

EFFECT OF RAINFALL AND ELEVATION ON SPECIFIC GRAVITY OF COAST DOUGLAS-FIR¹

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ABSTRACT

Analysis is made of the effects of five ranges of summer precipitation and three ranges of elevation on variation in specific gravity of Coast Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco). The average specific gravity of Coast Douglas fir wood formed during single growing seasons varied from 0.52 for dry summers to 0.45 for wet summers. The negative linear trend held for three elevational levels. Wood produced under a combination of dry summers at low elevations averaged 0.55 specific gravity, whereas wood produced during wet summers at high elevations averaged only 0.44 specific gravity. Both percentage of latewood and thickness of latewood tracheid wall followed trends that were similar to those of specific gravity with summer rainfall and elevation.

INTRODUCTION

Variation in specific gravity of Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) wood has been described in two extensive surveys, each different in its approach. The Western Wood Density Survey (U. S. Forest Service 1965) presents the magnitude of variation in specific gravity of the standing timber resource in the United States; a study by Snodgrass and Noskowiak (1968) gives the variation found by sampling boards obtained from sawmills. Both surveys showed that substantial variation in specific gravity existed within and among geographic localities. Although environmental conditions often vary with locality, neither survey was designed to quantify the environment and thereby to evaluate the influence of environmental conditions on specific gravity.

Studies that include an assessment of environmental effects on specific gravity of wood have been made for Douglas-fir and other species (Chalk 1930; Harris and Orman 1958; Kennedy 1961; Klauditz and

Stolley 1957; Knigge 1962; McMinn 1960; Spurr 1961). Limitations in these studies, however, prevent inferences from being made for any large segment of the Douglas-fir population on the influence of the environment on specific gravity of wood.

The widespread interest in variation in specific gravity and in the factors that influence the variation generates from the use of specific gravity as an indicator of wood quality. Douglas-fir is one of the primary North American species used for structural lumber, piling, and structural plywood. For these uses strength properties determine, in large measure, the quality of the product. Also, a considerable volume of Douglas-fir wood is pulped for paper-making. Both strength properties and pulp yield are related to specific gravity of wood; thus specific gravity becomes an indicator of wood quality (U. S. Forest Products Laboratory 1955). For example, a 0.10 decrease in wood specific gravity is accompanied by average decreases of 403,000 pounds per square inch (p.s.i.) in modulus of elasticity, 2,090 p.s.i. in modulus of rupture, 1,080 p.s.i. in maximum crushing strength, and 157 p.s.i. in shear strength. When pulped, a cord of wood would yield an average of 244 pounds less in dry pulp for the same decrease in specific gravity.

The economic implications of variation in specific gravity in the manufacture of wood

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products wherein strength or pulp yield is important can be easily understood. These economic implications were the motivational force for the two wood density surveys mentioned. The surveys established the range and magnitude of variation in specific gravity of Douglas-fir; a logical extension of this work is to seek the causes of the variation.

Reported here are the effects of two easily identified environmental conditions, summer precipitation and elevation, on the variation in specific gravity of Coast Douglas-fir.

METHODS AND MATERIALS

Douglas-fir is native to many areas of the western United States. The optimum growth rates, the greatest volume concentrations, and the most valuable commercial stands are found among trees of the Coast varietal form (*var. menziesii*) growing west of the Cascade Range in Washington and Oregon. Maritime climatic conditions prevail in this area, moderating the normal latitudinal temperature gradient between places of equal elevation. Both maritime conditions and the particular physiography of the area combine to produce climatic changes more closely associated with elevation than with latitude. Together, the ecological, climatic, and economic conditions along the West Slope are such that it seemed the most suitable area within the Douglas-fir growth range to accomplish the objectives of this research.

The influence of summer precipitation on specific gravity of wood was chosen as an environmental variable for investigation because of the theories that relate water availability to wood formation. Past research and new theory as reviewed and summarized by Zahner (1963) and further developed by Whitmore and Zahner (1966) indicate that the availability of soil moisture during the later part of the growing season influences wood specific gravity in conifers through its effect on wood formation.

Elevation was chosen as an environmental variable because it is easily determined and

because it represents the combined influence of soil properties, solar radiation, precipitation, temperature, and wind. The independent effect of the elevation factors on wood formation is difficult to assess. Thus, the choice of elevation is a compromise because it expresses the interaction of all factors.

