PACIFIC SOUTHWEST Forest and Range Experiment Station

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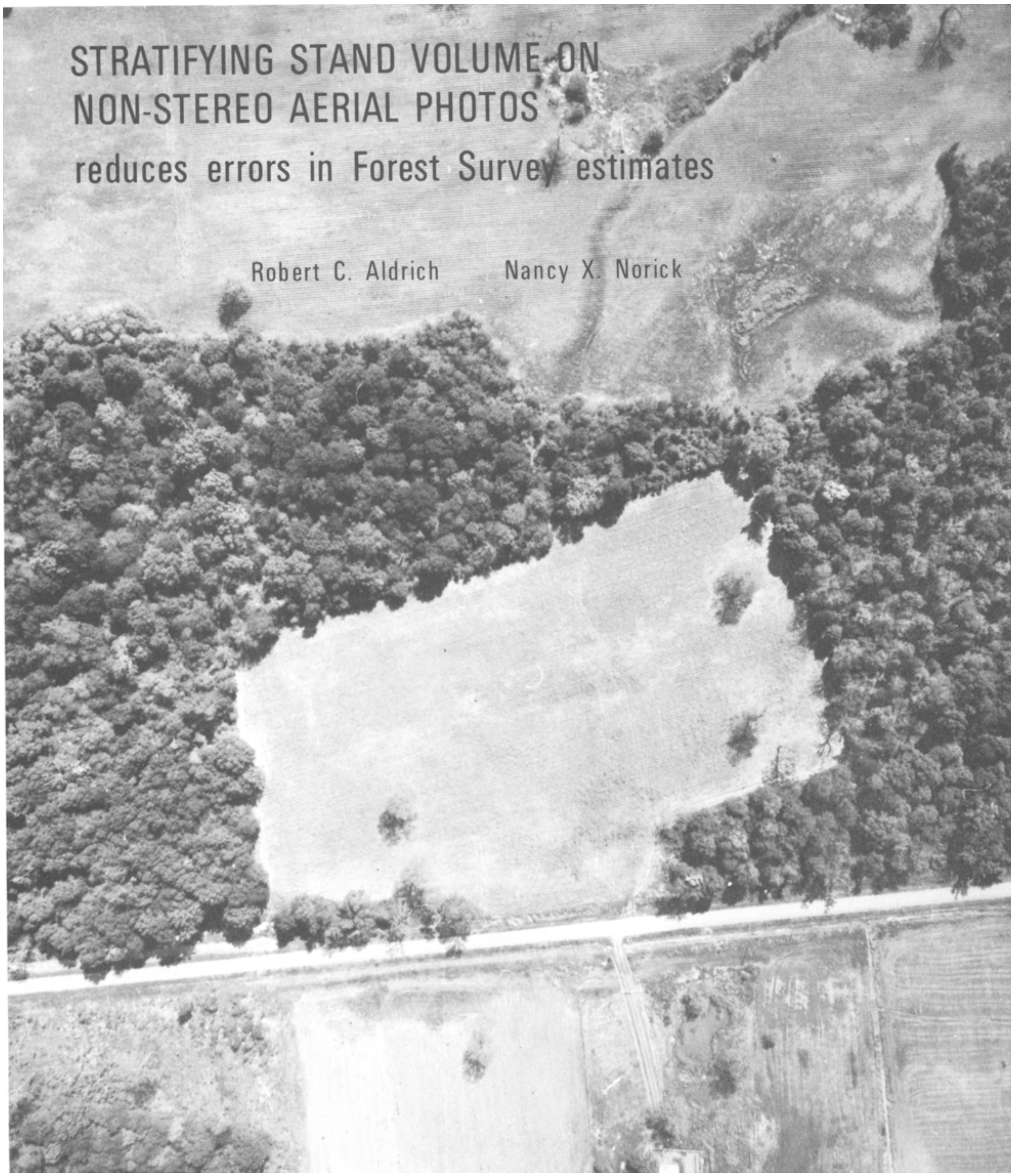

U.S.D.A. FOREST SERVICE RESEARCH PAPER PSW- 51 /1969

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The Authors

are studying problems in remote sensing of the forest environment, with headquarters in Berkeley, Calif. **ROBERT C. ALDRICH** joined the Forest Service in 1948, after earning bachelor's (1944) and master's (1948) degrees in forestry at New York State College of Forestry, Syracuse. After 6 years with the Forest Survey at the Southeastern Forest Experiment Station, he joined the Aerial Research Project at the Beltsville Forest Insect Laboratory, Md. He transferred to the Pacific Southwest Station in 1965. **NANCY X. NORICK,** a native of Cleveland, Ohio, is a 1964 graduate of the University of California, Berkeley, where she majored in statistics. She joined the Berkeley Station staff in 1964, and is now a mathematical statistician.

Classifying forest stand volumes on single aerial photographs is unique to the nationwide Forest Survey [1] — stratifying volume on photographs is not. In fact, since the late 1940's aerial photographs have been used in many classification schemes, including forest and nonforest, forest type, volume, and timber stand size. These classifications are normally made by using stereoscopic viewing techniques. Why? Because most photo interpreters believe that stereo examination improves interpretation and that the addition of measurements of photo stand height is important to photo volume estimates.

Stereo techniques require more photographs to cover a given area. The additional photographs, photo handling, preparations, and the increased interpretation time all result in higher survey costs. If volume could be classified on single aerial photographs with errors equal to or less than in classifications using stereo methods, then survey costs could be reduced.

Many tests of stereo classification schemes have been reported, but we did not find any precedent for nonstereo volume classification in the literature. Of the more recent stereo classification tests, Moessner (1963) compared photo and map stratification schemes for greater efficiency. He found that in volume estimating, photo volume classes offer the best means of stratification. Cubic-foot volume determined by photo measurements and photo volume tables is considered more useful than any other stratification scheme. Estimating commercial forest land area, MacLean (1963) found combined field and photo surveys 6 to 15 times as efficient as field surveys alone. Stellingwerf (1967) found that he could do as well using stereograms to classify volume as with other methods using photo volume tables.

Any of these stratifications will reduce the number of ground sample plots without sacrificing accuracy. As a result, national objectives [2] of accuracy in the Forest Survey for total cubic-foot volume could be met at the least possible cost. But the big question is: "Can single aerial photographs be used to better advantage and improve forest volume estimates in areas where no photo volume stratification is now used?"

