ANGLE-GAUGE SAMPLING OF TREE CROWN DIAMETERS FOR FOREST INVENTORY USING AERIAL PHOTOGRAPHS

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ABSTRACT:

The Forest Inventory and Analysis unit of the USDA Southern Forest Experiment Station is charged with conducting continuous inventories of the forest resources of the USA's Midsouth Region. One new approach for estimating the density of forest stands involves the derivation of a technique for obtaining stand density from aerial photographs based on the principles of selection with probability proportional to size. This is accomplished by the development and use of an aerial-photo angle-gauge that is used in a procedure very similar to the ground point-sampling technique developed by Bitterlich (1948).

Data from the 1984 forest inventory of Louisiana and the 1988 forest inventory of Tennessee were obtained; the relationship between diameter at breast height (dbh) and crown diameter was investigated and correlations and models analyzed. Sampling angles were calculated and dimensions of aerial-photo angle-gauges were determined and the gauges were constructed. Areas were inventoried using both the photo-based method and the standard ground-based method.

Though promising in theory, the angle-gauge sampling technique resulted in a forest inventory that vastly underestimated the number of trees, total volume, and total basal area of the forest resource. Problems encountered included an omission of both small diameter trees and large diameter trees from the tallied sample trees.

KEY WORDS: Remote Sensing Application, Renewable Resource, Forestry, Sampling

INTRODUCTION

The Forest Inventory and Analysis (FIA) unit of the USDA Southern Forest Experiment Station is charged with conducting continuous inventories of the forest resources of the Midsouth Region of the USA. Techniques that offer new and innovative approaches for improving the efficiency and accuracy of these inventories are in demand. Procedures based on remotely sensed data may fulfill this need by improving the timeliness of current ground-based forest surveys and by allowing efficient data collection in geographically remote locations.

The ability to obtain reliable measurements of forest stand characteristics from aerial photographs has long been recognized by both researchers and practicing foresters. However, the use of remotely sensed data, in most instances, has been limited to providing descriptions of land cover in the form of maps and summary statistics. Spurr (1948) observed that aerial photographs were used primarily to segregate forest stands, to classify them according to forest type, height, density and site, and to compile the areas of the various units. More than three decades later, Smith (1986) noted that the concept of estimating quantitative forest stand characteristics from aerial photographs had not yet reached its fullest potential.

The estimation of diameter at breast height (dbh) from photographically-measured variables has been of great interest to foresters for many years. One of the early simple linear regression models for predicting dbh from tree crown measurement was developed by Minor (1951). Husch and others (1982) described how visible crowns can be conventionally tallied from aerial photographs by crown diameter classes using circular fixed-area sample plots.

One approach for estimating the density of forest stands was introduced by McTague (1988). It involved the derivation of a technique for obtaining stand density from aerial photographs based on the principles of selection with probability proportional to size. The results of his study included the development of an aerial-photo angle-gauge that is used in a procedure very similar to the ground point-sampling technique proposed by Bitterlich (1948) and now widely used by foresters. For the photo-based method, the angle-gauge is rotated 360^{o} about the point center on the photograph and a count is made of all tree crowns that subtend an angle larger than that of the angle-gauge. McTague found that individual tree crowns were distinctly visible on 23x23-cm (9x9-inch) color prints with a nominal scale of 1:10,000 under monoscopic 22X magnification. He concluded that this method of estimating stand density is well suited to the ponderosa pine (Pinus ponderosa Engelm.) type of northern Arizona.

In a similar study, Gering and McTague (1988) calculated the dimensions of the aerial-photo angle-gauge for estimating stand density from aerial photographs of loblolly pine (Pinus taeda L.) sites in northern Louisiana. They concluded that the procedure appeared to have great potential because it is quick, relatively simple and eliminates the need for directly measuring plot areas or tree dimensions. However, they also noted that further research was needed to compare this method of forest inventory with more traditional, ground-based methods for areas in the South.

The FIA unit of the USDA Southern Forest Experiment Station provided resources for evaluating the angle-gauge sampling method on an applied, large-area basis. This project was recently completed and results were published in a final report submitted to the USDA Forest Service (Gering and May, 1991).

OBJECTIVES

The objectives of this study were to calculate the statistical correlations for ground-measured tree and stand variables, particularly crown width to diameter at breast height, and to construct angle-gauges suitable for use with aerial photographs of corresponding forest stands. A forest inventory was conducted using aerial photographs and the angle-gauge sampling method; results were compared with those obtained from the traditional ground-based inventory conducted by the field crews.

