Simplified Forest Inventory Using Large-Scale 70-mm Photography and Tarif Tables

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ABSTRACT: A different approach to large-scale 70-mm aerial photo forest inventory, including stand and stock tables, was developed to eliminate the need for currently used specialized and expensive equipment (stereo plotter, laser altimeter, and tilt indicator). Limited field work is required to establish a proper tarif access number and a stem to crown diameter relationship. The use of tarif volume tables eliminates the need for photo measurement of tree heights for volume estimates.

Empirical tests using 153 photo plots of three different sampling designs all produced results that were within ±5 percent of the mean volume per acre obtained from an intensive ground inventory. Stand and stock tables were accurate for all but the smaller diameter classes. The effect of using incorrect photo scales was examined and evaluated. Using consistently incorrect photo scales produced errors in opposite directions for individual tree volume and tree frequency per plot, which results in a compensating error effect for stand volume on a per acre basis.

INTRODUCTION AND BACKGROUND

PHOTOGRAMMETRIC TECHNIQUES and aerial photo volume tables were developed in the United States during the 1950s and 1960s for timber volume inventory purposes. These early methods involved photo measurement of tree or stand height, crown size, and percent crown coverage of stands on conventional 1:10,000 to 1:20,000 scale aerial photography and conversion to volume either by individual tree or stand photo volume tables (Spurr, 1960; Paine, 1981). When adjusted by ground double sampling, these methods result in reliable net stand volume estimates, but the adjustment is costly and no estimates of the distribution of the number of trees or volumes by species and diameter classes (stand and stock tables) are provided. Another problem is that photo height measurements are time consuming, frequently biased, and difficult for the practicing forester with limited photogrammetric training (Paine, 1983).

These limitations have been overcome by making individual tree measurements on large-scale 70-mm photography (LSP) in the 1:1000 to 1:4000 range. These measurements require an accurate knowledge of photo scale at each plot location obtainable through the use of either a laser or radar altimeter (Nielsen, 1974a; Kirby *et al.*, 1983) and adjusted for tilt using a tilt indicator (Nielsen, 1974b). Another approach utilizes twin cameras mounted a fixed distance apart on a low flying aircraft and fired simultaneously to produce a stereoscopic photo pair at each plot location (Sayn-Wittgenstein, 1962; Lyons, 1961, 1966, 1967). These methods have been developed and field tested in Canada (Aldred and Lowe, 1978; Nielsen *et al.*, 1979) where the remoteness and size of timber holdings justify large capital outlays for specialized equipment (stereo plotters, digitizers, laser or radar altimeters, tilt indicators) necessary for data acquisition, extraction, and management. This is not quite the situation in the United States where timber is more easily accessible.

PHOTO SCALE BIAS

There are three sources of bias resulting from the use of incorrect photo scales when using conventional photo mensuration techniques. First, photo-measured trees heights are biased. Eliminating photo-measured tree heights for volume estimation through the use of tarif volume tables eliminates this source of bias. Second, photo-measured crown area (CA) and crown diameter (CD) are biased, resulting in a biased prediction of stem diameter at breast height (DBH). Third, and most important, an incorrect photo scale creates incorrect photo plot sizes resulting in potentially large biases in tree frequency and perhaps in volume per plot. For example, a photo scale reciprocal (PSR) that is 5 percent smaller than the true PSR results in a theoretical fixed plot size error of $(1.05)^2 = 1.103 = 10.3$ percent, producing a similar error in tree frequency per plot. However, there is a compensating error effect when volume *per plot* is determined.

The reason is best understood by looking at the PSR equation, and solving it for ground distance (GD) and photo distance (PD); i.e.,

$$PSR = GD/PD$$
$$GD = PSR(PD)$$
$$PD = GD/PSR$$

For example, if the PSR used in a photo inventory is smaller than the true PSR, the CD (see GD equation) is also small, resulting in an *under* estimate of *volume per tree*. However, this should be partially or overly compensated for when determining plot size on the photo (see PD equation) resulting in an *over* estimate of *tree frequency per plot*.

