AN ABSTRACT OF THE THESIS OF

Faqir Mohammad Khan for the M.S. in Forest Management
(Name) (Degree) (Major)

Date thesis is presented March 8, 1966

Title DEVELOPING AN EQUATION FOR MAKING ESTIMATES OF DIAMETER INSIDE BARK AT VARIOUS HEIGHTS UP THE STEM IN DOUGLAS-FIR

Abstract approved Signature redacted for privacy.
(Major professor)

The purpose of this thesis was to develop a suitable multiple regression equation for making estimates of diameter inside bark at various heights up the bole in Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) tree. Data on 237 and 302 trees from Black Rock Forest Management Research Area, Polk County, Oregon, and scattered plots in the State of Washington respectively were analysed in a stepwise regression procedure. The results of regression analyses showed that:

a) Direct estimation of diameter inside bark at various upper stem points yield better results than expressing it as a ratio of diameter outside bark as practised previously.

b) Diameter inside bark at various heights up the stem has a high positive correlation with its respective diameter outside bark, and a negative correlation with height itself.

c) Bark ratio at breast height has been found to have a positive correlation with such ratio at upper stem points; both are negatively related to tree age.

Regression equations are presented for estimating diameter inside bark at various upper stem points. These equations are recommended for practical use under stand conditions comparable to those from where the original data were obtained.

DEVELOPING AN EQUATION FOR MAKING ESTIMATES OF DIAMETER INSIDE BARK AT VARIOUS HEIGHTS UP THE STEM IN DOUGLAS-FIR

by

FAQIR MOHAMMAD KHAN

A THESIS

submitted to

OREGON STATE UNIVERSITY

in partial fulfillment of
the requirements for the
degree of

MASTER OF SCIENCE

June 1966

APPROVED:

Signature redacted for privacy.

Professor of Forest Management
In Charge of Major

Signature redacted for privacy.

Head of Department of Forest Management

Signature redacted for privacy.

Dean of Graduate School

Date thesis is presented March 8, 1966

Typed by Trudie Vallier

ACKNOWLEDGEMENTS

The author wishes to express his gratitude to the Forest Research Laboratory, Oregon State University and to the Department of Natural Resources of the State of Washington for permission to use the data; to the School of Forestry at Oregon State University for financial assistance in the use of computer; and to the Government of West Pakistan and U.S. A.I.D. Mission in Pakistan for arranging the present program.

The constant encouragements by Mr. Amir Ahmad Khan, S.K., Secretary, Department of Agriculture, Government of West Pakistan have been a source of great inspiration for the author for which he is extremely grateful to the former.

He also likes to express his sincere appreciation for the kindness and generous cooperation extended to him throughout his stay in the United States by his major professor, Dr. J.R. Dilworth.

It has been a pleasure for the author to work with Professor John F. Bell. He is specially grateful to the latter for his continued assistance and guidance without which this little piece of work would never have been possible. The pains taken by Professor Bell in making this study a success will always remain enshrined in the heart of the author.

The author also likes to express his thankful appreciation to Dr. Roger G. Petersen for his generous guidance in the statistical analyses; and to Professor Alan B. Berg, and Dr. David P. Paine for their going through the manuscript, and making valuable suggestions. He is also indebted to Mr. Glenn C. Wolfe of the Statistics Computing Laboratory for taking personal interest in running all these analyses.

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

LIST OF TABLES

LIST OF FIGURES

DEVELOPING AN EQUATION FOR MAKING ESTIMATES OF DIAMETER INSIDE BARK AT VARIOUS HEIGHTS UP THE STEM IN DOUGLAS-FIR

INTRODUCTION

Need for Predicting Upper Stem Diameter Inside Bark

As a new concept in the theory of probability sampling in forest populations, Grosenbaugh (16) introduced what is known as sampling with probability proportional to prediction --3P (three-pee sample-tree-measurements). At the time of marking for harvest (or whenever it is desired to determine total growing stock), each tree in the population is arbitrarily assigned a relative probability. Each probability is then paired with some random number subsequently drawn from (and replaced in) an appropriately constructed population of integers. Trees having probability equal to or larger than the associated random number are measured as samples. The basic theory and derived formulae have been explained by Grosenbaugh while writing computer program 'THRP' to provide the artificial population of numbers appropriate to a given 3P sample design (18). With this technique now available, accurate volume estimate can be made without the use of volume tables.

The 3P sample-tree-measurements, as a means of getting away from volume tables, involve the use of optical dendrometers for obtaining outside bark dimensions at various heights along the bole. In dealing with this aspect of the new technique of 3P sampling, Grosenbaugh (16) emphasizes the need of a very high performance instruments (dendrometers) for determining upper stem diameters. Some of these optical dendrometers for out-of-reach diameters along with the underlying theory have been explained in Forest Science Monograph 4 (15).

For the purpose of volume computation in 3P sampling, all the outside bark dendrometer measurements must be converted into inside bark diameters. This has been made possible with the help of 'STX-fortran 4 program for estimates of tree populations from 3P sample-tree-measurements' written by Grosenbaugh (17). The program has been made flexible by providing the users with three options based on three assumptions of relating outside bark dendrometer measurements to inside bark diameters. The assumptions are that:

1. The ratio of diameter inside bark to diameter outside bark remains constant all along the bole.

2. The ratio of diameter inside bark to diameter outside bark increases up the bole. This assumption is supposedly based on the fact that losses in bark thickness at all levels within reach occur by fire, or through animals rubbing against the bark, or through the mechanical damage resulting from diameter tape or caliper in

measuring the tree several times.

3. The ratio of diameter inside bark to diameter outside bark diminishes from the bottom to top of the bole.

The parameters of the functions expressing mathematically the last two assumptions might be changed depending upon the tree species, experience of the cruiser, and local factors.

As can be easily seen, the program is very flexible for accommodating a wide variety of conditions. However, a certain amount of bias is accepted by employing any of the options and methods of obtaining the ratio of diameter inside bark to diameter outside bark. Also, there is no measure whereby statistical accuracy can be assessed in utilizing any of these functions developed by Grosenbaugh.

Purpose and Scope

The purpose of this thesis was to find out how best the diameter inside bark at various heights along the bole could be estimated in a Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) tree. Such a finding could be utilized for practical application in 3P sample-tree-measurements or any other operation where it is desired to convert upper stem dimensions into inside bark diameters.

Grosenbaugh does not specifically advocate the use of expressing diameter inside bark as a ratio of diameter outside bark at upper stem points.[1] In fact, he used ratios only because he had some experience seeing that the assumption of a constant ratio up the bole was going to be a satisfactory solution for some population of trees. However, this might not always be the case. Also, it might seem more logical to predict diameter inside bark up the stem directly rather than to express it as ratio of diameter outside bark. Accordingly, a provision was made in this thesis to test the suitability of bark ratio (diameter inside bark/diameter outside bark) or diameter inside bark at various upper stem points as dependent variable. In either case, a number of independent variables that could be measured easily on the tree were examined. The best dependent and independent variables were picked using standard error of estimate and coefficient of determination.

Data were placed at the disposal of the author by the Forest Management Department of the Forest Research Laboratory at Oregon State University, and the Forest Land Management Division of the Department of Natural Resources, State of Washington. The study was started with data

---

[1] Interview with Dr. L.R. Grosenbaugh on the 18th of November, 1965.

from young evenaged stand of Douglas-fir from Black Rock Forest Management Research Area in Polk County, Oregon with a view to establishing preliminary regression equations. Later, analyses were carried out on data from the State of Washington. The objectives were to examine the behavior of the same variables on different data, and to develop final equations for making estimates of diameter inside bark at various heights up the stem. Another objective was to see if tree age, which was available on data from the State of Washington, had any significant effect on the dependent variables. The results indicated that it was advisable to develop two equations - one each for the geographic locations from which the data were obtained.

It can be hopefully foreseen that time will make it possible to actually sample bark thickness at various heights up the bole. However, till then, it is expected that these equations will hold good for all comparable stand conditions.

The program written by Grosenbaugh (17) will require some modifications in case it is desired to use these equations in connection with 3P sample-tree-measurements.