METHODS

Data from the 1984 Forest Inventory of Claiborne and Union Parishes in northern Louisiana (Figure 1) were provided by the FIA unit of the USDA Southern Forest Experiment Station. Data represented approximately 100 ground-measured plots and included variables for individual trees as well as for stands. Statistical correlations (such as the dbh - crown diameter relationship) were calculated for these variables. Based on the correlations for ground-measured data, aerial-photo angle-gauges for conditions frequently encountered in northern Louisiana were developed.

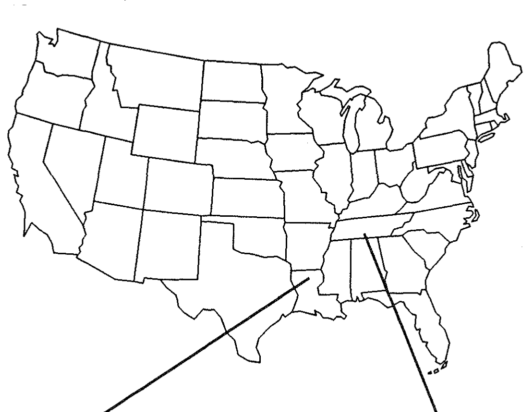

Figure 1. The location of Louisiana study area and the Tennessee study area.

Aerial photographs of portions of west-central Tennessee, Hardin and Wayne Counties (Figure 1) were flown in September 1988; photographs were color 23x23-cm (9x9-inch) prints with a nominal scale of 1:4800. Trained field crews from the USDA Forest Service conducted the 1988 survey of Tennessee and collected the necessary ground-plot data, and located all sample points on the photographs by pin-pricking and annotation.

It is important to note that the study area in Tennessee is located in the Cumberland Plateau region of the state. While the terrain does display changes in topographic elevation, the relative difference is minor. Thus, displacement of objects on the photographs due to relief was minimal. Similarly, the location of each ground plot was in the center of the photograph. On truly vertical photographs, this point would be identified as both the principal point and as the nadir. This results in minimal radial displacement of the object under study.

Ground-plot data and photographs were provided to the School of Forestry at Louisiana Tech University and the analytical portion of this study was conducted. Data from Hardin County were used to develop correlations based on ground-measured dbh and photographically-measured crown diameter. These data provided an opportunity to compare ground-measured crown diameters to photographically-measured crown diameters. Angle-gauges for stands in west-central Tennessee were constructed.

A forest inventory of Wayne County was conducted based on aerial photographs and samples obtained using the angle-gauges developed for west-central Tennessee. By doing this, the angle-gauges were not tested against the data from which they were developed. The results of this inventory were compared to the results of the ground-based inventory for estimates of number of trees, basal area and volume.

Finally, angle gauges derived for similar stand conditions were compared between the Louisiana and Tennessee study areas. This provided information regarding future use of angle-gauge sampling for forest inventories of other regions of the Midsouth.

RESULTS*

Louisiana Study Area

Data from the 1984 Forest Inventory of Claiborne and Union Parishes in Louisiana were analyzed to determine the statistical relationship between diameter at breast height and crown diameter, as measured from the ground. Claiborne Parish has 198,789 ha, with 161,272 ha (81%) in forest land. Union Parish has 234,280 ha, with 193,082 ha (82%) in forest land. Predominant tree species are loblolly pine (Pinus taeda L.), shortleaf pine (P. echinata), sweetgum (Liquidambar stryaciflua), blackgum (Nyssa sylvatica), hickory (Carya sp.), and oak (Quercus sp.).

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* FIA data were provided in English units of measure and analyses were conducted in English units. Data was converted to metric units for this publication.

Data were collected from 100 ground-measured plots in the two parishes with a total of 1319 trees. To evaluate the statistical relationships between dbh and crown diameter, the data were sorted into groups based on tree species and stand size. Correlations between dbh and crown diameter were determined for each group. Simple linear models were also fitted to the data. Prediction of crown diameter as a function of dbh was determined as well as prediction of dbh as a function of crown diameter.

Based on the strength of the relationship and on the number of observations in each group, it was decided that there was no advantage to sorting the data beyond two groups: one included all hardwood species, the other included loblolly and shortleaf pine. Using the pine species as an example, Figure 2 illustrates the relationship between dbh to crown diameter (as measured from the ground). Both a scatter plot of the data and a plot of the linear model are shown.

