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Tree Volumes from Large-Scale Photos

. . . forest inventories in which a small sample of precisely-measured individual trees may replace . . . ground work.

FRONTISPIECE. Illustration of N_6. (See text on page 71).

(*Abstract on next page*)

INTRODUCTION

RESEARCH on large-scale aerial photography in forestry strives to develop an efficient system for employing such photographs in forest inventories. If this is achieved, one will sample forests with photographs of scales in the vicinity of 1:1,200 to obtain estimates of timber volume and detailed information about the distribution of tree sizes, tree species and the quality of timber.

Early phases of this research program have involved the development of hardware and techniques for taking good large-scale photographs. Next, research concentrated on identifying tree species and obtaining accurate measurements of tree dimensions and stand characteristics which are visible on large-scale photographs. For example, investigations dealt with the accuracy of the measurements of tree height, crown dimensions, and with the estimation of number of trees per acre. Many significant problems were encountered, particularly the problem of reliable determination of photographic scale, but in general it has been proved that accurate species identification and measurements were feasible (Heller *et. al.*, 1963; Avery, 1958; Kippen and Sayn-Wittgenstein, 1964).

In typical-mixed coniferous and hardwood stands, for example, one may expect to identify about 85 per cent of the trees correctly, to determine heights of trees with a standard error of estimate of about 3.5 feet, to measure crown diameters of regular-crowned trees with an accuracy of about ± 2 feet, and to miss no more than 4 per cent of the trees on a sample, representing a volume loss of only 1.5 per cent because most of the omitted trees are small (Kippen and Sayn-Wittgenstein, 1964; Kippen and Aldred, 1966). However, in most cases stem diameter, which is another important variable in forest inventories, cannot be measured directly because a view of the bole is obscured by the crowns. Nevertheless, in spite of this limitation, one is left with an impressive number of stand and tree variables which can be measured.

We thus come to another problem: "Which variables should be measured and how should they be used to estimate timber volume?" This problem has received little attention, as far as the use of large-scale photography is concerned, and we shall therefore treat it in some detail.

LARGE-SCALE PHOTOGRAPHS

First, a very important point must be made. The methods that have been established for estimating timber volume on small-scale photographs have to be changed for the application of large-scale photographs. On small-scale photographs the estimation of

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volume has been based almost exclusively on stand variables such as average crown canopy density and average stand height. The principle was "measure stands, not trees" (Smith, 1965) and "individual trees have little meaning to the photointerpreter; he sees or measures plots or stands" (Moessner, 1960); photointerpreters were urged to think in terms of average volume per acre and average stand height, etc. For large-scale photographs one must abandon this approach and instead make estimates of timber volume based on the precise examination of samples of individual trees. To do otherwise would be to waste most of the accurate information that is potentially available from large-scale photographs.

ABSTRACT: *One may look forward to forest inventories in which a small photosample of precisely measured individual trees may replace or supplement ground work and aerial stand volume tables. Tree height, crown size and several expressions of tree crowding can be measured on large-scale (>1:3000) aerial photographs, and used to estimate tree volume. Tests on Vinten 70 mm, 1:1200 scale photography reduced 17 combinations of 7 measurable variables to 11 potentially useful combinations of 5 variables for estimating tree volume. Total tree height times the logarithm of crown area stood out as the most powerful variable.*

The first problem to be investigated can therefore be restated as: "How can we estimate the volume of an *individual tree* from the variables that can be measured on large-scale photographs?" It should be emphasized that one is interested in estimating volume and not tree diameter. Foresters are so accustomed to using diameter at breast height to estimate tree volume in field sampling procedures, that they find it difficult not to include this variable at some stage. Estimates of tree diameters can be obtained if they are required (Bonnor, 1964; Minor, 1951), but they should not necessarily form the basis for estimation of timber volume; it is more accurate to relate tree volume directly to photo-measured variables.

PHOTO-MEASURED VARIABLES FOR ESTIMATING TREE VOLUME

The least useful variables for estimating the volume of an individual tree will be estimates of average stand characteristics; the most useful variables will be direct measurements of the tree under consideration. A less important, yet useful group of variables are expressions of the position of a tree in relation to its neighbors; it is known from silvicultural studies that trees which are suppressed by their neighbors tend to have different crown and stem form than trees which grow freely and dominate their surroundings.

