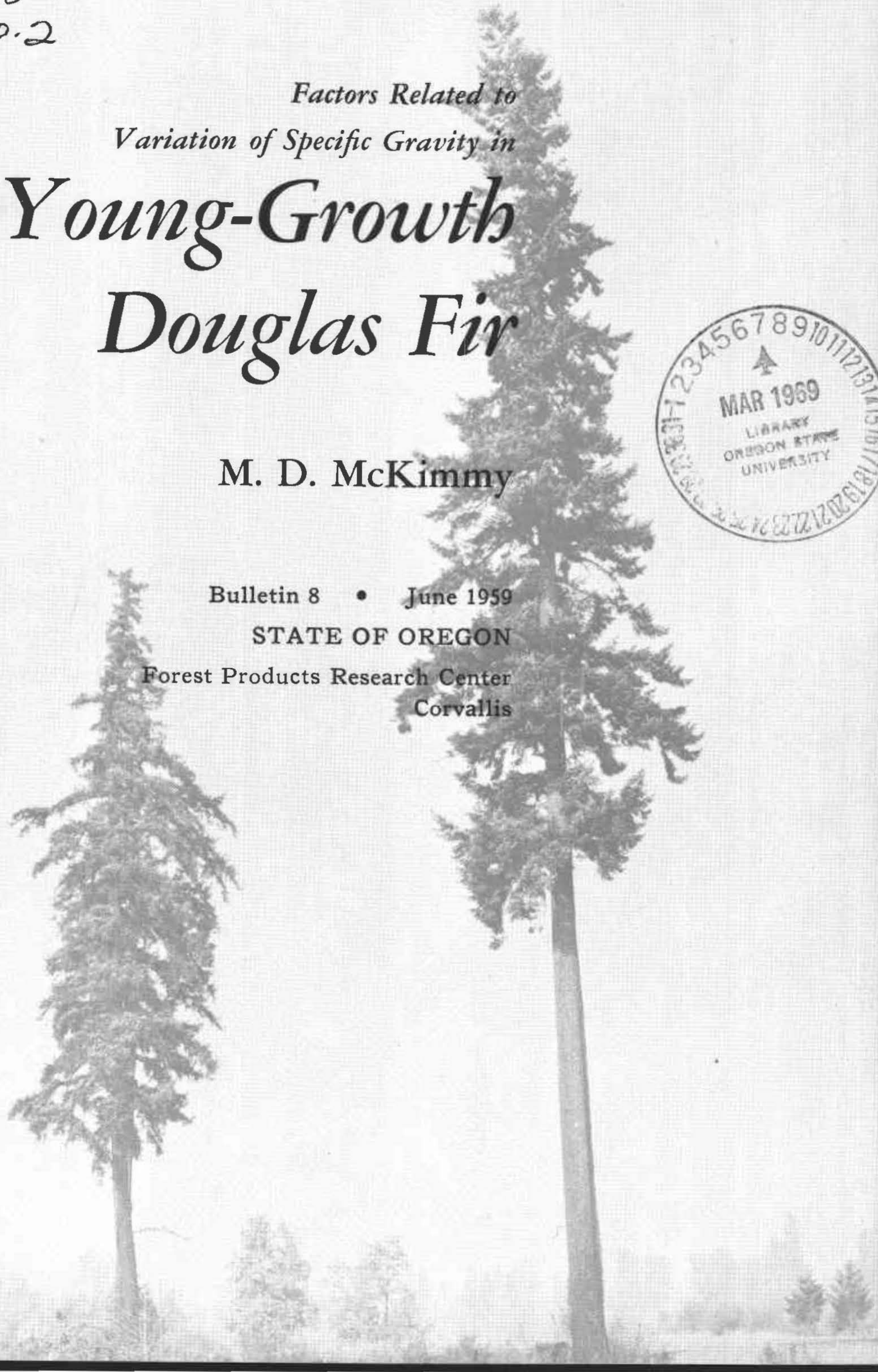

Factors Related to

Variation of Specific Gravity in

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M. D. McKimmy

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Appreciation also is due the administrations of Pacific Northwest Forest and Range Experiment Station, Forest Products Research Center, and Oregon State College School of Forestry for providing funds for this project.

Factors Related to Variation of Specific Gravity in

*Young-Growth Douglas Fir**

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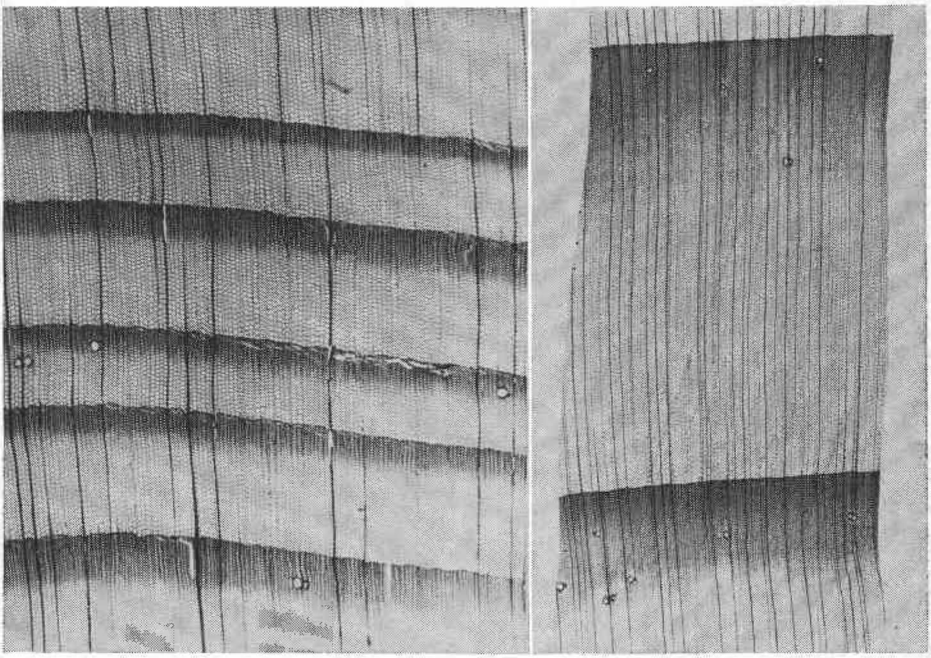
* This Bulletin is based largely on the author's Doctoral dissertation of similar title to the New York State College of Forestry, Syracuse. Research for the project was initiated at Corvallis, Oregon, in 1952, and analysis was expanded during 1954 and 1955 to be reported at this time.



Douglas fir varies considerably in proportion of summerwood present, and in abruptness of transition between springwood and summerwood; as above, left, abrupt, and right, gradual transition.

Foreword

Since young-growth Douglas fir supplies an ever-increasing proportion of timber products from the Douglas fir region, there is growing need for fundamental information on range of physical properties and other characteristics of this valuable wood resource. This bulletin, based largely on Professor McKimmy's doctoral thesis presented to the New York State College of Forestry in 1955, provides new information on specific gravity variation in young-growth Douglas fir. It also confirms importance of specific gravity as an index to strength properties of the wood. The study reviews earlier data on Douglas fir and discusses related studies of additional species. It provides, therefore, a base for planning needed work on Douglas fir and other Oregon woods.

For convenience of the general reader, the bulletin describes experimental procedure and results in as compact form as was practicable. The author's discussion of results about midway in the text should be particularly informative for all readers with more than casual interest in the subject. One appendix covers in considerable detail a survey of literature pertinent to the study that, for the sake of brevity, was not put in its usual place in the main body of text. For the technician, several appendices present details of experimental procedure, results, and statistical analyses.

Wide distribution of this report should help those concerned with management and utilization of young-growth Douglas fir and stimulate study of that and other species. The Forest Products Research Center is pleased to facilitate distribution of this information by publishing the work as a laboratory bulletin.

—J. B. GRANTHAM, *Director*
Forest Products Research Center
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Table of Contents

Introductiou

Specific gravity, or density, of wood has been the subject of considerable research in the field of wood technology. The feature frequently is considered a partial guide to strength, finishing, shrinkage, and other properties of wood. For that reason, much effort has been directed toward determining the manner in which specific gravity and various properties are related. Emphasis has been on the effect of specific gravity upon various mechanical properties of wood.

Although specific gravity is known to have an important effect on mechanical properties of wood, its great variation within an individual species has prompted considerable research to determine causes for the fluctuation. Many variables affecting specific gravity, such as rate of growth, percentage of summerwood, position in the tree, age, density of stocking, crown class, site, and geographical location have been investigated.

Workers recently have reached different conclusions on the relative importance of variables affecting specific gravity. Conflicting results have been reported by persons working in different countries, studying different species and age classes in both plantation and natural stands. Introduced and native species also were studied.

Considering these factors, dissimilarities in conclusions found in the literature are not surprising. From reported results, definite conclusions almost certainly cannot be reached for any group of woods, such as the angiosperms or gymnosperms, on the basis of studying one or two species in that group.

This study was undertaken to provide further information on some of the patterns of variation exhibited by specific gravity in young-growth Douglas fir, and the effect of several variables on this property.

Young-growth Douglas fir was selected because of the growing importance of this resource to the Douglas fir region of Western Oregon and Washington.[1] About 14 million acres now are covered with young-growth Douglas fir, and within the life span of many living foresters, commercial forests in the Douglas fir region will be almost entirely young-growth. Since, in the final analysis, quality of the product—wood—will be vital to any timber-management program, a project such as the present one might help assess the value of certain silvicultural practices and perhaps suggest management techniques for production of high-quality wood. Such information would be valuable, since the most important natural resource of the Douglas fir region is its forests.

Purpose

The whole question of the properties of young-growth wood is so broad no one study is likely to cover a large portion of the problem. The primary purpose of this study was to clarify somewhat the nature of specific gravity variation in young-growth Douglas fir and to learn the extent to which various factors such as crown class, site, geographical location, and age affect

[1] In this report, the Douglas fir region includes the portions of Oregon and Washington west of the summit of the Cascade Range.

specific gravity of Douglas fir wood. Furthermore, the aim was to determine the variation in rate of growth and percentage of summerwood to be expected, and the degree to which specific gravity is dependent upon these two features in young-growth wood.

Concurrently with the study of specific gravity, the strength of a limited number of young-growth Douglas fir trees was measured to see if it differed appreciably from values in the literature for virgin-growth material. The plan also was to determine the relationship between specific gravity and strength properties of young-growth Douglas fir.

Background[2]

In the United States, specific gravity of wood generally is understood to be the ratio of an oven-dry weight of wood to the weight of water equal in volume to either the unseasoned volume of the wood or the volume of the wood at some other moisture condition—which must be noted. Unless stated otherwise, specific gravity in this report is based on the unseasoned volume.

The specific gravity of wood cell-wall substance is fairly constant regardless of species and is taken to be about 1.53 when measured by the water-displacement method. Therefore, with the exception of wood having considerable extractive content, variations in specific gravity at a given moisture condition are due mainly to differences in the amount of cell-wall substance present. Thus, such factors as thickness of cell walls, size of cell lumens, and amount of ray tissue present which influence the volume of cell-wall material found in wood have important influences on its relative density.

Strength and specific gravity

A relationship between specific gravity and the various strength properties of wood has been reported by many workers. Although small discrepancies have been recorded in the manner in which specific gravity affects strength properties of different species, there usually seems to be close correlation between specific gravity and strength of wood. For this reason, factors tending to cause variation in specific gravity have interested many workers (47) (51)[3]. Among variables studied are rate of growth, position in the tree, percentage of summerwood, site, geographic location, crown class, density of stocking, age of tree when the wood was formed, and the nature of springwood and summerwood.

Summerwood and specific gravity

The summerwood portion of the annual ring of a typical coniferous species is composed of cells with thick walls and small lumens. The primary function of this material is mechanical support, and the structure of summerwood causes this portion of the annual ring to be more dense than the springwood. Therefore, if the percentage of a volume of wood occupied by summerwood increases, the specific gravity of the wood also should increase.

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[2] Appendix A is the detailed survey of literature from the original doctoral thesis. Only general background statements are given here.

[3] Numbers in parentheses refer to entries in the reference list.

Most authors are in agreement that the relative amount of summerwood present does affect the specific gravity of wood. However, they differ somewhat regarding the degree to which this factor influences specific gravity. In any event, the percentage of summerwood present on any particular cross section should be recognized as being important when considering factors which affect the specific gravity of wood.

A recent study (44) entailing careful measuring techniques together with microscopic means of summerwood determination has reported a very close correlation between the amount of summerwood present and the specific gravity of wood in wide-ring, young-growth Douglas fir.

Growth rate and specific gravity

There is some disagreement among various authors regarding effect of growth rate on specific gravity of wood. Many workers report as desirable an optimum growth rate that will produce wood with maximum specific gravity. They believe this relationship should be considered when managing forest stands. Other workers report little or no relationship between rate of growth and specific gravity. Since these contrasting results arose from studies of differing geographical regions and species, growth rate likely may affect the specific gravity of various species, although such influences might be modified by such factors as growth conditions, site, and age of tree.

Environment and specific gravity

Environment long has been considered a factor influencing specific gravity of wood. On the basis of results obtained by several authors, specific gravity does seem to differ with factors of site and geographical location. Interestingly enough, where differences were reported, they were among mean specific gravity values. If only mean values have been observed without considering variation within the sample, perhaps the effect of site and geographical location on the specific gravity of wood should be analyzed more critically.

