AN ABSTRACT OF THE THESIS OF

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Title: A PRELIMINARY INVESTIGATION INTO THE USE OF THE TARIF SYSTEM AND THREE TREE SELECTION METHODS FOR OBTAINING DOUGLAS-FIR STAND TABLES, STOCK TABLES, AND GROSS VOLUME ESTIMATES FROM LARGE-SCALE AERIAL PHOTOGRAPHY

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Abstract approved: ______________________

Dr. David P. Paine

As a preliminary step toward the establishment of a 70 mm. aerial photo timber inventory system capable of generating accurate stand tables, stock tables, and gross volume estimates, this project focuses on the development of a system which (1) eliminates the need to measure tree height on the photos through use of the tarif system and, (2) incorporates the use of three distinct tree selection methods-- fixed plot, variable plot, and line transect sampling. The methodology is developed and applied to a 346 acre parcel of Douglas-fir forestland.

The accuracy of individual tree predictions for diameter at breast height, volume, tarif number, and tree height (which is derived without traditional photo measurement) are evaluated by ground subsampling a 206-tree validation set and comparing actual and predicted

values. The results show that an average underprediction of ground-measured tarif number by about 5% occurs, which in turn results in similar underpredictions of tree volume and height.

The accuracy of the stand tables, stock tables, and gross volume estimates are examined by comparison to independently derived ground measurements. The photo estimates of mean gross volume per acre, using each of the three photo tree selection methods, are all within 5% of the ground-derived estimates; in all cases the 68% confidence intervals of the ground and photo estimates overlap. Graphic comparisons of the photo and ground-derived stand and stock tables are presented; they are similar, except for the inability of the photo method to accurately predict the stocking of trees less than twelve inches in stem diameter.

The aerial photo system, using each of the three tree selection methods, demonstrates an ability to produce results comparable to those derived from conventional ground inventory techniques. Future research is recommended, and specific needs for this research are identified.

A Preliminary Investigation Into the Use of the Tarif System and Three Tree Selection Methods for Obtaining Douglas-fir Stand and Stock Tables from Large-scale Aerial Photography

by

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INTRODUCTION

Many research projects have investigated the possibility of obtaining forest inventory data from aerial photographs. Most foresters would prefer trudging through the forest with tatums and diameter tapes as opposed to sitting at a desk shuffling through photos, but it is possible that the use of an effective photo inventory system could result in a savings of time and money over a conventional ground-based approach. There is a limitation to the amount of information that can be directly obtained from aerial photos, so a photo inventory necessarily involves some field work. The two are complimentary and, when used in the proper combination, may result in a more efficient inventory.

Research has demonstrated that volume, tree diameters, and tree frequency can be obtained from aerial photos (Aldred & Lowe 1978, Bonner 1977, and many others). Although this would seem to indicate the potential for photos to play a major role in timber inventory they have, in practice, generally served a minor role; as a means of stratification for subsequent ground sampling. There are three major problem areas which contribute to this situation. They are: (1) lack of accuracy in photo estimates, (2) potential economic inefficiency, and (3) failure of photo inventories to provide sufficient stand information

The first problem concerns biases in the photo inventory estimates. These systematic errors arise from many sources. Tip and tilt of the aircraft, geometric displacement on the photos, improper scale determination, poor film resolution, image motion, measurement errors, camera quality, and interpreter ability are all influencing factors. The Canadian Forestry Service developed a photo inventory system which reduces the effects of these systematic errors to the point that reasonable results are obtained (Aldred & Lowe 1978, Nielsen et. al. 1979). The Canadian system employs a penetrating radar altimeter (Nielsen 1974a) and a tilt indicator (Nielsen 1974b) which provide data on the exact position of the camera at the time each picture is taken. Photos are taken with a high-quality Vinten camera. Tree measurements are made and stored using a computerized digitizing system. A number of field trials have been performed using this system. One trial in Alberta (Aldred & Lowe 1978) reported the following results:

1. The total gross volume estimates in four strata ranging from 33.4 to 57.5 thousand hectares apiece were found to be within two to eleven percent of independently derived ground estimates.

2. The estimated standard error of these volume figures ranged from 8.1 to 18.8%. This includes the "combined effect" of sampling error and systematic error, as obtained by ground truthing.

The second problem area, lack of economic efficiency, is influenced by the photo inventory method used and the size of the area to which it is applied. For example, the cost of the necessary airborne equipment (excluding the plane and camera) in the Canadian system was estimated at $60,000 in 1978; the computerized measuring equipment at $30,000. These high initial fixed costs render the use of this system economical only for large, remote, and inaccessable areas (Aldred & Lowe 1978). The Canadian system, though adequate for the areas in which it was developed, is not directly useable for inventory situations typically encountered in the United States. No large-scale photo inventory method capable of achieving the accuracy demonstrated by the Canadian system, without the high initial fixed costs, has been reported.

The third area of concern for developing photo inventories is the type of information desired. Research emphasis has generally been on the prediction of total gross volume. This is often not adequate to meet management objectives. The usefulness of a photomensurational system is enhanced by the abilty to predict stand and stock tables by species. This has been attempted in past studies (i.e. the Canadian research just discussed) but empirical tests of the reliability of these predictions is generally lacking.

An aerial photo timber inventory system capable of producing stand tables, stock tables, and estimates of total volume with accuracy and precision comparable to that of the Canadian system, but without the high initial fixed costs, could prove to be an asset to forest managers. Such a system could be used to aquire data to supplement ground inventory plots, update existing inventories, monitor changes over time, or supply data on large land holdings or exchanges. Research is needed to test new approaches which could aid in the development of such a system. This is the purpose of this project. An understanding of past research helps to build both a foundation and a resource from which to construct a new approach to aerial photo timber inventory. Past research will now be briefly examined.