In our search for the best variables the following were considered; all these variables can be readily measured:

- *H*—the total height of the tree; this an obvious variable which is certain to appear in any final equation.
- *CW*—the diameter of the tree crown—a questionable variable because many tree crowns have irregular shapes which cannot be properly expressed by any measure of diameter (Figure 1). In this study crown width was measured at right

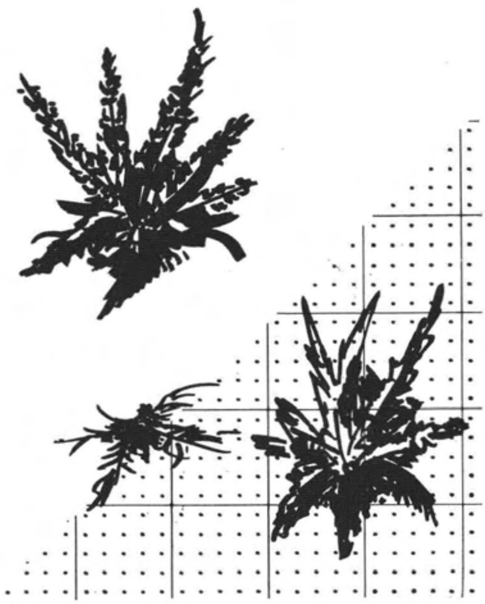

FIG. 1. Use of dot-grid for *CA* measurement of irregular crowns.

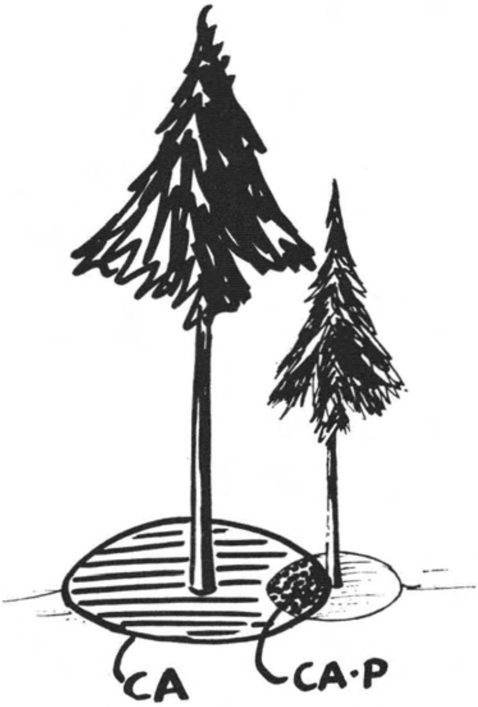

FIG. 2. Sketch showing P and $(CA \times P)$.

angles to the line drawn from the principal point through the crown center.

CA—crown area; the area covered by a vertical projection of the tree crown (Figure 2). It should be measured with a dot-grid overlay while viewing the tree stereoscopically (Figure 1).

P—the proportion of the tree crown area that is overlapped by the crowns of other trees (Figure 2). This variable is an expression of the extent to which a tree is suppressed by its neighbors. Estimates must to some extent depend upon the interpreter's subjective judgement.

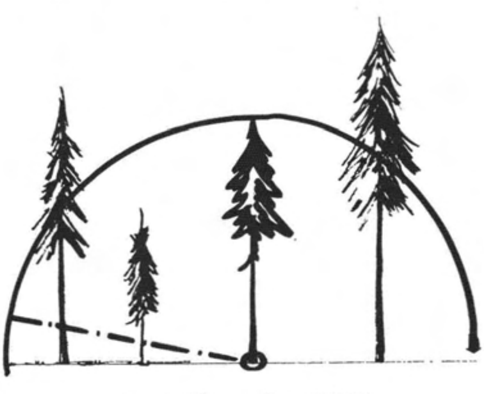

FIG. 3. Illustration of NH.

NH—the number of trees growing in a circular area surrounding the tree under consideration with the radius of this circle equal to the height of that tree (Figure 3). This variable is obviously highly correlated with H, but it is also an expression of the degree of crowding.

N_m—the number of a tree's m nearest neighbors that are taller than the tree under consideration. This is another variable expressing the relationship of a tree to its neighbors. We experimented with values of m equal to 3 and 6, i.e. N_3 and N_6 (Frontispiece).

A—the number of tree crowns that subtend an angle larger than a fixed angle (20° in our experiment) at the center of the tree under consideration. This count is easily obtained by rotating an acetate wedge, with the apex fixed at the center of the tree (Figure 4). If trees had circular crowns, A would be directly proportional to crown canopy density, and would thus be analogous to a tree count obtained with the relascope. But, A may also be regarded as a rough expression of crown density in the immediate vicinity of the tree examined.

