Pacific Northwest Research Station
319 S.W. Pine St.
P.O. Box 3890
Portland, Oregon 97208

United States
Department of
Agriculture

Forest Service

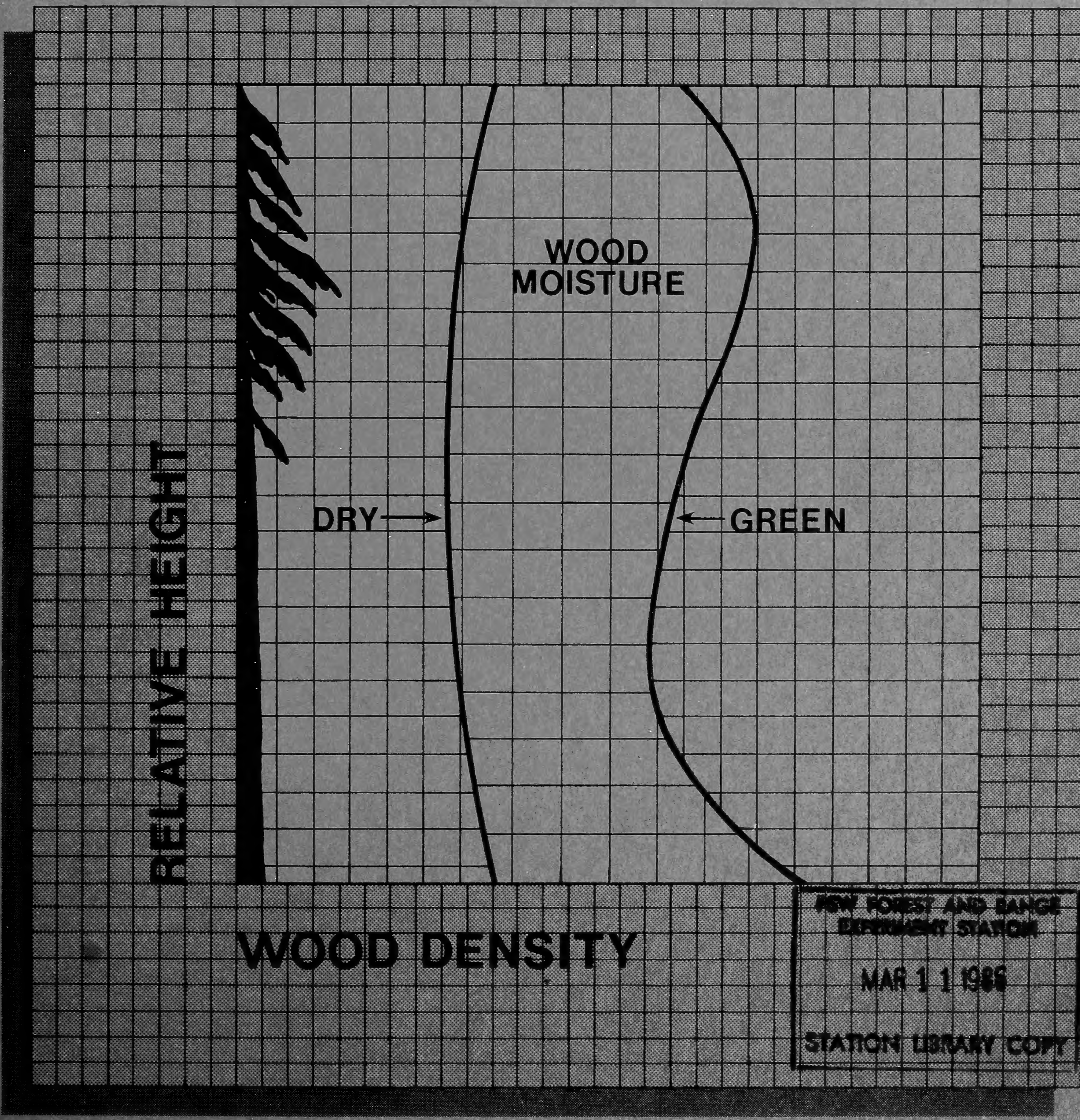
Pacific Northwest
Research Station

Research Paper
PNW-347

February 1986

Wood Density-Moisture Profiles in Old-Growth Douglas-Fir and Western Hemlock

W.Y. Pong, Dale R. Waddell, and Michael B Lambert



Authors

W.Y. PONG, DALE R. WADDELL AND MICHAEL B LAMBERT are, respectively, research forest products technologist, research forester, and mechanical engineer, Pacific Northwest Research Station, Forestry Sciences Laboratory, P.O. Box 3890, Portland, Oregon 97208.

Abstract

Pong, W.Y.; Waddell, Dale R.; Lambert, Michael B. Wood density-moisture profiles in old-growth Douglas-fir and western hemlock. Res. Pap. PNW-347. Portland, OR: US Department of Agriculture, Forest Service, Pacific Northwest Research Station; **1986.** 30 p.

Accurate estimation of the weight of each load of logs is necessary for safe and efficient aerial logging operations. The prediction of green density (lb/ft^3) as a function of height is a critical element in the accurate estimation of tree bole and log weights. Two sampling methods, disk and increment core (Bergstrom xylodensimeter), were used to measure the density-moisture complex in wood. The relationship between wood density and height was best described by either quadratic or cubic polynomial functions. Prediction functions for green and dry wood density are presented for old-growth western hemlock and Douglas-fir. Sapwood and heartwood functions were analyzed separately as were trees with and without heartrot.

Keywords: Wood density, moisture content (wood), old-growth stands, Douglas-fir, western hemlock.

Summary

Because of the critical weight limitations of many aerial logging systems, an accurate technique is needed for estimating tree bole and log weight. An integral part of a weight estimation procedure is the characterization of the wood density-moisture complex in trees.

To examine this complex a pilot study was conducted during the summers of 1981 and 1982 in the Wind River Experimental Forest in southwest Washington. Old-growth western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) and Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii*) on four experimental plots were tested. Various categories of wood density (dry-green, sapwood-heartwood, and defective-nondefective wood) were analyzed using relative height as the independent variable. Relative height is defined as the ratio of the height of any point on the bole to total tree height above a 1-foot stump. Regression analysis yielded quadratic and cubic polynomial equations for the various wood density categories.

Green density functions were found to be unique for each species and were undular in character (cubic equation). In comparison, dry density changed little, with height exhibiting a relatively flat function. The distribution of moisture in the bole was responsible for the difference between the green and dry functions. Heartwood moisture distributions, as measured by green density values, demonstrated large changes with relative height, while sapwood profiles were smoother with less change per increment of relative height. Heartrot and wetwood increased the amount of moisture in the boles.

Results indicated potential improvements in bole and log weight estimation when a predictive function is used instead of single value. Figures and examples are provided for potential application of the prediction functions.

Contents

1 **Introduction**
1 Objectives
2 **Methods**
2 Study Area
2 Tree Sample Selection
3 Field Measurements
4 Data Reduction and Compilation
6 Data Analysis
6 **Results**
7 Green Wood Density Profiles
10 Dry Wood Density Profiles
12 Green Sapwood and Heartwood Density Profiles
14 Dry Sapwood and Heartwood Density Profiles
16 Wood Moisture Profiles
18 Green Wood Density Profiles—Trees With and Without Heartrot
19 **Discussion**
19 Green Wood Density Profiles
20 Dry Wood Density Profiles
21 Green Sapwood Density Profiles
22 Green Heartwood Density Profiles
22 Dry Sapwood and Heartwood Density Profiles
23 Wood Moisture Profiles
23 Green Wood Density Profiles—Trees With and Without Heartrot
23 **Application of Results**
27 **Conclusions**
29 **Metric Equivalents**
29 **Literature Cited**

Introduction

Aerial logging systems ("heavy-lift" helicopters, balloons, and air ships) have critical weight limitations. Their efficient operation is dependent on the ability to carry the maximum payload on each turn without exceeding the lift capacity of the system. Because of this, accurate estimates of log weights are required. In aerial logging, the overload tolerance is zero. Errors in estimating log weights lead to aborted lifts and failure of the average payload to approach lift capacity. This, coupled with the high costs of aerial logging operations, makes errors in log weight estimation a critical factor in the performance of the logging system.

Accurate estimation of log weights is dependent on the ability to predict accurately the volume and green density of the wood-moisture complex in the bole of the tree.

The variation of wood density and moisture within boles of trees has been the subject of numerous investigations (Clark and Gibbs 1957, Markstrom and Hann 1972, Parker 1954, Stewart 1967) that were viewed as academic exercises with limited interest and application. This view, however, has changed. Recent studies have been conducted on biomass (Bones and others 1981, Tritton and Hornbeck 1982), weight scaling (Mann and Lysons 1972, Wensel 1974), wood quality evaluation (Okkonen and others 1972), logging equipment and design needs (Adamovich 1975, 1979; Conway 1976), and aerial logging (Dykstra 1975). In these studies, variability in density and moisture is recognized as an important factor in weight estimation. In many many applications a stand "average" for the weight per unit of volume is appropriate; in others, weight estimates are needed relative to bole location, such as butt, middle, and upper logs.

Objectives

We examined the density variation of the wood-moisture complex in tree boles of old-growth Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii*) and western hemlock (*Tsuga heterophylla* (Raf.) Sarg.). The study had three objectives:

1. To estimate the relationship between density and height in the tree for the wood-moisture complex in the sapwood and heartwood of old-growth Douglas-fir and western hemlock.

2. To determine the moisture distribution in the sapwood and heartwood of old-growth Douglas-fir and western hemlock.

3. To determine the effect of defect in tree stems on the relationship between density and height in the tree for the wood-moisture complex in old-growth Douglas-fir and western hemlock.

Findings presented in this paper will also be incorporated in a future paper with tree bole volume equations to develop a model for estimating bole weight and individual log weights.

Methods

Study Area

The study area is in the Wind River Experimental Forest, Trout Creek Hill Unit, Gifford Pinchot National Forest, in southwestern Washington. Terrain is moderately steep with slopes varying from 10 to 40 percent at an elevation of 2,000 feet. Old-growth Douglas-fir and western hemlock are the principal tree species in the study area (about 80 percent by volume); secondary species include western redcedar (*Thuja plicata* Donn ex D. Don) and true firs (*Abies* spp.).

Tree Sample Selection

Study trees were selected from a randomly stratified sample of old-growth (180 years and older) Douglas-fir and western hemlock in four plots; stratification was based on tree d.b.h. (diameter at breast height).[1]

Selection took place during the summers (June-September) of 1981 and 1982. Trees selected in 1981 were from three 5-acre plots and the 1982 trees were from one 20-acre plot. The 1981 sample consisted of 29 Douglas-fir and 29 western hemlock that were selected to fill predetermined d.b.h. classes for each species (table 1). In the 1981 sample, highly defective trees and trees that were damaged were excluded from selection because of a corollary study for developing crown weight estimators (Snell and Max 1984). Trees selected in 1982 were not analyzed for crown weights but were selected to fill predetermined size classes without regard to defect. The 1982 sample consisted of 25 Douglas-fir and 25 western hemlock (table 1).

[1]Diameter of the tree bole at 4-1/2 feet above ground level as measured on the uphill side of the tree.

Table 1—Frequency distribution of sample trees by diameter class

	1981 study		1982 study	
Diameter class 1/	Western hemlock	Douglas-fir	Western hemlock	Douglas-fir
Inches				
10.0 - 15.5	2	0	1	0
15.6 - 20.5	4	0	1	0
20.6 - 25.5	7	2	4	3
25.6 - 30.5	3	3	4	6
30.6 - 35.5	7	4	6	3
35.6 - 40.5	4	4	2	5
40.6 - 45.5	2	2	5	5
45.6 - 50.5	0	5	2	2
50.6 - 55.5	0	2	0	1
55.6 - 60.5	0	7	0	0
Total	29	29	25	25

1/ Diameter of the tree bole at 4-1/2 feet above ground as measured on the uphill side of the tree.

Field Measurements

Only a brief outline of the field procedures used to collect the data is presented. Readers are referred to Waddell and others (1984) for greater detail on the procedures employed.

Two different methods were used to obtain specimens for density determination in this study: disk and increment core.