To empirically test this idea and to establish the net magnitude of the compensating error effect, erroneous photo scales of ± 5 percent were used in an empirical test (described later). These results were compared with the results obtained using accurate photo scales for each plot location. It should be noted that the expected compensating error effect would be for plot *volumes* only, and that tree frequencies per plot would remain in error.

OBJECTIVES

The primary objective of this study was to develop and test a new photogrammetric approach to LSP tree and stand measurements, including stand and stock tables, without requiring tedious photo tree height measurements and the expensive equipment required in the Canadian system. The effects of using incorrect photo scales on three different commonly used ground sampling designs for selecting sample trees for measurement were also tested.

METHODS

This study incorporated the single camera LSP approach with a fixed wing aircraft and strip sampling on a low budget. The use of LSP was required for accurate species identification of individual trees and their measurements for the development of stand and stock tables. The only specialized equipment used was a digitizing tablet and microcomputer. All software was developed in house.

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Tarif Tables

The key to this approach was the use of tarif volume tables (Turnbull, and Hoyer, 1965; Turnbull *et al.*, 1980; Brackett, 1977; Chambers and Foltz, 1979) to eliminate the need for photo tree height measurement. These tables, frequently used in the Northwest for ground cruising, express volume as a function of stem cross sectional area (basal area) 4-1/2 feet above the ground. The choice of an appropriate function or tarif table depends on tree height and stem form (rate of taper) per unit of basal area. The forester then selects the appropriate table – a separate table for each stand of timber (stratum) – by making a limited number of preliminary field measurements. Once the proper table or tables have been selected, the only required measurements are stem diameters. Additional advantages of the tarif table system are that it is easily computerized, and it allows for easy and accurate conversion among different units of measure and different utilization standards.

Photo measured tree heights would not be necessary for estimating tree volumes if one starts with appropriate tarif tables and establishes a reliable regression relationship between photo-measured crown measurements and ground-measured stem measurements.

Photography

Fourteen continuous sample flight strips were flown over a 346 acre compartment in Oregon State University's McDonald Research Forest which had recently been intensively ground inventoried. A 250-mm lens was used on a 70-mm Hasselblad camera with Aerochrome negative film. The nominal contact scale was 1:3500, with the final print being enlarged to approximately 1:1750.

The stands consisted primarily of Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) with an occasional grand fir [*Abies grandis* (Dougl.) Lindl.], planted ponderosa pine (*Pinus ponderosa* Laws.), and clumps of native hardwoods. The Douglas-fir component comprised over 95 percent of the volume and represents a wide range of stocking, age, and diameter classes. Seven of the flight strips were set aside as an independent data set for a subsequent empirical test. A subsample of photo and field measurements were taken from the remaining flight strips to establish the DBH (field measured) to CD relationship (photo measured).

Scale Determination

Without the use of a radar or laser altimeter to obtain accurate photo scales at each plot location, it was necessary to establish from one to three field and photo-measured baselines at both ends of all flight strips and calculate the average flying height above sea level separately for each flight line. With one exception, flying heights were all within ±1 percent of each other for each flight line. Photo scales at ground level for each individual plot were calculated from the average flying height for each flight line and ground elevations were determined from a topographic map.

Scale Adjustments

Even though the need for photo-measured tree heights for volume estimates was eliminated through the use of tarif tables, tree height estimates were required for correct *photo* plot size. Because the distance from the tree tip to the plot center, or centerline for line transect sampling, determines which trees are in a plot, the photo scale of each plot center and plot boundary was adjusted to the elevation at the top of each candidate tree. A candidate tree is a tree in the vicinity of a plot that is obviously in the plot or has a chance of being in the plot for any of the three sampling designs.

Adjusting photo scales to the top of each candidate tree requires a knowledge of tree heights. This was accomplished using inverse regression i.e., calculating the height as a function of tree volume and DBH. This procedure is slightly biased, but acceptable. In a similar manner, photo scales were adjusted to the visible CD elevations for measurements of CD. Visible CD is the CD that is actually visible on the aerial photo.