The following combined variables were also tested:

$$H \times \log CA,\ H \times CA,\ \log (H \times CA),\ H \times (CA)^{1/2},$$
$$H \times N_6,\ H \times CA \times N_6,\ A \times CA,\ P \times CA,$$
$$H \times NH,\ \log (CA - (P \times CA)).$$

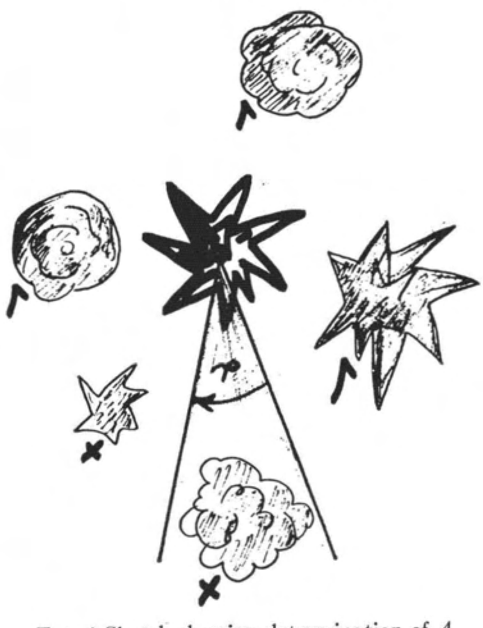

FIG. 4 Sketch showing determination of A.

TABLE 1.
RESULTS OF REGRESSION ANALYSIS

	White Spruce	*White Pine*	*Hardwoods*
Mean of dependent variable (volume, cu. ft.)	18.9	34.5	17.8
Dependent variables in equation with lowest standard error of estimate	$H \times \log CA$, $H \times CA$, CA, $P \times CA$	$H \times \log CA$, NH	$H \times \log CA$, CA, $P \times CA$
Standard error of estimate (cubic feet)	±4.95	±9.16	±6.71
Coefficient of multiple correlation	0.950	0.832	0.853
Independent variables of a consistently good equation	$H \times \log CA$, NH		
Standard error of estimate (cubic feet)	±5.57	±9.16	±7.15
Coefficient of multiple correlation	0.932	0.832	0.819

GROUND MEASUREMENT OF VOLUME

Measurements from 42 white spruce trees, 25 white pine, and 21 hardwoods (mostly maple) were obtained. Air photo measurements were made on 70 mm., 1:1,200 panchromatic photographs taken with a Vinten camera (focal length 12 inches, shutter 1/2,000 second) of a mixed forest near the Petawawa Forest Experiment Station in Ontario.

Total cubic-foot volumes inside bark were calculated from ground measurements of the above 88 trees. A dendrometer was used to measure the distance along the stem between successive 2-inch diameter steps, starting at the top of the tree and proceeding to the base. Diameter at breast height, diameter at stump height and a sample of bark thickness were also obtained for each tree. These data were fed into equations originally proposed by Grosenbaugh (1954) and modified by Honer (1965) to provide the required volumes.

PRELIMINARY SCREENING OF VARIABLES

The preliminary screening of variables was accomplished by analyzing the white spruce data; the other data were reserved for tests of regressions that were to be specified as a result of this preliminary analysis.

The screening of variables began with a stepwise regression in which variables were introduced into the regression in the order of their contribution in reducing the residual sum of squares. Stepwise regression is a most valuable method for such analysis, but it also has limitations because it leads to biased models; those interested in a clear description of this subject should read Furnival (1964).

As a result of this stepwise regression the following variables were eliminated:

$$P,\ A,\ CW,\ H \times N_6,\ H \times CA \times N_6,\ N_3,\ A \times CA,$$

$$H \times NH,\ \log\ (CA - (P \times CA)),\ H \times (CA)^{1/2}.$$

These variables either made non-significant contributions in reducing the residual sum of squares, or they were closely correlated, but inferior to other variables that were retained. For example, $[H \times (CA)^{\frac{1}{2}}]$ made a very strong contribution, but it was inevitably inferior to $(H \times \log CA)$; N_6 was better than N_3; P was replaced by $(P \times CA)$ which is not a ratio, but an absolute measure of overlap; CW was eliminated because it was inferior to CA and $(CA)^{\frac{1}{2}}$ and also more difficult to measure.