Disk.—The disk method was used for the 1981 trees only. Wood samples for density determination were obtained from the disks (cross-sectional wafers) sawn at intervals along the length of the bole of each study tree. Number and location of the disks taken from a given bole were limited by tree height, amount of breakage, the requirement that the bole was to be bucked into logs of merchantable lengths, and lengths such that the weights would not exceed the capacity of the front-end loader used for weighing. Because of these limitations, disks could not be taken at preset intervals along the bole except at the stump cut[2/] and at the merchantable top d.i.b. (diameter inside bark) of 6 inches. A minimum of at least five disks were taken from each tree. From each disk, wood samples approximately 1.5 x 1.5 x 3+ inches, representing the sapwood and heartwood zones, were taken from four wedge-shaped pieces cut radially along perpendicular diameters of the disk. If a disk contained only sapwood or too little heartwood to produce a separate density sample for heartwood, then only the sapwood sample was taken. All samples were labeled for identification and placed in separate, air-tight, tarred containers. At each point where the disk was cut from the tree, the d.i.b. along the longest axis and the axis at 90° to the longest axis, and the diameters of the heartwood zone along the same axes were measured. For western hemlock, heartwood included the wetwood-heartwood zone (Ward and Pong 1980). The length of each bucked segment of the merchantable bole, length of each disk, and total length of the bole were measured. In the laboratory, green weight, green volume (by water emersion)(Brown and others 1952), and ovendry weight of each sample were determined and recorded.

Increment core.—In the increment core method (used for both the 1981 and 1982 tree samples) density samples (increment cores) were extracted from the bole and measured directly using the Bergstrom xylodensimeter[3/] (Waddell and others 1984). This approach uses an increment core of specified diameter cut to a length such that the volumetric proportions of sapwood and heartwood in the core are the same as those of the tree at the point where the core was extracted. The core is inserted into a hydrometer tube that is calibrated and matched to a specific increment borer. The hydrometer containing the core is floated in a transparent vial of water and green density in pounds per cubic foot (lb/ft^3) is read directly from the meniscus on the graduated stem of the hydrometer.

[2/]At or near a stump height of 1 foot above ground level as measured on the uphill side.

[3/]The original prototype of this instrument was designed by Gary Bergstrom, logging specialist, USDA Forest Service, Rogue River National Forest, Medford, Oregon.

In the 1981 tree samples, two cores were extracted, one above and one below every disk sampling point adjacent to the cut. In the 1982 samples, increment cores were taken every 6 feet in the lower one-third of the merchantable bole[4] starting at d.b.h. In the upper bole, two additional cores were taken: one at a point located at two-thirds the length of the merchantable bole and the second at a point located at one-half the length of the upper one-third of the merchantable bole. Bole length to each core sampling point and total length of stem were recorded.

A comparison of green density values, as determined by both the disk and core methods on the 1981 trees, showed similar density results for both methods with negligible bias and only a slight change in variation (Waddell and others 1984). These results showed that the use of increment cores with the Bergstrom xylodensimeter can provide reliable density values that are comparable to those generated by the disk method. The core method was therefore used exclusively on the 1982 trees to collect green density data. Ovendry density determinations were not made for the 1982 trees.

Data Reduction and Compilation

Density.—The green and ovendry densities of each radial sample taken from disks of the 1981 trees were calculated by dividing the sample weight (green or ovendry) by green sample volume:

$$d(g) \text{ or } d(od) = \frac{w(g) \text{ or } w(od)}{v(g)} \; ; \qquad (1)$$

where:

d(g) or d(od)	=	green or ovendry sample density,
w(g) or w(od)	=	green or ovendry sample weight, and
v(g)	=	green sample volume.

An arithmetic average of the densities calculated in equation (1) for the four radial sapwood samples and the four radial heartwood samples from each disk was computed for the green and ovendry conditions:

$$dS \text{ or } dH = \frac{\sum_{i=1}^{4} d_i(g)}{4} \text{ , and} \qquad (2)$$

$$ds \text{ or } dh = \frac{\sum_{i=1}^{4} d_i(od)}{4} \; ; \qquad (3)$$

[4]Merchantable bole is the length of stem above a 1-foot stump to a 6-inch d.i.b. top.

where:

dS or dH = the arithmetic average of green densities of the sapwood heartwood radial samples from a given disk,

ds or dh = the arithmetic average of ovendry densities of the sapwood or heartwood radial samples from a given disk, and

$d_i(g)$ or $d_i(od)$ = the green or ovendry density values computed by equation (1) for individual samples (i=1 to 4) of heartwood or sapwood taken from a given disk.

A single weighted green or ovendry density value for the whole disk was determined by weighting the average density value of the heartwood and sapwood, as calculated by equation (2) or equation (3), with the volumetric proportions of heartwood and sapwood in the disk:

$$D(g) = \frac{dS\,VS + dH\,VH}{VS + VH}, \quad \text{and} \qquad (4)$$

$$D(od) = \frac{ds\,VS + dh\,VH}{VS + VH}; \qquad (5)$$

where:

D(g) or D(od) = weighted green or ovendry wood density of the disk,
dS or ds = average green or ovendry density of sapwood in the disk,
dH or dh = average green or overdry density of heartwood in the disk,
VH = calculated green volume of heartwood in disk, and
VS = calculated green volume of sapwood in the disk.

VH and VS were calculated using dimensions of the disk. We assumed the disk to be a cylinder with a diameter equal to the average of four diameter measurements taken on each disk. Two diameter measurements were made on each side of the disk; one measurement represented the longest diameter of that side and the other measurement was taken at 90° to the first measurement.

To examine the impact of defect on the density profile, the 1982 data (increment cores) were stratified into three groups: (1) sound (no rot or other major defects affecting density), (2) defective (with heartrot only), and (3) defective (all other defects). Only the first two groups were examined because the last group contained too few samples of any one category of defect to be analyzed.

Relative height (RH). —For analytical purposes, all height measurements were converted to relative heights by dividing the height to each sampling point (disk or core) by the total length of the tree bole above the stump. The use of relative height in place of absolute height on the analysis would tend to normalize the impact that varying tree height would have on wood properties of the tree, which are correlated with height (Cao and others 1980, Demaerschalk and Kozak 1977, Lenhart and others 1977, Long and others 1981). Treating heights on a relative basis was necessary because trees in this study varied considerably in height, because the number of disks taken from the 1981 trees varied, and because the disks were not sawn from the same height in every tree or at heights consistent with the sampling point of the increment cores extracted from the 1982 sample trees. With the relative height approach, density data collected either as cores or as disks from boles of trees of varying height could be used to develop a profile model of density.

Data Analysis

The compiled data were analyzed by regression analysis using linear combinations of wood density versus relative height (RH). Several curvilinear models (linear, quadratic, and cubic) using relative height and various transformation of relative height ($(RH)^2$, 1/RH, and $1/(RH)^2$) as independent variables were analyzed. Dependent variables regressed were wood density values for western hemlock and Douglas-fir in the following groups: (1) weighted green disk density (D(g)) (all trees), (2) weighted ovendry disk density (D(od)) (all trees), (3) average green sapwood disk density (dS), (4) average green heartwood disk density (dH), (5) average ovendry sapwood disk density (ds), (6) average ovendry heartwood disk density (dh), (7) green core density (D(g)) (all trees), (8) core density (D(g)) (defective trees; that is, with heartrot), and (9) green core density (D(g)) (sound trees).

Selection of functions to regress density values to relative height was based primarily on the highest coefficient of determination and lowest standard error of the estimate. In some cases, the magnitude of these measures was comparable for different functions; the selection, in these instances, was based more on the general shape of the regression through the range of data than on the statistics. Functions were rejected that did not conform to the general logical relationship among the variables as defined by current knowledge.

Results

Figures 1-14 are the wood density scattergrams and functions for the various measurements of green and ovendry wood density versus relative height. All the relationships were curvilinear and were fitted by either a quadratic or cubic polynomial function of the general form:

$$Y = B_0 + B_1x + B_2x^2 + e, \qquad \text{(quadratic), and}$$

$$Y = B_0 + B_1x + B_2x^2 + B_3x^3 + e, \qquad \text{(cubic);}$$

where:

Y = wood density value,
B = regression coefficients,
x = relative height, and
e = residual error.

Each function represents a composite profile of a combination of several individual trees for a specific form of wood density and will be referred to as either a "function" or a "profile" in this paper.

Green Wood Density Profiles

Scattergrams of weighted green wood density values as determined by equation (4) for the disks and those measured by the xylodensimeter for the increment cores are plotted against relative height in figure 1 (a-b) for western hemlock and in figure 2 (a-b) for Douglas-fir. Cubic polynomical functions are regressed through the plots. For comparative purposes, a composite plot of the disk and core functions for western hemlock and Douglas-fir are presented without the data scatter in figures 3 and 4, repectively. A statistical summary of the regression analysis for the disk and increment core data is presented in table 2.

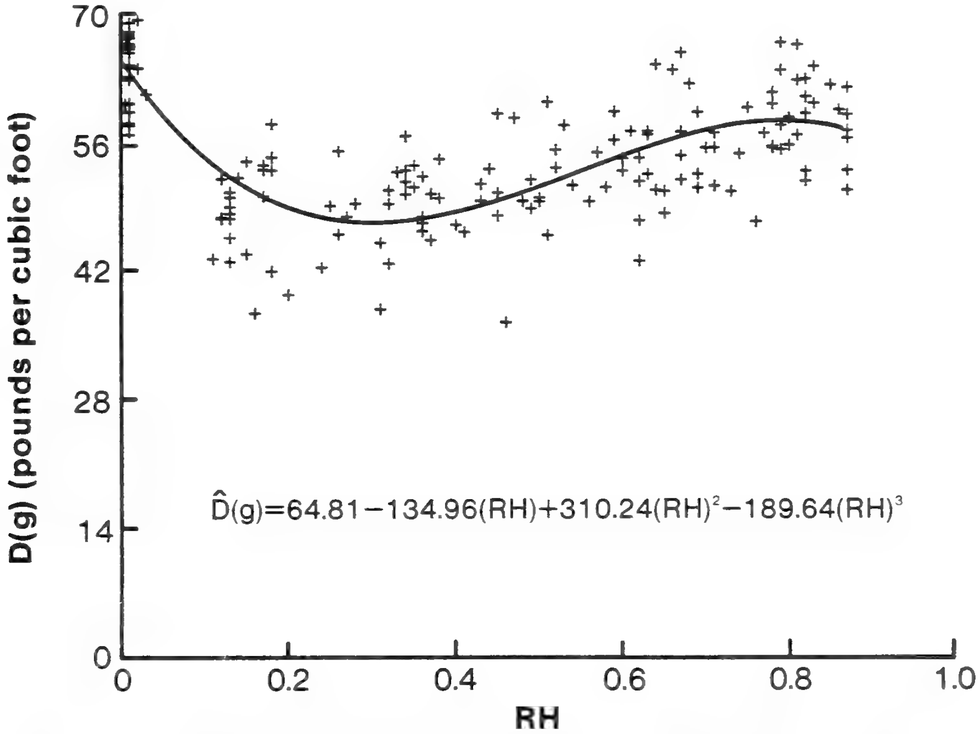


Figure 1a.—Green wood density profile of western hemlock based on disk samples where: $\hat{D}(g)$ = predicted green wood density, and RH = relative height (height to sampling point divided by total height of tree bole above a 1-foot stump).

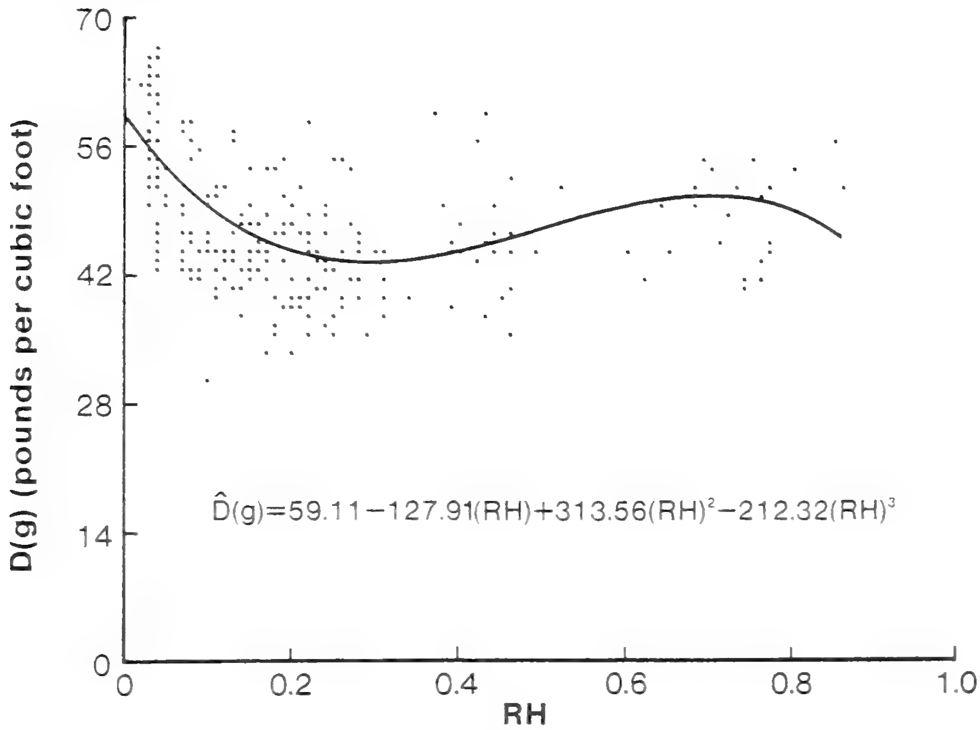


Figure 1b.—Green wood density profile of western hemlock based on core samples where: $\hat{D}(g)$ = predicted green wood density, and RH = relative height; height to sampling point divided by total height of tree bole above a 1-foot stump.

