ESTIMATION OF LODGEPOLE PINE DIAMETER, BASAL AREA, AND STAND VOLUME FROM MEASUREMENTS ON LARGE-SCALE AERIAL PHOTOGRAPHS

by

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ESTIMATION OF LODGEPOLE PINE DIAMETER, BASAL AREA, AND STAND VOLUME FROM MEASUREMENTS ON LARGE-SCALE AERIAL PHOTOGRAPHS

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INTRODUCTION

Presented here are eight equations and two methods for the estimation of lodgepole pine (*Pinus contorta* Dougl. var. *latifolia* Engelm.) diameter, stand basal area, and stand volume from large-scale aerial photographs. Previous works by Kippen and Sayn-Wittgenstein (1964), Heller, Doverspike and Aldrich (1964), Schut and van Wijk (1965), Lyons (1966, 1967), Aldred (1965, 1967), Aldred and Kippen (1967), and Sayn-Wittgenstein (1967) have proved the accuracy and precision of tree height and volume measurements on large-scale (1:2400 and larger) photographs; but methods for estimating stand volume and tree diameter, which are suitable for specific cover types, remain to be developed. Previously developed volume-estimating methods suitable for small-scale (1:15,840 and smaller) photography are not valid for large-scale photography where species recognition and more accurate measures of crown closure, individual tree height, and crown size are possible.

The study area is at the Kananaskis Forest Experiment Station, 50 miles west of Calgary in the SA1 section of the Subalpine Forest Region (Rowe, 1959).

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[1] Research Officers, Canadian Forestry Service, Department of Fisheries and Forestry, Edmonton, Alberta.

METHODS AND MEASUREMENTS

Sample Selection

Five, square, tenth-acre plots representing a range of sites (from sand to clay soils) and stocking (290 to 1120 stems per acre) were selected in areas where large-scale photography had already been done. They are located in 110-year-old lodgepole pine stands with some white spruce (Picea glauca (Moench) Voss) present on each plot. The locations of these plots are shown on stereo pairs of aerial photographs at a scale of approximately 1:15,840 (Figure 1).

Ground Measurements

The following information was recorded for all trees larger than 0.5 inches in d.b.h.: species, tree number, d.b.h. to the nearest tenth-inch (measured with a diameter tape), average crown width of the main crown to the nearest tenth-foot based on the average of two measurements at right angles (using a plumb bob and tape), and total tree height to the nearest foot (measured with an Abney level and a tape). Individual tree maps for each plot, showing tree location and crown areas represented by circles of average crown width, were prepared at a scale of 1 inch = 10 feet. Crown closure was determined from a count of the number of 1/100-inch squares covered by crown on the tree maps.

Table 1 presents on a per-acre basis: number of stems, averages of ground measurements for basal area, total cubic-foot volume on each plot for all trees 0.6 and 4.6 inches in d.b.h. and larger, and averages of crown width, tree height, and crown closure measurements.

