
WESTERN WOOD DENSITY SURVEY

REPORT NUMBER 1

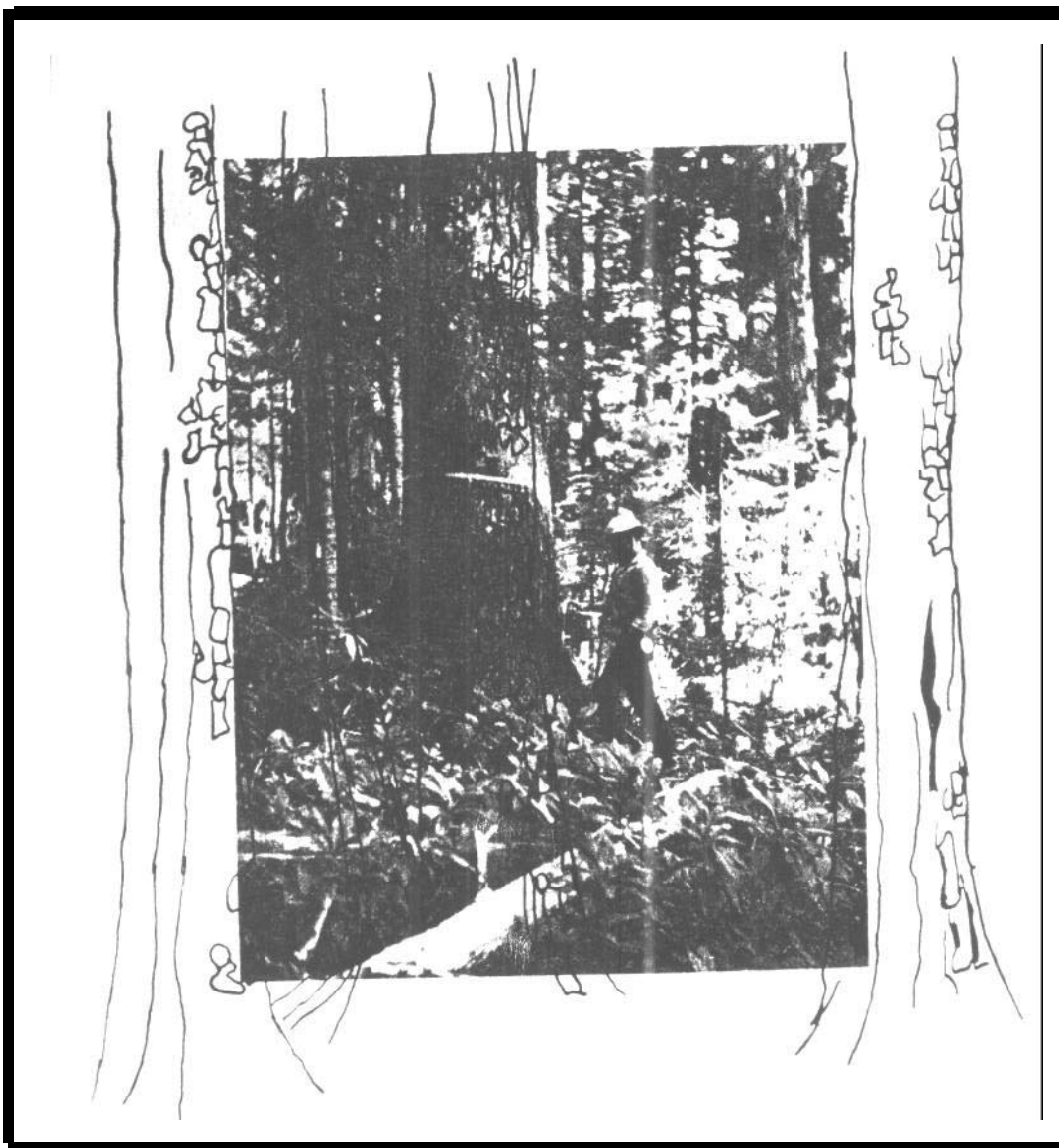
JOINT REPORT OF:

FOREST PRODUCTS LABORATORY

PACIFIC NORTHWEST FOREST AND RANGE EXPERIMENT STATION

INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION

PACIFIC SOUTHWEST FOREST AND RANGE EXPERIMENT STATION



ABSTRACT

Mean specific gravities by Forest Survey Units are presented for 9 species of the 23 sampled by the Western Wood Density Survey. Environmental relationships and strength-property relationships with specific gravity are discussed.

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ACKNOWLEDGMENT

The successful execution of the Western Wood Density Survey was dependent on the efforts of many organizations and individuals. Substantial financial support from the industry trade associations was essential to expedite the Survey. Large corporations and independent loggers helped smooth the way for sample collection. Assistance from various State agencies, the Bureau of Land Management, and cooperation among the Experiment Stations, Regions, and Ranger Districts of the Forest Service were of major importance. To all participants in the Western Wood Density Survey grateful acknowledgment is hereby given,

WESTERN WOOD DENSITY SURVEY

REPORT NUMBER 1

BY
FOREST SERVICE¹
U.S. DEPARTMENT OF AGRICULTURE

INTRODUCTION

The Western Wood Density Survey was initiated by the U.S. Forest Service in the spring of 1960 to meet increasing needs for better information on the specific gravity and related strength properties of western softwoods. The nondestructive calibrated increment borer technique, previously developed and tested in the South, was used in the sampling of 30,326 trees on 4,225 plots systematically located on commercial forest lands extending from the Great Plains to the Pacific Ocean

Field collection of increment core samples and related information was under the direction of Forest Survey units of the U.S. Forest and Range Experiment Stations in the Western United States. The original plan contemplated complete integration of the wood-quality study with the normal schedule of the Forest Survey, and the 1960 sampling was on this basis. Some 723 plots were occupied the first field season, and at this rate it would have taken from 10 to 15 years to complete the job to the original standards, all commercial species and areas considered.

Early in 1961 the western wood-using industries asked the Forest Service to develop a new plan that would assure the availability of data for Douglas-fir and certain associated high-priority species within 3 years, and offered to finance

certain phases of the accelerated program. A revised plan to meet this new timetable was drafted, submitted to and approved by the interested industry groups, and became apart of a formal cooperative agreement entered into by the West Coast Lumberman's Association, the Western Pine Association, the Douglas Fir Plywood Association, and the U.S. Forest Service. June 30, 1964, was the target date for a draft report covering the information called for in the cooperative agreement.

The revised plan, which was put into effect at the beginning of the 1961 field season, differed from the original plan in two respects: (1) the greatly accelerated timetable, and (2) the necessity to concentrate largely on Douglas-fir and other associated high-priority species specified by the industry cooperators in order to meet the deadline and stay within the financing available from Federal and industry sources. Accordingly, certain other "nonpriority" species in some areas were not sampled as adequately as contemplated in the fully Forest Survey-integrated plan originally proposed. The nine high-priority species specified in the agreement are: Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), white fir (*Abies concolor* (Gord. & Glend.) Lindl.), California red fir (*A. magnifica* A. Murr.), Pacific

¹Report issued by the Forest Products Laboratory, Madison, Wis. Collection and processing of data were handled cooperatively by the Laboratory, the Intermountain Forest and Range Experiment Station Ogden, Utah; the Pacific Northwest Forest and Range Experiment Station, Portland, Oreg; and the Pacific Southwest Forest and Range Experiment Station, Berkeley, Calif.

silver fir (*A. amabilis* (Dougl.) Forbes), grandfir (*A. grandis* (Dougl.) Lindl.), noble fir (*A. procera* Rehd.), western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), western larch (*Larix occidentalis* Nutt.), and black cottonwood (*Populus trichocarpa* Torr. & Gray).

The Western Woods Technical Committee, appointed by the three cooperating trade associations, was formed to work closely with the Forest Service on planning, coordination, review of progress, interpretation of results, and other matters of mutual interest. The full committee met with representatives of the Forest Service at least once each year for the duration of the study. To facilitate even closer cooperation, this industry committee formed a small task group, composed of experienced technical specialists. This group met more frequently and worked very closely at the technical level with their counterparts in the Forest Service. As a result, the project benefited greatly from this working relationship.

The primary purpose of this report is to make available to all interested parties the major findings of the Western Wood Density Survey for the nine high-priority species. There are many ways in which the basic data might be presented, but they are here summarized in tables that are believed to be the most informative and useful, all requirements considered. Other tabulations, such as with different area breakdowns, can of course be developed to meet specific needs. The results of statistical analyses, to the extent now completed, are also summarized in tables, and are accompanied by appropriate discussion and interpretation.

OBJECTIVES

The objectives of the Western Wood Density Survey, essentially as spelled out in the work plan, are as follows:

1. To obtain, by systematic sampling, adequate data on the average specific gravity and related quality characteristics of each priority species, the magnitude of the differences between species, and the range of variation within species for the commercial softwood timber stands of the West.

2. Although not specifically designed for this purpose, it was expected that this study would yield much valuable data on the extent to which

Although the data here presented are basic to more effective structural utilization and marketing of western softwoods, this report stops short of practical applications. It contains the essential factual information, but makes no recommendations regarding the establishment and administration of basic stresses and working stresses for use in structural applications. Such matters are beyond the scope of the present study. The Forest Service, however, expects to assist in such matters through cooperation with industry, the American Society for Testing and Materials, certifying agencies, building code authorities, the Federal Housing Administration, the National Bureau of Standards, and similar organizations.

As the report title implies, this is the first of a series of planned publications on the Western Wood Density Survey. It contains all the basic information called for in the cooperative agreement with industry, but is limited in scope to the nine priority species. Additional reports will be issued from time to time as continuing research rounds out data for other species or develops new interpretations, relationships, or applications. First consideration will be given to completion of basic data for such commercially important species as western redcedar, Engelmann spruce, Sitka spruce, ponderosa pine, lodgepole pine, redwood, and the soft pines. As time permits, data for all species will be subjected to the same rigorous statistical analysis as that here reported for Douglas-fir. Also planned are chemical analyses of selected sample material, and local in-depth studies of the effects of environmental and other factors on specific gravity variation in western softwoods.

specific gravity varies with tree age, tree volume, tree growth rate, climate, latitude, longitude, altitude, aspect, and other factors known to affect or suspected of affecting wood density. Such information is of interest to forest managers concerned with growing higher quality, higher value timber. It was also assumed, on the basis of experience in the South, that systematic sampling on such a gigantic scale would lead to the discovery of individual trees that are superior in wood quality as well as form, growth rate, and other desirable characteristics. Once located, such potentially

elite trees could be checked out by geneticists for possible use in breeding studies and to provide scion material for seed orchards.

3. When existing data are deficient, to conduct such studies as are necessary to better establish, for each of the priority species over the range of specific gravities found in the systematic

survey, the relationships between specific gravity and the strength and stiffness of clear wood specimens. Sound data on strength-specific gravity relationships are basic to the establishment of basic stresses and working stresses for use in structural applications.

ASSIGNMENT OF RESPONSIBILITIES

The Western Wood Density Survey divided logically into four phases, and completion of all four phases was necessary before primary data for the establishment of working stresses could be made available. Work included in each phase, and the assignment of responsibility therefore, is as follows:

Phase I--This phase was concerned with the planning and collection of increment cores and related data from sample trees on plots distributed throughout the commercial forest area of the 12 western States. The Forest Survey units of the western U.S. Forest and Range Experiment Stations were responsible for this work.

Phase II--Included in this phase were the laboratory processing of the sample cores, the statistical analysis and interpretation of the results, and a major part of the report writing. The Forest Products Laboratory had primary responsibility for Phase II.

Phase III--This task consisted of studies to determine, for each of the nine priority species over its natural range, the relationship between increment core specific gravity at breast height and the average (tree) specific gravity for the merchantable volume of the whole tree, or various portions thereof. Included were pre-sampling in the field, the felling and destructive sampling of 1,526 selected trees, the collection

of about 8,000 sample disks at various intervals up the bole from stump to merchantable top diameter, laboratory processing of the disks, and statistical analysis and interpretation of the resulting data. The Forest Products Laboratory had primary responsibility for this study. Significant contributions of time, materials, equipment, and logs were made by private loggers and District Hangers and Experiment Station personnel of the Forest Service.

Phase IV--This phase of the study was aimed at employing the wood density data derived from the earlier phases to obtain more reliable estimates of properties. This was to be done using a knowledge of the relationships between specific gravity and the modulus of elasticity and strength properties of clear wood specimens. The exact nature and magnitude of Phase IV could not be precisely determined until data from the other phases became available for inspection and comparison with existing information on the strength properties of the species concerned. However, on the basis of preliminary increment core data, additional sample trees of two important species--Douglas-fir and white fir--were sampled and strength and stiffness determinations made on clear wood specimens therefrom. This work was the responsibility of the Forest Products Laboratory.

PHASE I- Collection of Sample Increment Cores and Related Data²

This phase consisted of the physical task of collecting increment cores from sample trees and gathering related data concerning the trees and

their environment. The data were collected on sample plots distributed throughout the commercial forest area of 12 western States. Although

²M. E. Metcalf of the Pacific Northwest Forest and Range Experiment Station, A. B. Caporaso of the Intermountain Forest and Range Experiment Station, and E. M. Hornibrook of the Pacific Southwest Forest and Range Experiment Station were responsible for developing the sampling plan and collecting the samples.

some features of the sampling design and plot design varied between areas, the same information concerning trees, cores, and tree environment was collected in all cases as shown in table 1,

Table 1. --Field data collected

Trees	Cores	Plots
Species	Length (to 1/50 inch)	State
Diameter (to 1/10 inch)	Diameter ¹ (to 1/1000 inch)	County
Bark thickness (to 1/10 inch)	Radial growth, last 10 years in Washington, Oregon, and California (to 1/20 inch)	Latitude (to 15 minutes)
Total height (or cubic volume)		Longitude (to 15 minutes)
		Elevation (to 100 or 200 feet)
		Aspect
		Site tree
		Topographic site
		Basal area per acre

¹ The bore diameter of all increment borers used was measured with a taper gage and this measurement recorded as the core diameter.

Actual collection of cores and related data under Phase I started in 1960 in the States of Idaho, Montana, South Dakota, Utah, Wyoming, Washington, and Oregon, and was completed in all States by the fall of 1962. However, some additional cores for selected species in southwestern Washington were collected by the Forest Survey project in the summer of 1963.

A total of 30,326 sample cores were collected at 4,225 sample locations distributed by States as shown in table 2.

Table 2. --Geographical location of sample plots and cores

State	Number of sample locations	Number of sample cores
Arizona	184	1,254
California	539	4,960
Colorado	25	211
Idaho	711	5,114
Montana	463	4,284
New Mexico	109	672
Oregon	849	5,622
South Dakota	88	397
Utah	172	1,152
Washington	787	4,774
Wyoming	298	1,886
Total	4,225	30,326

Organization and Supervision

The organization and supervision of Phase I were carried out by the Forest Survey projects at the three western Forest and Range Experiment Stations. These Stations and the areas for which they were responsible are:

Pacific Northwest Forest and Range Experi-

ment Station, Portland, Oreg. (Oregon and Washington.)

Pacific Southwest Forest and Range Experiment Station, Berkeley, Calif. (California.)
 Intermountain Forest and Range Experiment Station, Ogden, Utah. (Montana, Idaho, Wyoming, Colorado, Arizona, New Mexico, Utah, Nevada, and western South Dakota)

In those areas where current Forest Survey inventories or National Forest working circle inventories were being carried on in the years 1961 and 1962, the collection of sample cores and related data was absorbed as part of these regular inventory projects. In the remaining areas, special crews were used. In all areas the system used was closely related to the Forest Survey inventory system in use in the area.

Procedures

The sampling design and plot procedures varied somewhat among the three principal areas--the Pacific Northwest, California., and the Intermountain States. A brief description of the principal features of the system used in each of the areas follows:

Pacific Northwest (Oregon and Washington)

The sampling design used for the Wood Density Survey in Oregon and Washington was based on the systematic grid established for forest inventory work in these two States by the Forest Survey and National Forest Administration. The sampling intensity of the Wood Density Survey was one field plot every 6.8 miles. A total of 1,878 plots from the sample grid were located on photos as potential Wood Density Survey plots in these two States. Of this total, 1,512 plots yielded sample cores. An additional 124 plots were later established without reference to the basic grid to obtain sample cores from species which were missed or too lightly sampled by the basic grid, bringing the total number of plots to 1,636. All field plots except the 124 extra plots were pinpricked on aerial photos and witnessed on the ground so that they could be relocated if necessary.

Two different collection procedures were used in these States. The first was used in 1960 on

plots established by Forest Survey, the Bureau of Land Management, and the States of Oregon and Washington in the course of their regular forest inventories.

Under these first procedures, the Wood Density Survey plots consisted of two variable-radius subplots located 2 chains apart. The center of the first subplot coincided with the pinpricked location on the aerial photograph; the second subplot was 2 chains north of the first. At each subplot the trees to be tallied were selected by means of a wedge prism. A prism with a basal area factor (BAF) of 40 was used for all plots west of the crest of the Cascade Range and a prism with a BAF of 25 was used for all plots east of the crest of the Cascade Range. One sample core was taken from every live, sound tree 5.0 inches d.b.h. and larger. Cores were taken from trees of all softwood species except white-bark pine (*Pinus albicaulis* Engelm.), subalpine larch (*Larix lyallii* Parl.), western yew (*Taxus brevifolia* Nutt.), and juniper (*Juniperus* sp.), and taken from three hardwood species--red alder (*Alnus rubra* Bong.), black cottonwood (*Populus trichocarpa* Torr. & Gray), and bigleaf maple (*Acer macrophyllum* Pursh).

Each tree was bored to the center or until 10 inches of wood were obtained, whichever came first. If a sample core contained rot, pitch pockets,

limbwood, or was too badly broken, the tree was rebored. No core with less than 5 inches of sound wood was accepted, provided the diameter of the tree was large enough for this. All of the information previously mentioned concerning the core, the tree, and the plot was recorded. A total of 215 plots were established in 1960 under these procedures, 44 in Oregon and 171 in Washington.

The second set of procedures was used beginning in 1961 for all the remaining Wood Density Survey plots established in Oregon and Washington. The plot design and procedures for selecting the trees to be tallied on the plot were identical to those adopted in that year by the Forest Survey for its forest inventories. Under these procedures each plot consisted of 10 variable-radius sample points systematically distributed over an acre. A wedge prism or angle gage with a BAF of 80 for plots west of the crest of the Cascade Range or a BAF of 50 for plots east of the crest was used to select the trees at each sample point. The first tree tallied at each point, of suitable size and species, was bored to obtain the Wood Density Survey sample core. If this tree failed to produce a satisfactory core, the second tree tallied was bored. Otherwise the procedures and data recorded were the same as in 1960. Table 3 shows the total number of plots established in Oregon and Washington by years.

Table 3. --Phase I sample plots in the Pacific Northwest

Agency	Oregon				Washington				Total				Grand	
	1960	1961	1962	1963	1960	1961	1962	1963	1960	1961	1962	1963	Total	
Wood Density Survey ¹	--	90	317	9	---	425	70	115	::	0	515	387	124	1,026
Forest Survey inventory	--	86	180	--	134	---	--	---	::	134	86	180	---	400
National Forest Admin.	30	59	57	--	30	6	--	---	::	60	65	57	---	182
Bureau of Land Management	5	7	---	--	---	---	--	---	::	5	7	---	---	12
State of Oregon	9	---	---	--	---	---	--	---	::	9	---	---	---	9
State of Washington	--	---	---	--	7	---	--	---	::	7	---	---	---	7
Total	44	242	554	9	171	431	70	115	::	215	673	624	124	1,636

¹Plots established by special crews financed by cooperative funds supplied by forest industry groups and the Forest Products Laboratory.

Intermountain (Arizona, Colorado, Idaho, Montana; New Mexico, South Dakota, Utah, Wyoming)

The sampling design varied from State to State; however, all wood density samples were taken at forest inventory locations--either previously established or in the process of being established by Forest Survey and National Forest inventory crews. National Forest inventory crews collected cores on National Forests in Idaho and Utah in the course of regular forest inventories in these areas. Forest Survey inventory crews collected cores in Arizona, New Mexico, and Utah, while cooperative Region 2 Forest Survey crews collected cores in eastern Wyoming and western South Dakota in the course of regular forest inventories in these areas. In the remaining areas where regular forest inventories were not currently under way, special wood density crews financed by special cooperative funds collected samples in western Wyoming, southern Idaho, Colorado, and Montana, from locations established in past Forest Survey programs.

Selection of sample trees varied between the plots established under the regular inventory program by Forest Survey and National Forest Administration (NFA) crews and those established by the wood density crews. On National Forest and Forest Survey inventory plots, merchantable trees 5 inches d.b.h. and larger that were bored for the growth sample were also used for the wood density sample.

The wood density crews, on the other hand, relocated sample plots established in previous forest inventories. At each location, two variable-radius subplots located 2 chains apart were surveyed. The center of the first subplot coincided with the center of the plot established previously for the inventory, and the second was 2 chains north. At each subplot all live merchantable softwood trees 5 inches d.b.h. and larger that were selected by means of a wedge prism were sampled. One increment core was extracted at breast height. Each tree was bored according to procedures used in the Pacific' Northwest. A prism with a BAF of 10 was used in pole timber stands, and a 20 BAF was used in sawtimber stands.

Montana--In western Montana (west of Continental Divide) sample plots were selected from the systematic grid established for forest inven-

tory by Forest Survey and NFA. The sampling intensity was one sample location at 4- by 8-mile grid intersections. A total of 374 locations were sampled.

In eastern Montana a special sample of Douglas-fir was made. Ninety-four samples were randomly selected from forest inventory plots classified as the Douglas-fir type. Eighty-nine out of 94 were found and sampled.

Special wood density crews collected the data in all of Montana.

Idaho--In northern Idaho samples were selected from the systematic grid established for forest inventory by Forest Survey and NFA. The sampling intensity was one sample location at approximately 4 by 8 miles. Southern Idaho did not have a systematic grid. Sample plots were randomly selected from those established previously by Forest Survey and NFA. In northern Idaho, Forest Survey and Region 1 NFA crews collected wood density data during the course of the regular forest inventory. In southern Idaho, Region 4 NFA crews collected similar data on the Cache, Salmon, and Challis National Forests, whereas wood density crews surveyed all the remaining area.

Western South Dakota--On the Black Hills National Forest, samples were selected from the systematic grid established for forest inventory. Using a 6- by 6-mile spacing, 58 plots were sampled. On the forest area outside the National Forest, wood density samples were taken on all of Forest Survey's 30 field locations. The collection of data was absorbed as part of the regular forest inventory project.

Colorado--A special sample of Douglas-fir was made. Twenty-five locations were selected at random from the list of Forest Survey inventory plots containing Douglas-fir. Wood density crews collected the data.

Wyoming--Sample plots were selected at random from forest inventory plots. Wood density crews surveyed plots on the Medicine Bow, Bighorn, Bridger, Teton, and Targhee National

Forests, whereas Forest Survey inventory crews collected wood density 'data on the Shoshone National Forest and all samples outside the National Forests. A total of 298 wood density plots were taken.

Utah--As part of the regular inventory program, Forest Survey collected wood density data on areas outside the National Forests. Region 4 inventory crews and wood density crews collected similar data on all of the National Forests. A total of 172 wood density plots were taken, selected at random from forest inventory plots.

Arizona and New Mexico--Special crews and regular Forest Survey crews collected cores from a total of 184 wood density plots in Arizona and 109 in New Mexico.

Pacific Southwest (California)

Sample plots for the Wood Density Survey were selected from Forest Survey plots containing Douglas-fir, white fir, or red fir already established on commercial forest land throughout California on a 4.75-mile systematic grid. Douglas-fir, white fir, and red fir, either individually or in combination, occurred on 1,100 plots. From these, 500 were selected as wood density sampling locations. Sampling locations were chosen to obtain the greatest possible geographical and altitudinal distribution. An additional 39 plots were later established, without reference to the basic grid, to increase the inadequate sample of red and white fir cores and also to increase the geographical and elevational range of these species. All plots were witnessed on the ground and

location descriptions prepared so that they could be relocated if necessary.