LITERATURE REVIEW - THE USE OF LARGE-SCALE PHOTOS

Early research investigating the use of aerial photos for obtaining stand volume information occured in Germany in the 1920's. Since that time, foresters worldwide have shown an interest in the use of photos for inventory purposes. There was a major push in the United States and Canada during the 1950's and 1960's to develop procedures for measuring stand variables -particularly gross volume- from photos. Two distinct types of photo volume tables (PVT's) developed: stand PVT's and tree PVT's.

Much of the early research was centered on the development of stand PVT's. These tables are generally developed and applied using resource scale photography (1:10,000 - 1:20,000). They use average stand height, percent crown closure, and sometimes average crown diameter within sample plots as independent variables to predict gross volume per acre (ie. Avery & Meyer 1959, Pope 1962). Volume estimates from stand PVT's tend to be biased due to measurement errors and the subjectivity of the independent variables. To solve this problem, double-sampling of field and photo plots is recommended to develop a correction factor. Stand PVT's, when combined with double-sampling, have the advantage of being robust to fluctuations in photo scale (Paine 1965). The information they provide, however, is simply an estimate of total gross volume, with no indication of how that volume is distributed among species and diameter classes.

The desire to obtain more detailed information from photos brought about a shift in research emphisis from stand-level to tree-level information. Tree PVT's and the individual-tree approach to photo inventory developed. Tree PVT's provide the volume of individual trees. They typically utilize tree height, crown diameter, and possibly a measure of density about a tree as predictors of its volume and DBH. Tree species can be determined if the photography is of sufficient quality and scale. This individual tree information can be converted to a stand basis through frequency conversion factors specific to the method used to select the sample trees; stand and stock tables result.

The use of this individual-tree approach is not accurate using the small photo scales with which stand PVT's are applied (Spurr 1960). Tree measurements and species identifcation become more accurate at larger scales (Pope 1957, Andrews 1936, Johnson 1958). Scales of 1:1000 to 1:3000 are generally used. Seventy milimeter film is commonly used because it is inexpensive and total area coverage is not required (MacLeod 1981). Also, the use of a larger film format, such as the traditional 9 X 9 inch format, may make stereoscopic viewing imposible due to excessive stereoscopic parallax. The use of large scale photos and the individual tree approach to forest inventory is recognized as being the only practical method of obtaining stand and stock tables from aerial photos. The necessary mensurational steps, common to all large scale photo inventories designed to produce stand and stock tables, are: (1) sample tree selection, (2) species identification of each tree, (3) determination of DBH of each tree, (4) determination of volume of each tree. Once these steps have been accomplished only mathematical calculations are necessary to produce stand and stock tables. Past findings on each of these mensurational steps will now be discussed.

Sample Tree Selection

Traditional Approach to Tree Selection

Sample trees have generally been selected using fixed plots on aerial photos. These plots, which are circular or square, are drawn on the photo. All live trees above a specified height (usually 10-20 feet) that fall within the plot boundary are tallied. The species of each tree is interpreted, and its DBH and volume estimated (using procedures explained shortly). Two types of errors can occur during tree selection that will have detrimental effects on the the resulting stand and stock tables: including trees which were not actually on the plot (comission) and excluding trees which should have been tallied (omission).

One source of omission and comission errors arises from photointerpretation problems. Omission errors often occur when small trees, obscured by the shadows and crowns of adjacent trees, are not noticed. Bonner (1977) reports a high rate of omission errors in plots which fell in dense, uneven-aged stands. Comission errors can occur when forked trees are mistakenly treated as two distinct trees. These photointerpretation errors are minimized by using clear, sharp photographs and experienced photointerpreters. Shadowless photography is especially useful for viewing trees in the understory.

Another source of both omission and comision errors stems from the inability to accurately determine which trees to include in the individual plot tallies. The correct trees to include in fixed plots are those whose stumps are within the delineated plot boundary, assuming that the plot has been drawn on the photo at the correct ground scale. The tree base is almost always obscured by the crown, making this a difficult and rather subjective decision (Aldred & Lowe 1978). The use of the position of the tree tip as the deciding factor is incorrect unless the change in photographic scale due to tree height (geometric displacement) is taken into consideration; ignoring this will lead to serious volume and tree count underestimation when using large-scale photos.

The effects of omission and commission errors do tend to partially compensate. Aldred and Lowe (1978) found that omissions on their Peace River Project averaged 10.6% and commissions averaged 4.2%. The net result on total volume was an overestimate of 0.6%. The reason for this seeming discrepancy is that small trees tended to be omitted, while larger trees tended to be committed. This compensating effect pertains to total volume only; the impact on stand and stock tables would be a noncompensating bias.

Other Approaches to Tree Selection

Fixed plots are not the only method that can be used to select sample trees on aerial photos. Paine (1965) and Wert (1966) experimented with using variable plots on 1:5000 scale photos in ponderosa pine. Using their method, the decision as to whether a tree is "in" or "out" of a plot is based on a critical angle which subtends the crown. The need to estimate the position of the tree base of borderline trees is eliminated. Paine (1965) found the use of variable plots to be "...more efficient with little or no loss in accuracy" as compared to fixed plots. The use of this method at larger photo scales has not been evaluated.

Another tree selection procedure, which has not been attempted on photos, is line transect sampling. Line sampling was concieved by Warren and Olsen (1964) for measuring logging waste in New Zealand. The general theory is described by Grosenbaugh (1958). Meeuwig and Budy (1981) have used this method to sample biomass of pinyon-juniper woodlands in the southwestern U.S. They suggest laying out transect lines on the ground and sampling each tree whose crown is over the line. Formulae appropriate for converting sample data to population estimates, which depend on the length of the transect and the biomass to crown diameter ratio of the sample trees, are given by Grosenbaugh (1958). This theory could be adopted for use in photo inventories if transects of a known length are placed on photos and all trees with crowns touching the line are sampled; this possibility has not been previously explored.