Careful photo observation indicated that visible CD was about one-third of the total crown length. A previous study indicated that the average crown length was 43 percent of total tree height. Therefore, the photo scale used to calculate visible CD was adjusted to 86 percent of total tree height or 100% − (0.33 × 43%) = 86 percent. Even if this figure is in error, there is no bias as long as the same procedure is used for the actual inventory and for the establishment of the regression equation.

Sampling Designs

An empirical test was made to test the accuracy of the entire system and to establish the approximate net magnitude of the compensating error effect for three different sampling designs: fixed plots (FP), variable plots (VP), and variable line transects (VLT). Foresters have used FP sampling for decades, but in recent years VP sampling has become the most widely used method. Variable line transects were used in this study because the probability of tree selection with regard to tree size is intermediate between FP and VP samplings which could be a factor in the accuracy of the stand tables.

Fixed plots consist of sample circular photo plots with a fixed radius within which all trees are measured. The probability of selecting a tree of a given DBH is therefore proportional to tree frequency of that DBH. Foresters use this method for both ground and photo sampling.

Variable plots are customarily used for ground sampling only, but there is one mention in the literature (Hitchcock, 1974) suggesting the use of VP sampling on aerial photographs. In VP sampling, the probability of a tree being selected is proportional to the basal area of the stem, frequently at DBH. On the ground this becomes a function of the tree's DBH and its distance from the plot center. Thus, one obtains a larger sample of the larger and more valuable trees and a smaller sample of the smaller trees. This is advantageous for total volume estimates but not for frequency distributions (stand tables) in the smaller diameter classes.

Variable line transect sampling is another form of variable probability sampling in which the probability of tree selection is proportional to its stem diameter. It is a function of DBH and the right angle distance to a *straight line segment* of a given distance as compared to its distance from a *point* in VP sampling. Thus, the sampling rate of large versus small trees is intermediate between fixed and variable plot sampling. For FP and VLT sample selection on the photos, crown diameters were substituted for stem diameters.

To keep parallax difference problems to a minimum, plot centers were established on the photo half way between the principal point (PP) and conjugate principal point (CPP) of each photo for the seven flight strips set aside for the empirical test. Lines connecting the PPs and the CPPs were established on the photo for VLT sampling.

Data Collection

Four to five trees were selected for measurement near the principal points on photos from 7 of the 14 flight strips to insure a wide range of crown sizes and stand density conditions. A total of 692 sample trees were measured of which 486 were used to establish the stem size to crown size regression relationship. The remaining 206 trees were set aside to be used as a validation set. The DBHs of all sample trees were measured in the field to the nearest 1/10 inch and total tree heights of the 206 tree validation set were measured to the nearest foot. The validation set was used to calculate tarif numbers for proper tarif table selection and as an independent data set for validation of the stem to crown regression relationship.

Crown maps of all sample trees were constructed and enlarged, and crown areas were calculated with the aid of a digitizing board and personal computer. Crown areas were then converted to circular crown diameters with equivalent crown areas.

Species Identification

One reason for using LSP is for accurate species identification. Lyons (1967) concluded that species identification on 1:1500 or larger scale panchromatic prints was nearly as accurate as ground identification—up to 99 percent accurate for mature conifers in British Columbia. Paine and McCadden (unpublished data, 1983) found that experienced interpreters could correctly identify tree species in mixed conifer-hardwood stands up to 90 percent of the time using 1:4000-scale aerocolor negative film (2445) enlarged to 1:2000-scale positive prints.

ANALYSIS

The steps involved in the data analysis consisted of (1) developing the stem size to crown size regression relationship, (2) developing software packages so that the entire process from photo measurement to stand and stock table production could be automated as fully as possible, (3) conducting a final empirical field test of the total system, and (4) evaluating the net compensating error effect caused by the use of incorrect PSRs.