Wood density sample plots consisted of two variable-radius subplots located 2 chains apart. The center of the first subplot coincided with the pinpricked location on the aerial photo; the second subplot was 2 chains north of the first, unless the second subplot fell in an area without trees. In such case the plot was relocated by turning in a clockwise direction by 45° intervals from north (from the center of subplot 1) until the second subplot center fell in timber at 2 chains distance. At each subplot the trees measured, tallied, and bared were selected by means of a wedge prism. The objective was to obtain a combined total of at least 10 cores on the two subplots. The appropriate prism was chosen after making a trial run. In general, a prism with a BAF of 10 was used for small pole timber and sparse open stands, BAF 20 for larger pole timber or fairly open stands, a BAF 30 for small sawtimber, and a BAF 40 for large sawtimber stands. One increment core was extracted according to procedures used in the Pacific Northwest. Cores were taken from all softwood species except pinyon pines, California torrey (nutmeg) (*Torreya californica* Torr.), Pacific yew (*Taxus brevifolia* Nutt.), juniper, and cypress. Neither red alder nor black cottonwood occurred on any of the sample plots.

The number of plots installed in California was 297 in 1961 and 242 in 1962, making a total of 539 for the State. A total of 4,960 sample cores were obtained from 18 softwood species and sent to the Forest Products Laboratory for analysis. Of the total number of cores collected, 20.2 percent were Douglas-fir, 31.3 percent were white fir, and 13.5 percent were red fir. The remaining 35 percent was distributed among the 15 associated softwood species.

PHASE II- increment Core Processing³

Increment cores and accompanying field data sheets were mailed to the Laboratory from the Experiment Stations responsible for their collection. The data gathered at the Laboratory included an estimate of age, sapwood thickness, and incre-

ment core specific gravity, which was added to the field data and punched on an automatic data processing (ADP) card--one card for each tree sampled,

Age estimates were based on annual ring counts

³D. Pronin and E. A. Okkonen of the Forest Products Laboratory performed the major part of the processing.

made on the cores. It should be pointed out that the ring counts furnished estimates of age which became less accurate with larger diameter, older trees. Cores were limited to 10 inches in length; therefore, in trees exceeding 20 inches diameter inside bark, the number of rings from the end of the core to the pith had to be estimated. The average ring count for the 2 inches of core nearest the pith was used to extrapolate the ring count to the pith. The same procedure was used in all situations where the core did not extend the full distance from the cambium to the pith. Although, admittedly, some age estimates are crude, they did provide the basis for segregating the sampled trees into age classes.

Information on sapwood width, to the nearest 1/10 inch, was collected largely from the viewpoint of its application to wood preservation, and as a potential estimate of the effect of extractives on specific gravity. Demarcation between heartwood and sapwood was usually apparent to the naked eye except for the true firs, spruces, and hemlock. Perchloric acid was the best stain indicator for heartwood-sapwood in the above genera, but the destructive effects of the acid made it necessary to use a less caustic stain. Of the other stains indicated in the literature

PHASE III-

Destructive Sampling to Estimate Tree Specific Gravity⁵

Several studies have shown that specific gravity is not the same in the upper portions of the tree as it is at breast height. However, sampling upper stem specific gravities is expensive. Thus, to get some measure of the average specific gravity of all the usable wood in the tree, it seemed desirable to develop a way of predicting this "tree specific gravity" from measurements that could be made at breast height. Following the methods of Wahlgren and Fassnacht (33), a destructive sample was taken and the relationships between tree specific gravity and various independent variables were studied by regression methods for each of the nine priority species.

(17),⁴ a solution of iodine was found to be the most effective. A benzidine solution worked very satisfactorily on the pines and Douglas-fir,

Use of an increment borer of known diameter and measurement of green core length by the field crews permitted calculation of the green volume of the core in cubic centimeters. Oven-drying and weighing to 0.001 gram was the final step in determining the specific gravity on an oven-dry weight-green volume basis. For reasons of economics the cores were not extracted before weighing.

The ADP cards containing field and laboratory data were used as a basis for the preparation of "working" data cards for the nine priority species. The working data cards contained, in addition to the collected data, an estimate of tree specific gravity computed from the regression equations using core specific gravity and tree diameter. Also, latitude and longitude minutes were converted to degree equivalents and the following growth functions computed: d.b.h./age, volume/age, and rings per inch. Replicated basic and working data cards were furnished to industry and Experiment Station cooperators, as stipulated in the original agreement.

Field Procedures

Plot Selection

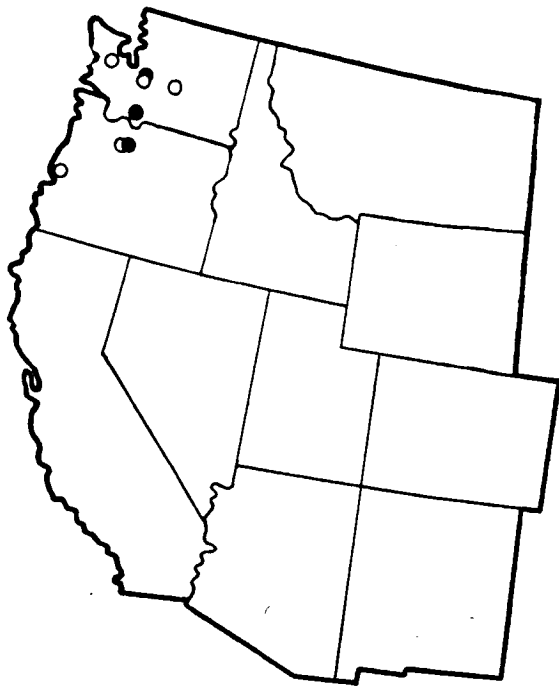
Trees were selected on plots throughout the western United States to insure a representative sample of the natural distribution and volume of each of the nine priority species (figs. 1 and 2). All plots were in areas of active logging to facilitate destructive sampling.

Presampling

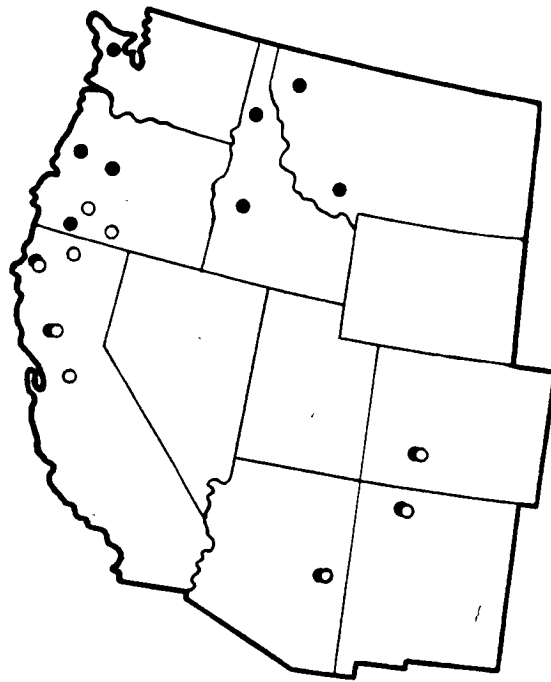
Preliminary tree selection was based on: form

⁴Underlined numbers in parentheses refer to Literature Cited at the end of this report.

⁵H. E. Wahlgren, R. R. Maeglin, and J. F. Heinrichs of the Forest Products Laboratory were responsible for the collection of samples and development of equations used to estimate tree specific gravity.



W. Hemlock ○ 142 Trees
Noble fir ● 75 Trees

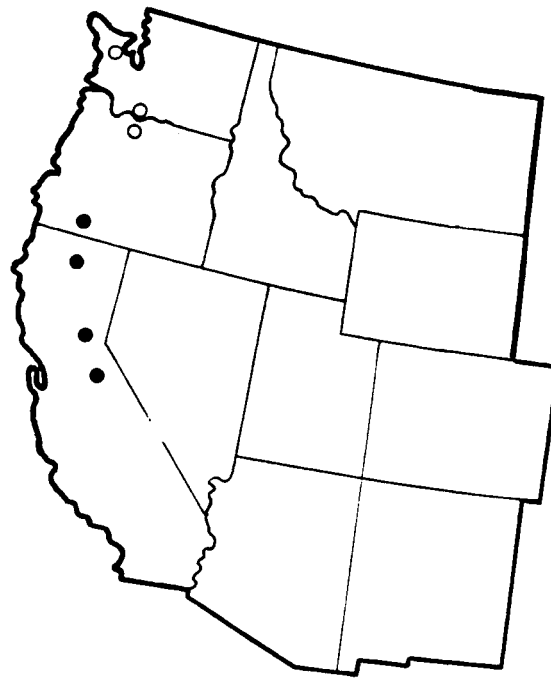


Douglas-fir ● 412 Trees
White fir ○ 280 Trees

Figure 1.--Phase III sample areas for western hemlock, Douglas-fir, noble fir. and white fir. (M 126 499)



Grand fir ● 209 Trees
W. Larch ○ 162 Trees
Blk. Cottonwood ● 78 Trees



Pac. Silver fir ○ 90 Trees
Calif. Red fir ● 157 Trees

(M 126 498)

Figure 2.--Phase III sample areas for grand fir, Pacific silver fir, California red fir. western larch, and black cottonwood.

Diameter : at breast : height : classes :	Increment core specific gravity classes				
	300 - .349	350 - .399	400 - .449	450 - .499	500 - .549
5.0 9.9					
10.0 14.9			30,33	34	31
15.0 19.9		27,39	16,17,28 38	29,29,50	41
20.0 24.9			8,5,12, 15,26,49	25,32,36 37	
25.0 29.9		7,46	9,10,14, 45	6,19,42	47,48
30.0 34.9		8,43,44	13,23	18,20	
35.0 39.9			21,22	35	
40.0 44.9			1,2	4,14	
45.0 49.9					

Figure 3.--Sample of stratification used to select trees for Phase III presampling.

(trees with excessive sweep, lean, or forking were not used); d.b.h. (a complete range of diameters for the area was taken); and soundness--no decayed trees were taken if they could be avoided. Cores were taken at breast height (4.5 feet) with a calibrated increment borer (33), and core length was measured and recorded to the nearest 0.01 inch, cambium to pith or to a maximum length of 10 inches. Cores were then stored in soda straws for later analysis. Each of the trees bored was banded with surveyor's flagging tape and given a preliminary number.

Increment core specific gravities were calculated from green volume and oven-dry weight. A portable oven and balance were used to get the oven-dry weights.

Final selection of about 20-40 trees for each area was made by two-way stratification (fig. 3), using 5-inch d.b.h. classes (e.g. 5.0-9.0 inches

and 0.050 specific gravity classes (e.g. 0.250-0.299). No more than three trees per category were retained. All others were rejected systematically using a random numbers table. Preliminary numbers of the selected trees were then changed to consecutive numbers for the species.

Collection

The selected trees were felled and logs cut⁶ progressively, starting at a point 4.5 feet from the ground, to a merchantable top diameter.⁷ Clear disks 1-1/2 inches thick were cut from the butt end of each log and from the top of the last log and debarked. Disk diameter inside bark (d.i.b.) was measured and recorded to the nearest 0.1 inch. On large trees the disks were reduced to

⁶Log lengths of 16 feet were used when possible.

⁷Merchantable top diameters varied from 3 to 10 inches with locale, species, and tree diameter.

wedges for ease of handling. Log lengths, live crown length, and unused length of top were recorded to the nearest 0.1 foot for each tree. The disks were bagged and shipped to the Forest Products Laboratory for further processing.

Laboratory Procedure

Disks were soaked in water to insure green volume. After soaking, green volume was determined by the water immersion method (13). The disks were then oven-dried to a constant weight; specific gravity for each sample was computed on a green volume-oven-dry weight basis.

Merchantable volume of each tree is the summation of log volumes, including disks. The average specific gravity for each log was estimated from the mean specific gravity of its terminal disks. (Computational details are shown in Appendix A.) The average specific gravity for each tree was weighted for proportional representation of the log volumes.

Development of Prediction

Equations

The relationship of tree specific gravity (Y)

to core specific gravity and other tree characteristics was examined by multiple regression analysis. Individual sampling areas were combined for each species in these analyses, The 10 independent variables considered were:

X₁ = Diameter at breast height

X₂ = Total height of tree

X₃ = Age of tree

X₄ = Merchantable volume

x₅ = (x₁)²

X₆ = Core specific gravity

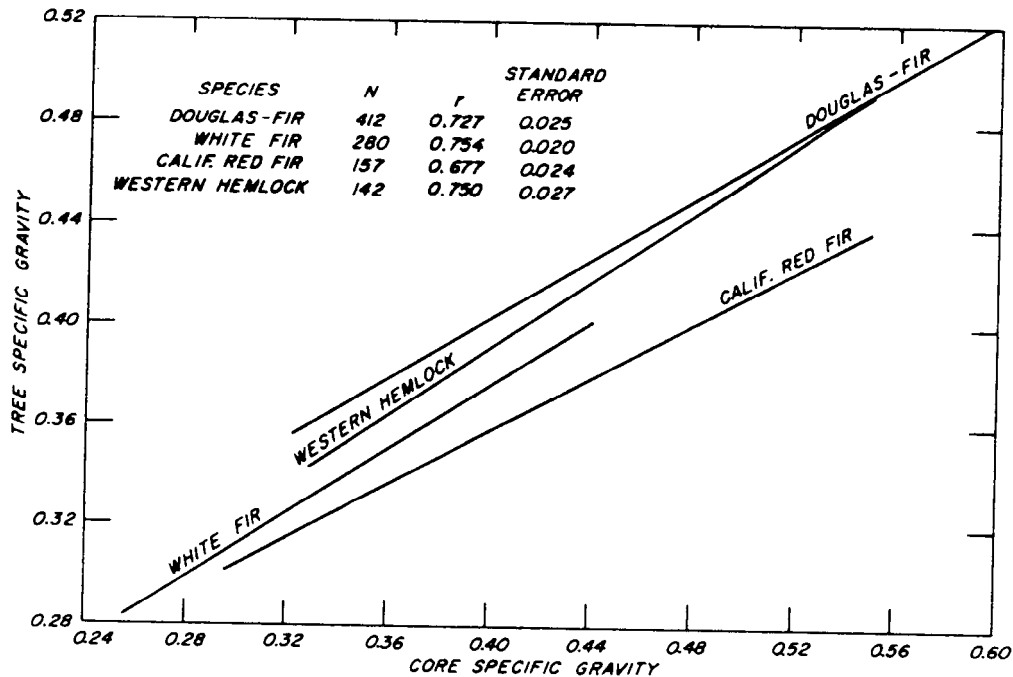
X₇ = X₄ divided by X₃

X₈ = Reciprocal of age

X₉ = X₁ divided by X₃

X₁₀ = Reciprocal of core specific gravity.

For simple linear regressions the only variable which was significant at the 5 percent level of probability for all species was core specific gravity. Graphic representations of these simple linear relations for four species are shown in figure 4.



(M 127 567)

Figure 4.--The relationship between increment core specific gravity at breast height and tree (average for merchantable volume) specific gravity for Douglas-fir, white fir, California red fir, and western hemlock.

Table 4. --Multiple regressions predicting tree specific gravity using core specific gravity and d.b.h.

Species	Equation	R^2 ¹	Standard deviation from regression
Douglas-fir	$Y = 0.17219 + 0.63623X_6 - 0.00107X_1$	0.6100	0.023
White fir	$Y = 0.13559 + 0.63528X_6 - 0.00062X_1$	.6095	.019
California red fir	$Y = 0.18053 + 0.47318X_6 - 0.00045X_1$	.4859	.023
Grand fir	$Y = 0.01876 + 0.80654X_6 - 0.00054X_1$	.6681	.024
Pacific silver fir	$Y = 0.14388 + 0.64930X_6 - 0.00096X_1$	.6492	.026
Noble fir	$Y = 0.29638 + 0.28141X_6 - 0.00161X_1$	.5887	.016
Western hemlock	$Y = 0.25630 + 0.47233X_6 - 0.00220X_1$	.7022	.023
Western larch	$Y = 0.27429 + 0.43400X_6 - 0.00199X_1$	.4394	.023
Black cottonwood	$Y = 0.14364 + 0.54095X_6 - 0.00055X_1$	.4828	.019

¹ The "coefficient of determination" (R^2) indicates the proportion of the variation in \underline{Y} that is associated with the regression.

The next "best"⁸ independent variable for seven of nine species was d.b.h. (X_1). The addition of d.b.h. resulted in a significant reduction in the residual sum of squares (probability, $P = 0.05$) for all species.

For uniformity and because only limited tree data were available from Phase II, the tree specific gravity equations for all species were fitted with core specific gravity and d.b.h as independent variables. The final regression equations for predicting tree specific gravity are shown in table 4.

These multiple regression equations provide an acceptable basis for estimating merchantable

tree specific gravity from a single increment core, taken at breast height, to a maximum depth of 10 inches. In large trees, such as the nine priority species investigated, a 10-inch core represents a partial radius and yet yields stronger correlations than previously achieved with southern pines where smaller diameters permitted taking cores to the pith center. This difference is attributed to the low density wood near the pith that is more variable than wood laid down later in the tree's life. This "older" wood is more proportionately sampled in large trees where a 10-inch core constitutes the bulk of the tree's volume.

⁸As used here, the "best" independent variable is the one giving the largest reduction in the residual sum of squares of the dependent (Y) variable.

ANALYSIS OF INCREMENT CORE

SAMPLE DATA⁹

The Western Wood Density Survey (Phase II) was designed to establish the mean and range of estimated tree specific gravity by species. Hopefully, the Survey would also provide information relating climatic and physiographic factors with variations in wood specific gravity. Estimates of tree specific gravity were calculated from regressions (table 4) developed from destructive specific gravity sampling (Phase III) using data collected in the field (Phase I) and at the Forest Products Laboratory (Phase II). Investigation of the possible sources of specific gravity variation was made with core specific gravity using field- and Laboratory-collected data.

Estimation of Specific Gravity

Means and Ranges by Species

Histograms of estimated tree specific gravity, along with sampling area maps, are shown in figures 5-16. Solid areas on the maps indicate where dispersion of the sample plots was within 15 minutes of latitude or longitude from each other. Table 5 presents the average estimated tree specific gravity and its standard error, the average core specific gravity, average diameter, and the standing volume weighting factor for sampled trees for the Forest Survey Units outlined in figure 17. Computational details for average tree specific gravities and for standard errors are given in Appendix A, No. 4.

A summary of the estimated specific gravity means, ranges, and sample size by the nine species is shown in table 6. Specific gravity means are weighted by volumes of standing timber according to table 5. Douglas-fir is divided into three areas (figs. 5-6) according to the work of Drow (6). This breakdown is supported by recognized botanical and physiographic differences (2, 10, 18, 29). A second breakdown subdivides the West Coast area into Coast and Interior

west regions (figs. 7-8). This was done because there is evidence that the strength property-specific gravity relationship is different between the two subdivisions as discussed in Appendix D.

The specific gravity values presented in tables 5 and 6 and figures 5-16 are the best estimates of specific gravity available for the nine priority species. It is the first time specific gravity data were collected systematically and intensively over the entire natural range of these species in this country.

Sources of Specific Gravity

Variation

Specific gravity of solid wood substance is essentially the same regardless of species. Differences in specific gravity between pieces of wood reflect differences in cell wall thickness, packing density, cell diameter, cell length, amount of extractives, and volume of mechanical tissue. Work has been done in evaluating the effects of environment and age on cell size, but far more has been concerned with the effects of environment and age on specific gravity. This is not a new area of research. Sanio (26) and Hartig (12) were working in this field almost a century ago and many others have followed (10, 16, 24, 29).

More recently, investigations on the genetic component of cell and wood specific gravity variations have been made by Brown and Klein (3), Dadswell et al (5), Fielding and Brown (7), Zobel (35), and others. Their work indicates the importance of heritability in wood density variation. Geneticists of Pacific Southwest Forest and Range Experiment Station are already locating trees with high quality potential as indicated by the Survey for genetic study.

One conclusion concerning the studies on factors controlling wood quality is that they are confusing and frequently contradictory. The results of individual studies cannot be compared or combined because of the arbitrary sampling procedures used in selecting the trees for study, and the type and number of samples extracted from the trees.

⁹L. E. Lassen of the Forest Products Laboratory was responsible for the analysis of the increment core data.

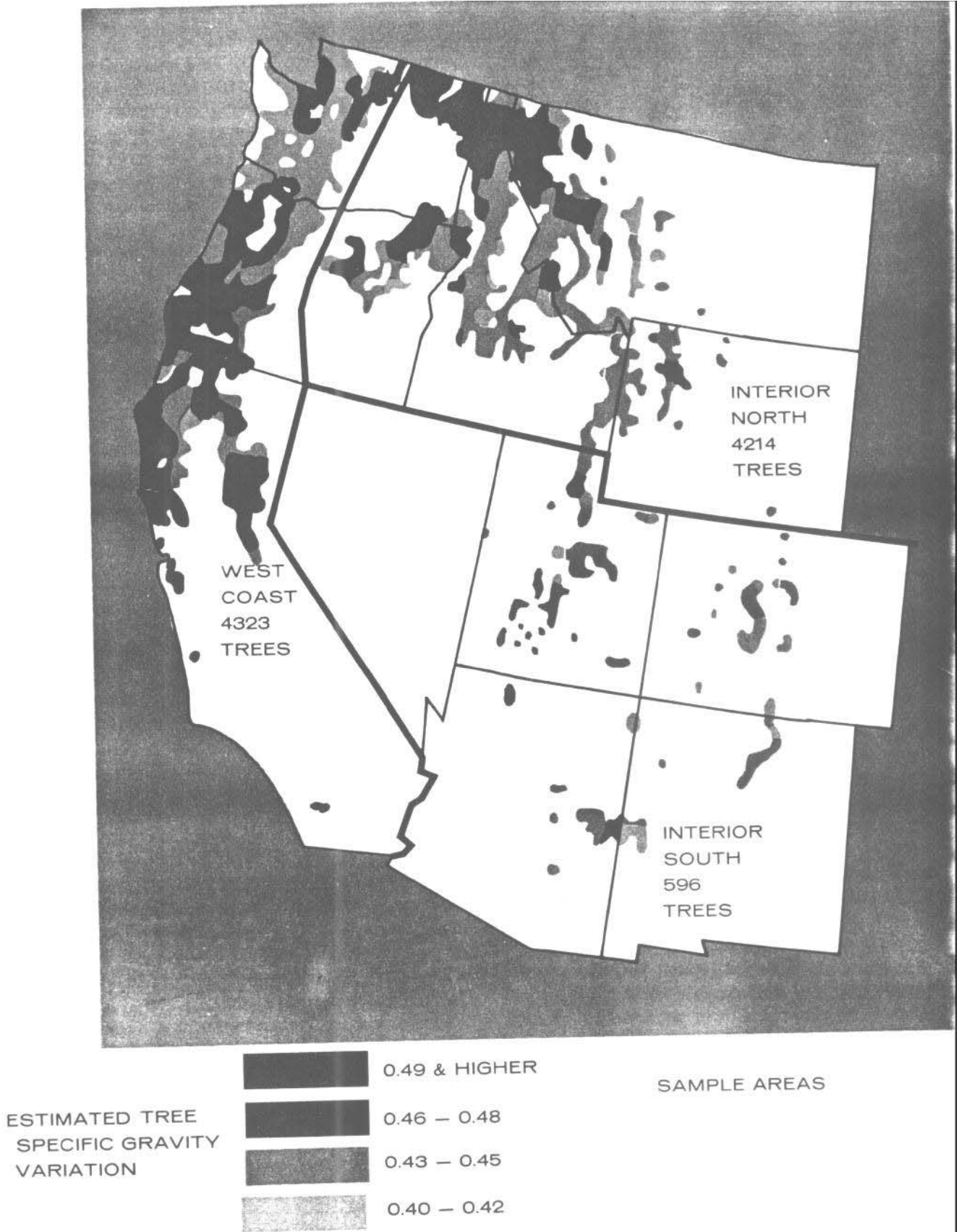


Figure 5.--Douglas-fir estimated tree specific gravity and variation. (M 127 582)

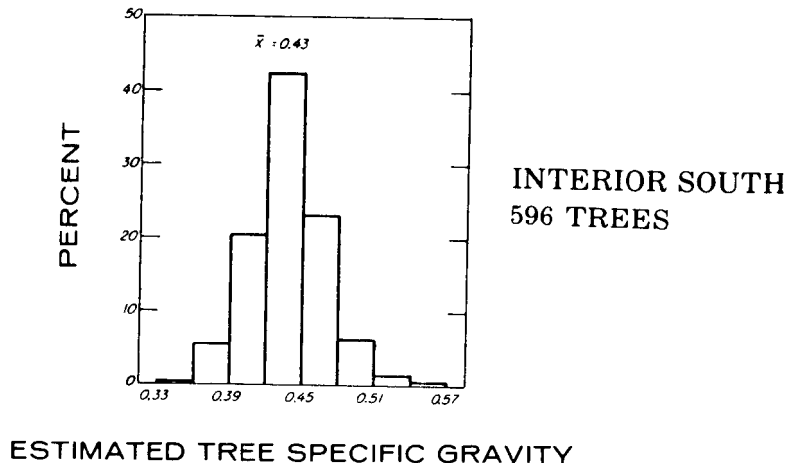
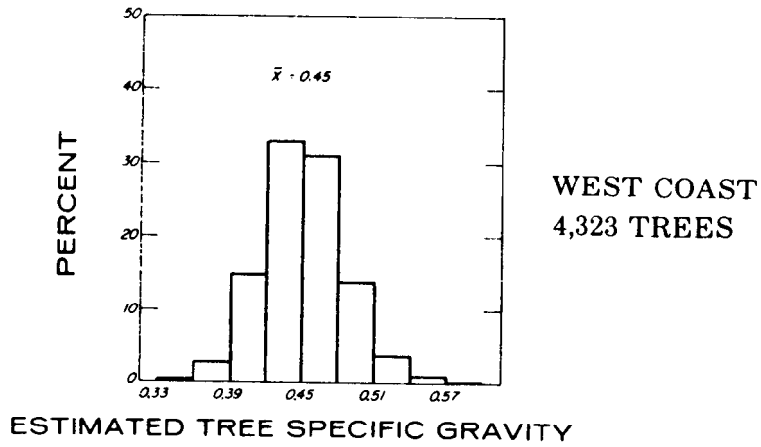
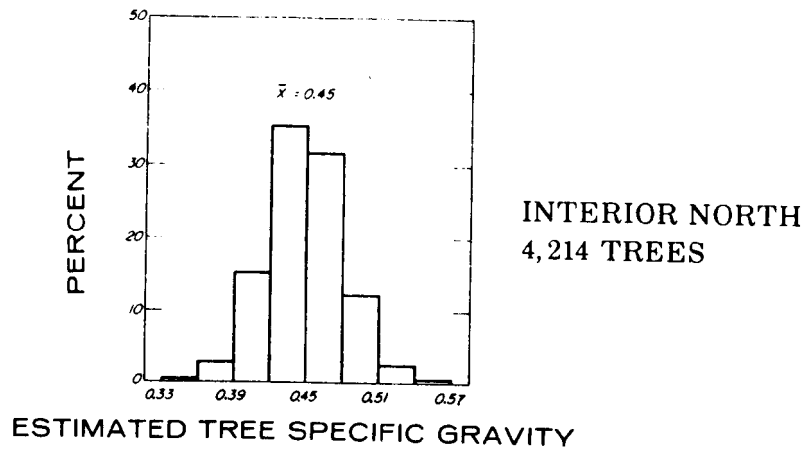


Figure 6.--Douglas-fir specific gravity by regions.