This paper reports a study to determine if the efficiency of extensive forest surveys in the southeastern United States could be improved by using photo volume stratification on single aerial photographs. Photo stratification was done after the ground sample plots had been selected, the plots having been selected and permanently established in an earlier survey. This unique situation complicated the problem because variance for stratum proportions estimated after sampling had to be added.

METHODS

The study was made in the Piedmont area of North Carolina *(fig. 1).* Ten counties were selected to form a continuous block of about 3.25 million acres. Ground volume data were collected on 548 commercial forest locations during the summer of 1964 by using 10-point clusters.[3] To verify photo land use classifications and to measure shifts in land-use between non-forest and forest area, 371 non-forest locations were examined.

Photographic Techniques

The photographs used in the study were conventional U.S. Department of Agriculture, [4] 9- by 9-inch panchromatic 1:20,000 scale prints. The aerial photography was taken 2 to 5 years before the 1964 survey. All permanent ground sample locations were marked on the photographs at the time of the survey.

Forest locations in three counties adjoining the

[1] Forest Survey is a branch in the Division of Forest Economics and Marketing Research, Forest Service, U.S. Department of Agriculture, Washington, D.C. The Forest Survey was authorized by the McSweeney-McNary Forest Research Act of May 22, 1928.

[2] The allowable sampling error in the eastern United States is 5 percent (in terms of one standard error) per 1 billion cubic-feet of growing stock on commercial forest land. The allowable error in the western United States is 10 percent.

[3] Plots were regular Forest Survey field locations for Unit 3, North Carolina. We thank the Southeastern Forest Experiment Station, Asheville, N.C., for the use of this information.

[4] Aerial Photography Division, Eastern Laboratory, U.S. Agricultural Stabilization and Conservation Service, Asheville, N.C.

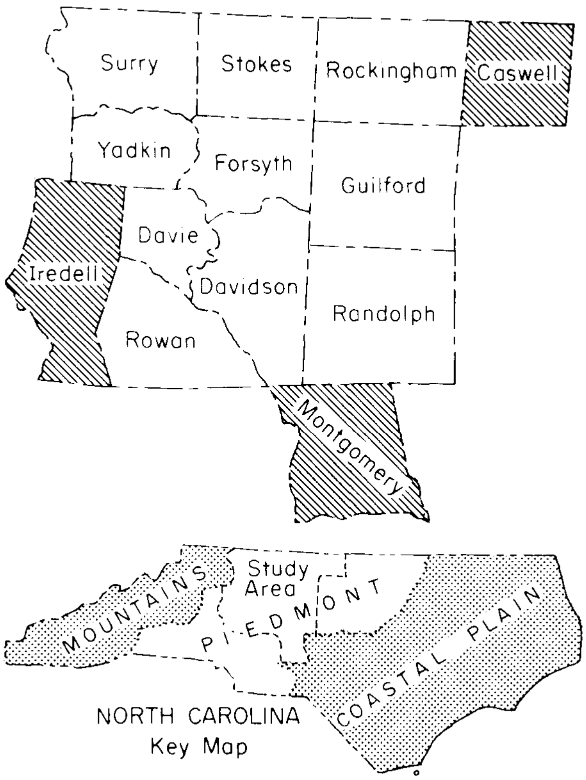


Figure 1.—*The photo volume classification study was made in 10 counties of the Piedmont area of North Carolina. In three other counties, shown by hatch marks, a study was made of photo interpretation techniques.*

study area were used to develop and test photo interpretation techniques *(fig. 1).* These methods included a cubic-foot volume classification based on crown closure and crown diameter, definitions for three broad forest types, and standards for measuring crown closure and diameter.

Cubic-foot volume classes were defined by studying the distribution of volume in 162 forest locations. By intuition, if we could stratify extremely low and extremely high volume plots by photo interpretation the mean volume variation should be reduced. Since these extremes of volume are easiest to recognize on aerial photographs, our aerial classification scheme was designed to take advantage of this characteristic.

We separated stands into six nonstereo-photo volume classes. Class boundaries were arbitrarily selected by examining the frequency distribution for 162 forest plots in three counties adjoining the study area.

Class	Cubic-foot volume
1	0 (nonforest)
2	1 to 100
3	101 to 400
4	401 to 1,250
5	1,251 to 2,250
6	2,251 +

Forest-type definitions were based upon what a photo interpreter can see best—the visible tree crowns. They were broad classifications—easily arrived at by mentally dividing the visible crown cover into quarters. Since pines are the most readily recognized trees on panchromatic photography, taken in winter and early spring, type definitions were based upon the ratio of pine to hardwood crowns:

- *Pine:* More than 50 percent of the visible crowns in the stand are pine species.
- *Pine-hardwood:* Less than 50 percent but greater than 25 percent of the visible crowns in the stand are pine species.
- *Hardwood:* Less than 25 percent of the visible crowns in the stand are pine species.

Obviously, the height component of stand volume would be difficult to measure on single aerial photographs because of their two dimensional effect. Average crown diameter and crown closure can both be readily measured. They were defined this way:

- *Crown closure:* The proportion of the ground area within a circular 1-acre photo plot covered by the dominant stand. In an unpublished study in 1952, Aldrich found that 10 feet is a good dividing line between merchantable and unmerchantable trees in the southeastern United States. Thus, if there are trees over 10 feet in crown diameter, only these are considered dominant stand. If there are no tree crowns over 10 feet in diameter then trees under 10 feet are considered dominant. Crown closure is expressed as a percent.
- *Average crown diameter:* The average for the dominant stand as defined under crown closure.

A crown closure comparator (Aldrich 1967) was developed to measure average crown diameter and crown closure *(fig. 2).* This aid is based on nine 10-percent crown closure classes and four 10-foot crown diameter classes. It gives the interpreter a basis for comparing closure standards directly with the photo plot in question. The introduction of crown diameter helps in decisions that are often difficult because of differences in timber size.