REVIEW OF LITERATURE

Bark Thickness at Breast Height

Meyer (39) presented plottings of double bark thickness at breast height over d.b.h based on data from 3,327 ponderosa pine (*Pinus ponderosa* Laws.) trees. The result was an almost straight line relationship between these two variables. Double bark thickness was also expressed as percentage of d.b.h (both outside bark and inside bark). Plottings of these percentages over d.b.h.o.b showed upward trend starting with four inches d.b.h.o.b and reaching the peak at six inches. The curves then became parallel to the horizontal axis and remained so up to the ten-inch d.b.h.o.b class. Thereafter, a gradual fall was registered in both the curves. This would mean that double bark thickness at breast height expressed as percentage of d.b.h is linearly related to the latter but the slope is negative.

Appendix B of the Forest Service publication entitled "Calculating the Growth of Ponderosa Pine Forests" by Philip A. Briegleb (4) contains two formulae by Keen and Grant based on 1,437 bark measurements. Both formulae predict double bark thickness at breast height for ponderosa pine. These are: (1) Bark thickness = 0.0787 (d.b.h.o.b) - 0.1615(age class) - 0.1235(vigor class)[2] + 1.981, and (2) Bark thickness = 0.08542(d.b.h.i.b) - 0.1615(age class) - 0.1235(vigor class) + 2.0869.

Based on more than 2,000 loblolly pine (*Pinus taeda* L.) stem measurements, Minor (41) developed a linear regression for the variables single bark thickness at breast height on d.b.h.o.b, and stand age. Addition of stand age increased the correlation coefficient from 0.73 to 0.74, and reduced standard error of estimate from $\pm$ 0.17 to $\pm$ 0.16. Such slight improvements led him to the conclusion that for practical purposes bark thickness may be estimated from tree d.b.h only.

Analysing data from 542 trees, ten inches in diameter and larger, Johnson (31) showed a linear relationship between d.b.h.o.b and double bark thickness at breast height in Douglas-fir. He also analysed data from 75 trees (ten inches in diameter and smaller), and established a regression equation linearly relating double bark thickness to diameter at breast height outside bark. The standard errors of the regression coefficients were $\pm$ 0.005 for trees having diameter at breast height ten inches and larger, and $\pm$ 0.003 for smaller trees. A similar relationship between these two variables was

[2]Vigor classes are expressed by the numerical values 1, 2, 3, and 4 for Keen's (35) ponderosa pine vigor classes A, B, C, and D respectively.

demonstrated by him (32) in ponderosa pine. The data analysed came from 123 trees with diameter less than 9.5 inches, and 1,951 trees 8.5 inches in diameter and larger. Later, Spada (50), through an analysis of a large number of trees, verified these results and published simple linear regression equations relating d.b.h.o.b and twice bark thickness at breast height in several species of the ponderosa pine sub-region of Oregon and Washington. Similarly, Burton (7), and Myers (44) established linear relationship between d.b.h.o.b and double bark thickness at breast height. The former worked with loblolly pine while the latter analysed data from lodgepole pine (*Pinus contorta* Dougl.) trees. The regression equations accounted for more than 95 percent of the total variation in bark thickness in both species.

Panic (46) found that single bark thickness at breast height in birch (*Betula verrucosa* Ehrh.) was linearly related to d.b.h.o.b but it exhibited a curvilinear relationship with total height.

Smelko (47) examined the relationship of double bark thickness with d.b.h.o.b, age, and site class in half a dozen coniferous and hardwood species. The data consisted of 14,630 measurements in 161 stands. He concluded that bark thickness depended mainly on species and d.b.h.o.b, and less on age and site class.

Bark Thickness at Other than Breast Height

Krastanov, Beljakov, and Andonov (36) carried out stem analysis of 120 spruce (*Picea* spp:) trees and found that bark thickness along the stem was a function of diameter outside bark at breast height.

Maezawa (37) analysed data from 40 young trees of Douglas-fir and established linear relationship between diameter outside bark and double bark thickness at several heights along the bole. All of the regression lines were significant at the one percent level. The correlation coefficients, the standard errors of estimate, and the standard errors of slope are reproduced as follows:

Height in Tree	Correlation Coefficient	Standard Error of	
		Estimate	Slope
(feet)		(inches)	
4.5	0.86	0.36	0.011
9.5	0.83	0.32	0.012
17.5	0.89	0.19	0.007
34.0	0.92	0.12	0.005

Apart from the fact that the data used in this study were very meager, the four regression equations developed were for heights only at 4.5, 9.5, 17.5 and 34.0 feet along the bole. The study has, therefore, very limited practical use. However, it does exhibit two potentially important relationships between various tree dimensions and, therefore, opens door for examining these in a greater detail. These relationships are that:

1. Twice bark thickness is very highly correlated with diameter outside bark at any point on the stem of a tree.

2. Height up the stem has a definite influence on the relationship between double bark thickness and diameter outside bark at such upper stem points.

Diameter Inside Bark at Various Stem Points

While describing a method of using increment cores for establishing a relationship between diameter increment, outside bark, and diameter at breast height, outside bark, Meyer (38) considered the relationship between d.b.h.i.b and d.b.h.o.b to be linear and the equation to be of the form, d.b.h.o.b = b(d.b.h.i.b).

Minor (41) analysed data from 2,000 loblolly pine stem measurements and developed a linear regression for d.b.h.i.b based on d.b.h.o.b, and stand age. Addition of stand age caused little gain in accounting for additional unexplained variance or in reducing the extent of standard error of estimate.

McCormack (40) plotted average values for diameter outside bark over those for diameter inside bark in two-inch diameter classes. The plottings disclosed a linear relationship between these two variables. The data came from a large number of trees comprising 55 different coniferous and hardwood species in the southwestern United States.

Myers (42), analysing data from 676 black-jack and 595 old-growth ponderosa pine trees, established linear relationship between breast high diameter inside bark and diameter outside bark, and vice versa. The correlation coefficient of all four equations was 0.9998, and the standard errors of estimate were $\pm$ 0.0165, $\pm$ 0.0186, $\pm$ 0.0143, and $\pm$ 0.0158 inches respectively.

Myers (44), after an analysis of data from 810 lodgepole pine trees in Colorado and Wyoming, demonstrated that diameter inside bark and diameter outside bark at breast height are related linearly to each other. The correlation coefficient was 0.999. The standard error of estimate was $\pm$ 0.077 inches for the equation predicting diameter inside bark for a given diameter outside bark at breast height. Similarly, for the other equation which would estimate diameter outside bark for a given breast high diameter inside bark, the standard error of estimate was $\pm$ 0.159 inches.

Myers (44) also showed a linear relationship between diameter inside bark at the top of stump 1.0 foot high and diameter outside bark at breast height. Two regression equations predicting diameter outside bark at breast height were developed, one for trees having stump diameter inside bark 3.0 to 13.9 inches, and the other for those with stump diameter inside bark 14.0 to 30.9 inches. The former explained 99.8 percent of the total variation in breast high diameter outside bark while the latter accounted for 98.8 percent of the variation in the dependent variable. The standard errors of estimate were $\pm$ 0.135, and $\pm$ 0.408 inches respectively. Similar linear relationship between diameter stump height (inside bark or outside bark) and d.b.h.o.b was also shown previously by a number of workers in a variety of species (1, 2, 9, 10, 19, 20, 21, 22, 23, 24, 25, 26, 43).

Bones (3) utilized data from 583 trees and established linear relationship between outside- and inside-bark diameter at the top of first 16-foot log for four southeastern Alaska coniferous timber species.

Bark Ratio at Various Stem Points

Form class does not utilize the ratio of diameter inside bark to diameter outside bark at the same point on a stem. However, it will not be out of place to mention that measurements at upper stem points have been related to those at lower stem points by various authors in connection with their studies on Girard form class. It has been shown that Girard form class can be estimated by the lower stem measurement method both in coniferous and hardwood species (5, 6, 12, 13, 27, 29, 48, 49).

All these studies involved measurements taken inside bark between six and seven feet (except Burns and Adams (6) who used d.o.b at 7.5 feet) and those taken outside bark at two to three feet above ground. Judson (34) selected the expression $\frac{d}{D+B}$ as providing close initial approximation of the form class ratio:

d = diameter outside bark at 17.3 feet

D = diameter outside bark at 4.5 feet

B = double bark thickness at 4.5 feet

Regression equations were developed between the expression $100\frac{d}{D+B}$ and Girard form class for pines and hardwoods from the State of Louisiana. Both equations were significant at the one percent level of confidence.