(M 127 583)

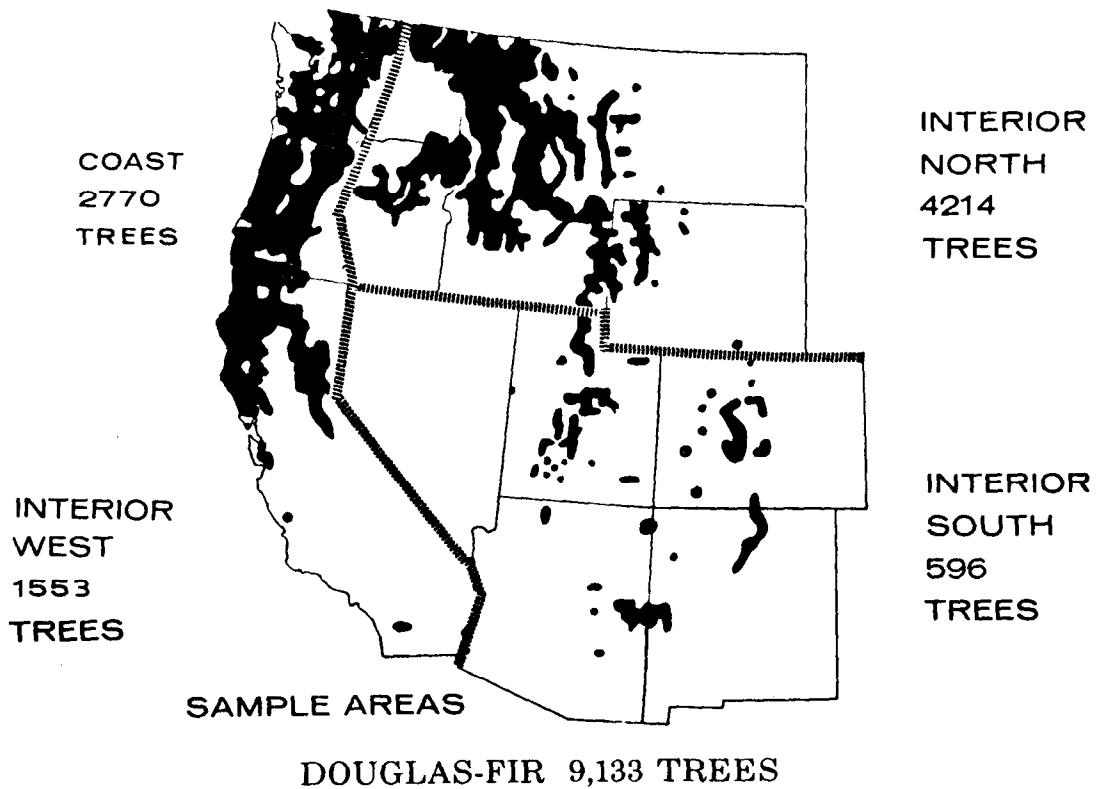


Figure 7.--Douglas-fir by strength property-specific gravity regions.

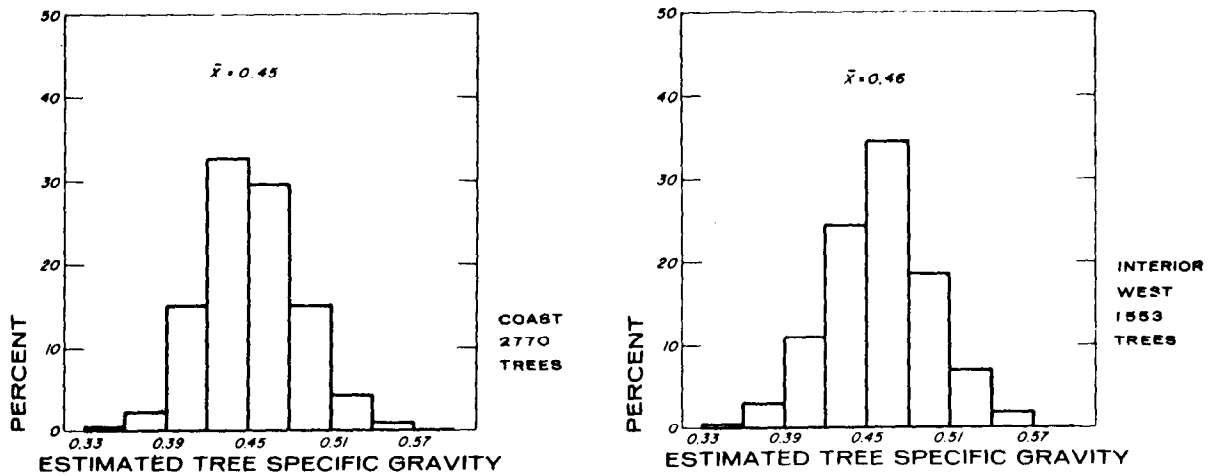
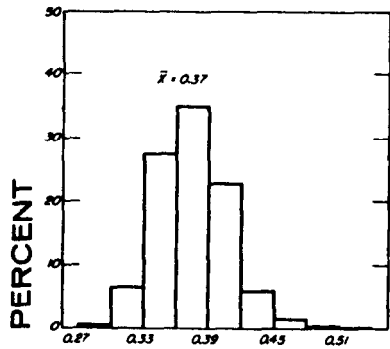
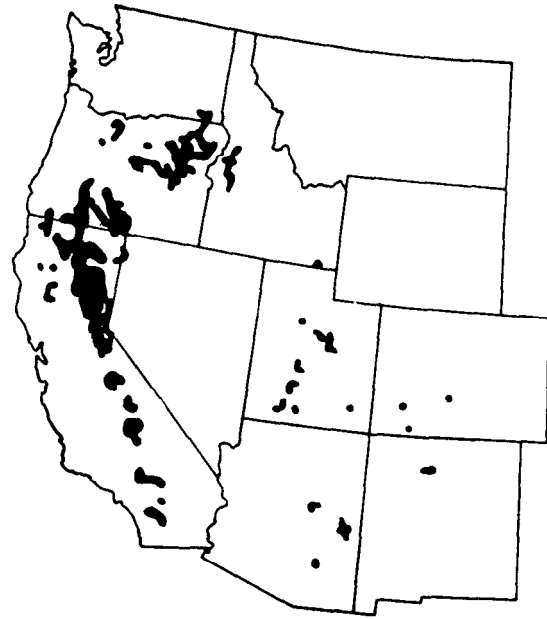


Figure 8.--Douglas-fir specific gravity by coast and interior west regions.

(M 127 584)



ESTIMATED TREE SPECIFIC GRAVITY

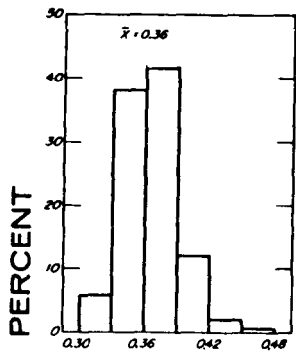


SAMPLE AREAS

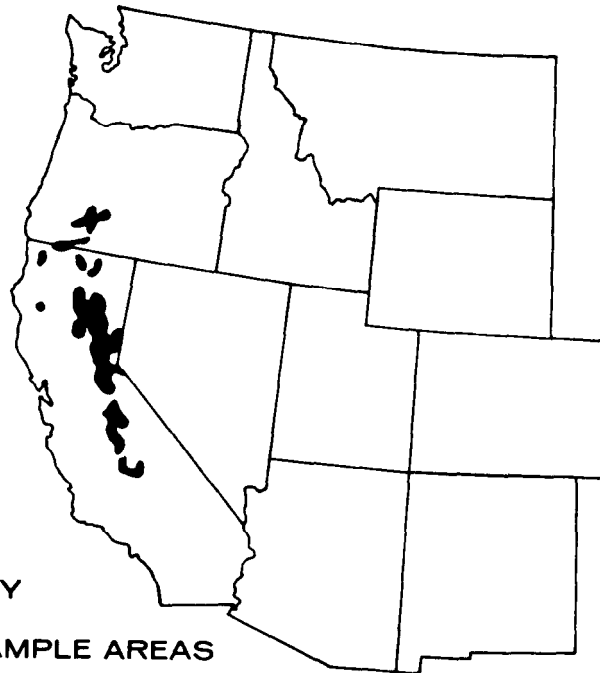
WHITE FIR 2,150 TREES

Figure 9.--White fir estimated tree specific gravity and sample areas.

(M 124 191)



ESTIMATED TREE SPECIFIC GRAVITY

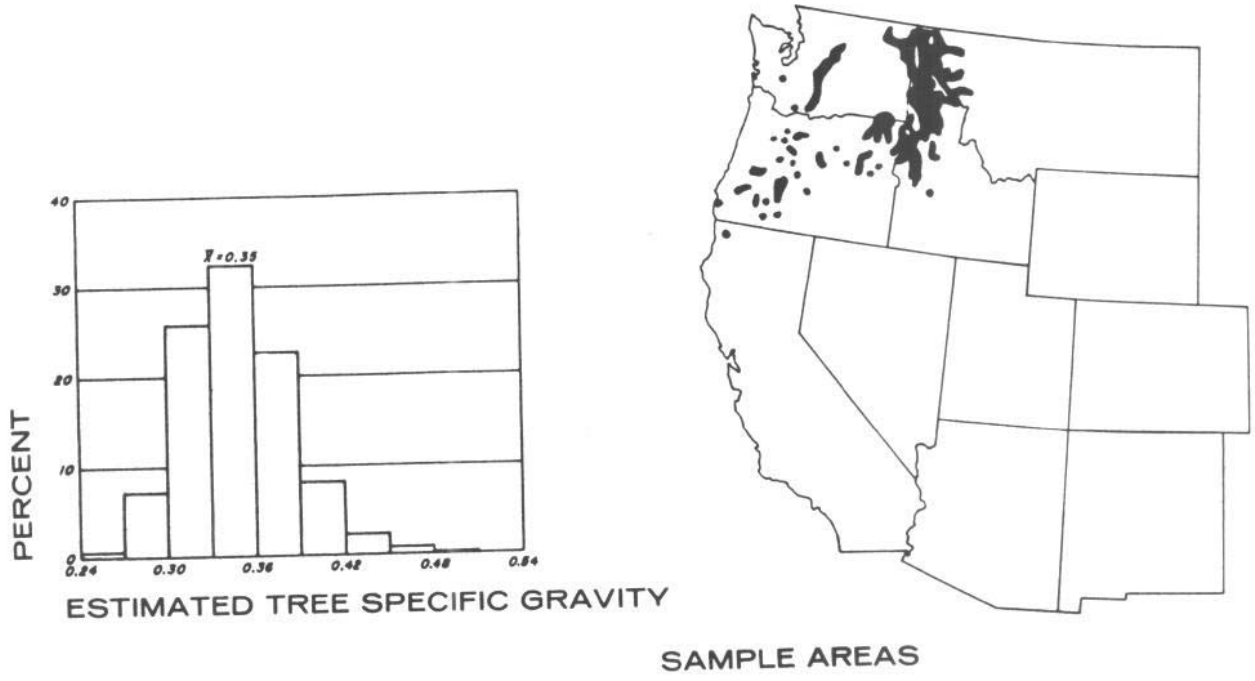


SAMPLE AREAS

CALIFORNIA RED FIR 840 TREES

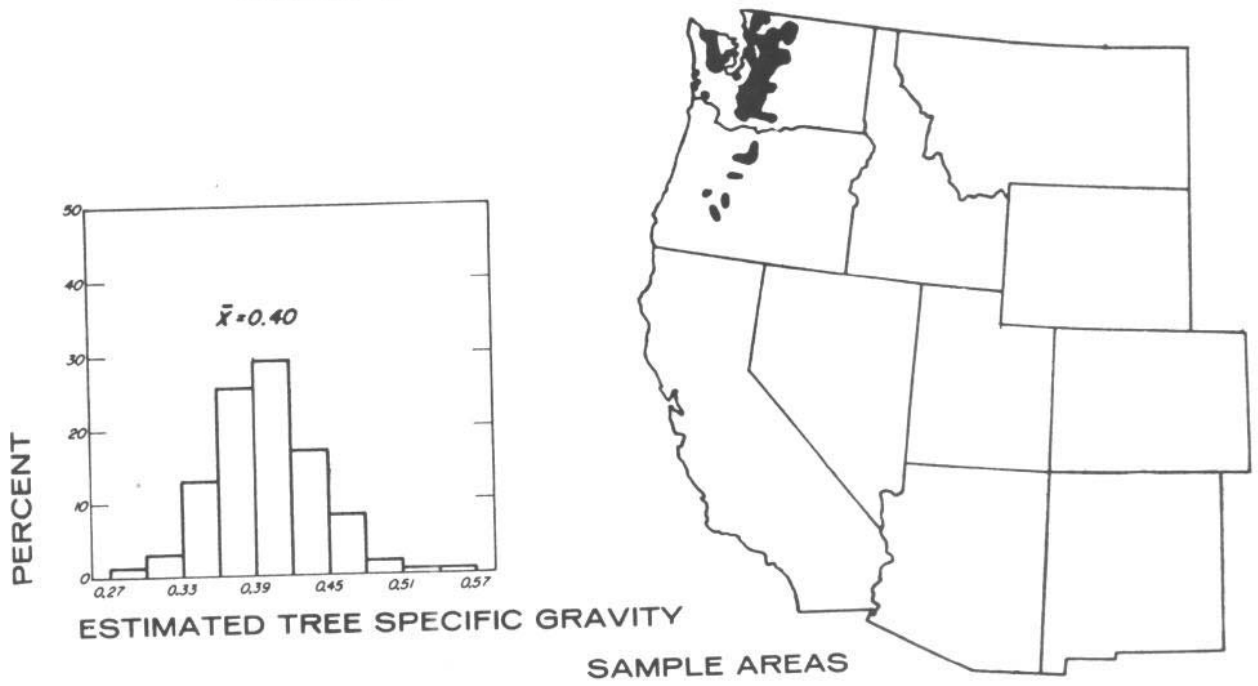
Figure 10.--California red fir estimated tree specific gravity, and sample areas.

(M 127 583)



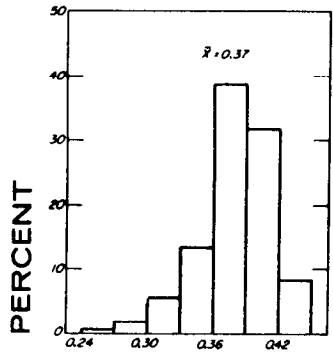
GRAND FIR 862 TREES

Figure 11.--Grand fir estimated tree specific gravity and sample areas. (M 124 699)

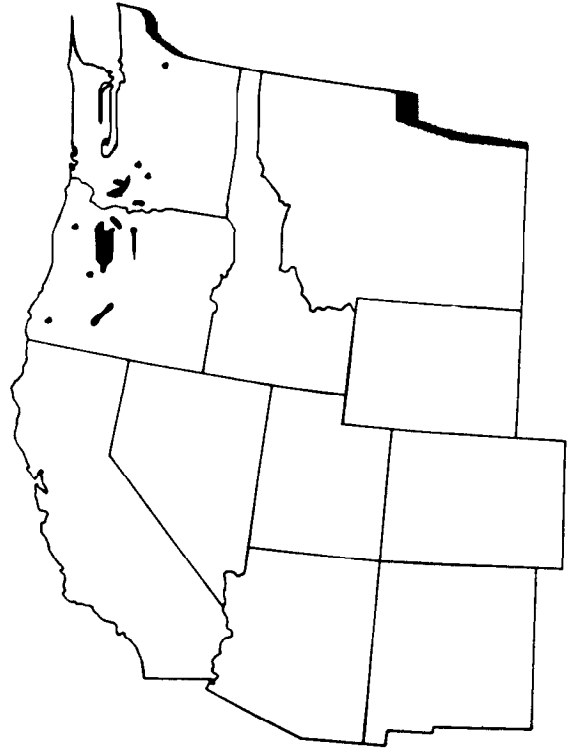


PACIFIC SILVER FIR 330 TREES

Figure 12.--Pacific silver fir estimated tree specific gravity and sample areas. (M 124 698)



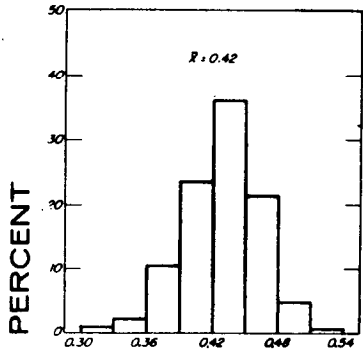
ESTIMATED TREE SPECIFIC GRAVITY



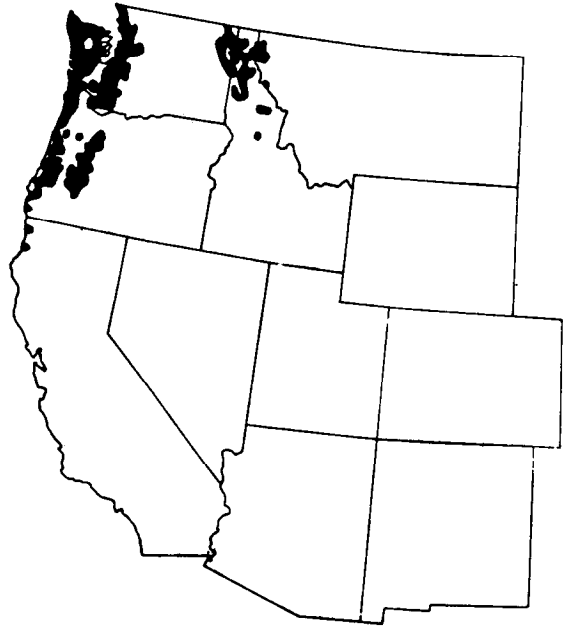
SAMPLE AREAS

NOBLE FIR 158 TREES

Figure 13.--Noble fir estimated tree specific gravity and sample areas. (M 134 697)



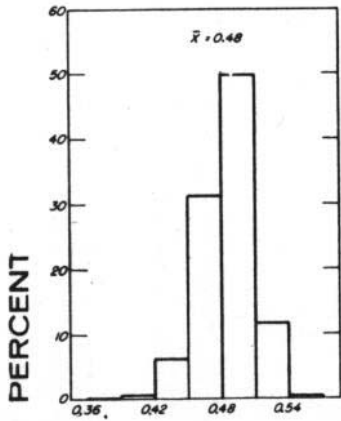
ESTIMATED TREE SPECIFIC GRAVITY



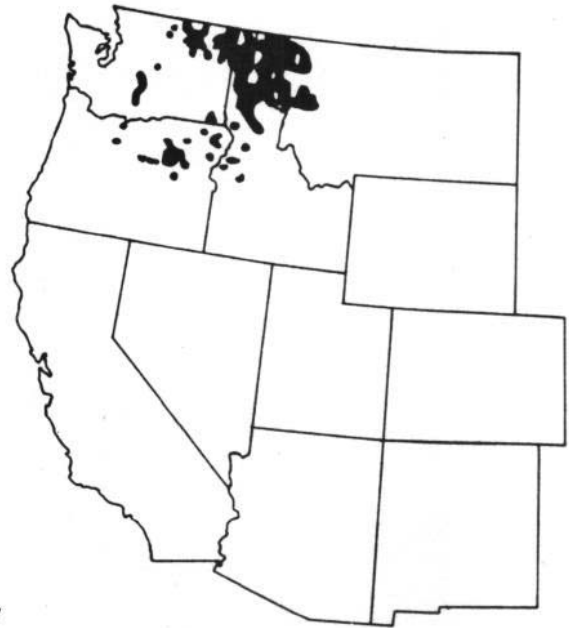
SAMPLE AREAS

WESTERN HEMLOCK 1,040 TREES

Figure 14.--Western hemlock estimated tree specific gravity and sample areas.