Species Identification

Subtle differences in texture, tone, and color help to identify individual species on aerial photos. The proper combination of focal length, flying height, film, and filter are of paramont importance in distinguishing individual tree species (Sayn-Wittgenstein 1978). Focal length and flying height, and their resultant influence on scale and tree tip displacement, can be manipulated to make species identification more efficient; larger scales allow the interpreter to see more detail while more displacement makes it possible to see tree profiles (Sayn-Wittgenstein 1978). Different films and filters offer a variation of tonal quality. The "proper" choice of these factors is specific to the area of study, specifically the age and species mix present. Mature trees are generally more easily identified than immature trees (Pope 1957). Obviously, a study site composed of two species which have completely different branching patterns will have different requirements than a site consisting of five similar species. Prior experience with the species present in a particular area, combined with knowledge of how distinguishable they appear on photos, will aid in making the most efficient choice.

Determination of Tree DBH

Two distinct methods for obtaining tree DBH from aerial photos have been attempted: measurement and regression prediction. Measurement methods, which include direct measurement of either the tree bole or its shadow, are reviewed by Aldred and Sayn-Wittgenstein (1972). They conclude that direct measurement is of little application due to numerous problems with scale, sun angle, and obscurity of target.

Regression methods of predicting tree DBH are more reliable. Crown measurements and tree height have proven to be the best predictors of DBH. Some measurements of the relationship of a tree to its neighbors have also proven significant. Each of these variables will be discussed.

The Best Independent Regression Variables

Crown Measurements. The fact that a strong correlation between crown width and DBH exists has been well established. (Dahl 1954, Bonner 1964, many others). This is not surprizing since the size of the tree crown reflects the photosynthetic capacity of the tree, which in turn indicates the ability for DBH growth. Crown width has been measured on photos using several techniques. Crown width can be a single measurement or two perpendicular measurements; it can include extended branch tips or it can ignore them (Bonner 1964, Kippen and Sayn-Wittgenstein 1964). The choice is arbitrary as long as the selected method is used consistantly. Since crowns often have irregular shapes, consistancy in the measurement of crown diameter can be difficult to maintain. Crown area, as determined by dot count, has been shown to be a more consistant measure (Aldred & Sayn-Wittgenstein 1972).

Tree Height. Many researchers have found that the inclusion of tree height significantly improves the correlation with DBH (Aldred & Sayn-Wittgenstein 1972, Dilworth 1956). The reasoning is straightforward: taller trees tend to have larger diameters. The determination of tree height on aerial photos, however, is difficult. This is likely why it has been studied so extensively (Moesner 1950, MacLean and Pope 1962, and many others). Tree height is commonly measured with a parallax bar or wedge, which is a time-consuming chore. Large biases in height measurements can occur if the exact scale is not known. Biases may also result if both photos in a stereopair are not perfectly vertical. For example, using 70 mm. photography, a 150 mm. lens, and an 1800 ft. flying height, a convergent tilt of only 2 degrees (one degree per photo) will cause height to be overestimated by 30 percent (Brun 1972). This bias increases with a longer focal length lens (Pope 1972).

Relations to Neighbors. Many different indices of density have been considered as independent variables for predicting DBH. Even the casual observer may notice that a tree under competition from surrounding trees will tend to have a smaller diameter than a similar tree under less competitive conditions. The use of an index which quantifies the influence surrounding trees on a subject tree, which shall be called "point density", would seem to be a reasonable independent variable for predicting the DBH of that tree. For a given subject tree, some characteristics of neighboring trees which would be influential include: (1) size of the neighboring trees, (2) distance to neighbors, (3) number of neighbors, (4) spatial distribution of neighbors, (5) species of neighbors, (6) root grafting to neighbors (Alemdag 1978). These factors are all interrelated. Both silviculturists and mensurationists have attempted to develop indices of point density that would give a high correlation with DBH (or radial growth) by including the influence of combinations of these factors. Of those reviewed, the following were found to have direct application to a aerial photo inventory:

1. Polygon Area. This involves allocating growing space to polygons about each tree. This is time-consuming, and is of most use in stands where adjacent trees do not overlap (Aldred & Sayn-Wittgenstein 1972).

2. Nm. This is simply a count of the subject tree's "m" nearest neighbors which are taller than it. Preliminary trials show m= 6 to be the most promising (Aldred & Sayn-Wittgenstein 1972) . This has not proved to be a very effective measure, but it is simple to aquire.

3. PC. The is the proportion of the subject tree crown area overlapped by neighboring trees. Aldred & Sayn-Wittgenstein (1972) found this to be of "no value" in several trials.

4. A. This is the number of tree crowns subtending an

angle larger than a given fixed angle centered at the subject tree. Aldred & Sayn Wittgenstein (1972) also found this to be of "no value" in their tests. A problem with this density measure is that it weights all "in" trees the same, while their effect may actually be quite different depending on how close to the subject tree they are.

5. Adjusted A. Paine (1965) made a modification to better adapt the density measure "A" for use on aerial photos for his work in ponderosa pine. He took the formula presented by Dilworth (1976) for calculating basal area factor and changed the scale to:

$$PCC = 100/(1 + 4(d/w)^2)$$

where: PCC = percent crown closure
d = distance from the point center to the center of the neighbor
w = crown width of the neighbor (same units)

Using a subject tree as a center point and assuming any given neighbor to be a borderline, this equation gives an estimate of the percent crown closure represented by that neighbor about the subject tree. Paine accumulated the percent crown closure represented by all neighbors which contributed at least "p" percent to this total, where "p" could be any specified percent. This point density measure, as described by Paine (1965) will be refered to as "adjusted A".

Although Aldred and Sayn-Wittgenstein (1972) and Paine (1965) found some of the aforementioned measures of point density to be statistically significant predictors of tree DBH, they did not prove effective when crown area and tree height were already included in the model. Tree height and crown diameter together are such good predictors of volume that a density measure offered little gain; a possible reason for this situation is that crown size is also a reflection of density. Aldred and Sayn-Wittgenstein(1972) suggest that density measures "warrent further investigation".