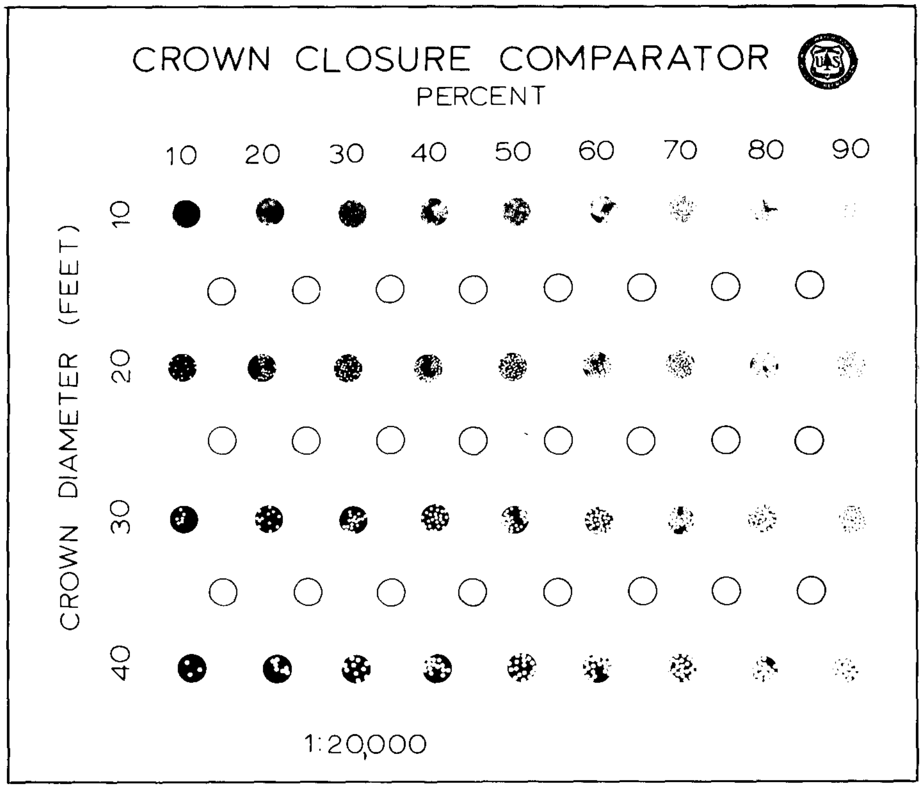


Figure 2.—*The crown closure comparator used for 1-acre forest plots on 1:20,000 scale photographs is normally reproduced as a positive transparency.*

Volume Classification

We had no precedent to follow in using non-stereo photo coverage for volume classifications. Therefore, our first problem was to associate crown closure and crown diameter with stand volume. Forest plots in three counties used for techniques development were classified by forest type, crown closure and average crown diameter. Closure was measured to the nearest 10-percent class, and crown diameter interpreted to the nearest 5 feet. The average crown diameter was plotted over cubic-foot volume measured on the ground for each 10-percent crown closure class *(fig. 3).* A line was ocularly fitted through the scatter of points, and the five volume classes were delineated on graphs. From the scatter graphs, we developed a cubic-foot volume class table *(table 1)* for use in the 10-county test as the basis for stratifying.

Is there a real relationship among crown closure, crown diameter, and cubic-foot volume and, if so, what is the best equation form to express this relationship? To find out, we tested these parameters using multiple regression techniques on a computer. Three equations for cubic-foot volume were tested for best fit; for pine type, they are:

(1) $V = a_1 + a_2 (D) + a_3 (C) + a_4 (C^2)$

(2) $V = a_1 + a_2 (D) + a_3 (C) + a_4 (C \times D)$

(3) $\text{Log}(V) = a_1 + a_2 (D) + a_3 (C) + a_4 (C \times D)$

in which: C = crown closure percent and D = crown diameter in feet.

The best equation form was also applied to pine-hardwood and hardwood types, and the multiple correlation coefficients (R) were computed and tested for significance.

Photo Interpretation

To test the accuracy of photo interpretation, we had five photo interpreters examine 548 plots classified on the photographs as forest. They used a 3-power magnifier mounted on a plywood board. Before beginning, the interpreters were instructed in the specifications for identifying forest type and measuring crown closure and crown diameter. They also studied stereograms that illustrated the six non-stereo volume classes *(fig. 4).* Each interpreter also performed a preliminary test on 60

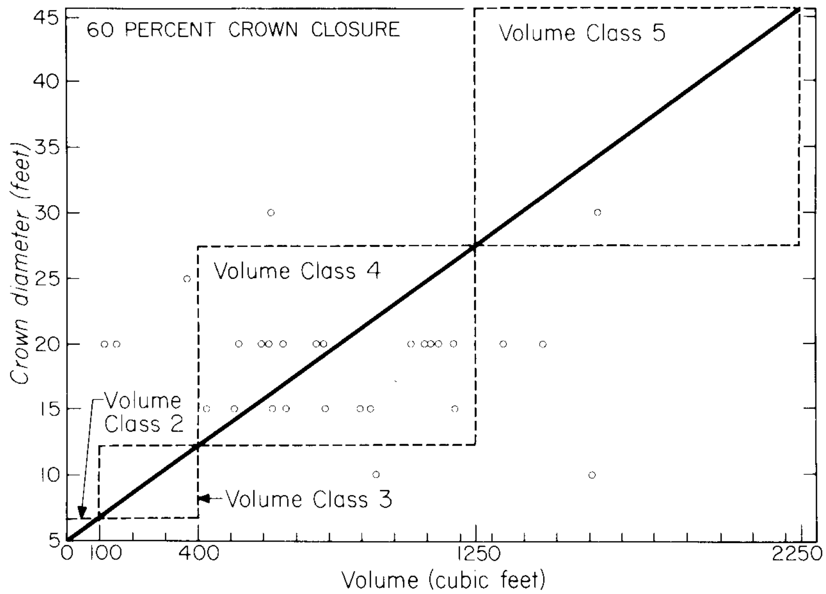


Figure 3.—*Scatter diagram for 60 percent crown closure class shows volume class limits, by crown diameter.*

Table 1.--*Cubic-foot volume class table based on 162 single-photo observations of* crown *closure and crown diameter* [1]

Crown diameter (feet)	Crown closure (percent)									
	0	10	20	30	40	50	60	70	80	90
	Cubic foot volume class[2]									
0	1	1	1	1	1	1	1	1	1	1
5	1	2	2	2	2	2	2	2	2	2
10	1	2	3	3	3	3	3	3	3	4
15	1	3	3	3	4	4	4	4	4	4
20	1	3	3	4	4	4	4	4	4	5
25	1	3	4	4	4	4	4	5	5	5
30	1	3	4	4	4	4	5	5	5	5
35	1	3	4	4	4	5	5	5	5	6
40	1	3	4	4	5	5	5	6	6	6

[1] Data outside of outlined area were added empirically to complete table for all possible combinations of crown diameter and crown closure. These data were used by a computer in decision-making.