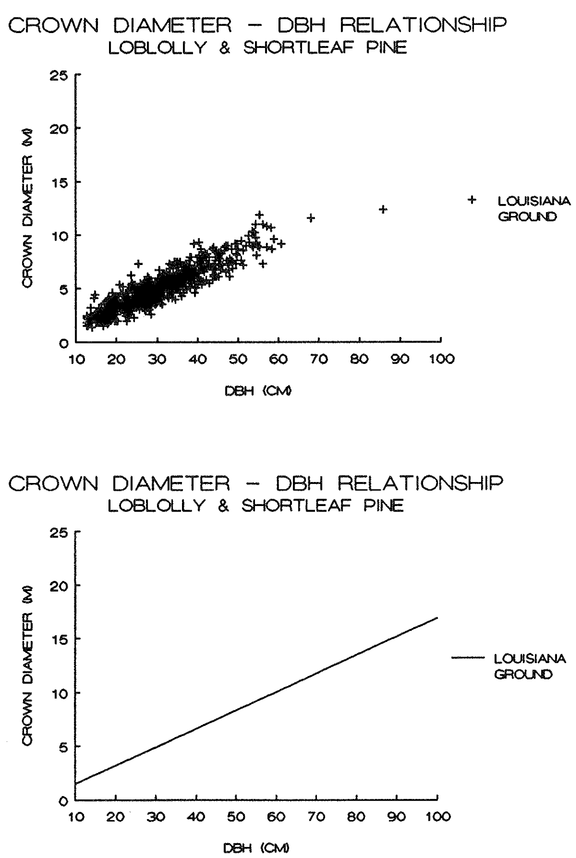


Figure 2. Relationship of diameter at breast height (DBH) to crown diameter (CROWN) for loblolly and shortleaf pine stands in Louisiana.

Tennessee Study Area

The USDA Forest Service conducted a survey of Tennessee in 1988. Data were collected using the standard FIA procedure. However, additional information was collected for two counties (Hardin and Wayne). This resulted in additional crown measurements made on trees located on and adjacent to the sample plot. Data were included as an addendum to the normal FIA ground-survey data.

Hardin County had 156,457 ha of land with 94,538 ha (58%) considered commercial forest land. Wayne County had 191,909 ha with 150,548 ha (78%) in commercial forest land. Species composition was similar to northern Louisiana, with loblolly and shortleaf pine, oaks, hickories, and gum dominating. Yellow poplar (Liriodendron tulipifera) was also common. However, hardwood species were in greater proportion than found in Louisiana. Sample plots were located in each county (46 in Hardin County and 55 in Wayne County). After screening from the data trees that were dead or less than 12.7 cm (5 in.) dbh, there were 939 trees measured in Hardin County and 878 trees in Wayne County.

The study plan called for an analysis of the data obtained for Hardin County. This included data from the ground inventory as well as data resulting from measurements made on the aerial photos. As with the earlier study in Louisiana, data could be sorted into subsets based on tree species and stand size classes. It was also possible to compare data obtained from ground measurements to data obtained from photographic methods. This resulted in four areas of concern: 1) hardwood trees with ground measurements, 2) softwood trees with ground measurements, 3) hardwood trees with photo measurements, and 4) softwood trees with photo measurements.

Hardin County was to be evaluated, using both the ground survey and the data resulting from the photographic study. Similarly to the Louisiana study area, it was found that there was no statistical advantage to separating the data beyond the division between pine species and hardwood species. Again, correlations between dbh and crown diameter were calculated and simple linear models were fitted to the data. Figure 3 illustrates the relationship between ground-measured dbh and crown diameter for loblolly and shortleaf pine. Both a scatter plot of the data and a plot of the linear relationship are shown.

For the Louisiana study area, it was only necessary to consider the relationship between dbh and ground-measured crown diameter. However, Hardin County data also included relationships for photographically-measured crown diameter. Figure 4 illustrates the relationship between ground-measured dbh and photo-measured crown diameter. Again, both a scatter plot of the data and a plot of the linear relationship are shown.

Finally, in comparing the statistical relationships between dbh and crown diameter, it was possible to consider the four categories of Tennessee data (ground-measured hardwood and pine, photo-measured hardwood and pine) and the two categories from the Louisiana study (ground-measured hardwood and pine). These corresponding relationships are compared in Figure 5. The graph of data from hardwood species shows a difference between the Louisiana and Tennessee data. It also appears that photo-based crown prediction underestimates crown diameter as measured from the ground (Tennessee data). For the pine species, the relationships appear much more similar. The two linear plots of the Tennessee data are nearly identical; the Louisiana model has a smaller intercept value but the slope of the line follows that of the Tennessee relationships.