U. S. Weather Bureau records for Washington (1956–1964) and Oregon (1956–1964) were used to establish 15 different precipitation–elevation categories that were incorporated in an experimental design permitting independent evaluation of precipitation for a given season and elevation and of their interaction. The 15 conditions described by the categories were all possible combinations of 5 ranges of summer precipitation and 3 ranges of elevation. Precipitation ranges were arbitrarily delineated from the summations of precipitation falling from June 1 through September 30:

Less than 5.00 inches
5.00 to 8.33 inches
8.34 to 11.67 inches
11.68 to 14.99 inches
15.00 inches or more

The elevation ranges were arbitrarily specified from the elevations published for Weather Bureau recording stations:

Less than 900 feet (low)
1,000 to 1,750 feet (middle)
2,000 to 3,000 feet (high)

Field Sampling

Forty-five sampling locations, 3 replicates for each of the 15 precipitation–elevation conditions, were established, using Weather Bureau records (Fig. 1). The summer precipitation of a single year (within the span 1956–1964) was used in the selection of Weather Bureau stations as sample locations. Five trees meeting sampling criteria were selected as close as possible (usually within 1 mile) to each station. Criteria for sample tree selection were that they be approximately 50-year-old, forest-grown dominants on sites of average quality (usually Site III, McArdle and Meyer 1930).

Two 8-mm-diameter increment cores were

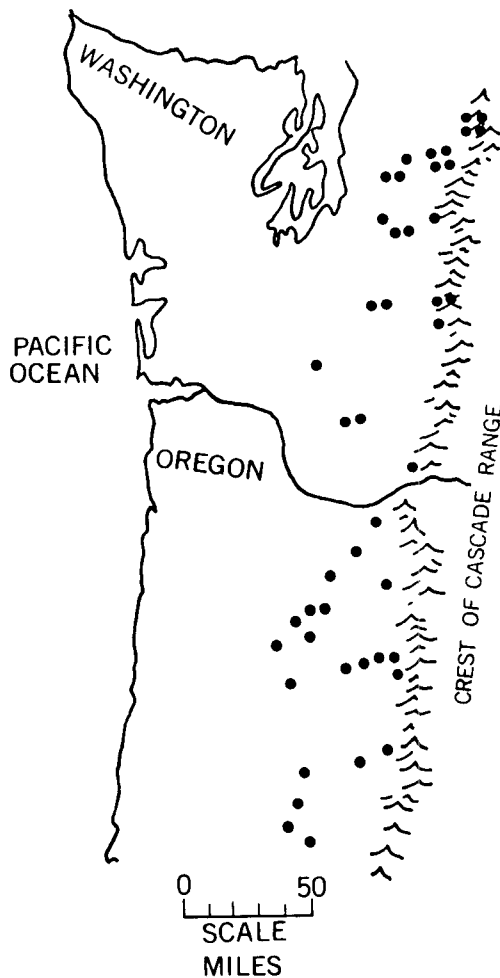


FIG. 1. Sampling locations along the west slope of the Cascade Range. Five trees were sampled at each location.

taken at breast height in each tree. The first was positioned randomly, and the second taken at least 90° circumferentially from the first. Samples of the particular growth ring appropriate to the summer rainfall data were later excised from the cores.

Soil samples were collected at each location for analysis of moisture retention characteristics.

Laboratory Sampling

Transverse surfacing of the single growth increment was done on a freezing microtome. After surfacing, the specimens were

dyed in methylene blue-malachite green stain to facilitate viewing and measuring with a dual-linear micrometer.

The dual-linear micrometer is a research microscope coupled with a traversing stage by which measurements (to ± 1 micron) can be separately recorded on two drums. Smith (1965) developed a technique for calculating the specific gravity of small samples of Douglas-fir wood from transverse surface measurements of tracheid diameter and wall thickness. Smith's technique obtains the following average values for the separate earlywood and latewood portions of an annual growth ring:

1. Specific gravity
2. Tangential tracheid diameter
3. Radial tracheid diameter
4. Tracheid wall thickness
5. Tracheid count

The technique also produced data necessary for determining the following values for the entire annual ring:

1. Ring width
2. Percentage of latewood (Mork 1928)
3. Specific gravity

Values for the two cores were averaged for each tree.

