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The effect of thinning on loblolly pine specific gravity as measured by the gamma densitometry technique

Deborah D. McRae

To the Graduate Council:

I am submitting herewith a thesis written by Deborah D. McRae entitled "The effect of thinning on loblolly pine specific gravity as measured by the gamma densitometry technique." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Forestry.

Ronald L. Hay, Major Professor

We have read this thesis and recommend its acceptance:

John Rennie, Robert Little

Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

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We have read this thesis
and recommend its acceptance:

Robert L. Little

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Accepted for the Council:

L. Evans Roth

Vice Chancellor
Graduate Studies and Research

THE EFFECT OF THINNING ON LOBLOLLY PINE SPECIFIC GRAVITY AS MEASURED BY THE GAMMA DENSITOMETRY TECHNIQUE

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Deborah D. McRae

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ABSTRACT

Study objectives were to correlate the gamma densitometry technique with conventional methods of measuring specific gravity and to use the gamma densitometer to analyze a thinned loblolly pine (Pinus taeda L.) stand for earlywood specific gravity, latewood specific gravity, average specific gravity, percent latewood and radial growth.

In 1980 a 12 mm increment core was extracted from each of 160 sample trees in a 40 year old planted loblolly pine plantation which had been thinned in 1963 to residual basal area of 60 ft^2/acre, 100 ft^2/acre, and 140 ft^2/acre; the control plot was unthinned and had a basal area of 158 ft^2/acre. Two conventional specific gravity estimates were obtained for each core: (1) ovendry weight divided by green volume measured physically; (2) ovendry weight divided by green volume measured by water displacement. Average specific gravity values were also obtained by the gamma densitometer. The correlation of specific gravities between the gamma densitometer and the first conventional method was high: R^2 = .76. The specific gravity correlation between the gamma densitometer and the second conventional method was not as high: R^2 = .56. The specific gravity correlation between the two conventional methods was high: R^2 = .73.

The gamma densitometry technique also provided estimates of earlywood specific gravity, latewood specific gravity, as well as average specific gravity, percent latewood and radial growth. Significant differences were not found among basal area treatments for average specific gravity or percent latewood. However, earlywood specific gravity decreased significantly after thinning to 60 ft^2/acre and 100 ft^2/acre. Latewood specific gravity increased significantly after thinning to a basal area 60 ft^2/acre and 100 ft^2/acre. Radial growth of trees in plots thinned to 60 ft^2/acre and 100 ft^2/acre was significantly greater after thinning than that of trees in the 140 ft^2/acre and control plots.

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CHAPTER I

INTRODUCTION

Wood products are important to the U. S. economy; they have comprised 20 percent of all non-fuel industrial materials over the past 50 years (Clawson, 1974). Past emphasis in managing this renewable resource has been on quantitative properties such as better growth, adaptability, and disease resistance. However, as demands for forest products increase, yields can be optimized by emphasizing the qualitative as well as the quantitative properties of wood.

One important qualitative property of wood is its specific gravity. Among other things, specific gravity is a measure of fiber yield; that is, it is a measure of the actual mass of usable fiber per unit volume of wood. Since specific gravity is also a good indicator of drying behavior, hardness and strength, more awareness of specific gravity can increase efficient manufacture of forest products into appropriate wood products.

A wide range of specific gravity values can be found among the many commercially important species in this country; often a wide variety of specific gravity values is represented within one species as well. Furthermore, studies have shown that specific gravity can be influenced by silvicultural practices and genetic selection (Van Buijtenen, 1975).

The objectives of this study were: (1) to correlate the gamma densitometry technique with two conventional techniques of measuring specific gravity; and (2) to determine whether differing stand basal area affected the specific gravity and radial growth of a loblolly pine (Pinus taeda L.) stand at age 23 when treatment took place.

CHAPTER II

LITERATURE REVIEW

I. CAUSES OF WOOD SPECIFIC GRAVITY VARIATION

Wood quality refers to its suitability for fabrication into a variety of end-use products. Wood quality expression can take many forms, with straight stem form and amount of clear wood indicating wood quality for some products. For products requiring strength, such as structural timbers, quality can best be expressed through specific gravity. Specific gravity is the ratio of the density of wood to the density of water at 20° C. Since the density of water is 1 gram per cubic centimeter, then the specific gravity and density of wood are numerically equal when expressed in metric units.

The specific gravity and strength of wood are highly related; a 0.02 change in specific gravity is reflected in a change of about 1000 pounds per square inch in the modulus of rupture of clear wood specimens, based on established density-strength relationships for the southern pines (Mitchell, 1964). To pulp and paper manufacturers, specific gravity gives a good estimate of the expected fiber yield. An increase or decrease of only 0.02 in the specific gravity means a 100 pound (45 kgm) difference in the dry weight of a cord of wood, or a 50 pound (23 kgm) difference in the dry processed pulp obtained from that cord (Mitchell, 1964).

The specific gravity of mature loblolly pine wood varies from .40 to .68 due at least in part to the large amount of additive gene action (Zobel and McElwee, 1958). In an effort to regulate wood quality of loblolly pine for specific end-use products, researchers have attempted to identify causes of specific gravity variation and their importance to the forest manager. A few of the many variation sources which have been identified are: soil moisture, site index, age, geography and genetics, stand density and thinning.

Soil Moisture

In a study by Paul (1939), the average specific gravity for loblolly pine springwood (earlywood) was .310 and the summerwood (latewood) average was .625. Dense loblolly pine was a high percentage of summerwood, the thick-walled cells put on late in the growing season (Zobel and Rhodes, 1955). Larson (1957) found that variation in the percentage of summerwood accounted for about 60 percent of the total variation in the specific gravity of slash pine (*Pinus elliotti* Engelm.). Therefore, environmental characteristics that extend the growth period during which summerwood cells are formed are correlated with specific gravity.

Fluctuations in soil moisture and soil texture are noteworthy factors (Jayne, 1958). Gilmore et al. (1966) stated that soil moisture availability had the greatest effect on wood specific gravity; depth of rooting, depth to an impervious layer, silt plus clay of the 0-6 inch layer, and July rainfall were all important factors. Larson (1957) came to the same conclusion, namely June and

July rainfall in combination with depth to a fine-textured horizon accounted for 55 percent of the total specific gravity variation in slash pine summerwood. On deep sandy soils in Florida, summerwood growth was increased significantly in trees that were irrigated late in the growing season (Kerr, 1931).

Site Index

Site index has not been satisfactory for predicting the quality of wood a tree will produce. The better of two sites for red pine (*Pinus resinosa* Ait.) produced a greater volume of wood of lower specific gravity than a poorer site (Jayne, 1958). Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) on good sites were found by Wellwood (1952) to have significantly lower densities than those on average sites. Fielding and Brown (1960) concluded that differences in site quality within one locality were not associated with large differences in specific gravity for *Pinus radiata*. Similarly Zobel and Rhodes (1955) could find no correlation between site index and specific gravity of loblolly pine.

Age

Previous failures to recognize the effects that age of the cambium at the time of wood formation had on its specific gravity led many to the conclusion that specific gravity was mostly controlled by growth rate. Juvenile loblolly wood (wood near the pith) has wide growth rings, very little summerwood, short tracheids and low specific gravity compared to mature wood (Goggans, 1961; Zobel et al., 1959). It had been shown that specific gravity significantly increased radially from the pith and when this effect was removed statistically, growth rate (or ring width) could not account for specific gravity variation (Yandle, 1956). In other words, specific gravity increased as the cambium matured, regardless of growth rate (Ralston and McGinnes, 1964). In addition, Okkonen et al. (1972) observed an overall decrease in specific gravity with an increase in stem height. Zobel et al. (1972) estimated the average specific gravity of the entire merchantable bole of loblolly pine to be .43 at ages 15 to 19 years, then .46 at ages 20 to 29 years before stabilizing at .47 beyond 30 years.

Geographic and Genetic Variation

Several wood density surveys have indicated that certain geographic trends occur in specific gravity of southern pines. Larson (1957) found that summerwood percentage increased along north to south and west to east gradients within the slash pine range. Mitchell (1964) came to the same conclusion for loblolly pine in Mississippi. Loblolly pine wood specific gravity was highest in the southern and coastal states and it decreased northward and inland (Saucier and Taras, 1969; Zobel et al., 1972). In the Coastal Plain, wood density decreased from south to north with the greatest decrease being in the northern areas. In the Piedmont, density was relatively constant along a north to south gradient, but it was almost always lower than that obtained in comparable regions of the Coastal Plain (Zobel et al., 1972).

Tree-to-tree variation, however, in the density of mature wood is always much greater than the variation between regions or sites (Zobel and McElwee, 1958; Whitesell et al., 1966). Zobel et al. (1972) predicted that significant increases in wood specific gravity will be made by selecting and propagating desirable individuals rather than relying upon certain seed sources. Since the narrow sense heritability (ratio of genetic variation to total variation)for specific gravity is high, good gains can be obtained by selection and breeding of desired parent trees (Van Buijtenen, 1975; Stonecypher and Zobel, 1966).