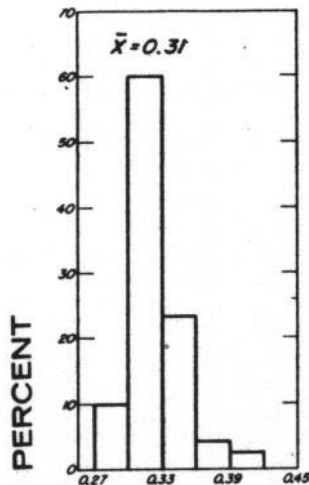
ESTIMATED TREE SPECIFIC GRAVITY



SAMPLE AREAS

WESTERN LARCH 678 TREES

Figure 15.--Western larch estimated tree specific gravity and sample areas. (M 124 690)



ESTIMATED TREE SPECIFIC GRAVITY



SAMPLE AREAS

BLACK COTTONWOOD 120 TREES

Figure 16.--Black cottonwood estimated tree specific gravity and sample areas. (M 124 694)

Table 5. --Specific gravity by species and Forest Survey Unit

Forest Survey Units	Average : estimated : tree : specific : gravity	Standard error : of estimated : average tree : specific gravity	Number : of : trees : sampled	Average : core : specific : gravity	Average : d.b.h. : for : sample : trees	Volume : weighting : factor for : species means
					In.	
<u>DOUGLAS-FIR</u>						
Arizona	: 0.435	: 0.0053	: 86	: 0.440	: 19.4	: 0.26
California	:	:	:	:	:	:
Eastside Sierras	: .438	: .0052	: 39	: .457	: 19.5	: .29
Westside Sierras	: .454	: .0030	: 273	: .478	: 20.1	: 2.14
Coast Range Pine	: .451	: .0035	: 325	: .484	: 23.9	: 4.42
Redwood-Douglas-fir	: .467	: .0039	: 378	: .506	: 29.0	: 12.08
Southern California	: .494	:	: 6	: .548	: 25.1	:
Colorado	: .429	: .0028	: 149	: .423	: 11.6	: 1.45
Idaho, North	: .452	: .0023	: 605	: .467	: 15.0	: 2.25
South	: .434	: .0018	: 1175	: .442	: 17.4	: 4.75
Montana, West	: .455	: .0018	: 1109	: .469	: 12.9	: 4.95
East	: .432	: .0020	: 538	: .428	: 12.9	: 1.91
New Mexico	: .430	: .0033	: 125	: .436	: 18.1	: .86
Oregon, West	: .452	: .0016	: 1861	: .491	: 28.2	: 39.59
East	: .446	: .0029	: 350	: .465	: 18.6	: 3.09
Utah	: .436	: .0044	: 236	: .440	: 14.7	: .82
Washington, West	: .437	: .0022	: 962	: .462	: 21.1	: 14.61
East	: .451	: .0022	: 683	: .473	: 16.9	: 5.72
Wyoming	: .434	: .0028	: 233	: .435	: 14.9	: .82
<u>WHITE FIR</u>						
Arizona	: .366	: .0064	: 31	: .385	: 18.9	: .21
California	:	:	:	:	:	:
Eastside Sierras	: .366	: .0027	: 505	: .386	: 18.3	: 13.85
Westside Sierras	: .364	: .0021	: 707	: .383	: 24.3	: 46.31
Coast Range Pine	: .374	: .0058	: 137	: .386	: 19.7	: 11.55
Redwood-Douglas-fir	: .386	: .0263	: 16	: .434	: 22.7	: 6.57
Southern California	: .363	: .0043	: 162	: .395	: 22.4	:
Colorado	: .366	: .0098	: 22	: .384	: 11.2	: 2.49
Idaho, South	: .363	: .0066	: 78	: .379	: 19.0	:
New Mexico	: .356	: .0052	: 63	: .373	: 16.6	: .57
Oregon, West	: .372	: .0079	: 62	: .401	: 20.0	: 8.36
East	: .370	: .0024	: 251	: .391	: 17.3	: 7.71
Utah	: .381	: .0069	: 107	: .405	: 14.9	: 2.38
Washington, East	: .380	: .0081	: 9	: .401	: 17.3	:
<u>CALIFORNIA RED FIR</u>						
California	:	:	:	:	:	:
Eastside Sierras	: .358	: .0033	: 214	: .402	: 26.2	: 19.76
Westside Sierras	: .356	: .0026	: 449	: .402	: 29.8	: 58.52
Coast Range Pine	: .360	: .0195	: 9	: .426	: 15.3	: 7.07
Redwood-Douglas-fir	: .368	: .0094	: 5	: .426	: 28.5	: 1.83
Oregon, West	: .357	: .0048	: 127	: .416	: 27.2	: 8.47
East	: .374	: .0067	: 36	: .439	: 25.7	: 4.36

Table 5. --Specific gravity by species and Forest Survey Units--Con.

Forest Survey Units	Average estimated specific gravity	Standard error of estimated specific gravity	Number of trees sampled	Average specific gravity	Average core d.b.h.	Volume weighting factor for species means
<u>GRAND FIR</u>						
California						
Redwood-Douglas-fir	0.397	0.0179	8	0.470	17.0	2.71
Idaho, North	.339	.0023	498	.386	14.8	26.28
South	.323	.0052	54	.364	16.4	6.29
Montana, West	.364	.0057	71	.411	8.3	3.72
Oregon, West	.376	.0073	51	.427	19.0	11.60
East	.341	.0062	94	.389	16.2	24.52
Washington, West	.390	.0047	3	.435	11.6	2.84
East	.351	.0047	83	.399	13.3	22.05
<u>PACIFIC SILVER FIR</u>						
Oregon, West	.436	.0171	24	.461	14.0	14.02
East	.402	.....	2	.421	16.2	.55
Washington, West	.387	.0038	239	.409	23.2	78.41
East	.402	.0074	65	.417	15.3	7.02
<u>NOBLE FIR</u>						
Oregon, West	.379	.0059	112	.429	22.7	54.53
East	.400	.0069	5	.476	21.1	8.05
Washington, West	.338	.0131	38	.403	35.1	36.32
East	.373	.0269	3	.397	22.3	1.10
<u>WESTERN HEMLOCK</u>						
California						
Redwood-Douglas-fir	.452	.0129	6	.499	16.4	.32
Idaho, North	.431	.0056	69	.447	13.3	1.91
Montana, West	.444	.0035	17	.463	12.9	.64
Oregon, West	.422	.0034	261	.445	20.7	30.83
East	.421	.0174	8	.437	22.0	.31
Washington, West	.420	.0023	645	.448	21.3	63.78
East	.433	.0092	34	.446	20.0	2.21
<u>WESTERN LARCH</u>						
Idaho, North	.484	.0026	143	.543	14.1	17.87
South	.467	.0091	6	.514	11.5	1.46
Montana, West	.480	.0020	326	.535	12.7	42.00
Oregon, West	.477	.0050	4	.546	18.3	.52
East	.468	.0039	59	.521	17.8	15.75
Washington, East	.475	.0038	140	.544	14.8	22.40
<u>BLACK COTTONWOOD</u>						
Oregon, West	.315	.0036	45	.339	22.4	20.00
East	.312	.0031	8	.336	23.1	6.89
Washington, West	.315	.0041	64	.353	23.2	46.56
East	.304	.0102	3	.334	22.1	26.56

¹Specific gravity estimates are given to three digits to permit further computations with minimum round-off error.



Figure 17.--Forest survey units. (M 124 693)

Table 6.--Estimated tree specific gravity¹ for priority species

Species	Mean specific gravity	Range of specific gravity	Number of trees sampled	Wood Handbook average specific gravity
Douglas-fir ²	.45	.33-.59	9,133	----
West Coast	.45	.34-.59	4,323	.45
Coast	.45	.34-.59	2,770	----
Interior west	.46	.34-.59	1,553	----
Interior north	.45	.33-.59	4,214	.41
Interior south	.43	.33-.55	596	.40
White fir	.37	.26-.54	2,150	.35
California red fir	.36	.31-.46	840	.37
Grand fir	.35	.24-.55	862	.37
Pacific silver fir	.40	.28-.55	330	.35
Noble fir	.37	.26-.44	158	.35
Western hemlock	.42	.30-.52	1,040	.38
Western larch	.48	.38-.54	678	.51
Black cottonwood	.31	.28-.40	120	.32

¹ Tree specific gravity values are estimated from core specific gravity and d. b. h. values. Specific gravity is on a green volume-oven-dry weight basis.

² West Coast, Interior north, and Interior south regions are shown in fig. 5; Coast and interior west regions are shown in fig. 7.

No attempt will be made to include a review of the literature here. Spurr and Hsuing (27), Goggans (9), and Paul (24) have compiled extensive reviews which can be used for background reference. In addition, Zimmermann (34) has edited an excellent reference book on the formation of wood in forest trees.

A study which deserves special mention, however, is the first wood-density survey of a western species using increment cores. In 1959, Knigge (16) selected 5 trees from each of 51 stands of Douglas-fir growing on different sites and of different stand structure. These stands were located in an area situated between the Canadian border and northern California and from the Coast Range to the western slopes of the Cascades. The stands were second growth with an upper age limit of about 100 years. The average specific gravity of two increment cores was fitted to a regression equation using reciprocal of annual ring width, reciprocal of age, reciprocal of site class, relative crown length, growing season precipitation, annual precipitation, and reciprocal of altitude as independent variables. They account-

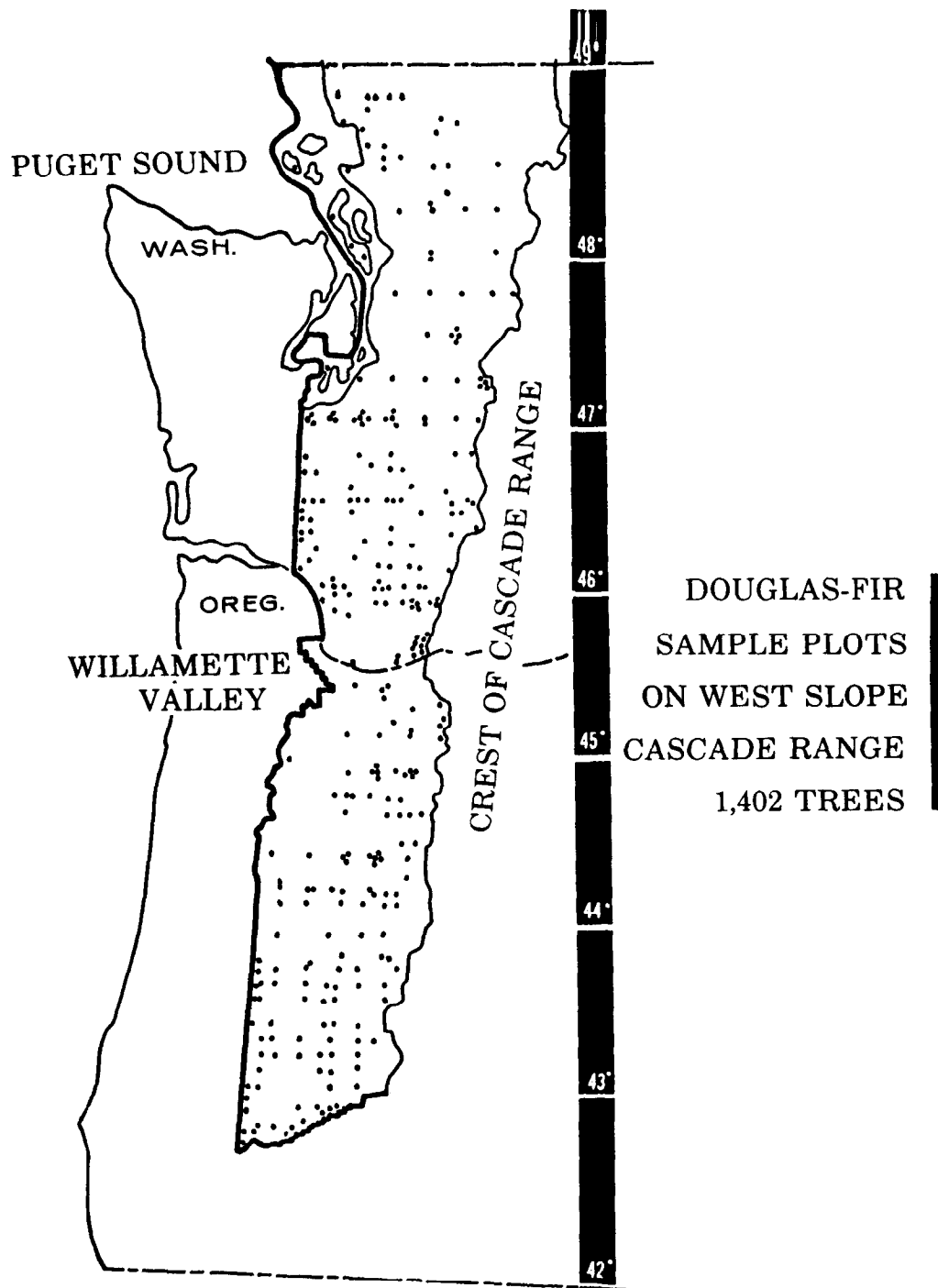


Figure 18.--Douglas-fir sample plots on west slope Cascade Range, 1,402 trees.

(M 124 692)

ed for 34 percent of the specific gravity variation. Functions of site class, ring width, and age showed the strongest association with specific gravity.

In general, specific gravity increased with age, improved with site class, increased with average growing season temperature, and decreased with increasing growing season precipitation and also with increasing altitude.

When increment cores. were separated according to age, it was found that ring width has a

very significant influence on specific gravity during the first decades of wood formation, whereas tree age has the greater influence in later life of the tree.

In any discussion of this type, it is important to remember that patterns of specific gravity vary within and between trees of any species. While differences in specific gravity do exist between geographical areas, they often are not as great as those within and between adjacent trees.

West Slope of Cascade Range

The Western Wood Density Survey offered a unique opportunity to study the association between specific gravity and environmental factors. Detailed study on these associations are planned for all priority species; however, Douglas-fir was singled out for pilot study because of its relative importance.

The natural range of Douglas-fir spans the entire western United States with its many diverse climatic and physiographic provenances. Figure 5 shows the sample distribution and specific gravity variation pattern. It is obvious that the variation pattern is not a clear-cut latitudinal nor longitudinal gradient. Because of the suspected complexity of the relationships, it seemed desirable to confine this initial study to a smaller, more homogeneous area. The area selected was the western slope of the Cascade Range in Washington and Oregon (fig. 18) where data were available from 1,402 Douglas-fir.

Climate and Physiography

The particular features of climate in the selected area are unique within the range of Douglas-fir distribution (30). Latitudinal climatic variations over the 400-mile north-south length are at a minimum because of the modifying influence of the Pacific Ocean. On the other hand, the east-west gradient is one of extremes even though the distance involved is only 50 to 100 miles. These extremes are associated with the elevational change from sea level or the low elevations of the Willamette Valley to 6,000-8,000 feet at the crest of the Cascades.

Latitudinal difference in day length reaches a maximum of 26 minutes from the Canadian border to southern Oregon at the summer solstice in June. This difference, of course, diminishes to about equal day lengths at the September equinox. January sunshine averages 2 hours per day at the Washington-British Columbia border to 3-1/2 in southern Oregon. In March the north-south gradient begins to shift to an east-west one closely aligned to elevational changes in the Cascades. While the average July temperature is 60° F. at Puget Sound and 65°F. in the Willamette Valley, this difference is probably due to the

modifying effects of the sound rather than latitudinal differences.

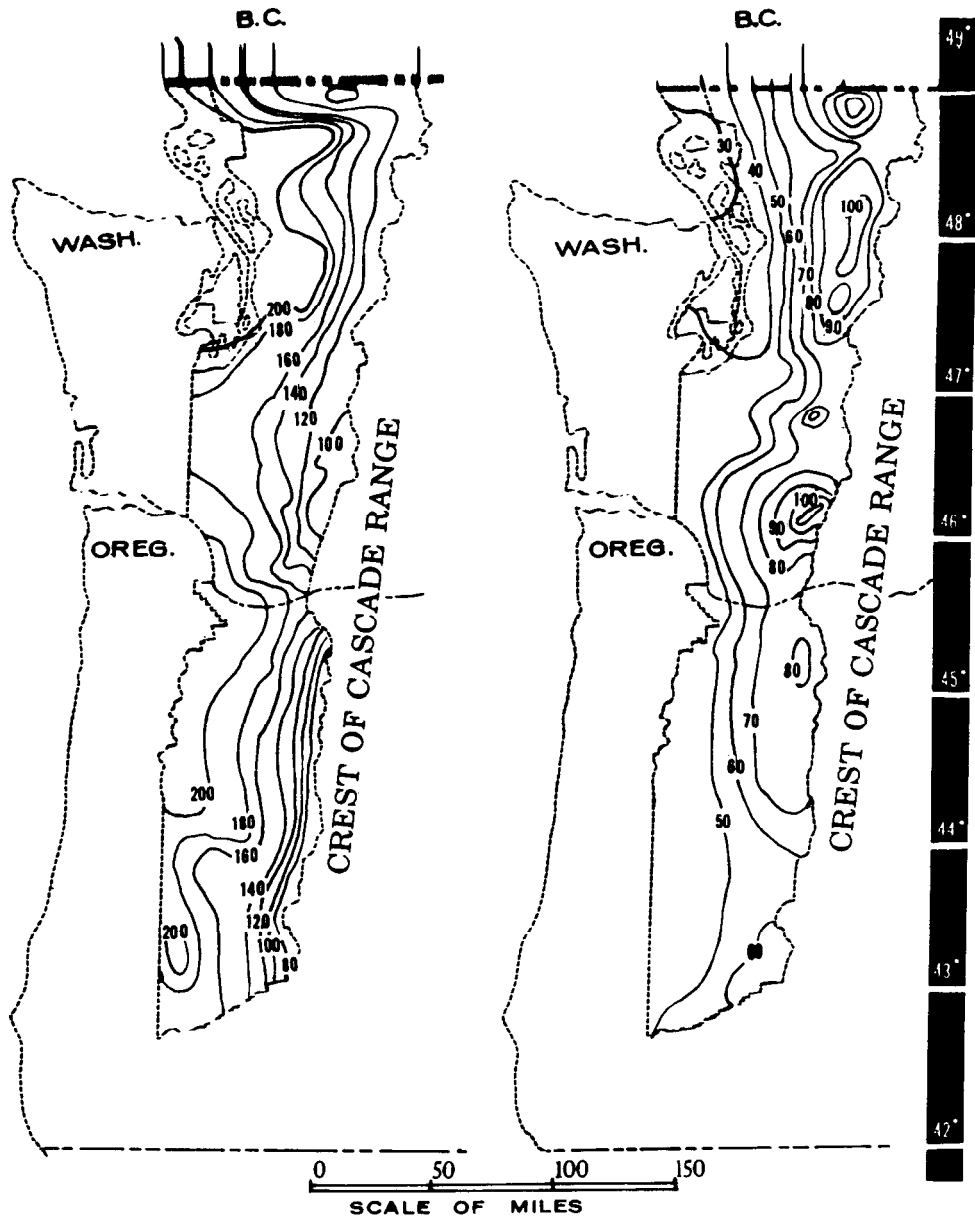
The elevational change, generally, produces severe climatic variation in an east-west direction as can be seen in figure 19. The growing season varies from 210 days at Puget Sound and the Valley to 90 days at the crest. Killing frost may occur up to May 1 and as early as November 1 in the Valley. At the higher elevations killing frost can occur up to June 1 and again as early as September 1. Average daily temperature ranges also follow elevational patterns with the range increasing with elevation. In July the range is 18°F. at sea level in Puget Sound, 28° F. in the Willamette Valley, and 36° F. at the Cascade crest. Free air temperature decreases 3.6° F. for every 1,000-foot increase in elevation, but seasons, local conditions, and temperature inversions in the colder months and at night can produce warmer temperatures on the slopes than at the lower elevations.

Precipitation definitely increases with elevation as shown in figure 19. The spring rainfall, March through May, may vary from 6 inches at the bottom to 21 inches at the top of the slope. Summers are usually dry with as little as 2 inches of rain falling in June, July, and August in the Valley to over 8 inches at the higher elevations. The greatest known snowfall in the United States, excluding Alaska, occurs on the west side of the Sierra Nevada Cascade Ranges. Snow at the 5,500-foot level reaches 200 to 600 inches annually and may persist through May.

Ecologically, Douglas-fir may be the climax species in the lowlands adjacent to the Valley, and is the predominant subclimax species below 3,000-foot elevation in the Cascades. This area plus the Coast Range takes in most of what is referred to by silviculturists as the Douglas-fir subregion (2).

Sample Characteristics

Histograms of the specific gravity of the samples are shown in figure 20. The upper histogram is based on specific gravity values estimated for whole trees using the regression equation given in table 4, which takes core specific gravity and tree diameter into account. The lower histogram shows the specific gravity values from the population of increment cores sampled. As might be expected, the predicted tree gravities



AVERAGE NUMBER OF DAYS WITHOUT KILLING FROST **AVERAGE ANNUAL PRECIPITATION (inches)**

Figure 19. --Variation in growing conditions and precipitation for west side of Cascades.

(M 124 691)

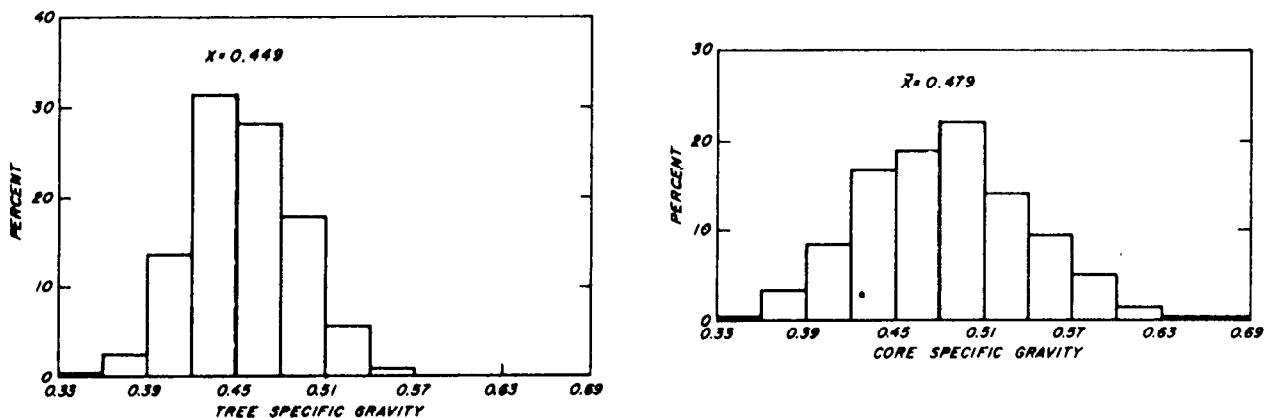


Figure 20. --Histograms of specific gravity of Douglas-fir on the west slope of the Cascade Range, 1,402 trees.

Table 7. --Percent of western Cascade Douglas-fir core specific gravity variation associated with selected independent variables (significant at the 1 percent level)

Tree age	Independent variables												
	Latitude	Elev.	D. b. h.	Age:1/age	Dbh/age	Vol/age	1/elev	Elev ²	Elev ² /age	Dbh ²	Dbh ² /age		
All trees	5		5	3	16	9	1		1	6	3		
Ages 5-34				13	12	7							
Ages 35-74		6						2	6	6			
Ages 75-149	1	5							6	6			
Ages 150-249	8	25	6	2	4	7	5	7	26	22	3	4	
Trees 250+	6	11	4	6	5			8	9	3	4		

have considerably less variability than that exhibited by the core gravities--a fact which is apparent in the histograms. Since some of the variation of true tree gravities around the regression may be associated with the climatic factors to be studied, it was decided that core gravities would be used in the analysis.

Analysis of Data

Multiple regression techniques were used to explore the relationship between core specific gravity and various functions of latitude, age, diameter, and elevation. The percentages shown in table 7 indicate the degree of association between specific gravity and the various independent variables. Of the single variables, the reciprocal of age is by far the most important, accounting for 16 percent of the total specific gravity variation. Diameter over age is the next best variable, but this may be a reflection of the age effect. The same qualification may apply to the third best variable, which was elevation²/age. The form of relationship between specific gravity and age is shown by the freehand curve in figure 21. This general form has been observed in studies of other species. Part of the rapid increase in core specific gravity followed by a leveling off at about age 100 can be tied in with the means of sampling. In this study, cores were taken to the pith or to 10 inches in length, whichever came first. Based on the diameter-age relationship, this would mean that most trees up to about 90 years of age would

be sampled by an increment core extending to the pith. These cores would contain lower density juvenile core wood in proportionately lesser amounts until about age 100, when little if any juvenile wood could be expected to be included in a 10-inch core.

About 5 percent of the total core density variation was associated with diameter, but diameter is also related to age and thus may be a reflection of the age effect. The relationship of core specific gravity and diameter is shown in figure 22.

Latitude also accounted for 5 percent of the total variation.

The functions of elevation were not significantly correlated with the overall specific gravity variation except for elevation² which accounted for less than 1 percent of the variation. However, elevation is not completely disassociated from specific gravity as it would appear from the simple correlation values. When fitted after the reciprocal of age in a multiple regression, elevation²,

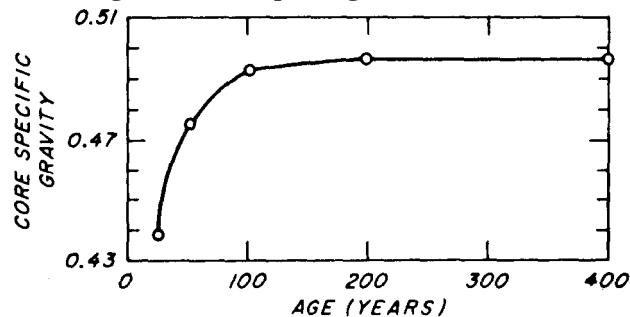


Figure 21.--General form of relationship between age and core specific gravity.

elevation, and the reciprocal of elevation, each made a significant ($P = 0.01$) reduction in the residual variation. A three-variable regression with elevation, reciprocal of age, and elevation² divided by age increases the R^2 significantly ($P = 0.01$) to 23 percent and indicates an interaction between age and elevation. on specific gravity variation.

