyses of the three thinning treatments.

The thinning/fertilization experiment of 1959 (Hill Forest) did not affect ring density significantly. There was a slight decrease in ring density from 0.46 g/cm$^3$ in 1958 to 0.42 g/cm$^3$ in 1959. On average, ring density of treatment F (Hill Forest) for the period 1958-1962 was about 2.6% less than the control plot. This relationship did not hold for the fertilization experiment of 1966. There was a highly significant difference in ring density between the control plot and the fertilization experiment. The application of fertilizer in 1966 caused a decrease in ring density from 0.45 g/cm$^3$ to 0.41 g/cm$^3$. It took about three years for the stand to return to previous density values. On average, ring density of treatment F (Hill Forest) for the period 1965-1969 was 11.7% less than the control plot. While there was a highly significant difference in ring density between the first and second period in the control plot, ring density in treatment F was not statistically different in those periods. What is surprising again is that ring width also decreased during the fertilization experiment of 1966. The thinning/fertilization experiment

(Hill Forest) of 1978/79 showed there was a highly significant difference in ring density between treatments F (Hill Forest) and C (control). On average, ring density of treatment F was 16.9% less than the control plot. Earlywood and latewood density were found to be the best predictors of ring density in treatment F. In comparing the results of ring density in treatment F (Hill Forest) with earlywood density (Figure 14) and latewood density (Figure 16) we find a typical tendency to increase for all the density values after thinning was applied in 1978, but a sudden decrease in latewood density after the stand was fertilized in 1979. Minimum earlywood density and maximum latewood density were the best predictors of ring density in treatment C, r value 0.843.

The thinning experiments of treatment S (Dunn Forest) also affected ring density. Considering the results in Figure 19 one might conclude that thinning at an early stage of stand growth does not affect ring density significantly even if it consists of a heavy thinning. Average ring density of treatment S was about 2% less for the period 1959-1963 than that of the control plot. After the thinning treatment of 1960, ring density of treatment S (Dunn Forest) fell slightly from 0.44 g/cm$^3$ to 0.42 g/cm$^3$ and recovered again 2 years after the treatment. The statistical analyses showed a highly significant difference between the first thinning experiment of 1960 and the second thinning experiment of 1970. However, there was no significant difference between the second and third thinning treatment. While ring density (also in mature wood) of the control plot increased with age, treatment S remained about constant. The r value of ring density and maximum latewood density of treatment S (Dunn

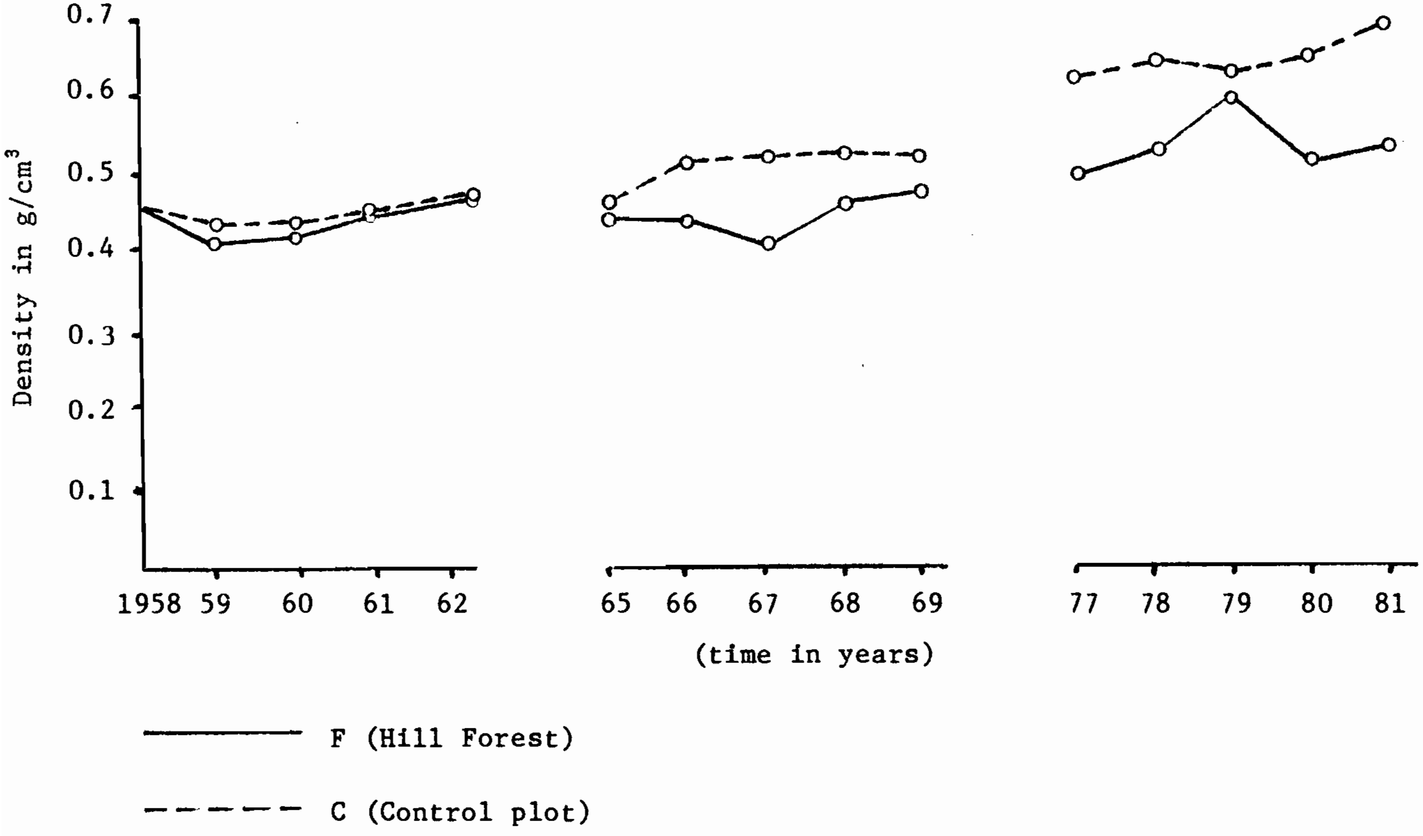

Figure 18. Ring density of treatment F (Hill Forest) and control plot C.

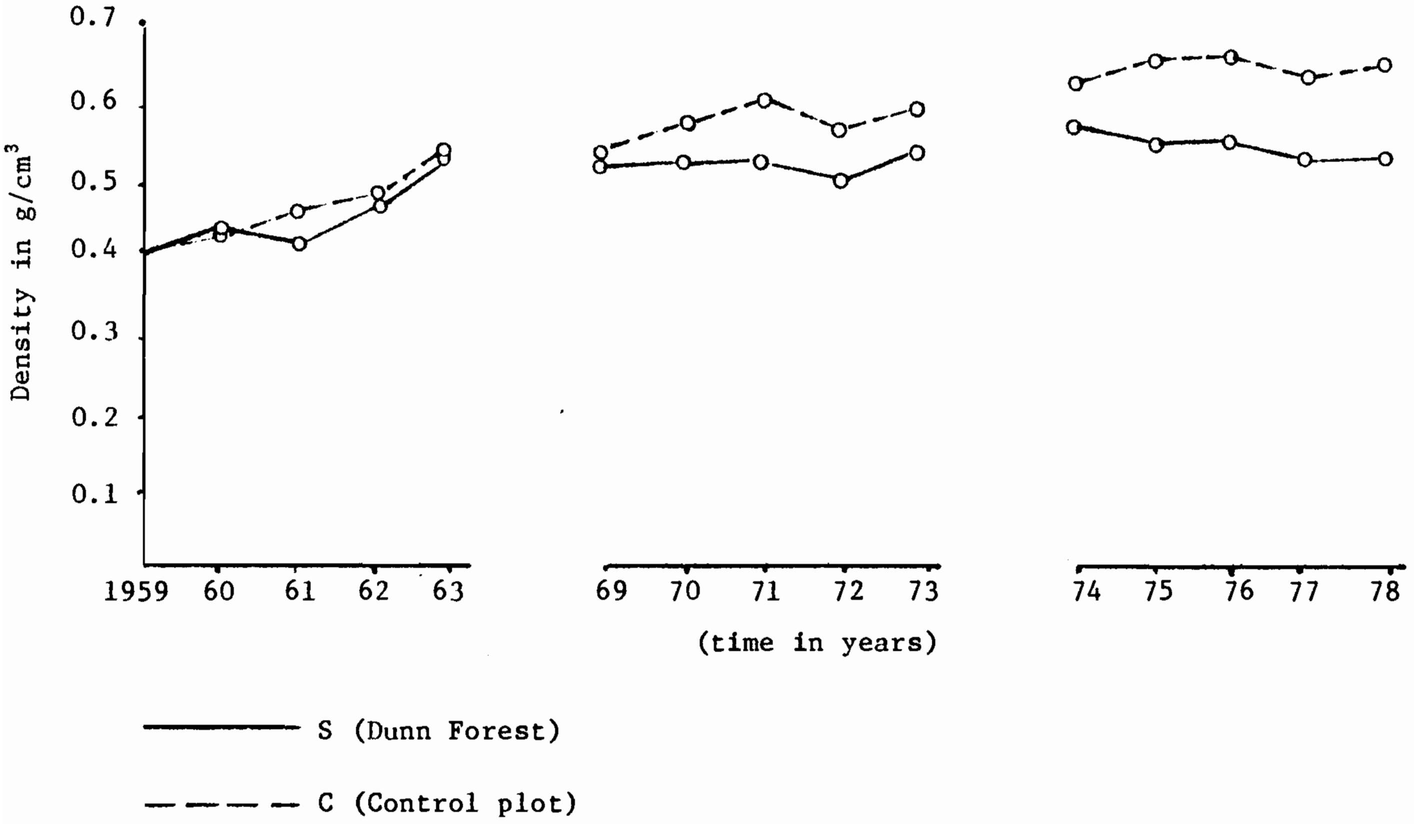

Figure 19. Ring density of treatment S (Dunn Forest) and control plot C.