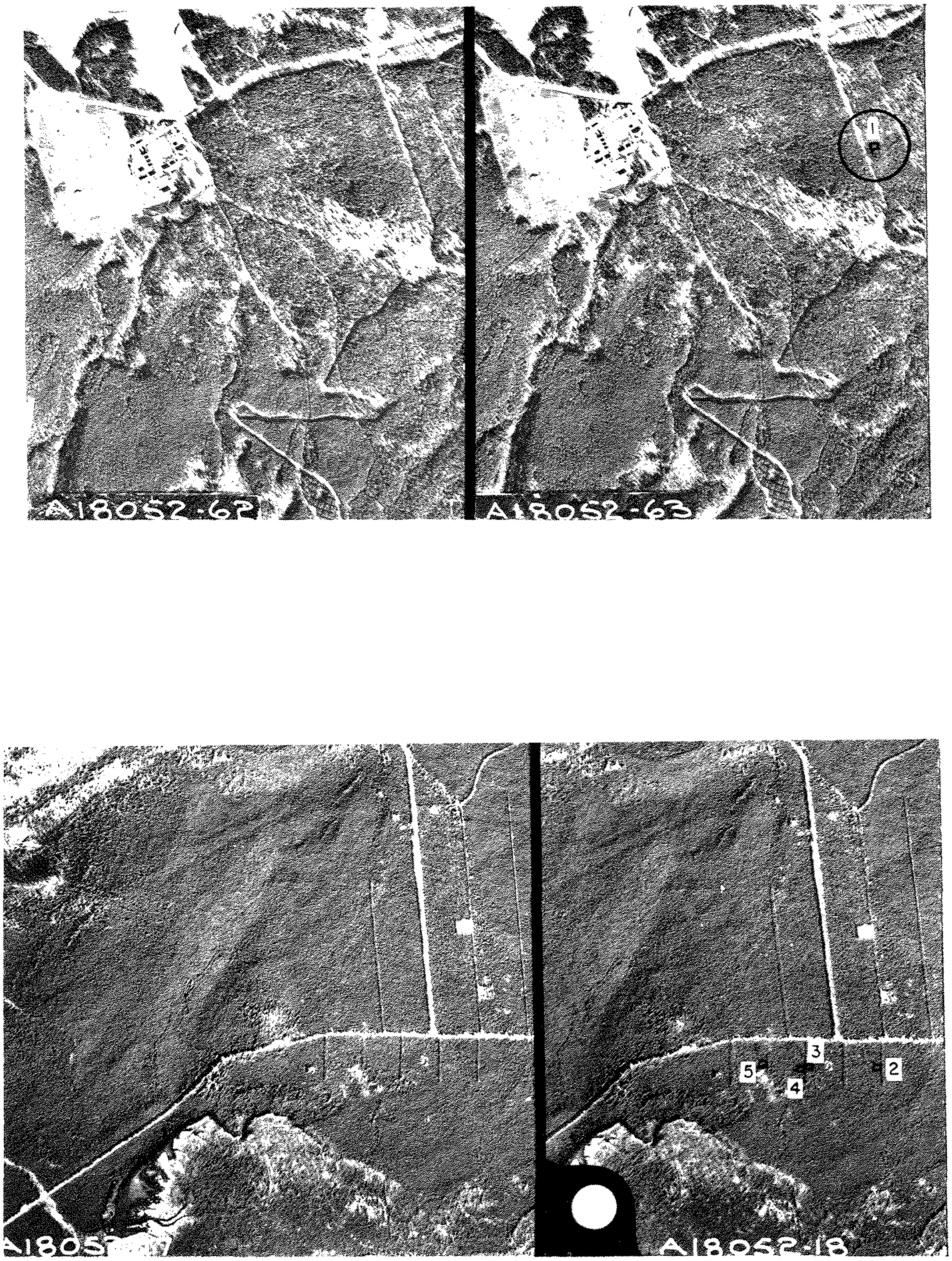


Figure 1. Plot locations on 1:15840 photography

Table 1. Plot description data based on ground measurement.

Plot No.	All Trees 0.6" in d.b.h. and larger: Basal Area (sq.ft.)	No. per Acre	Ave. d.b.h. (inches)	Total Cubic Volume[4] (cu.ft.)	All Trees 4.6" in d.b.h. and larger: Basal Area (sq.ft.)	No. per Acre	Ave. d.b.h. (inches)	Total Cubic Volume[4] (cu.ft.)	Ave. Tot. Ht. (feet): Ten Tallest Trees	All Trees 4.6" in d.b.h. & larger	Ave. Crown Width (feet): Ten Tallest Trees	All trees 4.6" in d.b.h.	Crown Closure (percent)
1	138	480	7.2	3682	136	390	8.0	3669	58.5	53.6	7.3	6.9	32
2	145	730	6.0	3245	133	580	6.5	3078	52.2	44.0	6.5	5.9	39
3	206	1120	5.8	5413	174	780	6.4	4925	62.2	53.8	6.3	5.1	41
4	227	1020	6.4	6356	204	810	6.8	5968	64.0	54.6	6.4	5.1	44
5	152	290	9.8	5107	150	280	9.9	5054	77.2	65.9	11.1	8.5	35

[4] Based on the following total cubic foot volume formulae (Alberta data).

lodgepole pine 0.6" to 3.5" d.b.h. = $-.007462 + .002975D^2H$ $r^2 = .97$

lodgepole pine 3.6" and larger d.b.h. = $.102600 + .002721D^2H$ $r^2 = .99$

white spruce 0.6" to 8.5" d.b.h. = $.039360 + .002250D^2H$ $r^2 = .96$

white spruce 8.6" and larger d.b.h. = $2.754700 + .002000D^2H$ $r^2 = .98$

Note: The lodgepole pine volume formulae are based on the complete stem analysis of fifty dominant and codominant 100-year-old trees at the Kananaskis forest experiment station. The white spruce volume formulae are based on data on 1757 trees that were used to produce standard volume tables by graphical techniques by A. W. Blyth (1952).

Aerial Photography

Aerial photographs were taken at a scale of 1:2400 for all plots. For Plot 1 only, photographs at a scale of 1:1200 were also taken. (See Fig. 2 and 3 for contact prints and Fig. 4 for 4x enlargements of 1:2400 photography). The film was a fast panchromatic type "Ansco Super Hypan". Photographs were taken with a "Vinten" 70 mm aerial camera equipped with a 305 mm lens with no filter, at an exposure setting of f5.6 and 1/500th of a second. The time of photography was between 9:30 and 10:30 A.M. on a cloudless day in September. The early hour was chosen because turbulence in this area is at a minimum before noon; it did, however, produce long shadows on the photographs.

Photo Measurements

All of the photo measurements were done on 4x enlargements of the 1:2400 photography as shown in Figure 4. No significant improvement was shown with measurements of height and crown width on aerial photographs taken at a scale of 1:1200. The principal and conjugate principal points on the 4x enlargements were oriented with the flight line for stereo-viewing as indicated in Figure 3.

A standard photogrammetric equation as discussed by Spurr (1960) was used for determining tree heights as follows:

$$h = \left(\frac{Hb}{Pb + dP}\right)\left(dP\right)$$

where:

h = total height of tree in feet.

Hb = height of camera above base of tree (determined by relating photo measurements to known ground distances).