RESULTS

Specific Gravity

For single growing seasons, a significant negative linear relationship was found between wood specific gravity and summer rainfall (Fig. 2). This relationship held at each of the three elevation ranges. Specific gravity was highest in trees from the lowest elevations. Trees from the middle elevations had the lowest specific gravity. The relationship between specific gravity and elevation was significant, but since only three elevation levels were sampled, the form of the relationship cannot be well defined. The maximum specific gravity, 0.552, was attained by those trees growing on the lowest and driest sites. The minimum specific gravity, 0.440, was found, with one excep-

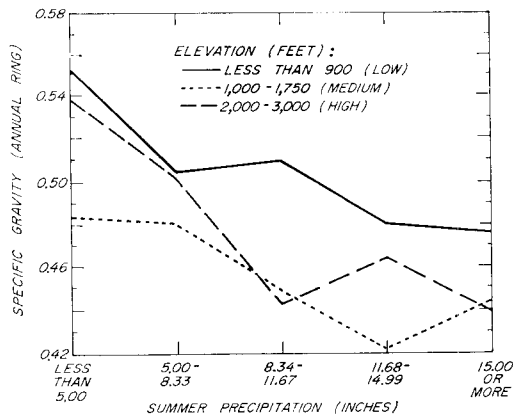


FIG. 2. Relationship of specific gravity of annual ring of 50-year-old Coast Douglas-fir to elevation and amount of summer precipitation. (Means are based on 15 values.)

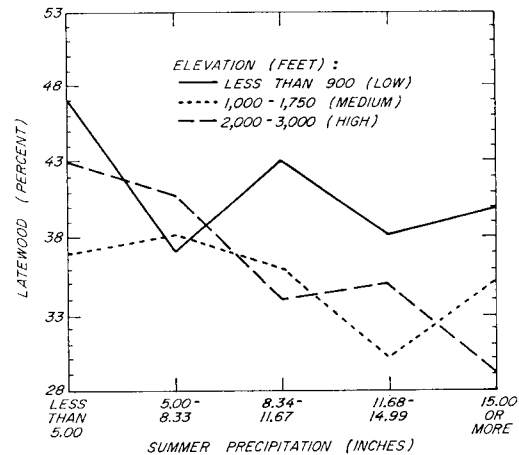


FIG. 3. Relationship of percentage of latewood of 50-year-old Coast Douglas-fir to elevation and summer precipitation. (Means are based on 15 values.)

tion, at the highest elevation-highest rainfall sites (Table 1).

Thirty-one per cent of the variation in specific gravity was associated with variation in summer precipitation. Fifty-three per cent of the variation was explained by the combination of precipitation and elevation. More of the variation in specific gravity could have been tied to moisture availability had measures more refined than that of summer precipitation been used. For instance, when maximum soil moisture-holding capacity was considered in addition to precipitation and elevation, 62% of

the variation in specific gravity was explained.

Percentage of Latewood

Obviously, variations in specific gravity are expressions of changes in cellular dimensions and arrangements. Percentage of latewood is a gross expression of these changes, and in this work was associated with more than 68% of the variation in specific gravity. This was not unexpected because the specific gravity of latewood is approximately 2.5 times greater than that of earlywood.

TABLE 1. Annual ring specific gravity of 50-year-old Coast Douglas-fir for three ranges of elevation and for five ranges of summer precipitation

Elevation, feet	Annual ring specific gravity (Summer precipitation, inches)					Average specific gravity (elevation)
	Less than 5.00	5.00 to 8.33	8.34 to 11.67	11.68 to 14.99	15.00 or more	
Less than 900 (low)	0.552	0.505	0.508	0.481	0.475	0.504
1,000-1,750 (middle)	0.484	0.480	0.447	0.422	0.444	0.455
2,000-3,000 (high)	0.538	0.501	0.442	0.464	0.440	0.477
Average specific gravity (precipitation)	0.524	0.495	0.468	0.456	0.453	

TABLE 2. *Percentage of latewood of 50-year-old Coast Douglas-fir for three ranges of elevation and for five ranges of summer precipitation*

Elevation, feet	Latewood (Summer precipitation, inches)					Average percentage of latewood (elevation) %
	Less than 5.00 %	5.00 to 8.33 %	8.34 to 11.67 %	11.68 to 14.99 %	15.00 or more %	
Less than 900 (low)	47	37	43	38	30	41
1,000-1,750 (middle)	37	38	36	30	35	35
2,000-3,000 (high)	43	41	34	35	29	36
Average percentage of latewood (precipitation)	42	39	37	34	35	

Percentage of latewood decreased with increasing summer rainfall in a linear trend similar to that of specific gravity with rainfall (Fig. 3). Percentage of latewood was highest, 47%, in the low elevation-low precipitation combination, and lowest, 29%, in the high elevation-high precipitation grouping (Table 2).

Half of the variation in percentage of latewood was related to summer rainfall, elevation, and the maximum soil moisture capacity. These same factors accounted for 62% of the variation in specific gravity.