Position in the stem, crown class, and density of stocking also are thought by some writers to be related to variation in specific gravity. On the basis of reported findings, these factors appear to have an important effect on specific gravity of wood, although their influence seems to differ with species. However, they evidently should be recognized as variables to consider in any study that analyzes factors affecting specific gravity of wood.

Age of wood and specific gravity

There is evidence that age has some influence on specific gravity of wood. Different workers do not agree on importance of this factor, but more emphasis now than in the past apparently might be directed toward determining the influence of age.

Finally, there is some evidence that genetic factors may be influential in controlling specific gravity. Present studies (28) (50) (62) are preliminary in nature, but silviculturists and wood technologists are confident that various properties and qualities are capable of being controlled genetically and will be so controlled in the future.

Procedure

Selection of sample trees

Young-growth Douglas fir was considered arbitrarily for the study to be trees under 160 years of age (55). Thirty-six young-growth Douglas fir trees were felled and bucked to obtain specimens for study. Trees were from four different crown classes (5), dominant, codominant, high intermediate, and low intermediate; they represented sites II, III, and IV at several geographic locations in Oregon and Washington. High and low intermediates were selected arbitrarily. High intermediates usually approached the position of the codominants, but were somewhat below the general level of the canopy. Low intermediates were generally the smallest intermediates that appeared healthy.

Specific information regarding locations of the 36 study trees is in Table 1. Average annual rainfall given in the table was at the nearest weather station. Since actual collections were made at higher elevations than the stations in some instances, rainfall at collection points might differ somewhat from values given.

Trees were selected randomly to the degree that accessibility allowed. Because collections had to be made at logging operations, free choice was not possible within stands sampled. No leaning, diseased, or obviously deformed trees were taken. Otherwise, no effort was made to select trees of either outstandingly high or low quality within each crown class. Diameter at breast height of each tree was determined before felling. Notes were taken indicating density of the stand from which the tree came. Slope, exposure, and general soil conditions were recorded, although no effort was made to incorporate these factors into the analysis.

Detailed information on individual trees is given in Appendix B.

Specimens from each tree

One-foot-long cross sections of the stem were cut at 16.5-foot intervals (for specimens to determine specific gravity) throughout the merchantable length of the tree. Also, two 4-foot bolts to yield bending-test specimens were cut from each tree. The first 1-foot cross section was cut from 3 to 4 feet above the stump, the second was cut between 20.5 and 21.5 feet, the third between 38.0 and 39.0 feet, and so on. Depending on their height, trees yielded from four to eight such sections. The 16.5-foot interval was selected to yield a maximum number of 16-foot logs (plus 6 inches for trim) between cuts to keep waste minimum.

The lower 4-foot bolts always were from 4 to 8 feet above the stump. Upper 4-foot bolts were cut at various heights from about 40 to 100 feet above the stump, depending on tree size. Cutting plan for a typical tree is illustrated in Figure 1.

A rectangular block of wood, starting at the pith and including the bark, was split from each 1-foot specific gravity section (Figure 2). One of the blocks is shown schematically in Figure 3. This block contained all annual rings from pith to bark.

A pie-shaped rail (Figure 2) was split from each 4-foot bolt, and these rails were taken to the Forest Products Research Center where a standard 2- by 2- by 30-inch bending-test specimen was cut from each.

At all times in handling material, considerable effort was devoted to pre-

Table 1. Descriptions of Locations of the Sample Collections.*

Geographic location					Age of stand	Stocking	Slope	Soil	Average annual rainfall	Notes
Site	State	Town-ship	Range	Forest or city						
					Years		*Percent*		*Inches*	
II	Oregon	6 S.	10 W.	Cascade Head Experimental Forest	101	Fully, with considerable understory	......**	Deep, black, loamy	89	Mixed spruce-hemlock and Douglas fir
III	Washington	4 N.	8 E.	Gifford Pinchot National Forest	110	90%, some open areas	30–40	Thin, sandy	87	
IV	Oregon	11 S.	5 W.	Corvallis	100	60%, few trees per acre	....	Sandy, shallow	37	From School Forest, Oregon State College.
II	Washington	18 N.	5 W.	McCleary Experimental Forest	55	Fully, young and vigorous	....	Deep, loamy	62	
III	Washington	19 N.	4 W.	Hood Canal Experimental Forest	67	Fully, well developed	....	Sandy, loamy	62	
IV	Washington	21 N.	3 W.	Shelton	110	50%, rather open stand	....	Sandy, shallow over gravel	62	The trees were quite limby and fire scarred at age 40. Lodgepole pine intermingled.
II	Oregon	18 S.	3 E.	Willamette National Forest	100	Fully	......**	Sandy, loamy	39	
III	Oregon	19 S.	2 E.	Willamette National Forest	100	Fully	40–50	Thin, sandy, loamy	39	
IV	Oregon	20 S.	5 E.	Willamette National Forest	150	60%, rather open stand	....	Thin, sandy, very rocky	39	Trees were well-formed despite open growing conditions.

* All stands are pure Douglas fir unless otherwise stated.
** The slope was negligible.

Note: In each instance the four trees represented the four crown classes defined on page 7. Soil drainage was good at each location, although there was a definite variation in moisture of the soil at the different sites because of porosity and depth of the soil, as well as density of stocking. All locations are in reference to the Willamette meridian.

venting specimens from drying. Sections were wetted and wrapped in asphalt-impregnated building paper immediately after felling. At the Center, specific gravity blocks and bending-test specimens were prepared and then submerged in water until studied further.

Each specific gravity cross-section was given a code number to indicate site, crown class, geographical location, and height in the tree from which it came.

Specific gravity

Individual specimens to determine specific gravity were split with a large wood chisel from the rectangular blocks collected in the field (Figures 2 and 3). Each specimen included 10-year growth periods starting at the pith. Blocks were trimmed so that each specimen was about 6 inches along the grain. Because of the desirability of studying the central, or young, portion of the tree critically, the first four decades were cut out individually (Figure 3). After the fourth decade, each split-out specific gravity specimen included two decades of growth, unless the number of rings was not exactly divisible by 10. In such pieces the outermost specimen did not contain an exact decade of growth or multiple thereof. Scope of sampling for specific gravity specimens by site, crown class, location, and age of wood is shown in Table 2.

The unseasoned-volume, oven-dry-weight specific gravity of each specimen was determined by the water-immersion method. Specimens stored

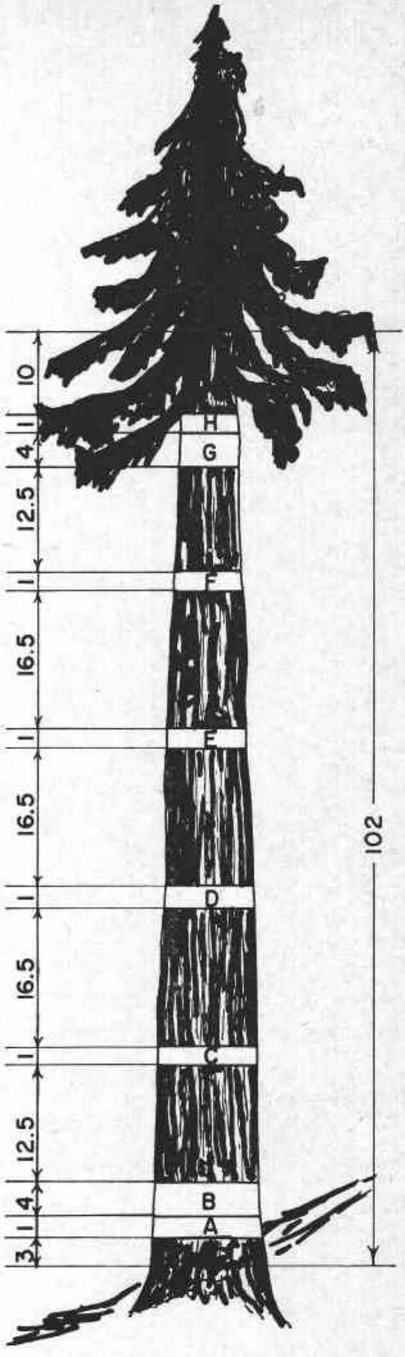

Figure 1. Diagram of a typical tree to denote location of specimen bolt, for testing strength, and disks for measuring specific gravity, growth rate, and summerwood. Stump height ranged from 15 to 24 inches, and merchantable length was assumed to be to an 8-inch top. Dimensions are not drawn to scale.

Table 2. Scope of Sampling Among Sites, Locations, Crown Classes, and Radial Positions (Decade) of Specific Gravity Blocks From the 20.5-Foot Height in 36 Young-Growth Douglas Fir Trees.

		Willamette National Forest		Wind River Expt. Forest		Cascade Head Expt. Forest		McDonald Forest		Olympic Peninsula		
Site	Crown class	No. trees	Decade* 1 2 3 4	No. trees	Decade 1 2 3 4	No. trees	Decade 1 2 3 4	No. trees	Decade 1 2 3 4	No. trees	Decade 1 2 3 4	Total trees
II	Dom	1	x x x x			1	x x x x			1	x x x x	3
	Codom	1	x x x x			1	x x x x			1	x x x x	3
	H.I.**	1	x x x x			1	x x x x			1	x x x x	3
	L.I.**	1	x x x x			1	x x x x			1	x x x x	3
	Subtotal	4				4				4		12
III	Dom	1	x x x x	1	x x x x					1	x x x x	3
	Codom	1	x x x x	1	x x x x					1	x x x x	3
	H.I.	1	x x x x	1	x x x x					1	x x x x	3
	L.I.	1	x x x x	1	x x x x					1	x x x x	3
	Subtotal	4		4						4		12
IV	Dom	1	x x x x					1	x x x x	1	x x x x	3
	Codom	1	x x x x					1	x x x x	1	x x x x	3
	H.I.	1	x x x x					1	x x x x	1	x x x x	3
	L.I.	1	x x x x					1	x x x x	1	x x x x	3
	Subtotal	4						4		4		12
	Total	12		4		4		4		12		36

* Decades are 10-year increments of material measured consecutively from the pith outward. More than 4 decades were obtained from most study trees, though scope of sampling beyond decade 4 is not shown.

** H.I.—high intermediate; L.I.—low intermediate.

Figure 2. A triangular piece was split from each 4-foot bolt to yield a specimen to test in bending. Each 1-foot disk provided a rectangular block that was split in pieces to include 10-year growth periods, starting at the pith.

in water were shaken to remove excess surface water. A dissecting needle was used to hold each sample below the surface of water in the measuring vessel, and the volumetric displacement was determined to the nearest gram on a direct-reading scale. Specimens were permitted to dry at room conditions for a time and then were oven-dried and weighed to the nearest gram on the same scale. Because of large size of the specimens, weighing to the second decimal place was adequate in determining specific gravity.

Specific gravity values were recorded by decade from the pith outward at each height level in every tree as illustrated by typical data in Table 3. The number of specific gravity specimens varied in the different radii, as did the number of height levels or specific gravity cross sections from the various trees, because of differences in tree size and age.

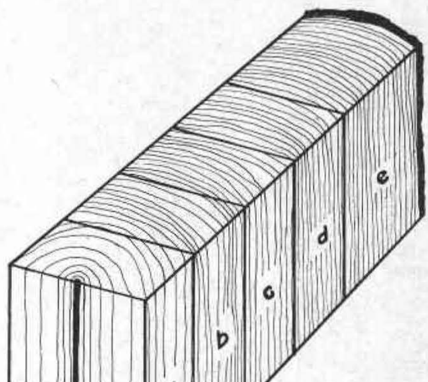

Figure 3. Blocks to measure specific gravity, growth rate, and summerwood percentage were split individually to include 10-year growth periods. After the fourth decade, each split piece included two decades of growth, except for the outermost piece.

Table 3. SAMPLES OF RECORDS ILLUSTRATING DATA OBTAINED FOR ALL SPECIFIC GRAVITY SPECIMENS FROM ONE TREE.