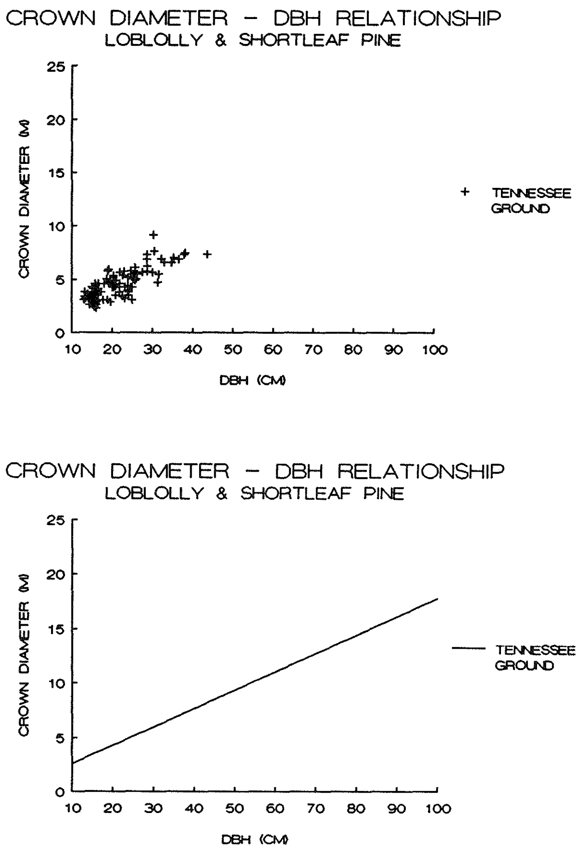


Figure 3. Relationship of diameter at breast height (DBH) to crown diameter (CROWN) for loblolly and shortleaf pine stands in Tennessee.

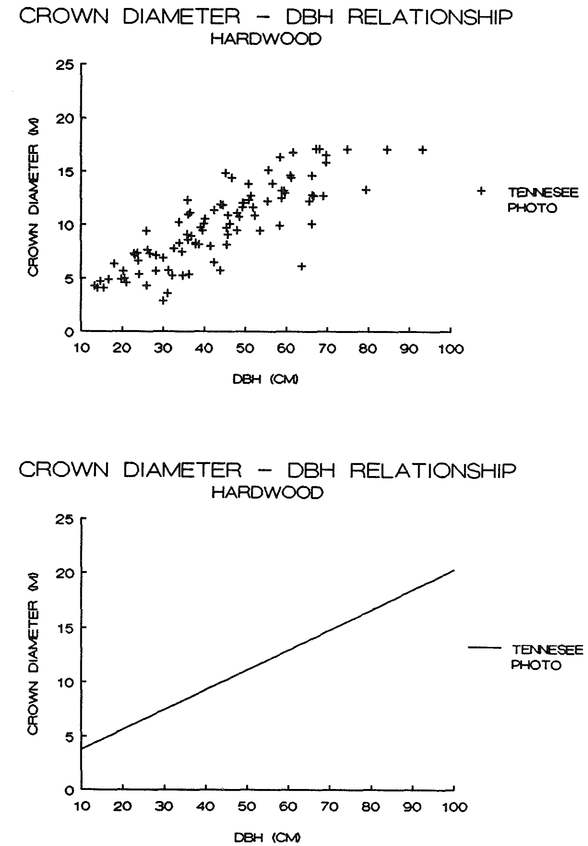


Figure 4. Relationship of diameter at breast height (DBH) to crown diameter (CROWN) for hardwood stands in Tennessee.

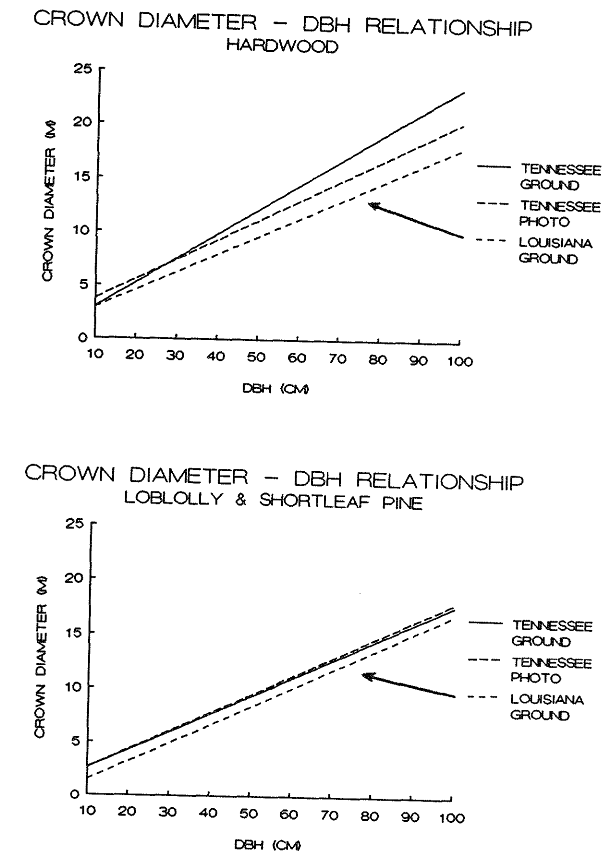
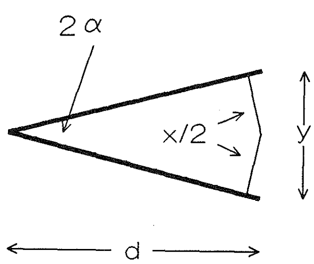


Figure 5. Comparison of crown diameter prediction models for Louisiana and Tennessee.