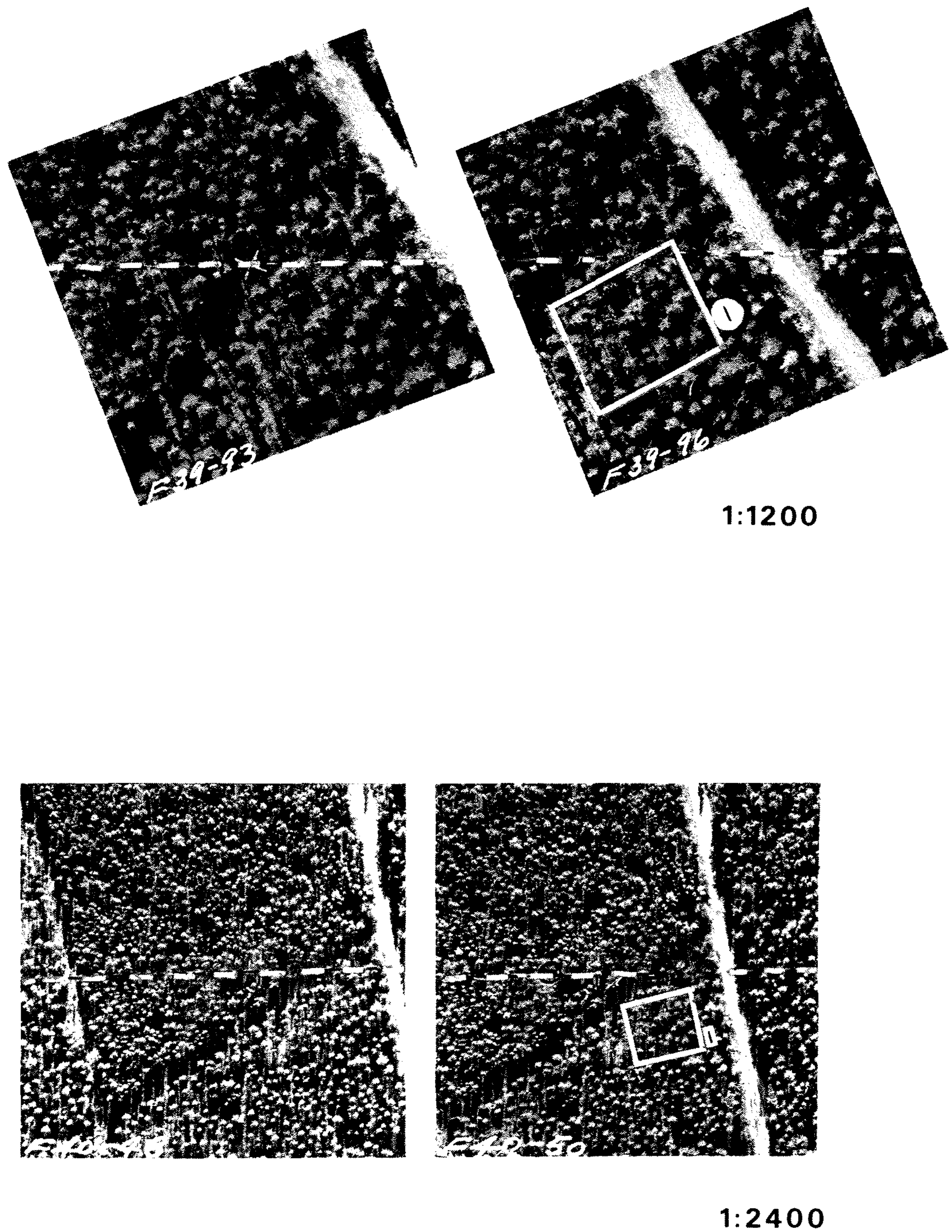


Figure 2. Plot 1 located on stereo pairs of contact prints at scales of 1:1200 and 1:2400

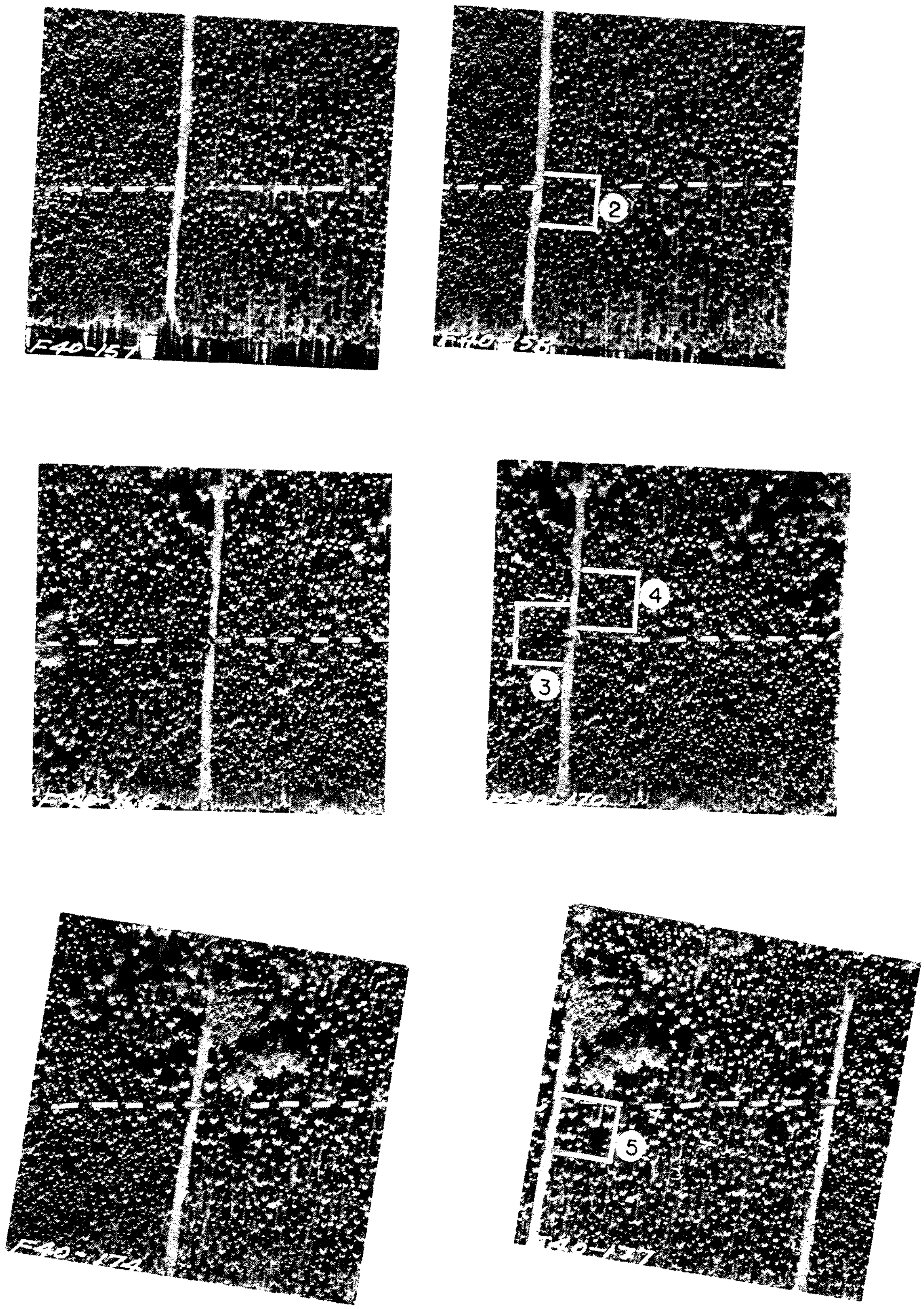
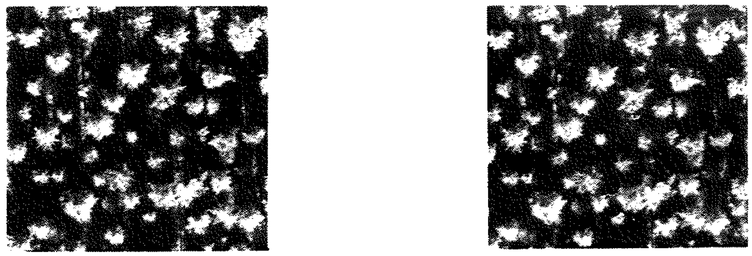
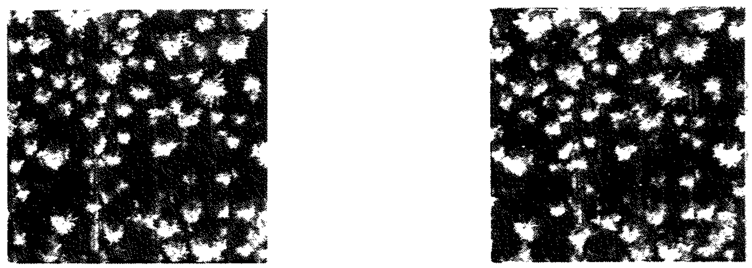