Examination of the altitudinal distribution indicates that there is a preponderance of young trees sampled in the lowlands with an increase in average age up to the 2,000- to 3,000-foot level. This is probably caused by the logging pattern where the lower, more accessible regions were logged first and have been replaced by second-growth material. The association between specific gravity and age is shown by elevational classes in figure 23. The spread in specific gravity between the elevational classes becomes more pronounced, particularly in the older age classes, despite little differences in diameter growth with age for the same elevational classes (fig. 24).

Figure 25 shows the core specific gravity-elevation relationship for a family of age curves as indicated by the fitted regression

$$\text{Core sp. gr.} = 0.548 - 0.00184 \text{ elevation} + \frac{0.00102 \text{ elevation}^2}{\text{age}} - \frac{2.269}{\text{age}}$$

According to the regression, 100-year-old trees would decrease in specific gravity from an average of 0.52 at 500 feet elevation to 0.46 at 5,000 feet elevation. A drop of 0.01 specific gravity per 1,000 feet in elevation is equivalent to slightly more than half a pound per cubic foot in density. The curve form taken by the 25-year-old trees is difficult to explain biologically. These cores contain low-density juvenile wood to a degree not found in the older cores. This, and the mathematical forcing of the data into a curve, are probably responsible for the peculiar shape.

When the sample is broken into the age groupings shown in tables 7 and 8, the age effect appears strongest in the younger ages, 5-34 years old, and masks the effect of elevation. After the early years, the influence of age diminishes and elevation and latitude appear to exert a strong influence on specific gravity. This appears to differ from Knigge's (16) conclusion that age has a greater influence on specific gravity in the later life of the tree.

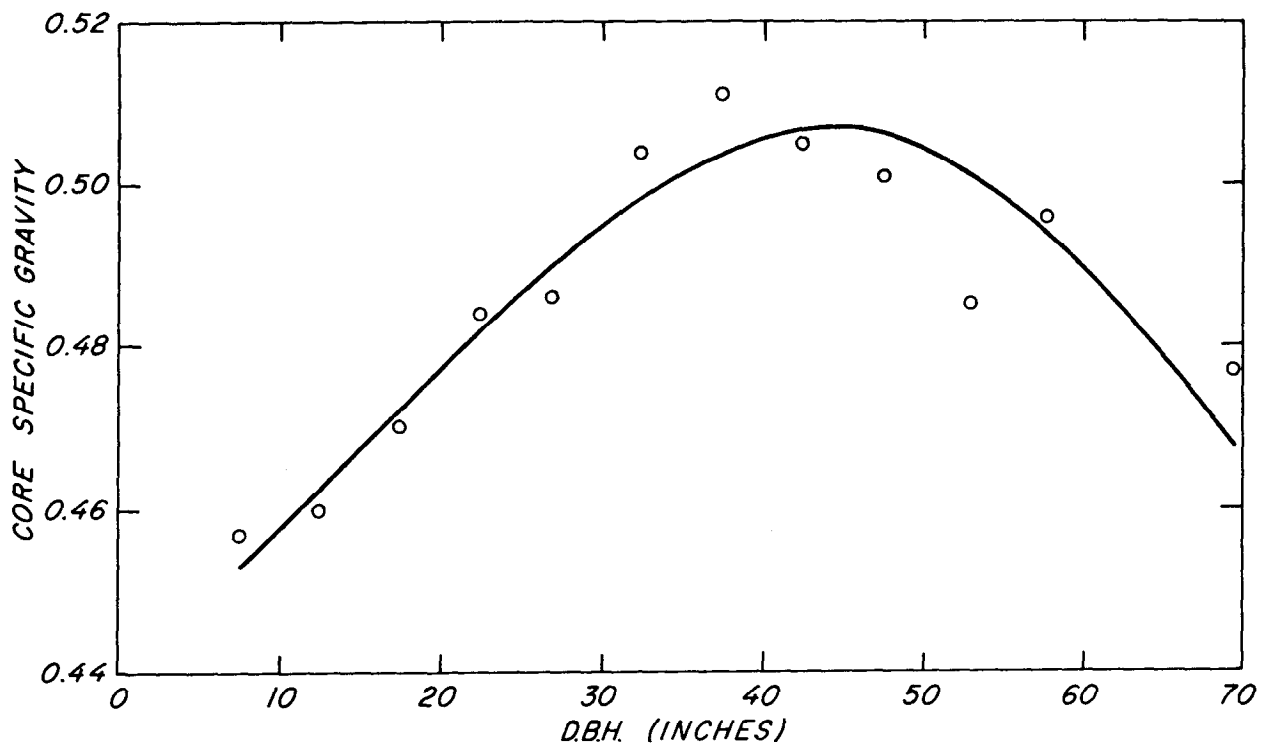


Figure 22. --Relationship of diameter and core specific gravity for Douglas-fir on the west slope of the Cascade Range. 1,402 trees.

(M 124 889)

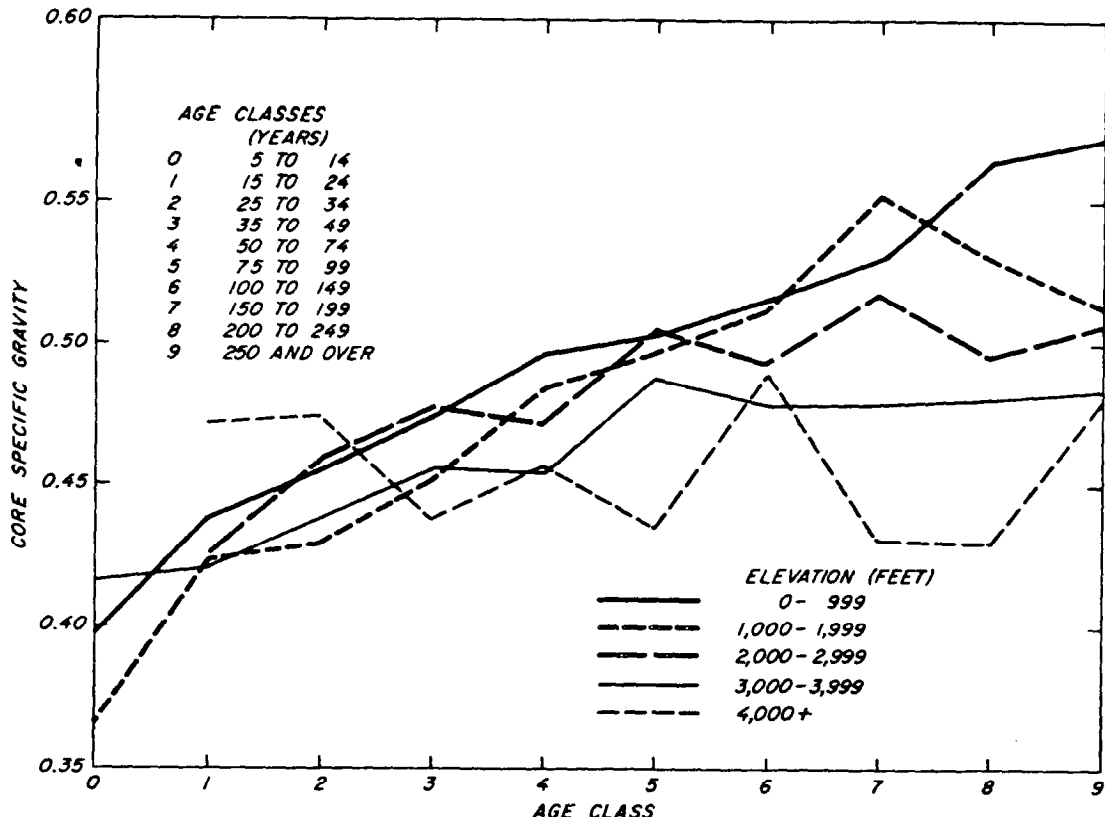


Figure 23.--Relation between age and core specific gravity by elevational classes for Douglas-fir on the west slope of the Cascade Range, 1,402 trees.

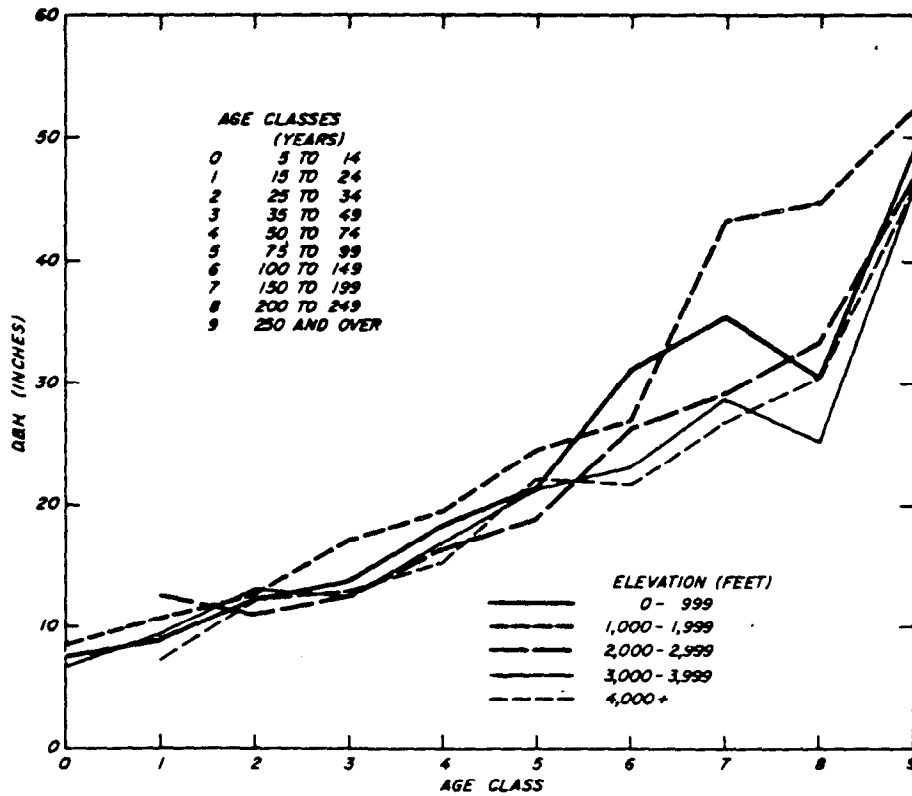


Figure 24.--Relation between age and diameter by elevational classes for Douglas-fir on the west slope of the Cascade Range, 1,402 trees.

(M 124 688)

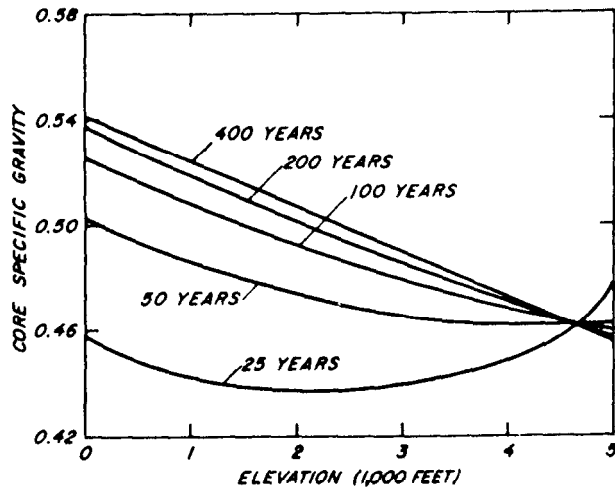


Figure 25.--Relation between elevation and core specific gravity for different ages of Douglas-fir on the west slope of the Cascade Range (1,402 trees), as indicated by the fitted regression. (M 127 586)

Latitudinal effects on specific gravity were also studied. Adding latitude to the multiple regression of elevation and the reciprocal of age on core specific gravity gave a significant ($P = 0.01$) increase in the accountable variation. When latitude was added to elevation, the reciprocal of age, and diameter over age, a significant ($P = 0.01$) improvement in the R^2 was again achieved.

After taking age, elevation, and diameter into account, specific gravity decreased in a northward direction.

Discussion of Results

In the initial analysis of increment core specific gravity for the west slope of the Cascades, no more than 30 percent of the total variation is accounted for by the variables used. Stratification of samples into smaller age classes and into diameter, topographic, aspect, and site quality classes would probably reduce the unexplained variation: however, even allowing for considerable experimental error, it is obvious that most of the specific gravity variation is not explained. There are environmental factors such as precipitation, soil, and microclimate, and expressions of tree vigor and growth such as crown class, site index, stocking density, and live crown ratio which may be important. Data on these factors are, unfortunately, very limited or nonexistent for this study. The genetic component of variation is not possible

to measure either, although it is likely to be important.

From the data available, however, it appears that there is a positive relationship between specific gravity and the reciprocal of age that is much stronger than the relationship with climate as represented by elevation. This age effect is strongest in the younger ages and decreases in importance past 35 years. It corresponds closely with the period of most rapidly increasing current annual growth (grand period of growth). Silviculturally, age of the stand is a factor over which the forester has partial control; it is interesting to note that there is little increase in specific gravity with age past the age of volume maturity, that is, the age at which the current annual growth and mean annual growth curves of the stand intersect (4).

After age is taken into consideration, then there is a trend of decreasing specific gravity with increasing elevation. The strongest influence of elevation on specific gravity occurs after the period of sharp decrease in current annual growth and during the years when both the current annual growth and mean annual growth of the stand are decreasing at moderate rates. During this period the trees have reached mature stature with large crowns and lessened height growth. Within the study area this could imply that a shorter, wetter, and cooler growing season or poorer soils at the higher elevations cause trees to produce slightly lower density wood than trees at the lower elevations.

Extractives may be an important source of specific gravity variation. Evidence from Thor (28) indicates a relationship between extractive content of wood and site factors for Virginia pine, and other studies have related resin content in southern pine to genetic inheritance (20).

With most commercial Douglas-fir logging taking place under the 3,000-foot level, the practical significance of an elevational specific gravity gradient is questionable.

The slight latitudinal effect is difficult to explain; however, the decrease in density northward may result from climatic conditions at a specific elevation in northern Washington being more severe than at the same elevation in southern Oregon.

Diameter functions in themselves do not appear to be very strongly associated with specific gravity after the effects of age have been considered. The

Table 8.--Coefficients of determination showing significant (P = 0.01) improvement by successive inclusion of variables for Douglas-fir on the west slope of the Cascade Range.

Number of variables showing significant (P = 0.01) increase in R ²	Independent variables													
	Latitude	Elev.	Dia.	Age	1/age	Dia/age	Vol/age	1/elev	Elev ²	Elev ² /age	Dia ²	Dia ² /age	R ²	
ALL SAMPLE DOUGLAS-FIR ON WEST SLOPE OF CASCADES														
1					X									0.16
2					X				X					.21
3	X	X			X									.26
4	X	X			X					X				.27
5	X	X			X	X				X				.28
6	X	X			X		X			X			X	.28
7	X	X	X			X	X			X	X			.29
8	X	X	X		X	X	X			X	X			.30
AGES 5-34														
1				X										.13
2						X	X							.18
3			X	X			X							.22
AGES 35-74														
1		X												.06
AGES 75-149														
1									X					.06
2	X								X					.10
AGES 150-249														
1									X					.26
2	X	X												.38
AGES 250 AND OVER														
1		X												.11
2	X	X												.19
3	X	X	X											.28
4	X	X	X					X						.29

observed association between specific gravity and diameter may be mostly due to the known relationship of diameter and age.

Recommendations for Additional Research

Exploratory analysis of the specific gravity variation of Douglas-fir on the western slope of the Cascades has pointed out some general relationships with age, elevation, and latitude which can be pursued further, Expressions of site

quality such as site index, aspect, and topography class can be investigated in light of their effect on specific gravity, It would be desirable to determine if extractives contribute extensively to specific gravity variation. Anatomical variations should be considered; i.e., does volume of summerwood, cell wall thickness, and cell diameter vary with climatic conditions implied by elevation and physiographic conditions tied with site and aspect. Microclimate, soil nutrients, and genetic factors should be studied in new research.

Variations in sapwood and bark thickness as well as specific gravity can be included in the scope of future research.

Core specific gravity was analyzed for three

geographic areas for Douglas-fir and for the entire sample of the other priority species according to the same multiple regression. No attempt will be made to explain the results shown in the tables in Appendix B, but the possibilities for areas of additional research are tremendous. Only a few of the possibilities have been mentioned

PHASE IV- Application of Western Wood Density Survey Data for Determination of Species Strength Properties¹⁰

Background

Strength and related properties of small clear specimens of wood of a species have customarily been expressed as average values determined directly by test and weighted in such a manner as to give each tree equal weight. Averages obtained in this fashion are reported in table 1 of USDA Technical Bulletin No. 479 (19) and in table 12 of the Wood Handbook (32). The averages have a great deal of significance relative to the use of wood as an engineering material. They provide the principal source of data for establishment of strength values for structural lumber.

The properties of interest for structural applications are primarily modulus of rupture and modulus of elasticity in flexure, because a large portion of the structural application of wood is in bending. In addition, the maximum crushing strength parallel-to-grain, shear strength parallel-to-grain, and to a lesser extent the tensile strength parallel-to-grain and compressive strength perpendicular-to-grain are important for structural design.

It is widely recognized that wood exhibits considerable variation in these properties. In order to take this variation into account in the past, the mean of each strength property for clear wood in the green condition has been **reduced** by one-fourth. Traditionally the modulus of elasticity has been expressed as a mean without any reduction for variability, because the result of obtaining a structural member low in this property is less severe than for strength properties.

The methods employed for sampling timber and

here. Imagination and special interests may suggest many more. This is the first time that this type of data of this magnitude in both quantity and quality has been available to serve such diverse groups of interests. Hopefully the data will serve its intended purpose and more.

evaluating the samples in the laboratory are described in ASTM Designation D 143-52 (1) or its predecessors. Evolution of the sampling method dates back to the early part of this century, when the science of sampling was not highly developed, and when the prevailing practices and economics of structural wood use did not demand the same close utilization existing today. Now there is increasing demand for greater reliability in the estimates that are made of wood properties.

It becomes readily apparent in trying to assess the reliability of existing property estimates that the sampling method does not clearly define the population to be sampled, and does not insure that the samples represent more than the particular trees from which they are drawn. According to ASTM Designation D 143-52, the samples are taken from shipments of five or more trees picked to be "representative" of the species. Depending upon the commercial importance of a species at the time of evaluation, one or more such shipments may have been taken to represent the entire geographical range of the species, possibly covering several states. Barely have more than one-half dozen shipments been taken for a single species, yet, in toto, several hundred thousand tests have been made to determine structural properties of American woods.

Clearly, the bulk of such a large number of individual evaluations represents a legitimate and substantial effort to establish properties, however difficult it may be to assess reliability. More thorough utilization and more efficient design criteria demand that efforts be made to increase the reliability with which properties are esti-

¹⁰R. L. Ethington of the Forest Products Laboratory was responsible for the Phase IV analysis.

mated, and at the same time reduce costs. New and improved sampling methods are known to be under various stages of development and trial. Of particular interest are the efforts being made in many parts of the world to evaluate structural lumber on a nondestructive basis as it is manufactured, and the sampling techniques discussed by Pearson and Williams (25). These latter methods have been used by Hellawell and Warren in New Zealand (14).

Noskowiak and Snodgrass (22) used basically similar statistical principles in a mill sampling scheme. The method consisted of objectively selecting a specified number of samples directly from the production line at a large number of randomly chosen mills distributed throughout the entire growth range of a species.

The current Forest Products Laboratory study has been designed to combine the data from available sources, including the Wood Density Survey, and yield more reliable estimates of properties than have previously been available for the species of interest. In addition, an effort has been made to disclose the heterogeneity in properties that exists over the range of a species, with the hope that recognition of such heterogeneity will lead to wiser use of the wood in structural applications. The technique for combining strength data collected during the last 50 years with the new specific gravity data is called double sampling.

Double Sampling Method

The double sampling method provides a technique for increasing the precision with which the mean of a variable is estimated, when the precision for a practical sample size for the variable is unacceptably low. This can be done if the variable bears a known relation to an auxiliary variable that can be estimated with a much higher degree of precision. Mathematically, if

$$y = f(x)$$

and if \bar{x} is known, then it is easy to compute a corresponding value of \bar{y} . In the context of double sampling, neither the true average of \bar{x} , nor the functional relationship between \bar{x} and \bar{y} is exactly known. However, the method lends itself to problems where it is difficult or expensive to obtain a large sample of \bar{y} , much easier or less expensive to obtain a large sample of \bar{x} , and where a

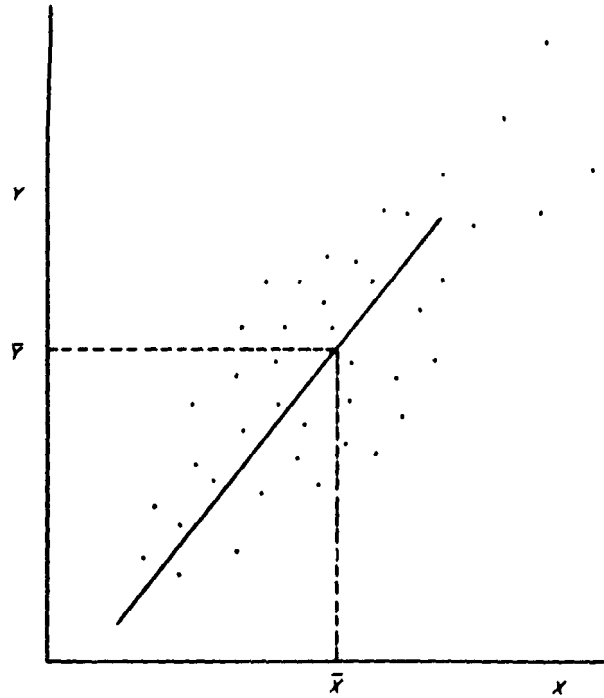


Figure 26.--Schematic representation of the use of the double sampling method to obtain a best estimate of \bar{y} , the mean of the dependent variable. The regression is reliably obtained from a relatively small joint sample of \bar{x} and \bar{y} ; in this application the mean of \bar{x} is obtained from a separate sample that provides increased precision.

(M 124 681)

strong correlation between the two can easily be established. Details of the double sampling computation have been reported by Freese (8). Figure 26 shows schematically how the method is used to obtain an improved estimate of the mean of the dependent variable.

In the case of mechanical properties, it is widely recognized that they bear a strong correlation with specific gravity for clear, straight-grained wood. Specific gravity, then, becomes the auxiliary variable. If it can be assumed that, for a given species or subspecies, the property-specific gravity relation holds even though the specimens were not randomly selected, then Forest Products Laboratory shipment data can be used to establish this relation. The much more thorough Wood Density Survey sample of specific gravity then supplies the estimate of the mean of the auxiliary variable. As an example, about 300 Douglas-fir trees have been sampled to provide all existing Forest Products Laboratory strength data: nearly 9,000 Douglas-fir trees have been sampled to provide specific gravity information. Even more important, the strength samples were obtained by means of the older cluster sampling technique; the specific gravity data for

the Western Wood Density Survey have been collected using the methods discussed under Phase I of this report, giving greater assurance that the species is well represented over its range.

In earlier publications of the Forest Products Laboratory (19,31,32) the power function

mechanical property = A (specific gravity)

has been used to describe the relation between properties and specific gravity. Plots of data have often indicated, however, that a curvilinear function is not justified for individual species. In order to test for curvilinearity, the standard shipment data of Douglas-fir for the properties of interest were analyzed by regressing properties on all combinations of the first six powers of specific gravity and testing the reduction in residual sums of squares due to adding one term on top of another. This was done for Douglas-fir data subdivided into regions delineated by Drow (6) with Coast and Interior West considered as a combined region, Interior North, and Interior South, and also for the combined data. In general, no significant terms higher than the first power were found, thus indicating that the data justify only a straightline relationship.