Specimen code no.	Green volume	Dry weight	Specific gravity	Radial dimensions: Total	Radial dimensions: Summerwood		Summer-wood	Number of rings	Growth rate
	Cu. cm.	*Grams*		*In.*	*Cm.*	*In.*	*Percent*		*Rings per inch*
6-A-1-1	287	101	0.35	2.84	0.985	0.388	13.66	10	3.5
6-A-1-2	312	112	.36	2.06	1.040	0.409	19.85	10	4.9
6-A-1-3	194	84	.43	1.41	1.214	0.478	33.90	10	7.1
6-A-1-4	173	84	.49	1.25	1.208	0.476	38.08	10	8.0
6-A-1-5	569	278	.49	3.87	4.008	1.578	40.78	22	5.7
6-A-2	4-foot bolt for determination of strength properties.								
6-A-3-1	388	121	.31	3.19	0.960	0.378	11.85	10	3.1
6-A-3-2	296	101	.34	1.75	0.994	0.391	22.34	10	5.7
6-A-3-3	138	62	.45	0.94	0.703	0.277	29.47	10	10.6
6-A-3-4	154	72	.47	1.03	0.968	0.381	36.99	10	9.7
6-A-3-5	209	102	.48	1.31	1.316	0.518	39.54	16	12.2
6-A-4-1	338	114	.34	2.78	0.989	0.389	13.99	10	3.6
6-A-4-2	217	83	.38	1.72	1.084	0.427	24.82	10	5.8
6-A-4-3	130	59	.45	1.12	0.987	0.388	34.64	10	8.9
6-A-4-4	119	56	.47	0.94	0.892	0.351	37.34	10	10.6
6-A-4-5	85	41	.48	0.69	0.625	0.246	35.65	9	13.0
6-A-5-1	327	118	.36	2.50	1.246	0.490	19.60	10	4.0
6-A-5-2	275	107	.39	1.53	1.220	0.480	31.37	10	6.5
6-A-5-3	204	95	.47	1.41	1.261	0.496	35.18	10	7.1
6-A-5-4	243	107	.44	1.41	1.156	0.455	32.27	13	9.2
6-A-6-1	332	115	.35	2.16	0.897	0.353	16.34	10	4.6
6-A-6-2	299	122	.41	2.12	1.478	0.582	27.45	10	4.7
6-A-6-3	267	108	.40	1.78	1.239	0.488	27.42	10	5.6
6-A-6-4	188	88	.47	1.25	1.223	0.482	38.56	8	6.4
6-A-7	4-foot bolt for the determination of strength properties.								
6-A-8-1	203	80	.39	1.78	0.827	0.326	18.32	10	5.6
6-A-8-2	280	110	.39	2.03	1.232	0.485	23.89	10	4.9
6-A-8-3	258	108	.42	1.56	1.008	0.397	25.45	10	6.4

Rate of growth and percentage of summerwood

Rectangular blocks about 1 inch along the grain were retained from the trim of the specific gravity specimens (Figure 3). These blocks were immediately adjacent along the grain to the blocks from which individual specific gravity specimens were split and consequently were end-matched to such specimens. These pieces served for measurement of the radial dimension of each decade of growth and the portion of that dimension occupied by summerwood. The rate of growth, in number of rings to an inch, and the percentage of summerwood then were computed for each decade.

Douglas fir frequently does not develop an abrupt transition from springwood to summerwood in rings found near the pith. This characteristic tends to make difficult the differentiation of springwood from summerwood in these rings. In this study, summerwood was considered as wood in which cell lumens have a maximum radial dimension equal to twice the thickness of the combined tangential cell walls of two adjacent tracheids (Figure 4). This criterion for summerwood was first stated by Mork (29) and has been

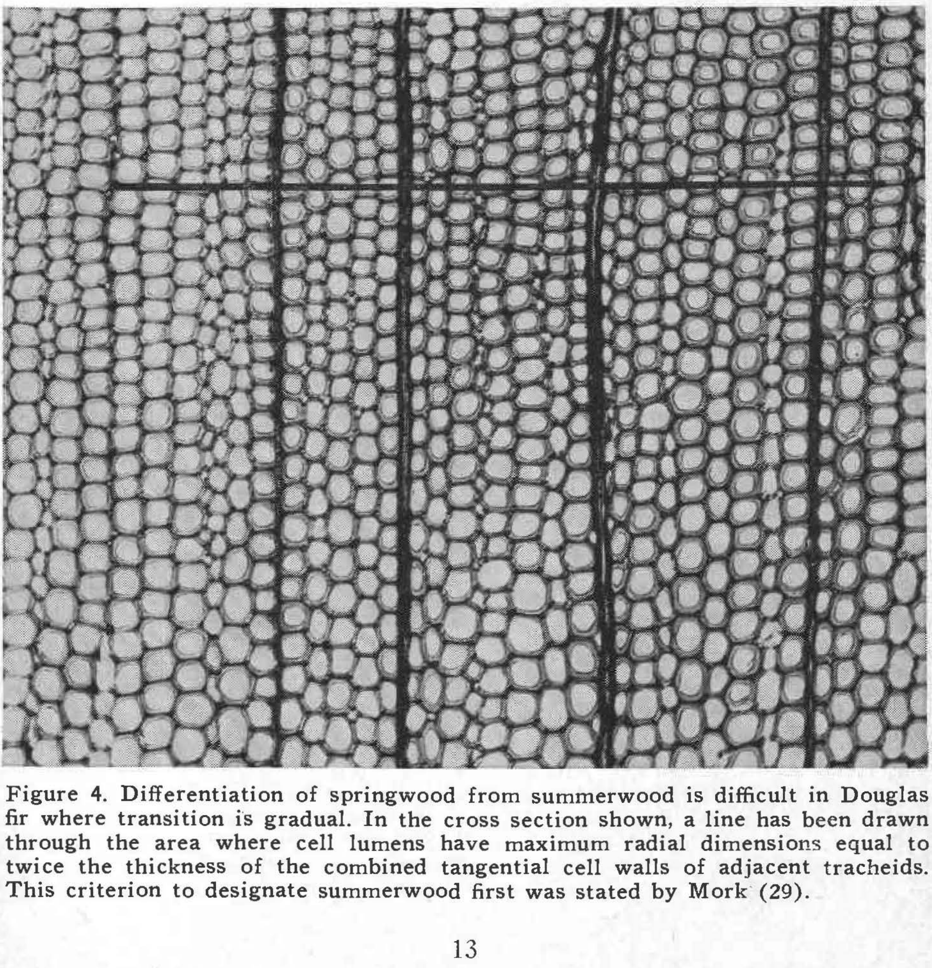

Figure 4. Differentiation of springwood from summerwood is difficult in Douglas fir where transition is gradual. In the cross section shown, a line has been drawn through the area where cell lumens have maximum radial dimensions equal to twice the thickness of the combined tangential cell walls of adjacent tracheids. This criterion to designate summerwood first was stated by Mork (29).

chosen by the U. S. Forest Products Laboratory as a definition for summerwood (35) (45).

To measure summerwood on the basis of the above criterion, cells were observed in cross section at 40-power magnification, by means of a microscope fitted with a traveling stage. Measurements to 0.01 millimeter were possible with the apparatus.

The type of information obtained about individual specimens from a particular tree is shown in Table 3.

Strength properties

From the 72 unseasoned rails split at collection locations from 4-foot bolts, 2- by 2- by 30-inch specimens of clear wood were cut for standard static bending tests, and 71 such tests were made. Horizontal shear and moduli of rupture and elasticity were determined from the bending tests. Following these tests, undamaged portions of specimens were tested to determine maximum crushing strength parallel to grain and stress at proportional limit in compression perpendicular to grain. All tests were made according to the pertinent ASTM Standard (3).

Scope of sampling and analysis

In summary, the 36 trees chosen yielded 944 specimens of wood from the total 184 cross sections cut. As few as four and as many as eight sections were obtained from the various trees, because tree height controlled the yield of sections (See Appendix E). There were 712 ten-year increments and 232 increments with more than 10 years included. Increments were as few as four and as many as eight in various trees at any one height. Again, the extent of sampling depended upon the height above stump from which cross section was taken.

Analysis and Results

Several analytical procedures were followed to organize and study data obtained from physical measurements on wood of young-growth Douglas fir. Procedures followed and results obtained are summarized briefly in following paragraphs, and a complete discussion of results is presented on pages 21-27.

Average specific gravity

Arithmetical averages of specific gravity were calculated when basic data were organized into various classifications. Average specific gravities of specimens from *all* heights and decade-increments arranged by sites and crown classes are given in Table 4. Average specific gravities for only the first four 10-year growth periods (decades) at all heights sampled are given in Table 6. Since the number of specimens obtainable diminished with height, with crown class, and with in-

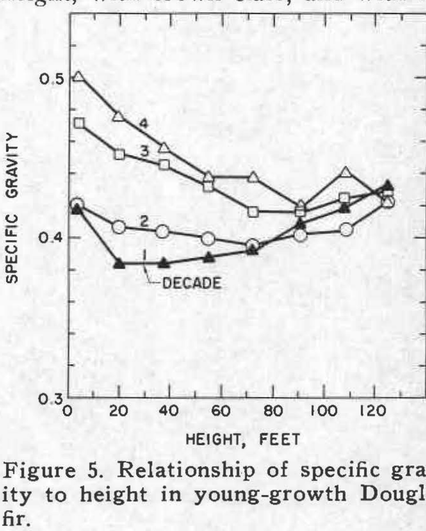

Figure 5. Relationship of specific gravity to height in young-growth Douglas fir.

Table 4. AVERAGE* SPECIFIC GRAVITIES FOR ALL DECADES AND HEIGHT LEVELS BY SITE, CROWN CLASS, AND GEOGRAPHICAL LOCATION.

Crown class	Location**											
	Site II				Site III				Site IV			
	1	2	3	Avg.***	1	2	3	Avg.***	1	2	3	Avg.***
Dom.	0.431	0.416	0.441	0.428	0.443	0.415	0.415	0.423	0.419	0.448	0.425	0.434
Codom.	.446	.430	.416	.434	.432	.417	.418	.423	.436	.486	.463	.464
H.I.	.432	.463	.394	.436	.424	.466	.462	.449	.440	.484	.421	.450
L.I.	.364	.445	.398	.398	.457	.442	.542	.471	.436	.472	.445	.452
*Average****	.424	.436	.416	.426	.436	.433	.449	.438	.432	.467	.437	.448

* Each value is the average specific gravity for an individual tree.
** Location 1—McDonald Forest, Gifford Pinchot National Forest, and Cascade Head Experimental Forest, combined.
Location 2—Willamette National Forest.
Location 3—Olympic Peninsula.
*** These are arithmetical averages based on all samples in each category.

Table 7. SUMMARY OF ANALYSIS OF VARIANCE (F VALUES) OF SPECIFIC GRAVITY AT THE 20.5-FOOT HEIGHT BY CROWN CLASS AND LOCATION WITHIN EACH DECADE AND SITE CLASS.

Source of variation	Degrees of freedom	Decade											
		1			2			3			4		
		Site			Site			Site			Site		
		II	III	IV	II	III	IV	II	III	IV	II	III	IV
Crown class	3	1.03	0.33	3.93	0.27	2.25	0.62	0.64	1.90	2.14	0.54	1.50	0.52
Location	2	0.04	0.12	11.12*	2.27	0.60	9.00*	0.37	2.98	4.68	1.58	1.68	1.56
Error	6	–	–	–	–	–	–	–	–	–	–	–	–
Total	11												

* Significant difference at 1% level.

Table 5. Over-all Average Specific Gravities for 4 Decades and All Height Levels for Specimens From All Sites, Locations, and Crown Classes Combined.

Height			Specific gravity for decade			
Level no.	Above stump	Specimens	1	2	3	4
	Feet	*Basis*				
1	3.0	148	0.418	0.420	0.471	0.502
2	20.5	144	.385	.408	.453	.476
3	38.0	142	.385	.404	.445	.456
4	55.5	123	.388	.400	.432	.438
5	73.0	77	.392	.395	.417	.438
6	90.5	43*	.409	.402	.416	.419
7	108.0	23**	.418	.405	.425	.442
8	125.5	12**	.433	.423	.430	.423

* No low-intermediate trees included in sampling.
** No low- or high-intermediate trees included in sampling.

creasing age measured from the pith, small numbers of specimens are included in averages for the upper heights. Virtually complete sampling was available only for the lower three height levels. Only four decades of growth were included in Table 5 and in subsequent statistical analyses. Data from Table 5 are shown graphically by Figure 5. Complete data forming the basis for Tables 4 and 5 and Figure 5 are included in Appendix E.

Table 6. Analysis of Variance: Specific Gravity of Specimens From First 4 Growth Decades at 20.5-Foot Height With Site, Location and Crown Class.

Source of variation*	Sum of squares	Degrees of freedom	Mean square	F
Total	0.421131	143	....	....
Crown classes	.003764	3	0.00125467	0.31
Locations	.022377	2	.01118850	2.76
Sites	.009593	2	.00479650	1.19
C x L	.014707	6	.00245117	0.61
C x S	.040891	6	.00681517	1.69
L x S	.014711	4	.00367775	0.91
Error a	.048338	12	.00402817	....
Decades	.187703	3	.06256767	87.56**
D x C	.007086	9	.00078733	1.10
D x L	.003734	6	.00062233	0.87
D x S	.008202	6	.00136700	1.91
Error b	.060025	84	.00071458	....

* The following abbreviations were used:
C—Crown class
L—Location
S—Site
D—Decade
** Significant at the 1% level.

Table 8. F VALUES FROM ANALYSIS OF COVARIANCE: SPECIFIC GRAVITIES AT LOWER 3 HEIGHTS AND FIRST 4 GROWTH DECADES WITH GROWTH RATE AND SUMMERWOOD PERCENTAGE.*

		Covariance		
Height level	Decade	Growth rate	Summerwood percentage	Growth rate and summerwood percentage
1	2	3	4	5
1	59.12	25.75	13.71	10.87
2	83.09	23.79	8.18	4.65
3	74.20	29.63	7.95	5.55

* All F values tested significant at the 1% level of probability.

Importance of site, crown class, location, and age

Several analyses of variance were made on data pertaining to the 21-foot height (level 2) to detect the significance[4] of geographic location and crown class, within each site and decade, for each of the first four decades. Results of the 12 separate analyses of variance performed for this statistical test are presented in Table 6. Detailed statistical data developed are provided in Appendix C.

Another analysis of variance was made to determine the significance of location, crown class, site, and decade (measured from the pith) in their relationship to specific gravity. Again, data on specimens from height level 2 were included in this analysis. Results of the analysis are given in Table 7. Only decade, or age from the pith, proved significant at the 1% level of probability in influence on specific gravity.