Angle-Gauge Construction

The derivation of the mathematics for the construction of the angle-gauge is relatively simple but the page-limitation of this paper precludes presentation here. Basically, the construction of an aerial-photo angle-gauge is based on the prediction of crown diameter from dbh and on the relationship between crown diameter and the point-sampling limiting distance. The concept of limiting distance and dbh is discussed in depth by Husch and others (1972). McTague (1988) and Gering and McTague (1988) present the theory and examples of angle-gauge construction.

An overview of the derivation of the aerial-photo angle-gauge for hardwood stands in Tennessee is shown in Figure 6. The photo-measured crown diameter was used because the angle-gauge would be used to evaluate tree crowns on aerial photos and the angle-gauge should be based on a similar relationship (as opposed to using the ground-measured crown).



R = aerial-photo angle-gauge ratio
C_i = crown dia. in feet (from prediction model)
L_i = corresponding limiting distance
n = number of observations

$$R = [\sum(C_i/L_i)] / n$$
$$= 11.813 / 17$$
$$= 0.695 \text{ or } 1/1.439$$
$$\text{set } d = 3.00\text{mm}$$
$$X = (1/1.439)(3.00)$$
$$= 2.085$$
$$X/2 = 1.043$$
$$\sin\alpha = (X/2) / d = (1.043/3.00) = 0.348$$
$$\alpha = 20.3^\circ \text{ and } 2\alpha = 40.6^\circ$$

Figure 6. Dimensions of a 10-basal area factor aerial-photo angle-gauge for hardwood stands in Hardin County, Tennessee.

Once the sampling angle was determined for the Tennessee study area (40.6° for hardwood and 36.2° for softwood) it was possible to construct the angle-gauge. Prior studies had used angles printed on transparent film which were then placed on top of the photograph and viewed stereoscopically (McTague 1988, Gering and McTague 1988). A new approach was used for the construction of the Tennessee angle-gauges. A 7X-power monoscopic comparator was obtained. This provided magnification of the area surrounding the sample point. A recticle was inserted into the comparator so actual measurements could be made. The recticle illustrated a series of circular diameters, increasing in size from 0.6mm to 2.5mm. The required sampling angle was etched onto the recticle using a carbide-tipped engraving pen (Figure 7). The resulting device could then be used to determine whether a given tree is included in the sample and provided an estimate of the crown diameter.

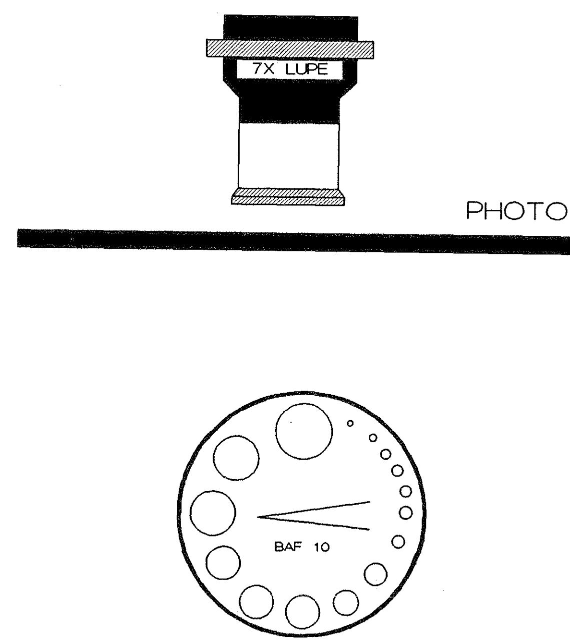


Figure 7. Sample trees are determined using a 7X-power monoscopic comparator with a recticle illustrating the sampling angle (BAF 10). A series of circular diameters is used to estimate tree crown diameter.

Use of the angle-gauge is simple. The device is placed on the aerial photo so that the vertex of the angle is directly on the center of the sample plot. The angle-gauge is rotated 360° about the point center on the photograph. A count is made of all tree crowns that subtend an angle greater than the angle-gauge (Figure 8 - top). The stand basal area is then calculated as the product of the count and the basal area factor.