Tree Species. The relationships between the aforementioned independent variables and tree diameter vary by species. Most researchers have found it necessary to develop separate equations for each species or species group (ie. Nielsen et.al. 1979) Aldred and Sayn-Wittgenstein (1972) suggest that each species should be analysed separately unless findings indicate this would be unneccesary.

Other Considerations. The independent variables mentioned thus far; crown measurements, tree height, relation to neighbors, and species do not compose an exhaustive list of the variables tested in the past, but it as a brief account of the ones found most useful. Other variables which have been tested and rejected as predictors of individual tree diameters include average stand height, average density (Aldred & Sayn-Wittgenstein 1974), crown class, crown ratio (Bonner 1964a), and site index (Bonner 1964a, Liew 1981).

Model Form

The most common model used to predict the stem diameter of stand-grown trees from photo variables has been a simple linear model. The use of this model results in heteroscedasticity of the error terms when either crown area, height, or both are used as predictor variables. This was pointed out by Aldred and Lowe (1978). It has generally been ignored by previous researchers dealing with stand-grown trees, although scatter plots of their data clearly reveal this tendency (Bonner 1964a, Ferree 1953, Hitchcock 1974). Two possible expanations for this heteroscedasticity are: (1) the true model form is linear with additive, heteroscedastic error terms, or (2) the true model form is non-linear, and the error terms are multiplicative (an intrinsically linear model). Although the differences in these two models are quite basic, they can be rather difficult to distinquish in practice. Each must be handled differently, as well be explained.

Simple Linear Model. The use of this model assumes that the dependent variable is a linear, additive function of appropriately transformed independent variables and an additive error term. The method of least squares is the appropriate technique to fit a simple linear model. The use of a simple linear model is suggested by its preponderate application in past studies. If used, it would be necessary to adjust for heteroscedasticity to obtain efficient parameter estimates. No attempts to stabilize variance using a weighted simple linear approach to predict diameter of stand-grown trees were uncovered. Paine and Hann (1982), however, did use a weighted simple linear model to predict the maximum crown width of open-grown trees from stem diameter. Using this approach, they were able to achieve more stable variance with errors whose distributions were not significantly different from normal (in most cases).

Intrinsically linear Model. The intinsically linear model mentioned above assumes that the dependent variable is multiplicative function of transformed independent variables and a multiplicative error term. Perhaps the easiest way to fit this model is to take the logarithmetic transform of both sides of the equation, thus deriving a linearized model. This linearized model can then be fit by the method of least squares. The residuals from the resulting model should be checked for homogenaity, thus the need for weighted solutions. The possibility of using a log-transform model for predicting diameter from crown area and height was suggested by Canadian researchers (Aldred & Lowe 1978, Neilsen et.al. 1979). No report on the stability of the variance or normality of the error terms achieved was presented. This is unfortunate, because it does not give clear indication of the success of using a log-linear approach.

Determination of Tree Volume

Tree photo volume equations (the computer-age counterpart of tree PVT's), as mentioned, can be used to predict the volume of individual trees using photo-measured independent variables. Two methods for constructing these equations have developed. These will be described.

Method (1) uses regression modeling to predict tree volume directly from photo-measured independent variables. To develop an accurate regression equation, tree volumes should be measured on the ground using a precise dendrometer or by felling and sectioning trees (Bonner 1964). The most useful photo variables for predicting volume are the same variables which were found to be the best predictors of DBH: tree height and crown size (width or area). Density measures have been found to be correlated with tree volume but are generally nonsignificant in equations which already contain height and crown measurements. Once developed, a volume equation can be used to predict volume of sample trees within the same general area of its development.

The development of a volume-predicting regression equation is unnecessary in the application of method (2). Using this method, tree volume is determined through an existing standard volume equation (or table) from tree DBH, as predicted through regression (page 9), and photo-measured tree height.

Method (1) above is the theoretically correct method to use. Method (2) violates a basic rule of regression by using a dependent variable (predicted DBH) as an independent variable in a volume equation (or table) which was developed using actual values (Aldred & Sayn-Wittgenstein 1972). The result can be biased volume estimates. In actual practice, however, method (2) is used most frequently. The popularity of this method comes from its relative simplicity and lower cost. The development of the volume-predicting regression equation used in method (1) is not an easy task -- the optical dendrometer can be difficult to use; felling and sectioning trees is a long, expensive procedure. Also, a separate volume-predicting equation must be developed for each species and geographic area (Bonner 1964, Aldred & Lowe 1977, Aldred & Sayn-Wittgestein 1972). Although the use of method (2) is simpler and less expensive, its theoretical shortcomings should be realized and evaluated if it is to be used with confidence.

An interesting application of method (2) was presented by Hitchcock(1974). In his study, tarif volume tables were used to predict individual tree volumes for open-grown ponderosa pine in Arizona. Tarif tables are a set of standardized local volume tables. The theory and use of tarif tables is given in detail by Turnbull et.al. (1980). Tarif volume equations require only tree diameter and a field-measured tarif number (an index to the appropriate volume table) as predictors of tree volume. Hitchcock demonstrated that, by using these tables, it is possible to construct a single-variable aerial photo volume table which does not require the measurement of tree height on the photos. This was accomplished using the following procedure:

1. An equation was developed, using a 600 tree sample, which enabled sample tree stem diameter to be predicted from crown diameter.

2. An average tarif access number was determined for the study area through field measurement.

3. Using predicted diameters and the appropriate tarif table, as indexed by the tarif number, an aerial photo volume table was constructed which enabled volume to be predicted from crown diameter only.

Unfortunately, no evaluation of the performance of the resulting aerial photo volume table was presented.

Past methods of constructing tree PVT's (or equations) have often introduced another error: indpendent variables were measured on the ground to construct tables intended to be used with photo measurements (Hitchcock 1974, Bonner 1964). This should be avoided if possible.