[4] Whenever a significant difference is indicated hereafter, it means a difference beyond the 5% level of probability has occurred, unless otherwise stated. Similarly, a highly significant difference means a difference has occurred beyond the 1% level of probability. These levels were selected arbitrarily, and the conditions of accepting such points should be remembered. Reference is made to standard statistics texts (12) (46).

Relationship of summerwood percentage and rate of growth to specific gravity

Analysis of covariance was performed with data on the first four decades of growth and the lower three height levels, to determine the relationships of summerwood percentage, growth rate, and age to specific gravity. Results of the covariance study are summarized in Table 8. This table should be inspected for the following effects:

Column 2: Effect of decade or age alone on specific gravity without considering rate of growth and summerwood percentage.

Column 3: Effect of decade when specimens were adjusted to a common number of rings per inch.

Column 4: Effect of decade when specimens were adjusted to a common summerwood percentage.

Column 6: Effect of decade when specimens were adjusted to a common number of rings per inch and percentage of summerwood.

Table 9. ANALYSIS OF MULTIPLE REGRESSION: SPECIFIC GRAVITY ON SUMMERWOOD PERCENTAGE AND GROWTH RATE FOR SPECIMENS FROM EACH OF FIRST 4 GROWTH DECADES AND THE 20.5-FOOT HEIGHT OF 36 YOUNG-GROWTH DOUGLAS FIR TREES.

Source of variation	Sum of squares	Degrees of freedom	Mean square	F
		Decade 1		
Total	0.06970	35	....	....
Regression	.00427994	2	0.00213997	1.08
Summerwood*	.00225493	1	.00225493	1.14
Growth rate*	.00121201	1	.00121801	0.61
Error	.06542006	33	.00198243	....
$R^2 = 0.061$ ($R = 0.247$)	$b_1 = 0.00184845$**		$b_2 = .00279359$**	
		Decade 2		
Total	.0625	35	....	....
Regression	.0271255	2	.0135628	12.65†
Summerwood*	.00859482	1	.00859482	8.02†
Growth rate*	.01301467	1	.01301467	12.14†
Error	.0353745	33	.00107195	....
$R^2 = 0.434$ ($R = 0.658$)	$b_1 = 0.00273810$		$b_2 = 0.00636183$	
		Decade 3		
Total	.0488	35	....	....
Regression	.0171120	2	.00855600	8.91†
Summerwood*	.00583273	1	.00583273	6.07††
Growth rate*	.00754600	1	.00754600	7.86†
Error	.0316880	33	.000960242	....
$R^2 = 0.351$ ($R = 0.592$)	$b_1 = 0.00211383$		$b_2 = 0.00271800$	
		Decade 4		
Total	.0524	35	....	....
Regression	.0161702	2	.00808510	7.36†
Summerwood*	.0161676	1	.0161676	14.73†
Growth rate*	.00000503	1	.00000503	0.005
Error	.0362298	33	.0010978	....
$R^2 = 0.309$ ($R = 0.556$)	$b_1 = 0.00336743$		$b_2 = 0.00005789$	

* Adjusted.
** b_1 is partial regression coefficient for summerwood percentage.
b_2 is partial regression coefficient for growth rate.
† Beyond the 1% level of probability.
†† Beyond the 5% level of probability.

The analysis of covariance confirmed early analyses where it was discovered that location, crown class, and site apparently had no significant effect on variation of specific gravity. In the next analysis, therefore, specific gravity values from all trees were pooled.

Two analyses of multiple regression were performed using pooled values for specific gravity. Results derived from computations with all values for specific gravity from the 21-foot height only are given in Table 9, and for data from all three lower levels in Table 10. Statistical information upon which the tables are based is presented in Appendix D. Although F-values[5] have been used in Table 10 for partial and multiple regression coefficients, the multiple regression coefficients themselves are shown in Table 12.

Strength properties of young-growth Douglas fir

Results of tests in bending and compression on standard, clear, unseasoned sticks of young-growth Douglas fir are given in Table 11, together with selected information on strength of this species obtained from references (15) (58). A complete record of individual test values developed in the study is given in Appendix F. Calculated horizontal shearing stresses in small clear beams at time of failure are tabulated in Appendix F, but are not included in Table 11.

Relationship of strength to specific gravity

A linear-regression analysis of modulus of rupture and specific gravity was made with data from the 71 bending tests. The regression curve is shown in Figure 6. Data pertaining to regression calculations are given in Table 13. Mean modulus of rupture was 7,530 psi; coefficient of correlation between rupture strength and specific gravity was 0.909.[6]

[5] F-values were considered valid for comparative purposes, since the degrees of freedom were, in all instances, the same in the numerator and only varied between 102 and 105 in the denominator, in ratios of which F is the quotient. See Anderson and Bancroft (4).

[6] Values for correlation coefficient, regression coefficient, and standard error of estimate were slightly lower as reported in the original thesis. This was due primarily to a greater rounding (to two decimal places) of the specific gravity values reported here.

Manner of expressing rate of growth

Growth rate can be expressed as rings to an inch, or as inches to a ring. Dissimilarity between the two methods of designating growth, as demonstrated by Table 14, was thought more apparent than real. In the present study, growth rate was expressed as rings to an inch.

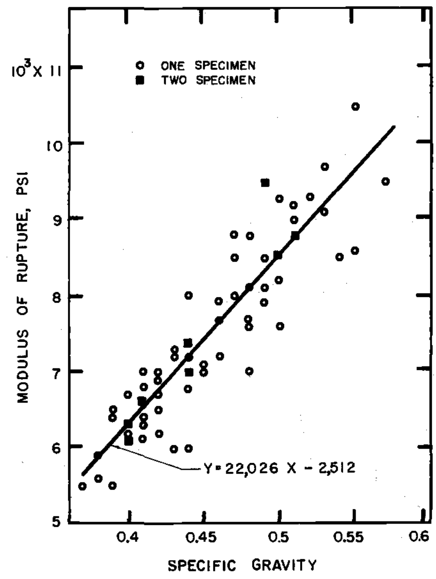

Figure 6. Relationship of specific gravity to modulus of rupture in young-growth Douglas fir as shown by linear-regression analysis.

Table 10. SUMMARY OF F VALUES FROM MULTIPLE REGRESSION ANALYSIS: EFFECT OF SUMMERWOOD PERCENTAGE AND GROWTH RATE ON SPECIFIC GRAVITY OF SPECIMENS FROM FIRST 4 GROWTH DECADES AND LOWER 3 HEIGHTS OF 36 YOUNG-GROWTH DOUGLAS FIR TREES.

	F values and their significance, for height								
	1 (3.0 feet)			2 (20.5 feet)			3 (38.0 feet)		
Growth decade	Regression	Summerwood percentage	Growth rate	Regression	Summerwood percentage	Growth rate	Regression	Summerwood percentage	Growth rate
1	0.10	0.004	0.15	1.08	1.14	0.61	15.62**	9.55**	4.92*
2	4.27*	6.96*	0.82	12.65**	8.02**	12.14**	21.31**	9.33*	25.39**
3	5.18*	5.05*	4.86*	8.91**	6.07*	7.86**	6.30**	9.59**	4.25*
4	2.82	3.66	0.64	7.36**	14.73**	0.005	14.38**	24.82**	3.56

* F Value significant at 5% level of probability.
** F Value significant at 1% level of probability.

Table 11. AVERAGE STRENGTH PROPERTIES, BASED ON TWO TESTS PER YOUNG-GROWTH TREE, OF TREES IN PRESENT STUDY COMPARED WITH ESTABLISHED STRENGTH VALUES* FOR DOUGLAS FIR LISTED IN USDA TECHNICAL BULLETIN No. 479.

Source	Trees sampled	Static bending: Modulus of rupture	Static bending: Modulus of elasticity	Maximum crushing, // grain	Stress at elastic limit ⊥ grain	Specific gravity**
	Basis	*Psi*	*Psi*	*Psi*	*Psi*	
Present study (young-growth)	36	7,530	1,450 x 10^3	3,560	440	0.456
Bulletin 479 (old-growth)	30, at least	7,600	1,550 x 10^3	3,890	510	0.450

* Values given in Technical Bulletin No. 479 were established from standard tests on small, clear wood specimens from 8 to 16 feet of stem above the stump. Both established values and ones for young-growth pertain to trees of Coast-type Douglas fir.
** Unseasoned volume, oven-dry weight.

Discussion of Results

Reliability of findings

Although this analysis was designed to define some factors affecting specific gravity of young-growth Douglas fir wood, caution is essential when drawing conclusions based on any limited study. Reference to the literature reveals the complexity of interrelationships of factors affecting wood quality and of problems presented by their study. One should not conclude, therefore, that in all other instances variables analyzed will have the same effect they appeared to have in the present study. Obviously, many similar studies are necessary before such conclusive statements can be made. Results obtained here do indicate, however, some trends which should influence the nature of future research.

Site, crown class, and geographical location

Generally, other workers have assumed that the factors of site, crown class, and geographical location appreciably affect specific gravity of wood (13) (22) (25) (59). The truth is, as reference to Tables 4 and 6 and Appendix E will show, that some differences usually are found between the average values for specific gravity of specimens from trees of different crown classes, sites, and geographic locations, and from different positions in trees. For example, the average values for specific gravity for sites II, III, and IV, given in Table 4, are 0.426, 0.438, and 0.448, respectively.

Sometimes only such averages are considered with no regard for variation exhibited among individual specimens from each site, crown class, or geographical location analyzed (22) (34). To assume, however, that a valid relationship between specific gravity and some one factor exists, merely because mean specific gravity values differ somewhat, may lead to error. When statistical methods were employed that took due consideration of variation within a given group of specimens, the interesting observation was made that in most instances in this study specific gravity was not found to be related significantly to the factors of site, crown class, and geographical location (Tables 4 and 7).

As shown in Table 7, only in two of 14 instances did geographical location affect specific gravity of the wood. Both instances occurred in site IV

Table 12. Multiple Regression Coefficients: Combined Influence Upon Specific Gravity of Summerwood Percentage and Growth Rate Based on Specimens From First 4 Growth Decades and Lower 3 Heights of 36 Young-Growth Douglas Fir Trees.*

Growth decade	Height level		
	1	2	3
1	0.076	0.247	0.693**
2	.455**	.658**	.750**
3	.489**	.592**	.526**
4	.382**	.556**	.682**

* These multiple regression coefficients, multiplied by 100, will express the percentage of specific gravity variation attributable to the combined influence of summerwood percentage and growth rate.
** Significant beyond the 1% level of probability when there were 35 degrees of freedom.

trees where average specific gravities in the first two decades for trees in the Willamette National Forest differed significantly from those of trees at McDonald Forest and the Olympic Peninsula. The F-values in some of the analyses of variance (Table 7) were sufficiently low to indicate that the number of specimens involved may have been too low. The results indicating that site, crown class, and location are in general completely without effect on specific gravity, are therefore open to question. These results, however, strongly suggested the possibility of combining material from all sites, crown classes, and locations into one analysis of variance calculation, and this was done in the present study.

When location, site, crown class, and age were so considered in a multiple analysis of variance, only the factor of age was found to seriously affect specific gravity (Table 6). Thus, apparently age of the tree at the time wood was formed was far more important than site, crown class, or geographical location of the tree.

If this situation is generally true, methods of selecting specimens for research study could be simplified greatly. If specific gravity of wood of Douglas fir cannot be shown to differ with site, crown class, and geographical location, then these factors logically need not be considered as variables when specimens of Douglas fir are selected for study of specific gravity.

Rate of growth and percentage of summerwood

From a practical standpoint, if a method could be devised for accurately correlating specific gravity of wood with some easily ascertained factor, it would be valuable. Two such factors, rate of growth and percentage of summerwood, frequently have been regarded as good indicators of specific gravity and therefore of strength (9)

Table 13. COMPUTATION OF REGRESSION STATISTICS FOR THE RELATIONSHIP BETWEEN SPECIFIC GRAVITY AND MODULUS OF RUPTURE.*

Regression coefficient $(b) = \frac{Sxy}{Sx^2} = 22{,}026$

Correlation coefficient $(r) = \frac{\frac{Sxy}{n-1}}{\sqrt{\left(\frac{Sx^2}{n-1}\right)\left(\frac{Sy^2}{n-1}\right)}} = 0.911$

Standard error of estimate $(s_{xy}) = \sqrt{\frac{Sy^2 - \frac{(Sxy)^2}{Sx^2}}{n-2}} = 483$

$SX = 31.94$	$SY = 526{,}900$	$n = 70$
$X = 0.456$	$Y = 7{,}530$	$SXY = 243{,}928$
$SX^2 = 14.7332$	$SY^2 = 4{,}059{,}230{,}000$	$(SX)(SY)/n = 240{,}417$
$(SX)^2/n = 14.5738$	$(SY)^2/n = 3{,}966{,}052{,}000$	$Sxy = 3{,}511$
$Sx^2 = 0.1594$	$Sy^2 = 93{,}178{,}000$	

* X = Specific gravity.
Y = Modulus of rupture.

(51) (57). As an extensive literature survey (Appendix A) pointed out, however, not all workers agree that these factors are always reliable (13) (18) (26). For this reason, effect of rate of growth and amount of summerwood, collectively and individually, on specific gravity was analyzed for wood formed at several different ages and height levels in the study trees.