Stand Density

The effect that various stand densities have on loblolly pine specific gravity is not clear. The existence of an optimum level of site utilization (in terms of stand density) with respect to wood quality is suggested in a study by Hamilton and Matthews (1965). In loblolly and shortleaf pine (*Pinus echinata* L.) plantations, 5 x 5 foot (1.5 x 1.5 m) spacings produced trees with higher specific gravity than 4, 6, 7 or 8 foot (1.2, 1.8, 2.1 or 2.4 m) spacings.

However, specific gravity may be increased by planting seedlings at wide spacings where soil moisture reaches critically low levels during the growing season. In southern Illinois, Geyer and Gilmore (1965) found significant differences in specific gravity due to spacing based on whole increment core values, but there were no differences in mature wood densities. Since the differences observed were only in the juvenile wood, the effects of stand density would probably disappear with the accretion of additional mature wood.

Jayne (1958) found only a slight relationship between stand density and specific gravity in red pine. But many others could find no evidence that stand density and specific gravity were related (Echols, 1959; Zobel, 1956; Zobel et al., 1965).

Effect of Thinning

One thinning objective in a timber stand is to reduce competition for light, soil moisture and nutrients so that the residual trees can grow rapidly. Studies involving the effect of this silvicultural practice on the specific gravity of wood have not been conclusive. Thinning has caused a slight decrease in specific gravity (Ericson, 1966; Paul, 1941), but Smith (1968) reported that heavy thinning and pruning of a nine year old loblclly pine stand produced wide growth increments with significantly higher specific gravity than that produced in unthinned stands. Similar results were found by Lowery and Schmidt (1967) for western larch (*Larix occidentalis* Nutt.) crop trees and by Paul (1957) in a red pine plantation. Thinning did not influence specific gravity in a Georgia loblolly pine stand (Jackson, 1968) or in ponderosa pine (*Pinus ponderosa* Laws.) (Myers, 1960).

Paul (1958) suggests that abrupt changes in the growing space of southern pine stands may affect in different ways the specific gravity of the wood. The first effect of release could be that greater amounts of soil moisture become available. This condition is favorable to the growth of summerwood which is more dense than springwood and thus raises the specific gravity. But as the tree crown receives more sunlight, the availability of water and nutrients causes the crown to expand and the foliage to become more vigorous and active. The enlarged crowns produce springwood more abundantly, and since springwood is less dense than summerwood, specific gravity decreases. Thus, specific gravity fluctuates according to how environmental factors are balanced for springwood or summerwood formation.

II. TECHNIQUES FOR MEASURING WOOD SPECIFIC GRAVITY

If specific gravity is to be a reliable indicator of wood quality, it is imperative that accurate, repeatable estimates be determined easily and on a large scale. Consequently many methods for determining specific gravity have been developed.

Specific gravity is usually expressed as a ratio of weight of the wood to the weight of an equal volume of water. Ovendry weight is always used because it can be reproduced experimentally, but the wood volume will vary depending on its moisture content. When the green volume is measured, the ratio is called basic specific gravity; it is one of the most commonly cited values.

Volumetric

Of the many methods for specific gravity determinations, the weight/volume method is perhaps the least complicated. Wood volume may be physically measured, but this works well only for easily measurable shapes such as increment cores or smoothly sawn blocks

(Walters and Bruckman, 1964). The volume of irregularly shaped pieces of wood must be found another way.

Several immersion methods have been developed to determine the volume of an irregular piece of wood or the weight of that volume by liquid displacement (Miller and May, 1958; Smith, 1961; Heinrichs, 1954). This procedure works especially well for saturated wood. When wood that is below the fiber saturation point is immersed in water, erroneous volumes may be measured because water will be absorbed into the wood. To minimize this loss of water volume, other displacement fluids have been used. Weatherwax and Tarkow (1968) found that hexane was least absorbed compared to water and alcohol. Mercury has been used as a displacement fluid (Yao, 1968), however, incomplete contact of mercury with small wood samples caused errors (Smith, 1954).

Maximum Moisture Content

Since the volume measurements of small wood samples are usually the least accurate and most difficult to obtain, a method for determining wood specific gravity that eliminates the need to find the sample volume has been developed. The technique is founded upon the relationship between the maximum moisture content of the wood and its specific gravity as shown in the following equation (Smith, 1954):

$$G_f = \frac{1}{M_{max} + \frac{1}{G_{so}}} \qquad (1)$$

$$M_{max} = \frac{m_m - m_o}{m_o}$$

where

G_f = specific gravity based on green volume.

M_{max} = maximum water content in grams of water per gram of ovendry wood.

G_{so} = specific gravity of wood substance comprising the cell walls.

m_m = mass of water saturated wood in grams.

m_o = mass of ovendry wood in grams.

Since Stamm (1929) has shown that the density of wood substance comprising the cell wall is relatively constant at 1.53, the ovendry and the completely saturated sample weights are all that need to be obtained. These values are then placed into the equation to determine the specific gravity based on the green volume. A tabular aid developed by Fogg (1967) further reduced the complexity of determining specific gravity. Once the ratio of the saturated weight to the ovendry weight is determined, the corresponding specific gravity can be readily obtained from the table.

Indirect Measurement by X-ray, Beta-ray, Gamma-ray

In an effort to facilitate specific gravity determinations, much attention has been given to developing the rapid, non-destructive methods of testing wood properties with radiation techniques. These radiation techniques exploit the relationship between density, thickness, and chemical consistency of wood, and the amount of energy the wood absorbs. The following equation defines this relationship (Loos, 1961; Kleuters, 1964);

$$\frac{I}{I_o} = e^{-\mu_m \rho t} \qquad (2)$$

where

I = intensity of radiation beam after passing through the wood (expressed in counts).

I_o = initial intensity of radiation beam.

e = base of the natural logarithmic system.

μ_m = mass attenuation coefficient for a given radiation wavelength and absorbing material (cm^2/g).

ρ = density of sample (g/cm^3).

t = thickness of sample (cm).

Polge (1963, 1970) was one of the first to use X-rays to determine wood density. His technique involved producing an X-ray image of the wood on film and then analyzing the film with a microdensitometer. This instrument converted the optical density of the film into a value for the physical density of the sample. Echols (1972) modified the technique by mounting the sample on a carrier which moved the sample through a beam of collimated X-rays. This removed the parallax distortions produced when source and sample are fixed. Parker and Jozsa (1973) reported that factors affecting the quality of the X-ray negative (and subsequently the ability to determine wood density) are the following:

a. fluctuations in supply voltage to the X-ray generator,

b. size of the beam restricting slit,

c. moisture content of wood,

d. lack of uniformity in sample thickness,

e. film processing methods, and

f. sample preparation techniques.

High quality radiographs can be made, however, when there is a stable supply of X-rays, constant scanning speed and the X-ray beam penetrates and sample in a direction parallel to wood grain.

When radioisotopes replaced X-ray machines as a source of radiation, the need to take a film image of the wood was eliminated. Instead, a scintillation detector placed in the path of the gamma or beta field measured the intensity of the radiation beam after it passed through the wood. Harris (1969) used the beta emitters, ^{90}Sr and ^{14}C effectively to determine wood densities. A chart recorder was used to plot the count rate as the sample moved through the radiation beam. These charts were compared to the chart of a standard (step wedge) to determine the density of the wood. Harris' technique provided detail on density not readily available with conventional methods (such as latewood density within one growth ring).

Some gamma emitters (^{55}Fe, ^{60}Co, and ^{241}Am) have proven to be useful radiation sources. A gamma densitometer using ^{55}Fe was developed by Woods and Lawhon (1974), which produced digital output of the data on punched paper tape as well as a graphic representation with a strip chart recorder. Measured values of thickness and μ_m were used in a computer program to solve Equation 2 for density values.

CHAPTER III

MATERIALS AND METHODS

I. TEST DESCRIPTION

The experimental site was The University of Tennessee Friendship Forest Experimental Area in Hamilton County, Tennessee. Friendship Forest is about 19 kilometers northeast of Harrison, Tennessee at an elevation of 244 meters. The test plots were on a moderate, southeast slope ranging from 2 to 12 percent. The predominant soils on the area are Cumberland, Etowah, Fullerton and Huntingdon which all showed moderate to severe sheet erosion. Numerous gullies are still evident although most of them seem to be stabilized by old brush dams and pine trees.

The test area was planted to loblolly pine at about 1200 trees per acre (2965 trees per hectare) during 1940 by the Civilian Conservation Corps. In 1963 a thinning study was established in the resulting pine stand. A randomized complete block design was used with four replications and four treatments per replication. Each replication contained 3 treatment plots 3721 square meters (.3718 hectare) and 1 control plot 61 meters by 30.5 meters (.1859 hectare) (Figure 1). The treatments were three levels of residual basal area as shown in Table 1.