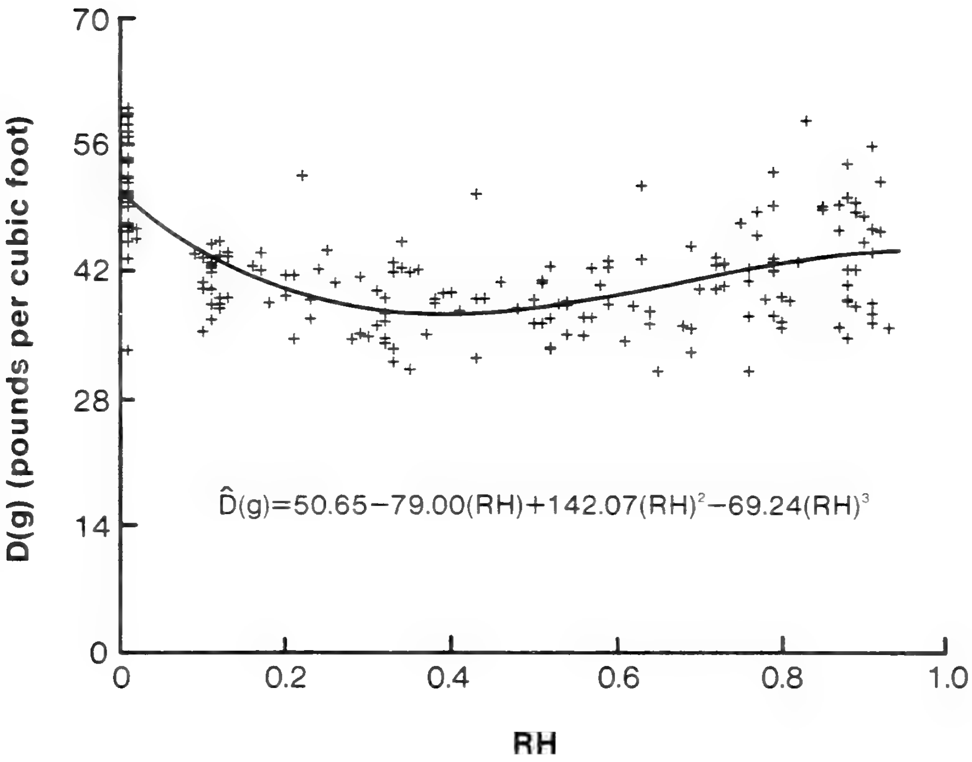


Figure 2a.—Green wood density profile of Douglas-fir based on core samples where:
$\hat{D}(g)$ = predicted green wood density, and
RH = relative height (height to sampling point divided by total height of tree bole above a 1-foot stump).

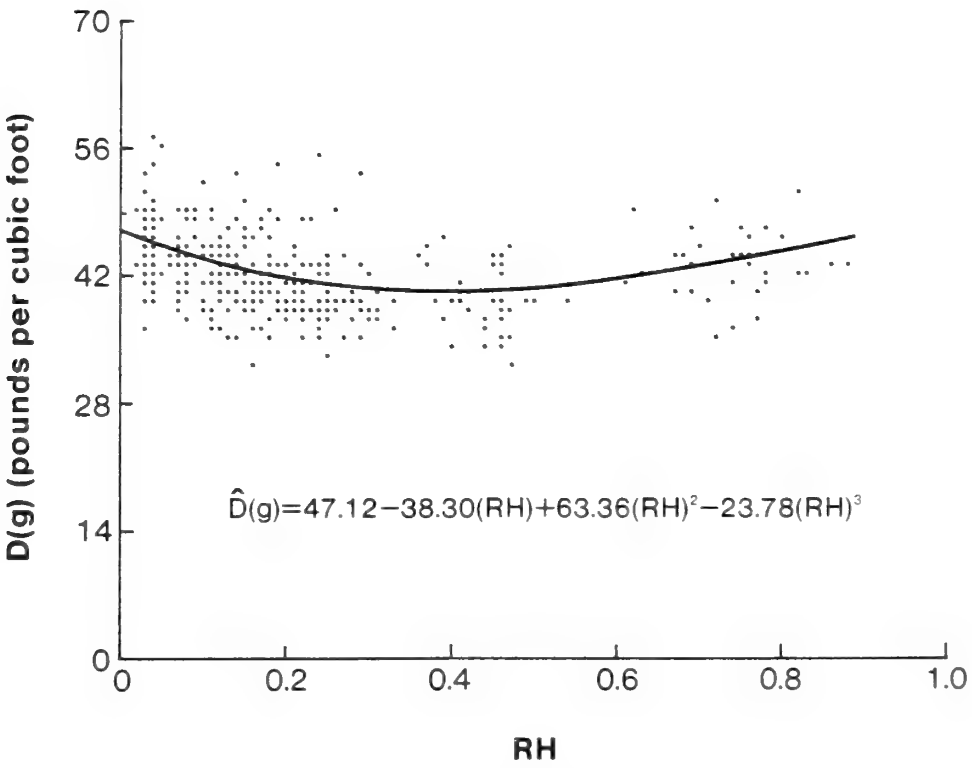


Figure 2b.—Green wood density profile of Douglas-fir based on core samples where:
$\hat{D}(g)$ = predicted green wood density, and
RH = relative height (height to sampling point divided by total height of tree bole above a 1-foot stump).

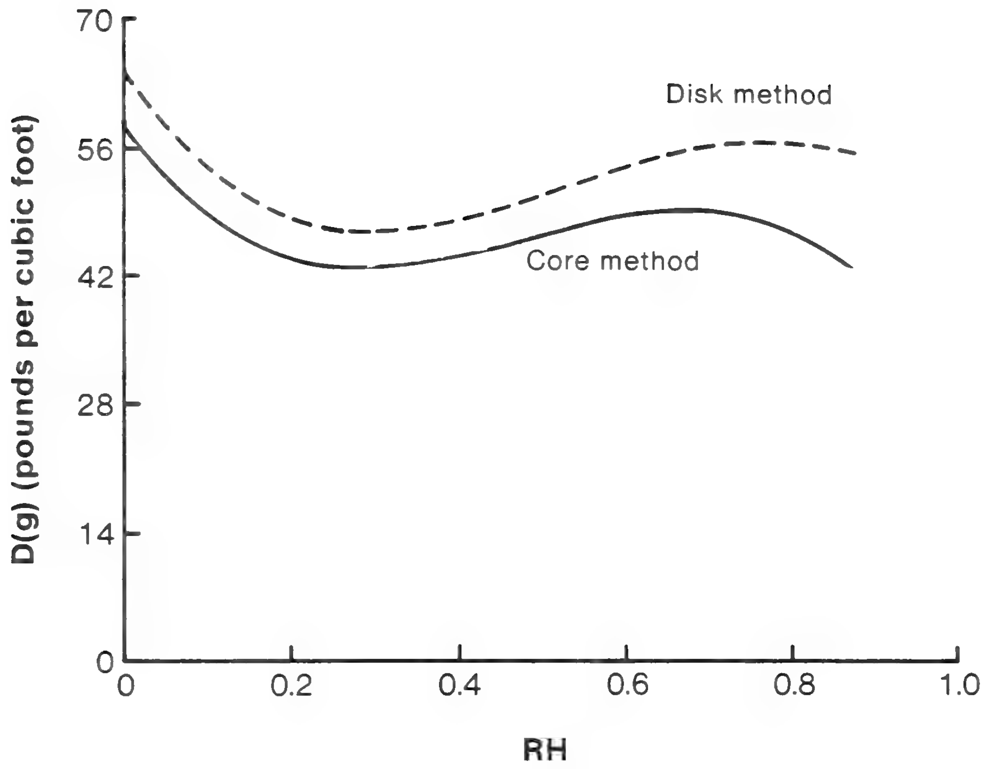


Figure 3.—Core and disk profiles of green western hemlock wood.

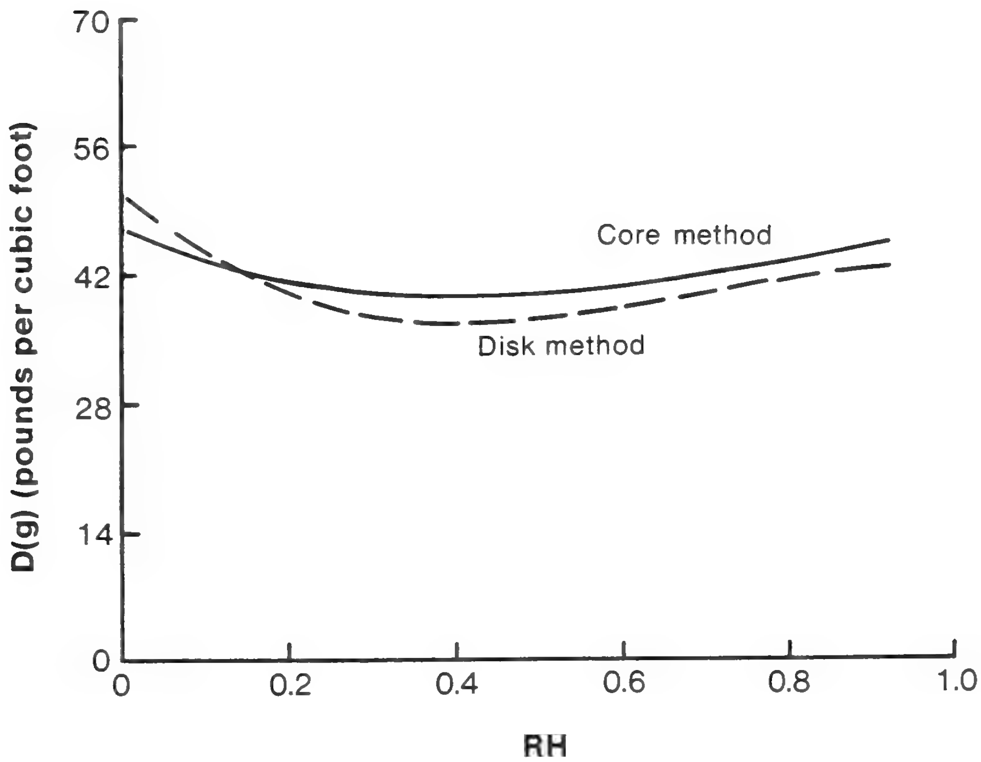


Figure 4.—Core and disk profiles of green Douglas-fir wood.

Table 2—Green wood density statistics for the disk and core samples

Species and samples	Regression constants a	b	c	d	Statistical measures 1/ $\bar{D}(g)$	R^2	SE	n
Western hemlock:								
Disk	64.81	-134.96	310.24	-189.64	54.9	0.55	4.9	166
Core	59.11	-127.91	313.56	-212.32	48.2	.35	5.8	247
Douglas-fir:								
Disk	50.65	-79.00	142.07	-69.24	42.4	.41	4.9	186
Core	47.12	-38.30	63.36	-23.78	43.1	.20	3.8	369

1/ $\hat{D}(g)=a+b(RH)+c(RH)^2+d(RH)^3$; where:
$\hat{D}(g)$ = predicted green density of wood (lb/ft^3);
RH = relative height (height to sampling point divided by total height of tree bole above a 1-foot stump);
$\bar{D}(g)$ = mean green density of wood samples (lb/ft^3);
R^2 = coefficient of determination;
SE = standard error of the estimate; and
n = sample size.

Dry Wood Density Profiles

Profiles of weighted ovendry wood density values as calculated by equation (5) are presented in figures 5 and 6 for western hemlock and Douglas-fir, respectively. Quadratic polynomial functions had the best fit to the data. Except for higher values at the stump and upper crown, densities remained fairly constant with the height and varied within a narrow band of values for both species. Statistical data for each function are presented in table 3. The number of disk samples (n) used in developing the dry polynomial functions differed from that used in developing the green functions (table 2). During the drying process some of the samples were inadvertantly overdried and had to be dropped from the analysis.