[2] Class: Volume (cubic-feet)

Class	Volume (cubic-feet)
1	0 (nonforest)
2	1-100
3	101-400
4	401-1,250
5	1,251-2,250
6	2,251 +

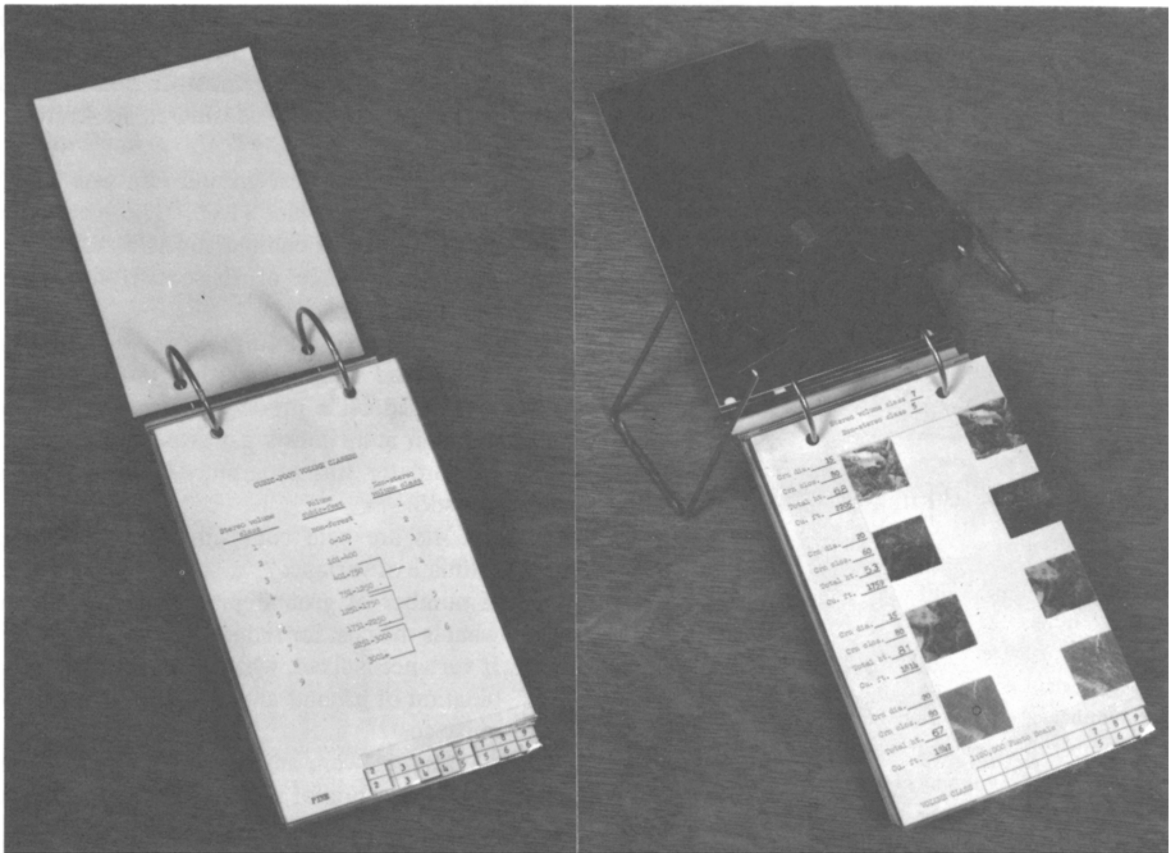


Figure 4.—*Stereogram illustrations for cubic-foot photo volume classes were used in training photo interpreters.*

plots in adjoining counties to check for consistency in interpretation and for conformance with measurement standards. Data for the 548 forest plots provided by the five interpreters were analyzed by analysis of variance.

Non-Stereo Volume Stratification

Stratified sampling can result in great gains in precision under certain circumstances. The method requires that a population be divided into subpopulations, or strata, and that a simple random sample be taken in each stratum. If each stratum is homogeneous, i.e., the measurements of the variable of interest vary little from one another within the stratum, a precise estimate of the stratum mean can be obtained with a small sample. And the estimates can be combined into a precise estimate for the population.

This method is not applicable, per se, to the present problem because the population was not divided into strata before sampling. Therefore, a random sample[5] was not taken within each stratum.

Post-sampling stratification is valid only when the exact proportion of the population falling in each stratum is known (Cochran 1963). If the proportion is estimated from the sample itself, the estimate of the population mean, or total, would be identical with the estimate obtained from simple random sampling. Hence, no gain in precision could be realized. On the other hand, if we estimate the proportions in the strata from an independent photo sample, the variance of the population mean would be greater than for pre-sampling stratification. This is because variance for the estimated proportions must be added to the total. If, however, the strata are homogeneous, we will still have a gain over a simple random sample estimate.

The Forest Survey sampling design in the

[5] The Forest Survey sample is systematic, but random sampling is assumed.

southeastern United States incorporates permanent ground sample plots that were not selected from volume strata. Hence, before a statistical measure of variance can be computed for a survey design using photo stratification after ground sampling, a new variance equation was necessary. This equation included the additional variance added for strata proportions found after sampling:

$$S_{\bar{y}}^2 = \Sigma_{j=1}^{h} S_j^2 \left(\frac{1}{n} - \frac{1}{M}\right) \left[\Pi_j + \frac{(1-\Pi_j)}{N} \left(1 - \frac{N}{M}\right)\right]$$

$$+ \frac{1}{N} \left(1 - \frac{N}{M}\right) \Sigma_{j=1}^{h} \Pi_j (\bar{Y}_j - \bar{Y})^2$$

$$+ \Sigma_j \frac{(1-\Pi_j)}{n^2 \Pi_j} \left[\Pi_j + \frac{(1-\Pi_j)}{N} \left(1 - \frac{N}{M}\right)\right] S_j^2$$

$\bar{Y}$ = population mean of variable Y (net cubic-foot volume)
h = number of strata
n = number of ground plots
n_j = number of ground plots falling into stratum j
N = number of photo plots
N_j = number of photo plots in stratum j
M = number of plots in population
Π_j = proportion of plots in population in stratum j
$W_j = \frac{N_j}{N}$, an estimate of Π_j
S_j^2 = the variance of Y in stratum j
$\bar{Y}_j$ = the mean of Y in stratum j

$$s_j^2 = \frac{\Sigma_{i=1}^{n_j} (Y_{ij} - \bar{Y}_j)^2}{n_j - 1}, \text{ an estimate of } S_j^2$$

$$\bar{y}_j = \frac{\Sigma_{i=1}^{n_j} Y_{ij}}{n_j}, \text{ an estimate of } \bar{Y}_j$$

$$\bar{y} = \Sigma_{j=1}^{h} W_j \bar{y}_j, \text{ an estimate of } \bar{Y}.$$

A computer simulation model was made up from data from 919 forest and non-forest sample plots in the 10-county area. Photo interpretation data for one experienced interpreter were used as computer input for the model. The relative efficiencies of various sample designs were examined by using an estimate of the variance and costs of ground and photo plots. This manipulation of the data was made possible by a random plot generator and a series of computer programs.