Johnson (33) analysed data from 540 young-growth Douglas-fir trees to study the effect of a number of independent variables on bark factor[3] along the bole. The trees ranged from 13 to 143 years in age and from 2 to 40 inches in outside bark diameter at breast height. The basic independent variables used were:

L = distance up the stem from ground

A = tree age

---

[3]Bark factor has been defined by Chapman and Meyer (8) as the percentage by which d.i.b is increased to equal d.b.h. Ibberson (30) defines bark factor as the ratio of diameter outside bark to diameter inside bark. Hoffman (28) expresses bark factor ratio as d.b.h o.b/u.b. Johnson calls d.i.b/d.o.b (which has been named as bark ratio elsewhere in this thesis) to be the bark factor.

D = diameter at breast height outside bark

H = total tree height from ground to tip

d_o = diameter outside bark at a point on the upper stem where the upper stem bark factor was taken

B_{LS} = bark factor at stump

Bark factor at stump was used as independent variable because of non-availability of bark factor at 4.5 feet from ground. This was done under the assumption that bark factor at stump height should approximately be the same as bark factor at 4.5 feet from ground.

The regression analysis led to the following equations:

1. Tree age and total height available

$$B_{US} = [6931 - 2.5A + 10.6D - 311(L/H)^2 + 1343(L/H)(d_o/D) + 2326B_{LS}]10^{-4}$$

2. Total height not available

$$B_{US} = [6194 - 2.6A + 3.2L + 2378(d_o/D) - 1545(d_o/D)^2 + 2533B_{LS}]10^{-4}$$

3. Both total height and tree age not available

$$B_{US} = [5590 + 0.6L + 2030(d_o/D) - 1542(d_o/D)^2 + 3413B_{LS}]10^{-4}$$

in which B_{US} is the upper stem bark factor, and L, A, D, H, d_o, and B_{LS} have been already defined.

Percentages of the total variation in bark factor accounted for were 40 by equation 1, 37 by equation 2, and 27 by equation 3. Standard error of estimate has not been given for any of these equations.

One inference that can be drawn from this regression analysis according to Johnson is that upper stem bark factor is not the same as lower stem bark factor on young-growth Douglas-fir trees. This nullifies one of the assumptions by Grosenbaugh (17) that ratio of diameter inside bark to diameter outside bark remains constant up the stem, at least in young Douglas-fir.

SOURCES OF THE DATA

Black Rock Forest Management Research Area

This area is located on the George T. Gerlinger Experimental forest in Polk County about 25 miles northwest of Corvallis, Oregon. About 500 acres in size, the area supports a natural stand of 50-year-old Douglas-fir. Sites range from II to IV with most of the area in Site III. Topography varies from gentle to very steep, and elevation from 700 to 2,000 feet. Soils of the area have been developed from sand-stones, shales and silt stones, and igneous rocks. Therefore, the soils vary greatly over the area in physical and chemical properties. On the whole, the soils are deep, well drained, light textured, and rich in nutrients to support Douglas-fir. The average monthly rainfall cycle starts from below three inches in August; rises abruptly to about 13 inches in November, and remains almost constant through February; thereafter falls gradually till it is at minimum of about two inches in July. The stand consists of almost pure Douglas-fir with scattered white fir (*Abies grandis* Lind.) western hemlock (*Tsuga heterophyla* Raf. Sarg.), alder (*Alnus rubera* Bong.), and big leaf maple (*Acer macrophyllum* Pursh.).

The area was established in 1953 by the Forest Management Department of the Forest Research Laboratory at

Oregon State University. Cutting began in the same year, partly for the purpose of construction of local volume tables, but mainly to study growth and development of individual trees and silvicultural and economic implications of intermediate cuttings in young-growth Douglas-fir stands in the Coast Range (45). Data for the present study came from such cuttings carried out from 1953 through 1957 over about 250 acres situated in the middle of the area.

There were 237 trees ranging from 4.1 to 20.7 inches in diameter at breast height. In all, there were 1,894 observations. The following information on each tree was utilized in the present study:

1. Diameter at breast height both inside bark and outside bark measured to the tenth of an inch.

2. Total height of the tree from ground to tip measured to the tenth of a foot.

3. Section lengths measured to the tenth of a foot.

4. Diameter inside bark and outside bark at the top of sections measured to the tenth of an inch.

State of Washington

Data were made available by the Forest Land Management Division of the Department of Natural Resources, State of Washington. These were collected on young-growth Douglas-fir trees on 23 plots located in western

Washington for the construction of Tarif Tables (51). Out of a total of 343 trees, only 302 could be utilized in the present study. These ranged from 2.6 to 30.0 inches in diameter at breast height, and 13 to 99 years in age. In all, there were 1,923 observations. Information utilized was:

1. Age of tree at stump height, i.e., 1.5 feet from ground.

2. Diameter at breast height, i.e., 4.5 feet from ground both inside bark and outside bark measured to the tenth of an inch.

3. Total height of tree from ground to tip measured to the tenth of a foot.

4. Section lengths measured to the hundredth of a foot.

5. Diameter inside bark and outside bark at the top of sections measured to the tenth of an inch.

Except for diameter outside bark at the top of the sections, all other information was punched on IBM data cards. The diameter outside bark was subsequently punched on a second set of IBM data cards.

METHODS

Procedure

The principal steps were:

a) Data from Black Rock Forest Management Research Area

1. Randomization of the data: Four points up the bole (constituting four different sets of data) were selected at random on each of the 237 trees. Bark ratio and/or diameter inside bark at these points were used as dependent variables in the preliminary analyses (steps 2, 3, and 4 below). For the final analysis in step 4, the entire data were utilized.

2. Selection of independent variables using bark ratio as dependent variable on one set of randomly selected data referred to above.

3. Examination of the best independent variables from step 2 above on the same set of data using diameter inside bark as dependent variable.

4. Comparison between bark ratio and diameter inside bark as dependent variables; analyses of the remaining three sets of data and final analysis; and selection of the equation.

b) Data from the State of Washington

1. Testing of the equation from step a (4).

2. Examination of the best independent variables from step a (2) plus tree age using bark ratio as

dependent variable.

3. Examination of the best independent variables from step a (2) plus tree age using diameter inside bark as dependent variable.

4. Comparison between bark ratio and diameter inside bark as dependent variables, and selection of the equation.

The five basic independent variables were:

1. Diameter at breast height (4.5 feet from ground) outside bark

2. Bark ratio at breast height

3. Total tree height

4. Length up the stem from ground

5. Diameter outside bark at the point of measurement of bark ratio or diameter inside bark

All squares and cross-products were also tested to see if there were interactions between various independent variables and/or curvilinearity between dependent and independent variables.

Since information on tree age was available for data from the State of Washington, this variable was added to the best independent variables from step a (2) and the effect was examined on both the dependent variables.

Statistical Design

The statistical design employed throughout these analyses was a stepwise multiple regression program described by Efroymson (11). An IBM 1410 high speed electronic data processing computer at Oregon State University was utilized for these analyses. Some simple linear regression problems were solved using IBM 1620, and in one case, plottings were carried out employing its plotter attachment on the campus.

IBM 1410 has the capacity of listing actual versus predicted values of dependent variable based on final regression equation. This function of the computer is exceedingly useful. At least in the present study, a lot of discrepancies which would otherwise be more difficult to detect were constructively reconciled.

The basic regression model as given by Graybill (14) is:

$$y = \beta_0 + \beta_1 x_1 + \cdots + \beta_k x_k + \epsilon$$

where:

y = value of random dependent variable

$x_1 \ldots x_k$ = particular values of random independent variables

$\beta_0 \ldots \beta_k$ = unknown parameters linearly relating independent variables to dependent variable

ϵ = unobservable random error, NID(0, σ^2)

The sample equation can be written as:

$$y = b_0 + b_1 x_1 + b_2 x_2 + \cdots + b_n x_n + e$$

where: y = value of dependent variables, i.e., diameter inside bark or bark ratio at various heights up the bole

$x_1, x_2 \ldots$ = values of independent variables

$b_0, b_1 \ldots$ = sample estimators of $\beta_0, \beta_1, \ldots$ i.e., coefficients of regression

e = random error, $NID(0,\sigma^2)$

The "F" level given both to enter and remove variables was at ten percent significance (90 percent confidence). The results of computer output were tested for acceptance using coefficient of determination. Standard errors of estimate were also examined to determine the reliability of regression equations.