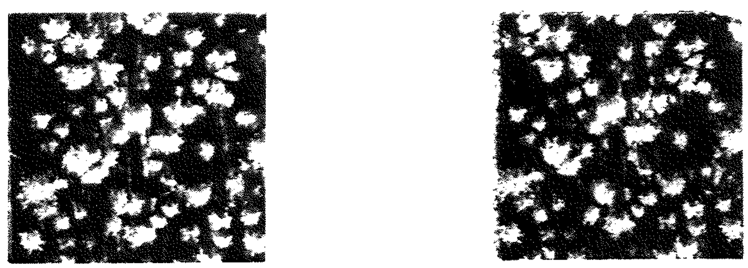
Figure 3. Plots 2,3,4 and 5 located on contact prints of 1:2400 photography



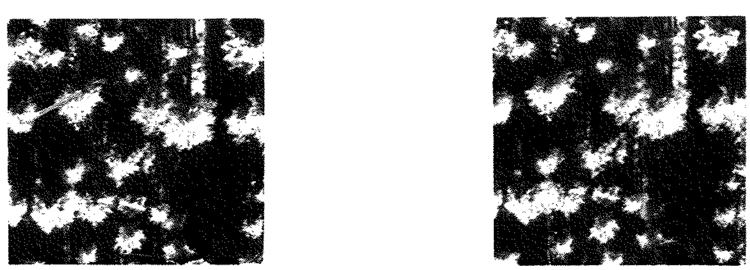
Plot 2



Plot 3



Plot 4



Plot 5

Figure 4. Enlargements (4×) of 1:2400 photography as shown in Figure 3 of tenth-acre plots 2,3,4 and 5.

dP = differential parallax.

Pb = average distance between principal and conjugate principal points of photographs over the test area.

Other equations may be required when tilt causes large differences in distances between principal and conjugate principal points (Schut and Van Wijk, 1965; Aldred, 1967).

Crown widths of individual trees were measured with a dot grid placed over one of the photographs of a stereo pair. The distance between dots on the 4x enlargements of the 1:2400 photographs was equivalent to 1 foot on the ground. Crown width estimates are an average of two measures of crown width of each tree taken at right angles to each other.

Comparison of measures of tree height and crown width obtained on the ground to measures obtained from large-scale photos showed no significant differences in the averages of these parameters. Based on differences of paired measurements (ground and photo) deviations ($S_{\bar{d}}$) for the standard tree height and for crown width are as follows:

$$S_{\bar{d}} \text{ height} = \pm 2 \text{ feet}$$

$$S_{\bar{d}} \text{ crown width} = \pm 1 \text{ foot}$$

Crown closure estimates were based on the proportion of the number of dots falling on crowns out of a possible 4256 dots for each tenth-acre photo plot. Precision estimates were based on the variance of a bionomial variate as presented by Sampford (1962), where:

$$\text{Precision} = \pm t\sqrt{\frac{p\,(1 - p)}{n}}$$

n = total number of dots per tenth-acre photo-plot

p = proportion of area covered by crown

t = student's "t" at 95% probability level

The estimated precisions of crown closure estimated for each photo plot were all less than ± 1% of the respective means.

EQUATIONS FOR ESTIMATING STAND BASAL AREA AND VOLUME, AND TREE D.B.H.

Stand Basal Area

The ratio of crown width (CW) in inches to d.b.h.o.b. (D) in inches ($\frac{CW}{D}$), which will be called K in this report, is most important in estimating stand basal area from measures of crown closure.