In this study, we assumed that ...

1. The 919-plot sample was random and normally distributed.
2. Both forest and non-forest photo plots were considered alike, i.e., they were examined without bias just as they were in the 1964 land-use classification. From this examination they were classed as forest or non-forest. A non-forest plot was considered in stratum 1 or 0 volume.
3. The cost of a forest ground plot was $30.00 and a non-forest plot $1.00.[6] The ground plot cost used in cost comparisons was based on a weighted average of these two figures, or $16.79.
4. The non-stereo photo plot cost was $0.07 as determined from the preliminary studies. It was based on a production rate of 40 plots per hour at an hourly pay scale of $2.80.

The computer was programed to answer these three questions:

1. If costs are held constant, what is the best estimate of variance?
2. If number of ground plots is held constant, what is the cost for reductions in variance?
3. If variance is fixed, what is the optimum combination of ground and photo plots that minimize cost?

The questions were answered for both a 2- and 4-strata classification of volume. The strata are defined as:

	Volume (cu.ft.)
2-strata:	
1 (non-forest)	0
2 (forest)	1 to 2,250 +
4-strata:[1]	
1 (non-forest)	0
2 (forest)	1 to 400
3 (forest)	401 to 1,250
4 (forest)	1,251 +

[1] The 6 strata described under photo interpretation techniques were modified because of an insufficient number of plots in proposed stratum 2 and 6. Plots in these strata were combined with original stratum 3 and 5, respectively.

The effect of forest type strata on variance reduction was also tested.

Non-Stereo vs. Stereo Stratification

Comparing the efficiencies of non-stereo and stereo photo volume stratification for the same population was unique. In this study, we wanted to find out if stand height would improve the efficiency of photo volume stratification. The cost of

[6] Ground plot costs estimated by Joe P. McClure, Forest Survey Project Leader, Southeastern Forest Experiment Station, Asheville, N.C.

a non-stereo photo volume plot was \$0.07; a stereo plot cost was \$0.17. Thus, the cost of a stereo photo sample design was about two and one-half times that of a non-stereo photo sample. To justify this difference, we had to show a substantial reduction in the Forest Survey sampling error by using stereo classification of volume.

Briefly, these are the steps we followed to prepare the photographs for interpretation:

1. Transferred the 919 photo plots in the study area to stereo photo coverage using a mirror stereoscope.
2. Located principal and conjugate principal points and marked them by a pin prick.
3. Found photograph scale by converting photo enlargement ratio factors furnished by the U.S. Agricultural Stabilization and Conservation Service office in Asheville, N.C., as follows:

$$\text{Scale} = \frac{1}{R(E)}\ 1\ \ R(E)$$

in which:

R = enlargement ratio factor.

E = enlargement scale in thousands (3960).

4. Fastened photographs in correct orientation with magnets *(fig. 5)* by using a photo alignment guide made of rolled steel on a plywood base. The correct orientation was facilitated by a clear plexiglass alignment rule with two pins 7 inches apart. The pins were placed through the photograph centers and into center holes in the steel alignment guide. Each photograph was rotated until a line connecting the pins on the alignment rule passed through the conjugate principal points. The magnets were placed at the photograph corners and the alignment rule removed.

An Old Delft Scanning Stereoscope was used to help interpret the photographs after they were correctly oriented. Crown diameter and closure were measured by the same standards used in the non-stereo part of the study. Average stand height was defined as the average for the dominant stand. Therefore, if there were trees more than 10 feet in crown diameter, only they were considered the dominant stand. When only trees less than 10 feet in crown diameter were present, they were considered the dominant stand. The total height was expressed in terms of differential parallax measured to the nearest .01 mm. with a Zeiss Stereometer. Differential parallax (dp) was converted to total height (h) in feet using the equation, $h = \frac{(FL \text{ X } S) \text{ X } dp}{AB + dp}$ in which FL = focal length (.687 ft.), S = scale number (20,000), and AB = air-

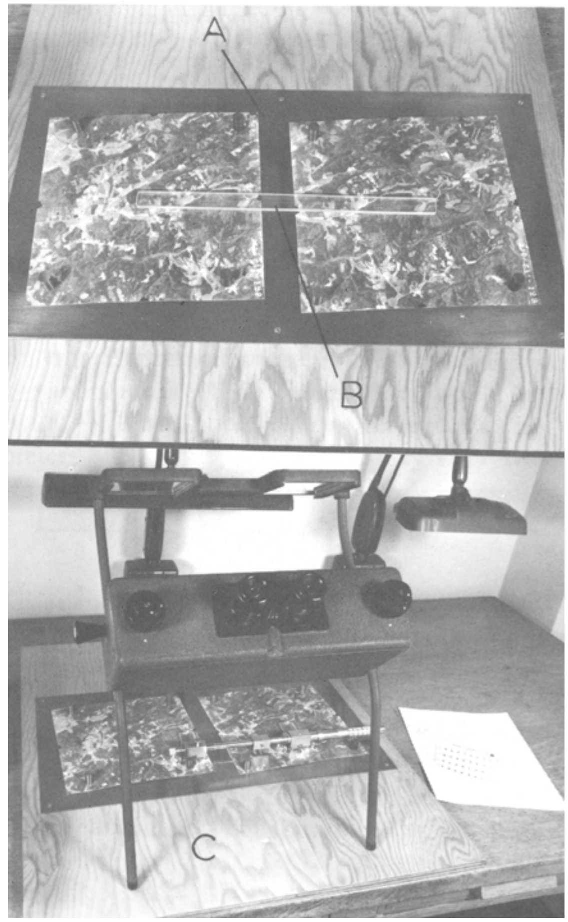


Figure 5.—*A photo alignment guide was developed for rapid orientation of overlapping photographs: (A) rolled steel plate with etched aligned center points; (B) photo alignment rule; (C) two overlapping photographs correctly oriented with Old Delft Stereoscope and Zeiss Stereometer.*

base in mm. A computer subroutine made this conversion. Forest type was recorded for each plot as previously defined for the non-stereo part of the study.