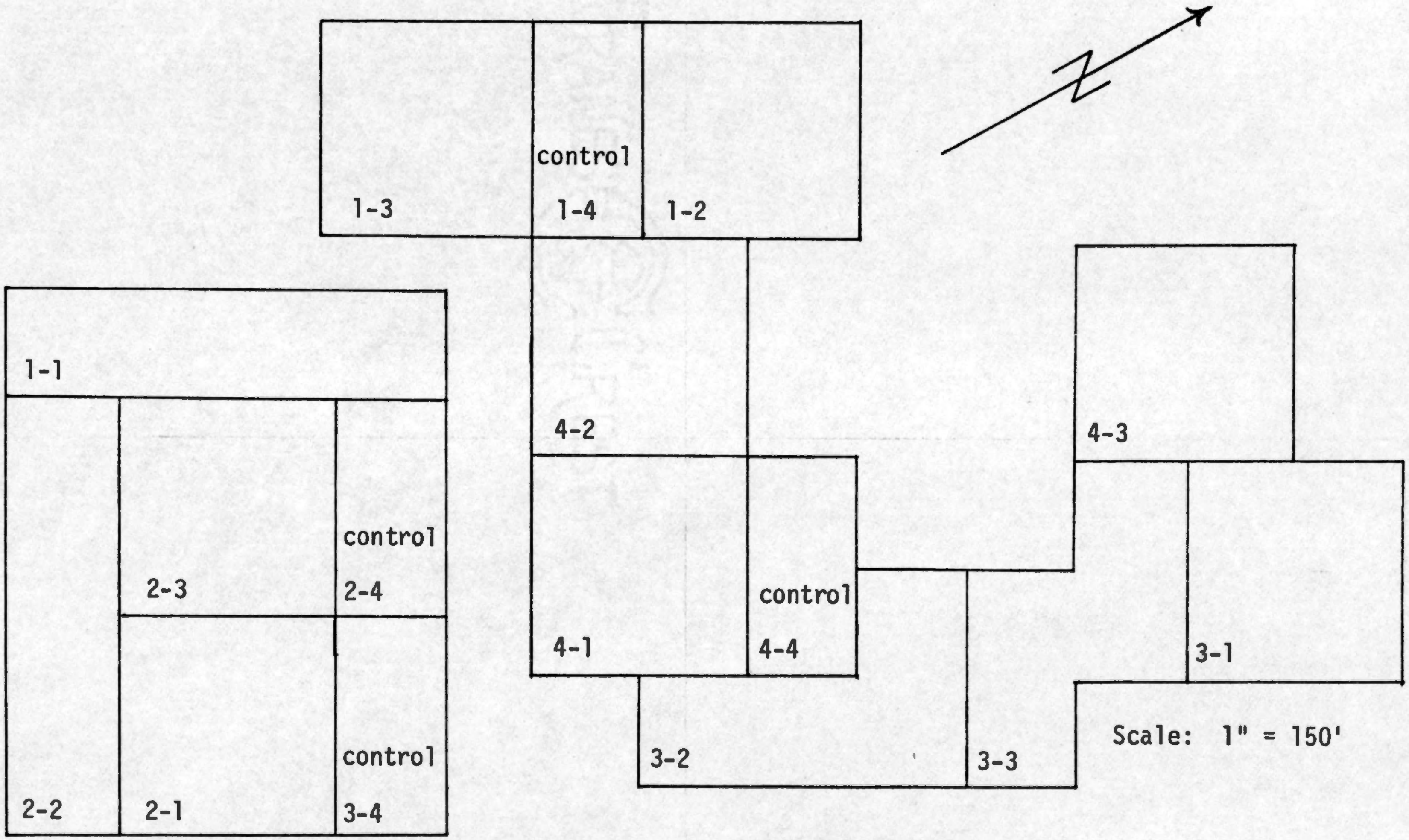

Figure 1. Plot layout of thinning study.

Table 1. Levels of thinning applied to the loblolly pine stand in 1963.

Treatment No.	Residual Basal Area (ft^2/acre)	Residual Basal Area (m^2/hectare)
1	60	13.8
2	100	23.0
3	140	32.1
4	No thinning	No thinning

II. MEASUREMENTS

The center of each plot was located and the 10 suitable trees nearest the center of the plot were sampled. Suitable trees were those without defects indicating disease or mechanical damage and without severe crook or sweep.

A 12 millimeter (mm) increment core was extracted from each sample tree. All trees were bored parallel to the land contour (avoiding knots) at breast height (1.37 m). The cores were sealed in plastic tubes and refrigerated until volume measurements could be determined.

A portion of the increment core representing years 1956 through 1971 was separated from the rest of the core. This portion corresponds to 8 years before and 8 years after treatment, the section to be used in the analysis. Three specific gravity determinations were made for each core: (1) ovendry weight divided by physical measurement of green volume; (2) ovendry weight divided by water displacement measurement of green volume; and (3) average specific gravity determined by the gamma densitometer.

For the first specific gravity measurement, the volume of the increment core was determined by using the formula for the volume of a cylinder:

$$V = \pi \left(\frac{d}{2}\right)^2 L$$

where

V = volume of a cylinder.

d = diameter of the increment core.

L = length of the core.

For the second specific gravity measurement, volume was found by water displacement. Since 1 gram of water occupies 1 cubic centimeter, the volume of each core was found by measuring the weight of water displaced when the core was held submerged in a graduated cylinder full of water on a top-loading balance. The cores were then oven dried for 24 hours at approximately 105° C. The first two specific gravity determinations were then calculated for each increment core by dividing the ovendry weight with the values for green volume.

The cores were allowed to equilibrate with the moisture content of the laboratory before being prepared for measurement by the gamma densitometry technique. The increment cores were mounted between two blocks of wood so that they could be cut into strips approximately 1 mm thick. The samples were cut radially using two parallel mounted, hollow-ground circular saw blades.

The density of the samples was then found using the gamma densitometer. The technique is a modification of that developed by Woods and Lawhon (1974). Wood samples were passed in front of a highly collimated beam of ^{55}Fe gamma radiation by using a stepping motor and worm gear to move the samples. A two second count was taken, and the sample was moved one step over. Another two second count was taken and the sample was moved another step over. This way the sample was completely scanned one step at a time.

The gamma source used was 100 millicurie (mCi) ^{55}Fe with an energy of 0.0059 million electron volts (MeV) and a half-life of

2.6 years. The scintillation detector was a sodium iodide crystal encased in brass and fitted with a beryllium window. An adjustable collimator in front of the detector restricted the scanning field to 0.127 mm by 1.8 mm. Power for the detector came from a Tennelec TC 941 high voltage power supply.

Light signals from the detector passed into a Tennelec TC 154 photo-multiplier tube and were converted into electrical impulses. These impulses were fed into a Tennelec TC 216 linear amplifier and single channel analyzer which measured the pulse height. The pulses were then counted on a Tennelec TC 592P digital ratemeter and digital output was obtained by routing the signal through a Tennelec TC 570 automatic recycle control and teletype interface to a Teletype 33 Teletypewriter, which punched the output on paper tape (Lawhon, 1973). The data from the paper tape were then read into the Decsystem-10 computer and stored on IBM disk.

The relationship between count rates obtained by the gamma densitometer and density is shown in the following equation:

$$\frac{I}{I_o} = e^{-\mu_1 t}$$

where

I = intensity of the gamma ray beam after passing through the wood (counts).

I_o = intensity of the gamma ray beam before passing through the wood (counts).

e = base of the natural logarithm system.

t = absorber thickness (cm).

μ_l = linear absorption coefficient (cm^{-1}).

and

$$\mu_l = \mu_m \times \rho$$

where

μ_m = mass absorption coefficient (cm^2/g).

ρ = density (g/cm^3).

The mass absorption coefficient was assumed to be constant and its value was found by regressing the mean linear coefficient for each sample against the specific gravity value measured by the volumetric method (ovendry weight divided by physical measurement of green volume; see Figure 2). Using the resulting regression equation of Y = 0.03389 (X) + 0.14755, the linear coefficient values were converted to specific gravity values.