Since:

$$\frac{K}{1} = \frac{CW}{D} \text{ as previously defined}$$

$$\frac{K^2}{1} = \frac{CW^2 \frac{\pi}{4}}{D^2 \frac{\pi}{4}} = \frac{\text{Crown Area}}{\text{Basal Area}}$$

$$\text{Basal area per tree} = \frac{\text{Crown Area}}{K^2}$$

$$\text{Basal Area per acre} = \frac{43{,}560 \times \text{proportion of area covered by crown}}{\text{Ave. } K^2} \qquad (1)$$

Similar relationships are used in point sampling (Kirby, 1964). Stands with the same crown closure but with different K factors will have different basal areas per acre. For example, two stands with 40 per cent crown closure, but with average K ratios of 9 and 10, will have the following basal areas per acre:

where: K = 9 Basal Area per acre = $\frac{43,560 \times .40}{(9)^2} = 215$

K = 10 Basal Area per acre = $\frac{43,560 \times .40}{(10)^2} = 174$

Figure 5 shows the scatter of d.b.h.o.b. on crown width measurements around regression lines determined by the least-squares method with the model d.b.h.o.b. = $\frac{CW}{K}$. Average K values for lodgepole pine on each plot are also indicated. The statistically significant lower-than-average K ratios for lodgepole pine on plots 3 and 4 may be attributed to the high number of stems per acre on these plots. In addition the K ratios for white spruce are higher than for lodgepole pine. The average K ratio for all trees on the five plots is 10.

Volume Per Unit of Basal Area

The following equations were derived graphically and are based on plot data presented in Table 1.

$$V.B.A.R. = 4.5 + .44\ (\overline{H}_{all}) \qquad (2)$$

$$V.B.A.R. = .44\ (\overline{H}_{10}) \qquad (3)$$

where:

V.B.A.R. = volume basal area ratio (total cubic foot volume ÷ basal area).

$(\overline{H}_{all})$ = average height of all trees 4.6 inches in d.b.h. and larger, on tenth-acre plot.

$(\overline{H}_{10})$ = average height of ten tallest trees on tenth-acre plot.

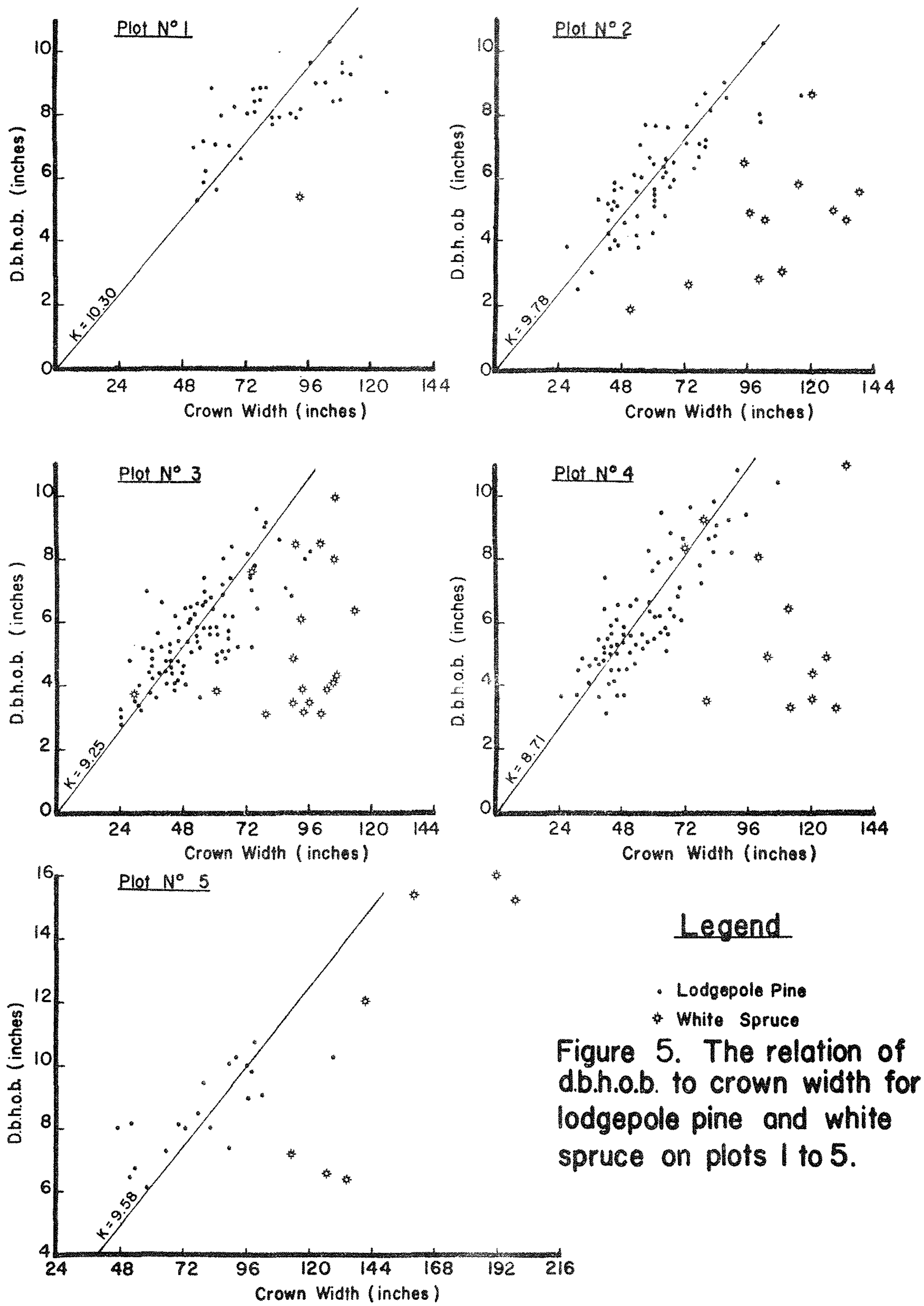


Figure 5. The relation of d.b.h.o.b. to crown width for lodgepole pine and white spruce on plots 1 to 5.