Forest) was 0.971. Thinning in 1970 decreased ring density slightly by about 5.6%. On average, ring density of treatment S (Dunn Forest) was about 7.32% less for the period 1969-1973 than the control plot. The thinning treatment of 1975 revealed a highly significant difference in ring density between Treatment S and the control plot. On average, ring density of treatment S (Dunn Forest) was about 15.6% less in the period 1974-1978 than in the control plot. Thinning caused a slight decrease in ring density of 5.5% which was associated with a decrease in ring width of 4.3% at the same time. While ring density of treatment C (control) increased by 11.1% between the period 1969-1973 and the period 1974-1978, ring density of treatment S (Dunn Forest) only increased by 2.2%.

After observing the large decrease in density values for thinning treatments F (Hill Forest) and S (Dunn Forest), one might question why statistically significant differences were not obtained in the overall density values. One reason for this is probably because the experiments covered only a relatively short time period which exhibited limited influence on overall specific gravity. Another reason might result from the individual variation in samples being sufficient to make tests for differences of means nonsignificant.

## Effect of Treatments on Minimum Earlywood Density

Minimum earlywood density of treatment F (Hill Forest) was influenced by silvicultural practices. Figure 20 shows the upward trend of minimum earlywood density in the control plot. The statistical analyses showed a highly significant difference within the control plot between the periods 1958-1962 and 1965-1969, and between the

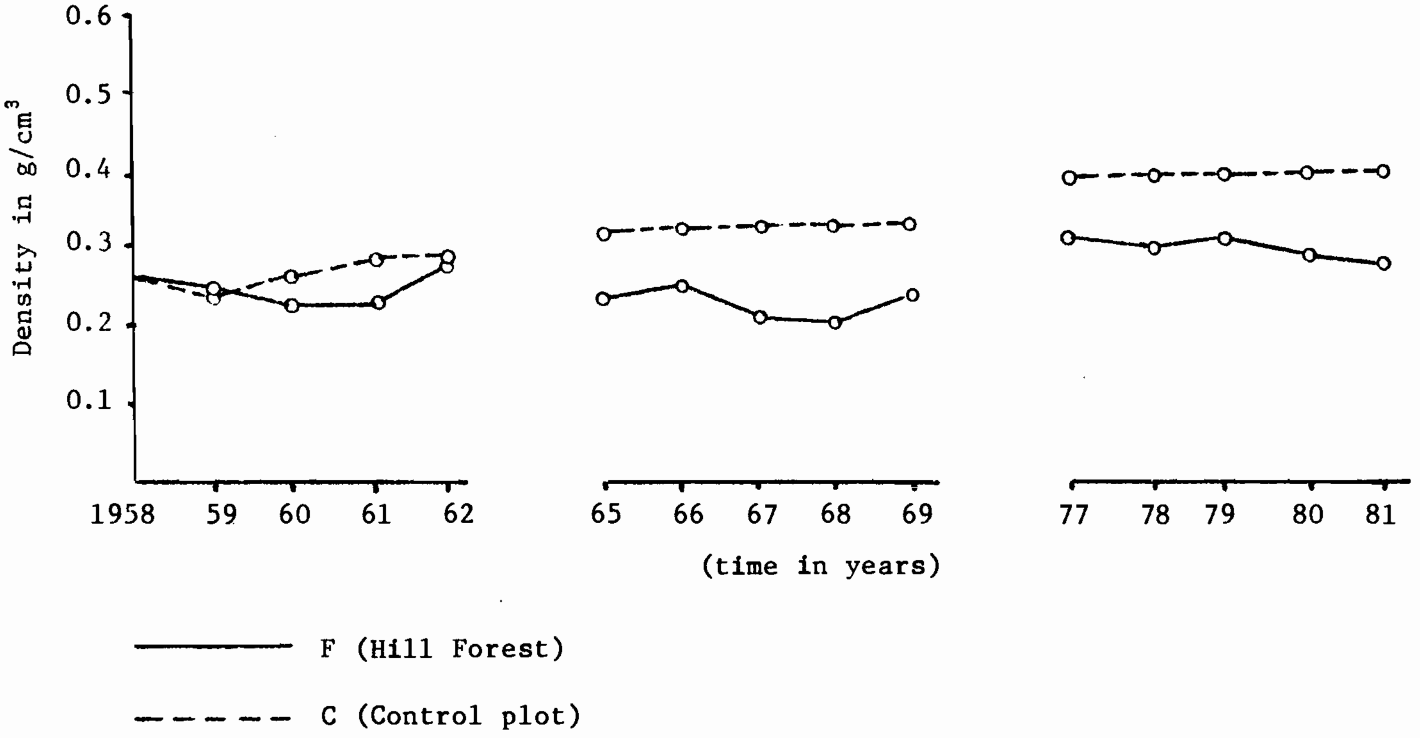

Figure 20. Minimum earlywood density of treatment F (Hill Forest) and control plot C.

periods 1965-1969 and 1977-1981. The fertilization experiment of 1966 and the thinning/fertilization experiment of 1978/79 (Hill Forest) affected minimum earlywood density statistically. This situation did not hold for the thinning/fertilization experiment of 1959. That thinning/fertilization experiment caused a slight decrease in minimum earlywood density and recovered again in the following two years. On average, minimum earlywood density of treatment F (Hill Forest) was 10.1% less than that of the control plot in the 1958-1962 period and 30.1% less than that of the control plot in the 1965-1969 period. Fertilization in 1966 caused a decrease in minimum earlywood density similar to the decrease in ring width. Only 4 years after treatment minimum earlywood density recovered again. A decrease of ring width by 20% after fertilization is associated with a decrease in minimum earlywood density of 30.1%. The thinning/fertilization treatment of 1978/79 showed different results. Here, a decrease of minimum earlywood density by 5.5% is associated with an increase in ring width of 10%. Minimum earlywood density of the control plot correlated best with ring density having an r value of 0.972. Thinning in 1978 caused a slight increase in minimum earlywood density from 0.30 g/cm$^3$ in 1978 to 0.32 g/cm$^3$ in 1979. There was a highly significant difference between the thinning/fertilization experiment (Hill Forest) of 1978/79 and the control plot values. So far an upward trend of all the density parameters has been found with increasing tree age in the control plot. Within 20 years earlywood density increased by 30.7% and ring density by 32.3%. In general this was also found in treatment F (Hill Forest).

Though minimum earlywood density of treatment F increased by 17.2% within 20 years and ring density by 16.6%, these density values actually decreased after the fertilization treatment of 1966. In this time period minimum earlywood density decreased by 8.1% and ring density by about 3.1% when compared to the mean values of the previous period (1958-1962).