Property Estimation and

Geographical Heterogeneity

Results from Phase II of this study indicated considerable heterogeneity in specific gravity over the producing range of a species. This observation is apparent for Douglas-fir in figure 5. If specific gravity is a good index of mechanical properties, then the same sort of heterogeneity in these properties may be expected. The work of Noskowiak and Snodgrass (22) provided sufficient Douglas-fir strength data to show the existence of areas within the species range containing material with relatively low properties.

To disclose the heterogeneity, and assess its importance in establishing useful properties, new methods of analysis have been developed. The methods are designed to take into account estimated average properties of timber growing in small geographic areas in estimating properties of any specified populations of timber. Comparisons of populations can then be made not only by comparing population means, but also by

comparing the material represented by the lowest properties from each population. The philosophy here is that two populations--say, two species--may be equally acceptable from a structural point of view if the poorest lot of material the user can draw from either population has equivalent properties. The analytical methods developed in the following pages are expected to serve as guidelines in combining populations where it is technically sensible to do so.

The methods are workable only so long as extensive information is available on specific gravity for the species of interest. In this study, specific gravity samples were taken at plots on a grid system, as discussed under Phase I of this report. The sampling system did not prove very effective for black cottonwood, although the species has a large range. (Cottonwood habitually occurs in low moist areas along streams.) For this reason, sample plots on the grid rarely included cottonwood, and one-third of the specific gravity samples were taken in a single county in Oregon. The analysis for heterogeneity was not found to be effective for black cottonwood.

In its initial form, the method of analysis was proposed by the Western Woods Technical Committee. It has been developed and put into the form given here by the joint efforts of a task group from the Western Woods Technical Committee and the staff of the Forest Products Laboratory. The method consists of the following steps:

- (1) Subdivision of the geographical range of a species into smaller parts (unit areas) which will be assumed homogeneous with respect to properties of the species.
- (2) Estimation of average specific gravity of trees within each unit area
- (3) Estimation of average strength properties of each unit area.
- (4) Combination of unit areas into any desirable larger population groups, with average property estimates for the groups.
- (5) Determination of the heterogeneity of averages within each group.

Implementation of the steps is discussed in subsequent sections.

Subdividing Geographic Range of a Species

The range of the species may first be subdivided into "regions" for the establishment of

strength-specific gravity regressions. Regions may be proposed to block out large geographic subdivisions having distinctly different characteristics--for example, site conditions. Separate regions may be justified if regressions for two adjacent regions are shown to be significantly different in a statistical sense. Regions can never be justified unless enough data are available within each region to establish reliable regressions. The criteria to be used to assess if enough data are available are, as a matter of judgment, taken to be (1) at least five shipments of specimens from distinctly different places in the proposed region must be available and (2) the correlation coefficients from the strength-specific gravity regressions must be 0.50 or greater. For most species, regions are not justified when the importance of the species, the limitations of the species range, and the cost of additional sampling are considered. The region is defined to permit a more homogeneous treatment of strength-specific gravity regressions for the few important commercial species having a very large range,

For the purposes of this study, the smallest geographical area that is considered by itself is a Forest Service Survey Unit, or subdivision of a Survey Unit. It is necessary that a reliable volume estimate be available for each Unit or Subdivision. In the discussion that follows, the smallest subdivision for which the volume is reliably estimated will be referred to simply as an "area." In some cases, as for Douglas-fir in western Washington and Oregon, an area is a county. In other cases, where there is relatively little timber volume, an entire state makes up an area.

By the procedure described here, adjacent areas are combined to build up larger subdivisions of the forest which are called "unit areas." Nominally a unit area is expected to contain at least 1 percent of the entire species volume existing in the United States. In addition, a unit area is required to be represented by at least a minimum number of tree specific gravity samples.

The rules for developing unit areas represent an effort to objectively and uniquely subdivide the range of a species into small sections which are assumed to be considerably more homogeneous with respect to the mechanical properties of the species than is the entire range itself. The development of unit areas is done in

three basic steps:

- (1) Selection of a base area to be combined with others.
- (2) Combination with other areas to make up a unit area on a timber volume basis.
- (3) A check to insure that the unit area defined in (2) above meets the requirement for minimum number of tree specific gravity samples.

Specific rules for completing the three steps are given in Appendix C.

The rules maintain a general philosophy of combining areas in north-south bands. This is done because the general geographic features which affect growth conditions in the West exist in a north-south orientation. It is suspected that greater homogeneity in unit areas can be produced by developing unit areas more or less parallel to the dominant geographic features. Elsewhere, for other species, prevailing features may require reorientation of the rules,

The number of unit areas associated with a species is a function of the volume of timber on the smallest usable areas, and the number of tree specific gravity samples taken. In general, the larger the range and the greater the commercial importance of the species, the greater are the number of unit areas. This is because the volumes are more intensively evaluated under the above circumstances, thus permitting greater subdivision. The number of unit areas for the nine species studied were:

<u>Species</u>	<u>Number of unit areas</u>
Douglas-fir	40
White fir	13
California red fir	5
Grand fir	12
Pacific silver fir	11
Noble fir	3
Western hemlock	21
Western larch	9
Black cottonwood	1

Determining Average Specific Gravity for a Unit Area

In this study, the average specific gravity is taken as the simple average of available estimates

of tree specific gravities, given by

$$\bar{X} = \frac{\sum X_i}{n}$$

where X_i is an individual estimate of tree specific gravity and n is the number of such estimates. The individual estimates employed were those obtained from Phases II and III.

Estimating Average Strength Properties of Each Unit Area

The double sampling method provides a means for estimating average strength properties for a unit area. It is assumed that strength-specific gravity relations do not exhibit the degree of heterogeneity found in properties, so that a single regression may be used for a number of unit areas.

The data available for computation of strength-specific gravity regressions were primarily those from Forest Products Laboratory shipments. An additional set of data for Douglas-fir was obtained by Noskowiak and Snodgrass (22) from a selection of nominal 2-inch material from the production of about 400 sawmills, randomly chosen from the 1,600 mills existing in 1960. These data were made available to the Forest Products Laboratory to be considered for providing additional information in the regression determinations. It was decided that Douglas-fir data from the two sources are compatible for the establishment of regressions, and they were combined. Details of the tests for compatibility are given in Appendix D.

It was necessary to establish a criterion for determining if the available data were adequate to compute reliable regressions. If it is known with certainty 'a priori that the relationships are' straight lines, the data collected to establish a regression should be sampled in the vicinity of the extremes of the variables, because this fixes the end points of the line, thus estimating the line with greatest efficiency. However, in this case, the data were already in existence for computing regressions. It was therefore required that the sample specific gravity distribution from shipment compression parallel-to-grain data be near-

ly coincident with the sample specific gravity distribution from Wood Density Survey data, and, in particular, that the range of specific gravities from the former set of data be nearly as wide or wider than from the Wood Density set. It was found that the criterion was reasonably well met.

In the regression computations, modulus of rupture and modulus of elasticity were regressed on specific gravity obtained from bending specimens; maximum crushing strength was regressed on specific gravity from compression specimens. No specific gravities are measured according to the ASTM standard shear test. Shear strength values were regressed on gravities taken from compression specimens from the same tree, bolt, and stick as the shear specimens. Where shear strength was measured at 0° and 90° to the growth rings (in the LT and LR planes) using two specimens from the same stick, these strength values were averaged so that for each specific gravity value there was a single estimate of shear strength.

In order for the double sampling method to insure increased reliability in estimating averages, each regression must be truly representative of the geographical area to which it is applied. It was suggested earlier that, where large geographical subdivisions of the range of a species have distinctly different characteristics, separate regions may be justified. It is possible to postulate *regions* within a species range as having different regressions, and then test statistically from a sample to determine if the regressions are the same. Four regions were postulated for Douglas-fir, and found to have significantly different regressions, Details of the statistical tests are given in Appendix D. The Douglas-fir regions are essentially those described by Drow (6)¹¹ and shown in Appendix D in figure D5.

Of the other eight species included in this study, none ranges nearly so far geographically as Douglas-fir. Probably none has a range with such striking contrasts in physiographic features, excepting hemlock, white fir, and grand fir. Seven hemlock shipments have been evaluated; property data are available for white fir from seven shipments, and only two shipments of grand fir have been collected. These data are not considered

¹¹ Coast and Interior West are slightly modified from those given by Drow. Coast includes all of Oregon and Washington west of the summit of the Cascade Mountains. Interior West includes the State of California and all counties in Oregon and Washington east of, but adjacent to, the Cascade summit.

sufficient to test hypotheses about regional differences in any of the species. For these eight species, then, a single regression of each property on specific gravity has been used.

Tables 9, 10, 11, and 12 give the regression coefficients, coefficients of correlation, number of specimens, and standard deviations from regression for the nine species evaluated. Viewing the regression results from all species, modulus of elasticity is the least well correlated with specific gravity, modulus of rupture and maximum crushing strength are most highly correlated, and shear is intermediate. For the three strength properties, correlation coefficients are greater than 0.50 except in five cases. Three of the five cases are for black cottonwood, one for noble fir, and one for grand fir. All are associated with relatively small samples.

The standard deviation from regression provides a measure of expected dispersion of properties about the regression. This parameter is sometimes called the standard error of estimate. It is recorded in the tables because it can be used to compute confidence bands around the regressions, or test certain hypotheses on the regression coefficients. Any standard text in elementary statistics can be consulted for computational methods.

Given sets of unit areas associated with known average specific gravities, and the regression coefficients, it is possible to compute average mechanical properties for each unit area. Furthermore, it is possible to compute a standard error associated with each property.¹² The average properties for unit areas are not tabulated here because this would involve lengthy tabulations, and because the ultimate value of the method is not in these properties, but in the way they are to be used.

Combining Unit Areas into Groups

For each unit area., the volume of a species of interest is known, and average properties are estimated. It may be desirable to combine unit areas into larger groups due to practical marketing considerations or for other reasons. It is possible to compute a volume-weighted mean for each property in any group of unit areas of interest. Unit areas may be represented by verti-

Table 9.--Regression results for modulus of rupture versus specific gravity

Species	$\frac{1}{2}$		Coefficient of correlation	Number of specimens	Standard deviation from regression ³
	A	B			
	P.s.i.	P.s.i.			P.s.i.
Douglas-fir					
Coast.....	-1,757	20,894	0.88	2,158	572
Interior west....	-1,750	20,694	.89	885	571
Interior north....	-1,396	19,783	.82	1,585	635
Interior south....	25	15,679	.79	465	576
White fir.....	-277	16,650	.81	327	588
California red fir..	57	15,993	.76	249	562
Grand fir.....	2,516	9,591	.55	79	538
Pacific silver fir..	-1,861	21,086	.89	256	447
Noble fir.....	-1,148	19,518	.73	165	487
Western hemlock....	-365	16,623	.76	363	637
Western larch.....	1,004	13,905	.67	337	742
Black cottonwood....	352	14,269	.40	77	815

¹Coefficients in the relation $Y = A + BX$ where Y is modulus of rupture in pounds per square inch and X is specific gravity.

²All digits retained through the unit's position to permit further computations with minimum round-off error. Original data contained three significant digits.

³The standard deviation from regression is a measure of dispersion about the regression. It is assumed that it represents the standard deviation of property about the line at any choice of specific gravity. This parameter is often called the standard error of estimate.

Table 10.--Regression results for modulus of elasticity versus specific gravity

Species	$\frac{1}{2}$		Coefficient of correlation	Number of specimens	Standard deviation from regression ³
	A	B			
	$\frac{1,000}{P.s.i.}$	$\frac{1,000}{P.s.i.}$			P.s.i.
Douglas-fir					
Coast	-259	4,036	0.69	2,158	216
Interior west	-408	4,203	.73	885	215
Interior north	-212	3,631	.63	1,585	208
Interior south	151	2,346	.54	465	171
White fir	-226	3,770	.72	327	183
California red fir	179	2,759	.43	249	240
Grand fir	679	1,650	.38	79	148
Pacific silver fir	109	3,343	.64	256	169
Noble fir	-588	5,253	.55	165	214
Western hemlock	214	2,597	.47	363	218
Western larch	726	1,534	.30	337	237
Black cottonwood	263	2,580	.34	77	176

¹Coefficients in the relation $Y = A + BX$ where Y is modulus of elasticity in thousand pounds per square inch and X is specific gravity.

²All digits retained through the unit's position to permit further computations with minimum round-off error. Original data contained three significant digits.

³The standard deviation from regression is a measure of dispersion about the regression. It is assumed that it represents the standard deviation of property about the line at any choice of specific gravity. This parameter is often called the standard error of estimate.

¹²For the computational procedure, see Freese (8).

Table 11.--Regression results for maximum crushing strength versus specific gravity

Species	$\frac{1}{2}$		Coefficient of corre- lation	Number of speci- mens	Standard deviation from re- gression ³
	A	B			
	P.S.I.	P.S.I.			P.S.I.
Douglas-fir					
Coast	-1,087	10,803	0.81	3,042	403
Interior west	-1,548	11,854	.84	1,267	414
Interior north	-905	9,797	.79	1,789	360
Interior south	21	7,174	.66	531	369
White fir	-854	10,200	.88	688	265
California red fir	-267	8,411	.80	500	286
Grand fir	991	5,623	.60	170	269
Pacific silver fir	-568	9,459	.89	524	227
Noble fir	-1,285	11,467	.74	332	272
Western hemlock	-764	9,804	.81	738	329
Western larch	-31	7,921	.67	703	414
Black cottonwood	484	5,396	.34	154	308

¹Coefficients in the relation $Y = A + BX$ where Y is maximum crushing strength in pounds per square inch and X is specific gravity.

²All digits retained through the unit's position to permit further computations with minimum round-off error. Original data contained three significant digits.

³The standard deviation from regression is a measure of dispersion about the regression. It is assumed that it represents the standard deviation of property about the line at any choice of specific gravity. This parameter is often called the standard error of estimate.

Table 12.--Regression results for shear strength versus specific gravity

Species	$\frac{1}{2}$		Coefficient of corre- lation	Number of speci- mens	Standard deviation from re- gression ³
	A	B			
	P.S.I.	P.S.I.			P.S.I.
Douglas-fir					
Coast	193	1,580	0.66	1,579	96
Interior west	174	1,669	.69	609	98
Interior north	184	1,711	.66	1,137	94
Interior south	18	2,171	.67	261	118
White fir	306	1,223	.75	139	56
California red fir	287	1,336	.40	57	134
Grand fir	218	1,505	.61	26	72
Pacific silver fir	70	1,725	.83	81	56
Noble fir	275	1,408	.25	37	122
Western hemlock	221	1,529	.70	141	67
Western larch	294	1,204	.69	56	61
Black cottonwood	52	1,761	.48	15	69

¹Coefficients in the relation $Y = A + BX$ where Y is shear strength in pounds per square inch and X is specific gravity.

²All digits retained through the unit's position to permit further computations with minimum round-off error. Original data contained three significant digits.

³The standard deviation from regression is a measure of dispersion about the regression. It is assumed that it represents the standard deviation of property about the line at any choice of specific gravity. This parameter is often called the standard error of estimate.

cal lines on a plot of volume versus average property, as shown in figure 27. Then the overall mean property for the combination is located at the centroid of the family of unit area lines, and has a height equal to the total volume of

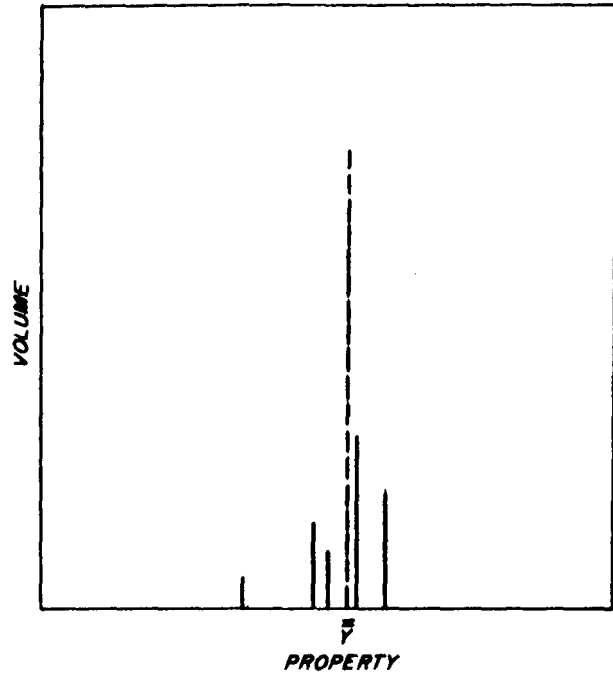


Figure 27.--Schematic representation of a volume-weighted property for the unit area in a group, and the mean of the group, shown by the dashed line. (M 124 687)

all the unit areas in the group. Algebraically, the mean of the group, \bar{Y} , is given by

$$\bar{Y} = \frac{\sum Y_i V_i}{\sum V_i}$$

where Y_i is the mean property for the i th unit area and V_i is the volume of the species for the i th unit area. Table 13 gives average properties obtained in this fashion, along with previous estimates published by the Forest Products Laboratory.

If a group of unit areas is relatively heterogeneous, this is analogous to wide spacing of the lines in figure 27. Where safe design criteria are needed, it is important that the poorest wood in a group not be represented by property values far below the mean for the group. As an indicator of heterogeneity below the group mean, the variability index is defined as the group mean divided by the lowest unit area mean in the group. By definition, the variability index is always greater than or equal to unity. The larger the variability index, the less homogeneous the group in the property range below the group mean. Caution must be observed in comparing variability indices between groups. Equal variability indices

Table 13.--Estimates of average strength properties for clear, green wood

Groups	Property							
	Modulus of rupture		Modulus of elasticity		Maximum crushing strength		Shear strength	
	Current estimate	Previous estimate ¹	Current estimate	Previous estimate ¹	Current estimate	Previous estimate ¹	Current estimate	Previous estimate ¹
	P.s.i.	P.s.i.	1,000 P.s.i.	1,000 P.s.i.	P.s.i.	P.s.i.	P.s.i.	P.s.i.
Douglas-fir								
Coast ²	7,700	7,500	1,560	1,540	3,780	3,820	900	920
Interior west ²	7,700	7,700	1,510	1,580	3,870	3,940	940	930
Interior north	7,400	6,800	1,410	1,280	3,470	3,160	950	880
Interior south	6,800	6,200	1,160	1,050	3,110	2,920	950	860
White fir	5,900	5,700	1,160	1,030	2,900	2,710	760	750
California red fir	5,800	6,000	1,170	1,210	2,760	2,850	770	800
Grand fir	5,800	6,100	1,250	1,300	2,940	3,020	740	760
Pacific silver fir	6,400	5,700	1,420	1,260	3,140	2,670	750	670
Noble fir	6,200	5,800	1,380	1,270	3,010	2,740	800	750
Western hemlock	6,600	6,100	1,310	1,220	3,360	2,990	860	810
Western larch	7,700	8,200	1,460	1,530	3,760	3,990	870	900
Black cottonwood	4,900	4,800	1,080	1,070	2,200	2,160	610	600

¹Douglas-fir estimates from Forest Prod. Lab. Rpt. 2078, "Relationship of Locality and Rate of Growth to Density and Strength of Douglas-Fir." All others from U.S.D.A. Agriculture Handbook 72, "Wood Handbook."

²Values from FPL Report 2078 are for virgin material only.

Table 14.--Parameters of interest for groups of unit areas

Groups	Property ¹											
	Modulus of rupture			Modulus of elasticity			Maximum crushing strength			Shear strength		
	Average	Vari-ability	Standard ²	Average	Vari-ability	Standard ²	Average	Vari-ability	Standard ²	Average	Vari-ability	Standard ²
	: index	: deviation	: ation	: index	: deviation	: ation	: index	: deviation	: ation	: index	: deviation	: ation
P.s.i.		P.s.i.	1,000 P.s.i.		1,000 P.s.i.	P.s.i.		P.s.i.	P.s.i.		P.s.i.	
Douglas-fir												
Coast	7,665	1.05	1,317	1,560	1.05	315	3,784	1.05	734	904	1.03	131
Interior west	7,713	1.03	1,322	1,513	1.04	324	3,872	1.04	799	936	1.02	137
Interior north	7,438	1.04	1,163	1,409	1.04	274	3,469	1.04	602	947	1.03	126
Interior south	6,784	1.01	908	1,162	1.00	200	3,113	1.01	489	953	1.00	153
White fir	5,854	1.01	949	1,161	1.02	249	2,902	1.02	528	756	1.01	78
California red fir	5,809	1.01	885	1,170	1.01	267	2,758	1.01	459	767	1.00	146
Grand fir	5,839	1.03	680	1,250	1.03	164	2,939	1.04	363	739	1.04	97
Pacific silver fir	6,410	1.07	1,296	1,420	1.05	255	3,142	1.06	591	746	1.05	114
Noble fir	6,169	1.07	966	1,380	1.08	310	3,013	1.08	560	802	1.04	136
Western hemlock	6,637	1.03	1,088	1,307	1.02	258	3,364	1.03	615	864	1.02	105
Western larch	7,652	1.04	1,001	1,458	1.02	249	3,756	1.04	564	869	1.03	85
Black cottonwood ³	4,890	1.00	951	1,083	1.00	197	2,200	1.00	360	612	1.00	92

¹ All digits retained in the averages and standard deviation through the unit's position to permit further computations with minimum round-off error. Original data contained 3 significant digits.

² Estimated by regression method (see Appendix E).

³ Variability indices for black cottonwood are unity because a single unit area was available.

for a relatively strong group and a relatively weak group seem to indicate equal variability in means, but on an absolute basis the stronger group will exhibit greater variability in means. The variability index should only be interpreted

in association with the corresponding group mean.

Table 14 repeats average properties from table 13 and gives variability indices. The Douglas-fir groups chosen correspond to the four Douglas-fir regions, and for the other eight species, all unit areas together are treated as a group.

The computation of the mean for a group of unit areas is entirely rigorous, although the distributional forms of the unit area populations are unknown. However, the distributional forms of population built up from unit areas will be a function of the particular unit areas placed in that population, and in general will not be normal, even if the unit area populations are normal. It is not practical at the present time to establish

the distribution function for unit areas even if normality is assumed because of the lack of sufficient data with which to estimate individual unit area variances with acceptable precision.

Potentially, several species may be combined

In exactly the same manner as employed for combining unit areas into groups. Although the component populations may be normal, there is no reason to believe that the combination is also normal. Hald (11) has termed such distributions "heterogeneous distributions," and discusses briefly the nature of them with arbitrary weighting. It is possible to write the distribution function of the combination if the distributional forms of the components are known or can be assumed (see Appendix E). In the context of this study, it should be possible to establish the distribution function for groups of species (regions in the case of Douglas-fir) if species distributions can be assumed normal. Under the normality assumption, each species distribution is completely

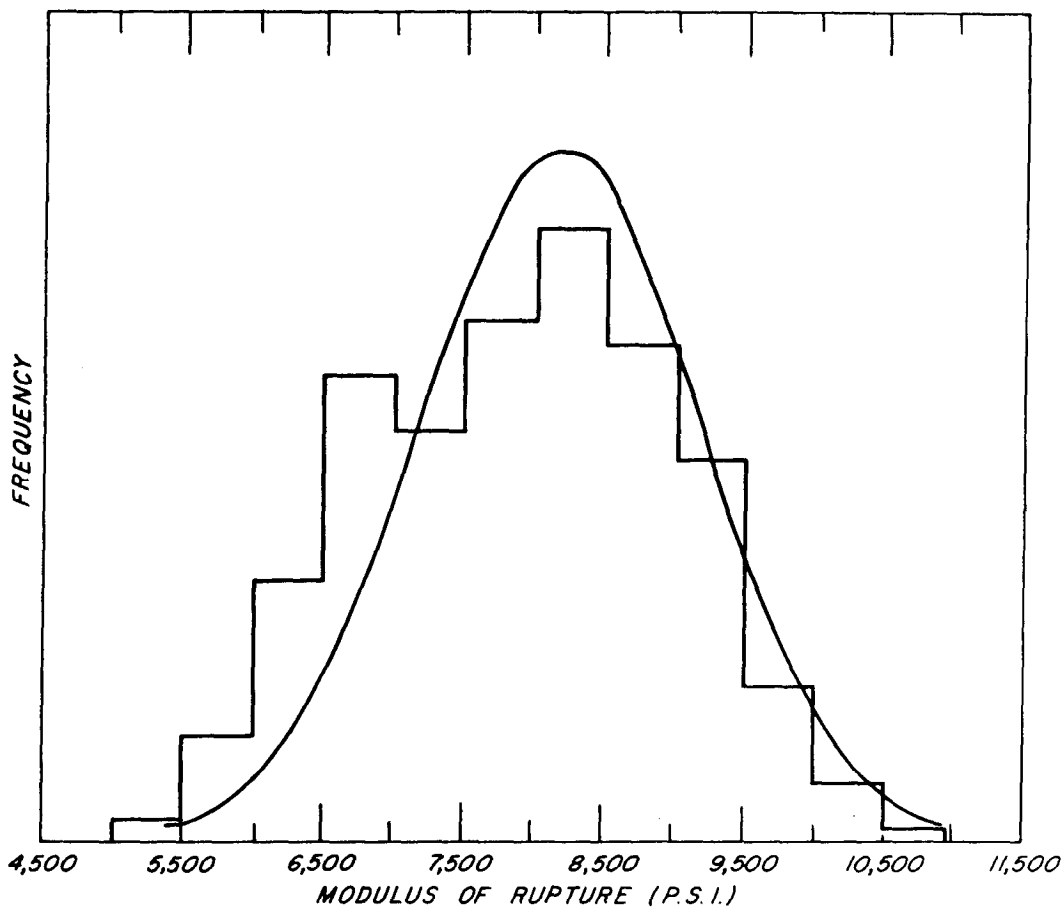


Figure 28.--A comparison of actual distribution with assumed normal distribution curve for modulus of rupture of western larch. (M 124 686)

specified by a mean and standard deviation, The means are given in table 14, and methods for estimating standard deviations will be discussed in paragraphs to follow, Plots of shipment data have indicated that the normality assumption may be quite reasonable. Figure 28 gives a typical sample distribution, and the continuous distribution obtained by computing a mean and standard deviation under the normality assumption.