Smith and Munro (1965) found a similar relationship for lodgepole pine in the interior of British Columbia. In addition, an unpublished report by Kirby (1969)[2] on lodgepole pine tree volume equations based on data from all lodgepole pine forest regions in Alberta shows similar results.

Predication of d.b.h.

The following two equations are based on ground measures of tree height and photo measures of crown width as these were considered to be the most accurate. Individual-tree data on 301 lodgepole pine trees from the five photo plots established were used.

$$D = 3.13 + .012\ (CW)\ (HT) \qquad r^2 = .78 \quad SE_E = .85'' \qquad (4)$$

$$D = 13.26 + 8.24\ Log._{10}\ (CW)\ (HT) \qquad r^2 = .82 \quad SE_E = .78'' \qquad (5)$$

where: D = d.b.h.o.b. (inches)

CW = crown width (feet)

HT = total tree height (feet)

$Log._{10}$ = logarithm to the base 10

The scatter by plot of individual tree data around the average regression lines (equations 4 and 5 are based on data from all plots), is shown in Figures 6 and 7. Equations based on data from each photo plot had statistically different intercepts and slopes but these are not presented in this report because they are not sufficiently understood. Mitchell (1965) has shown that white spruce diameter and crown width ratios are apparently more closely related to changes in age than to site index and basal area.

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[2]Kirby, C. L. 1969. Tree volume equations and volume basal-area ratios for white spruce and lodgepole pine in Alberta. File report, 8 pp., 1 Figure, 14 Tables. Canadian Forestry Service, Edmonton.

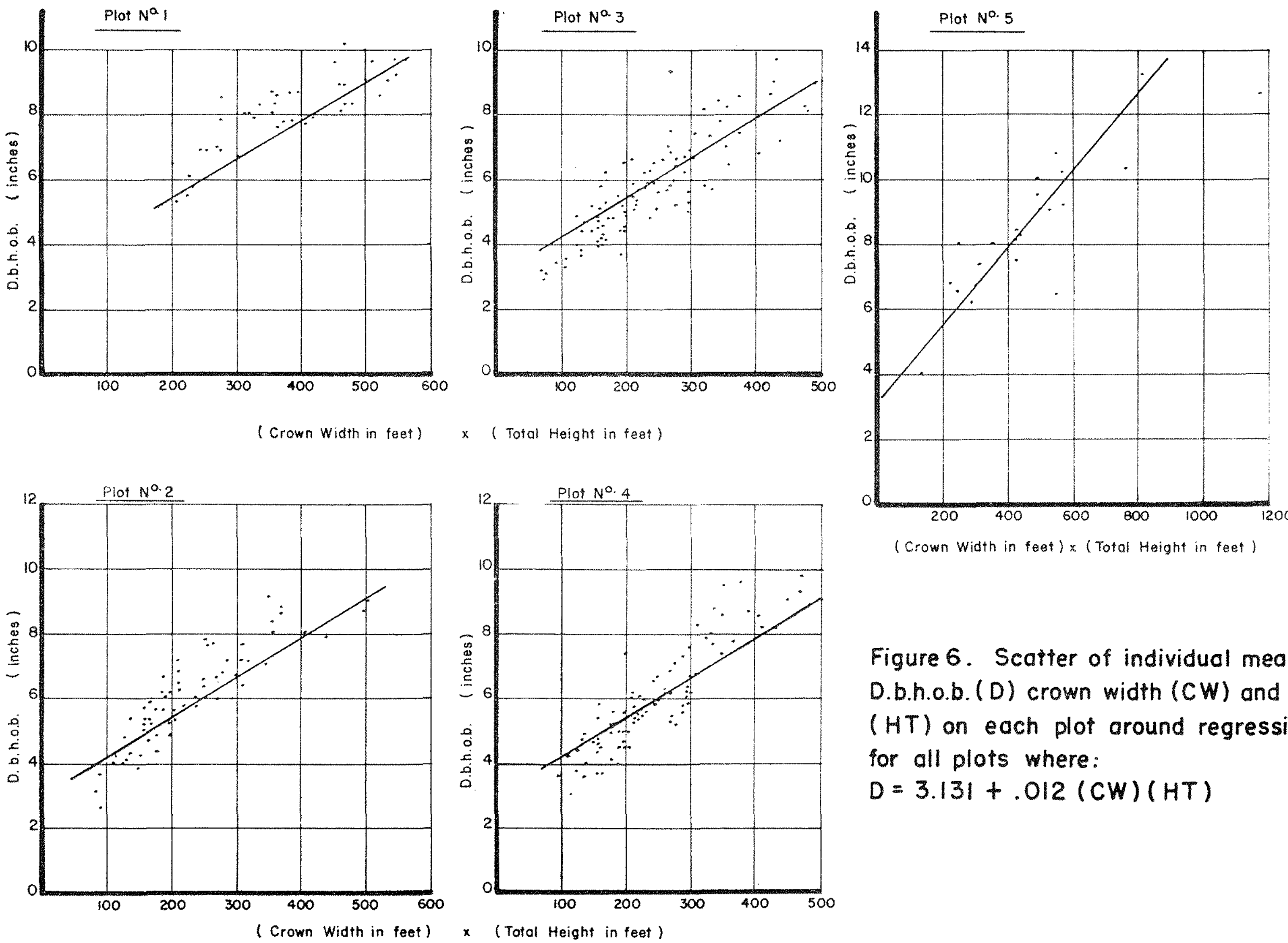
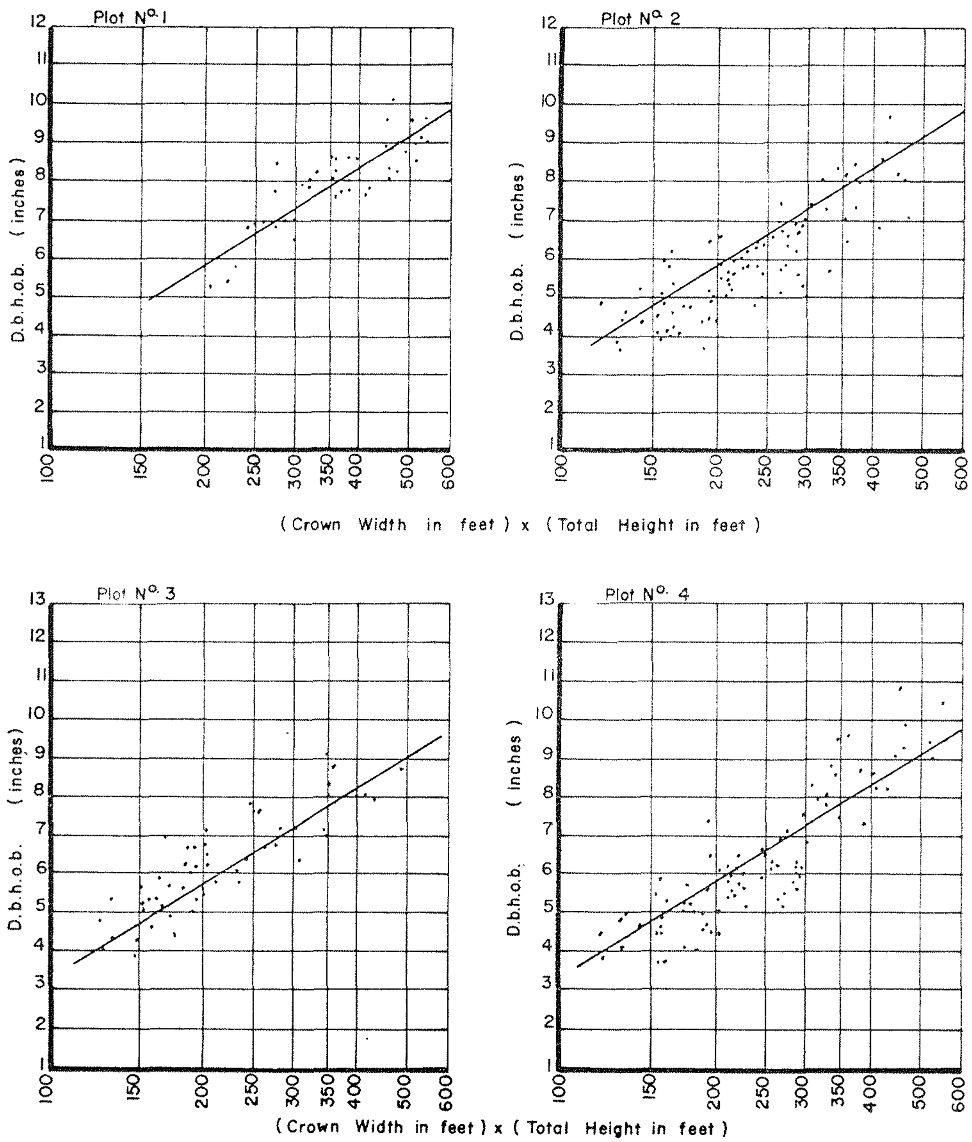