Application of Reviewed Literature to Current Project

The literature offers general guidelines for the conduct of a photo timber inventory. It is also the basis for the following conclusions, which are essential concepts in the current project.

1. An individual-tree large-scale photo (LSP) inventory approach is necessary to develop stand and stock tables by species.

2. Measurement of tree height on photos is a major way in which bias is introduced into the predictions of tree diameter and volume. This bias, since it originates from several sources, is difficult to control. The incorporation of the tarif system into an LSP inventory presents a potential method for eliminating the need to measure tree height, possibly resulting in less biased estimates.

3. Use of fixed plots as the sampling unit for a photo timber inventory may result in biased estimates of total volume and tree frequency due to the inability to accurately specify the position of the tree base. Variable plots and the use of the line intercept sampling method on photos have not been fully evaluated, and may offer results superior to those obtained using fixed plots.

With these points in mind, it is possible to formulate more specific objectives for this project.

OBJECTIVES AND SCOPE

The thorough development and testing of an aerial photo inventory system is a lengthy process, which requires more time than is available for this project. It is not, therefore, the intent of the author to devise a detailed aerial photo inventory system for immediate use. Instead, this is a preliminary project, the goal of which is to develop a photo inventory system, incoporating some ideas for potentially increasing accuracy, and test it empirically. Through this process, potential problems can be identified, and recommendations for continued investigation and testing will be made. The specific objectives are:

1. Develop a general method for conducting a large-scale photo inventory capable of producing stand tables, stock tables, and a gross volume per acre estimate using fixed plot, variable plot, and line transect sampling methods. Eliminate the need to measure tree height on the photos through use of the tarif system. Special emphasis is placed on the identification of the necessary assumptions.

2. Evaluate the developed theory, using each of the three sampling methods, through an empirical test on a 346 acre parcel of Douglas-fir forestland. The predictions of the individual tree measurements within photo plots will be evaluated by subsampling a portion of the trees used in the photo cruise, henceforth called the validation data set, and comparing actual and predicted measurements. Results of the photo-derived stand tables, stock tables, and gross volume estimates will be compared estimates derived from existing inventory data collected on 206 plots

in the same area using conventional ground inventory techniques (see appendix A for a description of the ground inventory, henceforth refered to as the "OSU inventory").

3. Based on the results of the first two objectives, make a recommendation as to whether further research involving the proposed inventory system is warrented. If so, define areas in which this research is needed.

The system being developed will, by design, involve lower costs than the Canadian system. Costs are kept to a minimum when possible, but no economic analysis is performed. The importance of the relationship between costs and practical application was noted previously, but is best studied in a later project, after the results from this project are evaluated.

Without the use of height as an independent variable for predicting tree diameter or volume it is not expected that estimates for any single tree will be very accurate. The attempt is to produce estimates of mean values, namely stand tables, stock tables, and gross volume per acre estimates which are accurate. A high degree of precision in these mean estimates is also considered desirable; standard error of the gross volume per acre estimates will be calculated.

THEORY DEVELPMENT AND APPLICATION: MEETING THE FIRST OBJECTIVE

The basic mensurational steps necessary to carry out a large-scale aerial photo inventory were presented earlier. They are: 1) sample tree selection, 2) species identification, 3) determination of tree diameter, and 4) prediction of tree volume. Each of these steps will now be examined by looking at the problem, a general theoretical solution, and a method for applying this solution in context with the first stated objective.

Determination of Tree Species

Problem: Specify a method which allows the species of individual trees to be determined on aerial photos.

Theory and application: The color and branching pattern of individual trees on large-scale aerial photos can be used to determine tree species. The choice of the scale, film, and filter combination which best facilitate this process must be made with knowledge of the specific area of interest. The use of experienced interpreters is desirable.

Determination of Tree Stem Diameter

Problem: Specify a method which will allow the diameter of individual trees to be obtained from aerial photos without the need to measure tree height.

Theory and application: Regression can be used to predict tree diameter from photo-measured independent variables. Crown area is the most promising independent variable (Aldred & Sayn-Wittgenstein 1972). Without the option to use height as an independent variable it is also possible that inclusion of a point density variable would prove useful. The DBH of sample trees are measured in the field; crown area and point density for these same trees are measured on photos. It is necessary to use the scale at the ground elevation to calculate crown area from the photo measurements since scale at the elevation where the crown is observed and measured on the photo is unknown. This will introduce some variation into the regression equation, but should not produce bias as long as the developed equation is applied in the same manner. The standard deviation about the regression is expected to be high, therefore a large sample size is recommended. Once derived, the regression equation can be used to predict DBH of trees within the same general area.

Determination of Tree Volume

Problem: Specify a method that will allow the volume of individual trees to be obtained from aerial photos without the need to measure tree height.

Theory and application: An estimate of tree volume can be obtained through the use of the tarif system. The theory of the tarif system is presented elsewhere (Turnbull & Hoyer 1965) and will not be repeated here. Given that the DBH of sample trees can be calculated through regression, as just discussed, the only obstacle to volume calculation is that of accessing the correct tarif table. Field measurements must be used to determine an average tarif access number of the area of interest or, if the area is large, it may be stratified into smaller strata more homogeneous in tarif number and an average tarif number would be determined for each strata (see appendix B). Once this is accomplished, the volume of any single tree could be calculated through the "equation form" of the tarif volume tables, which is:

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CVTS=TAR*((1.0330*(1.0+1.382937*EXP(-4.015292*(DBH/10))))*
                        (BA+0.087266)-0.174533)/0.917233
```

where; CVTS=the total cubic tree volume including top and stump,

TAR=average tarif number,

DBH=the predicted DBH of the tree from regression,

BA=basal area of the tree, as calculated using the predicted DBH.

EXP(x)= e^x

This CVTS volume can then be converted to many other units of measure and merchantability limits using equations supplied by Brackett (1973) and Chambers and Foltz (1979).

Sample Tree Selection

Problem: Develop quantitative methods for applying fixed plot, variable plot, and line transect sampling schemes on aerial photos without the need to measure tree height.

The solution to this problem is complex. It will be presented through the examination of five "subproblems" to facilitate clarity. Four basic assumptions are necessary to develop and apply the following techniques. They are stated here without qualification, but will be examined more closely after the five subproblems have been presented. The basic assumptions are:

1. Flying height above the ground is known for each

photo plot center.

2. The topography at each plot center is horizontal (elevation may change between plots).

3. All trees are perfectly vertical.

4. All photos are free from tip and tilt.

Examination of the Subproblems

Subproblem 1: It is necessary to obtain an estimate of photographic scale at the tops of individual trees.

Theory and Application: Flying height above the ground (Hg) is assumed known, so:

$$St = (Hg-h)/f$$

where; St = scale at tree top,
h = height of subject tree,
f = camera focal length.

But, since h is unknown, it must be estimated using the following procedure:

1. A standard volume equation, applicable to the area of interest, of the form

$$\text{Volume} = \text{function}(h,\text{DBH})$$

must be available. Such an equation is generally used to determine tarif access and is a requirement of most inventory projects.

2. Algebraically solve the standard volume equation, which was used for tarif access, for height so that an equation of the form

$$h = \text{function}(\text{Volume}, \text{DBH})$$

is obtained.

3. Insert the predicted volume and DBH for a subject tree, which can be obtained using the methods previously described, into this equation and solve for height.

This is a biased estimate of tree height due both to the use of inverse regression and the use of predicted values of DBH and volume instead of actual values. If the bias is small, however, it may be of little practical importance. It is possible to reduce the amount of scale change between the ground surface and the tree top (geometric displacement), and thus the effect of any bias introduced in the estimation of tree height, by using the highest possible flying height to aquire the photography. To maintain the same desired photo scale it is necessary to use a longer focal length camera lens and (or) photographic enlargement as flying height is increased.

Subproblem 2: It is necessary to obtain an estimate of photographic scale at the height above the ground where the crown area is measured on the photo.

Theory and Application: Using the same reasoning as in subproblem (1):

$$Sc = (Hg - hc)/f$$

where; Sc = scale at the base of visible crown,

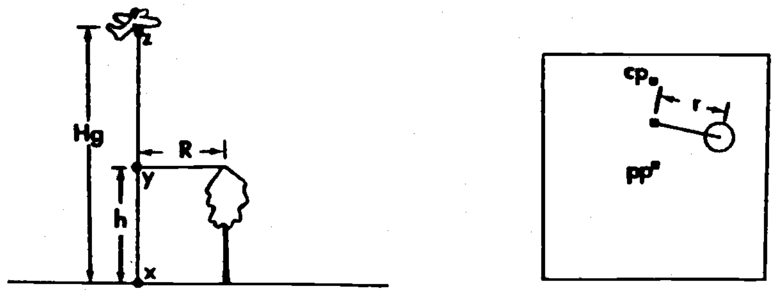
f = camera focal length,
Hg = flying height above the ground,
hc = average height above the ground at which the crown area of the subject tree is determined on the photo.

An estimate of hc can be obtained if the visible crown is assumed to be a constant proportion of total tree height, where tree height is calculated as in subproblem 1. This proportion is henceforth refered to as the "visible crown ratio".

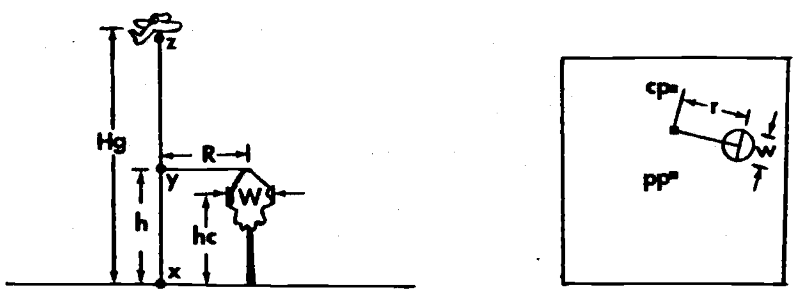
Subproblem 3: Determine a method for applying fixed plot sampling on aerial photos without the need to measure tree height.

Theory and application: For fixed plot sampling on photos, just as in ground sampling, trees are selected in a probability proportional to their frequency. In the procedure outlined below, however, frequency is determined by the position of tree tips as opposed to the conventional use of tree bases. Each "in" tree represents [1/SIZE] trees per acre, where SIZE refers to the fixed plot size in acres.

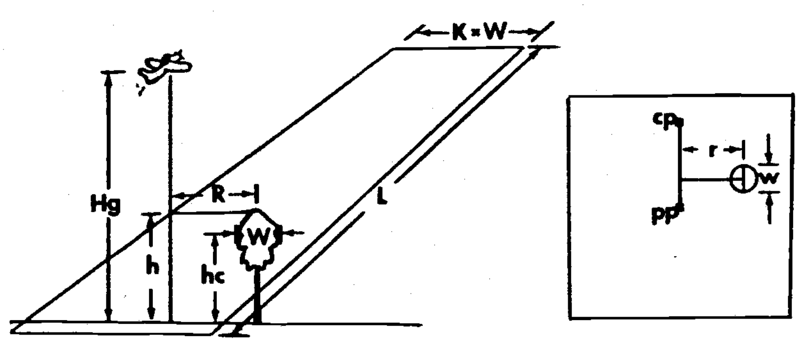
Refering to Figure 1a, line XZ is perpendicular, passing through the plot center, point X. By locating the plot center on a photo at a point midway between the principal and conjugate principal points of a photo, points X, Y, and Z would all coincide when viewing in stereo. This happens because all displacement occurs radially from this point when viewing a perfectly vertical stereopair, thus giving the impression of looking straight down on this particular point. The true horizantal distance from point Y to the tree tip (distance R) can then be found by measuring on the photo from plot center to the desired tree tip (r) and converting to ground



1a. Fixed Plot



1b. Variable Plot



1c. Line Transect Plot

Figure 1. Geometric representations of fixed, variable and line transect tree selection methods as viewed from the ground and photo.

distance using the scale at the elevation of the tree tip, as determined in subproblem (1).

For a fixed plot of a given SIZE, then, a limiting distance (LD) can be determined for which only trees with R less than LD are included in the plot tally. For example, if SIZE = 0.2 acre, then LD = $\sqrt{43560*0.2/pi}$ feet.

Subproblem 4: Determine a method for applying variable plot sampling on aerial photos without the need to measure tree height.

Theory and application: The application of variable plot sampling on photos is similar to ground methods, but trees are selected in proportion to their crown area as opposed to their basal area. A "crown area factor" (CAF) is used in place of the typical "basal area factor". Each "in" tree represents [CAF/(crown area of subject tree)] trees per acre.

Although the use of an angle guage to determine whether a tree is "in" a plot has been used on aerial photos (Paine 1965) it is not a particularly accurate or efficient method. It is possible to develop a better approach (Figure 1b) using the formula (Dilworth, 1976):

$$CAF = 43560/(1+(R/W)^2)$$

where; W = crown diameter in feet,

R = horizantal distance from the plot center to the tree tip in feet.

Using this formula, an "in" tree is defined as one which has a CAF greater than the specified constant CAF for the cruise; a procedure analagous to using a specified basal area factor in ground cruising.