The statistical analyses of treatment S (Dunn Forest) showed minimum earlywood to be highly significantly different between each of the three thinning treatments and the results in the control plot. Figure 21 illustrates the upward trend of minimum earlywood density with increasing tree age in the control plot. On average, minimum earlywood density was 30.5% less in treatment S (Dunn Forest) in the period 1959-1960 compared to the control plot. Minimum earlywood density correlation with ring density was not very good with an r value of 0.02. The thinning treatment of 1959 reduced minimum earlywood density in the following year. The results showed a slight decrease in minimum earlywood density from 0.21 g/cm$^3$ in 1959 to 0.18 g/cm$^3$ in 1961. While there was a highly significant difference in minimum earlywood density within the control plot between the 1959-1963 and 1969-1973 time periods, that variable in treatment S showed only a significant difference for those time periods. Minimum earlywood density of the control plot increased by 20.3% between the first and the second period of observation, while treatment S (Dunn Forest) only increased by 16.3% during those time periods. This indicates that thinning not only decreases minimum earlywood density in-situ but also for the long range. Though minimum earlywood density best predicts ring density in unmanaged stands, it does not seem to have the same

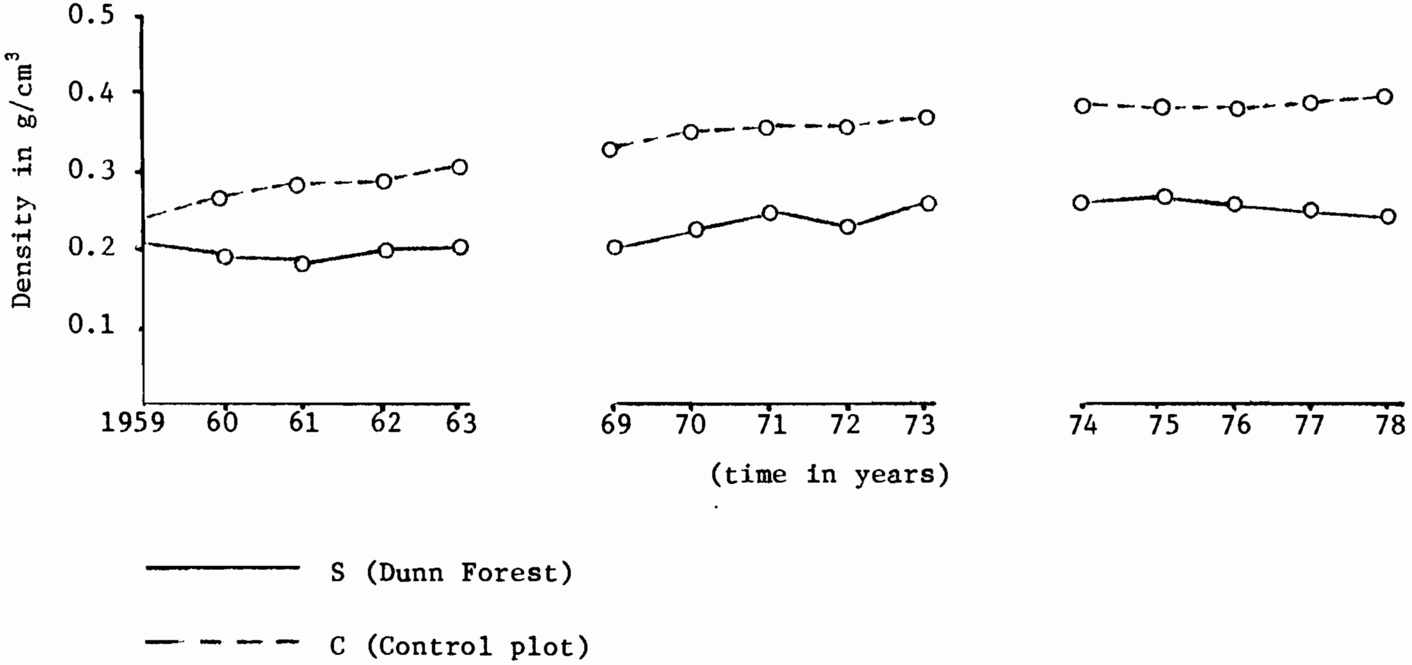

Figure 21. Minimum earlywood density of treatment S (Dunn Forest) and control plot C.

important correlation with wood quality (ring density) in managed stands. The thinning treatment in 1970 showed a slight increase in minimum earlywood density in the year following thinning. In absolute values minimum earlywood density increased from 0.23 g/cm$^3$ in 1970 to 0.25 g/cm$^3$ in 1971. Two years after the thinning experiment MED dropped back down to 0.23 g/cm$^3$ again and increased one year later to 0.26 g/cm$^3$. While statistical analyses showed there was a highly significant difference in the 1969-1973 and 1974-1978 time periods of the control plot, minimum earlywood density of treatment S (Dunn Forest) did not change significantly for these periods. The thinning treatment of 1975 caused earlywood density to decrease constantly until 1978 (four years after application). On average, minimum earlywood density of treatment S (Dunn Forest) was 39.8% less in the last time period (1977-1981) when compared to that of the control plot. This is contrary to the results found on ring width. Figure 13 illustrates a decrease in ring width after the thinning treatments. One would expect that with decreasing ring width minimum earlywood density would increase as was found in the control plot.

## Effect of Treatments on Maximum Latewood Density

Maximum latewood density in treatment F (Hill Forest) differed significantly when compared to that of the control plot. Tree age and ring width had a highly significant effect on maximum latewood density in the control plot. Statistical analyses showed a significant difference in maximum latewood density between the thinning/fertilizer experiment of 1959 and that of the control plot (C). On average, maximum latewood density of the 1958-1962 period was 10.1% less when compared with the control plot. The mean values of maximum latewood density for the first period of observations in the control plot were 0.91 g/cm$^3$ compared to 0.81 g/cm$^3$ for treatment F. Both minimum earlywood density and maximum latewood density were good predictors of ring density in the control samples. The large fluctuations in maximum latewood density, especially those in the control plot, cannot be explained by the data collected so far. Maximum latewood density of the control plot in 1981 (1.41 g/cm$^3$) comes close to the density values of cellulose and lignin, indicating that nearly the whole cross-section of the fiber must have been occupied by cell wall material at that point. The lumen apparently represented only a small part of the cell diameter.

Maximum latewood density from the fertilizer experiment of 1966 was highly significantly different from similar values in the control plot. Within two years after fertilization maximum latewood density decreased from 0.88 g/cm$^3$ in 1966 to 0.72 g/cm$^3$ in 1968. On average, the mean maximum latewood density values of treatment F (Hill Forest) for the 1965-1969 period were 0.02 g/cm$^3$ higher than those of the previous period. We found an increase of 0.20 g/cm$^3$ in the control plot for the same period. As with the other intra-ring density parameters already discussed, we found that fertilization decreased maximum latewood density which was also associated with a decrease in ring width. These results did not occur in the control plot. In that plot ring width correlated well with maximum latewood density. A decrease in ring width increased maximum latewood density. Looking at the printout of all density readings (4000 to 6000 per sample) we found that maximum latewood density occurred very close to the borderline of