In comparing bark ratio with diameter inside bark for the best dependent variable, deviations of the predicted diameters inside bark from the actual diameters inside bark were computed. In case of bark ratios, the predicted diameter inside bark was calculated by the relationship:

$$D.i.b_r = D.o.b_r(D.i.b_r/D.o.b_r)$$

where:

$D.i.b_r/D.o.b_r$ = diameter inside bark/diameter outside bark or bark ratio at upper stem points

Comparison between the two predicted values of diameter inside bark was then made using the standard deviation of their deviations from the actual values of diameter inside bark along the bole.

RESULTS

Data From Black Rock Forest Management Research Area

Bark Ratio as Dependent Variable

The analysis was made on the first set of randomly selected data comprising 237 observations from Black Rock Forest Management Research Area. Bark ratio up the bole was used as dependent variable. The basic independent variables were:

X_1 = diameter at breast height

X_2 = bark ratio at breast height

X_3 = total tree height

X_4 = length up the stem from ground

X_5 = diameter outside bark at the point of interest on the stem

All squares and cross-products of the basic independent variables were also included in the same order. Because of a high correlation between some independent variables, square of bark ratio at breast height, i.e., X_2^2 was not accepted by the computer, and was, therefore, left out. Hence, a total of 19 independent variables were examined.

The analysis showed that two of the basic variables, i.e., X_3 and X_5 did not enter the regression. The former appeared in combination with X_1 in step 3 but was later dropped out in step 8. Variable X_2 showed highest correlation with the dependent variable. The individual correlations[4] are tabulated as follows:

Independent Variable	Percent Correlation with Dependent Variable
X_1 = d.b.h.o.b	1.80
X_2 = breast high bark ratio	33.62
X_3 = total tree height	6.14
X_4 = length up the stem	18.13
X_5 = upper stem d.o.b	- 2.85
${X_4}^2$	7.07
X_1X_2	3.74
X_2X_4	18.96
X_4X_5	30.11

Johnson (33) had used d_o/D, and L/H in his analysis of bark factor (bark ratio), where:

d_o = diameter outside bark at a point on the upper stem where the upper stem bark factor was taken

D = diameter at breast height outside bark

L = distance up the stem from ground

H = total tree height from ground to tip

[4]The correlations are shown for the basic variables, and those of the rest which appeared in the final regression equation.

In order to determine whether or not these variables had any significant effect in the present case, they were added to those appearing in the final step of the previous analysis (of course all the basic variables were retained), and the same set of data was re-run in a stepwise regression program. The results showed that neither of these two variables entered the analysis. The same variables appeared in the final regression equation here also, but with a slight modification of their coefficients. The standard error of estimate and r-squared values were also identical in both the cases.

Diameter Inside Bark as Dependent Variable

All the basic variables plus those appearing in the final step of the previous analysis were examined through stepwise regression analysis on the first set of data from Black Rock Forest Management Research Area using diameter inside bark at various places along the bole as dependent variable. The independent variables used in this analysis have been employed in all subsequent analyses, and have been commonly referred to as "nine best independent variables." These are:

X_1 = diameter at breast height

X_2 = bark ratio at breast height

X_3 = total tree height

X_4 = length up the stem from ground

X_5 = diameter outside bark at the point of interest on the stem

$X_6 = X_4^2$

$X_7 = X_1X_2$

$X_8 = X_2X_4$

$X_9 = X_4X_5$

The results indicated that three of the basic variables, i.e., X_1, X_3, and X_4 did not enter the regression. Variable X_4 appeared as its square, X_4^2; and in combination with X_5, i.e., X_4X_5. Among the rest, X_1X_2 and X_2X_4 did not enter the analysis.

The individual correlations of the independent variables with diameter inside bark at upper stem points as dependent variable are tabulated as follows:

Independent Variable	Percent Correlation with Dependent Variable
X_1 = d.b.h.o.b	70.00
X_2 = breast high bark ratio	- 9.52
X_3 = total tree height	58.68
X_4 = length up the stem	-36.66
X_5 = upper stem d.o.b	99.89
$X_6 = X_4^2$	-36.59

Independent Variable	Percent Correlation with Dependent Variable
$X_7 = X_1X_2$	70.45
$X_8 = X_2X_4$	-37.10
$X_9 = X_4X_5$	40.47

Variables X_1, X_3, and X_1X_2 which have high correlation with the dependent variable did not enter the regression analysis. Perhaps this could be a masking effect of X_5 which is also highly correlated with these variables. Probably for a similar reason, X_2 appeared in the regression analysis inspite of its negative correlation with the dependent variable.

Comparison and Final Analysis

Diameter inside bark at various points along the bole was computed with both the final equations described in the earlier paragraphs. In case of bark ratio, the diameter inside bark was obtained using the relationship:

$$D.i.b_r = D.o.b_r(D.i.b_r/D.O.b_r)$$

where:

$D.i.b_r/D.O.b_r$ = diameter inside bark/diameter outside bark or bark ratio at upper stem points

Then, the deviations of both the predicted values from the actual values of diameter inside bark were obtained.

Finally, the standard deviation of these deviations was computed. The results are summerized as follows:

Dependent Variable	Standard Deviation of the Differences
Bark ratio	0.084
Diameter inside bark	0.102

The standard deviation in case of bark ratio is seemingly small. However, it can be easily noticed that in converting into bark ratio and in recalculating diameter inside bark from the relationship $D.i.b_r = D.o.b_r (D.i.b_r/D.o.b_r)$, a certain amount of error due to truncating is introduced. If means were available to estimate the degree of this error, it could probably be shown that diameter inside bark is as good a dependent variable as bark ratio. Also, the comparatively higher percentage of total variation accounted for in diameter inside bark than in bark ratio by the respective final equations justifies the fact that better results will be achieved if the former is used as dependent variable.

Having decided on diameter inside bark at various points up the stem to be a better dependent variable, the remaining three sets of data as well as the entire data from Black Rock Forest Management Research Area were run through the regression analysis program using the nine best independent variables. The correlations of individual independent variables with diameter inside bark are given in Table 1.

Table 1

Correlations of Independent Variables with Upper Stem Diameter Inside Bark

Independent Variables*	Percent Correlations with Dependent Variable using Various Sets of Data			
	Second	Third	Fourth	All Data
X_1	62.72	59.85	71.68	61.10
X_2	- 4.21	- 3.32	-18.02	-10.08
X_3	57.92	54.87	63.11	53.62
X_4	-51.08	-45.68	-43.65	-50.01
X_5	99.84	99.93	99.91	99.90
$X_6 = X_4^2$	-46.86	-43.45	-41.85	-48.50
$X_7 = X_1X_2$	63.39	60.56	71.30	61.10
$X_8 = X_2X_4$	-51.29	-46.22	-44.29	-50.34
$X_9 = X_4X_5$	30.04	35.56	37.63	33.96

*X_1 = d.b.h.o.b; X_2 = breast high bark ratio; X_3 = total tree height; X_4 = length up the stem; and X_5 = upper stem d.o.b.

An examination of Table 1 reveals a considerable consistency in the relationship between dependent and various independent variables in all the analyses.

The best equation was selected from the analysis of entire data from Black Rock Forest Management Research Area using standard error of estimate, and coefficient of determination. The equation is:

$$D.i.b_r = 2.01839X_2 + 0.909116X_5 - 0.383417^{10^{-4}} X_4^2 + 0.849269^{10^{-3}} X_4X_5 - 1.76845$$

where:

$D.i.b_r$ = diameter inside bark at the point of interest on the stem

X_2 = bark ratio at breast height

X_4 = length up the stem from ground

X_5 = diameter outside bark at the point of interest

This equation is highly significant; it accounts for 99.87 percent of the total variation in diameter inside bark, and has a standard error of $\pm$ 0.00264 inches (standard error of estimate = $\pm$ 0.115 inches or $\pm$ 1.703 percent).

Data From the State of Washington

Testing of the Equation

The best equation from the analysis of entire data from Black Rock Forest Management Research Area (as referred to in the foregoing paragraph) was tried on data from the State of Washington. Using "t" test, it was found that the difference between actual and predicted values of the upper stem diameter inside bark was significant. Accordingly, it was decided to develop a separate equation based on data from the State of Washington.