Cellular Dimensions

Although percentage of latewood accounted for much of the variation in specific gravity, other factors were obviously involved. Because specific gravity was calculated as a function of the area occupied by tracheid walls (Smith 1965), the cellular dimensions were examined for their influence on specific gravity. For both latewood and earlywood, no significant differences were found in either mean radial or mean tangential tracheid diameters among either the rainfall or the elevation ranges. These results concentrated attention on thickness of tracheid wall as the predominant source (in an anatomical sense) of variation in tracheid wall area and ultimately of variation in specific gravity.

In the latewood, tracheid wall thickness followed the same negative linear trend

with summer precipitation as did specific gravity and percentage of latewood (Fig. 4). Although wall thickness of latewood did not have a significant relationship with elevation, mean thickness was greatest at the lowest elevation range. The extremes in average wall thickness, 5.95 microns to 7.47 microns, were not associated with either of the precipitation-elevation extremes (Table 3); but again, the trends followed those of specific gravity and percentage of latewood.

To summarize, Coast Douglas-fir wood produced in the course of single growing seasons was of highest specific gravity under conditions of low summer rainfall and low elevation. Specific gravity followed a negative linear trend with summer rainfall, but its relationship with elevation, although significant, was not well defined. The percentage of latewood and the thickness of the mean latewood tracheid wall varied with summer rainfall and elevation in the same manner as did specific gravity. For the sample material in this study, the contributions of percentage of latewood and mean thickness of latewood cell wall to variation in specific gravity reinforced each other and were of about equal importance.

DISCUSSION

If the specific gravity and structure of wood produced under extreme conditions of rainfall in summer and low elevation are

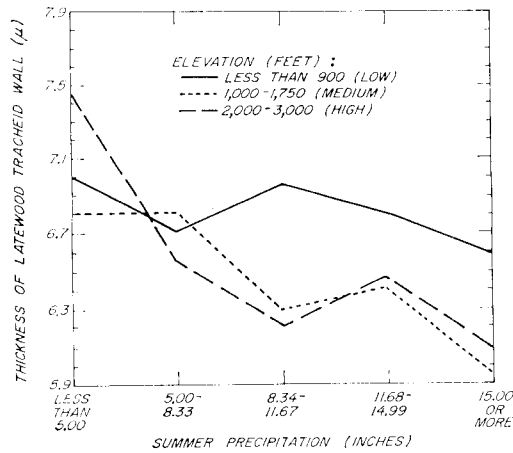


FIG. 4. Relationship of thickness of latewood tracheid walls of 50-year-old Coast Douglas-fir to elevation and summer precipitation. (Means are based on 15 values.)

compared with similar data from wood produced under the opposite extreme conditions, some concept of the importance of summer rainfall and elevation on Douglas-fir wood quality can be obtained. In this work, average increases in summer precipitation of about 14 inches and in elevation of about 1600 feet were associated with decreases of 0.112 in specific gravity, 15.6 in percentage of latewood, and 0.91 micron in wall thickness of latewood. Based on regressions of various strength evaluators on specific gravity, there would be differ-

ences of 452,000 p.s.i. in modulus of elasticity, 2,340 p.s.i. in modulus of rupture, 1,210 p.s.i. in maximum crushing strength, and 177 p.s.i. in maximum shear strength.

Evidence has been presented that relates changes in the specific gravity of Douglas-fir wood to changes in summer rainfall and elevation. Positive results were obtained because many of the confounding influences common to these types of studies were minimized. For example, tree age was eliminated as a source of confounding. Only trees with dominant crowns from stands of similar stocking density were sampled to avoid potential bias imposed by crown differences and unequal competition.

The effects of latitudinal climatic gradients were minimized by the selection of a unique study area. Each observation was limited to one growth ring for which concomitant precipitation data from nearby weather stations were available. Circumferential variation within a growth ring is always a potential source of error in increment core sampling, but in this work measurements averaged from two samples of the same annual ring reduced this variation. Interpretation of variation in specific gravity in terms of wood anatomy was made possible by restricting the anatomical measurements and the specific gravity determination to the same annual ring. Finally, the factorial design of the experiment per-

TABLE 3. Thickness of latewood tracheid walls of 50-year-old Coast Douglas-fir for three ranges of elevation and for five ranges of summer precipitation

Elevation, feet	Thickness of tracheid wall (Summer precipitation, inches)					Average wall thickness (elevation) μ
	Less than 5.00, μ	5.00 to 8.33, μ	8.34 to 11.67, μ	11.68 to 14.99, μ	15.00 or more, μ	
Less than 900 (low)	7.01	6.72	6.94	6.80	6.59	6.81
1,000-1,750 (middle)	6.80	6.79	6.26	6.38	5.95	6.44
2,000-3,000 (high)	7.47	6.57	6.19	6.45	6.10	6.55
Average wall thickness (precipitation)	7.09	6.69	6.46	6.55	6.22	

mitted the independent evaluation of the effects of summer rainfall and elevation on specific gravity and cell dimensions.