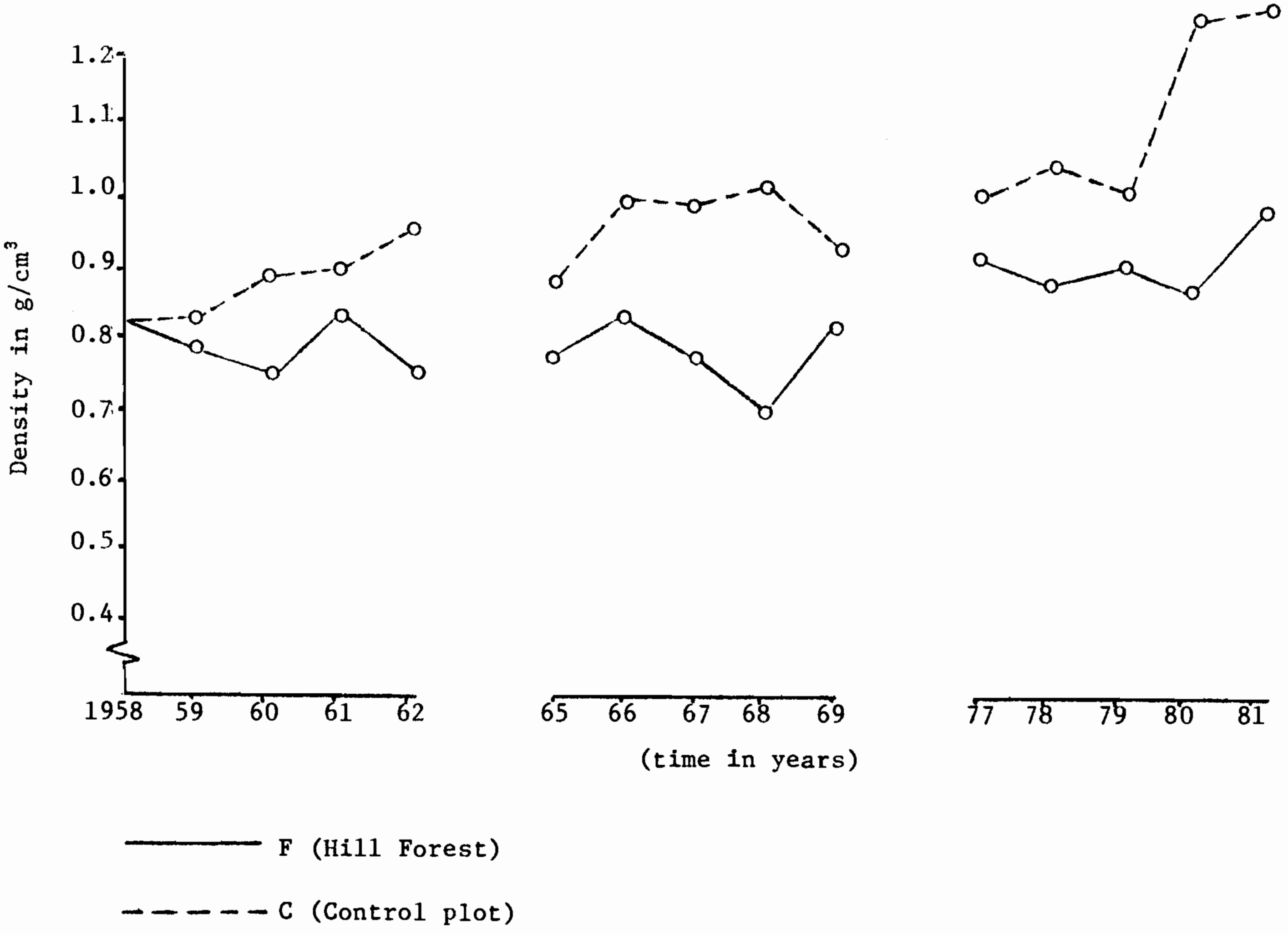

Figure 22. Maximum latewood density of treatment F (Hill Forest) and control plot C.

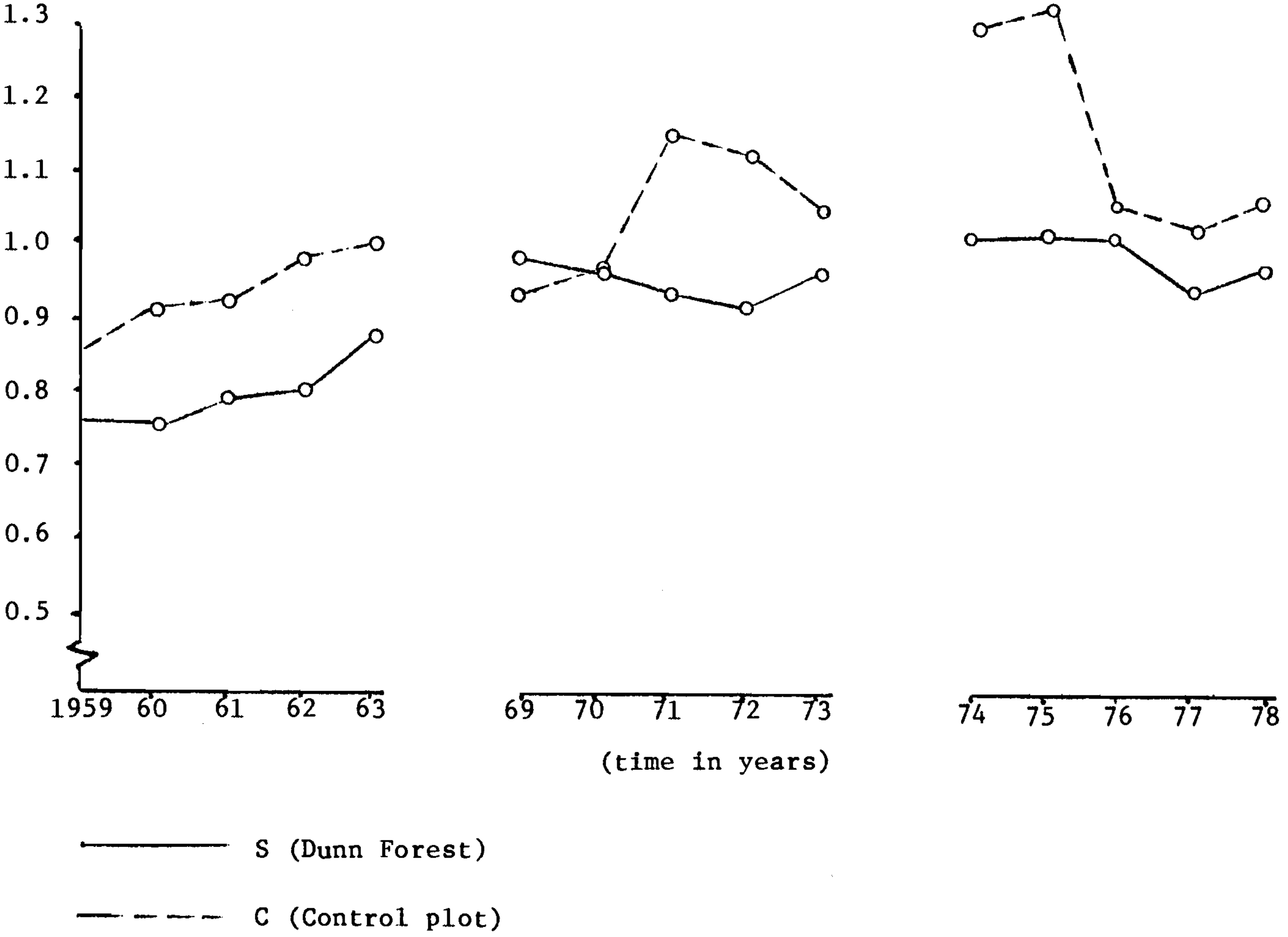

Figure 23. Maximum latewood density of treatment S (Dunn Forest) and control plot C.

a new growing season. The thinning/fertilization experiment (Hill Forest) of 1978/79 had a significant difference in maximum latewood density when compared to those values in the control plot. After thinning in 1978 maximum latewood density increased from 0.91 g/cm$^3$ in 1978 to 0.95 g/cm$^3$ in 1979 and then decreased to 0.91 g/cm$^3$ in 1980. This occurred while ring width increased. Figure 24 summarizes the results.

Maximum latewood density of treatment S (Dunn Forest) differed significantly from those in the control plot. Maximum latewood density correlated best with ring density with an r value of 0.972. There was a significant difference in maximum latewood density between each of the three thinning experiments when compared to those values in the control plot. Maximum latewood density increased with tree age. The fluctuations of maximum latewood density within treatment S (Dunn Forest) were less than those of the control plot. On average, maximum latewood density was 11.4% less for the 1959-1963 period when compared to the mean values in the control plot. The thinning treatment of 1960 increased maximum latewood density from 0.77 g/cm$^3$ in 1960 to 0.80 g/cm$^3$ in 1961. This change can probably be explained by the fact that the first thinning experiment still deals within the range of juvenile wood. The second thinning treatment in 1970 gave different results than the previous one. In this case, thinning decreased maximum latewood density from 0.97 g/cm$^3$ to 0.92 g/cm$^3$ and then recovered again three years after treatment. For the period of 1969-1973 maximum latewood density was 11.6% less than the control plot. In the thinning experiment of 1970 maximum latewood density decreased by 8.2% within two years after the treatment. The values