Using the Statistical Analysis System (SAS·79) formulated by Barr et al. (1979), programs were written to create data sets containing the various response variables that were of interest for analysis. Growth rings were counted by identifying the minimum points in each sample (Figure 3). Using the growth rings as a counter, each sample was divided into two time regions: Time 1 = eight growth rings before thinning, Time 2 = eight growth rings after thinning. Earlywood density was defined as the average of minimum values for each sample and time region. The average density was defined as the average of all points for each sample and time region. Percent latewood, however, was defined as that percent of the growth ring with density values above the midpoint density for each ring. Radial

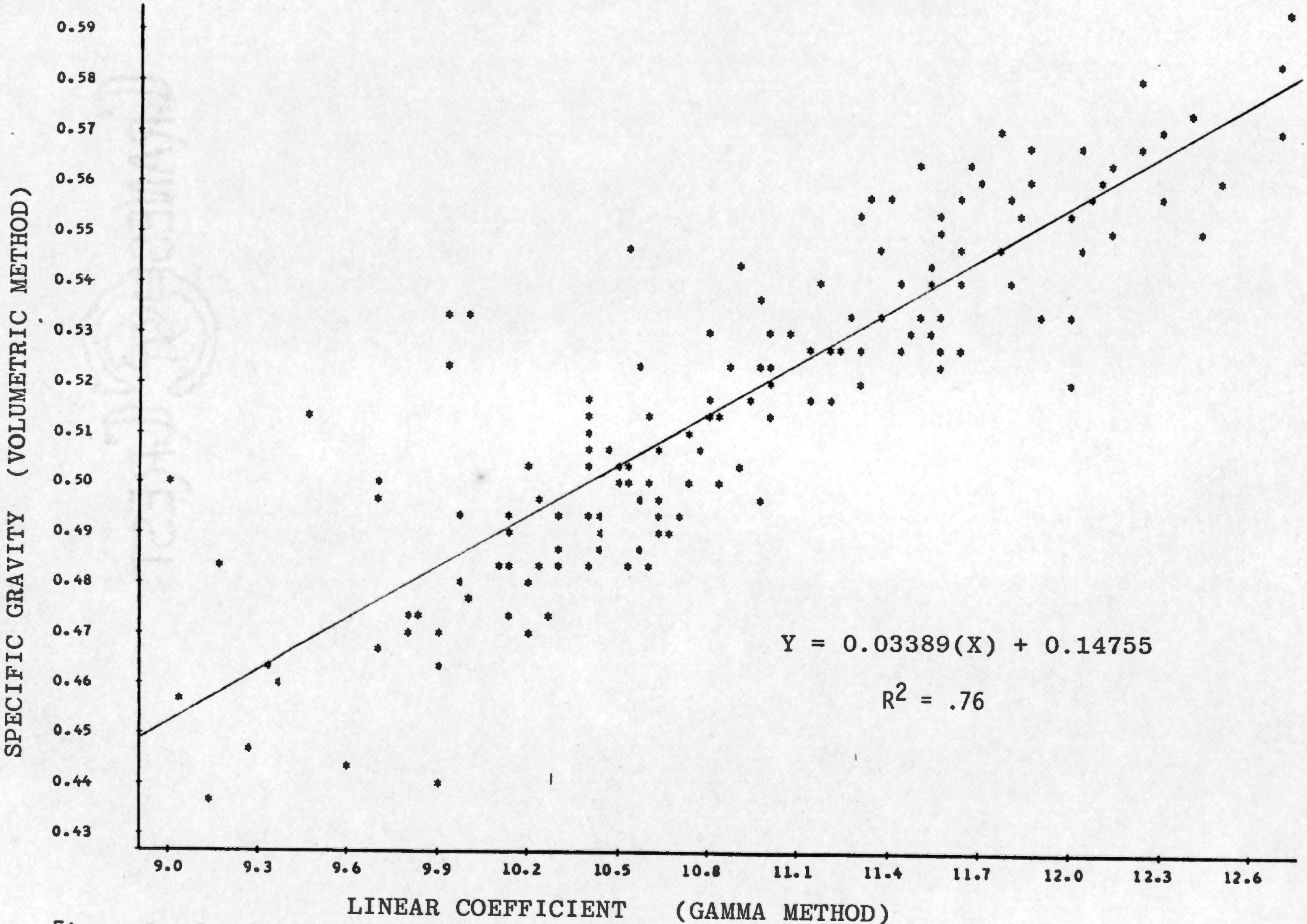

Figure 2. Specific gravities of 160 loblolly pine increment cores (growing seasons 16 through 31) regressed against the corresponding linear coefficients.

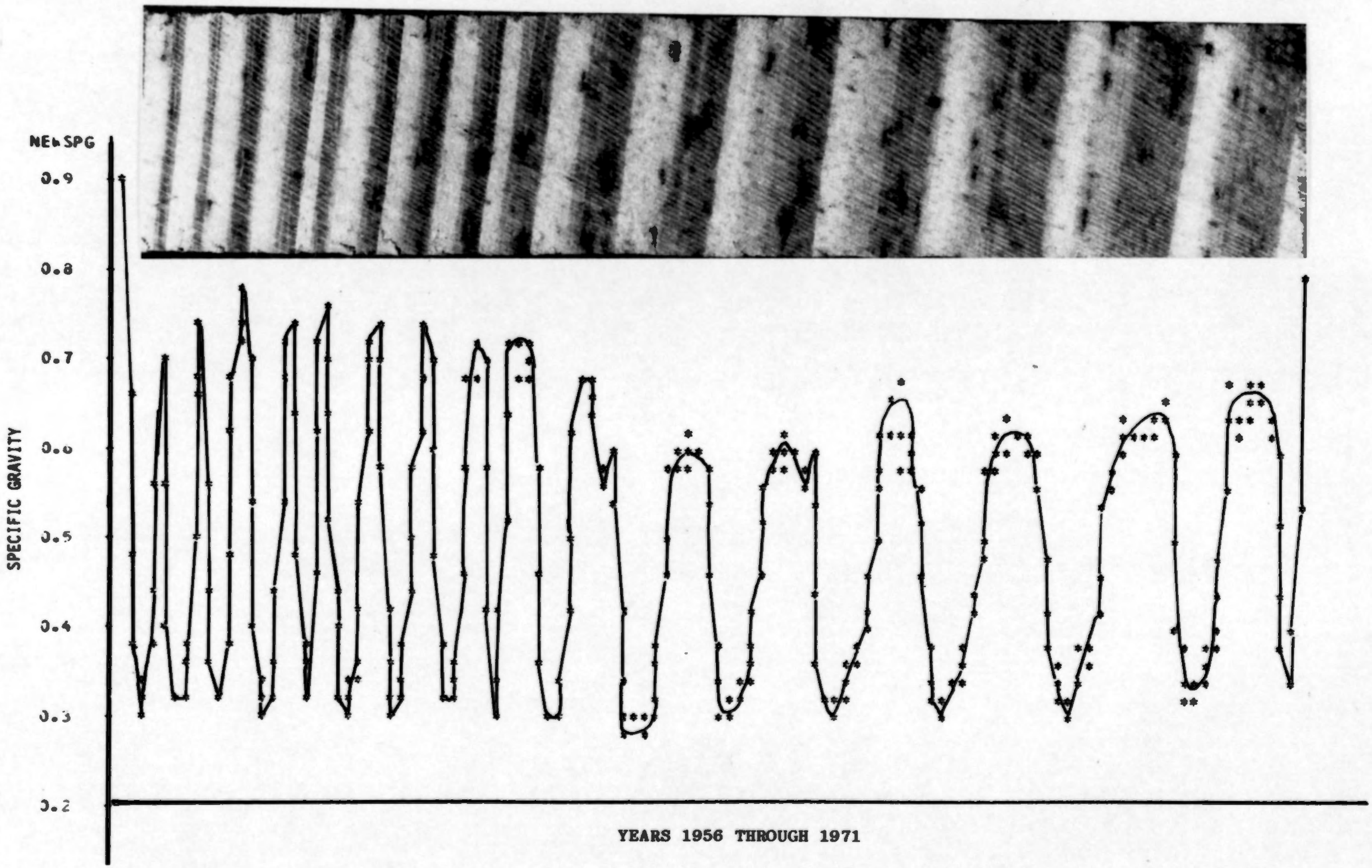

Figure 3. Loblolly pine increment core (growing seasons 16 through 31) and corresponding specific gravity variation.

growth was defined simply as the length in centimeters of the time regions in each sample.

The volume of wood produced for each treatment during the 16 years of growth being considered was compiled using data collected by Agricultural Experiment Station personnel. Diameters to the nearest 1/10 inch (1/4 centimeter) and heights to the nearest 1/10 foot (3/1000 meter) were measured on 1/50 acre (1/124 ha.) plots (32 per treatment) established in 1963, and remeasured in 1972. Individual tree volumes to a 3 inch (8 cm) top were computed using a volume prediction equation developed by Smalley and Bower (1968). Heights in feet and diameters in inches were converted to their metric counterparts before being used in the following equation:

$$V = 0.00003782(D^2H) - 0.00297609$$

where

V = volume in cubic meters.

D = diameter at breast height (dbh) in centimeters.

H = total tree height in meters.

Table 2 presents the conversion to this equation from the original formula which computed volumes in cubic feet.