Volume classes were defined as:

Class:	Volume (cu. ft.)
1	0 (non-forest)
2	1-100
3	101-400
4	401-750
5	751-1,250
6	1,251-1,750
7	1,751-2,250
8	2,251-3,000
9	3,000 +

Table 2.--*Stand volume class table for stereo interpretation; 50 foot height class* [1]

STAND HEIGHT--50 FEET

Crown diameter *(feet)*	Crown closure (percent)									
	0	10	20	30	40	50	60	70	80	90
	Cubic-foot volume class [2]									
0	1	1	1	1	1	1	1	1	1	1
5	1	2	3	3	3	4	4	5	5	5
10	1	3	3	4	4	4	5	5	5	5
15	1	4	4	4	5	5	5	5	6	6
20	1	4	4	5	5	5	6	6	6	6
25	1	5	5	5	5	6	6	6	6	7
30	1	5	5	6	6	6	6	7	7	7
35	1	5	6	6	6	7	7	7	7	8
40	1	6	6	6	7	7	7	7	8	8

[1] Data outside of the outlined area were added empirically to complete the table for all possible combinations of crown diameter, crown closure, and stand height. These data were used by a computer in decision-making.

[2] Class: Volume (cubic-feet)

Class	Volume (cubic-feet)
1	0 (nonforest)
2	1-100
3	101-400
4	400-750
5	751-1,250
6	1,251-1,750
7	1,751-1,250
8	2,251 +

An aerial cubic-foot volume table [7] based on the three components of volume — crown closure, crown diameter, and total height — was converted to a volume class table *(table 2).* Volume class 9 was combined with class 8 because it was apparent that too few plots would fall in the former class. The volume class table was written into a computer program to stratify photo plots into classes.

RESULTS

Best Volume Relationship

The best relationship among the variables crown closure (C), crown diameter (D), and net cubic-foot volume (V) for pure pine type was expressed by the equation:

$$V = a_1 + a_2(D) + a_3(C) + a_4(C \times D).$$

hip is .682.

When the equation was used for all forest types it resulted in the following multiple correlation coefficients and levels of significance:

	Number of plots	R
Pine	58	[1] .682
Pine-hardwood	[2] 29	[3] .429
Hardwood	69	[4] .352

[1] Significant if greater than .379 at 5 percent level of significance; significant if greater than .449 at 1 percent.

[2] Insufficient samples.

[3] Not statistically significant.

[4] Significant if greater than .336 at 5 percent level; not significant at 1 percent.

The photographs used in this test were taken in winter. This means that pine crowns were fully resolved and easily separated from hardwoods. Hardwoods on the other hand were in most in-

[7] Aerial stand volume table for southern pine. (Unpublished report on file at Southeastern Forest Experiment Station, Asheville, N.C.)

stances (an exception was white oak) completely leafless and difficult to resolve for measurements. This difference explains why the multiple correlation coefficient (R) for pine was greater than for either of the other two types and why (R) for pine-hardwood was greater than that for hardwood. This relationship will always be true in the southeastern United States, where almost all aerial photography of agriculture is taken in the late fall, winter, and early spring.

Interpreters' Accuracy

Analysis of variance to test crown closure and crown diameter means showed that there was a significant difference among all five interpreters. Duncan's Multiple Range Test was used to compare the means by individual interpreter. In the measurement of closure, only two interpreters were not different from each other in their interpretations. A similar test for crown diameter showed that three interpreters were not significantly different from each other in their interpretations. These results suggest that the effectiveness of nonstereo interpretation may depend largely upon the interpreter.

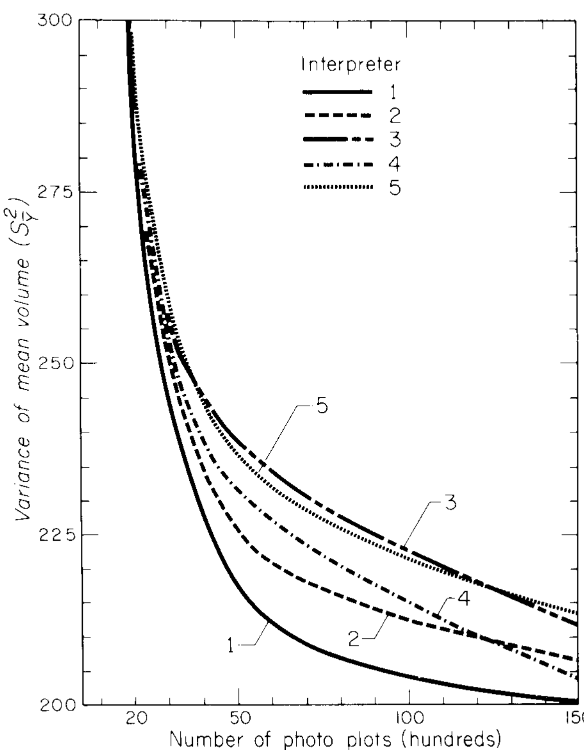


Figure 6.—*Variance of mean volume per acre ($S^2_{\bar{Y}}$) for five interpreters using nonstereo classification shows interpreter differences. A fixed ground sample of 919 plots was examined.*

The abilities of five interpreters to classify cubic-foot volume were compared *(fig. 6).* Interpreter No. 1 was more familiar with the area than the other interpreters. Moreover, the cubic-foot volume class table was based upon his measurements in the preliminary study. This should have given us greater confidence in his results, but it did not necessarily mean that he was a better interpreter. Despite the dispersion of the curves, the mean volume variance for all five interpreters would be within 17 if 8,000 photo plots were used. All interpreters showed a gain in efficiency over two strata.

Non-Stereo Volume Stratification

The data were first analyzed by forest types. This analysis proved that type strata did not contribute significantly to the reduction of mean volume variance. Therefore, the remaining analysis was done with the data combined. Only data for interpreter No. 1 were used in the analysis.

When the 919 sample plots are treated as a random sample without photo stratification, the mean net volume per acre was 432 cubic-feet, with a variance of 385. The corresponding cost was $15,593.