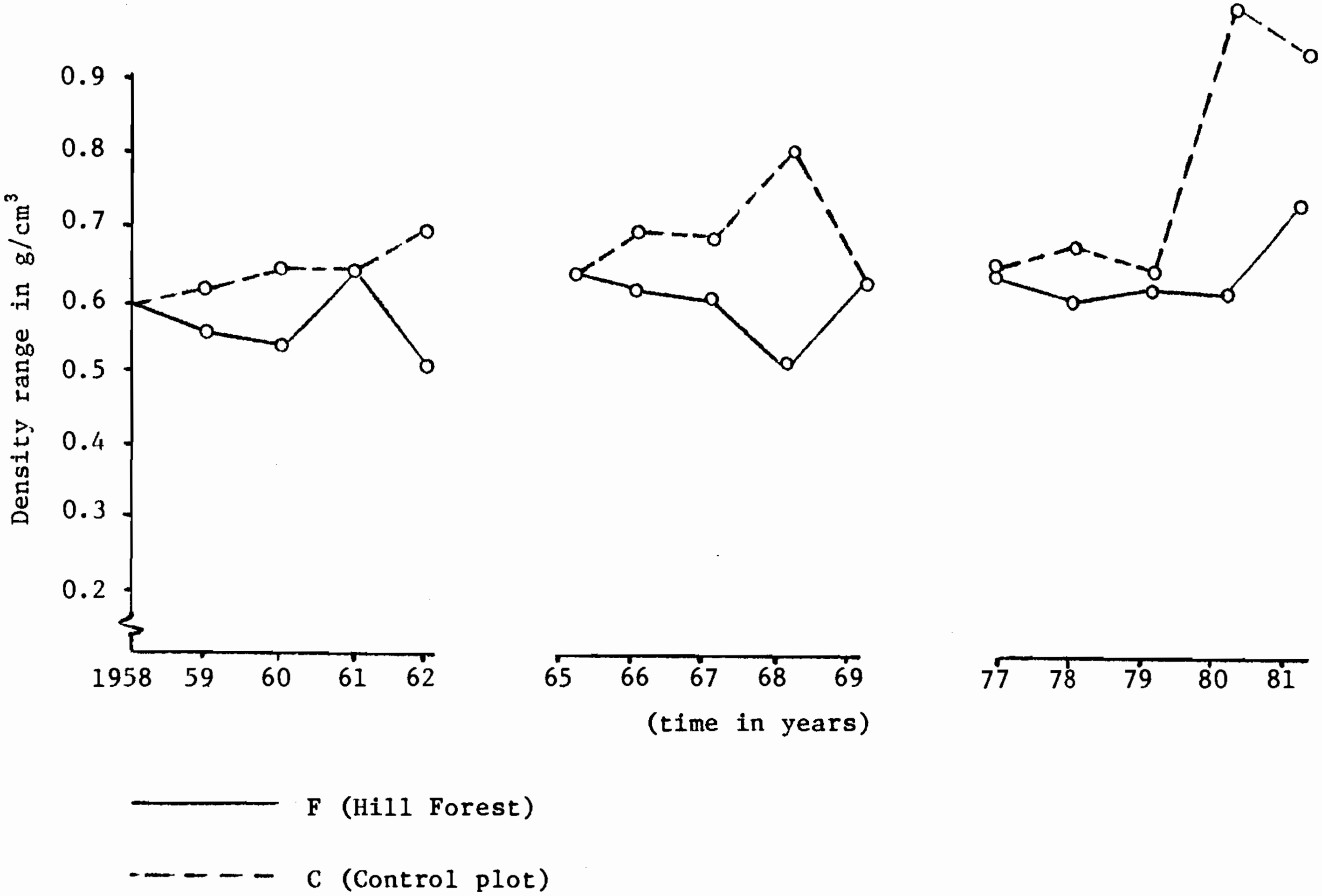

Figure 24. Density range of treatment F (Hill Forest) and control plot C.

of maximum latewood density represented only one reading out of 32 within a range of 1 mm. This means it represents the value of a very high peak within the latewood. Figure 25 summarizes the results.

## Effects of Treatments on Density Range

Density range represents the value of maximum latewood density minus minimum earlywood density. It is supposed to be a measure of density uniformity in wood. It is quite clear in Figure 24 that fluctuations between minimum and maximum density values within a year are much smaller in wood from treated stands. Figure 24 and 25 summarize these results. The thinning/fertilization experiment (Hill Forest) of 1959 reduced density range the following two years. Fertilization in 1966 decreased the range between minimum earlywood density and maximum latewood density, too. On average, density range within the first period of treatment (thinning/fertilization experiment) was about 0.52 g/cm$^3$. This was about 16.1% less than the values of the control plot. The fertilization experiment of 1966 decreased density range from 0.63 g/cm$^3$ in 1965 to 0.48 g/cm$^3$ in 1968. Following the thinning/fertilization experiment of 1978/79 density range increased by 7.1% to about 0.63 g/cm$^3$ in 1981.

The statistical analyses of treatment S (Dunn Forest) did not show any significant differences in density range between the thinning experiments and the values of the control plots. On average, the thinning treatment of 1960 did not change density range drastically. This was not so for the second thinning treatment experiment of 1970. Density range decreased continually following the experiment in 1970

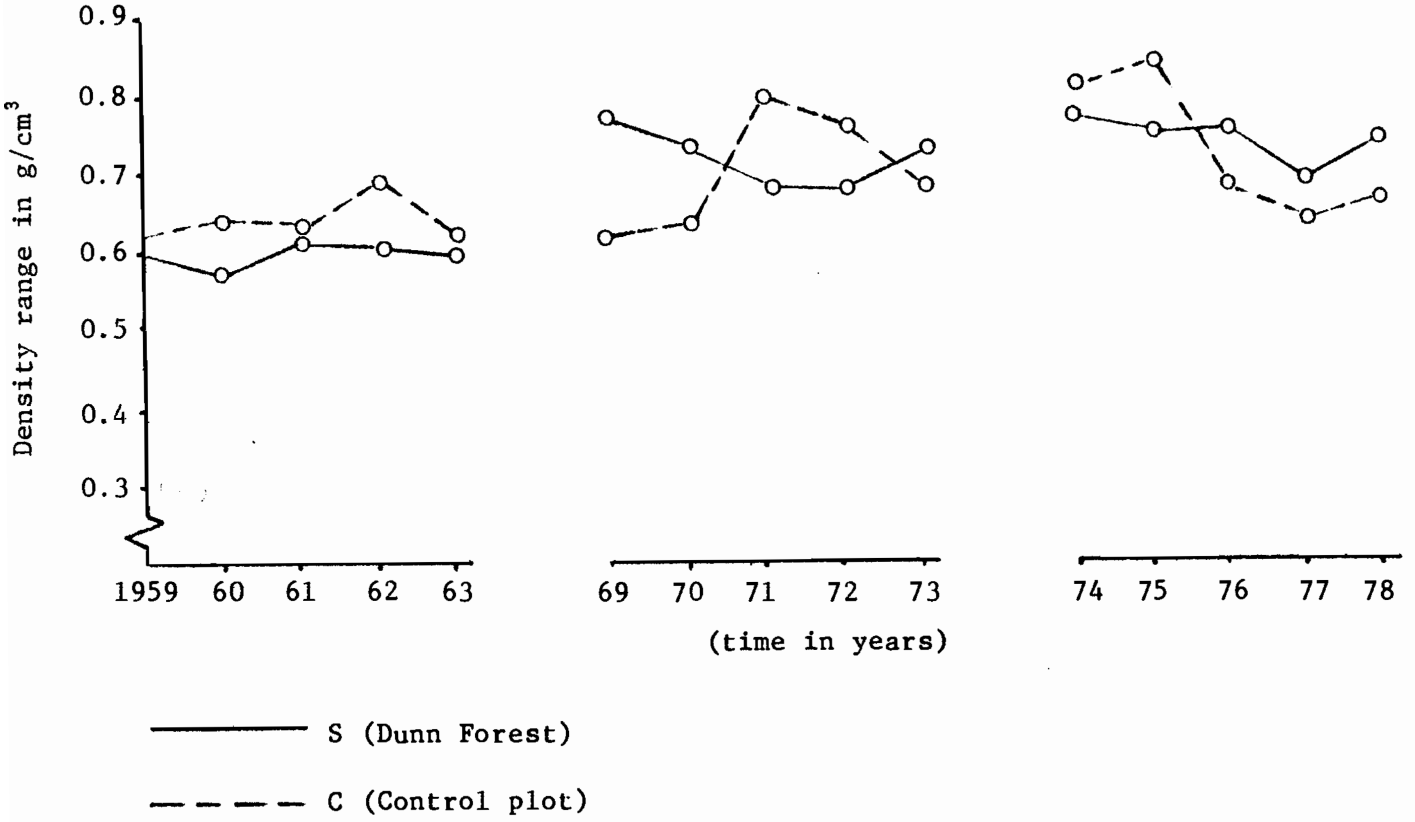

Figure 25. Density range of treatment S (Dunn Forest) and control plot C.

and recovered again 4 years later. Similar results were obtained after the third thinning treatment in 1975.

## Effect of Treatment on Percentage of Latewood

In considering thinning and fertilization in forest stands, most researchers think that a reduction of latewood width causes a decrease in percentage of latewood which is responsible for lower strength values. The results of this particular study do not support that argument. The statistical analyses proved that a significant difference occurred in percent latewood between the thinning/fertilization experiment of 1959 and those values in the control plot. The treatment actually did not reduce percentage of latewood. As is shown in Figure 26, the thinning/fertilization experiment of 1959 (supposedly juvenile wood) increased percentage of latewood comparable to that of the control plot. On average, percentage of latewood of treatment F (Hill Forest) was 18.1% higher (during the first treatment period) than the control plot for the same period. Within six years after the first treatment, the relationship between earlywood width and latewood width reached roughly the same percentage as that of the control plot (37.2%). After fertilization in 1966, percentage of latewood reached 37.7%. This was slightly higher than was found in the control plot (36.1%). The thinning/fertilization (Hill Forest) experiment of 1978/79 showed results similar to the previous treatment. Percentage of latewood increased in the year following thinning in 1978 but decreased in 1979, the year after fertilization. Figure 26 summarizes the results for percent latewood. On average, percentage of latewood in treatment F (Hill Forest) was