III. STATISTICAL ANALYSIS

The experiment was designed to determine whether thinning levels had a significant effect on the following response variables:

Earlywood specific gravity

Latewood specific gravity

Average specific gravity

Table 2. Conversion of volume equation to compute volume in metric units.

Equation		Calculations
Vol (ft^3)	=	$a + b(D_{in})^2 (H_{ft})$
$D_{(in)}$	=	$D_{cm} / 2.54$
$D_{(ft)}$	=	$H_m * 3.28084$
Vol (ft^3)	=	$a + b (D_{cm} / 2.54)^2 (H_m * 3.28084)$
Vol (ft^3)	=	$a + (b * 3.28084/2.54^2) (D_{cm})^2 (H_m)$
Vol (m^3)	=	0.0283168 * Vol (ft^3)
Vol (ft^3)	=	35.3198 * Vol (m^3)
Vol (m^3) * 35.3198	=	$a + (b * 3.28084/2.54^2) (D_{cm})^2 (H_m)$
Vol (m^3)	=	$[(a * 0.0283168) + (b * 3.28084 * 0.0283168/ (2.54)^2) (D_{cm})^2 (H_m)]$
IF a	=	-.1051[a] b = .0026271[a]
Then a'	=	-.00297609 b' = .00003782
Hence		
Vol (m^3)	=	.00003782 (D^2H) - .00297609

[a]From Smalley and Bower (1968), Table 9, page 10, outside bark volume to a 3.0 inch top.

Percent latewood

Radial growth

The linear model for the Analysis of Variance (ANOVA) is the following:

$$Y_{rtsiw} = M + R_r + T_t + RT_{rt} + S/RT_{s/rt} + I_i + TI_{ti} + RI_{ri} + RTI_{rti} + E_w$$

where

Y_{rtsiw} = individual observation.

M = mean.

R_r = replication effect, with r = 1,2,3, . . ., j, and j = number of replications represented.

T_t = main treatment effect, with t = 1,2,3, . . ., k, and k = number of treatments represented.

$S/RT_{s/rt}$ = effect of sample within replication and treatment interaction, with s = 1,2,3, . . ., p, and p = number of samples represented.

I_i = sub-plot treatment effect (time), with i = 1,2,3, . . ., m, and m = number of sub-plot treatments represented.

TI_{ti} = interaction effect of main treatment and sub-treatment.

RI_{ri} = interaction effect of replication and sub-treatment.

RTI_{rti} = interaction effect of replications, main treatments and sub-treatment.

E_w = residual error.

The ANOVA model used is presented in Table 3.

Table 3. Source of variation, degrees of freedom and expected mean squares for five response variables.

Source of Variation	d.f.	Expected Mean Squares[a]
Replication	r-1	$\sigma_s^2 + s\sigma_{RT}^2 + t\sigma_R^2$
Treatment	t-1	$\sigma_s^2 + s\sigma_{RT}^2 + r\sigma_T^2$
Replication x Treatment	(r-1)(t-1)	$\sigma_s^2 + s\sigma_{RT}^2$
Sample / Replication x Treatment	(s-1)rt	σ_s^2
Time	(i-1)	$\sigma_w^2 + w\sigma_{RTI}^2 + t\sigma_{RI}^2 + r\sigma_{TI}^2 + rt\sigma_I^2$
Treatment x Time	(t-1)(i-1)	$\sigma_w^2 + w\sigma_{RTI}^2 + r\sigma_{TI}^2$
Replication x Time	(r-1)(i-1)	$\sigma_w^2 + w\sigma_{RTI}^2 + t\sigma_{RI}^2$
Replication x Treatment x Time	(r-1)(t-1)(i-1)	$\sigma_w^2 + w\sigma_{RTI}^2$
Residual	(w-1)(i-1)rt	σ_w^2

[a]Explanation of symbols:

σ_w^2 = residual variance component.

σ_{RTI}^2 = variance component for replication with treatment and time interaction.

σ_{RI}^2 = variance component for replication and time interaction.

σ_{TI}^2 = variance component for treatment and time interaction.

σ_I^2 = among time variance component.

σ_{RT}^2 = variance component for replication and treatment interaction.

σ_T^2 = among treatment variance component.

σ_R^2 = among replication variance component.

All calculations were performed on an IBM 370 model 3031 computer at The University of Tennessee, Knoxville. The Analysis of Variance Procedure in SAS·79 was used to compute F values used in testing for significance. Mean separation of significant effects was determined by Duncan's New Multiple Range Test. Simple linear regression was used to correlate the density values of the gamma densitometry technique with the density values obtained by the two conventional methods.

CHAPTER IV

RESULTS

I. RESPONSE VARIABLES MEASURED BY GAMMA DENSITOMETER

Degrees of freedom, mean squares and levels of significance for the five response variables measured (earlywood specific gravity, latewood specific gravity, average specific gravity, percent latewood and radial growth) are presented in Table 4.

Earlywood Specific Gravity

Significant differences ($P < 0.05$) among residual basal area treatments were found for earlywood specific gravity. Mean separation by Duncan's New Multiple Range Test is presented in Table 5. The earlywood specific gravity for the control plots and 140 ft^2/acre (32.1 m^2/ha) plots were not significantly different. The earlywood specific gravity on the 100 ft^2/acre (23.0 m^2/ha) plots was significantly lower; and the earlywood specific gravity on the 60 ft^2/acre (13.1 m^2/ha) plots was the lowest of all.

Mean earlywood specific gravity before thinning (.425) differed significantly ($P < 0.01$) from earlywood specific gravity after thinning (.408). Significant differences ($P < 0.01$) were found for the treatment x time interaction. Figure 4 illustrates these relationships. After thinning, earlywood specific gravity decreased significantly on the 60 ft^2/acre plots and 100 ft^2/acre plots.

Table 4. Degrees of freedom, mean squares and levels of significance for wood characteristics measured with the gamma densitometer.[a]

Source of Variation	df	Early-wood Sp Gr	Late-wood Sp Gr	Aver-age Sp Gr	% Late-wood	Radial Growth
Replication	3	10.41	7.21	3.39	69.46	0.59
Treatment	3	19.53*	61.89	1.66	70.14	4.72*
Replication x Treatment	9	4.48	24.14	4.65	92.71	0.74
Sample/ Treatment x Replication	144	3.22	4.98	1.30	44.39	0.36
Time	1	22.81**	367.38**	18.59**	6.67	1.83*
Treatment x Time	3	12.32**	42.72**	0.31	63.78	4.54**
Replication x Treatment x Time	12	1.17	3.19	0.62	25.10	0.17
Residual	144	1.00	1.65	0.25	15.99	0.11

*$P < 0.05$.

**$P < 0.01$.

[a]Specific gravity mean squares presented times 1000.

*Probability of obtaining a significant result is less than 5 chances out of 100.

**Probability of obtaining a significant result is less than 1 chance out of 100.

Table 5. Duncan's New Multiple Range Test of mean earlywood specific gravities for four thinning levels.

Thinning Level (Residual Basal Area)	Mean Earlywood Specific Gravity[1]	
NONE (158 ft^2/acre)	.4354	a
LIGHT (140 ft^2/acre)	.4224	a
MODERATE (100 ft^2/acre)	.4097	b
HEAVY (60 ft^2/acre)	.3993	c

[1]Means with same letter are not significantly different from each other ($P < 0.05$).