This is not to imply that confounding influences did not exist. Sampling from large trees in natural stands and the vagueness of summer rainfall and elevation associations with tree growth offered some confounding. The dependency of sampling in the proximity of established weather stations inadvertently led to confounding of latitude with elevation and summer rainfall. Most of the highest elevation and wettest sampling locations are in the northern part of the sampling area, which would tend to magnify the effects of climatic conditions normally associated with latitude. The term "normally" is important because the maritime climate greatly diminished the normal temperature and growing-season gradients associated with latitude. Photo-periodic differences still exist, but the shorter days in the north and the drier conditions in the south would have a compensating effect on latitudinal influences for latewood differentiation.

Confounding may also have been induced by the preconditioning effects of weather prior to June 1 of each year sampled, as for example, a warm, early spring. Different patterns of rainfall distribution among locations, particularly in previous years, could have important effects on water availability and wood formation. For example, moisture stress during late summer and early fall of the previous year could be reflected in lower photosynthate production and less overwintering food storage, which would reduce wood formation during the current growing season. However, a check of August and September precipitation prior to the year of wood formation revealed no consistency between the pattern of that rainfall and the summer rainfall classification used in this study. Also, significant differences in April–May precipitation totals among the summer rainfall groupings were not found.

Environmental conditions inevitably vary with elevation and confound any interpretation based solely on any single environ-

mental factor. Examples are the gradients of increasing total rainfall and decreasing temperature with increasing elevation. The lowest site indices (tree height at age 100), poorest soil characteristics, and least tree diameter growth found at the highest elevation locations give further indications of confounding environmental conditions among elevation ranges. It can also be surmised that in the mountainous topography, considerable subsurface water movement supplements moisture recharge from precipitation (McMinn 1960). The soil at the lowest elevation locations would be expected to receive the most subsurface seepage.

If one is mindful of the limitations on the interpretations of the results, the specific gravity and wood structure relationships found here can be explained reasonably within the framework of current theory on water relations and latewood initiation and development. It can be hypothesized that latewood initiation was earliest during dry years because moisture stress was sufficient to slow the production of new xylem cells; this reduced competition in the cambial region for photosynthates and stored foods, and allowed ample substrate for secondary wall formation over a long period of time. The net result is a wide latewood band and wood of high specific gravity. However, increased moisture availability, presumed to be represented by the years with greater summer rainfall, can be responsible for extending the length of time for rapid maturation of new xylem cells during which thin-walled, low-density earlywood is produced.

Differences in specific gravity among elevations are more difficult to explain hypothetically because temperature gradients, changes in soil and other site properties, and possible genetic differences confound any explanation based solely on the water regime. Differences in several climatic conditions between low and medium elevation, although not great enough to change substantially the length of the growing season (Carmean 1954), may speed the depletion of soil moisture at low elevations

through higher rates of evapotranspiration. The resulting moisture deficits would promote the earlier initiation of latewood and thus yet higher specific gravities at the low elevation.

At the highest elevations cooler temperatures and poorer soil properties combine to produce a shorter growing season and a slower growth rate within that growing season. Breast-height cambial growth in trees at the highest elevations starts later than at lower elevations and is closer to the time when climatic conditions are such that evapotranspiration increases, soil moisture decreases, and latewood is initiated. Extended latewood development is restricted, however, by low temperatures bringing an early end to the growing season and reduced water availability. The thicker cell walls and slower growth rate at the highest elevations suggest that more cell wall substrate is going into secondary thickening rather than into new cell formation.

Further investigation to explain these results might include more sophisticated approaches such as procedures for calculating daily moisture stress, temperature trends, and other seasonal changes (Zahner and Stage 1966) and a technique for dating cambial activity (Wolter 1968).

CONCLUSIONS

The specific gravity of Coast Douglas-fir wood formed at a cambial age of about 50 years had a negative linear trend with summer rainfall, independent of the elevation at which trees were growing. Specific gravity increased with a decrease in summer rainfall primarily because of similar increases in the percentage of dense latewood tracheids within a growth ring and increases in the average thickness of those latewood tracheids. When earlywood and latewood tracheids were considered independently, their average diameters did not vary with either summer rainfall or elevation.

Specific gravity also varied with elevation in a nonlinear relationship independently of summer rainfall. Specific gravity was greatest at the lowest elevations because the

percentage of latewood and the average tracheid wall thickness were again greatest at the lowest elevation.

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