We held the cost constant ($15,593.00) and introduced two-stage stratified sampling. By varying the number of ground and photo plots, a low variance of 233 cubic-feet was reached by reducing the ground plots to 850 and adding 16,724 photo plots in two strata *(table 3).* If 4 strata are used, 825 ground plots and 22,784 photo plots would reduce the variance to 206 cubic-feet *(table 4).*

If the number of ground plots were held constant at 919, changes in the number of photo plots caused reductions in variance *(fig. 7).* By adding 8,000 photo plots in two strata the variance was reduced to 237. If four strata were used, the same number of photo plots reduced variance to about 210. The added cost for the four-strata method would be $560.

For a fixed variance of mean volume of 206 cubic-feet, we found that 4-strata photo volume stratification did not reduce cost below that for ground plots alone. The optimum sample for the lowest variance at the least cost would require 925 ground plots and 9,370 photo plots at a cost of $16,350. This requirement does not mean that we cannot reduce survey costs by using photo volume

Table 3.--*Comparison of the variance of mean volume per acre ($s^2_{\bar{y}}$) for 2- and 4-strata double sample designs at fixed cost of $15,593*[1]

Ground plots (number)	Photo plots	Variance ($s^2_{\bar{y}}$)	
		2-strata	4-strata
	Number	*Cubic feet*[2]	
550	89,442	360	312
575	83,382	356	309
600	77,322	326	292
625	71,262	335	280
650	65,203	314	263
675	59,143	315	253
700	53,083	293	244
725	47,023	283	236
750	40,964	278	231
775	34,904	264	226
800	28,844	271	218
825	22,784	251	206
850	16,724	233	217
875	10,665	247	211
900	4,605	256	229

[1] Cost of a simple random sample of 919 one-acre ground plots. Mean volume per acre is 432 cubic-feet with a variance of 385.

[2] Average of six variances.

Table 4.--*Optimum combination of ground and photo plots for lowest variance*[1] *at three fixed cost levels*

Fixed cost (dollars)	Ground plots	Photo plots	Variance ($s^2_{\bar{y}}$)
	Number		*Cubic feet*
	2-STRATA		
11,965	643	11,211	321[2]
15,5933	850	16,724	241
19,491	1,101	11,574	193
	4-STRATA		
11,695	638	12,423	284
15,593	855	15,513	209
19,491	1,099	12,059	171

[1] Average of 10 variances and ground and photo samples around the lowest point.
[2] Mean volume for a simple random sample was 432 cubic feet, with a variance of 385.
[3] Cost of a simple random sample.

stratification. Several combinations of photo and ground plots will reduce the variance of mean volume per acre, costs, or both. For instance, if we are interested in estimating only the mean volume per acre, the number of ground plots can be reduced and photo stratification after sampling used to reduce variance from 385 cubic-feet for simple random sampling to 250 cubic-feet for $13,000—a 17 percent reduction *(fig. 8).* On the other hand, if we want to keep the ground sample intact to measure growth, timber quality, mortality, and stocking in addition to volume, we can reduce vari-

Figure 7.—*By combining 2 or 4 non-stereo photo volume strata with ground sampling, variance can be reduced below that for random sampling with ground plots only. A fixed ground sample of 919 plots was examined.*

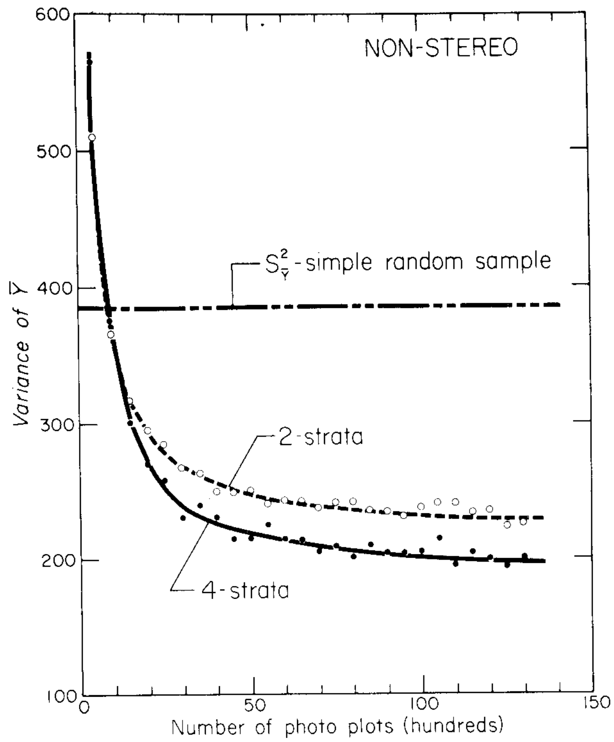
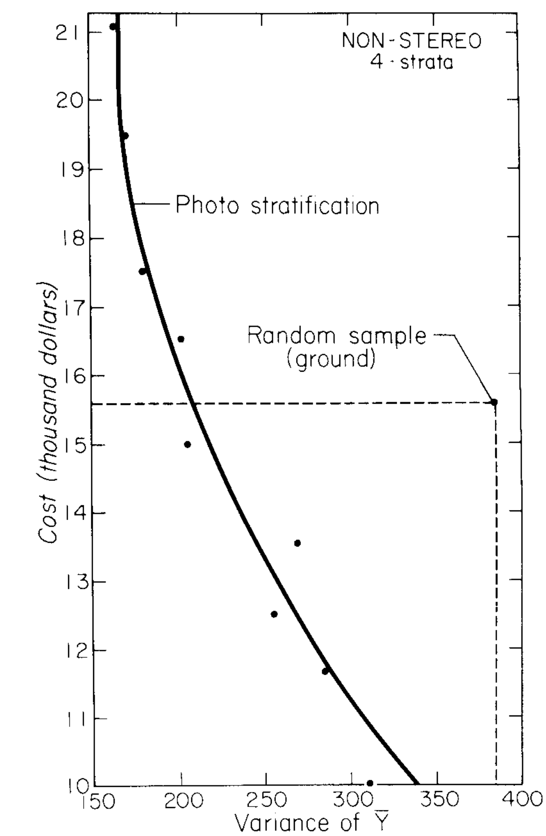


Figure 8.—*The mean volume variance was reduced by using non-stereo photo volume stratification combined with a permanent ground sample. The dashed lines represent the cost and variance for a simple random sample using 919 ground plots.*



ance to 175 cubic-feet by increasing the cost to $18,500—a 19 percent increase. Thus, depending on the survey objective, photo stratification of cubic-foot volume after ground sample selection can be a useful tool for improving forest resource statistics.