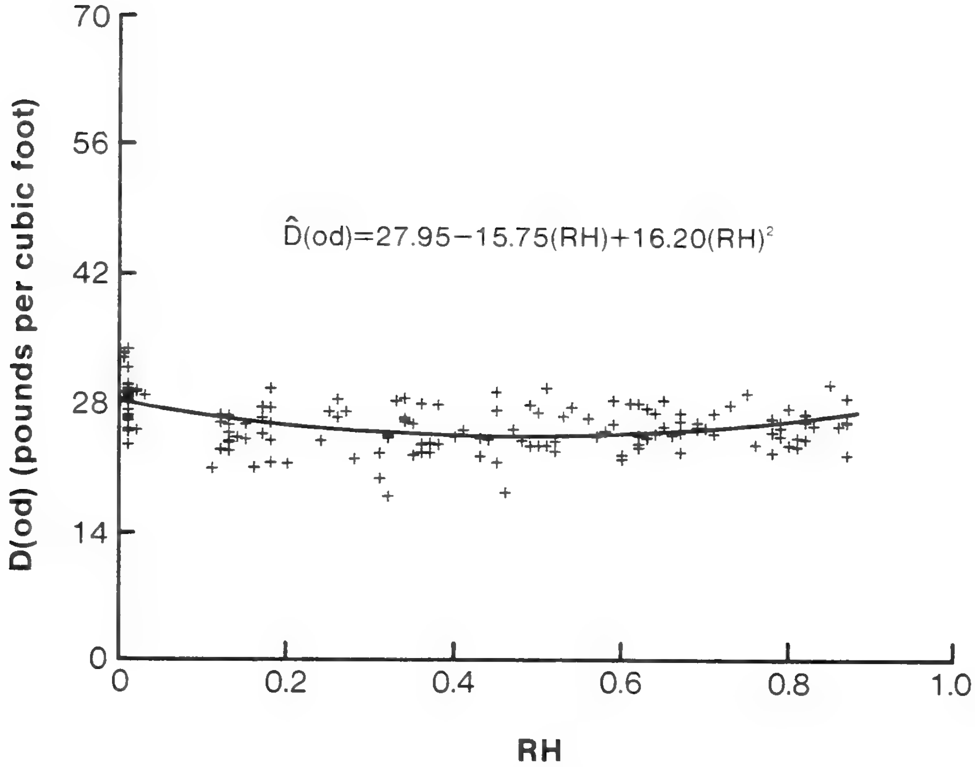


Figure 5.—Ovendry wood density profiles of western hemlock based on disk samples where:
$\hat{D}(od)$ = predicted ovendry wood density, and
RH = relative height (height to sampling point divided by total height of tree bole above a 1-foot stump).

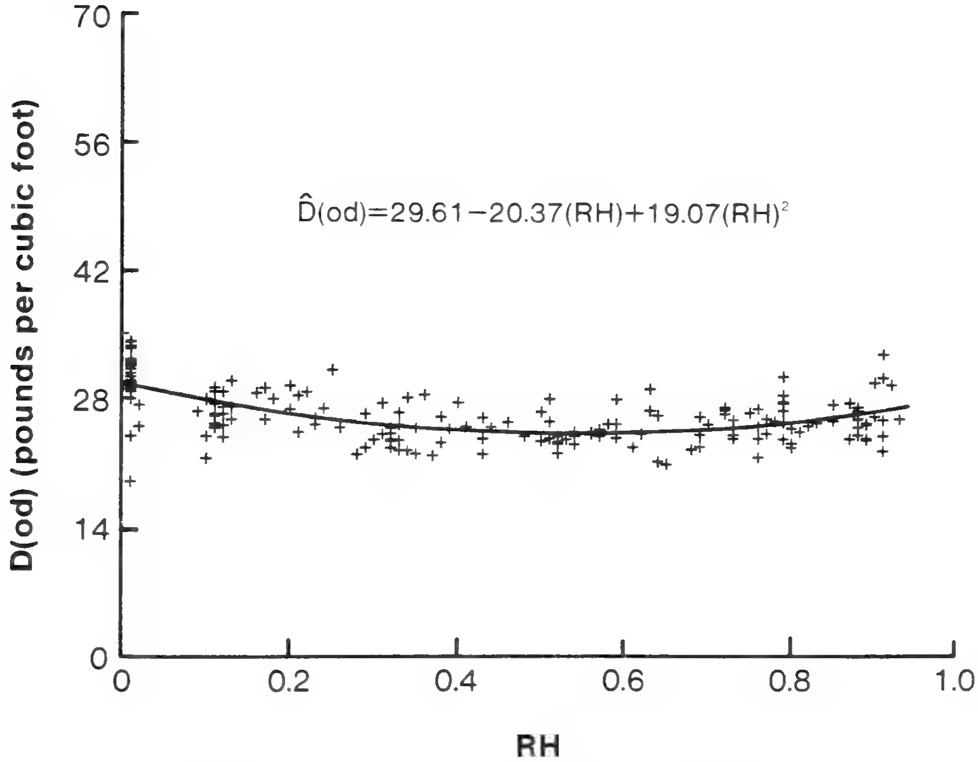


Figure 6.—Ovendry wood density of Douglas-fir based on disk samples where:
$\hat{D}(od)$ = predicted ovendry wood density, and
RH = relative height (height to sampling point divided by total height of tree bole above a 1-foot stump).

Table 3—Dry wood density statistics for the disk samples

	Regression constants			Statistical measures 1/			
Species	a	b	c	$\bar{D}(od)$	R^2	SE	n
Western hemlock	27.95	-15.75	16.20	25.5	0.22	2.4	156
Douglas-fir	29.61	-20.37	19.07	26.2	.38	2.3	183

1/ $\hat{D}(od) = a + b(RH) + c(RH)^2$; where:

$\hat{D}(od)$ = predicted ovendry density of wood (lb/ft^3);

RH = relative height (height to sampling point divided by total height of tree bole above a 1-foot stump);

$\bar{D}(od)$ = mean ovendry density of wood samples (lb/ft^3);

R^2 = coefficient of determination;

SE = standard error of the estimate; and

n = sample size.

Green Sapwood and Heartwood Density Profiles

Average green wood density values, as calculated by equation (2), for samples taken from the sapwood and heartwood zones of the disks were plotted separately against relative height for each species (figs. 7 and 8). The density of green sapwood was generally higher than that of green heartwood. The profiles of sapwood were poorly correlated and showed little or no change with relative height; heartwood, on the other hand, formed profiles that were more curvilinear. Statistical data for each function are presented in table 4.

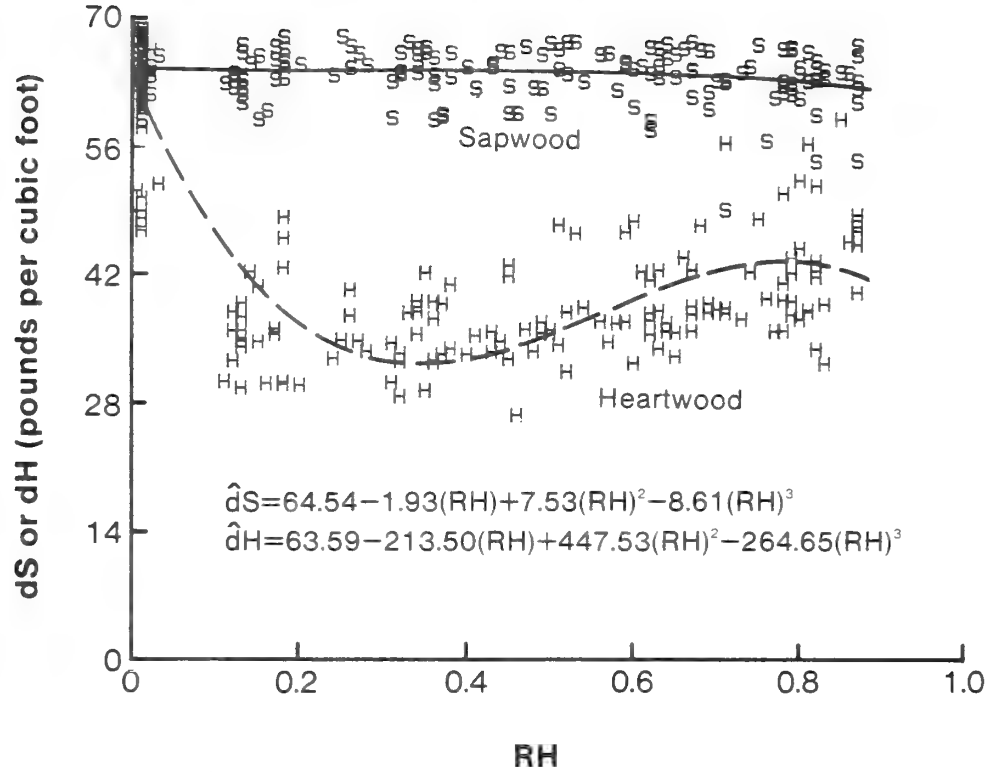


Figure 7.—Green sapwood and heartwood density profiles of western hemlock based on disk samples where:

$\hat{d}S$ = predicted green sapwood density,
$\hat{d}H$ = predicted green heartwood density, and
RH = relative height (height to sampling point divided by total height of tree bole above a 1-foot stump).

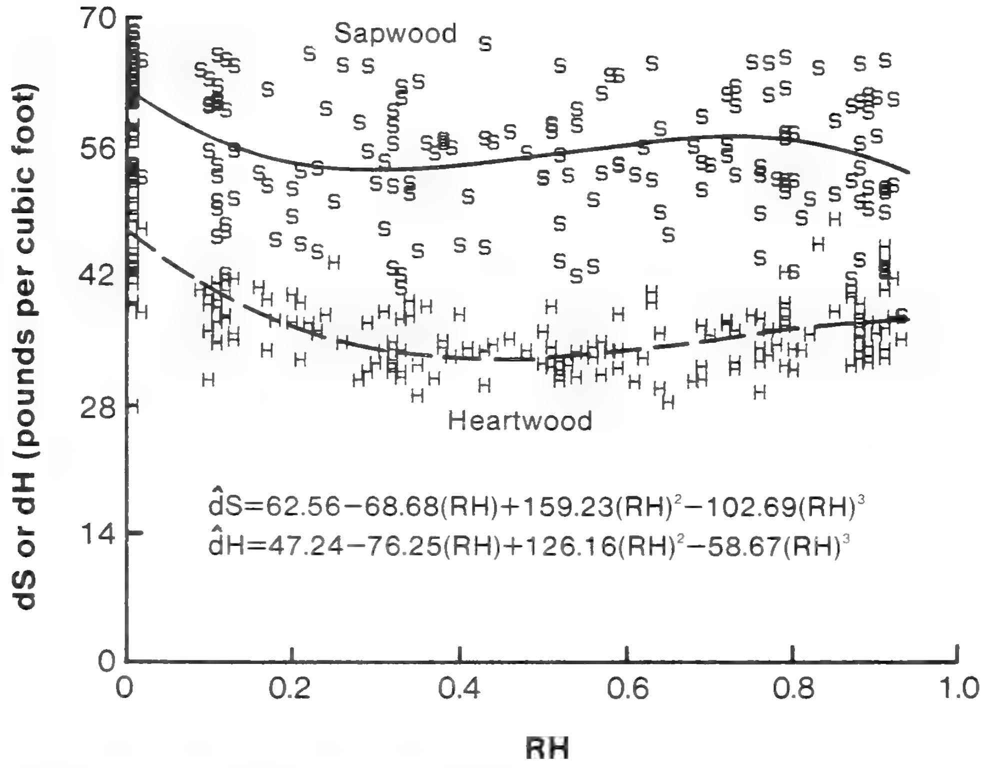


Figure 8.—Green sapwood and heartwood density profiles of Douglas-fir based on disk samples where:

$\hat{d}S$ = predicted green sapwood density,
$\hat{d}H$ = predicted green heartwood density, and
RH = relative height (height to sampling point divided by total height of tree bole above a 1-foot stump).

Table 4—Green wood density statistics for sapwood and heartwood samples

Species and samples	Regression constants a	b	c	d	Statistical measures 1/ $\bar{d}(S),\bar{d}(H)$	R^2	SE	n
Western hemlock:								
Sapwood	64.54	-1.93	7.53	-8.61	64.1	0.02	2.9	166
Heartwood	63.59	-213.50	447.53	-264.65	42.9	.67	6.6	166
Douglas-fir:								
Sapwood	62.56	-68.68	159.23	-102.69	56.0	.17	6.5	186
Heartwood	47.24	-76.25	126.16	-58.67	37.7	.54	4.1	186

1/ $\hat{d}(S),\hat{d}(H)=a+b(RH)+c(RH)^2+d(RH)^3$; where:

$\hat{d}(S)$ = predicted green density of sapwood (lb/ft^3);

$\hat{d}(H)$ = predicted green density of heartwood (lb/ft^3);

RH = relative height (height to sampling point divided by total height of tree bole above a 1-foot stump);

$\bar{d}(S)$ = mean green density of sapwood samples (lb/ft^3);

$\bar{d}(H)$ = mean green density of heartwood samples (lb/ft^3);

R^2 = coefficient of determination;

SE = standard error of the estimate; and

n = sample size.