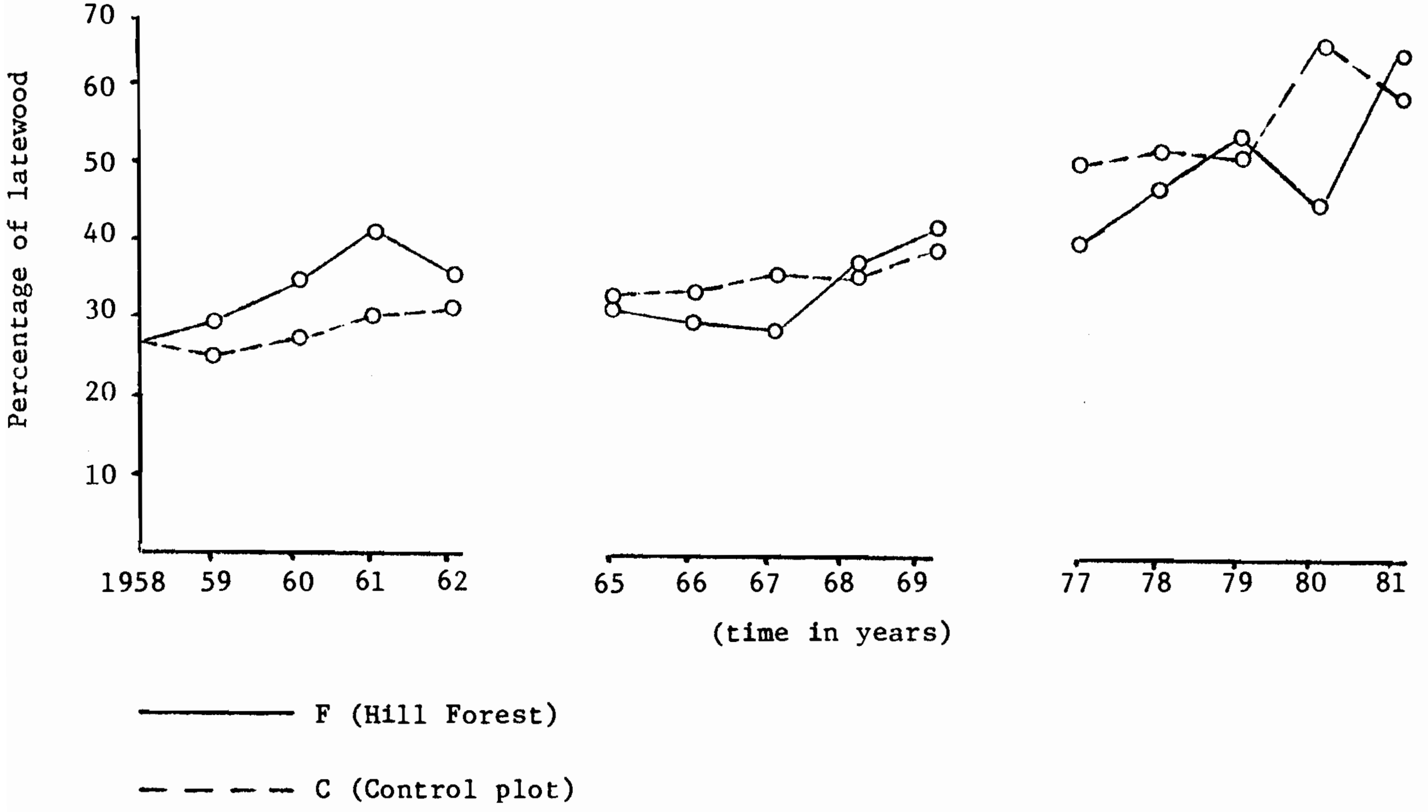

Figure 26. Percentage of latewood of treatment F (Hill Forest) and control plot C.

51.4% for the period 1977-1981 and was 56.2% in the control plot. Percentage of latewood and age had a high correlation with an r value of 0.843.

The statistical analyses of the thinning experiment of 1960 proved there was a highly significant difference in percentage of latewood between the thinned and the control plot. After the thinning treatment of 1960 (Figure 27) percentage of latewood decreased slightly from 42.9% to 39.6% in 1961 and then increased again two years after treatment reaching a value of 48.6%. The thinning treatment nine years later decreased percentage of latewood slightly reaching a level in 1973 (46.2%) that was lower than it had been nine years previously. During the period 1974-1978 (third thinning treatment) percentage of latewood increased slightly reaching a value of 50.8% in 1978.

## Recommendation

The X-ray portion of this study might have been improved in some respects. One source of variation is related to the development of the X-ray film negative because it is difficult to precisely control development variables. The film itself is another source of variation since the film does not have absolutely uniform grain which causes some fluctuation of voltage values from the densitometer output. The best way to avoid these possible sources of error would be to convert to a direct X-ray scanning method with an X-ray detector under the exposed specimen. This conversion, however, is quite expensive.

Another improvement could be made associated with placement of the X-ray generator with respect to the specimens. The distance

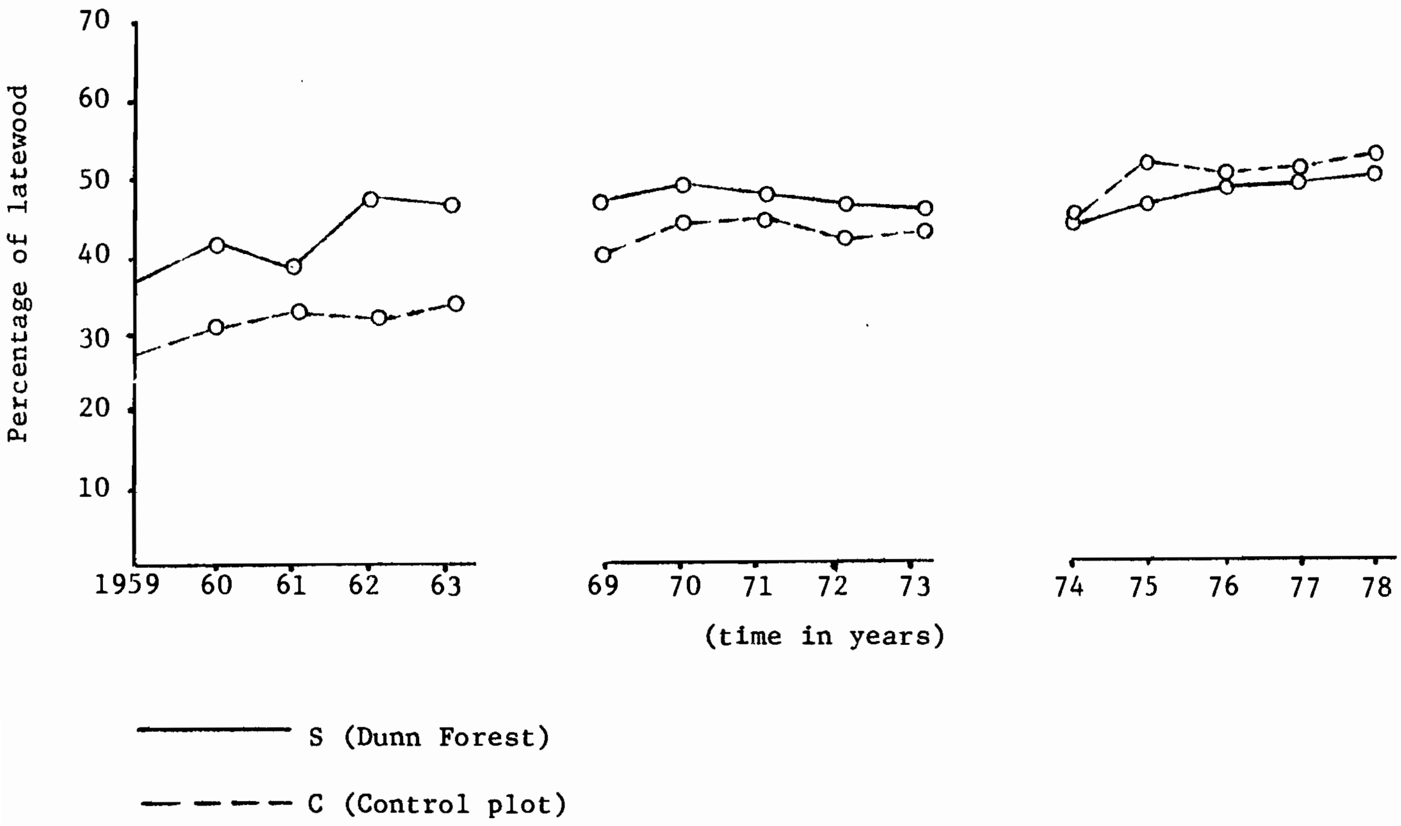

Figure 27. Percentage of latewood of treatment S (Dunn Forest) and control plot C.

between the X-ray source and the samples being scanned should be larger (about 2 meters). The calibration wedge consisting of different species of wood, could be extended by adding two or three more species with different density values to improve the wedge data.

The ring boundary, which affects most of the intra-ring parameters, could be improved by divising a more flexible way of determining the boundary between earlywood and latewood.