Bark Ratio as Dependent Variable

Data from the State of Washington were analysed in a stepwise regression procedure and the nine best independent variables were tried using bark ratio as the dependent variable. Since information on tree age was also available in these data, this was included as the tenth independent variable, i.e., as X_{10}. A total of ten independent variables were, therefore, examined for their effect on the dependent variable (bark ratio at various upper stem points).

The individual correlations of independent variables with the dependent variable are tabulated as follows:

Independent Variable	Percent Correlation with Dependent Variable
X_1 = d.b.h.o.b	10.05
X_2 = breast high bark ratio	42.05
X_3 = total tree height	18.49
X_4 = length up the stem	- 4.20
X_5 = upper stem d.o.b	22.44
$X_6 = X_4^2$	- 8.38

Independent Variable	Percent Correlation with Dependent Variable
$X_7 = X_1X_2$	12.81
$X_8 = X_2X_4$	- 2.69
$X_9 = X_4X_5$	28.83
X_{10}= tree age	-36.00

These correlations compare in some respects but differ widely in others from those obtained on the first set of data from Black Rock Forest Management Research Area. As is evident from the comparison that X_2 and X_4X_5 have exhibited a high correlation with the dependent variable in both cases. Variable X_4 shows positive correlation with bark ratio in the analysis of data from Black Rock Forest Management Research Area but has exhibited a negative correlation in that of data from the State of Washington. On the other hand X_3, exhibiting poor correlation with bark ratio in the analysis of data from Black Rock Forest Management Research Area, has registered higher correlation in the analysis of data from the State of Washington. Similarly X_5, which has a negative correlation with bark ratio in the analysis of data from Black Rock Forest Management Research Area, has developed a positive correlation - third in order of numerical superiority in the analysis of data from the State of Washington.

Tree age, i.e., X_{10} has exhibited a negative correlation with the dependent variable. This variable entered the analysis in the third step, and reduced considerably the unexplained variance and standard error of estimate.

Diameter Inside Bark as Dependent Variable

The nine best independent variables in combination with tree age as X_{10} were examined in a stepwise regression procedure using data from the State of Washington. The dependent variable used was diameter inside bark at upper stem points.

The correlations between individual independent variables and the dependent variable are tabulated as follows:

Independent Variable	Percent Correlation with Dependent Variable
X_1 = d.b.h.o.b	68.29
X_2 = breast high bark ratio	8.19
X_3 = total tree height	59.18
X_4 = length up the stem	-36.39
X_5 = upper stem d.o.b	99.90
$X_6 = X_4{}^2$	-34.34
$X_7 = X_1 X_2$	68.45
$X_8 = X_2 X_4$	-35.89

Independent Variable	Percent Correlation with Dependent Variable
$X_9 = X_4X_5$	37.67
X_{10}= tree age	18.03

As can be seen, these correlations compare fairly well with those of all the previous analyses using diameter inside bark at various upper stem points as dependent variable.

Although the entry of tree age as X_{10} in the fourth step of analysis was found to be highly significant, yet this variable did not materially reduce either unexplained variance or standard error of estimate.

Comparison and Selection of the Equation

The predicted values of upper stem diameter inside bark were computed for data from the State of Washington with both the final equations developed as per preceding paragraphs. Here again, bark ratio was converted to diameter inside bark with the use of the relationship:

$$D.i.b_r = D.o.b_r \ (D.i.b_r/D.o.b_r)$$

where:

$D.i.b_r/D.o.b_r$ = diameter inside bark/diameter outside bark or bark ratio at upper stem points

The deviations of both these predicted values from actual values of the diameters inside bark were then computed. And finally, the standard deviations of these differences between the actual and the predicted values of diameter inside bark were calculated. The results are:

Dependent Variable	Standard Deviation of the Differences
Bark ratio	0.148175
Diameter inside bark	0.155742

The standard deviation is slightly in favor of bark ratio. If, however, these results are compared with those obtained on data from Black Rock Forest Management Research Area, it can be seen that the difference between the two standard deviations is smaller here. This suggests that with still bigger sample, perhaps diameter inside bark could prove to be a better dependent variable even if the error due to truncating associated with bark ratio is ignored. Again, all the analyses have shown that a very high percentage of total variation is accounted for by the equation in using diameter inside bark rather than bark ratio as dependent variable. Accordingly, it is concluded that use of diameter inside bark as dependent variable will yield better results.

The best equation was selected using standard error of estimate, and coefficient of determination. It is given as follows:

$$D.i.b_r = 4.34159X_2 + 0.928333X_5 + 0.24567 \, 10^{-3} X_4X_5 - 3.97289$$

where:

$D.i.b_r$ = diameter inside bark at the point of interest on the stem

X_2 = bark ratio at breast height

X_4 = length up the stem from ground

X_5 = diameter outside bark at the point of interest

The equation is highly significant at the one percent level of confidence. It explains 99.87 percent of the total variation in diameter inside bark at upper stem points, and has a standard error of $\pm$ 0.00389 inches (standard error of estimate = $\pm$ 0.171 inches or $\pm$ 1.876 percent).

DISCUSSION

An important feature of the present regression analyses is the indication that better results will be achieved if diameter inside bark up the bole is predicted directly rather than to express it as ratio of the diameter outside bark. A detailed discussion of the findings is presented in the following paragraphs.

Bark Ratio as Dependent Variable

There are marked differences in the effect of most of the independent variables on bark ratio. The correlation between bark ratio and the various independent variables, as given earlier, has not been consistent in the analyses of data from the two sources. Analysis of data from Black Rock Forest Management Research Area has indicated that bark ratio increases up the tree. However, that of data from the State of Washington has absolutely nullified such possibility. Similarly, all other variables, with the exception of X_2, and X_4X_5 have exhibited contrasting relationship with bark ratio under the two analyses.

A comparison of the present study with that of Johnson's (33) shows that the only apparent similarity is high correlation between the lower stem bark ratio and the upper stem bark ratio. The fact that he had used bark ratio at stump height, as against that at breast height used in the present study, should not jeopardize this relationship. His contention that bark ratio decreases with age has also been confirmed by the analysis of data from the State of Washington.

Therefore, if Johnson's findings (33) are also taken into consideration, it can be seen that (except for the effect of X_2, X_4X_5, and X_{10}) bark ratio has responded differently to various independent variables under different analyses.

Diameter Inside Bark as Dependent Variable

As brought out earlier, an examination of correlation matrices revealed a considerable consistency in the behavior of upper stem diameter inside bark to various independent variables. The most important effect has been exhibited by X_2, X_5, $X_4{}^2$, and X_4X_5 on the dependent variable.

At first, the exorbitantly high correlation of diameter outside bark at upper stem points, i.e., X_5 with diameter inside bark at the same point on the stem was viewed with suspicion. However, a closer consideration of the problem has proved to support the high correlation between these two variables.

Double bark thickness at breast height has been shown by a number of authors to be linearly related both to d.b.h.o.b (4, 7, 31, 32, 39, 44, 50) and d.b.h.i.b (4, 39). As a part of the present study also, double bark thickness at breast height was found to be linearly related to diameter outside bark and to diameter inside bark at breast height. The first set of data from Black Rock Forest Management Research Area was analysed using an IBM 1620 computer. The equations obtained were:

B_t = 0.10957(D.b.h.o.b) - o.12258

(r-squared = 0.7440; $Sy_x = \pm$ 0.245 inches or $\pm$ 24.53 percent)

and

B_t = 0.11723(D.b.h.i.b) - 0.08345

(r-squared = 0.6787; $Sy_x = \pm$ 0.274 inches or $\pm$ 27.48 percent)

where:

B_t = double bark thickness at breast height

Since double bark thickness (d.b.h.o.b minus d.b.h.i.b) is linearly related both to diameter outside bark and diameter inside bark at breast height with an almost equal r-squared value, it follows that the latter two variables are highly correlated between themselves. In fact, all previous workers have demonstrated this same relationship between diameter inside bark and diameter outside bark at breast height (38, 40, 41, 42, 44). As a part of the present study, an attempt was also made to relate breast high diameter inside bark to that outside bark and vice versa. The first set of data from Black Rock Forest Management Research Area was analysed using an IBM 1620 computer. The results confirmed the previous findings and showed a high correlation (r-squared = 0.99481) between diameter inside bark and diameter outside bark at breast height. The two regression equations developed were:

$$D.b.h.o.b = 1.11723(D.b.h.i.b) - 0.08345$$
$$(Sy_x = \pm 0.274 \text{ inches or } \pm 2.67 \text{ percent})$$

and

$$D.b.h.i.b = 0.89042(D.b.h.o.b) + 0.12258$$
$$(Sy_x = \pm 0.245 \text{ inches or } \pm 2.64 \text{ percent})$$

Once it is agreed that diameter inside bark is highly correlated with that outside bark at breast height, there seems to be every justification to establish the contention that these two variables will behave in a similar way at any height up the bole. At least, Bones (3) has shown this to be true for measurements at the top of first 16-foot log. Also, if viewed closely, the findings of Maezawa (37) indirectly support this contention. In order to present it graphically, it was decided to plot the inside bark diameter readings at various upper stem points on their respective outside bark measurements. Preliminary casual plottings of the data from Black Rock

Forest Management Research Area had indicated a straight line relationship between these two variables. Final plottings were carried out with the help of IBM 1620 computer utilizing data from the State of Washington. The results are shown in Figure 1. The equation for regression line of Figure 1 is given as follows:

$$D.i.b_r = 0.93424(D.o.b_r) - 0.01916$$

(r-squared = 0.9979; $Sy_x = \pm 0.215$ inches or $\pm$ 2.358 percent)

Where $D.i.b_r$, and $D.o.b_r$ are upper stem diameter inside bark and diameter outside bark respectively.