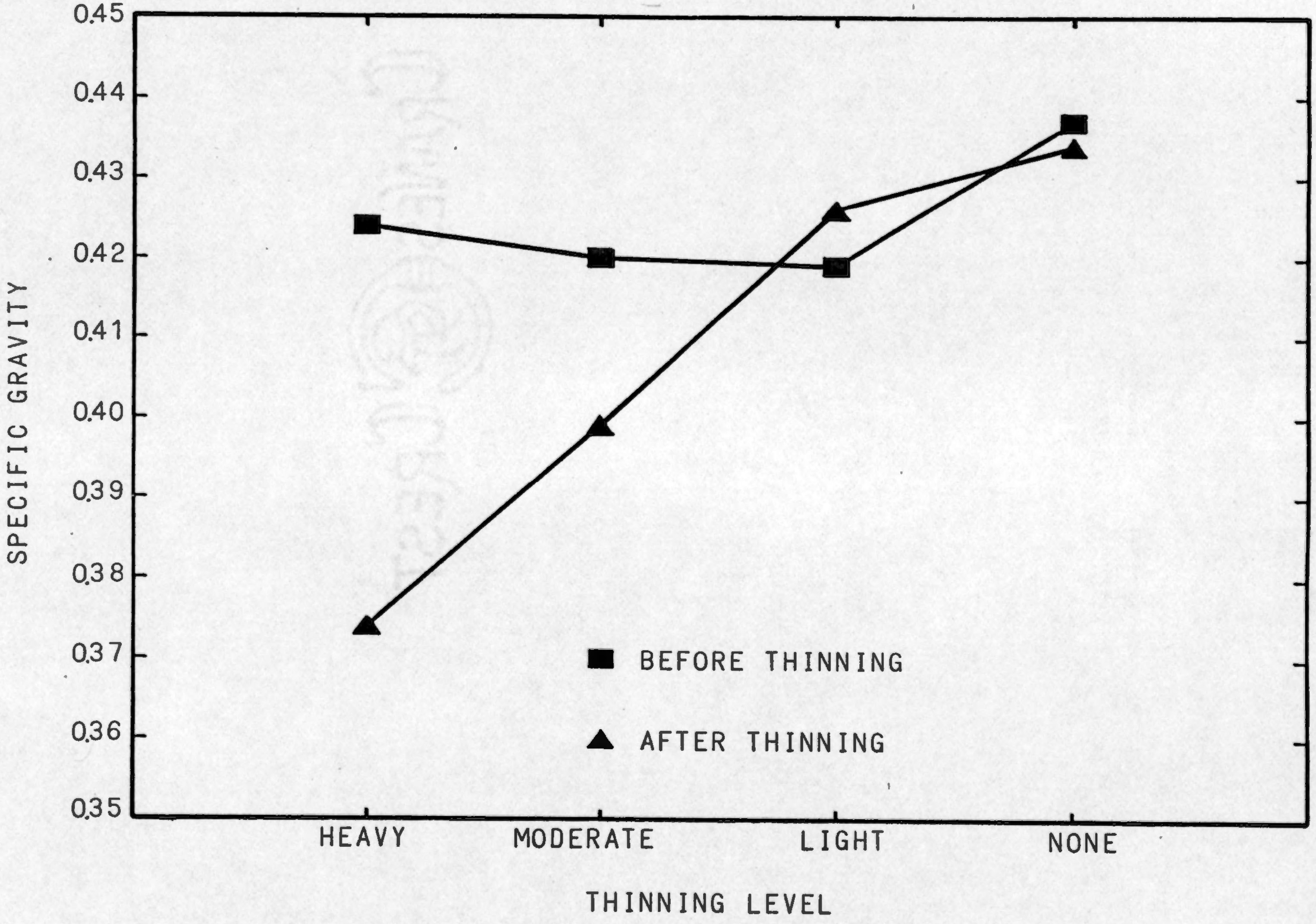

Figure 4. Earlywood specific gravity before and after thinning for each thinning level.

Earlywood specific gravity did not change significantly after thinning on the 140 ft^2/acre and control plots.

Latewood Specific Gravity

Significant differences ($P < 0.01$) were found before and after thinning for latewood specific gravity; the mean before thinning was .576 and after thinning it was .643. Figure 5 illustrates that latewood specific gravity increased significantly after thinning on the 60 ft^2/acre and 100 ft^2/acre plots, but only a slight increase in latewood specific gravity was detected on the 140 ft^2/acre and control plots.

Average Specific Gravity

Significant differences among treatments or the treatment x time interaction were not apparent for average specific gravity. Significant differences occurred before and after thinning; mean specific gravity before thinning was .509 and after thinning it was .525. Figure 6 shows that the average specific gravity was greater after thinning for all treatments.

Percent Latewood

No significant differences for percent latewood were found.

Radial Growth

Significant differences ($P < 0.05$) were found among treatments for radial growth. Mean separation by Duncan's New Multiple Range Test is presented in Table 6. Radial growth was significantly greater

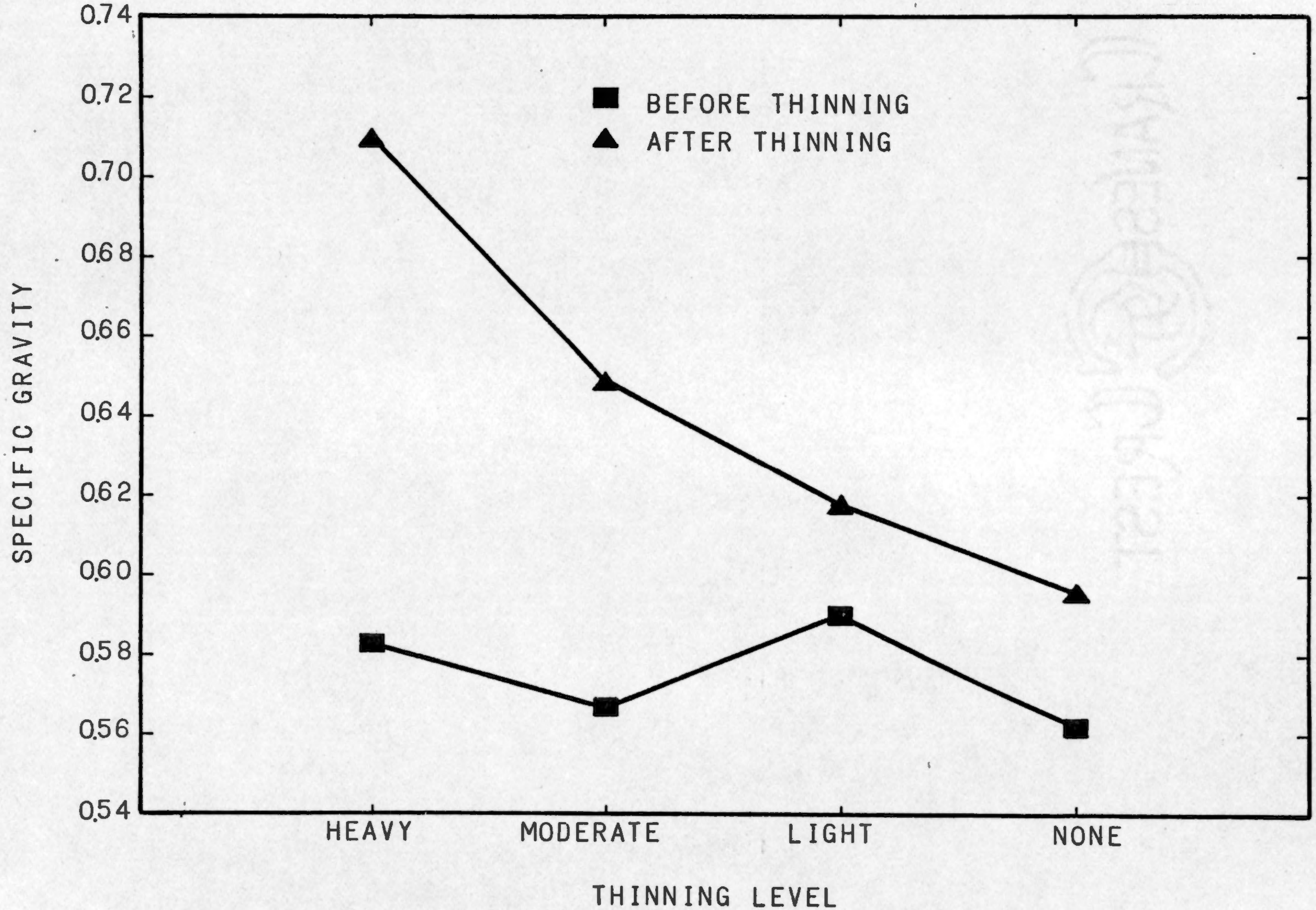

Figure 5. Latewood specific gravity before and after thinning for each thinning level.