Multiple regression analyses were made for each decade and for three height levels to determine these relationships. This procedure (Table 9) showed the total regression or the degree to which percentage of summerwood and growth rate collectively affected specific gravity. The effect is expressed numerically by the multiple correlation coefficient (Table 12), which indicates the amount of variation in specific gravity explained by variations in percentage of summerwood and growth rate. At the same time, partial regression coefficients for the two factors were calculated, and they revealed how much effect percentage of summerwood and growth rate individually had on specific gravity when each was adjusted to the other. The F-values for partial and multiple regression coefficients are presented in Table 10 for comparison. This table shows that the effects of all factors varied considerably among different decades and height levels.

Data from the covariance calculations presented in Table 8 and from the multiple regression calculations in Tables 9, 10, and 12 appear to be results of a duplication of analysis, since information obtained by the different calculations was similar. Information in Table 8 was obtained with little work at the same time the analysis was made on site, crown class, and location. Also, results given in this table applied over all decades at each height level analyzed, rather than for each decade separately as in Table 10.

Differences between Tables 12 and 10 should be pointed out. Table 12 shows actual multiple regression coefficients, while Table 10 shows F-

Table 14. FREQUENCY DISTRIBUTIONS OF GROWTH RATE FOR 33 SPECIMENS OF GROWTH-DECADE 2 FROM THE 20.5-FOOT HEIGHT.

Growth rate		Number of trees
Rings an inch	Inches a ring	
3.40	0.294	2
4.85	0.206	2
5.36	0.187	5
6.45	0.155	6
7.52	0.133	7
8.41	0.119	3
9.50	0.105	3
10.30	0.097	1
11.40	0.088	1
12.30	0.081	1
13.90	0.072	1
20.00	0.050	1
		33

values for multiple regression coefficients as well as partial regression coefficients. Note that occasionally when a multiple regression coefficient tested highly significant, its F-value did not. Decade 4, height level 1, is an example of that situation. Despite this fact, either Table 10 or 12 will serve for comparison purposes when appraising the effect of growth rate and percentage of summerwood on specific gravity variation in different decades and height levels.

For comparison purposes, the F-values for partial regression coefficients and multiple regression coefficients are given in Table 10. The table shows which F-values in the multiple regression calculations tested significant in various decades and at different height levels. The column for regression (multiple regression coefficients) indicates the degree to which growth rate and percentage of summerwood, collectively, affected specific gravity. The respective columns for percentage of summerwood and growth rate (partial regression coefficients) indicate the degree to which each of these factors affected specific gravity when the other variable was adjusted to a constant value.

Study of Table 10 reveals some interesting relationships among decades and height levels. Specific gravity tended to be more dependent upon the combined effect of percentage of summerwood and growth rate with increasing height. In the first decade, variation in specific gravity was influenced significantly by growth rate and percentage of summerwood only at the 37-foot level. Also, the percentage of summerwood, in general, tended to influence specific gravity more than did growth rate. In the first decade at height levels 1 and 2, the specific gravity was not affected by percentage of summerwood and growth rate, while at height level 3 it was.

Table 8 contains convincing evidence that,

1. specific gravity differed with decade at the three height levels studied, and
2. there appeared to be a consistent pattern in regard to the effect of adjusting to a common growth rate and percentage of summerwood.

In brief, this pattern seemed to indicate that a constant rate of growth with differing percentages of summerwood will cause more variation in specific gravity than will a constant percentage of summerwood under differing rates of growth. In making the calculations, a noteworthy observation was that in no instance did the variables of site, crown class, and geographical location test significant even when their total effect was pooled. However, decade, when adjusted to a common rate of growth and percentage of summerwood, was found to have a highly significant effect on specific gravity.

Despite the many multiple regression coefficients that tested highly significant (Table 10), none were of sufficient magnitude to permit specific gravity to be predicted reliably from growth rate and percentage of summerwood in any of the decade-height combinations. The reasons for such results with respect to rate of growth and percentage of summerwood are assessed with difficulty. In a material subject to as many variables as is wood, extraneous factors not even considered here might be responsible for the situation found. Very likely, a tree changes physiologically with age, and this change might affect the minute anatomy of the wood (cell-wall thickness, type of transition between springwood and summerwood, presence of extractives, and so on) and, consequently, specific gravity. Likewise, hereditary traits of the various trees might have been involved. These factors were not included in this study.

Certain other factors, however, may be important and consequently should be discussed. Among these are method of summerwood determination, method of expressing growth rate, and age from the pith at which the wood was formed.

Summerwood determination

Douglas fir wood in the vicinity of the pith does not always exhibit the abrupt transition between springwood and summerwood characteristic of old wood. In the central zone, to discern exactly where springwood ends and summerwood begins in an annual ring sometimes is difficult. To be consistent in this study, Mork's method (29) was followed to determine the beginning of summerwood in the annual ring (Figure 4). A valid criticism of this method is that thickness of cell walls in wood designated as summerwood will vary with radial diameter of the cells involved. However, since the minimum percentage of cell-wall material present in summerwood is the same under Mork's definition, irrespective of the radial diameter of the cells, the minimum specific gravity of summerwood as classified by Mork's definition also should be comparable regardless of their radial cell diameters.

One could reasonably question, however, that the specific gravity of material designated by Mork's method as summerwood in annual rings near the pith, where transitions are gradual, is the same as that of summerwood in rings with abrupt transition between springwood and summerwood. The material designated as summerwood was believed to differ considerably in specific gravity, and summerwood in early rings was thought lower in specific gravity than was summerwood of late rings. Smith (45) found specific gravity of summerwood increased with successive zones from the pith.

Because most rings examined had the usual abrupt transition from springwood to summerwood, Mork's method really was necessary only to designate summerwood in the first decade. This situation conceivably may be responsible in part for detection of a lack of effect of percentage of summerwood on specific gravity in that decade. Where there is especially lightweight summerwood in an annual ring, a high percentage of it must be present to cause an effect on specific gravity of the entire ring. However, rate of growth also was without significant effect on specific gravity in the first decade, except at height level 3.

Factors not considered also were believed responsible, possibly largely so, for the situation observed. An example might be the tendency for pitch to be present more frequently near the pith than remote from the pith. Small but influential amounts of this material are difficult to detect visually, yet its presence could cause a higher measured average specific gravity than would be representative for a given observed percentage of summerwood.

The practice of grading Douglas fir structural lumber on the basis of the percentage of summerwood present (60) might well be questioned, if pieces contain material from near the pith. This is especially true since summerwood usually is estimated visually on the basis of its color as contrasted to springwood. Tissue classified as springwood according to Mork's definition often was observed to occur well within a definite color transition zone and within material visually considered as summerwood in annual rings near the pith.

To consider ring count independently of age or decade when appraising specific gravity variation may lead to error, since this factor appeared to affect specific gravity very little in wood formed during late decades, measured from the pith.

Age from pith

Age of the wood measured from the pith was found to be correlated with specific gravity and was so indicated by the analysis of variance summarized in Table 7. These results indicated that age had a much larger effect on specific gravity than had any of the other variables considered. Furthermore, the effect of percentage of summerwood and rate of growth on specific gravity differed with age in the multiple regression results given in Tables 10 and 12.

There seemed to be, however, no consistent pattern among these factors at the different height levels. At height level 1, the third decade showed the greatest effect from growth rate and percentage of summerwood, while the effect diminished in the fourth decade. Individually, percentage of summerwood was the more important at this height level.

At height level 2, the second decade showed the greatest combined effect of growth rate and percentage of summerwood, with their influence falling off as decade increased. At this height level, growth rate was found most influential in decades 2 and 3. At height level 3, the combined effect of growth rate and percentage of summerwood was highly significant in all four decades. It was not significant in the first decade at height levels 1 and 2. Except for decade 2, the percentage of summerwood was most influential at height level 3.

The lack of consistent pattern or influence of percentage of summerwood and growth rate with height level is puzzling, particularly the tendency for percentage of summerwood in some instances to be less effective with increasing age. One possible explanation for the diminished summerwood influence in old wood might be that many of the trees studied had slowed appreciably in growth near the bark. Perhaps these slow-growing specimens were dissimilar in their percentage of summerwood-specific gravity relations. This possibility is suggested, since such specimens also showed a poor rate of growth-specific gravity relationship in older decades.

To illustrate the tendency for specific gravity to increase with decade or age, the arithmetical averages for different height levels and ages are given in Tables 4 and 5. Remember that these averages in themselves are meaningless unless there is knowledge of the variation present. The tables illustrate, however, a general pattern of specific gravity variation which the statistical calculations substantiated.

Influence of age apparently should be given more consideration than has been done in the past. Although evidence in these data is convincing that specific gravity did increase with age, age alone was not clearly responsible for such increase. The relationship between age and specific gravity still needs clarification. In any event, the factor of age does not appear so important in influencing the specific gravity of Douglas fir as Turnbull and others (53) (54) found for pine in South Africa.

Strength

On the basis of the limited tests made, the young-growth Douglas fir wood tested apparently compared favorably with both old- and young-growth Douglas fir previously studied. Comparisons are provided in Table 11 of average values determined from this study for modulus of rupture, modulus of elasticity, and compression perpendicular or parallel to the grain, with selected values for a few classifications of Douglas fir reported by others (15) (49) (58).

Differences among values in all instances were so small as to warrant little concern that young-growth Douglas fir is significantly weaker than old-growth material. Values obtained in this study, however, were from a limited number of samples not collected strictly according to standard methods. Their close agreement with results of previous, more extensive or detailed samplings should be noted, nonetheless.

The regression analysis (Table 13) of modulus of rupture on specific gravity produced the surprisingly high correlation coefficient of 0.911. The regression coefficient was 22,026 (psi). Comparison of this value with prior studies is difficult, since most workers plotted strength values on semilogarithmic paper to obtain a curvilinear relationship between bending strength and specific gravity. In this study, a linear regression was found to fit the data better than a curvilinear one. Possibly this result was caused by the small number of specimens at the extreme high and low specific gravities, as well as the somewhat limited range in specific gravities of the specimens. Minimum specific gravity was 0.37 and maximum was 0.57.

The correlation coefficient of 0.911 is of interest. Apparently, if the specimens studied were truly representative of the clear wood of young-growth Douglas fir, then specific gravity is a distinctly reliable indicator of strength of this material.

Conclusions

Although this study was designed to define some of the factors affecting specific gravity of young-growth Douglas fir wood, caution is essential when drawing conclusions based on limited study. Reference to the literature reveals the complexity of the problems and of the interrelationships affecting wood quality. Therefore, one should not conclude that in all other instances the variables analyzed will have the same effect as they appeared to have in this study. Obviously, many more studies of similar nature are necessary before such conclusive statements can be made. Some interesting results, however, were obtained. These may be summarized as follows:

1. Site, crown class, and geographical location appeared to have little effect on specific gravity. Variation of this property observed within a given group of specimens usually was sufficient to offset any effect these factors might have on specific gravity.

2. Age of the tree at time the wood was formed appeared to be an important factor affecting specific gravity. This phenomenon occurred independent of the factors of site, crown class, and geographical location.

3. A constant rate of growth with

differing percentages of summerwood caused more variation in specific gravity than did a constant percentage of summerwood under differing rates of growth.

4. Specific gravity tended to be more dependent upon the combined effect of percentage of summerwood and growth rate as the height level increased.

5. Percentage of summerwood, in general, tended to influence specific gravity more than did growth rate.

6. Although the combined effect of the two factors, percentage of summerwood and growth rate, was highly significant in certain decades, at no time in these data was it sufficient to permit a reliable prediction of specific gravity on the basis of the two factors.

7. The strength of young-growth Douglas fir appeared comparable to established values given for the species.

8. Modulus of rupture was found closely correlated with specific gravity in specimens tested. This correlation was considered sufficient to permit reliable prediction of this strength value from specific gravity of the wood, if properly qualified.

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Appendix A

Survey of Literature

In the United States, specific gravity of wood is considered as the ratio of the oven-dry weight of the wood to the weight of water equal in volume to the unseasoned volume of the wood, or to the volume of the wood under some other condition, which must be noted. Unless stated otherwise, all references here to specific gravity will be based on unseasoned volume. Furthermore, all literature cited pertains to coniferous woods, unless designated otherwise.

The specific gravity of wood substance has been determined by Dunlap (16), Kollman (24), and Stamm (48) to be about 1.53 by the water-displacement method. Stamm (48) further states that this value is too high. He noted that dry wood attracts water with such force that the water is actually compressed and occupies less space than normal. With helium gas as the displacement medium, he found the specific gravity of wood substance to be 1.46. This value is considered to be the more accurate, since helium is not attracted by wood and the gas molecules are small enough to penetrate all interstices in cell walls of the wood. For most investigations, however, the water-displacement method is considered sufficiently accurate, since the results are close approximations.

Specific gravity of cell-wall substance is almost constant, regardless of species. With one exception, therefore, variations in specific gravity of wood for a given moisture condition are due mainly to differences in amount of cell-wall material present. The exception arises when wood contains an appreciable amount of extractives, or infiltrating materials. Those materials are part of the dry weight, and their presence results in a higher specific gravity than would otherwise be expected. In such woods, a high value for specific gravity does not always assure the presence of a large amount of cell-wall substance.