The intercept is almost negligible and, therefore, diameter inside bark at any point on the stem can be taken as a function of diameter outside bark at that point and vice versa.

Bark Ratio Versus Diameter Inside Bark as Dependent Variable

Bark ratio has exhibited poor correlation with the most important variable that could be measured with optical dendrometer, i.e., diameter outside bark at the point of interest on the stem. This was confirmed by casual plottings of upper stem bark ratios over their respective outside bark diameters from data of both the sources. The expected line was almost parallel to the horizontal axis exhibiting absolutely no correlation

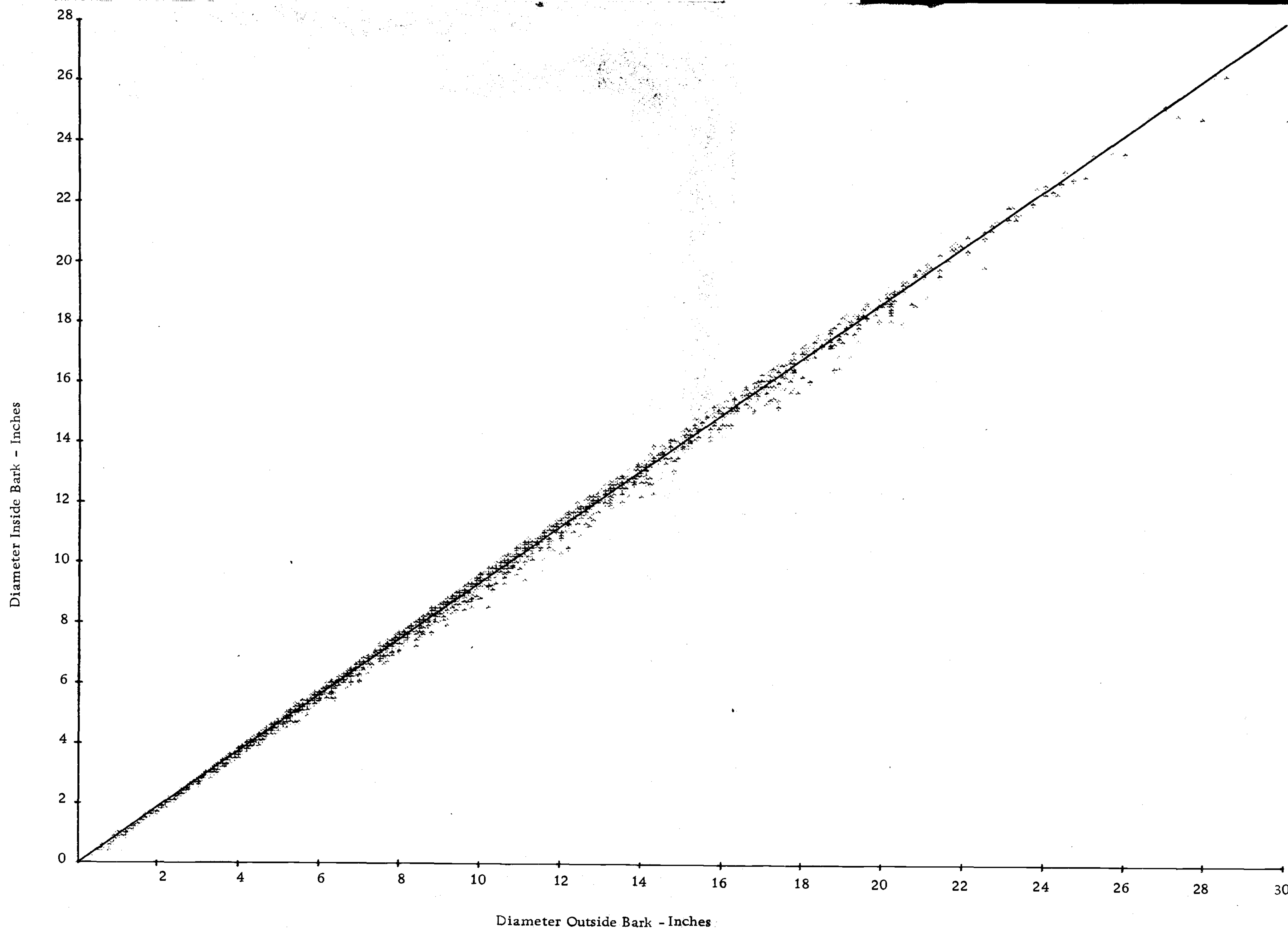

Figure 1. Relationship of Diameter Inside Bark to Diameter Outside Bark at Various Upper Stem Points in Douglas-fir.

between the two variables.

The final equation of the analysis of first set of data from Black Rock Forest Management Research Area accounts for 42.38 percent, and that of the State of Washington for 43.69 percent of the total variation in bark ratio. Johnson's (33) "best" equation explained 40 percent of the total variation in bark ratio, which is in conformity with the present findings. However, using diameter inside bark as dependent variable, an exceedingly high percentage of the total variation (99.9 percent) has been accounted for by the final equation of all the analyses.

Otherwise, use of bark ratio as dependent variable did not give any better results. This was verified by subjecting the deviations of predicted values from actual values of the upper stem diameter inside bark to a simple test of standard deviation.

Above all, the identical results obtained from a number of analyses in the present study speak of the usefulness of diameter inside bark as dependent variable.

The Equations

All analyses in the present study have indicated that variable X_5 (diameter outside bark) accounts for almost all (over 99 percent) variation in diameter inside bark up the bole. It follows that equation of the very first step of analysis, in which X_5 has invariably entered the regression, could be utilized for all practical purposes. However, reliability of the prediction equation is increased considerably if other stem measurements are also taken into consideration in addition to diameter outside bark up the bole as independent variable.

Using standard error of estimate, and coefficient of determination as criteria of selection, the following equation is reproduced from the analysis of data from Black Rock Forest Management Research Area, and is recommended for use in places having similar stand characteristics.

$$D.i.b_r = 2.01839X_2 + 0.909116X_5 - 0.383417^{10^{-4}} X_4^{\;2} + 0.849269^{10^{-3}} X_4 X_5 - 1.76845$$

where:

$D.i.b_r$ = diameter inside bark at the point of interest on the stem

X_2 = bark ratio at breast height

X_4 = length up the stem from ground

X_5 = diameter outside bark at the point of interest

The equation is highly significant; it accounts for 99.87 percent of the total variation in diameter inside bark, and has a standard error of $\pm$ 0.00264 inches (standard error of estimate = $\pm$ 0.115 inches or $\pm$ 1.703 percent).

Similarly, an equation to predict diameter inside bark up the stem is reproduced from the analysis of data from the State of Washington as follows:

$$D.i.b_r = 4.34159X_2 + 0.928333X_5 + 0.24567^{10^{-3}} X_4X_5 - 3.97289$$

in which $D.i.b_r$, X_2, X_4, and X_5 have been already defined.

The equation is highly significant at the one percent level of confidence. It explains 99.87 percent of the total variation in upper stem diameter inside bark, and has a standard error of $\pm$ 0.00389 inches (standard error of estimate = $\pm$ 0.171 inches or $\pm$ 1.876 percent). As already brought out, data for the development of this equation came from plots situated in various localities representing fairly well the existing stand conditions in western Washington. The equation can, therefore, be employed effectively throughout this region and other stands having comparable description.