I recommend that additional X-ray studies be carried out on cross-sections of the specimens used for the bending strength portion of this study. In this way the stepwise regression analyses of the modulus of elasticity and modulus of rupture values with the intra-ring parameters would have been more precise.

Finally I recommend that the intra-ring parameters be correlated with values of various environmental factors, like precipitation and temperature, in order to more fully explain factors regulating tree growth and intra-ring quality parameters.

# CONCLUSIONS

A summary of the conclusions that can be drawn from the data obtained in this study are as follows:

1. The overall average specific gravity did not differ significantly among the various thinning/fertilization treatments. The average specific gravity values of the Hill Forest (treatment F) were 4.22% and those of the Dunn Forest (treatment S) were 8.24% less than the average of the control plot. There was no significant difference (Hill Forest) in the overall average specific gravity values between the butt and 18 foot-height level. At a height of 18 feet treatment F showed slightly higher (non-significant) density values than those of the control plots.
2. A combination of fertilization and thinning did not change fiber length significantly. Increasing diameter (age) has a significant effect on latewood fiber length. Heavy thinning (during juvenile wood formation) reduced latewood fiber length drastically by 26.5%. Light thinning did not decrease latewood fiber length significantly. There was no significant difference between butt and 18 foot-level wood values in treatment S (Dunn Forest). Further, all fiber length values generally increased with height of the trees.
3. Modulus of elasticity (MOE) values were significantly different among treatments. The mature wood MOE values of treatment F (Hill Forest) were 10.6% less at the butt of the trees and 2.6% less at a height of 18 feet than the control

plot MOE. These values averaged 3.9% less than the Wood Handbook MOE for coast Douglas-fir. The modulus of elasticity values in treatment S (Dunn Forest) were much lower than those in treatment F. The mature wood modulus of elasticity values of treatment S (at the butt) was 17.3% less than those values in the control plot. Ring width was the most important independent variable in the MOE regression analyses of juvenile wood. Ring density was the most important independent variable affecting MOE regression for mature wood.

4. Modulus of rupture (MOR) values showed a significant difference among treatments. The juvenile wood modulus of rupture (Dunn Forest) values were 12.4% less than those in the control plot. The mature wood modulus of rupture values were also much less (6.0%) than those in the control plot. The values at the butt of the trees and at 18 feet were 6.3% and 6.0% less, respectively, than MOR values in control plot. Juvenile wood MOR values of treatment S (Dunn Forest) correlated best with maximum latewood density and mature wood MOR values correlated best with ring width.

5. Ring width, earlywood density, latewood density, ring density, minimum earlywood density and maximum latewood density proved there were highly significant differences between one or more of the three applications (thinning/fertilization, fertilization, thinning/fertilization) and also between the treatments (control and treatment F). Fertilization without thinning showed not only a decrease in ring width but also a decrease in all the density parameters according to the law

of minimum (minimum factor regulates growth). Treatments within the range of juvenile wood formation affected intra-ring parameters less than those made when the tree was producing mature wood. Only a combination of thinning and fertilization increased growth. Minimum earlywood density and maximum latewood density were the most important independent variables in the RD (ring density) regression. Percentage latewood did not change drastically in treated stands (Hill Forest).

6. Ring width, earlywood density, ring density, minimum earlywood density and maximum latewood density proved there were highly significant differences between one or more of the thinning applications and also between the treatments (control and Dunn Forest). Latewood density showed a highly significant difference between treatments C (control) and S (Dunn Forest).

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# APPENDICES

# APPENDIX A

## Overall Average Specific Gravity Data

| | Butt | | 18-foot level |
|---|---|---|---|
| C1 | 0.501 $g/cm^3$ | C1 | 0.419 $g/cm^3$ |
| C2 | 0.429 $g/cm^3$ | C2 | 0.330 $g/cm^3$ |
| C3 | 0.460 $g/cm^3$ | C3 | 0.406 $g/cm^3$ |
| C4 | 0.500 $g/cm^3$ | C4 | 0.329 $g/cm^3$ |
| F1 | 0.421 $g/cm^3$ | F1 | 0.410 $g/cm^3$ |
| F2 | 0.460 $g/cm^3$ | F2 | 0.380 $g/cm^3$ |
| F3 | 0.552 $g/cm^3$ | F3 | 0.397 $g/cm^3$ |
| F4 | 0.384 $g/cm^3$ | F4 | 0.329 $g/cm^3$ |
| S1 | 0.434 $g/cm^3$ | S1 | 0.325 $g/cm^3$ |
| S2 | 0.450 $g/cm^3$ | S2 | 0.397 $g/cm^3$ |
| S3 | 0.403 $g/cm^3$ | S3 | 0.300 $g/cm^3$ |
| S4 | 0.450 $g/cm^3$ | S4 | 0.359 $g/cm^3$ |

# APPENDIX B

## Fiber Length

| | Years | | | | | |
|---|---|---|---|---|---|---|
| | 1958 | 1958 | 1966 | 1966 | 1978 | 1978 |
| | EW | LW | EW | LW | EW | LW |
| AC | 3.06[1] | 3.64 | 3.19 | 3.99 | 3.42 | 4.16 |
| BC | 2.97 | 3.64 | 3.40 | 4.07 | 3.78 | 4.26 |
| AF | 2.88 | 3.28 | 3.18 | 3.79 | 3.33 | 4.11 |
| BF | 2.57 | 3.26 | 3.52 | 4.24 | 3.28 | 4.36 |
| | 1960 | 1960 | 1970 | 1970 | 1975 | 1975 |
| | EW | LW | EW | LW | EW | LW |
| AS | 2.25 | 3.51 | 3.19 | 3.86 | 3.48 | 4.09 |
| BS | 2.31 | 3.31 | 3.22 | 3.99 | 3.48 | 4.24 |
| AC | 3.03 | 3.62 | 3.20 | 3.97 | 3.53 | 4.15 |
| BS | 2.91 | 3.59 | 3.48 | 4.11 | 3.47 | 4.27 |

[1] Each number represents the mean of 8 fibers measured.

A indicates butt.
B indicates 18-foot level.
C indicates control plot.
F indicates Hill Forest
S indicates Dunn Forest.

## APPENDIX C

### Mechanical Properties Data in kg/cm$^2$

| | MOE | | | | MOR | | | |
|---|---|---|---|---|---|---|---|---|
| | Butt | | 18-foot level | | Butt | | 18-foot level | |
| 1C | 69438[1] | 120377[2] | 99728[1] | 137606[2] | 744[1] | 942[2] | 701[1] | 993[2] |
| 2C | 75768 | 145077 | 93493 | 127453 | 721 | 1007 | 724 | 884 |
| 3C | 83256 | 127586 | 93496 | 126484 | 700 | 953 | 648 | 907 |
| 4C | 83532 | 128882 | 89896 | 126918 | 768 | 926 | 751 | 963 |
| 5C | 86619 | 123787 | 88860 | 127776 | 783 | 945 | 725 | 914 |
| 6C | 82275 | 126351 | 85366 | 120892 | 756 | 951 | 660 | 884 |
| 7C | 78104 | 137074 | 93357 | 116204 | 735 | 937 | 768 | 889 |
| 1F | 88421 | 116544 | 87123 | 115844 | 620 | 890 | 706 | 886 |
| 2F | 69014 | 117068 | 97723 | 129915 | 586 | 899 | 735 | 936 |
| 3F | 75849 | 97825 | 96123 | 123101 | 754 | 965 | 756 | 915 |
| 4F | 76937 | 124867 | 99244 | 130035 | 575 | 1015 | 856 | 914 |
| 5F | 77791 | 113682 | 83196 | 115120 | 691 | 929 | 694 | 893 |
| 6F | 94328 | 132953 | 83840 | 129538 | 860 | 1016 | 696 | 942 |
| 7F | 82557 | 107715 | 89501 | 117075 | 670 | 780 | 795 | 889 |
| 1S | 61800* | 109462 | 86402 | 119346 | 642 | 930 | 811 | 938 |
| 2S | 60356 | 113757 | 77437 | 110600 | 568 | 843 | 664 | 851 |
| 3S | 50687 | 107054 | 75926 | 106788 | 657 | 921 | 724 | 868 |
| 4S | 60060 | 105605 | 81454 | 106844 | 622 | 922 | 679 | 806 |
| 5S | 66335 | 109650 | 68013 | 98221 | 661 | 911 | 754 | 837 |
| 6S | 71797 | 104948 | 63562 | 108902 | 674 | 902 | 588 | 891 |
| 7S | 74699 | 101458 | 78068 | 105519 | 729 | 890 | 672 | 884 |

[1] Juvenile wood.

[2] Mature wood.

*Each number represents the mean of 7 samples tested.