Dry Sapwood and Heartwood Density Profiles

Figures 9 and 10 present profiles of average dry density values, as calculated by equation (3), for samples taken from the sapwood and heartwood zones of the study disks and plotted separately by species against relative height. Not included are the disk samples that were overdried (see previous discussion on dry wood density profiles) and one disk of Douglas-fir and one of western hemlock that were too small to produce separate radial samples of sapwood and heartwood. Table 5 presents statistical data for each profile.

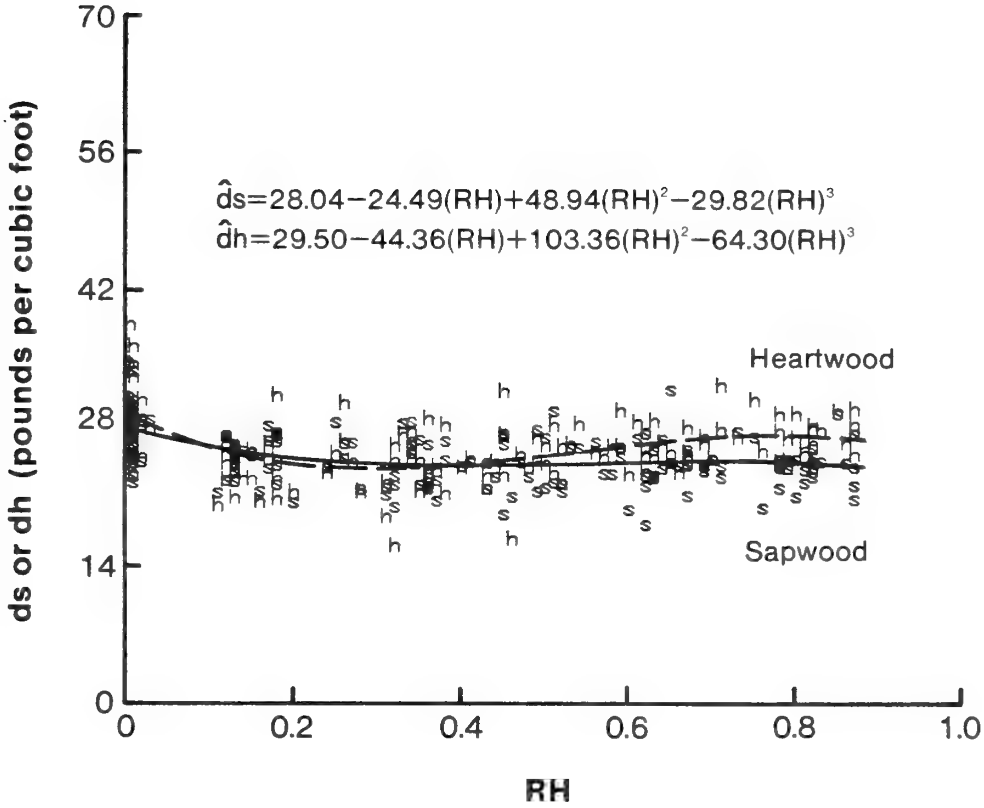


Figure 9.—Ovendry sapwood and heartwood density profiles of western hemlock based on disk samples where:
$\hat{d}s$ = predicted ovendry sapwood density,
$\hat{d}h$ = predicted ovendry heartwood density, and
RH = relative height (height to sampling point divided by total height of tree bole above a 1-foot stump).

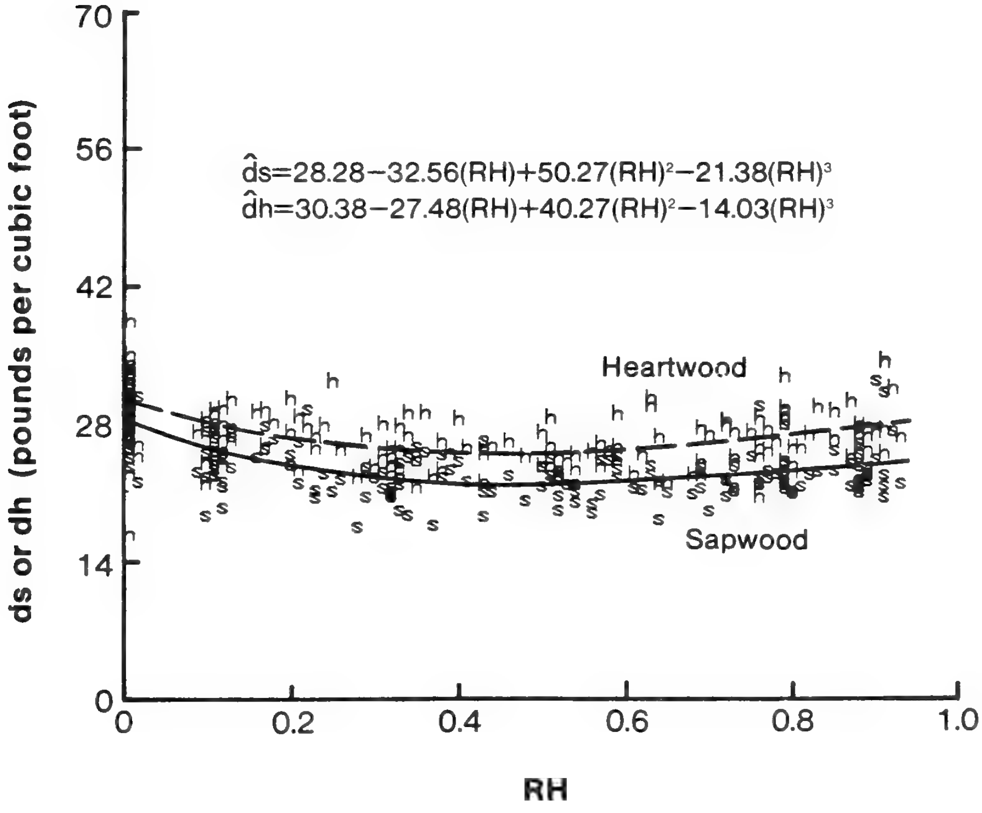


Figure 10.—Ovendry sapwood and heartwood density profiles of Douglas-fir based on disk samples where:
$\hat{d}s$ = predicted ovendry sapwood density,
$\hat{d}h$ = predicted ovendry heartwood density, and
RH = relative height (height to sampling point divided by total height of tree bole above a 1-foot stump).

Table 5—Dry wood density statistics for sapwood and heartwood samples

Species and samples	Regression constants a	b	c	d	Statistical measures 1/ $\bar{d}(s),\bar{d}(h)$	R^2	SE	n
Western hemlock:								
Sapwood	28.04	-24.99	48.94	-29.82	25.2	0.23	2.4	155
Heartwood	29.5	-44.36	103.36	-64.30	26.2	.30	2.8	155
Douglas-fir:								
Sapwood	28.28	-32.65	50.27	-21.38	24.0	.43	2.4	182
Heartwood	30.38	-27.48	40.27	-14.03	27.0	.30	2.7	182

1/ $\hat{d}(s),\hat{d}(h)=a+b(RH)+c(RH)^2+d(RH)^3$; where:

$\hat{d}(s)$ = predicted ovendry density of sapwood (lb/ft^3);

$\hat{d}(h)$ = predicted ovendry density of heartwood (lb/ft^3);

RH = relative height (height to sampling point divided by total height of tree bole a 1-foot stump);

$\bar{d}(s)$ = mean ovendry density of sapwood heartwood samples (lb/ft^3);

$\bar{d}(h)$ = mean ovendry density of heartwood samples (lb/ft^3);

R^2 = coefficient of determination;

SE = standard error of the estimate; and

n = sample size.

Wood Moisture Profiles

The moisture profiles in the boles of western hemlock and Douglas-fir are shown in figures 11 and 12, respectively. The shaded areas bounded by the green and dry wood density functions (see figs. 1a, 2a, 5, and 6) represent the wood moisture in the tree stem. The actual water content at various heights in the stem is presented in the figures as a dashed curve and was determined by subtracting values of dry wood density from corresponding values of green wood density. In both species, moisture concentration was highest at the base of the tree and in the upper crown portion of the tree stem.

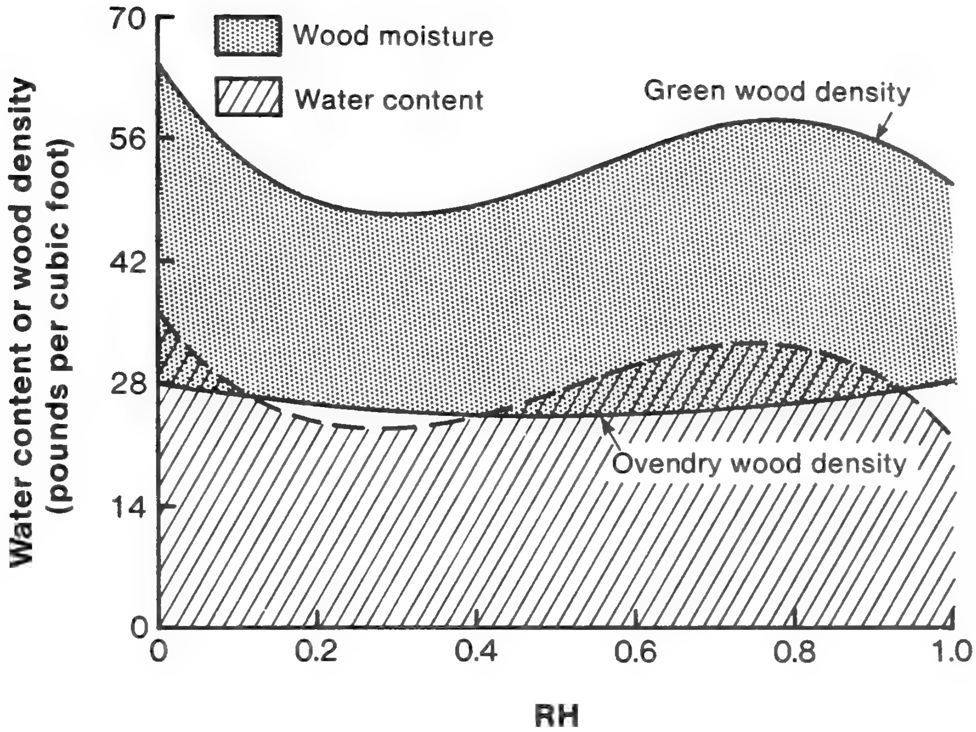


Figure 11.—Wood moisture profile in western hemlock (shaded area). Actual water content (dashed line) equals green wood density value minus ovendry wood density value.

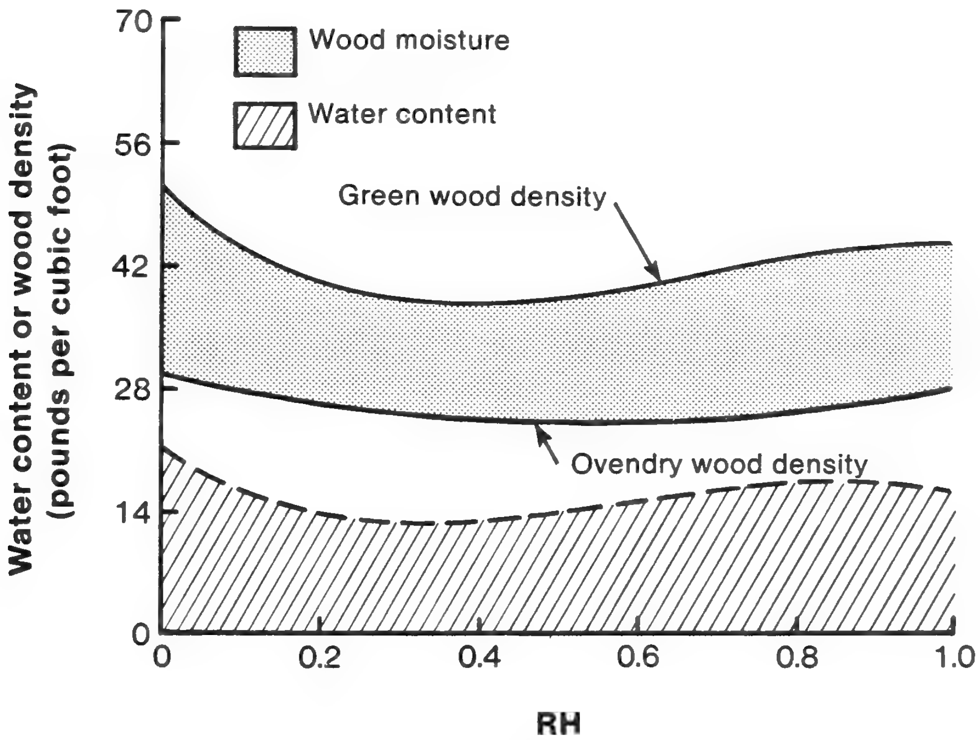


Figure 12.—Wood moisture profile in Douglas-fir (shaded area). Actual water content (dashed line) equals green wood density value minus ovendry wood density value.