Comparison of Two Techniques

A 5-strata stereo photo sampling design increased sampling efficiency over a 2-strata non-stereo design *(table 5)*. But the increase is only slight. The fact that a non-stereo photo sampling design using 4-strata is more efficient than either stereo photo stratifications is of much greater interest. This is only true, however, when survey cost is kept constant at its present level. To keep costs constant would mean sacrificing a number of expensive ground plots (69) to pay for 6,958 stereo photo plots. Thus, we cannot benefit from a stereo volume stratification without sacrificing valuable ground data—unless additional funds are made available to cover the photo sample cost.

By holding the number of ground plots constant at 919 and varying the photo samples up to 12,000, we reduced the variance to 206 for a 5-strata photo design *(fig. 9)*. An 8-strata design with 13,000 photo samples would reduce the variance as low as 198. These reductions in variance would improve the efficiency of the present Forest Survey design only slightly. The volume error for 10 counties would be reduced from 3.60 to 3.26 percent. But this small reduction would cost $2,210.00—a 14 percent increase in survey costs.

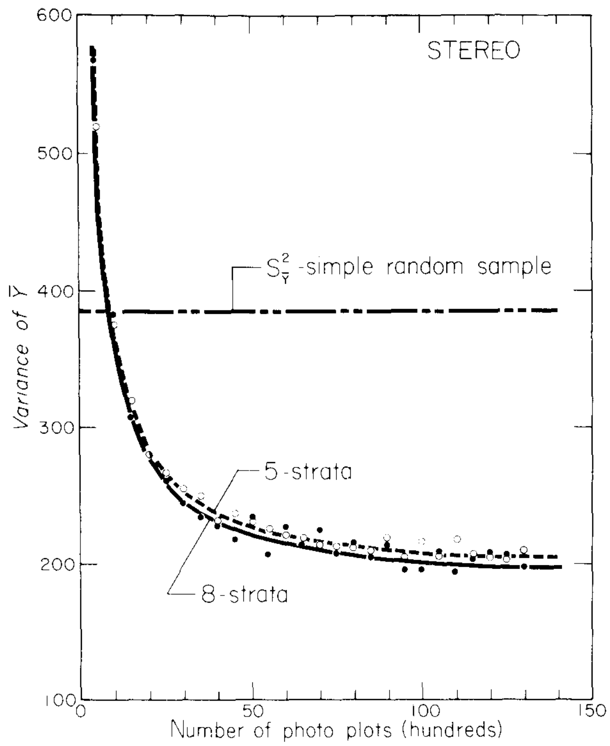


Figure 9.—*Either 5 or 8 stereo photo volume strata combined with ground sampling will reduce variance below that for simple random sampling with ground plots only. A fixed ground sample of 919 plots was examined.*

Table 5.--*Number of ground and photo plots, estimated low variance, and efficiency for non-stereo and stereo photo stratification with survey cost fixed at $15.593*

Photo sample	Ground plots	Photo plots	Lowest variance	Efficiency[1]
	Number			
Non-stereo:				
2-strata	850	16,725	241	1.00
4-strata	855	15,513	209	1.15
Stereo:				
5-strata	837	8,270	229	1.05
8-strata	859	6,051	241	1.00

[1] Non-stereo 2-strata (forest, nonforest) photo classification used by Forest Survey in southeastern United States was the base for computing efficiency. (Example:

$$\text{efficiency} = \frac{241}{209} = 1.15.)$$

DISCUSSION AND CONCLUSIONS

Why does the addition of height in the stereoscopic model fail to improve stratification by volume density classes? This addition should, by intuitive reasoning, reduce variance estimates considerably because stand height is more closely correlated with stand volume than with either crown diameter or closure. Why there is no improvement can be answered only by speculation.

Regardless of method, non-forest (0-volume strata) was correctly classified about 90 percent of the time. This class represents from 30 to 70 percent of the land area, by county, in the Southeast. Thus, when non-forest is used as a volume strata, it removes a large source of variation and dramatically improves mean volume variance. In this study, the variance for simple random sampling without stratification was reduced from 385 to 241 cubic-feet by using a 2-strata land-use classification. This was a 37 percent reduction. Any gains from other photo strata will be smaller than this reduction because of greater difficulties in making correct interpretations.

One difficulty is the fact that ground volumes for permanent 10-point cluster samples are not always comparable with volumes on circular 1-acre photo plots. Any agreements are more by chance than by correct interpretation. As a result, volume representing the photo class and actual ground volume will vary widely. For example, one combination of photo plot measurements can result in only one volume class; on the other hand volume on the ground might vary from 0 to 3,000 cubic-feet.

Plots cut-over or cleared for other purposes must be considered in the photo stratification. If not, they can result in additional variation; for example, a photo plot with large merchantable volumes on the photo and assigned a volume class of 6 (2,251 cu.ft.+) may represent 0 volume on the ground if it has been cut.

Quality of the photographs will affect interpretation. The photographs used in this study would be rated from poor to good—depending on the county. Poor quality resulted from one of two sources, or both: (1) low resolution(15-20 lines/mm.) aerial camera lenses or, (2) improper printing by electronic dodging printers. Better liaison between the user and the supplier should improve photography. In addition, specifications for aerial imagery in the future should be more rigid and should include the use of high-resolution camera lenses and films. Shorter rephotography cycles will reduce errors caused by changes due to growth, mortality and cutting.

Another problem is that specifications for photo stratification are not adequate. For instance, the relationships between volume and average crown diameter, crown closure, and average total height are not clear. We also need to know how volume is affected by such other parameters as forest type, site, presence or absence of understory vegetation, multiple crown levels, and others.

Although photo sampling using available 1:20,000 scale U.S.D.A. photography might be improved, the greatest improvement will undoubtedly come from a different approach. One possible approach might be to use photo-oriented sampling schemes, such as multiple-stage photo sampling, to supplement the present 10-point permanent Forest Survey ground samples. For instance, simultaneous small- and large-scale photography might permit multiple-stage sampling that would increase the area represented in the sample and improve estimates of volume and area statistics.

This study suggests that volume density can be stratified on single aerial photographs almost as well as by stereoscopic methods. The reduction in mean volume variance ($S^2_{\bar{Y}}$) using stratification after sampling is too small in either case to justify the additional costs and changes in current Forest Survey techniques. These conclusions apply only to the conditions involved in this study, i.e., where permanent ground samples have been selected without stratification and a layer of photo plots is used in resurveys to determine proportionate areas in volume density classes.

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