The heterogeneous distribution may or may not be conspicuously different from a normal distribution, depending on the relative differences between component population parameters and volumes. Figure 29 is the heterogeneous distribution obtained by combining modulus of rupture parameters for white fir and western hemlock, treated as normal distributions. Although it has a general normal shape, it begins to take on a bimodal shape near the peak.

Two possible methods for estimating standard deviation have been explored, and have not been found to give greatly different results for the

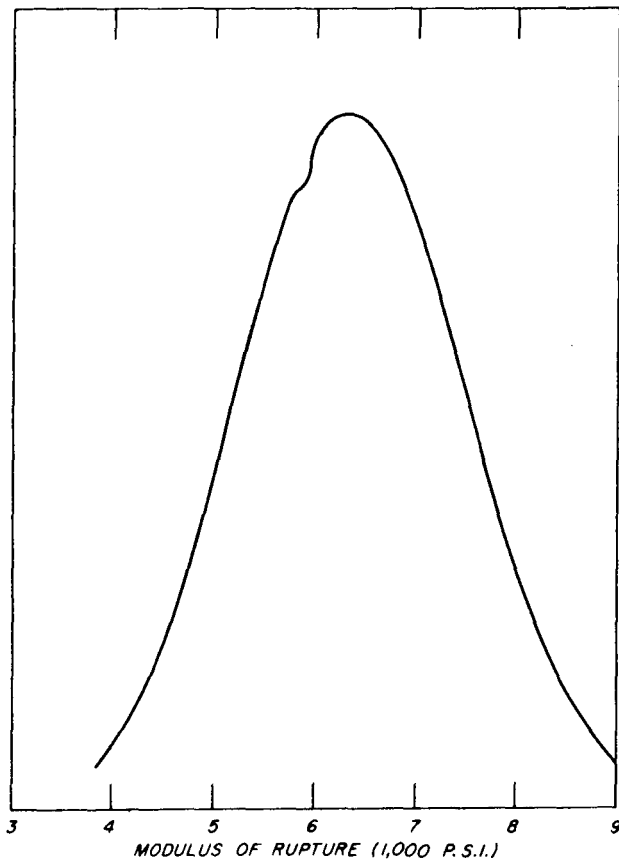


Figure 29.--The distribution function for white fir and western hemlock considered as a heterogeneous population. (M 124 685)

species considered in this study. In one case, the standard deviation is estimated from the sample in more or less classical fashion (components of variance method) from Forest Products Laboratory shipment data. In the other case (regression method), the between-tree component of variance is obtained from Wood Density Survey data, combined with a within-tree component from Forest Products Laboratory shipment specific gravity data, and the relation between property and specific gravity is used to obtain the property standard deviation. The two methods are discussed fully in Appendix E. Standard deviation estimates obtained by the regression method are given in table 14.

Summary of Phase IV

The double sampling method provides a means for estimating average mechanical properties with greater precision than has previously been achieved. This has been done by establishing relations between properties and specific gravity using available data, and then applying mean specific gravities from the Western Wood Density Survey to these relations to estimate mean properties.

In general, regressions have been established using Forest Products Laboratory data which have been collected and accumulated for some 60 years. In addition, data have been made available from a very comprehensive study of structural properties of Douglas-fir conducted by Noskowiak and Snodgrass. The Douglas-fir data from these two sources appear to be reasonably compatible for establishing regressions, and have been pooled to provide additional reliability.

For purposes of establishing regressions, the range of Douglas-fir was subdivided into four regions. All regressions were found to be significantly different between these regions, using the combined data. A single regression has been used for each property of each of the eight other species of interest in this study.

In order to describe the heterogeneity in properties over the range of a species, a method of analysis has been developed which involves estimation of mean properties for small "unit areas" where sufficient data are available. The unit areas may be combined into larger "groups" which

are practical in terms of marketing considerations. The variability index is a statistic which has been defined so as to indicate the degree of heterogeneity below the mean for a group of unit areas. The variability index gives an indication of the average properties that may be expected from the lowest strength material available from a group of unit areas, Standard devia-

tions for species (regions for Douglas-fir) have been estimated by two methods, and the limitations of each have been explored. The estimates of standard deviations by the two methods for the species in this study were not found to be greatly different.

Average properties, variability indices, and standard deviations are given in table 14.

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APPENDIX A --COMPUTATIONAL DETAILS

1. Log volume was computed by the following formula:

$$V = (\text{d.i.b.})^2 \times 0.0054542 \times \text{length in feet}$$

2. Specific gravity of each disk was computed by the following formula:

$$\text{Disk specific gravity} = \frac{\text{ovendry weight of disk}}{\text{displaced volume of disk}}$$

3. Increment core specific gravity was computed with the following formula:

$$\begin{aligned} \text{Increment core specific gravity} &= \text{ovendry weight (grams)} \\ &\div \frac{(\text{core diameter})^2 \times 0.7854 \times \text{core length (inches)}}{0.061} \end{aligned}$$

4. Specific gravity means and standard errors for Forest Survey Units were computed as follows:

(a.) Specific gravity means.

Given: k = number of locations from which density samples were obtained.

n_i = number of trees (of a given species) sampled at location i (i = 1...k).

G_{ij} = specific gravity of the jth sampled tree at the ith location (j = 1... n_i).

B_i = basal area per acre observed at the ith sample location.

$$G_i = \frac{\sum_{j=1}^{n_i} G_{ij}}{n_i} \quad = \text{average specific gravity for location } i$$

$W_i = B_i G_i$ = weighted specific gravity for location i

$$\text{then, } \bar{G} = \frac{\sum_{i=1}^k B_i G_i}{\sum_{i=1}^k B_i} = \frac{\sum_{i=1}^k W_i}{\sum_{i=1}^k B_i} \quad = \text{average specific gravity for a Survey Unit.}$$

(b.) Standard error.

$$\text{Standard error of } \bar{G} = \sqrt{\frac{k}{(\sum B_i)^2} \left[\frac{\sum W_i^2 + \bar{G}^2 (\sum B_i^2) - 2 \bar{G} \sum B_i W_i}{k-1} \right]}$$

APPENDIX B--COEFFICIENTS OF DETERMINATION FROM INITIAL

MULTIPLE REGRESSION ANALYSIS

Examination of Douglas-fir coefficients of determination shown in table B1 suggests questions to be answered in further research. For example, the reciprocal of age, latitude, and elevation appear to be much more strongly associated with specific gravity on the West Coast than in the Rocky Mountains, as indicated by the significance of the coefficients of determination. The reasons for the change in specific gravity relationships with site and growth factors between regions are unanswered. Many more questions implied by these relationships can be formulated by additional study of tables B1 and B2.

Table B1.--Coefficient of determination showing significant (P = 0.01) improvement by successive inclusion of variables

Number of variables showing significant (P = 0.01) increase in R ²	Independent variables											R ²	
	Latitude	Elev.	Dia.	Age:1/age	Dia/age	Vol/age:1	elev:Elev ²	Elev ² /age	Dia ²	Dia ² /age	R ²		
DOUGLAS-FIR (WEST COAST)													
1					X								: 0.17
2			X		X								: .22
3	X	X			X								: .24
4	X	X			X				X				: .25
5	X	X			X				X	X			: .26
6	X	X			X	X			X	X			: .26
7	X	X			X	X		X	X	X			: .27
8	X	X	X		X	X	X			X	X		: .27
9	X	X	X		X	X	X		X	X	X		: .28
10	X	X	X		X	X	X	X	X	X	X		: .28
DOUGLAS-FIR (INTERIOR NORTH)													
1								X					: .10
2						X		X					: .14
3		X				X			X				: .18
4		X	X		X				X				: .19
5		X				X			X		X	X	: .20
DOUGLAS-FIR (INTERIOR SOUTH)													
1								X					: .04
WESTERN LARCH													
1			X										: .10
2			X					X					: .17
3						X	X		X				: .19
4		X				X	X		X				: .20
WHITE FIR													
1			X										: .06
2			X		X								: .10
3			X			X						X	: .12
4			X			X			X			X	: .13
5	X		X			X			X			X	: .14

Table B1. --Coefficients of determination showing significant (P = 0.01) improvement by successive inclusion of variables (continued)

Number of variables showing significant (P = 0.01) increase in R ²	Independent variables											R ²	
	Latitude	Elev.	Dia.	Age	1/age	Dia/age	Vol/age	1/elev	Elev ²	Elev ² /age	Dia ²		Dia ² /age
CALIFORNIA RED FIR													
1			X										0.17
2			X								X		.18
3	X		X								X		.20
4	X		X		X						X		.21
5	X		X		X					X		X	.22
6	X		X	X	X	X						X	.23
GRAND FIR													
1						X							.07
2						X		X					.14
3			X		X			X					.16
4			X		X			X			X		.18
5			X	X		X		X				X	.19
PACIFIC SILVER FIR													
1						X							.14
2				X		X							.23
3	X			X		X							.27
4	X		X			X	X						.31
NOBLE FIR													
1								X					.28
2		X	X										.31
3		X		X		X							.36
WESTERN HEMLOCK													
1					X								.09
2			X		X								.13
3		X	X		X								.16
4		X				X					X	X	.20
5		X				X				X	X	X	.22
6		X	X		X	X				X		X	.22
BLACK COTTONWOOD													
1								X					.06

Table B-2.--Percent of core specific gravity variation accounted for by simple regression (significant at the 1 percent level)

Species	Independent variables											
	Latitude	Elev	Dbh	Age	1/age	Dbh/age	Vol/age	1/elev	Elev ²	Elev ² /age	Dbh ²	Dbh ² /age
Douglas-fir	:	:	:	:	:	:	:	:	:	:	:	:
West Coast	4	1	8	5	17	7	2	:	:	5	5	1
Interior north	8	4	:	:	1	:	:	10	:	:	:	1
Interior south	:	3	:	4	:	:	:	:	3	:	:	:
White fir	:	:	6	1	:	4	3	:	:	:	5	4
California red fir	:	:	17	:	:	:	9	:	:	:	13	9
Grand fir	:	:	:	:	:	7	:	:	:	:	:	:
Pacific silver fir	9	4	13	:	:	14	13	4	5	:	10	14
Noble fir	13	28	14	:	:	7	12	28	26	10	12	13
Western hemlock	:	:	:	1	9	7	:	:	:	:	:	1
Western larch	:	:	10	5	6	:	10	3	:	:	10	5
Black cottonwood	:	:	:	:	:	:	:	6	:	:	:	:

APPENDIX C--DEVELOPMENT OF UNIT AREAS FOR INDIVIDUAL SPECIES

Unit areas are nominally defined as an individual or group of Forest Survey Units (or subdivisions of Survey units for which volume data are available) containing 1 percent or more of the species cubic foot volume existing in the United States. In addition, unit areas are required to be represented by specific gravity samples from at least 20 trees. The smallest subdivision of a species growth range for which volume data are available is referred to as an "area." Areas are combined by these rules until sufficient volume and specific gravity samples are represented to obtain a unit area.

In the rules for selecting unit areas, preference has arbitrarily been given to the northwest direction in selecting base areas. It has been found that the northwestern-most eligible area may easily be identified by drawing a true northwest line at any convenient location on a map, and simply sliding a draftsman's triangle along this line in the northwesterly direction to establish perpendiculars to it. The northwestern-most area is the last one to be touched by a perpendicular. This technique is shown in figure C1. True northwest may be expected to change relative to the areas with the map projection used, and with each point on the map. The system is only unique for a given projection, and some defined point on the map. In this study, cleartype county outline map No. 6244, made by American Map Company, Inc., was used and true northwest was taken as 45° from the north declination on the map.

1. Base Areas

Select a base area to be combined with other areas using one of the criteria listed below. Where more than one criterion is applicable, give priority to the one with the lowest number. When a base area has been selected, proceed to step 2.

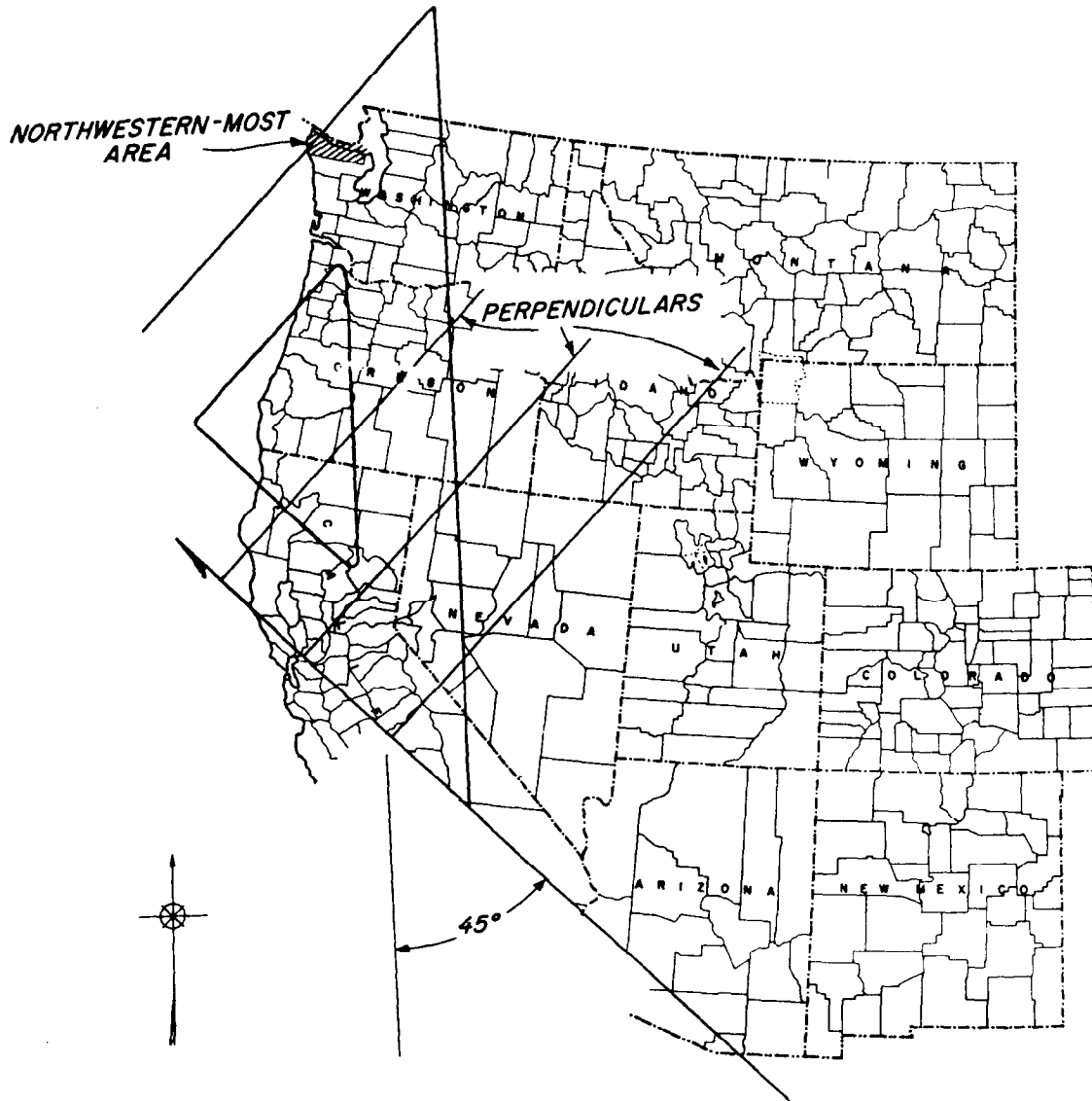


Figure C1.--Method for establishing northwestern-most area relative to north designation on map.

1.1. For the first base area to be selected for a species, always start from the northwest extremity of the species range, giving highest priority to the westerly direction.

1.2. For any succeeding base area, use the area immediately to the south of the last area considered in the previous unit area combination (only if in the same state as the previous base). Where more than one eligible area exists under this criterion, select the western-most area. If blocked on the south by a state line, regional boundary, major geographical site feature, or area containing no volume, use the area to the west of the last area considered in the previous unit area Combination.

1.3. In the same state in which the previous base area was chosen, return to the northwestern-most unused area.

1.4. In the state south of the state in which the previous base area was chosen, consider the northwestern-most unused area as the base area.

1.5. In the northwestern-most state where unused areas exist, consider the northwestern-most unused area as the base area.

2. Determining Need for Additional Combining to Meet Timber Volume Requirements

2.1. If the base area or any combination of areas contains 1.00 percent or more of the total volume of the species, it automatically constitutes a unit area. Proceed to step 4 and check sample size requirements.

2.2. If the base area or any combination of areas contains less than 1.00 percent of the total volume of the species, further area combining must be carried out except as noted under 2.3. Proceed to step 3.

2.3. If the base area or any combination of areas contains between 0.90 and 0.99 percent of the total volume of the species, and the addition of another area creates a fractional volume greater than 1.50, then the area before the last combination is a unit area. Proceed to step 4 and check sample size requirements.

3. Combining Areas to Meet Timber Volume Requirements

3.1. Only an area containing less than 1.00 percent of the volume of the species is eligible to be added to a base area or any other combination of areas.

3.2. Areas should never be combined across regional boundaries, major geographical site features, or areas containing no volume except where instructed otherwise.

NOTE: Zero volume areas for which tree specific gravity samples are available should be treated as areas containing a measurable volume of timber.

3.3. Areas shall be combined using the ordered procedures given below. The lowest numbered procedure that will permit combining should be used in each instance. After adding an area to a base area, or after adding each new area to an area combination, return to step 2 except where instructed otherwise.

3.3.1. Addition to base area

3.3.1.1. Within a state, combine the base area with the eligible area immediately to the south. If more than one eligible area exists on the south, select the area with the longest boundary common with the base, as measured in an east-west direction. Where more than one eligible area exists with approximately equal boundaries common with the base, combine first the area with the least volume, then the other if necessary.

3.3.1.2. If there are no eligible areas within the state south of the base area, use a rule analogous to 3.3.1.1 to combine the base with areas to the west of the base. If no eligible areas exist to the west, consider areas to the east in similar fashion.

3.3.1.3. If none of the above criteria 3.3.1.1 and 3.3.1.2 permit combining an area with the base, and the base is bordered by a state line, move south or east, in that order of preference, across the state line and combine with an eligible adjacent area. Use the length of common boundary rule as in 3.3.1.1 above if necessary. If volume criteria of step 2 are not met by the base and added area, ignore the state line crossed when applying the rules given under 3.3.2.

3.3.1.4. If none of the above criteria 3.3.1.1 through 3.3.1.3 permit combining an area with the base, and if the base is bordered by one of the lines not to be crossed as described in 3.2, and if the volume of the species in the base is less than 0.90, combine the base with the unit area adjacent to it which contains the least volume of the species. If no adjacent unit areas exist, combine with the adjacent area having the least volume, even if this volume exceeds 1.00 percent, If the volume of the species in the base is 0.90 or greater (rather than less than 0.90), the base becomes a unit area. Proceed to step 4 and check sample size requirements.

3.3.1.5. If none of the above criteria permit combining an area with the base, combine the base with the nearest unit area, crossing the boundaries, site features, or volumeless areas mentioned in 3.2. If two or more unit areas are equally near, combine with the unit area containing the least volume, even though the least volume exceeds 1.00 percent.

3.3.2. Addition to a combination of two or more areas

3.3.2.1. Within a state, combine the combination with an area immediately to the west of the base, if more than one eligible area bounds the west boundary of the base, use the length of common boundary rule as in 3.3.1.1, but with the boundary measure in the north-south direction.

3.3.2.2. Within a state, combine the combination with an eligible area immediately to the west of the last area used. Use the length of common boundary rule as in 3.3.2.1 above if necessary.

3.3.2.3. Within a state, combine the combination with an area immediately south of the last area used. Use the length of common boundary rule as in 3.3.1.1 above if necessary.

3.3.2.4. Within a state, repeatedly combine the combination with eligible areas immediately adjacent, moving in a clockwise direction around the combination.

3.3.2.5. If none of the above criteria 3.3.2.1 through 3.3.2.4 permit adding to a combination, and the combination is bordered by a state line, move south or east, in that order of preference, across the state line and combine with an eligible adjacent area. Use the common boundary rule as in 3.3.1.1 if necessary. If volume criteria of step 2 are not met by the new combination, ignore the state line when considering additional combining under the rules of 3.3.2.

3.3.2.6. If none of the criteria 3.3.2.1 through 3.3.2.5 above permit adding to a combination, and the combination is bordered by one of the lines not to be crossed as described in 3.2, combine the combination with the unit area adjacent to it which contains the least volume of the species. If no adjacent unit areas exist, combine with the adjacent area having the least volume even if this volume exceeds 1.00 percent.

3.3.2.7. If none of the above criteria permit adding to a combination, combine with the nearest unit area, crossing the boundaries, volumeless areas, or site features mentioned in 3.2, in this order of preference. Where adjacent unit areas are involved, use the length of common boundary rule if necessary. If two or more unit areas are equally near, in crossing areas with no volume, combine with the unit area containing the least volume.

4. Minimum Number of Tree

Specific Gravity Samples

The unit area is required to be represented by specific gravity samples from at least twenty (20) trees. If less than twenty (20) samples are available, add areas according to the rules for combining given in step 3.3.2 until the twenty (20) sample size requirement is met. The rules in step 3.3.2 may be made to apply by substituting the words "number of samples" for the word "volume." Areas are considered eligible for combining even if they contain more than twenty (20) samples. Areas represented by no samples but containing some timber volume shall be treated as areas containing core samples when applying the rules of step 3.3.2.

When a unit area containing twenty (20) samples has been developed, return to step 1 and begin developing a new unit area for the species.

APPENDIX D--DEVELOPMENT OF REGRESSIONS FROM AVAILABLE DATA

Compatibility of Data from Two Sources

Strength and specific gravity values taken each from the same sample are, in general, only available from Forest Products Laboratory shipment evaluations. However, for Douglas-fir, many more values were made available from the study of Noskowiak and Snodgrass (20). It does not necessarily follow that data from the two sources can be pooled for estimating regressions. The sampling plans from the two sources are known to be different. The population which the Forest Products Laboratory data represents is Douglas-fir wood at heights from 8 to 16 feet above stump taken from selected stands. The population for the other

set of data is Douglas-fir that was processed at sawmills in 1960.