Tree crowns that have been determined to be part of the sample can then be measured. The crown diameter is estimated using the circle that most closely approximates it. The circle diameter is converted to meters using the photo scale (Figure 8 - bottom).

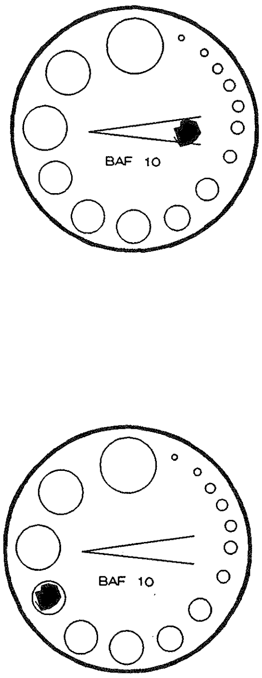


Figure 8. The tree crown that subtends an angle larger than the angle-gauge is counted as an "in" tree and is included in the sample. The crown diameter is estimated using the circle that most closely approximates it and is converted to meters using the photo scale.

Inventory Results

An inventory of Hardin County was conducted using the angle-gauges. At each ground plot (identified on the aerial photos) a series of ten points were sampled during the ground-based inventory, following standard FIA procedures. For the photo-based inventory, two points were sampled. In order to compare the results of the two inventory methods, it was necessary to convert plot data to "per-hectare" values; this avoided problems in having different numbers of sample points.

For each pair of plots (photo and ground), number of trees (per hectare), basal area (m^2/acre), and total volume (m^3/acre) were calculated. Number of trees and basal area were determined based on sample basal area factor and number of tallied trees. Gross volume in the merchantable portion of individual tallied trees was calculated using a volume equation:

$$VOL = -0.065 - 0.001\ (DBH) + 0.00062\ (DBH^2)$$

Volumes used to derive this equation were based on ground-tallied trees that were deterministically segmented in the field and processed with the Smalian formula. The model was applied to both ground- and photo-based data. Finally, per-hectare volume was obtained by using individual tree volume and size and number of trees per hectare.

The original study plan called for using Hardin County data to construct the angle-gauges. A forest inventory would then be conducted to determine the necessity of an "adjustment factor". It is not uncommon to require a small correction factor when using aerial inventory methods. The angle and adjustment factor would then be used to inventory Wayne County. Comparison with ground results would then be made.

Problems arose when it appeared that the "small" correction factor could be a multiplicative value between 2X and 5X for the number of trees/hectare. It was decided to go ahead and conduct the photo inventory of Wayne County to see if this relationship was consistent. Again, results from the ground inventory greatly exceeded results from the corresponding photo plots for Wayne County.

Comparison of individual plot data for the ground inventory and for the photo inventory did not provide a view of the overall sampled-area inventory. It was necessary to calculate a diameter distribution for each inventory method to compare the true relationship. This is presented in Figure 9 for Wayne County. The top graph shows the relationship between dbh and frequency for all trees; the bottom graph shows the relationship for dominant and codominant trees only.

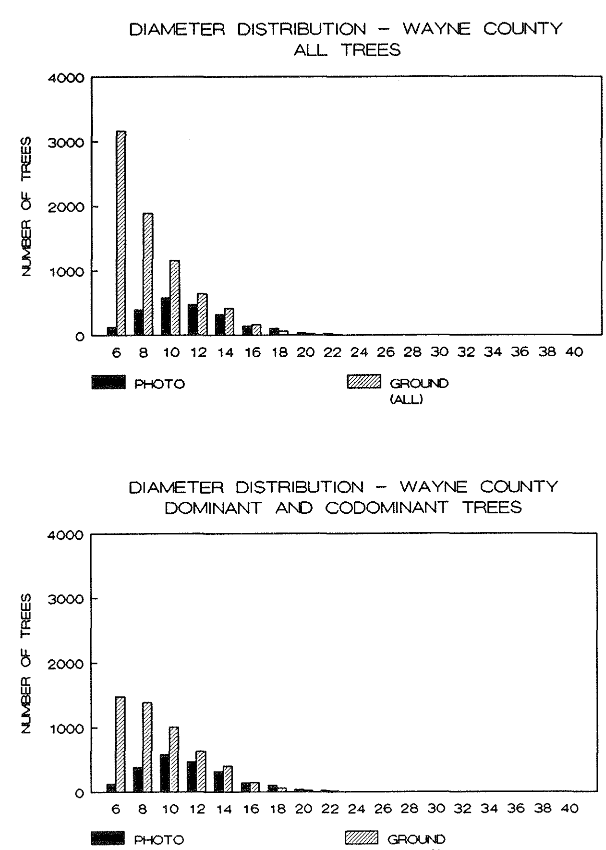


Figure 9. Comparison of diameter distribution from ground inventory to distribution from photo inventory for sampled area in Wayne County, Tennessee. Top graph shows data for all trees. Lower graph shows data for dominant and codominant trees only.