The list of eligible variables was thus reduced to the following: H, CA, NH, N_6, $H \log CA$, $H \times CA$, $\log\ (H \times CA)$, $P \times CA$. Furthermore, it appeared that it would not be necessary to have more than four variables in any regression.

REGRESSIONS

Next, a series of regressions was drawn up from the variables which had survived the screening process. One criterion was that no regression should contain more than four independent variables; also, each set of variables had to contain at least one measure of the dimensions of the tree under investigation and at least one measure of the relationship of a tree to its neighbors. Some of the results are summarized in Table 1.

It was almost inevitable that a different equation gave the lowest standard error of estimate for each species. However, these "best" equations may well include variables that appeared to be meaningful only because of peculiarities of the sample under consideration. An equation based on only ($H\times\log CA$) and NH is perhaps of more general significance, because it gave a good solution for all species groups (see Table 1). Incidentally, in some regressions the variable NH was introduced following the variable H, with which it is highly correlated; NH still made a significant contribution, which proves that its contribution is not merely due to correlation with H.

Another general conclusion was that the combined variable ($H\times\log CA$) was always superior to the joint effect of the separate variables H and $\log CA$. The combined variable ($H\times\log CA$) is probably the most powerful variable that can be used in estimating volume of trees on large-scale photographs. A further argument for its acceptance are the results of Bonnor (1964) and Minor (1960) who found that the variable ($H\times CW$) had the best correlation with diameter at breast height; the variable ($H\times CW$) is roughly equivalent to $[H\times(CA)]^{\frac{1}{2}}$, which in turn could not improve upon ($H\times\log CA$).

More extensive data will have to be analysed before the best variables for expressing the relationship of a tree to its neighbors can be isolated; in selecting these variables one should not rely on computers alone, but should begin with a consideration of the silvicultural characteristics of different species in reacting to competition. More sensitive measures of dominance and suppression of trees will inevitably lead to better estimation of volume.

In general the results obtained in this study are encouraging and the equations already precise enough to be useful. One may look forward to forest inventories in which a small sample of precisely measured individual trees will, to a large extent, replace or supplement ground work and aerial stand volume tables.

References

Avery, T. E. 1958. Helicopter stero-photography of forest plots. *Photogrammetric Engineering*, Vol. 24, No. 4.

Bonnor, G. M. 1964. A tree volume table for red pine by crown width and height. *Forestry Chronicle*, Vol. 40, No. 3.

Furnival, G. M. 1964. More on the elusive formula of best fit. Proceedings Society of American Foresters Meeting, Denver, Colorado.

Grosenbaugh, L. R. 1954. New tree-measurement concepts: height accumulation, giant tree, taper and shape. Forest Service, U. S. Department of Agriculture, Southern Forest Experiment Station, Occasional paper No. 134.

Heller, R. C., G. E. Doverspike and R. C. Aldrich. 1963. Identification of tree species on large-scale panchromatic and color photographs. Paper presented at Annual Meeting of American Society of Photogrammetry, Washington.

Honer, T. G. 1965. Height accumulation method of determining tree volume. Department of Forestry, Canada, Unpublished Report.

Kippen, F. W. and A. H. Aldred. 1966. Plot volumes from large-scale 70 mm. air photographs. Department of Forestry of Canada, Unpublished Report.

Kippen, F. W. and L. Sayn-Wittgenstein. 1964. Tree measurements on large-scale, vertical, 70 mm. air photographs. Department of Forestry, Canada, Departmental Publication No. 1053.

Lyons, E. H. 1964. Recent developments in 70 mm. stereo photography from helicopters. *Photogrametric Engineering*, Vol. 30, No. 5.

Minor, C. O. 1951. Stem-crown diameter relations in southern pine. *Journal of Forestry*, Vol. 49, No. 6.

——— 1960. Estimating tree diameters of Arizona ponderos pine from aerial photographs. Forest Service, U. S. Department of Agriculture, Rocky Mountain Forest and Range Experiment Station, Research Note No. 46.

Moessner, K. E. 1960. Aerial volume tables for ponderosa pine type in the Rocky Mountains. Forest Service, U. S. Department of Agriculture, Intermountain Forest and Range Experiment Station, Research Note No. 76.

Smith, J. H. G. 1965. Biological principles to guide estimation of stand volumes. *Photogrammetric Engineering*, Vol. 31, No. 1.

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