Green Wood Density Profiles—Trees With and Without Heartrot

The green wood density profiles for trees with and without heartrot are separately presented by species in figures 13 and 14. Table 6 presents statisical data for each function. Plotted density values were from trees selected during the 1982 season. As previously noted, trees in the 1981 sample contained little defect as defective trees were purposely avoided during selection.

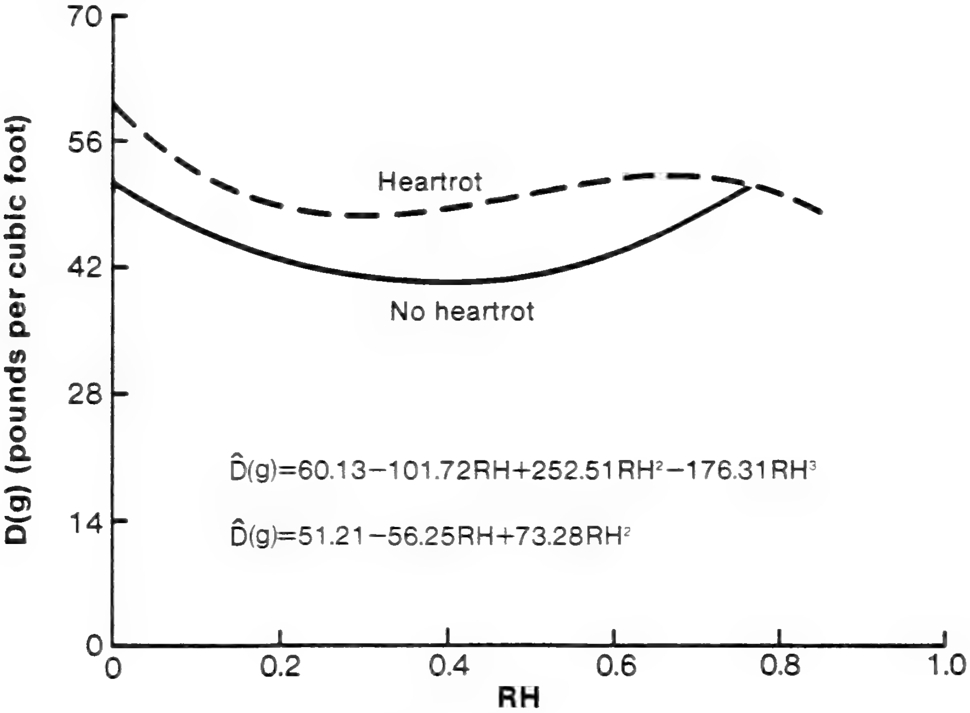


Figure 13.—Green wood density profiles of western hemlock for trees with and without heartrot.
$\hat{D}(g)$ = predicted green wood density, and
RH = relative height (height to sampling point divided by total height of tree bole above a 1-foot stump).

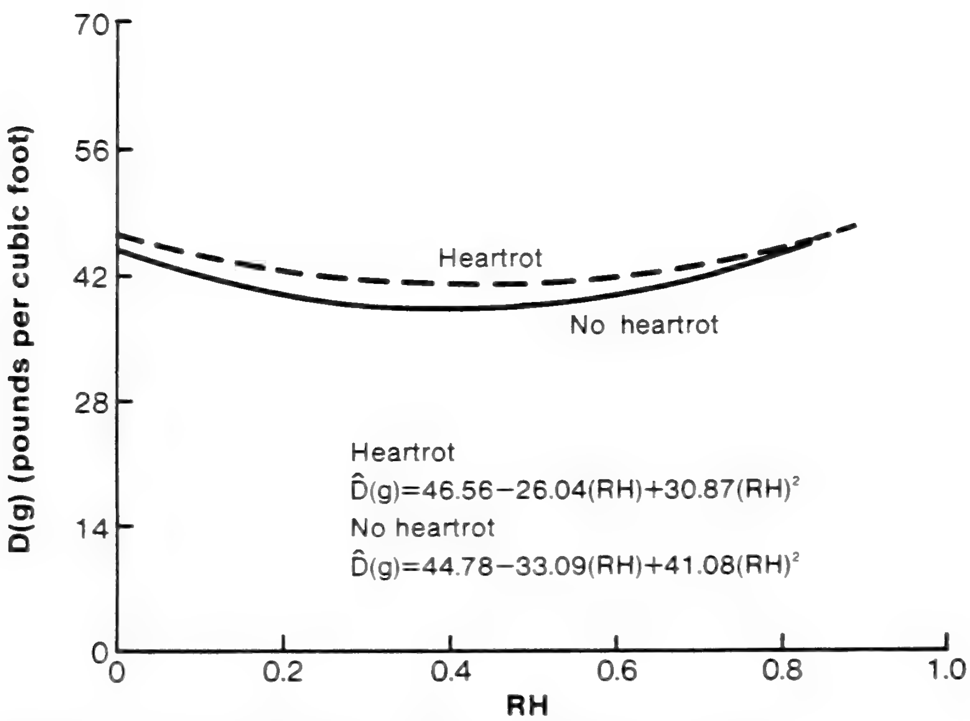


Figure 14.—Green wood density profiles of Douglas-fir for trees with and without heartrot.
$\hat{D}(g)$ = predicted green wood density, and
RH = relative height (height to sampling point divided by total height of tree bole above a 1-foot stump).

Table 6—Green wood density statistics for trees with and without heartrot

Species and defect condition	Regression constants				Statistical measures 1/			
	a	b	c	d	$\bar{D}(g)$	R^2	SE	n
Western hemlock:								
With heartrot	60.13	-101.72	252.51	-176.31	51.4	0.25	6.0	74
Without heartrot	51.21	-56.25	73.28		45.2	.30	5.2	65
Douglas-fir:								
With heartrot	46.56	-26.04	30.87		43.5	.17	3.6	187
Without heartrot	44.78	-33.09	41.08		41.1	.38	2.6	125

1/ $\hat{D}(g)=a+b(RH)+c(RH)^2+d(RH)^3$; where:

$\hat{D}(g)$ = predicted green density of wood (lb/ft^3);

RH = relative height (height to sampling point divided by total height of tree bole above a 1-foot stump);

$\bar{D}(g)$ = mean green density of wood (lb/ft^3);

R^2 = coefficient of determination;

SE = standard error of the estimate; and

n = sample size.

Discussion

Green Wood Density Profiles

Two methods used in this study to sample green wood density (disk and increment core) produced wood density profiles that are similar in form but not in magnitude because of moisture differences in the trees sampled. Each profile shows density values decreasing from a high at the stump to a low in the lower third of the bole, and then gradually increasing again in the upper bole. In the extreme upper portions of the bole of western hemlock (fig. 1), the density profile leveled off and then decreased; in Douglas-fir (fig. 2) a gradual increase was evident. The high value of green wood density at the stump was particularly apparent in the profile of western hemlock. In this species a core of extremely high moisture occurs at the base of the trees, producing an anomaly in the heartwood called wetwood[5/] (Ward and Pong 1980). This condition results in wood with exceptionally high green densities.

The function fitted for the increment core data of western hemlock (fig. 3) gave lower values and that of Douglas-fir (fig. 4) higher values than did comparable curves through the disk data. Because only the disk samples were ovendried, moisture content comparisons between the 1981 (disk) and 1982 (core) green density profiles were not possible. If we assume that the dry wood density profiles were consistent for the disk and core data (both species), then the observed difference in the green wood density profiles must have been mainly due to moisture difference in the disk and core samples. These results suggest that the 1981 sample trees of western hemlock were wetter and those of Douglas-fir were drier than the trees selected in 1982. Average green wood density for western hemlock based on disk samples was 54.9 lb/ft^3; based on cores, it was 48.2 lb/ft^3. Comparable values for Douglas-fir were disks—42.4 lb/ft^3, and cores—43.1 lb/ft^3 (table 2).

[5/]Wetwood is a type of heartwood in standing trees that has been internally infused with water and differs from normal wood in physical and chemical properties.

Polynomial functions developed from the disk data had higher coefficients of determination (R^2) than those developed from the core data (table 2). With disk samples it was possible to examine the variation in green wood density in a tree along the radial, longitudinal, and circumferential planes. With the increment core approach, variation around the circumference of the tree could not be examined because only a single core was extracted at any given height.

For western hemlock, the variability or deviation of the data around the fitted regression, as measured by the standard error of estimate (SE), was slightly greater for the core data (5.8 1b/ft^3 than for the disk data (4.9 lb/ft^3) (table 2). For Douglas-fir, the disk data had a slightly greater SE (4.9 lb/ft^3) than did the core data (3.8 lb/ft^3). For both western hemlock and Douglas-fir, the accuracy with which a fitted function predicted green wood density was generally comparable whether determined by disk or core samples. There appeared, however, to be a slightly greater degree of unexplained variability with the core approach when sampling a tree species in which the sapwood-heartwood zones are not readily discernible (western hemlock) than in a species where these zones are quite distinct (Douglas-fir). Because the wood-moisture differential in a tree is closely related to the sapwood and heartwood zones (discussed later), accurate proportioning of the increment core relative to the amount of sapwood and heartwood becomes a critical factor in minimizing variability. Even though accuracy in differentiating the sapwood and heartwood zones is also important in the disk approach to density determination, the impact is much more critical in the core approach because of the size of the sample involved (Waddell and others 1984).

Functions derived from the increment core data (figs. 1b and 2b) do not fully represent the density profile for the base portion of the core sample trees as density samples were not taken from the stump height position of these trees. Results from the disk sample trees (figs. 1a and 2a) suggest that the curves for the increment core data would have been steeper and higher at the base (Y-intercept) if stump height densities had been included. The core and disk functions for Douglas-fir (fig. 4) probably would not have crossed but would have formed parallel profiles, each having a similar trend but at different levels.

Dry Wood Density Profiles

Dry wood density for western hemlock (fig. 5) and Douglas-fir (fig. 6) varied within a very narrow band of values but remained fairly constant with height. Density values were highest at the stump, decreased slightly through midbole, and then increased slightly again in the upper bole. In both species, the magnitude of change in density with relative height was considerably less than that recorded for the samples in the green condition (figs. 1a and 2a). Similar patterns of change in dry wood density with height have been recorded for a number of other coniferous species (Okkonen and others 1972, Wilcox and Pong 1971).

Average dry wood density (table 3) was 25.5 lb/ft^3 for western hemlock and 26.2 lb/ft^3 for Douglas-fir. The variability around the regression function was approximately the same for both species (SE = 2.4 for western hemlock and SE = 2.3 for Douglas-fir). These standard errors were approximately half of those recorded for the green disk data (table 2).

The quadratic functions (figs. 5 and 6) of the dry wood density of Douglas-fir had a higher coefficient of determination with relative height (R^2 = 0.38) than did western hemlock (R^2 = 0.22). For both species, however, the correlation of dry density with height was not as high as that recorded for green density (table 2). These results suggest that the physical-mechanical properties of the tree as expressed by dry wood density are less related to tree height than are the physiological properties. Except for the high values recorded for the base of the tree, where physical-mechanical requirements are probably the greatest, dry density exhibited very little change with relative height (figs. 5 and 6). Green wood density, on the other hand, changed dramatically with height (figs. 3 and 4). The changes reflect the distribution of wood moisture in the tree rather than the wood density.

Green Sapwood Density Profiles

In both species green sapwood was considerably heavier than the adjacent green heartwood at all heights (figs. 7 and 8) and averaged over 21 pounds per cubic foot more in western hemlock and 18 pounds per cubic foot more in Douglas-fir (table 4). Moisture content of the wood in the two radial zones accounted for most of the weight difference. Only at the stump level of western hemlock, where wetwood occurred, was the green density of heartwood nearly the same as that of green sapwood (fig. 7).

Density values varied with height in a band considerably wider for Douglas-fir (SE=6.5) than for western hemlock (SE=2.9) (table 4). Much of this variation in the sapwood profile of Douglas-fir was related to the inherent narrow band of sapwood typically found in old-growth trees. Consequently, samples extracted from the sapwood zone seldom were composed of pure sapwood material but frequently contained wood from the heartwood and heartwood-sapwood transition zones. Because the material in these zones is extremely variable in moisture content (Stewart 1967), their inclusion in the sapwood samples had a direct impact on the amount of variation recorded in the sapwood profile. Inclusion also caused the sapwood profile to take on a form similar to that of the heartwood profile (fig. 8).