The Stem Size to Crown Size Relationship

Based on 484 sample trees and several different regression models, a weighted nonlinear model of $DBH = 0.4713(CD)^{1.18779}$ to predict DBH from photo measured CD was selected. This equation has an adjusted 'r' square value of 0.90 and a standard deviation of 5.5 inches. This model form resulted in a homogeneous variance of the residuals, but they were not normally distributed. However, normality is only necessary for the establishment of valid confidence limits and is not essential for unbiased predictive purposes. The chosen model proved to be best compared to several other model forms as determined by Furnival's index of fit (Furnival, 1961). Using the selected equation to predict DBH of the 206-tree independent validation set resulted in an average under prediction of 0.37 inches. A second equation was developed to predict basal area directly from CA. Both equations were evaluated in the empirical test. The results are discussed later.

Software Development

Because most LSP inventories require hundreds to thousands of aerial photographs with many bits of information extracted from each sample plot, efficient methods of measurement and analysis become necessary (Spencer, 1984). To solve this problem, three software programs were written for a personal computer with digitizing board (CROWN MAP, PRECRUISE, and CRUISEIT) (McCadden, 1985).

CROWN MAP controls the entire digitizing process and calculates CA and equivalent CDs for potential "in" trees for all sampling designs. It also calculates and/or stores the grid coordinates of the photo PPs, CPPs, plot centers, end points for VLT sampling, and the tree tips of all candidate trees. These data are required for the PRECRUISE program.

Based on *individual tree tip photo scales*, PRECRUISE mathematically calculates the horizontal distance from each candidate tree to the plot center (properly adjusted for scale) or centerline for VLT sampling, and selects the "in" trees for all sampling designs. Using the regression equation, PRECRUISE then calculates all DBHs and, with the addition of an appropriate tarif number, calculates cubic-foot volume from stump height to total tree height (CVTS). The CVTS volume is then transformed to cubic-foot volume to a 4-inch top (CV4), and to Scribner board-foot volume to a 6-inch top in 16-foot logs (SV616).

The CRUISEIT program summarizes all the data created by PRECRUISE and develops stand and stock tables in 2-inch DBH classes for all sampling designs. The mean gross volume per acre is calculated as the sum of the volume per acre estimates for all diameter classes.

Empirical Test

The empirical test consisted of a photo inventory using 153 sample photo plots for each sampling design located on seven different flight strips over the same 346 acre compartment described earlier. A crown map was made of all conifers at each plot location by tracing visible crown outlines onto a clear overlay while viewing the photos with a 2 power lens stereoscope. The average photo scale was about 1:1750 after a 2× enlargement. Tree tips were all located on the crown map as well as the PPs and CPPs. Because it was not possible at this point to determine exactly which trees would be "in" any of the three plot types, the interpreter crown mapped well beyond the approximate plot boundaries to insure the inclusion of all qualifying trees. Only Douglas-fir were inventoried because the only use for hardwoods in this forest is for fuel and other coniferous species were so scarce (less than 2 percent) that it would be difficult to establish a significant DBH prediction equation.

For this test, measurement for tarif number determination was obtained from the ground cruise. The test area was stratified by tarif number into six strata and an average tarif number was calculated for each stratum. This procedure could be used anytime the photo inventory is an update of a previous inventory where tarif numbers were obtained. Without a previous inventory, tarif information could be obtained at the same time DBHs are field measured for the DBH prediction equation.

The effects of using incorrect photo scales on tree frequency and volume estimates for all three sampling designs were also evaluated. This was accomplished by recalculating the empirical test data with altered photo scales of ±5 percent and the *original* DBH prediction equation. New DBH prediction equations based on CDs obtained from erroneous ±5 percent photo scales were also developed and used, once again with the empirical test data set to predict total stand volume, stand, and stock tables.

RESULTS

The results of the empirical test using the DBH prediction equation and the best estimates of photo scale are summarized in Table 1 for volume per acre, and Table 2 for tree frequencies. The comparison ground inventory consisted of 206 independent nested (FP and VP) plots compared to the 153 photo plots of each type. The photo fixed plot sizes represented 1/5 acre on the ground. It is impossible to determine the exact average plot size of the variable probability sampling systems (photo and ground), but an attempt was made to sample *approximately* the same number of trees for all sampling plot designs—both on the photos and in the field.