The final comparison between inventory methods involves looking at the "bottomline" values for the sampled area in both Hardin and Wayne Counties. Total number of trees (Figure 10), basal area (Figure 11), and volume (Figure 12) were calculated using the photo inventory results as well as the results from the ground inventory. Both "all trees" and "dominant and codominant trees only" results from the ground inventory were summarized.

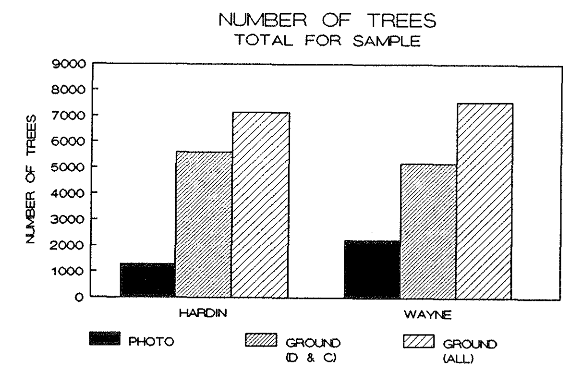


Figure 10. Comparison of total number of trees estimated for sampled area in Hardin and Wayne Counties, Tennessee. Graph shows results from three different inventories - photo, ground (with dominant and codominant trees only), and ground (all trees).

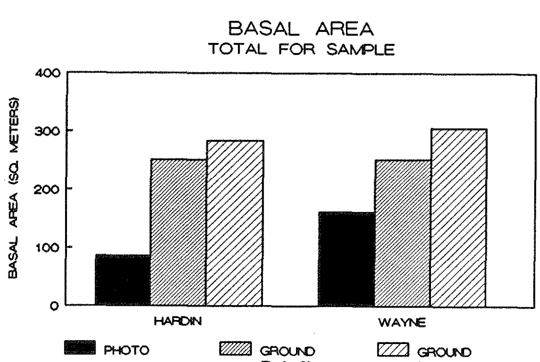


Figure 11. Comparison of total basal area estimated for sampled area in Hardin and Wayne Counties, Tennessee. Graph shows results from three different inventories - photo, ground (with dominant and codominant trees only), and ground (all trees).

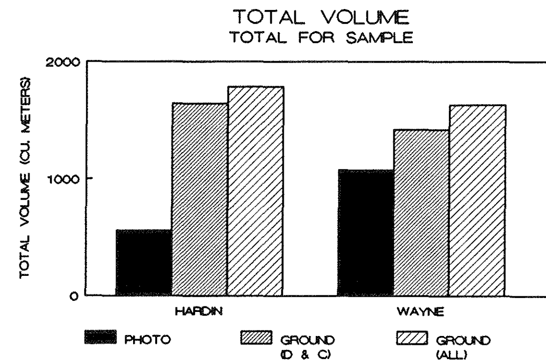


Figure 12. Comparison of total gross volume estimated for sampled area in Hardin and Wayne Counties, Tennessee. Graph shows results from three different inventories - photo, ground (with dominant and codominant trees only), and ground (all trees).

The number of trees for the sample areas was significantly greater in both considerations of the ground data than for the photo-based data, though Wayne County results did appear to be slightly more consistent than Hardin results. A similar relationship exists for the basal area estimated for the sample areas. Results of the estimates for total volume for the photo-based inventory are still less than results from the ground-based inventories, though much more similar (particularly for Wayne County).

CONCLUSIONS

Theoretical evaluations of the aerial-photo angle-gauge sampling technique demonstrated that the procedure was mathematically sound and had potential for field use in the southern region of the USA. This study provided empirical data and an opportunity to evaluate the procedure with regard to a traditional ground survey.

The Louisiana study area only had ground-derived data. However, it was possible to compare dbh and crown diameter for the data. The Tennessee study area had both ground- and photo-derived data, and both were analyzed and subsequently compared.

The photo-derived data provided an opportunity to calculate sampling angles and actually construct the angle-gauges. The use of a comparator and a recticle etched with the desired angle was an improvement over using transparent film as in prior studies. The series of circular diameters on the same recticle provided an easy means of estimating crown diameter. The gauges allowed an actual inventory to be conducted; the main purpose of this study was the inventory itself.

The inventories of Hardin County demonstrated that significant differences existed between the photo-derived data and the ground-derived data. It is accepted that inventories based on aerial photos often underestimate timber resources relative to ground inventories of the same area. This is due to the inability of photo-based inventories to adequately include values for culled tree volume. A small correction factor is often used to adjust results of photo-based inventories. However, by initially screening

Hardin and Wayne Counties to remove dead trees and by using gross volume, the potential difference could be minimized.