Figure 6. Scatter of individual measures of D.b.h.o.b. (D) crown width (CW) and height (HT) on each plot around regression line for all plots where:

$$D = 3.131 + .012\,(CW)(HT)$$



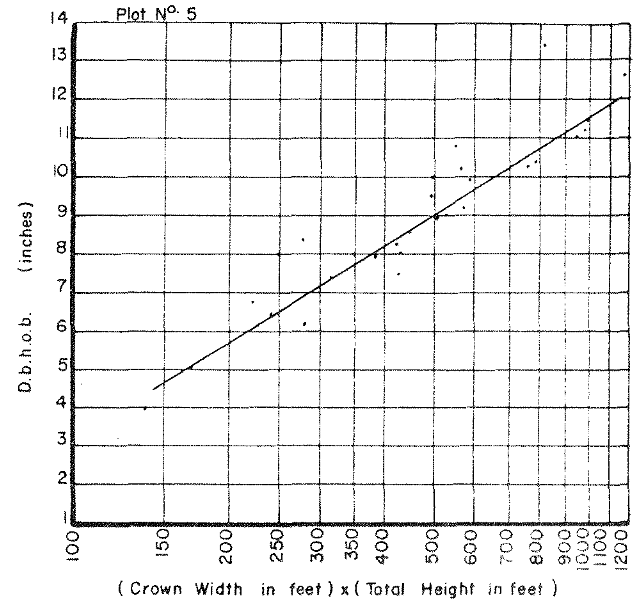


Figure 7. Scatter of individual measures of D.b.h.o.b. (D) crown width (CW) and height (HT) on each plot around regression line for all plots where: D = −13.26 + 8.24 Log. (CW)(HT).

Equation 5 (logarithmic) to predict d.b.h. from measures of crown width and total height had the highest precision of all equations tested, including Bonnor's (1968).

Equation 4 is presented so that it may be compared with previous work by Bonnor (1964), Bailey (1964), Boulter (1966)[3], and Lyons (1966).

APPLICATION

Two methods, both based on the equations developed in this paper, for estimating stand volumes from measures obtainable on large-scale photographs are applied to the data collected for this report.