Because specific gravity is affected by the amount of cell-wall material present, factors which influence the volume of this material should be considered. Thickness of cell walls, size of cell lumen, and amount of ray tissue present are important factors. Wood which possesses thick cell walls and small cell lumens will have high specific gravity.

Specific gravity and strength

A relationship between specific gravity and the various strength properties of wood has been recorded by many workers. Newlin and Wilson (30) (31) determined that, for the average of a great number of species, all strength properties except modulus of elasticity increased at an exponential rate with an increase in specific gravity.

Wangaard and Zumwalt (58) plotted the logarithms of values for modulus of rupture and modulus of elasticity when working with young-growth Douglas fir. This was done to get a linear relationship, because of the exponential relationship between specific gravity and these strength properties in their data.

Alexander (1) (2), working with Douglas fir, presented a graphic relationship between specific gravity and strength properties and showed by charts that strength within an individual stem seemed to follow rather closely the variation in specific gravity throughout the same stem. Schrader (40), in his comprehensive study, found that in small, clear specimens of Douglas fir, the distribution or variation of specific gravity in the cross section of the piece was an important factor affecting strength properties of such specimens. Hughes and Allen (22), studied strength properties of young-growth Douglas fir and eliminated the variable of specific gravity by working with specific strength. Specific strength is actual strength value divided by specific gravity.

Some workers have reported slight discrepancies in the manner in which specific gravity affects strength of wood. Regardless of this fact, it is apparent that this factor should be considered an important aid in estimating strength values of a given piece of wood. Most textbooks concerned with mechanical properties of wood devote considerable discussion to significance of specific gravity as a factor in evaluating strength of small, clear specimens of wood.

Since close correlation between specific gravity and strength of wood may be regarded as a function of the amount of wood substance present, factors that tend to cause variation in specific gravity have interested many workers. Among variables studied were rate of growth, position in the tree, percentage of summerwood, site, geographic location, crown class, density of stocking, age of tree when the wood was formed, nature of springwood and summerwood, and infiltrates.

Percentage of summerwood

The summerwood portion of the annual ring of a typical coniferous species is composed of cells with thick cell walls and small lumens. The primary function of this material is mechanical support, and, since cell walls are much thicker and lumen of the cells much smaller than in springwood, this portion of the annual ring is more dense. Therefore, if the percentage of the volume occupied by summerwood increases, evidently specific gravity also should increase.

Forsaith (17) tested in bending small beams which consisted of all springwood, all summerwood, and various combinations of both. As would be expected, he found summerwood to be stronger than springwood. He also found that small beams consisting of one face springwood and one face summerwood were strongest when loaded on the radial face and weakest when loaded on the springwood face. Since summerwood is stronger than springwood, he concluded that local differences in structure, if large in comparison to over-all dimensions of the beam, may influence its strength more than would specific gravity.

Paul and Smith (34), in analyzing young-growth Douglas fir, found that near the pith annual rings of the same width as those farther out on the radius have a lower percentage summerwood and, therefore, a lower specific gravity. They also found, in general, a close correlation between variation in summerwood and variation in specific gravity. They observed on good sites, however, where annual rings were usually wide, the specific gravity tended to be low for a given percentage of summerwood. These relationships led them to believe specific gravity of summerwood from fast-growing trees is less than that from slow-growing trees.

Rochester (37) shows curves for several Canadian conifers that reveal, within a species, timber having the greatest amount of summerwood has the highest strength value. Schafer (38) found in southern pine the proportion of summerwood contributed more to variation in specific gravity than did rate of growth. However, Berkley (7), in a thorough study of southern pine, concluded the percentage of summerwood—without regard for density—is not an accurate measure of strength of the wood studied.

Bethel (8), working with loblolly pine, was interested in finding if percentage of summerwood had a relationship to strength that is independent of specific gravity. He was particularly concerned with the percentage of summerwood, because it is indicative of both the amount of wood substance present and its distribution. He was aware, however, of Garland's (18) statement that variation in density of summerwood within any species is such that amount of summerwood cannot be taken as a criterion of strength unless it is qualified by specific gravity. Bethel found by statistical analysis the optimum summerwood volume was 47.57% when specific gravity was held constant.

Cline and Knapp (11) showed diagrams indicating an increase in strength with increase in percentage of summerwood for Douglas fir. However, none of these relationships were straight lines. They observed this was due to variation in density of summerwood. They stated rings containing a large proportion of summerwood have more porous and less dense summerwood than that found in pieces which contain little summerwood. They noted this decrease in density is not taken into consideration in measuring summerwood. They conclude that over a large dimension, as a large timber, the wide variation in percentage of summerwood in different parts of the cross section will be such that the average percentage of summerwood will bear no relationship to strength of the member. They thought the amount of summerwood present, therefore, is applicable only to small, clear specimens as far as indicating strength is concerned.

Lodewich (26), in his study of southern pines, stated many properties of wood can be correlated with specific gravity, but that specific gravity of wood is not necessarily dependent upon percentage of summerwood. He observed that the nature of summerwood must be considered; i.e., it may vary in specific gravity. Schrader (39) substantiated this observation. He determined the specific gravities of specimens of springwood and summerwood separately for four species of southern pines. He found the specific gravity of summerwood varied from 0.35 to 0.85 and of springwood, from 0.20 to 0.35. These were minimum and maximum values for loblolly, slash, longleaf, and shortleaf pine. With different combinations of these values, variations in specific gravity evidently will occur independently of the amount of summerwood present.

Trendelenburg (51), in an article dealing with Douglas fir, showed that specific gravity increases as percentage of summerwood increases. He cautioned, however, that the percentage of summerwood cannot account entirely for specific gravity and strength because the further factor of anatomical structure of summerwood must be considered.

A recent study (44) which utilized careful measuring techniques together with microscopic means of summerwood determination has reported very close correlation between amount of summerwood present and specific gravity of the wood. In a later report (45) on the same data, multiple regression analyses combined the three variables, percentage of summerwood, specific gravity of springwood, and specific gravity of summerwood. These two variables were found to account for 96.90% of the variation in specific gravity.

Most authors evidently are in agreement that the relative amount of summerwood present does affect the specific gravity of wood. However, they differ somewhat regarding the degree to which this factor influences specific gravity. In any event, the percentage of summerwood present on any particular cross section must be recognized as being important when considering factors which affect the specific gravity of wood.

Rate of growth

Trendelenburg (51) showed summerwood width in annual rings of the Douglas fir he studied tended to remain constant with a decrease in growth rate. Such being true, specific gravity will increase with a decrease in growth rate, providing specific gravity of the summerwood and springwood remains constant. This situation has been regarded as a general rule with conifers.

Paul (32) has assumed this relationship to hold true at all times throughout the age of the tree in advocating dense stocking when the stand is young. His premise is that wood with close annual rings will be dense, while fast-growing wood will be less dense and hence weaker. He maintains, therefore, that the stand should be managed at a stocking consistent with that growth rate which will produce wood with high specific gravity.

Several workers (1) (19) (20) (37) have indicated an optimum rate of growth for certain conifers growing in Canada. Their curves indicate the number of rings per inch that will yield the highest values of specific gravity are 18 for jack pine, 26 for red pine, and 22 for white pine. Betts (9) listed some rates of growth associated with high specific gravity and, therefore, high strength for several coniferous species native to the United States. The following growth rates, in rings per inch, are given: 24 for Douglas fir, 18 for western larch, 18 for Norway pine, 30 for redwood, 6 for loblolly pine, 12 for shortleaf pine.

A close correlation between specific gravity and rate of growth has not always been observed. Cockrell (13), in studying the relationship between specific gravity and shrinkage in ponderosa pine, found that specific gravity appeared to be independent of growth rate. Wangaard (57) concluded that in no wise should rate of growth be given preference over actual density in selecting material for strength purposes. Garland (18) likewise found poor correlation between strength properties and rate of growth. He concluded other unknown factors affecting strength vary fairly regularly with growth rate and were responsible for the results he observed. In studying the strength-specific gravity relationships in red pine, Kraemer (25) concluded the effect of growth rate in red pine was greater than the effect of specific gravity when several sites were involved. It might be pointed out, however, that Kraemer did not exclude specimens containing compression wood from his tests. Compression wood has been found to be low in strength for its specific gravity. This fact may have contributed to results he observed.

Several South African authors (14) (42) (43) (53) (54), have concluded rate of growth has no significant effect on specific gravity. They believe age is the primary factor controlling specific gravity of wood. In fact, Turnbull (53) has presented curves showing an increase of specific gravity with increase in growth rate as age increases, which is contrary to findings of many writers mentioned above. Turnbull was working with young, plantation-grown, introduced and exotic pines, such as loblolly, jelecote, cluster, and Monterey pine. These species appear to grow very rapidly when introduced to South Africa. Turnbull also introduced a variable difficult to evaluate when he selected specimens from different trees at various distances from the pith. On the basis of his method of sample selection he appears hardly justified in concluding that variation in specific gravity is due entirely to age of the tree at time the wood is formed, since he does not consider the effect of other variables, such as percentage of summerwood, and variations in density of the summerwood.

Spurr and Hsiung (47) have pointed out that curves showing a relationship between rate of growth and specific gravity usually exhibit a wide range and a poor correlation. They state a great number of specimens averaged for all positions and height levels in the trees tend to confound variables to the point that it is impossible to learn the precise effect of ring width on specific gravity. This is because such a sampling method involves the effect of age and position in the tree in addition to ring width. They also point out it is natural for a tree to produce narrow annual rings as it grows old. Therefore, an increase in specific gravity in this old material may be due to ring width, age, or position in the stem, since these factors vary simultaneously.

There appeared to be some disagreement among various authors regarding effect of growth rate on specific gravity of wood. Many workers reported an optimum growth rate that will produce wood with a maximum specific gravity, and they believe this relationship should be considered when managing forest stands. Other workers reported little, or no, relationship between rate of growth and specific gravity. Since these results differed with geographical regions and species considered, growth rate likely may affect specific gravity of various species, although such influence might be modified by such factors as growth conditions, site, and age of the tree.

Site, location, and crown class

Environment long has been considered a factor influencing specific gravity of wood. Cockrell (13), in studying shrinkage and density of ponderosa pine, concluded that wood quality on the whole is influenced more by stand and site conditions under which they were grown than whether they were old-growth or second-growth. Kraemer (25) also concluded that site significantly affected mechanical properties of the static bending tests in red pine. Hughes and Allen (22), after adjusting their specimens to specific strength, found a noticeable variation in site. They found the highest specific strength associated with good sites.

Kienholz (23) studied environmental factors affecting wood of lodgepole pine. He determined the variation in percentage of summerwood in wood from stands representing two greatly differing environmental conditions: a rather open, young-growth forest and a dense, old-growth stand growing in a sphagnum bog. Thus, a wide range in stand density, crown development, and soil conditions was involved. Although he did not give specific gravity values for the wood he collected, he did find a considerable variation in percentage of summerwood in the different stands. The material growing in the sphagnum bog had the highest percentage of summerwood, while young-growth trees on a lava bed were lowest.

Newlin and Wilson (30), in a comprehensive report on strength of American woods, pointed out that silviculturists recognized two types of Douglas fir, Coastal and Rocky Mountain. They further indicated that strength tests justified this separation, since the coastal type appeared to be stronger.

Wellwood (59), in testing the effect of several variables on specific gravity of young-growth Douglas fir, found that wood from good sites has specific gravity significantly lower than that from average sites for comparable sections within the tree.

Paul and Smith (34) studied young-growth Douglas fir from site II and site IV. They found average specific gravity of wood from site II was less than the value given by the U. S. Forest Products Laboratory for old-growth Coast-type Douglas fir in U.S.D.A. Technical Bulletin No. 479, while the average specific gravity from site IV exceeded the old-growth value. The range in variation of specific gravity on these two sites is of interest. Minimum and maximum values from site II were 0.324 and 0.574, while similar values from site IV were 0.369 and 0.557. However, an average specific gravity of 0.437 for site II is not necessarily significantly different from an average of 0.467 for site IV, the values found by these two workers, since the number of specimens and their variations about the means for each site were not given, and significance of difference tests, if made, were not reported. Scott (42) concluded that, for timbers grown in South Africa, variation caused by locality is slight when compared to individual variation found within a stand.

On the basis of results obtained by most authors mentioned, specific gravity does seem to differ with factors of site and geographical location. Most differences reported were mean values. If only these values are considered without taking cognizance of variation within the sample, the effect of site and geographical location on specific gravity of wood should be analyzed more critically.

Crown size and condition: position in the stem

Some of the earliest workers who studied the relationship between growth conditions and quality of wood believed size and condition of the crown were important factors in controlling specific gravity of the wood. Position in the stem, crown class, and density of stocking, with its effect on the crown, also are thought by some writers to be related to variation in specific gravity.

Metzger (27), as discussed by Bryant (10), considers the crown of a tree as the point of attack for wind and regards the shaft of the bole below this point as a cantilever beam that automatically adjusts its size and taper to accommodate the high bending moment near the base. A bole with high taper, therefore, might have little variation in specific gravity with height in the tree and with distance from pith near the base, or a more cylindrical tree might have a pronounced variation of specific gravity with height in the tree and with distance from pith near the base. Both types of bole could correspond to a beam of uniform resistance, if strength properties increase with an increase in specific gravity.