Both the equations involve measurements to be taken of (a) breast high diameter inside bark and diameter outside bark; (b) height up the stem from ground; and (c) diameter outside bark at a point on the upper stem where diameter inside bark is to be calculated. Double bark thickness at breast height can be measured with a suitable bark guage, and by substracting it from diameter outside bark, breast high diameter inside bark will be obtained. Alternatively, diameter inside bark at breast height can be measured directly with caliper after stripping off bark at four points on the stem so that two measurements are taken at right angle to one another. Diameter inside bark at breast height divided by diameter outside bark at breast height will give bark ratio at breast height, i.e., X_2. Other variables necessary for these equations, i.e., length up the tree from ground or X_4, and diameter outside bark at the point of interest on stem or X_5 can be read directly from optical dendrometer.

The program written by Grosenbaugh (17) will require some modifications in case it is desired to use these equations in connection with 3P sample-tree-measurements.

As is evident, both the equations given above involve rather tedious calculations which would be facilitated only with the use of electronic computers. A comparatively crude but easily made estimate of upper stem diameter inside bark can, however, be obtained using the following equations reproduced from the first step of regression analyses.

Black Rock Forest Management Research Area:

$$D.i.b_r = 0.928712(D.o.b_r) + 0.0416447$$

where $D.i.b_r$, and $D.o.b_r$ are upper stem diameter inside bark and diameter outside bark respectively.

This equation is highly significant; it accounts for 99.80 percent of the total variation in upper stem diameter inside bark, and has a standard of $\pm$ 0.00330 inches (standard error of estimate = $\pm$ 0.144 inches or $\pm$ 3.265 percent).

State of Washington:

$$D.i.b_r = 0.934242(D.o.b_r) - 0.01916$$

in which $D.i.b_r$, and $D.i.b_r$ have been already defined.

It can be noticed that this is the same equation which expresses mathematically the regression line of Figure 1. It is highly significant at the one percent level of confidence explaining 99.80 percent of the total variation in upper stem diameter inside bark. The standard error is $\pm$ 0.00492 inches (standard error of estimate = $\pm$ 0.215 inches or $\pm$ 2.358 percent).

The intercept in both these equations is almost negligible, and could be ignored for all practical purposes.

CONCLUSION

From the results of this study on Douglas-fir it is concluded that:

a) Direct estimation of diameter inside bark at various upper stem points yield better results than expressing it as a ratio of diameter outside bark.

b) Diameter inside bark at various heights up the stem has a high positive correlation with its respective diameter outside bark, and a negative correlation with height itself.

c) Bark ratio at breast height has been found to have a positive correlation with such ratio at upper stem points; both are negatively related to tree age.

SUMMARY

The 3P sampling technique as developed by Grosenbaugh (16) requires the application of some sort of procedure whereby outside bark dendrometer measurements can be converted into inside bark volumes. Some of the procedures that have been used require the use of bark ratio (diameter inside bark/diameter outside bark) at various heights up the tree.

The purpose of this study was to develop a suitable regression equation for making estimates of diameter inside bark at various heights up the stem in a Douglas-fir tree. Data on 237 and 302 trees from Black Rock Forest Management Research Area, Polk County, Oregon, and scattered plots in the State of Washington respectively were analysed in a stepwise regression procedure. Five basic independent variables, their squares, and cross-products were used to test the suitability of two dependent variables - bark ratio, and diameter inside bark at upper stem points. The basic variables were:

X_1 = diameter at breast height (4.5 feet from ground) outside bark

X_2 = bark ratio at breast height

X_3 = total tree height

X_4 = length up the stem from ground

X_5 = diameter outside bark at the point of interest on the stem

Regression analyses indicated that bark ratio up the stem increases with increase in breast height bark ratio, and decreases with increase in tree age. Also, a high positive correlation was observed between the inside bark diameter and outside bark diameter all along the bole. An important indication of the present study is that better results will be achieved if diameter inside bark rather than bark ratio at upper stem points is used as dependent variable.

The best equation from the analysis of data from Black Rock Forest Management Research Area was tried on data from the State of Washington. The difference between actual and predicted values of the upper stem inside bark diameter was found to be significant. Accordingly, it was decided to develop a separate equation based on data from the State of Washington. The following are two equations selected from the regression analyses on the basis of standard error of estimate, and coefficient of determination. Equation (1) is recommended for practical use in Black Rock Forest Management Research Area and comparable young-growth evenaged Douglas-fir stands. Equation (2) may be employed in young-growth all-aged Douglas-fir stands throughout western Washington. The two equations are:

$$D.i.b_r = 2.01839X_2 + 0.909116X_5 - 0.383417^{10^{-4}} X_4^{\ 2} + 0.849269^{10^{-3}} X_4X_5 - 1.76845 \text{ - - - - - - - - - - - - - - } (1)$$

and,

$$D.i.b_r = 4.34159X_2 + 0.928333X_5 + 0.24567^{10^{-3}} X_4X_5 - 3.97289 \text{ - - - - } (2)$$

in which $D.i.b_r$ is upper stem diameter inside bark, and X_2, X_4, and X_5 have been already defined.

Equation (1) accounts for 99.87 percent of the total variation in upper stem diameter inside bark, and has a standard error of ± 0.00264 inches (standard error of estimate = ± 0.115 inches or ± 1.703 percent). Equation (2) explains 99.87 percent of the total variation in upper stem diameter inside bark, and has a standard error of ± 0.00389 inches (standard error of estimate = ± 0.171 inches or ± 1.876 percent). Both equations are highly significant at the one percent level of confidence.

Measurements necessary to be taken for these equations are: (a) diameter at breast height - both inside bark and outside bark; (b) height up the stem from ground; and (c) diameter outside bark at the point of interest on the stem. Diameter inside bark at breast height can either be measured directly after bark is stripped off at the points of putting caliper, or it can be calculated by substracting double bark thickness (measured with a suitable bark guage) from diameter outside bark at breast height. Diameter inside bark at breast height divided by diameter outside bark at breast height will give bark ratio at breast height, i.e., variable X_2. Other variables necessary for these equations, i.e., length up the stem from ground or X_4, and upper stem diameter outside bark or X_5 can be read directly from optical dendrometer.

The program written by Grosenbaugh (17) will require some modifications in case these equations are used in connection with 3P sample-tree-measurements.

BIBLIOGRAPHY

1. Bones, James T. Estimating d.b.h from stump diameter in the Pacific Northwest. Portland, 1960. 1 p. (U.S. Forest Service. Pacific Northwest Forest and Range Experiment Station. Research Note 186)

2. ______________ Estimating spruce and hemlock d.b.h from stump diameter. Juneau, 1961. 2 p. (U.S. Forest Service. Northern Forest Experiment Station. Technical Note 51)

3. ______________ Relating outside- to inside-bark diameter at top of first 16-foot log for southwest Alaska timber. Juneau, 1962. 2 p. (U.S. Forest Service. Northern Forest Experiment Station. Technical Note 52)

4. Briegleb, P.A. Calculating the growth of ponderosa pine forests. Portland, U.S. Forest Service. Pacific Northwest Forest and Range Experiment Station. 1945. 60 p.

5. Briscoe, Charles B. Tests of Girard form class estimation from lower bole taper. Journal of Forestry 57(3): 207-208. 1959.

6. Burns, Paul Y. and Raymond J. Adams. Girard form class can be estimated from lower bole taper. Baton Rouge, 1956. 2 p. (Louisiana State University. Forestry Note 8)

7. Burton, James D. Tennessee timber trends. New Orleans, 1962. 4 p. (U.S. Forest Service. Southern Forest Experiment Station. Southern Forestry Note 142)

8. Chapman, Herman H. and Walter H. Meyer. Forest mensuration. New York, McGraw-Hill, 1949. 522 p.

9. Church, Thomas W. Jr. Converting Virginia pine stump diameter to diameter breast high. Upper Darby, 1953. 2 p. (U.S. Forest Service. Northeastern Forest Experiment Station. Forest Research Note 23)

10. Cunningham, F.E., S.M. Filip, and M.J. Ferree. Relation of stump diameter to diameter breast high. Upper Darby, 1947. 3 p. (U.S. Forest Service. Northeastern Forest Experiment Station. Station Note 1)

11. Efroymson, M.A. Multiple Regression Analysis. In: Mathematical methods for digital computers, ed. by Anthony Ralston and Herbert S. Wilf. New York. John Wileys & Sons, 1960. p. 191-203.