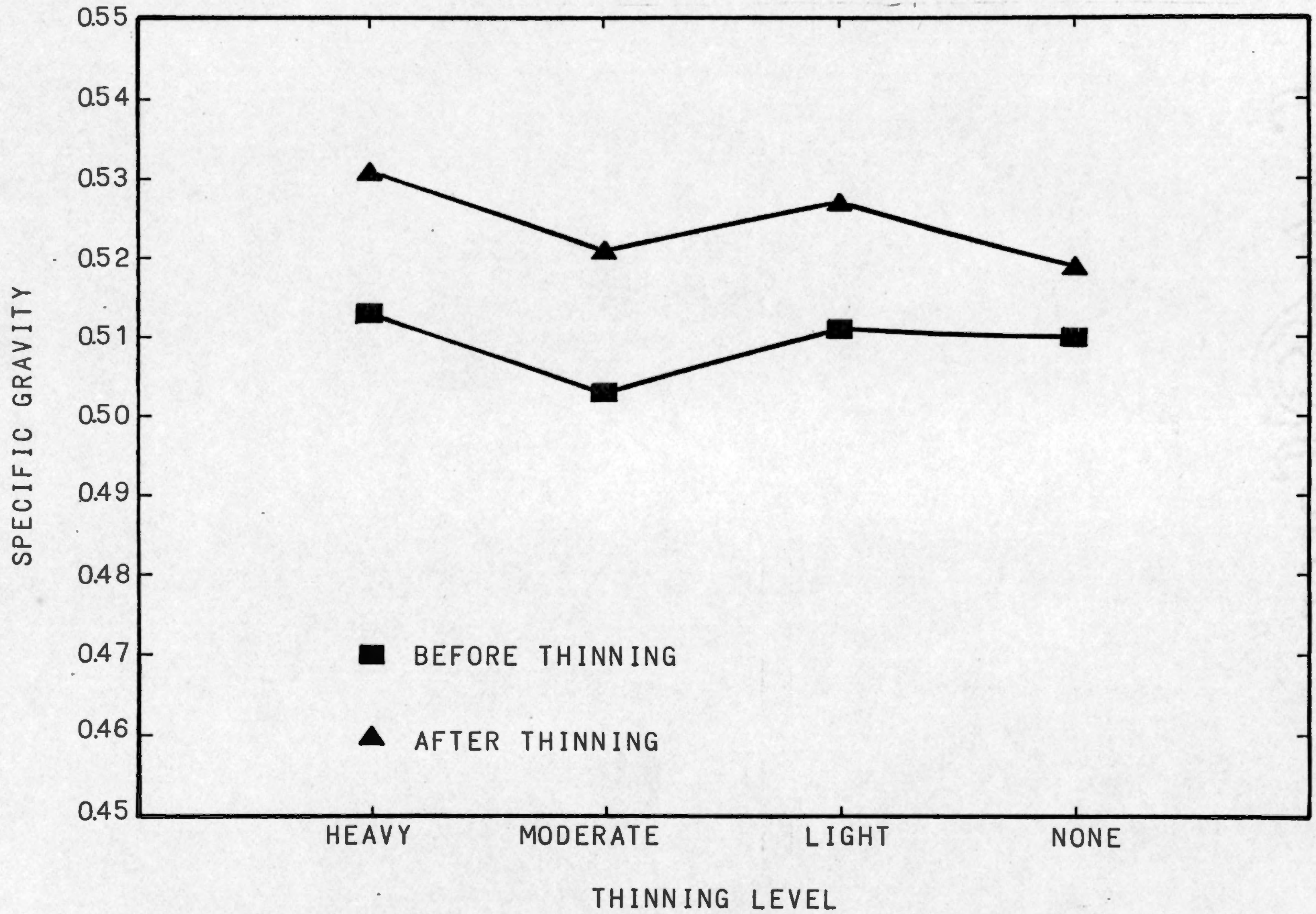

Figure 6. Average specific gravity before and after thinning for each thinning level.

Table 6. Duncan's New Multiple Range Test of mean radial growth for four thinning levels.

Thinning Level (Residual Basal Area)	Mean Radial Growth[1] (cm)	
HEAVY (60 ft^2/acre)	1.850	a
MODERATE (100 ft^2/acre)	1.495	b
LIGHT (140 ft^2/acre)	1.395	b
NONE (158 ft^2/acre)	1.265	b

[1]Means with same letter are not significantly different from each other ($P < 0.05$).

on the 60 ft^2/acre plots. There were no significant differences in radial growth among the other three residual basal area treatments.

Differences in radial growth before and after thinning were also significant ($P < 0.05$); the mean width (for all treatments) of the 8 year growth increment before thinning was 1.56 cm and after thinning it was 1.45 cm. Normally a tree's radial growth slows down (annual rings become narrower) with advancing age. The control plots and 140 ft^2/acre plots both exhibit such a decline in radial growth for the second 8 year growth period. Trees on the 100 ft^2/acre plots decreased only slightly in radial growth after thinning. However, radial growth of trees on the 60 ft^2/acre plots actually increased after thinning (see Figure 7).

II. HEIGHT, DIAMETER AND VOLUME INCREMENT FROM 1963 TO 1972

Table 7 presents treatment summaries for diameter (cm), height (m) and volume (m^3/ha) in 1963 (the year thinning took place) and in 1972 (8 years after thinning). Although heights were nearly the same for all treatments, diameter growth was the greatest on the 60 ft^2/acre plots. Volume was maximized on the 140 ft^2/acre and control plots. Diameter, height and volume growth increase percentages from 1963 to 1972 are also presented in Table 7. The 60 ft^2/acre plots had the greatest percentage increase in volume (116 percent) and diameter (25 percent). The 140 ft^2/acre and control plots had the greatest increase in height (34 percent).

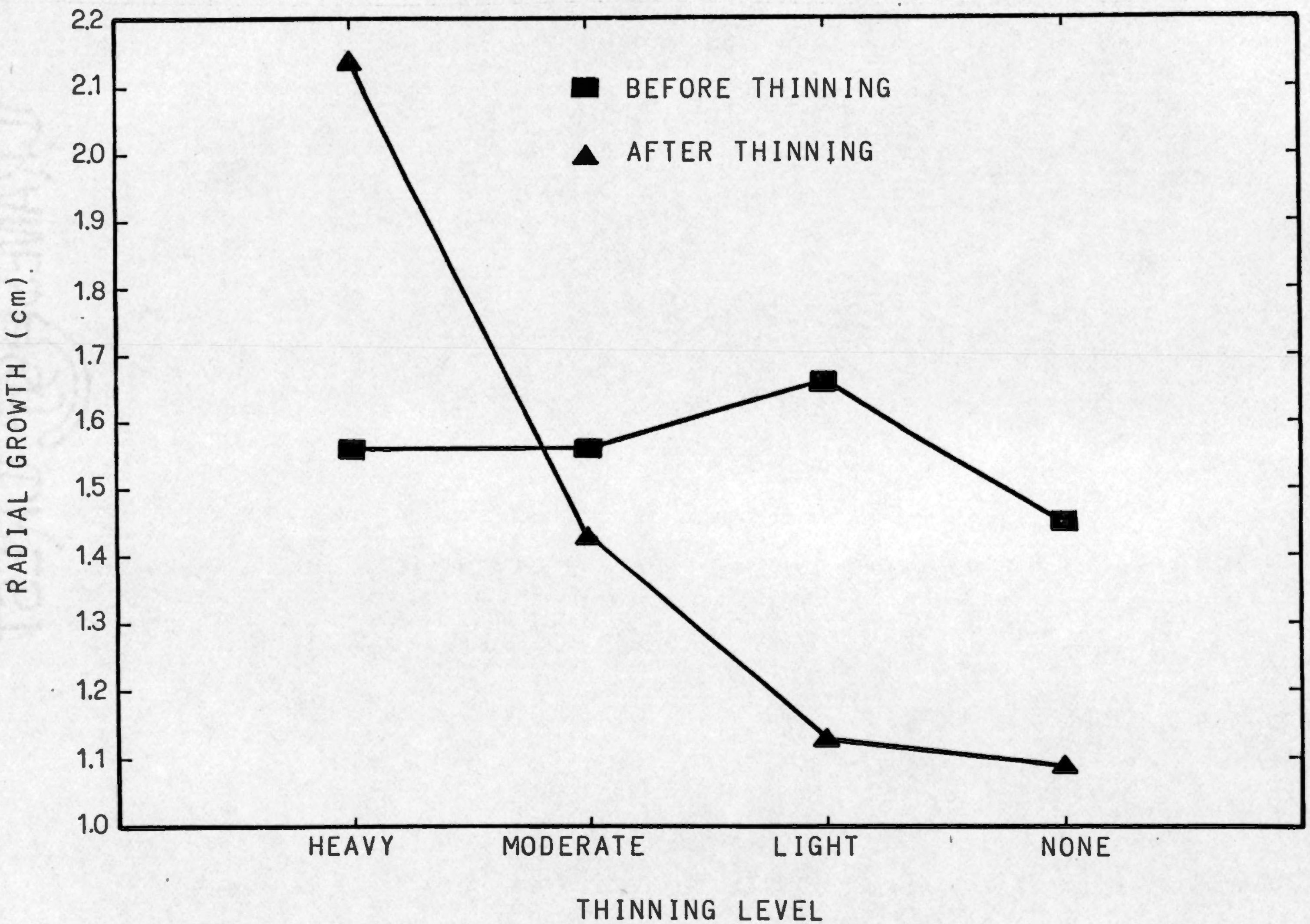

Figure 7. Radial growth (cm) before and after thinning for each thinning level.

Table 7. Treatment summaries of diameter, height and volume in 1963 and 1972, and growth increase percentages.