Volkert (56) made a thorough study of specific gravity distribution within the stems of coniferous trees and presented diagrams of stem forms showing how specific gravity varies within them. On this basis, he was able to come to certain conclusions regarding the relationship between specific gravity and stem form. He observed that in conifers specific gravity tends to be low near the pith and high near the periphery of the tree. He further noted that, in an even-aged stand, specific gravity of the small-diameter trees tended to be higher than that of the large trees. Volkert found that of two trees from the same diameter class, the more strongly tapered had a lower average specific gravity. He observed in fir (Abies) that when two trees of the same stem form (diameter and length) were compared, the tree with the larger crown had the higher specific gravity. Thus, Volkert and Metzger thought that dynamic influences affect both stem form and wood density.

Hartig's (21) nourishment theory, as explained by Paul (32), postulates that specific gravity of wood is dependent on relationships of soil fertility, transpiration of water by the tree crown, and assimilation.[6] Hartig asserted that specific gravity of wood was influenced by the proportional quantity of conduction tissue to supporting tissue. In essence, his theory states that the greater the transpiration as compared with the production of wood substance, the greater the amount of conduction tissue formed and the lighter the wood. Heavy wood, therefore, results when the most abundant assimilation possible accompanies normal transpiration. This situation is best realized when volume of crown is small compared to the stem.

Paul (32) applied Hartig's nourishment theory in suggesting silvicultural means for controlling specific gravity of wood. He found that the proportionate amount of springwood formed was influenced largely by crown size. Development of the summerwood portion depended largely upon favorable conditions for continued growth throughout the season.

Wellwood (59) concluded from his analysis of young-growth Douglas fir that specific gravity of wood from dominant trees differed significantly from codominants and intermediates at one height level, if all sites together and average sites are considered. On good sites, no significant difference in specific gravity existed among any crown classes.

The factors of position in the stem, crown class, and crown size appear to have an important effect on specific gravity of wood. Although influence of these factors seems to differ with species, on the basis of reported findings, they should be recognized as variables to consider in any study analyzing factors affecting specific gravity of wood.

Age

As mentioned previously, several South African authors (14) (42) (43) (53), believe age of the cambium at time the wood is formed is the primary factor affecting specific gravity. Turnbull was able to show an increase in specific gravity as rate of growth increased and cambium producing the

[6] The term assimilation is used here in the broad sense to include production of cell-wall substances.

wood became older. These authors reason that since specific gravity of wood is dependent upon age of the tree at time of formation, a tree that initially grew rapidly and therefore possessed a large volume of core material with low specific gravity would produce a greater volume of high-density wood at a given older age than would one initially slower growing. This is because of the increased circumference and enlarged area which a corresponding annual ring would occupy in the cross section of the fast-growing tree. They believe, therefore, that a stand should be managed in such a manner as to allow a rapid rate of growth initially. These workers, of course, studied young, plantation-grown species. No one has demonstrated conclusively that specific gravity is dependent primarily upon age of cambium at time of wood formation in coniferous trees in the United States.

Trendelenburg (52) prepared a chart showing variation of specific gravity with age. He used Schwappach's extensive data (41) and found for Norway spruce average specific gravity increased up to an age of about 105 years, then decreased. For Scotch pine, specific gravity increased until about 40 years of age, then decreased. These data represent only average values; i.e., Trendelenburg made no attempt to consider percentage of summerwood or rate of growth in their relationship to specific gravity.

Paul and Smith (35), in discussing effect of age on specific gravity, stated that any relationship between these two variables was subject to interruption by environmental factors. They indicated such interruptions occurred in dense stands, on dry sites, as a result of partially cutting a stand, by radical crown reduction, and by production of compression wood in leaning trees. Paul (33) studied specific gravity and shrinkage variations occurring when slow-growing ponderosa pine trees were released. He found specific gravity of wood formed before and after accelerated growth differed only slightly; that formed before release was slightly the heavier. This situation is in contrast to results reported by Turnbull (53) and others (14) (42) (43).

There seems to be evidence that age does have some influence on specific gravity of wood. Different workers do not agree on relative importance of this factor; however, apparently more emphasis than in the past might be directed toward determining the influence of age.

Genetics

An interesting sidelight on growth conditions was given by Zobel (61). He indicated growth is controlled primarily by genetic make up of the plant, and importance of environment was completely dependent upon rigidity with which genetic factors control the plant. He asserts that the silvicultural approach (stocking, thinning, and pruning) has been shown to be insufficient to produce wood for specialized uses. Present studies (28) (50) (62) are preliminary in nature, but silviculturists and wood technologists are confident that various properties and qualities are capable of being changed genetically and will be so controlled in the future.

Appendix B

Data on Individual Trees Studied

TABLE 15

Code no.	Location	Site class	Crown* class	D.B.H. o.b.**	Height to base of live crown	Mer-chant-able length	Total height
				Inches	*Feet*	*Feet*	*Feet*
O-A	Wind River	III	Codom.	18.0	76	103	126
O-B	Wind River	III	L. I.	12.4	53	52	94
O-C	Wind River	III	Dom.	24.4	83	123	150
O-D	Wind River	III	H. I.	14.1	46	76	123
1-A	Rigdon***	IV	Dom.	26.7	95	128	158
1-B	Rigdon	IV	Codom.	17.1	78	96	132
1-C	Rigdon	IV	L. I.	13.0	41	66	98
1-D	Rigdon	IV	H. I.	13.7	66	66	94
2-A	Lowell***	III	Dom.	23.0	88	109	138
2-B	Lowell	III	Codom.	19.0	90	105	130
2-C	Lowell	III	H. I.	13.0	88	85	121
2-D	Lowell	III	L. I.	16.4	60	84	105
3-A	Lowell	II	L. I.	13.1	88	66	114
3-B	Lowell	II	Dom.	18.0	115	120	148
3-C	Lowell	II	Codom.	21.7	78	118	145
3-D	Lowell	II	H. I.	14.3	83	89	130
4-A	McCleary Exp. For.	II	L. I.	11.5	82	52	104
4-B	McCleary Exp. For.	II	Dom.	22.7	80	103	133
4-C	McCleary Exp. For.	II	H. I.	13.1	80	66	115
4-D	McCleary Exp. For.	II	Codom.	18.5	70	89	125
5-A	Simpson Log. Co.	IV	H. I.	13.3	30	60	94
5-B	Simpson Log. Co.	IV	L. I.	12.8	50	47	83
5-C	Simpson Log. Co.	IV	Codom.	14.4	65	65	92
5-D	Simpson Log. Co.	IV	Dom.	21.4	50	86	112
6-A	Hood Canal Exp. For.	III	Dom.	23.6	57	102	134
6-B	Hood Canal Exp. For.	III	Codom.	16.2	65	78	113
6-C	Hood Canal Exp. For.	III	L. I.	12.3	37	49	93
6-D	Hood Canal Exp. For.	III	H. I.	15.3	48	65	104
7-A	Cascade Head	II	Dom.	34.5	85	138	160
7-B	Cascade Head	II	Codom.	25.2	112	132	155
7-C	Cascade Head	II	L. I.	19.8	63	83	111
7-D	Cascade Head	II	H. I.	19.6	65	100	128
8-A	McDonald Forest	IV	Dom.	19.2	78	84	103
8-B	McDonald Forest	IV	Codom.	18.2	52	69	101
8-C	McDonald Forest	IV	H. I.	15.0	84	65	103
8-D	McDonald Forest	IV	L. I.	12.3	89	63	103

* The following abbreviations have been used for crown classes: Dom., Dominant; Codom., Codominant; H. I., High Intermediate; L. I., Low Intermediate.
** Diameter at breast height, outside bark.
*** Rigdon and Lowell are ranger districts in the Willamette National Forest.

Appendix C

Summaries of Analyses of Variance

Table 16. Summary of Analyses of Variance of Specific Gravity by Crown Class and Location Within Each Decade for Site Class II at the 20.5-Foot Height.

Source of variation	Sum of squares	Degrees of freedom	Mean square	F
		Decade 1		
Total	0.042617	11	....	....
Crown class	.014350	3	0.004783	1.03
Location	.000392	2	.000196	0.04
Error	.027875	6	.004646	....
		Decade 2		
Total	.011625	11	....	....
Crown class	.000835	3	.000278	0.27
Location	.004650	2	.002325	2.27
Error	.006140	6	.001023	....
		Decade 3		
Total	.011802	11	....	....
Crown class	.002625	3	.000875	0.64
Location	.001017	2	.000508	0.37
Error	.008160	6	.001360	....
		Decade 4		
Total	.015367	11	....	....
Crown class	.002300	3	.000767	0.54
Location	.004517	2	.002258	1.58
Error	.008550	6	.001425	....

Table 17. Summary of Analyses of Variance of Specific Gravity by Crown Class and Location Within Each Decade for Site Class III at the 20.5-Foot Height.

Source of variation	Sum of squares	Degrees of freedom	Mean square	F
		Decade 1		
Total	0.009492	11	....	....
Crown class	.001892	3	0.000631	0.33
Location	.000467	2	.000233	0.12
Error	.007133	6	.001888	....
		Decade 2		
Total	.032167	11	....	....
Crown class	.016567	3	.005522	2.55
Location	.002617	2	.001308	0.60
Error	.012973	6	.002162	....
		Decade 3		
Total	.025092	11	....	....
Crown class	.008092	3	.002697	1.90
Location	.008467	2	.004234	2.98
Error	.008533	6	.001422	....
		Decade 4		
Total	.027425	11	....	....
Crown class	.008892	3	.002964	1.50
Location	.006650	2	.003325	1.68
Error	.011883	6	.001980	....
		Decade 5		
Total	.020425	11	....	....
Crown class	.003692	3	.001231	0.45
Location	.000330	2	.000165	0.06
Error	.016403	6	.002734	....

Table 18. Summary of Analyses of Variance of Specific Gravity by Crown Class and Location Within Each Decade for Site Class IV at the 20.5-Foot Height.

Source of variation	Sum of squares	Degrees of freedom	Mean square	F
		Decade 1		
Total	0.013892	11	....	....
Crown class	.004092	3	0.001364	3.93
Location	.007717	2	.003858	11.12*
Error	.002083	6	.000347	....
		Decade 2		
Total	.010625	11	....	....
Crown class	.000758	3	.000253	0.62
Location	.007400	2	.003700	9.00**
Error	.002467	6	.000411	....
		Decade 3		
Total	.008892	11	....	....
Crown class	.002625	3	.000875	2.14
Location	.003817	2	.001908	4.68
Error	.002450	6	.000408	....
		Decade 4		
Total	.007267	11	....	....
Crown class	.001067	3	.000356	0.52
Location	.002117	2	.001058	1.56
Error	.004083	6	.000680	....
		Decade 5		
Total	.004225	11	....	....
Crown class	.000625	3	.000208	0.69
Location	.001800	2	.000900	3.00
Error	.001800	6	.000300	....

* Beyond the 5% level of probability.
** Beyond the 1% level of probability.

Appendix D

Statistical Data Related to Regression

Table 19. Calculation of Sums of Squares and Products for Percentage of Summerwood, Growth Rate and Specific Gravity Data in Four Different Age Periods.*

	Decade 1	Decade 2	Decade 3	Decade 4
S X_1^2**	11,657.1735	28,796.5114	43,035.6287	52,530.9431
C.T.	10,970.8167	27,599.1769	41,664.2940	51,103.8771
S x_1^2	686.3568	1,197.3345	1,371.3347	1,427.0660
S X_2^2	1,130.8000	2,551.1200	7,110.3600	12,642.9500
C.T.	969.2844	2,215.2711	6,037.2900	11,140.8025
S x_2^2	161.5156	335.8489	1,073.0700	1,502.1475
S Y^2	5.3981	6.0650	7.4472	8.2225
C.T.	5.3284	6.0025	7.3984	8.1701
S y^2	0.0697	0.0625	0.0488	0.0524
S X_1X_2	3,326.2520	7,949.9630	16,126.0510	23,816.5410
C.T.	3,260.9572	7,819.1853	15,859.9945	23,860.8089
S x_1x_2	65.2948	130.7777	266.0565	−44.2679
S X_1Y	243.2298	411.1289	558.8238	650.9626
C.T.	241.7787	407.0185	555.2019	646.1596
S x_1y	1.4511	4.1104	3.6219	4.8030
S X_2Y	72.4380	117.8080	214.8230	301.6350
C.T.	71.8661	115.3133	211.3440	301.6971
S x_2y	0.5719	2.4947	3.4790	−0.0621

* Thirty-six specimens were included in the first four decades.
** X_1—percentage of summerwood; X_2—rings per inch; C.T.—correction term.

Table 20. SCHEMATIC PRESENTATION OF SUMS OF SQUARES AND PRODUCTS (FROM TABLE 19) FOR PERCENTAGE OF SUMMERWOOD (x_1), GROWTH RATE (x_2) AND SPECIFIC GRAVITY (y) FOR CALCULATION OF TOTAL REGRESSION, MULTIPLE CORRELATION COEFFICIENTS AND PARTIAL REGRESSION COEFFICIENTS.

	x_1	x_2	y
	Decade 1		
x_1	686.3568	65.2948	1.4511
x_2		161.5156	0.5719
y			0.0697
	Decade 2		
x_1	1,197.3345	130.7777	4.1104
x_2		335.8489	2.4947
y			0.0625
	Decade 3		
x_1	1,371.3347	266.0565	3.6219
x_2		1,073.0700	3.4790
y			0.0488
	Decade 4		
x_1	1,427.0660	–44.2679	4.8030
x_2		1,502.1475	–0.0621
y			0.0524

Appendix E

Data on All Specific Gravities; By Height, Crown Class and Decade

Table 21. AVERAGE SPECIFIC GRAVITY FOR THE DIFFERENT CROWN CLASSES AT DIFFERENT HEIGHT LEVELS AND DECADES FOR SITES II, III, AND IV.