12. Goebel, N.B. Estimation of form class from lower bole measurements for southern red oak, white oak, and short leaf pine in upper South Carolina Piedmont. Clemson, 1961. 8 p. (South Carolina. Agricultural Experiment Station. Forest Research Series 2)

13. ________________ Estimation of form class from lower bole measurements for Virginia pine and yellow poplar in the upper South Carolina Piedmont. Clemson, 1962. 10 p. (South Carolina. Agricultural Experiment Station. Forest Research Series 6)

14. Graybill, Franklin A. An introduction to linear statistical models. New York, McGraw-Hill, 1961. 2 vols.

15. Grosenbaugh, L.R. Optical dendrometers for out-of-reach diameters: a conspectus and some new theory. Washington, D.C., Society of American Foresters, 1963. 47 p. (Forest Science Monograph 4)

16. ________________ Some suggestions for better sample-tree-measurements. In: Proceedings of the Society of American Foresters, Washington, D.C., 1963. p. 36-42.

17. ________________ STX - fortran 4 program --- for estimates of tree population from 3P sample-tree-measurements. Berkeley, 1964. 50 p. (U.S. Forest Service. Pacific Southwest Forest and Range Experiment Station, Research Paper PSW-13)

18. ________________ Three-pee sampling theory and program 'THRP' for computer generation of selection criteria. Berkeley, 1965. 53 p. (U.S. Forest Service. Pacific Southwest Forest and Range Experiment Station. Research Paper PSW-21)

19. Hampf, Frederick E. Relationship of stump diameter to d.b.h for white pine in the Northeast. Upper Darby, 1954. 4 p. (U.S. Forest Service. Northeastern Forest Experiment Station. Forest Research Note 38)

20. ________________ Relationship of stump diameter to d.b.h for sugar maple in the Northeast. Upper Darby, 1955. 3 p. (U.S. Forest Service. Northeastern

Forest Experiment Station. Forest Research Note 42)

21. Hampf, Frederick E. Relationship of stump diameter to d.b.h for American beech in the Northeast. Upper Darby, 1955. 3 p. (U.S. Forest Service. Northeastern Forest Experiment Station. Forest Research Note 43)

22. ______________ Relationship of stump diameter to d.b.h for yellow birch in the Northeast. Upper Darby, 1955. 3 p. (U.S. Forest Service. Northeastern Forest Experiment Station. Forest Research Note 45)

23. ______________ Relationship of stump diameter to d.b.h for northern red oak in the Northeast. Upper Darby, 1955. 3 p. (U.S. Forest Service. Northeastern Forest Experiment Station. Forest Research Note 46)

24. ______________ Relationship of stump diameter to d.b.h for yellow poplar in the Northeast. Upper Darby, 1955. 3 p. (U.S. Forest Service. Northeastern Forest Experiment Station. Forest Research Note 55)

25. ______________ Relationship of stump diameter to d.b.h for pitch pine in the Northeast. Upper Darby, 1957. 3 p. (U.S. Forest Service. Northeastern Forest Experiment Station. Forest Research Note 65)

26. ______________ Relationship of stump diameter to d.b.h for white oak in the Northeast. Upper Darby, 1957. 3 p. (U.S. Forest Service. Northeastern Forest Experiment Station. Forest Research Note 66)

27. Harris, Jack D. and Andrew J. Nash. Girard form class estimation from lower bole measurements on upland white oak trees in Missouri. Journal of Forestry 58(7): 534-36. 1960.

28. Hoffmann, J. The bark thickness of spruce on various sites in the southeastern Thurvinger Wald. Reprinted from Wissenschaftliche Zeitschrift der Technischen Hochschule Dresden 7(2): 361-68. 1957/58. (Abstracted in Forestry Abstracts 21(2): 2167. 1960)

29. Horn, Allen F. A simplified method for estimating form class of loblolly and short leaf pine stands in Mississippi. Journal of Forestry 54(3): 185-87. 1956.

30. Ibberson, J.E. New diameter increment rule. Journal of Forestry 53(1): 34. 1955.

31. Johnson, Floyd A. Estimating past diameters of Douglas-fir trees. Portland, 1955. 3 p. (U.S. Forest Service. Pacific Northwest Forest and Range Experiment Station. Research Note 112)

32. ______________ Use of a bark thickness - tree diameter relationship for estimating past diameters of ponderosa pine trees. Portland, 1956. 3 p. (U.S. Forest Service. Pacific Northwest Forest and Range Experiment Station. Research Note 126)

33. ______________ Bark factors for Douglas-fir. Portland, 1966. 3 p. (U.S. Forest Service. Pacific Northwest Forest and Range Experiment Station. Research Note PNW-34)

34. Judson, George M. Inexpensive and accurate form class estimates. New Orleans, 1964. 6 p. (U.S. Forest Service. Southern Forest Experiment Station. Research Paper SO-11)

35. Keen, F.P. Ponderosa pine classes redefined. Journal of Forestry 41(4): 249-53. 1943.

36. Krastanov, K., P. Beljakov, and A. Andonov. Distribution of spruce bark along the stem. Gorskostop. Nauka, Sofija 1(3): 57-70. 1964. (Abstracted in Forestry Abstracts 26(1): 1017. 1965)

37. Maezawa, K. Bark thickness at several heights in young Douglas-fir trees. Vancouver, 1956. 4 p. (University of British Columbia. Forest Club. Research Committee. Research Note 131)

38. Meyer, H.A. Methods of forest growth determination. State College, 1942. 93 p. (Pennsylvania State College. Agriculture Experiment Station. Bulletin 435)

39. Meyer, W.H. Growth in selectively cut ponderosa pine forests of the Pacific Northwest. Washington, D.C., 1934. 64 p. (U.S. Department of Agriculture. Technical Bulletin 407)

40. McCormack, J.F. An allowance for bark increment in computing tree diameter growth for southern species. Asheville, 1955. 6 p. (U.S. Forest Service. Southeastern Forest Experiment Station. Station Paper 60)

41. Minor, Charles O. Loblolly pine bark thickness. Baton Rouge, 1953. 2 p. (Louisiana State University. Forestry Note 1)

42. Myers, Clifford A. Estimating past diameters of ponderosa pines in Arizona and New Mexico. Fort Collins, 1963. 4 p. (U.S. Forest Service. Rocky Mountain Forest and Range Experiment Station. Research Note RM-7)

43. ______________ Estimating volumes and diameters at breast height from stump diameters, southwestern ponderosa pine. Fort Collins, 1963. 2 p. (U.S. Forest Service. Rocky Mountain Forest and Range Experiment Station. Research Note RM-9)

44. ______________ Taper tables, bark thickness, and diameter relationships for lodgepole pines in Colorado and Wyoming. Fort Collins, 1964. 6 p. (U.S. Forest Service. Rocky Mountain Forest and Range Experiment Station. Research Note RM-31)

45. Oregon. Forest Research Center. Corvallis, 1960. 50 p. (Annual Report 1959)

46. Panic, D. The thickness of birch (*Betula verrucosa* Ehrh.) bark. Sumarstvo 12(11/12): 583-94. 1959. (Abstracted in Forestry Abstracts 22(1): 866. 1961)

47. Smelko, S. Determining the bark coefficient. Lesnicky Casopis 8(6): 445-55. 1962. (Abstracted in Forestry Abstracts 24(3): 4020. 1963)

48. Shipman, R.D. Bottomland sweetgum form class estimation. Clemson, 1961. 5 p. (South Carolina Agricultural Experiment Station. Forest Research Series 4)

49. ______________ Girard vs. Horn form class estimation on sweetgum. Journal of Forestry 60(5): 343-44. 1962.

50. Spada, Benjamen. Estimating past diameters of several species in the ponderosa pine sub-region of Oregon and Washington. Portland, 1960. 4 p. (U.S. Forest Service. Pacific Northwest Forest and Range Experiment Station. Research Note 181)

51. Turnbull, K.J., Gene Roy Little, and Gerald E. Hoyer. Comprehensive tree-volume tarif tables. Olympia, Washington, Department of Natural Resources. 1963. 23 p.