Overtopped and intermediate trees are also often a problem as they cannot be easily observed on the photos. Problems with such trees were anticipated and analyses of the data included a comparison of photo-derived data with ground data that had been screened to leave only dominant and codominant trees.

The results of the Hardin County inventory (and the Wayne County inventory) showed that a major correction factor would be necessary (exceeding a factor of 2X). Obviously, it is unsettling to find out that photo inventory results would have to be doubled or tripled to equal results of a corresponding ground inventory. A careful analysis of the data and diameter distribution associated with each method shows that the photo method underestimates the number of trees and basal area. Volume is also underestimated, though not by as great a factor.

Looking at the graphs of the diameter distribution it appears that the photo-based inventory failed to tally many of the smaller diameter trees, 15.2 cm to 20.3 cm dbh (6 in to 8 in). Many of the larger diameter trees were also excluded from this sample. This would indicate that the angle-gauge technique was valid for sampling mid-sized trees, 25.4 cm (10 in), and had great difficulty sampling small trees that were "close in" to the apex of the angle. Likewise, large trees that were relatively far from the apex were also not included in the sample. In both cases, the true problem is most likely the difficulty associated with identifying individual tree crowns.

One interesting observation is that the values for total volume are much closer than for number of trees and basal area. One possible reason for this is that the angle-gauge sampling technique was able to include trees that possessed most of the timber volume; these trees were from the middle of the diameter distribution. Trees with small diameters were omitted from the photo-based inventory but they constituted a relatively small amount of overall volume.

Geographical consistency is an important aspect of inventory techniques. It would be ideal if the aerial-photo angle-gauge performed similarly in all parts of the southern region of the USA. A comparison of the models representing the relationship between dbh and crown diameter for Louisiana and Tennessee cannot be made directly because photo-derived data from Louisiana were not available. However, it does appear likely that this relationship is not constant between the two study areas. This would indicate that the relationship between dbh and crown diameter would have to be determined for each geographical unit. Angle-gauges could then be constructed, based on the mathematical model.

In summary, the development of the angle-gauge for the Tennessee study area is mathematically sound. Results from its use are questionable due to significant differences with corresponding ground-based inventories. The single most important factor causing problems in using the angle-gauge is the difficulty of isolating and identifying individual tree crowns. Trained USDA Forest Service personnel, familiar with the study area, were able to rapidly locate a tree crown and identify the tree species. Research associates with less experience often found the identification process tedious and difficult. It is believed that, with additional training of personnel and with nominal photo scale larger than the 1:4800 used in this study, the procedure may provide better results. The use of the magnifying comparator did not compensate for problems of having a too-small photo scale.

The procedure discussed in this study is one that may have allowed more efficient processing of forest inventory data, particularly in areas that are difficult to physically visit due to geographic remoteness or to inhospitable terrain. While many current procedures rely on satellite imagery or other forms of digital data, the relatively high costs of equipment and training preclude many foresters from using such technology. However, the use of aerial photographs may provide a source of data that falls within budgetary constraints. It is only through attempts such as this that new procedures can be brought from the theoretical to the applied.

LITERATURE CITED

Bitterlich, W. 1948. Die Winkelzahlprobe. Allgem. Forest-u, Holzw. Ztg. 59 (1/2): 4-5.

Gering, L.R. and D.M. May. 1991. The use of aerial photographs and angle-gauge sampling of tree crown diameters for forest inventory. Final Report; Coop. Forestry Res. Project 19-88-076. Louisiana Tech Univ., School of Forestry. 75 pp.

Gering, L.R. and J.P. McTague. 1988. Estimating stand density of loblolly pine in northern Louisiana using aerial photographs and probability proportional to size. In: Technical Papers of 1988 Annual Convention of the American Society for Photogrammetry and Remote Sensing; Vol. 4: 222-228.

Husch, B., C. Miller and T. Beers. 1972. Forest Mensuration. John Wiley and Sons; New York, NY. 337 pp.

McTague, J.P. 1987. Estimation of stand density with probability proportional to size from aerial photography. Western Journal of Applied Forestry 3(3): 89-92.

Minor, C.O. 1951. Stem-crown diameter relations in southern pine. Journal of Forestry 49: 490-493.

Smith, J.L. 1986. Evaluation of the effects of photo measurement errors on prediction of stand volume from aerial photography. Photogrammetric Engineering and Remote Sensing 52: 401-410.

Spurr, S. 1948. Aerial Photographs in Forestry. Ronald Press; New York, NY. 340 pp.

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