Method 1 (Crown closure)

Method 1 is based on an equation involving the proportion of crown closure (CC), average K ratio of 10 to predict basal area per acre, and average height of the ten tallest trees ($\bar{H}_{10}$) to predict volume per unit of basal area. Table 2 presents a comparison of the ground measurements on the five plots to the photo estimates of average crown closure, average height of ten tallest trees, basal area, and volume per acre.

Total cubic-foot volume (T.C.F.V.) per acre was estimated from equations 1 and 3.

$$\text{T.C.F.V. per acre} = \frac{\text{CC} \times 43{,}560}{(10)^2} \times (.44)(\bar{H}_{10}) \qquad (6)$$

Method 2 (Average tree crown width and height)

The average crown width and tree height, number of stems per acre, and volume per unit of basal area related to average tree height

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[3] Boulter, D. 1966. Correspondence. Alberta Forest Service, Edmonton, Alberta.

Table 2. Comparisons of ground and photo measures of per cent crown closures, and average height of ten tallest trees, to predict basal area and total cubic foot volume per acre.

Plot Number	Average Crown Closure (proportion)		Average Height[2] Ten Tallest Trees (feet)		Basal Area per acre (squ. ft.)		Total Cubic Volume per acre (cu. ft.)	
	Ground[1]	Photo	Ground[1]	Photo	Ground[1]	Photo[3]	Ground[1]	Photo[4]
1	.32	.32	58.5	58.9	136	139	3669	3602
2	.39	.41	52.2	51.2	133	179	3078	4033
3	.41	.42	62.2	60.7	174	183	4925	4888
4	.44	.40	64.0	68.8	204	174	5968	5267
5	.35	.34	77.2	77.5	150	148	5054	5047
Averages of all plots	.382	.378	62.8	63.4	161	164	4539	4567

[1] Ground estimates obtained from Table 1 are based on plot measurement of all trees 4.6" in d.b.h. and larger.

[2] Average height of 10 tallest trees on tenth acre ground and photo plot.

[3] Photo basal area per acre $= \frac{(\text{porportion of crown closure})\ (43{,}560)}{(\text{K Factor}^2) = 10^2}$ Equation 1

[4] Total cubic foot volume per acre = (Photo basal area per acre) x (Average height of ten tallest) (.44) Equation 3

are the parameters used in this method. Measurements are taken from 1:2400 vertical large-scale photographs.

A point sampling technique is suggested to reduce the number of measurements required to define average stand height and volume. A dot grid with 81 dots per tenth-acre photo-plot (one thirtieth of an inch between dots on 1:2400 photos) was placed over the sample area on one of the photographs of a stereo pair. While the stereo pair is viewed stereoscopically, trees in the tenth-acre photo plot are marked for measurement of height. Only those trees whose crown coincides with a dot are marked for height measurement. If more than one dot appears on a crown, the sample average is weighted accordingly.

Average crown width and number of merchantable stems 4.6 inches in d.b.h. and larger were obtained by measurement of all merchantable trees on the tenth-acre plots. Because the measurement of crown width is a relatively easy procedure, all crown widths were measured to obtain an average stand crown width.

Average diameter (d.b.h.) for each photo plot was predicted from estimates of average stand height ($\overline{H}$) and crown width ($\overline{CW}$) as follows:

$$\overline{d.b.h.} = -13.26 + 8.24 \log_{10} (\overline{CW})(\overline{H}) \qquad (7)$$

Total cubic-foot volume per acre was determined by equations 7 and 2.

$$T.C.F.V. = .005454 \ (\text{Predicted } \overline{d.b.h.})^2 \times \left(\begin{matrix}\text{No. stems} \\ \text{per acre}\end{matrix}\right) \times \ (4.5 + .44\overline{H}) \qquad (8)$$

Table 3 presents a comparison between ground measures and photo estimates of average crown width, tree height, d.b.h., number of trees, basal area, and volume.

Table 3. Comparisons of ground and photo measures of average crown width, height and number of trees, to predict average d.b.h., basal area and total cubic foot volume per acre.

METHOD 2

Plot Number	Average Crown Width		Average Height of all Trees		Ave. d.b.h.		No. of Trees per Acre		Basal Area		Total Cubic volume	
	Ground[1]	Photo[2]	Ground[1]	Photo[3]	Ground[1]	Photo[4]	Ground[1]	Photo[2]	Ground[1]	Photo[5]	Ground[1]	Photo[6]
1	6.9	7.3	53.6	52.5	8.0	8.0	390	390	136	136	3669	3760
2	5.9	5.7	44.0	43.8	6.5	6.5	580	580	133	133	3078	3162
3	5.1	4.9	53.8	51.2	6.4	6.5	780	800	174	184	4925	4973
4	5.1	5.0	54.6	54.0	6.8	6.8	810	790	204	199	5968	5623
5	8.5	8.2	65.9	69.1	9.9	9.4	280	280	150	135	5054	4712
Average all plots	6.3	6.2	54.4	54.1	7.2	7.2	568	568	159.4	157.4	4539	4446

1 Ground estimates obtained from Table 1 based on plot measurement of all trees 4.6" in d.b.h. and larger.

2 Average photo crown width and no. of trees based on measurement of all trees estimated to be 4.6" in d.b.h. and larger on tenth-acre photo plot.

3 Average height of 20 to 30 point sampled trees on photo-plot (sampling proportional to crown area).

4 Photo average d.b.h. = $-13.26 + 8.24 \text{ Log.}_{10} (\overline{CW}) (\overline{HT})$. Equation 5

5 Photo basal area per acre = (number of trees on tenth-acre photo plot) (.005454) (Photo average d.b.h.)^2 x (10).

6 Photo total cubic foot volume per unit of basal area = 4.5 + .44 (average photo height of all trees estimated to be 4.6" in d.b.h. and larger). Photo total cubic foot volume per acre = (photo basal area per acre) x (Photo total cubic foot volume per unit of basal area). Equation 6

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