Western hemlock trees typically contain wide bands of sapwood. This minimized the potential of producing sapwood samples with inclusions of heartwood or wood of the heartwood-sapwood transition zone. The sapwood profile of western hemlock (fig. 7) was a narrow band of values remaining fairly constant with relative height. When compared to the sapwood profile of Douglas-fir (fig. 8), recorded differences in variation, previously mentioned, became apparent. For western hemlock, the extremely poor correlation of green sapwood density to relative height (R^2= 0.02, table 4) strongly indicate that a mean value of sapwood density would be appropriate when determining log weights for this species.

Green Heartwood Density Profiles

The green density profiles of heartwood for western hemlock (fig. 7) and Douglas-fir (fig. 8) resembled closely their respective profiles of green wood density (figs. 1a and 2a). The trends began with the highest densities at the stump, decreased to a low in the lower third of the bole, and then increased in the upper bole. Predictive functions developed for green density of heartwood had considerably higher coefficients of determinaton (table 4) than those developed for the corresponding sapwood.

In western hemlock, green heartwood at the stump was almost as dense as green sapwood. This is because many of the sample trees for this species contained a base core of wetwood. This material had moisture contents as high as or higher than that of sapwood.

When wetwood occurred in combination with the larger sample trees of western hemlock, there was greater potential of producing extremely heavy butt logs. The occurrence of wetwood was not restricted to the center core of lower logs from western hemlock. Scattered pockets of wetwood also occurred in the middle and upper bole. Some of the variation in green density recorded in these regions (fig. 7) may be related directly to the occurrence of these pockets of wetwood. The inclusion of some sapwood material in the samples designated as heartwood may also have contributed to the observed variation; this was especially true in the extreme upper crown where small-diameter logs limited the extraction of discrete samples of sapwood and heartwood

The heartwood of Douglas-fir produced a green density profile (fig. 8) similar in form to that of western hemlock; that is, highest density values occurred at the stump, then decreased with increasing height to about midbole, and then increased again in the upperbole. Unlike western hemlock, heartwood of Douglas-fir was never as dense as its corresponding sapwood at any point along the bole. The infrequent occurrence of wetwood in Douglas-fir (Ward and Pong 1980) precludes green heartwood of Douglas-fir from attaining the density of green sapwood.

Dry Sapwood and Heartwood Density Profiles

The removal of moisture from the sapwood and heartwood produced nearly identical dry density profiles for these two radial zones within a given species (figs. 9 and 10). Water removal attenuated the fluctuating changes in the density profiles of green wood (figs. 7 and 8) and, except for slightly higher values at the stump and upper bole, the profiles of dry sapwood and heartwood remained fairly constant with relative height.

The predictive functions of dry density for sapwood and heartwood of western hemlock were at approximately the same level; those developed for Douglas-fir showed the density profile of dry sapwood to be consistently lower than that of heartwood. The lower densities were due to the overmature and senescent condition of the Douglas-fir trees included in the sample. Wood of extreme age (that is, age of the wood relative to the pith) is characteristically lower in density (Kellogg 1979, Panshin and DeZeeuw 1970). Ring counts at the stump gave the average age of the Douglas-fir trees in the sample as 431 years; ring counts of western hemlock averaged 259 years. Average dry density of sapwood from Douglas-fir was 3 lb/ft^3 less than the heartwood (table 5) and 1.2 and 2.2 $1b/ft^3$ less than the dry density of sapwood and heartwood, respectively, of western hemlock.

Wood Moisture Profiles

Wood moisture profiles of western hemlock (fig. 11) and Douglas-fir trees (fig. 12) had patterns that closely resembled their respective density profiles of green wood (figs. 1 and 2). Highest concentration of moisture occurred at the base of the tree, decreased with height to a low in the middle third of the stem, and then increased again in the upper stem. Western hemlock as a species was considerably wetter than Douglas-fir at all heights and in both the sapwood and the heartwood. Moisture tended to concentrate in equal amounts in both the sapwood and heartwood at the base of western hemlock. This produced butt logs that are exceptionally heavier than logs of equivalent size in Douglas-fir. Above the butt, and in both species, there was considerably less moisture in the heartwood than in the sapwood.

Our data strongly suggested that the fluctuations in profiles of green wood density (figs. 1 and 2) were due mainly to fluctuations in the water content along the length of the tree bole and that the impact of moisture on the green density profiles was much more evident in heartwood than in sapwood (figs. 7 and 8). Fluctuations such as those recorded in the sapwood profiles of Douglas-fir (fig. 8) were due mainly to the inclusion of heartwood material in the sapwood samples and were not due to moisture changes in the sapwood per se. Results suggested that the moisture profile in green sapwood remains fairly constant with height.

The weight of water in the boles of western hemlock equaled or exceeded the dry weight of wood substance (dry density) at nearly all heights (fig. 11). Only a short portion of the lower boles above the stump and the terminal end of the stem contained less water than dry wood material. In Douglas-fir the water content of the boles never equaled or exceeded the dry density of the wood at any height. (fig. 12).

Green Wood Density Profiles—Trees With and Without Heartrot

Heartrot in western hemlock and Douglas-fir produced green density profiles that were similar to, but heavier, than those recorded in trees without heartrot (figs. 13 and 14). The profile shift was more evident in trees with large amounts of incipient decay. The impact of decay on the green density profile were more noticeable in western hemlock than in Douglas-fir. Our data suggested that decay may affect the sapwood-heartwood boundary and allow moisture to move radially from the sapwood into the heartwood. Moisture produced by the causal agent in the heartwood tends to accumulate in that location (Shigo and others 1977) and results in higher green densities. Density values for trees with heartrot averaged over 6 lb/ft^3 greater than for trees without heartrot in western hemlock and nearly 2.5 lb/ft^3 greater in Douglas-fir (table 6). That higher green densities occurred in trees with heartrot was substantiated when logs from these trees were weighed in the field. Generally, heavier weights per unit of volume were recorded for defective logs than for sound logs.

Applications of Results

In the past the estimates of green log weight have been determined using a single average green density for a species or a form of running averages (Mann and Lysons 1972, Wensel 1974). Table 7 shows the limitations associated with using a single green density value on logs originating from different heights within a tree. Two trees were selected to validate estimates of log weights. Neither tree was part of the sample used to develop the prediction function. Diameter measurements were made on the cut surfaces of the bucked logs from both validation trees

Table 7—Log weight estimates for western hemlock using a single green wood density value versus green wood density values from a prediction function[1]

Log position	Log length	Log volume 2/ Total	Wood	Bark	Single density 3/ Wood	Bark	Estimated log weight 4/	Average functional density 5/	Estimated log weight 6/	Actual log weight 7/
		- - Cubic feet - -			Pounds per cubic foot		Pounds	Pounds per cubic foot	- - - Pounds - - -	
TREE NO. 1 (d.b.h. 8/ 44 in; height 175 ft)										
Butt	17.5	151.6	119.0	32.6	52	44	7,623	54.2	7,885	8,056
Second	17.5	123.8	99.3	24.5	52	44	6,242	46.8	5,725	5,784
Third	17.5	113.6	91.7	21.9	52	44	5,732	43.8	4,980	4,160
Fourth	17.6	102.4	81.6	20.7	52	44	5,154	43.9	4,493	3,654
Fifth	17.5	84.0	66.6	17.4	52	44	4,228	45.8	3,815	3,366
Sixth	20.5	83.1	68.5	14.6	52	44	4,205	48.4	3,958	3,434
TREE NO 2 (d.b.h. 8/ 39 in; height 180 ft)										
Butt	17.8	119.7	87.5	32.2	52	44	5,966	54.2	6,160	5,130
Second	17.5	93.4	68.4	25.0	52	44	4,657	46.9	4,308	3,790
Third	17.5	77.1	59.2	17.9	52	44	3,866	43.8	3,380	2,980
Fouth	17.5	64.6	51.6	13.0	52	44	3,255	43.8	2,832	2,610
Fifth	17.6	58.2	47.0	11.2	52	44	2,937	45.5	2,631	2,120
Sixth	14.4	38.3	30.9	07.4	52	44	1,932	47.7	1,799	1,640
Seventh	20.5	36.7	29.1	07.6	52	44	1,848	49.5	1,775	1,550

1/ Prediction function used was: $\hat{D}(g) = 59.11-127.91(RH)+313.56(RH)^2 -212.32(RH)^3$; where:
$\hat{D}(g)$ = predicted green density of wood (lb/ft^3); and
RH = relative height (height to sampling point divided by total height of tree bole above a 1-foot stump).

2/ Volumes calculated using the Smalian formula.

3/ Averaged from field samples.

4/ Estimated weights are the products of log volume and single green density values of wood and bark.

5/ Average functional density was the mean of the density values determined for the relative height position of the log ends.

6/ Estimated log weights were the sum of the products of the wood volume of the log and average functional density plus bark volume and single density.

7/ Measured with a load cell.

8/ Diameter of tree bole at 4-1/2 feet above ground as measured on the uphill side of the tree.

(western hemlock), and volumes were determined using the Smalian formula. Single density values of 52 and 44 lb/ft^3,[6] respectively, were applied to the wood and bark volumes to obtain an estimated green weight. In addition, a series of incremental (average) green wood densities were determined using the western hemlock increment core function (table 2, fig. 1b) and were applied to each log. The actual weights of the logs were determined using a load cell attached to a front-end loader (Waddell and others 1984).

[6]These density values are averages as determined from disk measurements of wood and bark densities.

The green density fluctuation with height in a tree was substantial enough to cause additional weight error or bias in various portions of the tree. The use of a density function multiplied by the gross volume of a log was superior to a single green density value for most logs. The use of a single average green density value (versus predicted values from a function) is more appropriate for tree species such as Douglas-fir where the change in the green density profile with height is less pronounced. Even for Douglas-fir, improvements in log weight estimates can be made with the use of predicted green density values; this would be especially true in estimating butt log weights.

The variation in green density between trees within a given site limits the accurate estimation of log weights using either a function or a single-value approach. This is illustrated in figure 15 where the 90 percent confidence bands have been added to the western hemlock density function. Log weights for the two validation trees were calculated using the green density values from the lower and upper confidence bands. These weights are presented in table 8. The wide interval of estimated weights for a particular log illustrates the moisture content-green density problem associated with weight estimation procedures in old-growth timber.

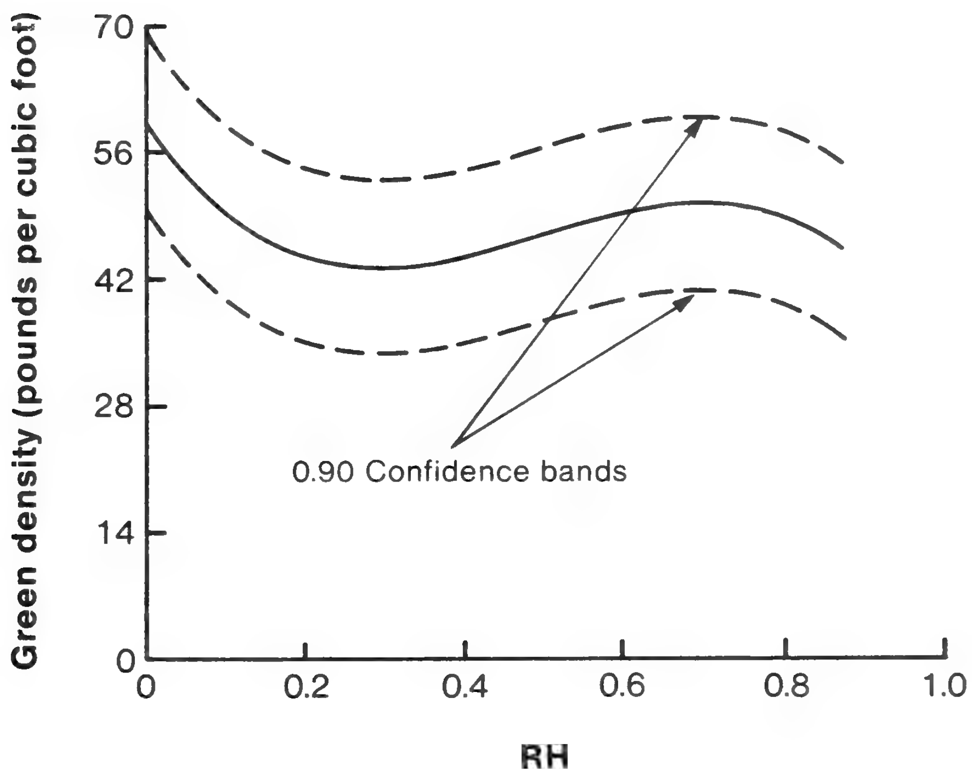


Figure 15.—Green wood density profile of western hemlock with 90 percent confidence bands.