To apply this theory to aerial photos, estimates of R and W must be obtained. As with fixed plots, it is desireable to locate the photo plot center at the point midway between the principal and conjugate principal points on a photo so that points X, Y, and Z all coincide in stereo. The distance, R, can then be found in the same manner as described for fixed plot sampling. An estimate of crown area can be found by measuring crown area on the photo, transfoming to photo crown diameter, and converting to a ground measure using the scale at that point, as described in subproblem (2).

Subproblem 5: Determine a method for applying line transect sampling on aerial photos without the need to measure tree height.

Theory and application: Line transect sampling has been described as a method for selecting trees proportional to both DBH and height (Grosenbaugh 1958). The use of line transect sampling on aerial photos is a natural extention of this theory to one of selecting trees proportional to their crown diameter.

Refering to Figure 1c, L is the total length of all flight lines. K is any desired prespecified constant, which will determine the cruise intensity. R is the perpendicular distance from the tree tip to the flight line. Using this terminology, an "in" tree is defined as one in which R is less than (K*W). Each "in" tree represents [43560/(K*W*L*2)] trees per acre, when the units for L and W are in feet. (The factor "2" is necessary since the tree may be on either side of the flight line.)

To apply this method on aerial photos the location of the flight line is determined by drawing a line between the principal and conjugate principal points on each photo. R is then found by measuring the perpendicular distance from the tree tip to this line and converting to the true distance using the tree tip scale, as determined in subproblem (1). W is found using the same procedure described in subproblem (4). There are two possible procedures for calculating L. They are:

1. On each photo, determine the true distance from the principal to conjugate principal point and sum these distances over all photos. This requires that the scale at the elevation at which the flight line is drawn on the photo be known. The easiest way to do this is to place the conjugate principal point on the photo so that, in stereo, it appears to be "floating" at the ground surface; in this way ground scale can be used to determine the distance from the principal to conjugate point. Unfortunately it is often impossible to see the ground in dense stands, so an alternative is to place the conjugate principal point so it "floats" at the average elevation of the tree tips. The scale at the average elevation of the tree tips can then be used to determine distance (although this may introduce some bias).

2. Transfer all plot centers to a map using a radial line plotter. The length, L, is calculated by measurement on the map and conversion to the true distance using the map scale.

A Look at the Basic Assumptions

The basic assumptions used to develop the tree selection theory were presented on page 23. They will now be examined in more detail.

Assumption 1: Flying height above the ground (Hg) is known exactly at each plot center. This assumption is necessary for the calculation of exact photo scale. Scale should be determined as accurately as possible but some error is inevitable. The bias created is most severe for fixed plot and line transect sampling and somewhat less for variable plot sampling (see Appendix C).

The most accurate method for determing Hg, without the use of a radar altimeter, is by ground truthing each photo. The economic inefficiency of this method necessitates the use of a simpler method, such as a combination of ground truthing a few photos in a flight line to establish flying height above sea level and radial-line plotting to a contour map to determine ground elevation of each photo.

Assumption 2: The ground surface at each plot is horizantal. This is seldom true. As a result, the frequency of trees on the "downhill" side of the plot (any trees for which flying height above the tree base is greater than the assumed Hg) will be overestimated, while the frequency of those on the "uphill" side will be underestimated. These errors are partially compensating, and can be treated as random.

Assumption 3: All trees are perfectly vertical. Violation of this assumption is of minor concern under normal circumstances. Theoretically, some trees will be leaning "in" to plots, while others will be leaning "out", indicating a random error. Since lean is not considered in the estimation of tree height (subproblem 1), the heights of leaning trees (defined as the tree top vertically above the ground) will be "overestimated" as compared to the same measurement if lean were considered. This would be of little consequence unless lean was greater than ten degrees.

Assumption 4: All photos are free from tip and tilt. The degree of tip and tilt affects photo scale. This is especially important if height is being detemined from the photos, a problem which has been eliminated using the procedures described above. Tip and tilt also effect other photo measurements, but a correction for this error requires sophisticated equipment and procedures, therefore cost. Tip and tilt can be minimized, however, through careful photo mission planning and execution. The stability of the aircraft used in the photo mission, the type of camera mount, the experience of the pilot and photographer, and the weather conditions on the day of photography determine how well this assumption is satisfied.

METHODS FOR THE EMPIRICAL TEST

There are two major stages in the empirical test: building the regression model (stage I) and performing the actual photo cruise (stage II). A number of preliminary tasks are necessary before stage I can begin.

Preliminary Tasks

Site Selection

A 346 acre tract in McDonald State Forest in the Oregon Coast Range was selected as the site for the empirical test. This particular area was chosen because wide ranges of diameter and density classes are represented. Also, very little thinning activity had taken place for at least 30 years, thus providing an advantageous setting for evaluating the effectiveness of using a density measure as an independent variable in the DBH regression model. Due to time constraints it was decided that stand tables, stock tables, and volume estimates would be developed only for the predominate species, Douglas-fir (Psuedotsuga menziesii).