The mean volumes per acre for all photo inventories (see the total row, Table 1) were all within 5 percent of the ground inventory, and the 68 percent confidence limits (standard errors) all overlap. None of the three photo sampling methods produced accurate estimates of tree frequencies for DBHs below the 10.5-inch DBH class. However, above this limit all sampling methods produced very accurate tree frequency estimates (Table 2). Photo tree frequency underestimates in the lower DBH classes were probably due to some of the smaller trees being in the understory and not visible on the photos. Because the missed trees were relatively small, they contributed little to the total volume per acre (Table 1).

TABLE 1. COMPARISON OF STOCK TABLES AND TOTAL VOLUMES FOR THREE SAMPLING METHODS WITH THE EMPIRICAL TEST

DBH Class (inches)	CV4* in 10s of cu. ft. per acre				SV616** in 100s of bd. ft. per acre			
	Ground Fixed Plots	Photo Fixed Plots	Photo Variable Plots	Photo Line Transects	Ground Fixed Plots	Photo Fixed Plots	Photo Variable Plots	Photo Line Transects
2.5	0	0	0	0	0	0	0	0
6.5	11	6	6	6	2	1	1	0
10.5	18	17	19	18	7	7	8	7
14.5	33	31	31	37	17	16	16	19
18.5	62	54	52	57	34	30	29	28
22.5	74	71	66	73	44	41	39	43
26.5	97	95	89	102	59	58	54	62
30.5	97	104	99	99	61	65	62	62
34.5	82	85	83	84	53	54	53	53
38.5	73	57	66	67	47	36	42	43
42.5	42	28	38	41	28	18	24	27
46.5	21	40	33	37	14	27	21	24
50.5	8	12	18	17	5	8	12	11
54.5	6	7	9	6	4	4	6	4
58.5+	15	0	9	4	8	0	4	3
Total <10.5 in.	11	6	6	6	2	1	1	0
Total >10.5 in.	627	601	612	636	381	364	370	386
Grand Total	638	607	618	642	383	365	371	386
Standard Error of the Total	28	26	24	24	18	17	16	16
Standard Error % of the Total	4.4	4.3	3.9	3.7	4.7	4.7	4.3	4.1

*Cubic-foot volume to a 4-inch top
**Scribner board-foot volume to a 6-inch top in 16-foot logs

TABLE 2. COMPARISON OF STAND TABLES AND TOTAL TREE FREQUENCIES FOR THREE PHOTO SAMPLING METHODS WITH THE EMPIRICAL TEST.

DBH Class (inches)	Tree Frequency Per Acre			
	Ground Plots	Photo Fixed Plots	Photo Variable Plots	Photo Line Transects
2.5	3.0	1.8	5.9	1.8
6.5	19.6	9.3	10.3	9.2
10.5	8.7	7.7	8.5	8.3
14.5	7.2	6.7	6.8	8.0
18.5	8.0	7.1	6.9	6.5
22.5	5.9	6.0	5.6	6.3
26.5	5.5	5.7	5.4	6.2
30.5	4.2	4.5	4.5	4.5
34.5	2.7	2.9	2.9	2.8
38.5	2.0	1.6	1.9	1.9
42.5	0.9	0.5	0.9	1.0
46.5	0.3	0.7	0.6	0.7
50.5	0.0	0.1	0.1	0.2
54.5	0.0	0.0	0.0	0.0
58.5+	0.0	0.6	0.2	0.0
Total below 10.5 in.	22.6	11.1	16.2	11.0
Total above 10.5 in.	45.4	44.1	44.3	47.4
Grand Total	68.0	55.2	60.5	58.4

Only the results of the empirical test using the DBH prediction equation (from crown diameter) are presented here, although the basal area prediction equation (from crown area) produced results almost as good. Basal areas were converted to DBHs for the stand and stock tables. The DBH equation produced volume estimates that were 2.3 percent low as compared to the ground inventory when averaged over all sampling designs and both measures of volume. The basal area equation overestimated the field measured volumes by an average of 2.5 percent. In addition, the photo-derived stand and stock table distributions tracked the ground derived distributions better when the DBH equation was used.