Analyses of variance were conducted to determine, for each region and each property, if the regression obtained from Forest Products Laboratory data is the same regression as the counterpart computed from the data of Noskowiak and Snodgrass. The computational techniques used were those discussed by Ostle (21) on pages 133 through 137. Table D1 gives the variance ratios (F). In all instances, except for shear in the Interior West and Interior North, the regressions from the two sources were found to significantly differ at the 5 percent level of probability. According to the statistical methods employed, it may be concluded that the regressions are different 5 percent of the time if, in fact, they are the same. It can also be seen in the table that at the 1 percent level of probability, the regressions for modulus of rupture in the Interior West and Interior South and modulus of elasticity in the Coast and Interior South are probably the same. The variance ratios are quite large only for maximum crushing strength in the Coast and Interior West and shear in the Coast and Interior South. Figures D1, D2, D3, and D4 show the graphs of the regressions. It is apparent from the figures that, although the regressions are statistically different, they do not appear noticeably different. In general, the statistical tests have a large number of degrees of freedom; that is, they are extremely sensitive tests and are capable of resolving very small differences. It is not surprising, then, that the regressions are significantly different, when the differences in sampling methods are considered. It is felt that, in general, the differences between regressions in this case are not necessarily practical differences, and that probably the entire population of merchantable Douglas-fir is better represented by working with pooled data from the two sources.

Table D1.--Values of F and corresponding degrees of freedom for tests of differences between regressions. Comparisons are for regressions from Forest Products Laboratory data versus regressions from data due to Noskowiak and Snodgrass

Property	Coast		Interior West		Interior North		Interior South	
	F	Degrees of freedom	F	Degrees of freedom	F	Degrees of freedom	F	Degrees of freedom
Modulus of rupture	16	2,154	² 3.16	881	33	1,581	² 3.57	461
Modulus of elasticity	² 3.20	2,154	20	881	17	1,581	² 3.88	461
Maximum crushing strength	198	3,038	143	1,263	16	1,785	10	527
Shear strength	60	1,575	³ 2.20	605	³ 2.94	1,133	83	257

¹Only the denominator degrees of freedom are listed. The numerator degrees of freedom are 2 in all cases.

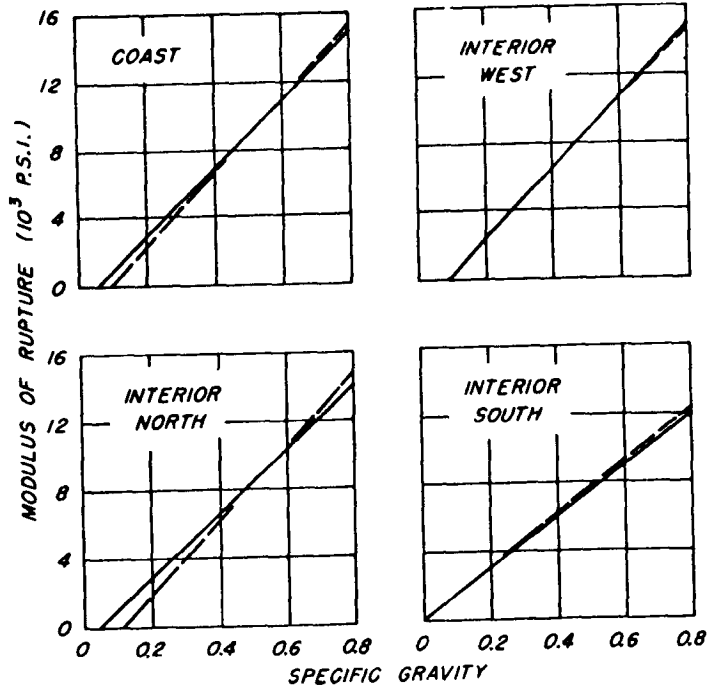
²Significant at the 5 percent level of probability but not at the 1 percent level.

³Not significant at the 5 percent level of probability.

Differences in Regressions Between Regions

Isaac and Dimock (15) have indicated that authorities universally agree that Douglas-fir growing on the east slopes of the Cascade Range and the Sierra Nevada and in the Rocky Mountains is a varietal form, *Pseudotsuga menziesii* var. *glauca*. Some authorities designate additional varieties. For example, Göhre (10), as recently as 1958, published an extensive work on Douglas-fir in which three varietal forms were designated corresponding more or less to what might be called West Coast, Northern Rocky Mountain, and Southern Rocky Mountain areas. It is not surprising that a species having such a large geographical range would

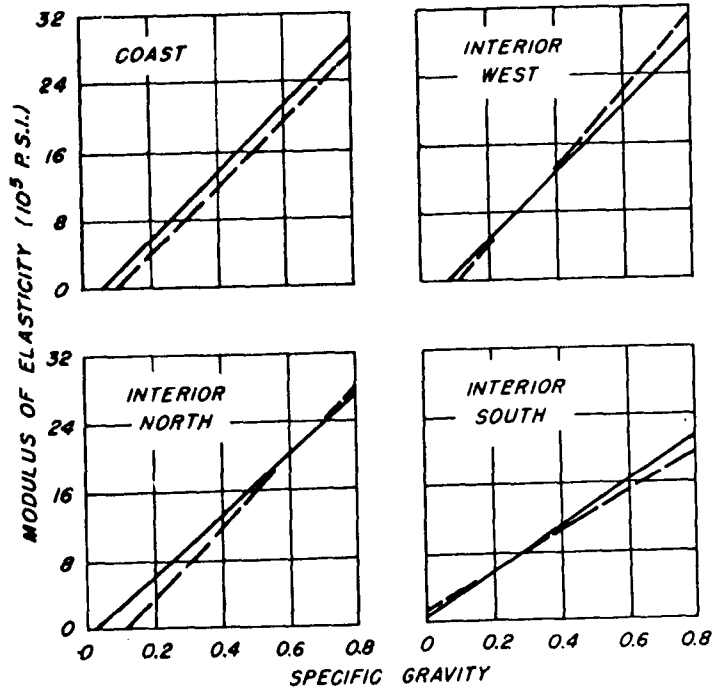
LEGEND:
 - - - FOREST PRODUCTS LABORATORY DATA
 ——— DUE TO NOSKOWIAK AND SNODGRASS



(M 127 548)

Figure D1.-- Regressions for modulus of rupture on specific gravity from two data sources.

LEGEND:
 - - - FOREST PRODUCTS LABORATORY DATA
 ——— DUE TO NOSKOWIAK AND SNODGRASS

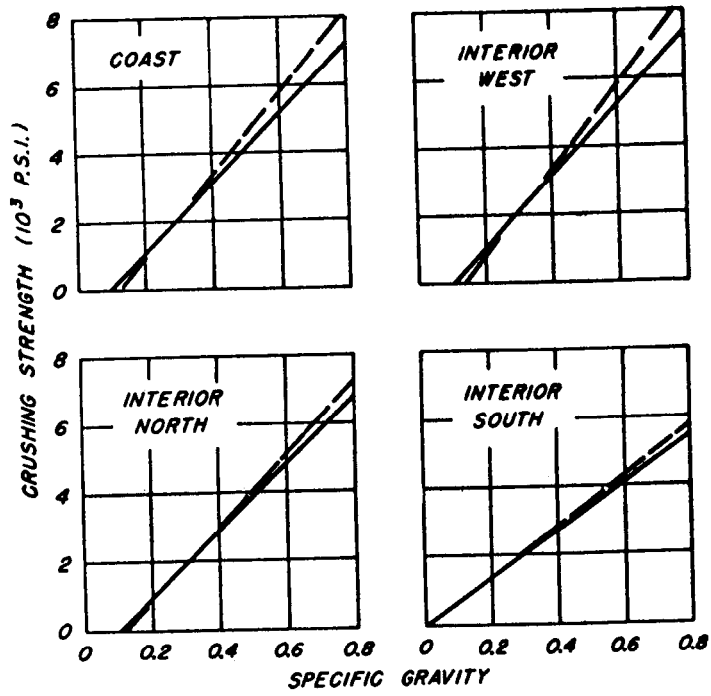


(M 124 662)

Figure D2.-- Regressions for modulus of elasticity on specific gravity from two data sources.

LEGEND:

--- FOREST PRODUCTS LABORATORY DATA
 — DUE TO NOSKOWIAK AND SNODGRASS

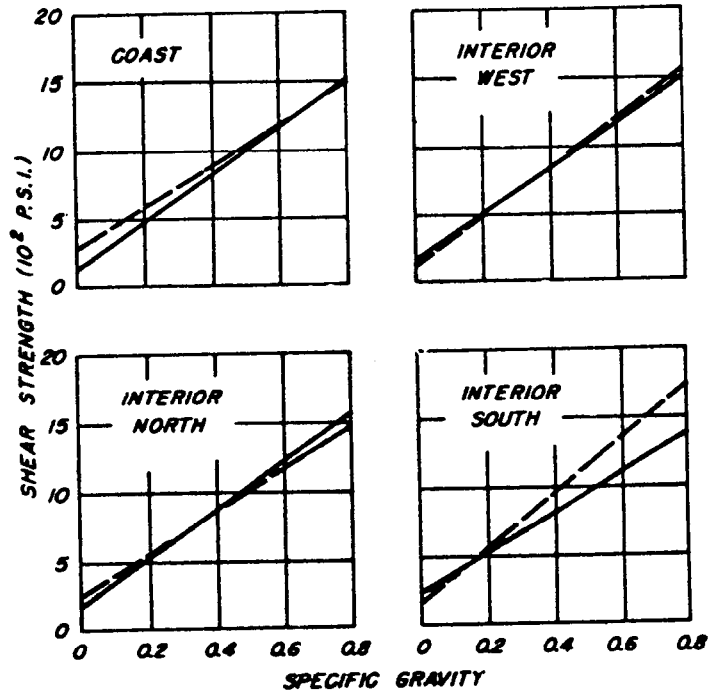


OM 134 689

Figure D3.--Regressions for crushing strength on specific gravity from two data sources.

LEGEND:

--- FOREST PRODUCTS LABORATORY DATA
 — DUE TO NOSKOWIAK AND SNODGRASS



OM 134 689

Figure D4.--Regressions for shear strength on specific gravity from two data sources.

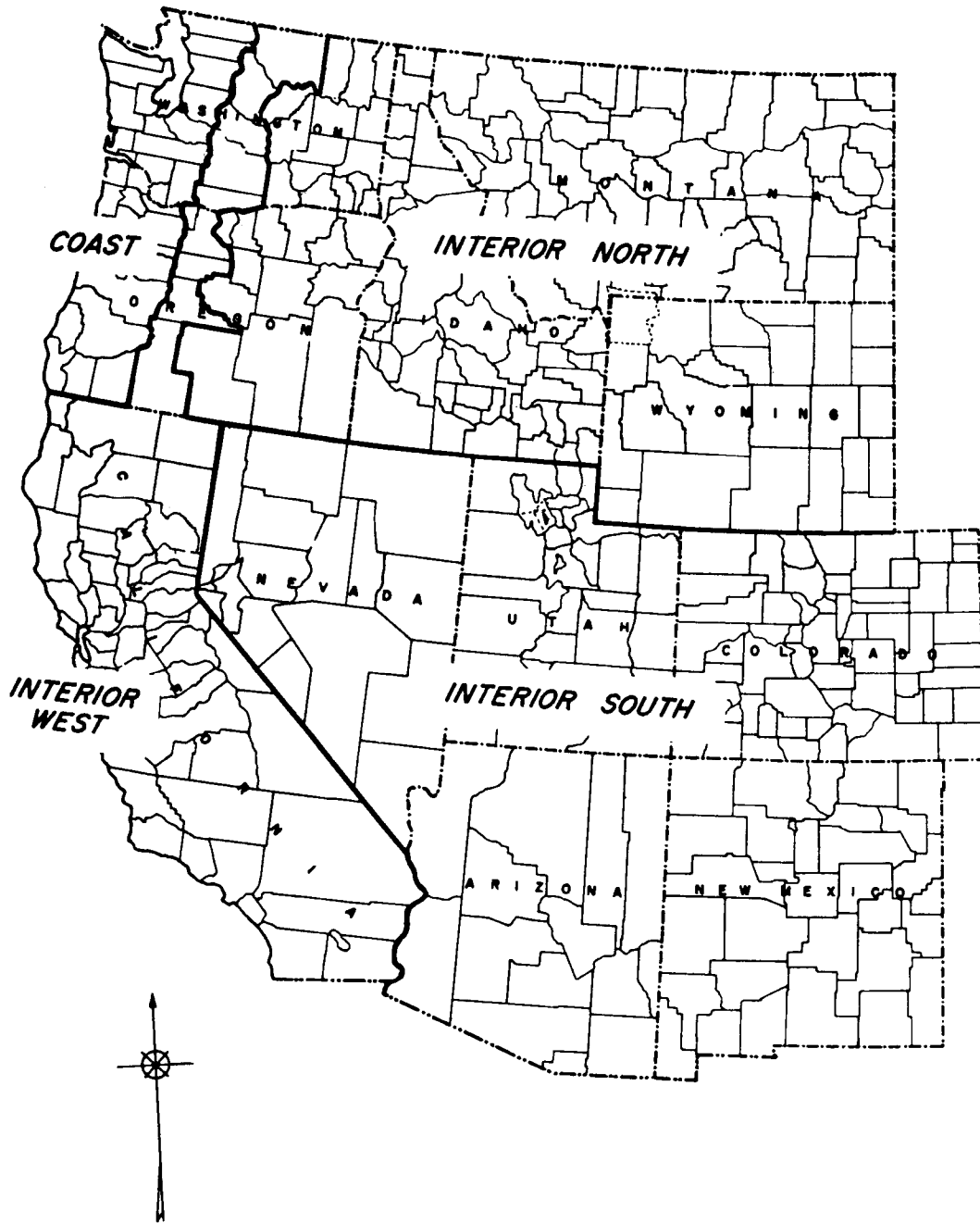


Figure D5.--Four regions for establishment of strength-specific gravity regressions for Douglas-fir.

Table D2. --Values of F and corresponding degrees of freedom for tests of differences between regressions. Data are pooled results of Forest Products Laboratory data and data due to Noskowiak and Snodgrass

Property	Regression comparison					
	Coast versus Interior West		Interior West versus Interior North		Interior North versus Interior South	
	F	Degrees of freedom ¹	F	Degrees of freedom ¹	F	Degrees of freedom ¹
Modulus of rupture	6.50	3,039	3.19	2,466	48	2,046
Modulus of elasticity	38	3,039	24	2,466	265	2,046
Maximum crushing strength	8.77	4,305	183	3,052	53	2,316
Shear strength	9.77	2,184	18	1,742	13	1,394

exhibit striking differences over its range, because of the large differences in site conditions known to exist. Barrett (2) and others, on the basis of site and ecological vegetation types, have separated out a region called Northern Rocky Mountain consisting of Idaho, Montana, and northeastern Washington, and another called the Middle and Southern Rocky Mountains. The specific gravity patterns from the Wood Density Survey also indicate rather general differences in Douglas-fir over its range.

In view of the observations mentioned in the preceding paragraph, it has seemed desirable to subdivide the Douglas-fir range into four regions for purposes of establishing strength-gravity regressions, and test the hypotheses that no differences really exist in the regressions on the basis of the available sample. The physical observations provide broad indications of where boundaries may be drawn for this purpose, but some judgment is required in placing the boundaries exactly. The criteria used were that, where possible, boundaries should not pass through areas containing Douglas-fir, and that they should follow recognizable boundary features. The boundaries established are shown in figure D5, and are essentially the same as those given by Drow (6). The Coast region includes all of the states of Washington and Oregon west of the summit of the Cascade Mountains. Interior West is the State of California, and all counties in Washington and Oregon east of, but adjacent to, the Cascade summit. Interior North is composed of the remainder of Washington and Oregon, Idaho, Montana, and Wyoming. Interior South is Nevada, Utah, Colorado, Arizona, and New Mexico.

Table D2 gives the values of F and degrees of freedom for the tests of differences between regional regressions. All regressions are significantly different at the 5 percent level of probability. It may be argued that, analogous to the tests summarized in table D1, significance is shown in table D2 because of the extremely sensitive tests, i.e., because a large number of degrees of freedom exist, In this case, however, there is no question regarding the usefulness of data, and all data are being used. On the average, maintaining separate regions when the regressions are significantly different will improve the precision of the double sampling estimators. There is no reason to pool data from separate regions.

FOR REGIONS OR SPECIES

Heterogeneous Distribution

The heterogeneous distribution is discussed by Hald (11). If a population is composed of several subpopulations of unspecified form $p_i(x)$ with means μ_i , variances σ_i^2 , and weights α_i such that $\sum \alpha_i = 1$, the heterogeneous population has the distribution function

$$p(x) = \sum_i \alpha_i p_i(x) \tag{1}$$

The mean of the heterogeneous population is

$$\mu = \sum_i \alpha_i \mu_i \tag{2}$$

The variance of the heterogeneous population is

$$\sigma^2 = \sum_i \alpha_i \sigma_i^2 + \sum_i \alpha_i (\mu_i - \mu)^2 \tag{3}$$

In most applications, the subpopulation parameters μ_i and σ_i^2 are not known. If the functional forms of the subpopulations are known, then it is possible to derive unbiased estimators for the parameters which can be calculated from a sample. For example, if the subpopulations are known to be normal, then unbiased estimators for the the mean and variance are well known, and the heterogeneous distribution can be completely specified.

Estimating Standard Deviations for a Group of Unit Areas

For a population known to be normal, an unbiased estimator of the variance is computed from the sample observations, Y_i , as

$$s^2 = \frac{\sum (Y_i - \bar{Y})^2}{n - 1} \tag{4}$$

where \bar{Y} is the mean of the observations and n is the total number of observations, In the context of sampling trees for properties, it is inherent in expression (4) that the samples are drawn at random from the population of trees, and more than one sample will be taken from a tree only occasionally by chance. The standard deviation is presumed to be a function of within-tree and between-tree standard deviations. Symbolically,

$$s = \sqrt{s_w^2 + s_b^2} \tag{5}$$

where s_w is the within-tree standard deviation and s_b is the between-tree standard deviation. In the ASTM sampling scheme, once a tree is selected, several samples are taken according to a systematic method. As additional samples are taken within a tree, they provide additional information about that tree, but they provide no information about other trees, except by inference. Where sampling within trees occurs, an estimate, which on the average estimates the same standard deviation shown symbolically above, can be

made by suitable consideration of the components of variance (see Ostle (21). p. 247).

Table E1 gives standard deviations obtained from Forest Products Laboratory shipment data by components of variance considerations. For white fir, western hemlock, and Douglas-fir from the Interior South, portions of the sample were purposely stratified to obtain special information. Clearly, a sample which is deliberately collected to spread out the data will give an estimate of standard deviation that is larger, on the average, than the true standard deviation. For this reason, the stratified shipments were not included in the standard deviation computations. These shipment numbers are given in the footnotes in table E1.

Forest Products Laboratory strength data were not collected for the purpose of computing standard deviations. There is no assurance that specimens taken by the cruciform pattern from logs between 8 and 16 feet above stump, and from a few selected clusters of trees, will give a good estimate of standard deviation. Certainly the estimate will be biased in a statistical sense. Good estimates of standard deviations could be obtained by selecting specimens at random from each group of unit areas to be evaluated for strength properties. However, this would be an imposing and expensive task. An effort has been made to develop estimates of property standard deviations using information on specific gravity variability from Phases II and III of this study.

The method developed here is based on the assumption that the cruciform sampling pattern provides good estimates of variation within trees, but that the ASTM tree selection scheme gives estimates of between-tree variation of lower reliability. It is further assumed that data from the Wood Density Survey provide very good estimates of between-tree variation in specific gravity, and that the relationships between specific gravity and mechanical properties can be used to translate this into between-tree variation in mechanical properties. Computationally, the steps are as follows:

(a) Within-tree variance in specific gravity is estimated from Forest Products Laboratory shipment data, using conventional analysis of variance techniques. Two sources of specific gravity are available from these data--from bending specimens and from compression specimens. At the Forest Products Laboratory specific gravities are estimated on the basis of the weight of entire bending specimens, and on the basis of a small wafer taken from compression specimens. Because bending specimens may contain small knots near the ends, and because the entire bending specimen is not oven-dried, it is assumed that the specific gravities obtained for the compression specimens are somewhat more reliable, and these data have been used for the variance determination.

(b) An estimate of between-tree variance in specific gravity is obtained from Wood Density Survey data. This estimate is taken to be the sum of the variance obtained by expression (4). where the Y_i values are individual estimates of tree specific gravity, and the residual mean square from the regression of core specific gravity on tree specific gravity and diameter at breast height. The Y_i are not measured directly, but rather are computed from a multiple linear regression. Each observation is given by

$$y_i = Y_i + \epsilon_i = A_0 + A_1 X_{1i} + A_2 X_{2i} + \epsilon_i \quad (6)$$

where the X_{1i} are measured increment core specific gravities

X_{2i} are measured tree diameters at breast height

ϵ_i is the error associated with a single application of the regression

y_i is the true tree specific gravity

If a variance operator is applied to (6)

$$\text{VAR}(y) = \text{VAR}(Y) + \text{VAR}(\epsilon) = A_1^2 \text{VAR}(X_1) + A_2^2 \text{VAR}(X_2) + 2 A_1 A_2 \text{COV}(X_1, X_2) + \text{VAR}(\epsilon) \quad (7)$$

In the use of the variance operator, it has been assumed that the coefficients of the independent variables are known without error, and that the error is normally and independently distributed with zero mean and constant variance. It is seen in expression (7) that the appropriate computation may be made either by computing the Y_i from (6) and then computing $\text{VAR}(Y)$ from (4), or by computing the variances and covariance

of the X's directly. The best estimate of VAR(ε) is the residual mean square associated with the regression.

Total specific gravity variance is taken to be the sum of the within-tree estimate from step (a) and the "between-tree" estimate obtained by using equation (7).

Table E1. --Standard deviations estimated by two methods

Species	Property							
	Modulus of rupture		Modulus of elasticity		Maximum crushing strength		Shear strength	
	Components of variance	Regression method	Components of variance	Regression method	Components of variance	Regression method	Components of variance	Regression method
	P.s.i.	P.s.i.	$\frac{1,000}{P.s.i.}$	$\frac{1,000}{P.s.i.}$	P.s.i.	P.s.i.	P.s.i.	P.s.i.
Douglas-fir Coast	1,163	1,317	285	315	694	734	132	131
Interior west	1,172	1,322	297	324	746	799	154	137
Interior north ¹	989	1,163	242	274	549	602	100	126
Interior south ¹	852	908	181	200	507	489	128	153
White fir ²	828	949	204	249	484	528	70	78
California red fir	874	885	271	267	475	459	159	145
Grand fir	643	680	160	164	339	363	94	97
Pacific silver fir	1,017	1,296	223	255	503	591	109	114
Noble fir	720	966	255	310	404	561	149	136
Western hemlock ³	1,002	1,088	254	258	564	615	111	105
Western larch	1,009	1,001	250	249	562	564	88	85
Black cottonwood	883	951	188	197	336	360	91	92

¹Shipments 1755, 1756, 1757, 1758, 1759, and 1760 represent stratified samples and were not included in the standard deviation computations by the components of variance method.

²Shipments 1736, 1737, 1740, and 1741 represent stratified samples and were not included in the standard deviation computations by the components of variance method.

³Shipments 1748 and 1750 represent stratified samples and were not included in the standard deviation computations by the components of variance method.

(c) The standard deviation for a property in a particular group of unit areas is estimated from the total specific gravity variance estimate and the regression statistics between property and specific gravity for that group. The computation is

$$s = \sqrt{B^2 (s_{\text{within trees}}^2 + s_{\text{between trees}}^2) + \text{RMS}} \quad (8)$$

where B is the slope of the strength-gravity relation and RMS is the residual mean square from the strength gravity relation.

Step (c) lacks rigor in the Same ways as step (b). Expression (8) is a special case of (7) in which there is one independent variable and therefore a single covariance term.

This method, which will be called the "regression method for estimating variance," entails a great number of assumptions that cannot be easily assessed. In favor of the method, as contrasted with the components of variance method, is that it is not so closely linked to the obvious problems associated with the ASTM standard sampling plan, and that it incorporates information available from the Wood Density Survey. Values obtained by the regression method are given in table E1. It can be observed that, for these species, the regression method usually gives slightly higher estimates of standard deviation than the components of variance method.

Related Report

Information on the specific gravity of the four major southern pines is given in the Forest Service's:

SOUTHERN WOOD DENSITY

SURVEY--1965 Status Report,

U.S. Forest Service Research Paper FPL 26

(Available from Forest Products Laboratory
Madison, Wis., 53705)