		Crown classes								
		Dominant		Codominant		High int.		Low int.		
Height level*	Decade	Sp gr	Specimens	Sp gr	Specimens	Sp gr	Specimens	Sp gr	Specimens	Average**
1	1	0.421	10	0.412	9	0.424	9	0.413	9	0.418
	2	.415	10	.417	9	.418	9	.431	9	.420
	3	.460	10	.463	9	.477	9	.482	9	.470
	4	.483	10	.501	9	.507	9	.514	9	.501
	5	.512	10	.511	9	.516	8	.531	7	.517
	6	.506	8	.514	7	.520	6	.530	3	.515
	7	.490	7	.507	3	.537	3	.520	1	.506
	8	.570	1	....	..	....	..	....	..	.570
	*Avg***	.469		.470		.477		.477		
2	1	.391	9	.390	9	.384	9	.373	9	.385
	2	.391	9	.402	9	.416	9	.422	9	.408
	3	.444	9	.462	9	.458	9	.450	9	.454
	4	.463	9	.482	9	.483	9	.477	9	.476
	5	.476	8	.476	8	.480	8	.484	8	.479
	6	.453	7	.478	7	.495	6	.480	4	.475
	7	.480	2	.435	2	....	..	....	..	.466
	8	.470	1	....	..	....	..	....	..	.470
	*Avg***	.437		.466		.450		.445		

* Height level 1—3 to 4 feet above stump,
2—20.5 to 21.5 feet above stump.

** Weighted averages.

Table 21. (Continued)

		Crown classes								
		Dominant		Codominant		High int.		Low int.		
Height level*	Decade	Sp gr	Speci-mens	Sp gr	Speci-mens	Sp gr	Speci-mens	Sp gr	Speci-mens	Average**
3	1	0.372	9	0.401	8	0.388	9	0.379	9	0.384
	2	.387	9	.404	9	.407	9	.418	9	.404
	3	.436	9	.442	9	.453	9	.448	9	.445
	4	.442	9	.451	9	.472	8	.459	8	.456
	5	.424	8	.361	8	.455	6	.433	6	.440
	6	.420	6	.460	4	.447	3	.480	1	.441
	7	.430	1	....	..	....	..	....	..	.430
	*Avg***	.413		.434		.434		.427		
4	1	.384	8	.401	9	.391	9	.370	6	.388
	2	.390	8	.404	9	.409	9	.392	6	.400
	3	.428	8	.433	9	.439	9	.422	5	.432
	4	.430	8	.438	8	.444	7	.440	5	.438
	5	.422	6	.454	5	.460	5	.420	3	.440
	6	.413	3	.535	2	.440	1	....	..	.458
	7	.420	1	....	..	....	..	....	..	.420
	*Avg***	.410		.428		.425		.406		

* Height level 3—38.0 to 39.0 feet above stump,
4—55.5 to 56.5 feet above stump.

** Weighted averages.

Table 21. (Continued)

Height level*	Decade	Crown classes: Dominant Sp gr	Dominant Speci-mens	Codominant Sp gr	Codominant Speci-mens	High int. Sp gr	High int. Speci-mens	Low int. Sp gr	Low int. Speci-mens	Average**
5	1	0.396	8	0.404	7	0.385	4	0.350	2	0.392
	2	.392	8	.401	7	.400	4	.375	2	.395
	3	.406	8	.418	7	.438	4	.410	2	.417
	4	.414	7	.442	5	.448	4	.420	2	.430
	5	.414	5	.430	5	.440	3	.470	1	.429
	6	.410	2	....	..	....	..	....	..	.410
	7	.440	1	....	..	....	..	....	..	.440
	*Avg***	.405		.417		.421		.398		
6	1	.420	6	.404	5	.370	1	....	..	.409
	2	.403	6	.402	5	.390	1	....	..	.402
	3	.414	5	.415	4	.430	1	....	..	.416
	4	.415	4	.415	4	.450	1	....	..	.419
	5	.410	2	.420	2	....	..	....	..	.415
	6	.400	1	....	..	....	..	....	..	.400
	*Avg***	.412		.410		.410				

* Height level 5—73.0 to 74.0 feet above stump,
6—90.5 to 91.5 feet above stump.

** Weighted averages.

Table 21. (Concluded)

Height level*	Decade	Crown classes: Dominant Sp gr	Dominant Specimens	Codominant Sp gr	Codominant Specimens	High int. Sp gr	High int. Specimens	Low int. Sp gr	Low int. Specimens	Average**
7	1	0.420	4	0.415	2	....	..	....	..	0.418
	2	.408	4	.400	2	....	..	....	..	.405
	3	.420	4	.435	2	....	..	....	..	.425
	4	.447	3	.435	2	....	..	....	..	.442
	5	.425	2	.430	1	....	..	....	..	.427
	6	.430	1	....	..	....	..	....	..	.430
	*Avg***	.423		.326						
8	1	.435	2	.430	1	....	..	....	..	.433
	2	.415	2	.440	1	....	..	....	..	.423
	3	.420	2	.450	1	....	..	....	..	.430
	4	.415	2	.440	1	....	..	....	..	.423
	*Avg***	.421		.440						

* Height level 7—108.0 to 109.0 feet above stump,
8—125.5 to 126.5 feet above stump.

** Weighted averages.

Appendix F
Data on Results of Strength Tests

Table 22. TEST DATA FOR CERTAIN STRENGTH PROPERTIES OF YOUNG-GROWTH DOUGLAS FIR SELECTED FROM NINE DIFFERENT AREAS.

Test specimens	Static bending: Modulus of rupture	Static bending: Modulus of elasticity	Static bending: Horizontal shear	Compression parallel to grain	Compression perpendicular to grain	Height in tree*	Specific gravity
	Lb/in.^{2}	*M Lb/in.*^{2}	*Lb/in.*^{2}	*Lb/in.*^{2}	*Lb/in.*^{2}	*Feet*	
0-A-2	8,400	1,800	950	4,100	500	6	0.49
0-A-6	7,000	1,370	980	2,500	460	74	.42
0-B-2	8,100	1,680	970	3,920	540	6	.48
0-B-5	8,000	1,470	970	3,720	520	37	.44
0-C-2	7,000	960	770	3,490	560	6	.44
0-C-7	6,100	1,060	780	3,200	340	88	.41
0-D-2	5,500	1,000	710	2,490	280	6	.37
0-D-5	6,500	1,240	840	2,990	260	41	.39
1-A-2	8,800	1,820	1,010	4,520	570	6	.51
1-A-9	7,000	1,410	800	3,200	380	110	.44
1-B-2	8,800	1,820	1,090	3,800	520	6	.51
1-B-6	7,200	1,270	930	3,490	520	70	.46
1-C-2	9,400	1,750	1,110	3,650	430	6	.50
1-C-6	7,900	1,440	930	3,350	440	58	.49
1-D-2	9,400	1,720	1,080	4,470	570	6	.57
1-D-5	8,800	1,680	1,010	3,400	410	53	.47
2-A-2	8,000	1,510	1,000	3,670	660	6	.47
2-A-8	6,800	1,250	730	3,150	340	93	.41
2-B-2	8,200	1,560	910	........**	550	6	.48
2-B-8	5,900	1,150	630	3,590	240	93	.38
2-C-2	9,100	1,890	1,080	4,680	450	6	.53
2-C-6	7,000	1,350	860	3,340	310	70	.41

Table 22. (Continued)

Test specimens	Static bending: Modulus of rupture	Static bending: Modulus of elasticity	Static bending: Horizontal shear	Compression parallel to grain	Compression perpendicular to grain	Height in tree*	Specific gravity
	Lb/in.²	*M Lb/in.²*	*Lb/in.²*	*Lb/in.²*	*Lb/in.²*	*Feet*	
2-D-2	8,400	1,990	930	3,830	480	6	0.47
2-D-5	6,800	1,300	880	3,250	370	70	.44
3-A-2	9,400	1,920	1,040	4,780	500	6	.50
3-A-6	7,200	1,490	940	3,880	430	58	.44
3-B-2	7,900	1,660	880	4,220	590	6	.49
3-B-8	5,600	1,060	670	2,820	290	105	.38
3-C-2	8,800	1,680	1,100	3,510	740	6	.48
3-C-6	7,200	1,230	870	3,500	360	93	.43
3-D-2	10,500	1,750	1,220	5,350	570	6	.55***
3-D-5	7,400	1,470	830	3,640	390	70	.44
4-A-2	6,700	1,440	780	2,720	330	6	.42
4-A-5	6,000	1,240	910	2,830	400	50	.44
4-B-2	9,200	1,540	990	3,660	530	6	.52
4-B-7	6,400	1,340	........**	........**	........**	88	........**
4-C-2	6,500	1,240	780	3,110	320	6	.42
4-C-5	6,600	1,300	790	2,810	340	53	.41
4-D-2	7,900	1,700	920	3,920	490	6	.46
4-D-7	5,500	1,130	830	2,860	350	76	.39
5-A-2	9,300	1,700	1,020	4,670	550	6	.50
5-A-5	6,800	1,120	730	3,030	340	41	.41
5-B-2	7,600	1,480	810	3,510	380	6	.47
5-B-4	6,400	1,170	770	2,980	290	35	.41
5-C-2	8,200	1,850	800	4,370	540	6	.49
5-C-6	7,100	1,410	790	3,180	260	58	.45
5-D-7	6,400	1,240	710	2,200	260	76	.39
6-A-2	8,900	1,680	900	4,040	600	6	.51
6-A-7	6,100	1,130	740	2,950	340	88	.40†
6-B-2	9,700	1,750	870	5,120	710	6	.53
6-B-6	7,300	1,240	820	3,650	410	76	.43

Table 22. (Concluded)

Test specimens	Static bending: Modulus of rupture	Static bending: Modulus of elasticity	Static bending: Horizontal shear	Compression parallel to grain	Compression perpendicular to grain	Height in tree*	Specific gravity
	Lb/in.²	*M Lb/in.²*	*Lb/in.²*	*Lb/in.²*	*Lb/in.²*	*Feet*	
6-C-2	8,600	1,850	1,190	4,600	550	6	0.55
6-C-4	8,500	1,750	1,090	4,760	450	35	.54
6-D-2	7,000	1,440	950	3,860	460	6	.48
6-D-6	7,400	1,390	900	3,480	530	58	.44
7-A-2	7,800	1,270	1,020	3,610	590	6	.48
7-A-9	7,000	1,120	740	2,980	360	121	.45
7-B-2	9,300	1,750	1,040	3,890	600	6	.53
7-B-7	7,800	1,440	820	2,790	400	110	.46
7-C-2	6,200	1,270	840	2,970	240	6	.42
7-C-6	6,100	1,130	750	2,630	250	71	.40
7-D-2	6,100	1,030	940	2,000	340	6	.43
7-D-7	6,700	1,150	860	2,910	410	76	.40***
8-A-2	7,600	1,540	870	3,910	640	6	.50
8-A-7	6,300	1,000	640	2,870	300	76	.41
8-B-2	8,100	1,660	930	4,310	430	6	.49
8-B-6	6,900	1,170	840	3,220	320	58	.42
8-C-2	8,200	1,780	920	4,430	620	6	.49
8-C-5	6,600	1,540	860	3,610	360	53	.41
8-D-2	8,200	1,630	970	4,290	560	6	.50
8-D-5	6,200	1,480	790	2,760	380	53	.40

* Height above stump to center of 4-ft. bolt. Stump height varied from 15 to 24 inches.
** Data missing.
*** Exceeded capacity of machine.
† Brashy.

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Lee J. Nelson	West Coast Lumbermen's Association
Walter F. McCulloch	School of Forestry
Freeman Schultz	Western Pine Association

R. M. Kallander, Administrator

Forest Products Research Center

. . . Its Purpose

Fully utilize the resource by:

- developing more by-products from mill and logging residues to use the material burned or left in the woods.
- expanding markets for forest products through advanced treatments, improved drying, and new designs.
- directing the prospective user's attention to available wood and bark supplies, and to species as yet not fully utilized.
- creating new jobs and additional dollar returns by suggesting an increased variety of saleable products. New products and growing values can offset rising costs.

Further the interests of forestry and forest products industries within the State.

. . . Its Program

- Accelerated air drying of lumber with fans, to lower shipping costs.
- Kiln schedules for thick Douglas fir lumber, to speed drying.
- Bevel siding from common lumber, to increase sales.
- End gluing of dimension lumber, to utilize shorts.
- Effect of spacing and end distance on strength of bolted joints.
- Production and bleaching of high-yield pulps from Douglas fir mill residues.
- Strength of wood and wood structures.
- Douglas fir wood and bark lignin and bark extractives for full recovery.
- Ammoniated wood and bark as improved soil amendments.
- Service tests of treated and untreated wood products.
- Floor tile from wood and bark residues.