Table 8—Predicted green wood density values and weight estimates for two western hemlock trees, as derived from calculated (0.90) confidence bands of the green wood density function[1/]

Log position	Green density			Log weight			Actual
	Low	Function	High	Low	Function	High	log weight 2/
	Pounds per cubic feet			Pounds			
TREE NO. 1 (d.b.h. 3/ 44 in; height 175 ft)							
Butt	44.6	54.2	63.7	6,741	7,885	9,014	8,056
Second	37.3	46.8	56.4	4,777	5,725	6,675	5,784
Third	34.2	43.8	53.4	4,099	4,980	5,860	4,160
Fourth	34.3	43.9	53.4	3,709	4,493	5,268	3,654
Fifth	36.2	45.8	55.3	3,176	3,815	4,442	3,366
Sixth	38.8	48.4	57.9	3,301	3,958	4,609	3,434
TREE NO 2. (d.b.h. 3/ 39 in; height 180 ft)							
Butt	44.3	54.2	63.4	5,295	6,160	6,964	5,130
Second	37.4	46.9	56.5	3,655	4,308	4,796	3,790
Third	34.3	43.9	53.4	2,818	3,380	3,911	2,980
Fourth	34.2	43.8	53.3	2,338	2,832	3,353	2,610
Fifth	36.0	45.5	55.1	2,238	2,631	3,136	2,120
Sixth	38.2	47.7	57.3	1,535	1,799	2,126	1,640
Seventh	40.0	49.5	59.1	1,522	1,775	2,079	1,550

1/ Prediction function used was: $\hat{D}(g) = 59.11 - 127.91(RH) + 313.56\,(RH)^2 - 212.32(RH)^3$; where:

$\hat{D}(g)$ = predicted green density of wood (lb/ft^3); and

RH = relative height (height to sampling point divided by total height of tree bole above a 1-foot stump).

2/ Measured with a load cell.

3/ Diameter of tree bole at 4-1/2 ft above ground as measured on the uphill side of the tree.

The combination of green density prediction and volume variation will undoubtedly produce considerable within-site variation for individual log weight estimates. For the user of either single or functional density values this variation results in uncertainty regarding estimates of load weights for aerial logging. For example, if we assume little or no error in estimating volume, the variation within a site for green density produces a possible range of weights (tree no. 1, table 8) from 6,741 to 9,014 lb in a typical large butt log. This band of uncertainty spans nearly 2,300 lb (90 percent confidence interval).

Further research is needed on the variability of the moisture regimes in trees located on specific, well-defined sites. For example, if a given species exhibits similar profile characteristics for different sites (similar functional forms) but merely shifts along the Y-intercept in response to changes in moisture, a methodology for indexing the green density profile from a single measurement (for example, increment core at d.b.h.) could increase accuracy and reduce bias within and among sites.

Conclusions

Our results are based on a case study of a limited sample of trees selected from a given area and may not necessarily be applicable to or indicative of old-growth western hemlock and Douglas-fir in other locations. The data do, however, provide a base on which certain inferences can be drawn concerning the wood density-moisture profiles in trees of these two species:

1. Both western hemlock and Douglas-fir exhibited similar green density profiles. Each profile showed density values decreasing from a high at the stump to a low in the lower third of the bole and increasing again in the upper bole. Because moisture levels are considerably higher in western hemlock, the green density profile for this species was consistently heavier at all heights than the profile for Douglas-fir. Use of disks and increment cores produced profiles that were similar in form but not in magnitude because of differences in moisture level in the trees sampled. Fitted functions for both the core and the disk approach for predicting green density for western hemlock and Douglas-fir were comparable in accuracy; the disk approach, however, produced functions with higher correlations.

2. Except for slightly higher values at the stump and upper bole, dry wood densities for both western hemlock and Douglas-fir remained fairly constant with height and varied in a very narrow band of values. The magnitude of change in dry density with relative height was considerably less than that recorded for the green condition. For both species the correlations of dry density with relative height were not as high as those recorded for green wood density.

3. Green sapwood was considerably heavier than green heartwood in both species and at all heights. Moisture content of the wood material in the two radial zones was the major factor in this difference. There was a greater difference in the green densities of sapwood and heartwood in western hemlock than there was in Douglas-fir. The green density profile of sapwood in both western hemlock and Douglas-fir was essentially the same; that is, a profile of density values showing little change with height but varying in a band considerably wider for Douglas-fir than for western hemlock. Predictive functions of green sapwood density with relative height registered low coefficients of determination.

4. Green density profiles of heartwood in western hemlock and Douglas-fir resembled closely their respective profiles of green wood density; that is, highest densities at the stump, decreasing to a low in the lower third of the bole, and then increasing again in the upper bole. A base core of water-infused wood occurred in many western hemlock trees and resulted in green heartwood nearly as dense as green sapwood at the stump. Except for this anomaly, green heartwood in both western hemlock and Douglas-fir formed profiles of lower green density values than did sapwood at any point along the bole. Predictive functions developed for green density of heartwood registered considerably higher coefficients of determination than did those developed for the corresponding sapwood.

5. The removal of moisture from the sapwood and heartwood attentuated the fluctuating changes in the green density profiles of these two radial sections. Dry density profiles of sapwood and heartwood were nearly identical to one another for a given species and each resembled closely the profile of dry wood density of that species. Predictive functions developed for sapwood and heartwood of western hemlock were approximately of the same magnitude. Those developed for Douglas-fir showed the sapwood profile to be consistently lower than that of heartwood. This was attributed to the overmature and senescent condition of the Douglas-fir in the sample.

6. Wood moisture profiles for western hemlock and Douglas-fir had patterns that closely resembled their respective density profiles of green wood. Fluctuations in the profiles of green wood density were due mainly to fluctuations in the spatial distribution of water in the tree bole. The impact of moisture on the density profile of green wood was more evident in heartwood than in sapwood. Moisture concentrations were highest at the base of the tree, decreased to a low in the middle third of the stem length, and then increased again in the upper stem. Western hemlock as a species is considerably wetter than Douglas-fir at all heights in both the sapwood and heartwood.

7. Heartrot in the study trees resulted in green density profiles that were similar to but heavier than those recorded in trees without heartrot. The impact of decay was more noticeable in western hemlock than in Douglas-fir. Results suggested decay may affect the sapwood-heartwood boundary and allow radial moisture movement from the sapwood zone into the heartwood. Respiratory moisture accumulation from the decaying agent was also suggested.

8. The fluctuation of green density with tree height was significant enough to cause additional error or bias when weights of logs from various portions of the tree were estimated. We found that the use of a functional estimate of green density to determine log weights was superior to using a single green density value.

Metric Equivalents

When you know:	Multiply by:	To find:
Inches	2.540	Centimeters
Feet	0.305	Meters
Cubic feet	0.028	Cubic meters
Pounds	0.454	Kilograms
Pounds per cubic foot	16.019	Kilograms per cubic meter

Literature Cited

Adamovich, L.L. Engineering characteristics of Canadian trees—centre of gravity and green weight of components of four species in interior British Columbia. Inf. Rep. FMR-X-74. Ottawa, ON: Canadian Forestry Service, Forest Management Institute; **1975.** 78 p.

Adamovich, L.L. Engineering characteristics of Canadian trees: Douglas-fir and western hemlock in interior British Columbia. Tech. Note No. TN-27. Vancouver, BC: Forest Engineering Research, Institute of Canada; **1979.** 51 p.

Bones, James T.; Gerhard, Ralie K.; Wharton, Eric H., [and others]. Tree biomass—a state-of-the-art compilation. Gen. Tech. Rep. WO-33. Washington, DC: U.S. Department of Agriculture; **1981.** 34 p.

Brown, H.P.; Panshin, A.J.; Forsaith, C.C. Textbook of wood technology. New York: McGraw-Hill Book Company; **1952.** Vol. 2.

Cao, Qunag V.; Burkhardt, Harold E.; Max, Timothy A. Evaluation of two methods for cubic-volume prediction of loblolly pine to any merchantable limit. Forest Science. 26(1): 71-80; **1980.**

Clark, J; Gibb, R. Darnely. Studies in tree physiology: IV. Further investigations of seasonal changes in moisture content of certain Canadian forest trees. Canadian Journal of Botany. 35: 219-253; **1957.**

Conway, Steve. Logging practices: principals of timber harvesting systems. [San Francisco]: Miller Freeman Publications, Inc.; **1976.** 416 p.

Demaerschalk, J.P.; Kazak, A. The whole-bole system: a conditioned dual-equation system for precise prediction of tree profiles. Canadian Journal of Forest Research. 7: 448-497; **1977.**

Dykstra, D.P. Production rate and costs for cable, balloon, and helicopter yarding systems in old-growth Douglas-fir. Res. Bull. 18. Corvallis, OR: Oregon State University, Forestry Research Laboratory; **1975.** 57 p.

Kellogg, Robert M. Physical properties of wood. In: Wangaard, F.F., ed. Wood: its structure and properties. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, **1979:** 195-223. In cooperation with: University Wisconsin-Extension.

Lenhart, David J.; Cutter, Bruce E.; Shinn, Kun Ho. Specific gravity at various positions along the stem of planted loblolly pine trees. Forest Products Journal. 27(9): 43-44; **1977.**

Long, James N.; Smith, Fredrick W.; Scott, David R.M. The role of Douglas-fir stem sapwood and heartwood in the mechanical and physiological support of crowns and development of stem form. Canadian Journal of Forest Research. 11: 459-464; **1981.**

Mann, Charles N; Lysons, Hilton H. A method of estimating log weights. Res. Pap. PNW-138. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; **1972.** 75 p.

Markstrom, Donald C.; Hann, Robert A. Seasonal variation in wood permeability and stem moisture content of three Rocky Mountain softwoods. Res. Note RM-212. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station; **1972.** 7 p.

Okkonen, E.A.; Wahlgren, H.E.; Maeglin, R.R. Relationships of specific gravity to tree height in commercially important species. Forest Products Journal. 22(7): 37-42; **1972.**

Panshin, A.J.; DeZeeuw, Carl. Textbook of wood technology. 3d ed. New York: McGraw-Hill Book Company; **1970.**

Parker, Johnson. Available water in stem of some Rocky Mountain conifers. Botanical Gazette. 115: 380-385; **1954.**

Shigo, Alex L.; Shortle, Walter C.; Ochrymowych, Julian. Detection of active decay at groundline in utility poles. Gen. Tech. Rep. NE-35. Broomall, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station; **1977.** 26 p.

Snell, J.A. Kendall; Max Timothy A. Estimating the weight of crown segements for old-growth Douglas-fir and western hemlock. PNW Res. Pap. PNW-329. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; **1985.** 22 p.

Stewart, Charles M. Moisture content of living trees. Nature. 214: 138-140; **1967.**

Tritton, Louise M.; Hornbeck, James W. Biomass equations for major tree species of the Northeast. Gen. Tech. Rep. NE-69. Broomall, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station; **1982.** 46 p.

Waddell, Dale R.; Lambert, Michael B; Pong, W.Y. Estimating tree bole and log weights using green densities measured with the Bergstrom xylodensimeter. Res. Pap. PNW-322. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; **1984.** 18 p.

Ward, J.C.; Pong, W.Y. Wetwood in trees: a timber resource problem. Gen. Tech. Rep. PNW-112. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; **1980.** 56 p.

Wensel L.C. Estimators for use in weight scaling of sawlogs. Stat. Bull. 866. Berkeley, CA: University of California, California Agriculture Experiment Station; **1974.** 23 p.

Wilcox, Wayne W.; Pong, W.Y. The effects of height, radial position, and wetwood on white fir wood properties. Wood and Fiber. 3 (1):47-55; **1971.**

Pong, W.Y.; Waddell, Dale R.; Lambert, Michael B. Wood density-moisture profiles in old-growth Douglas-fir and western hemlock. Res. Pap. PNW-347. Portland, OR: US Department of Agriculture, Forest Service, Pacific Northwest Research Station; **1986**. 30 p.

Accurate estimation of the weight of each load of logs is necessary for safe and efficient aerial logging operations. The prediction of green density (lb/ft^3) as a function of height is a critical element in the accurate estimation of tree bole and log weights. Two sampling methods, disk and increment core (Bergstrom xylodensimeter), were used to measure the density-moisture complex in wood. The relationship between wood density and height was best described by either quadratic or cubic polynomial functions. Prediction functions for green and dry wood density are presented for old-growth western hemlock and Douglas-fir. Sapwood and heartwood functions were analyzed separately as were trees with and without heartrot.

Keywords: Wood density, moisture content (wood), old-growth stands, Douglas-fir, western hemlock.

Pacific Northwest Research Station
319 S.W. Pine St.
P.O. Box 3890
Portland, Oregon 97208

U.S. Department of Agriculture
Pacific Northwest Research Station
319 S.W. Pine Street
P.O. Box 3890
Portland, Oregon 97208