1963 (Before Thinning)			1963 (After Thinning)					1972			Percent Increase		
Basal Area (ft^2/ha)	Stem Frequency (#/ha)	Volume (m^3/ha)	Basal Area (ft^2/acre)	Stem Frequency (#/ha)	dbh (cm)	hgt (m)	Volume (m^3/ha)	dbh (cm)	hgt (m)	Volume (m^3/ha)	dbh %	hgt %	vol %
155.6	2026	264.3	60	620	17.5	16.2	88.3	21.8	20.6	190.7	25	27	116
157.8	1992	219.9	100	1109	16.5	15.6	148.2	19.3	20.5	274.2	17	31	85
156.1	1641	234.0	140	1305	16.2	15.5	207.2	19.1	20.7	325.2	18	34	57
162.5	2125	201.1	162	2125	14.7	14.6	201.1	17.5	19.6	308.1	19	34	53

III. SPECIFIC GRAVITY CORRELATIONS BETWEEN THE GAMMA DENSITOMETRY TECHNIQUE AND TWO CONVENTIONAL METHODS

Three specific gravity determinations were made for each core: (1) ovendry weight divided by physical measurement of green volume; (2) ovendry weight divided by water displacement measurement of green volume; (3) average specific gravity determined by gamma densitometer.

The correlation of specific gravities as measured by the gamma densitometer and the physical measurement of volume method was high: $R^2 = .76$. The correlation between the gamma densitometer and water displacement method was not as high: $R^2 = .56$. Specific gravity correlation between the two conventional methods was also high: $R^2 = .73$.

CHAPTER V

DISCUSSION AND CONCLUSIONS

I. RESPONSE VARIABLES MEASURED BY GAMMA DENSITOMETER

In the study, the average wood specific gravity for loblolly pine aged 16 to 23 years was .509, and for the eight years following (aged 24 to 31) the average was .525. This emphasizes the usual response in loblolly pine of increasing specific gravity with age. Average specific gravities for the 16 years of growth (aged 16 through 31) among the four basal area levels were not significantly different. Similar results were found for loblolly pine by Jackson (1968). There were no significant differences in percent latewood among the four basal area levels. Since percent latewood did not increase at low stocking densities, soil moisture probably was not the major limiting factor for radial growth. If soil moisture had been limiting, summerwood growth would have continued longer into the growing season on the low basal area stands because of reduced root competition for available soil moisture. This would have resulted in an increase in percentage of latewood, and thus a significant increase in the average specific gravity of the annual rings as found by Smith (1968).

Although the average ring specific gravity was not changed by any of the basal area treatments, fiber densities and types of fibers produced perhaps were changed. In fact, earlywood specific gravity decreased significantly after thinning on the 60 ft^2/acre and 100 ft^2/plots. This could have been the result of changes in cell length, cell wall thickness, cell diameter, amount of cells produced or a combination of these factors to produce an overall lower fiber density (Panshin and DeZeeuw, 1970). Smith (1968) found that thinning produced earlywood tracheids that were narrower than those found in the unthinned stands.

Latewood specific gravity, however, increased significantly on the 60 ft^2/acre and 100 ft^2/acre plots. Again, these higher density cells could have resulted from changes in cell length, cell diameter, cell wall thickness or amount of cells produced. Reducing stand competition produced latewood tracheids that were wider than those found on control plots according to Smith (1968). These findings contrast with those of Megraw and Nearn (1972) who observed that thinning and/or fertilization of Douglas-fir stands produced earlywood of higher specific gravity and latewood of lower specific gravity than that produced before treatment.

Even though the percentages of latewood and earlywood did not change after thinning, the total amount of wood produced did increase. On the 60 ft^2/acre plots reduced competition for soil moisture and nutrients, and the resulting enlarged crowns and root systems of the residual trees caused radial growth to be greater after thinning. Paul (1963) found similar results, reporting that residual trees in a thinned shortleaf pine stand increased diameter growth during a 10-year period to more than double that of the preceding 10 years. Radial growth on the 60 ft^2/acre plots for the eight year period after thinning was 2.14 cm as compared to the radial growth for the eight years prior to thinning which was 1.56 cm. Competition was reduced enough on the 100 ft^2/acre plots to maintain radial growth at nearly the same rate after thinning (1.43 cm) as before thinning (1.56 cm). But on the 140 ft^2/acre plots and control plots, a greater number of trees were in competition for available soil moisture and nutrients. As a result, radial growth was less on the individual trees for the eight years following thinning. This is in agreement with the results of Zahner and Whitmore (1960), Williston (1967) and Jackson (1968) who found that diameter growth was significantly greater on stands of reduced stocking density as compared to unthinned controls.

II. HEIGHT, DIAMETER AND VOLUME INCREMENT FROM 1963 TO 1972

Although reducing the stand density had no effect on average specific gravity, it had a very definite influence on diameter and volume increment. Total height was very nearly the same for all plots, varying only from 19.6 m (control plots) to 20.7 m (140 ft^2/acre plots). Keister and McDermid (1968) and Zahner and Whitmore (1960) reported that height growth varied little among different residual basal area levels. Small differences also were observed in the percent increase in height from ages 23 to 31. A 27 percent increase was observed on the 60 ft^2/acre plots and a 34 percent increase was observed on the 140 ft^2/acre and control plots.

Diameter (dbh), however, was greatest on the 60 ft^2/acre plots. Mean dbh was 21.8 cm in 1972 as compared to 19.3 cm and 19.1 cm for the 100 ft^2/acre and 140 ft^2/acre plots, respectively. The control plots had the lowest mean dbh which was 17.5 cm. Similar results were found by Burton and Shoulders (1974) who observed that stands with reduced stocking densities produced a greater number of sawtimber size trees (24 cm) than unthinned plots. The percent increase in dbh from 1963 to 1972 (aged 23 to 31) was also maximized on the 60 ft^2/acre plots; a 25 percent increase was observed.

Total residual volume was greatest on the 140 ft^2/acre plots which had a mean of 325.2 m^3/ha. The control plots were next with 308.1 m^3/ha. The 100 ft^2/acre plots were next with 274.2 m^3/ha; and the 60 ft^2/acre plots were last in residual volume with 190.7 m^3/ha. When total volume production is taken into account, the differences between plots are not as great. Since 176.0 m^3/ha (18 cords/plot) were removed from the 60 ft^2/acre plots, the total wood produced was 366.7 m^3/ha. The amount of wood removed from the 100 ft^2/acre plots was 71.7 m^3/ha (7.4 cords/plot) and when this is added to the residual volume, the total is 345.9 m^3/ha. Only 26.8 m^3/ha (3.6 cords/plot) were removed from the 140 ft^2/acre plots so the total wood produced was 352.0 m^3/ha. The 60 ft^2/acre plots had the highest percent increase in volume with 116 percent. The 100 ft^2/acre plots were next with 85 percent and the 140 ft^2/acre and control plots were last with 57 percent and 53 percent, respectively. Little and Mohr (1963) also observed that growth percent on residual volume was greatest on stands with the least residual basal area (50 percent increase) and least on control plots (20 percent increase).

The volume increment from 1963 to 1972 was very nearly the same for all levels of residual basal area. On the 60 ft^2/acre plots, this volume was spread over fewer trees, so volume per tree was maximized. On the 140 ft^2/acre and control plots, this volume was spread over many more trees. The stem frequency was greater than on the heavily thinned plots but stem size (dbh) was smaller. Bower (1965) came to the same conclusion, reporting that ultimate cordwood yield may be greatest on control plots but that growth is concentrated on fewer stems in stands of reduced stocking density, thus increasing individual tree size.

III. GAMMA DENSITOMETRY TECHNIQUE

The correlation (R^2 = .73) between the two conventional methods suggests that specific gravity measurements of wood samples is subject to error. These conventional techniques are quite time consuming and require some expertise to obtain precise estimates. The correlation (R^2 = .76) between the gamma densitometer and the first conventional method (physical measurement) assured accurate specific gravity determinations from the gamma densitometer. This contrasts with the results by Ross (1975) who found a low correlation between a modification of the gamma densitometry technique and a conventional method (R^2 = .36).

This technique provided details within annual ring structure (latewood specific gravity, earlywood specific gravity, percent latewood) more quickly and easily than with conventional methods. Computer analysis of all data further enhanced the speed of specific gravity determinations.

IV. CONCLUSIONS

The following conclusions were drawn:

1. Three levels of residual basal area (60 ft^2/acre, 100 ft^2/acre, and 140 ft^2/acre) applied to a 23-year-old loblolly pine stand did not significantly change average specific gravity or percent latewood as compared to unthinned stands. Earlywood specific gravity decreased on the 60 ft^2/acre and 100 ft^2/acre plots; while latewood specific gravity increased on these plots. Radial growth also increased on the 60 ft^2/acre stands.
2. Height growth was essentially the same on all plots, while diameter growth was maximized on the 60 ft^2/acre plots. Total volume in 1972 was greatest on the 140 ft^2/acre and control plots.
3. The gamma densitometry technique proved to be useful for measuring earlywood specific gravity, latewood specific gravity, average specific gravity, percent latewood, and radial growth more quickly and easily than with conventional methods. It has high potential for being a sensitive method for testing silvicultural effects on wood specific gravity, early assessment of density trends in

provenance trials and genetic tests, and environmental effects in dendrochronological research.

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