There are two possible explanations for the sampling errors (SE or $SE_{\%}$) of the photo estimates being consistently less than the field estimates even though the number of photo plots was less than the number of field plots (153 verses 206). First, it is possible that the average *plot size* was larger for the variable-probability photo sampling designs than the field inventory. This would reduce the coefficient of variation among photo plots. The same reasoning would account for the smaller SE for the variable-probability sampling designs compared to the fixed-plot designs when comparing the three photo-measured estimates. Second, it has been the experience of the authors that the coefficient of variation is usually less for photo inventories when comparing photo and field measured estimates using the same plot locations and the same size plots.

Altering photo scale ±5 percent in the cruise programs and using the *original* DBH prediction equation resulted in tree frequency errors of from −9.6 to + 11.0 percent (Table 3). However, volume per acre errors were much less, ranging from −2.1 to +3.3 percent for cubic feet and from −3.1 to +4.3 percent for board feet. The change in sign between tree frequency and volume errors indicates that the error in tree volume more than compensates for the error in tree frequency as a result of using incorrect photo scales. The compensating error effect greatly reduced the magnitude of volume errors but not tree frequency errors.

As expected, altering photo scales both in the development of the DBH equation and in the empirical test did not produce a compensating error effect. Both the frequency and volume per acre errors ranged from −8.3 to +12.2 percent for all sampling methods when using the altered photo scales.

SUMMARY AND CONCLUSIONS

The results of this study strongly indicate that it is possible to inventory coniferous forests for total volume with a reason-

TABLE 3. PHOTO INVENTORY RESULTS USING THE ORIGINAL DBH EQUATION WITH INCORRECT PSRS IN THE EMPIRICAL TEST

All values are on a per hectare basis						
Change % PSR	No. Trees Per Acre	Change %	CV4*	Change %	SV616**	Change %
FIXED PLOT						
−5	60.8	+10.1	5982	−1.5	3559	−2.4
0	55.2	0.0	6071	0.0	36461	0.0
5	50.6	−8.3	6278	+3.3	38026	+4.3
VARIABLE PLOT						
−5	67.1	+10.9	6047	−2.1	36020	−3.0
0	60.5	0.0	6176	0.0	67149	0.0
+5	54.7	−9.6	6298	+2.0	68200	+2.8
LINE TRANSECT						
−5	64.8	+11.0	6289	−2.0	37412	−3.1
0	58.4	0.0	6420	0.0	38593	0.0
+5	52.8	−9.6	6547	+2.0	39694	+2.9

*Cubic-foot volume to a 4-inch top
**Scribner board-foot volume to a 6-inch top in 16-foot logs

able degree of accuracy without the use of specialized and expensive equipment and to produce accurate stand and stock tables—except in the lower stem diameter classes.

As in previous studies, a limited amount of field work is required to establish a DBH to CD relationship. In addition, limited field work is also required to establish suitable tarif access numbers. However, the use of tarif volume tables eliminates the need for photo measurements of individual tree height, a difficult and time consuming task of questionable reliability when performed by field foresters with limited photogrammetric training and without the use of high precision instruments to remove the effect of tilt displacement.

Due to the partially compensating error effect when using incorrect photo scales, it follows that, if the DBH prediction equation is based on accurate CDs whether they are measured on the ground or on an independent set of aerial photos, reasonably accurate inventories for volume can be obtained even with errors up to 5 percent in photo scale.

It is difficult to recommend any one of the three photo sampling designs over the other two. The cost of *photo sampling* would be approximately the same for all designs and the results are similar. This is in contrast to ground sampling were VP sampling is the most efficient for volume estimation but not necessarily for tree frequency distributions. Photo FP sampling would require a few minutes less computer time and the production of crown maps would be easier. This is because the interpreter would have a better idea of which candidate trees would be in the plot, requiring less crown mapping time.

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