# APPENDIX D

## Intra-ring Parameters

Ring width for control plot (C), Hill Forest (F) and Dunn Forest (S) in mm.

| | C | F | | C | S |
|---|---|---|---|---|---|
| 1958 | 5.86 | 5.86 | 1959 | 5.19 | 2.68 |
| 1959 | 5.19 | 5.67 | 1960 | 4.87 | 2.91 |
| 1960 | 4.87 | 5.58 | 1961 | 4.31 | 3.13 |
| 1961 | 4.31 | 5.78 | 1962 | 4.47 | 3.05 |
| 1962 | 4.47 | 5.86 | 1963 | 4.46 | 3.04 |
| 1965 | 4.50 | 5.03 | 1969 | 2.89 | 3.07 |
| 1966 | 3.97 | 5.07 | 1970 | 2.30 | 3.22 |
| 1967 | 3.35 | 4.11 | 1971 | 2.07 | 3.30 |
| 1968 | 3.02 | 3.93 | 1972 | 2.13 | 3.17 |
| 1969 | 2.89 | 3.51 | 1973 | 2.01 | 3.04 |
| 1977 | 1.47 | 2.20 | 1974 | 1.89 | 3.35 |
| 1978 | 1.41 | 2.24 | 1975 | 1.67 | 3.74 |
| 1979 | 1.50 | 2.11 | 1976 | 1.49 | 3.47 |
| 1980 | 1.52 | 3.32 | 1977 | 1.47 | 3.78 |
| 1981 | 1.61 | 4.31 | 1978 | 1.41 | 3.74 |

Earlywood density, latewood density and ring density for control plot (C) and Hill Forest (F) in g/cm$^3$.

| | ED | | LD | | RD | |
|---|---|---|---|---|---|---|
| | C | F | C | F | C | F |
| 1958 | 0.35 | 0.35 | 0.67 | 0.67 | 0.46 | 0.46 |
| 1959 | 0.34 | 0.33 | 0.67 | 0.65 | 0.44 | 0.42 |
| 1960 | 0.35 | 0.33 | 0.66 | 0.67 | 0.43 | 0.42 |
| 1961 | 0.36 | 0.34 | 0.70 | 0.66 | 0.46 | 0.46 |
| 1962 | 0.34 | 0.35 | 0.73 | 0.66 | 0.48 | 0.47 |
| 1965 | 0.37 | 0.31 | 0.76 | 0.71 | 0.47 | 0.45 |
| 1966 | 0.39 | 0.33 | 0.78 | 0.68 | 0.52 | 0.44 |
| 1967 | 0.39 | 0.30 | 0.78 | 0.67 | 0.53 | 0.41 |
| 1968 | 0.39 | 0.30 | 0.82 | 0.63 | 0.54 | 0.42 |
| 1969 | 0.40 | 0.32 | 0.70 | 0.68 | 0.53 | 0.49 |
| 1977 | 0.49 | 0.38 | 0.76 | 0.69 | 0.63 | 0.51 |
| 1978 | 0.51 | 0.39 | 0.80 | 0.71 | 0.65 | 0.54 |
| 1979 | 0.48 | 0.43 | 0.82 | 0.75 | 0.63 | 0.61 |
| 1980 | 0.51 | 0.35 | 0.92 | 0.71 | 0.66 | 0.51 |
| 1981 | 0.48 | 0.36 | 0.89 | 0.72 | 0.71 | 0.55 |

Appendix D (continued)

Minimum earlywood density, maximum latewood density and percentage latewood for control plot (C) and Hill Forest (F).

| | MED | | MLD | | PL | |
|---|---|---|---|---|---|---|
| | C | F | C | F | C | F |
| 1958 | 0.26 | 0.26 | 0.85 | 0.85 | 27.47 | 27.47 |
| 1959 | 0.24 | 0.25 | 0.86 | 0.81 | 26.01 | 32.98 |
| 1960 | 0.27 | 0.23 | 0.92 | 0.77 | 28.54 | 35.30 |
| 1961 | 0.29 | 0.23 | 0.93 | 0.88 | 31.32 | 42.56 |
| 1962 | 0.29 | 0.28 | 0.99 | 0.78 | 32.86 | 37.37 |
| 1965 | 0.32 | 0.24 | 0.95 | 0.85 | 34.89 | 32.01 |
| 1966 | 0.33 | 0.26 | 1.03 | 0.88 | 34.01 | 31.61 |
| 1967 | 0.33 | 0.21 | 1.02 | 0.81 | 37.01 | 30.17 |
| 1968 | 0.33 | 0.21 | 1.15 | 0.72 | 36.09 | 37.70 |
| 1969 | 0.33 | 0.24 | 0.95 | 0.89 | 40.14 | 43.87 |
| 1977 | 0.39 | 0.31 | 1.04 | 0.95 | 51.70 | 41.36 |
| 1978 | 0.40 | 0.30 | 1.09 | 0.91 | 53.90 | 49.11 |
| 1979 | 0.40 | 0.32 | 1.03 | 0.95 | 52.67 | 55.45 |
| 1980 | 0.40 | 0.29 | 1.37 | 0.91 | 66.45 | 45.18 |
| 1981 | 0.40 | 0.29 | 1.41 | 1.02 | 56.52 | 64.12 |

Earlywood density, latewood density and ring density for control plot (C) and Dunn Forest (S) in g/cm$^3$.

| | ED | | LD | | RD | |
|---|---|---|---|---|---|---|
| | C | S | C | S | C | S |
| 1959 | 0.33 | 0.29 | 0.67 | 0.62 | 0.42 | 0.41 |
| 1960 | 0.35 | 0.29 | 0.66 | 0.63 | 0.42 | 0.44 |
| 1961 | 0.36 | 0.27 | 0.70 | 0.62 | 0.43 | 0.42 |
| 1962 | 0.34 | 0.30 | 0.73 | 0.63 | 0.46 | 0.45 |
| 1963 | 0.33 | 0.30 | 0.74 | 0.65 | 0.51 | 0.52 |
| 1969 | 0.40 | 0.31 | 0.70 | 0.69 | 0.53 | 0.52 |
| 1970 | 0.41 | 0.31 | 0.77 | 0.72 | 0.57 | 0.53 |
| 1971 | 0.42 | 0.33 | 0.85 | 0.69 | 0.61 | 0.54 |
| 1972 | 0.43 | 0.32 | 0.83 | 0.72 | 0.57 | 0.50 |
| 1973 | 0.43 | 0.34 | 0.79 | 0.76 | 0.59 | 0.57 |
| 1974 | 0.46 | 0.33 | 0.82 | 0.81 | 0.63 | 0.57 |
| 1975 | 0.46 | 0.33 | 0.85 | 0.79 | 0.66 | 0.55 |
| 1976 | 0.50 | 0.33 | 0.78 | 0.77 | 0.66 | 0.55 |
| 1977 | 0.49 | 0.33 | 0.76 | 0.74 | 0.63 | 0.52 |
| 1978 | 0.51 | 0.31 | 0.80 | 0.74 | 0.65 | 0.53 |

Appendix D (continued)

Minimum earlywood density, maximum latewood density and percentage latewood for control plot (C) and Dunn Forest (S).

| | MED | | MLD | | PL | |
|---|---|---|---|---|---|---|
| | C | S | C | S | C | S |
| 1959 | 0.24 | 0.21 | 0.86 | 0.76 | 26.01 | 37.69 |
| 1960 | 0.27 | 0.19 | 0.92 | 0.77 | 28.54 | 42.96 |
| 1961 | 0.29 | 0.18 | 0.93 | 0.80 | 31.32 | 39.62 |
| 1962 | 0.29 | 0.20 | 0.99 | 0.81 | 40.14 | 48.52 |
| 1963 | 0.32 | 0.20 | 1.02 | 0.89 | 40.02 | 47.04 |
| 1969 | 0.33 | 0.20 | 0.95 | 0.81 | 40.14 | 47.11 |
| 1970 | 0.35 | 0.23 | 0.99 | 0.98 | 44.35 | 49.70 |
| 1971 | 0.36 | 0.25 | 1.17 | 0.97 | 45.41 | 47.58 |
| 1972 | 0.36 | 0.23 | 1.13 | 0.92 | 42.25 | 45.11 |
| 1973 | 0.37 | 0.26 | 1.06 | 0.94 | 44.78 | 46.26 |
| 1974 | 0.39 | 0.26 | 1.21 | 1.04 | 44.97 | 51.20 |
| 1975 | 0.39 | 0.27 | 1.24 | 1.03 | 52.10 | 46.02 |
| 1976 | 0.38 | 0.26 | 1.07 | 1.02 | 50.34 | 49.12 |
| 1977 | 0.39 | 0.25 | 1.04 | 0.95 | 51.70 | 46.57 |
| 1978 | 0.40 | 0.24 | 1.01 | 0.99 | 53.90 | 50.80 |