The study site ranges in elevation from 540 to 1134 feet. Average slopes range from 5 to 60 percent. The majority of the stands are even-aged Douglas-fir, 80 to 150 years old, with scattered younger stands. There are hardwoods, mostly Acer macrophyllum and Quercus garryana dispersed throughout most of the area, sometimes occurring in nearly pure stands. Grand fir (Abies grandis) grows in association with the Douglas-fir on a few sites. There is an isolated plantation of ponderosa pine (Pinus Ponderosa).

Photo Aquisition

Preliminary tests indicated that prints made from Kodak Aeronegative film, using 2X photographic enlargement and an effective scale (after enlargement) of 1:1500, would be satisfactory for successful photo identification of the tree species present (Paine & McCadden 1985). On a calm, clear day in early July between 11:00 a.m. and 2:00 p.m. a series of 17 flight lines were flown over the test site. Photos were taken at an average scale of 1:3500 (1:3000 attempted) using a 70 mm. Hasselblad camera and a 250 mm. lens. Examination of the negatives revealed problems with duplication of coverage, so only the usable photos in fourteen lines were targeted for printing.

The seven flight lines most evenly distributed across the site were selected as the database for carrying out the photo cruise. These lines contained 153 usable photos,and will be refered to as the "cruise photos". The remaining photos, henceforth called the "regression photos" were reserved for developing the DBH regression model. The subjective method of selecting the flight lines to be used in the photo cruise was necessary to insure adequate site coverage of both cruise and regression photos, since some flight lines nearly overlapped.

Determination of Photo Scale

Principal points were pinpricked on each photo. Each conjugate principal point was transfered from the adjacent photo so that the point, in stereo, appeared to be floating at the average elevation of the tree tops (for the purpose of line transect sampling, see page 28). A plot center for the fixed and variable plots was established on each photo halfway between the principal and conjugate principal point.

Each plot center was transferred to an existing contour map using radial line plotting. An intermediate step, in which each plot center was carefully transfered to existing 1:12000 photography of the site, was necessary to establish ground control for radial line plotting.

Flying height above sea level (Hs) was established by ground truthing at least two locations of known elevation at each end of the flight line. The flying height above sea level for each flight line was determined by averaging the mean Hs estimates from the two ends, and was used as a constant for each photo in that flight line. In only one instance did the mean Hs from the two ends of a flight line differ by more than 1%. In that case a correction was applied to each photo in the flight line by assuming Hs to have changed at a constant rate.

The scale at each plot center was determined using the estimated flying height above sea level and the ground elevation of each plot center as determined from the contour map.

Automation of Photo Measurements

Both stage I and stage II involve a large number of photo measurements including: (1) the crown area of all trees used in stage I, (2) the distances to all neighboring trees and their crown areas for computation of point density about any subject tree (discussed on page 35), and (3) the crown area and distance from plot center for any tree suspected of being an "in" tree in stage II.

Fortunately, these measurements lend themselves to automation through the use of a personal computer equipped with a digitizer. To accomplish this, it was necessary to make crown maps for each photo by transfering all pertinent information - crown perimeters, tree tip locations, and principal and conjugate principal points - to overlays while viewing in stereo. A micro-computer program was developed which allows mapped crown areas and associated points to be digitized and stored in a data file; points being stored as X,Y coordinate pairs. Computer programs, discussed later, utilize this information and determine distances geometrically and mathematically from the coordinate pairs and crown areas.

Stage I: Developing the Regression Equation

The Choice of Dependent Variable

There were two possible choices for the dependent variable: tree diameter and tree basal area. DBH was selected because of its use in the creation of stand and stock tables.

The Choice of Independent Variables

Crown area, as mentioned, was singled out as the most promising independent variable. Because a linear relationship between crown diameter and DBH was indicated by the literature a square root transformation of crown area was expected to do quite well, so crown areas were simply transformed to crown diameters.

The point density measure "adjusted A" (AA) was also selected as a potential independent variable. Alemdag

(1978) points out that density measures with larger influence zones (those including more neighbors) tend to be more effective as predictors of growth. In this light, a range of density measures, each accounting for a wider sphere of influence, were devised. Adjusted A's accumulating the percent crown closure for all neighbors contributing 15 (AA15), 10 (AA10), and 5 (AA5) percent crown closure (see page 12) were selected. Furthermore, the contribution from hardwoods (H) and conifers (C) were kept separate to form six additional density measures (AA5C,AA10C,AA15C,AA5H,AA10H,AA15H) since it was suspected that the influence of these two species groups would differ.

Data Collection

A total of 484 trees were located on the regression photos distributed throughout the site for use in building the regression equation. Four to five trees were selected on each photo, making an effort to select one tree which was small, one large, one under strong competition, one under little competition, and one randomly. The selections were confined to trees which were near plot center (up to about 1.5 inches photo distance away), since the equation was going to be applied to trees in a similar position relative to the plot center (but on different photos). These 484 trees were visited in the field, and their DBH's were measured to the nearest 1/10 inch.

Crown maps were constructed for all regression photos on which the 484 sample trees were selected. For each photo, the principal and conjugate principal points, crown perimeters of the sample trees, crown perimeters of all neighbors which had any potential for contributing to the density measures, and a point marking the tips of these same trees were transfered to a crown map while viewing in stereo. The crown maps were enlarged using a distortion-free copying machine. The copies were digitized and the crown areas and tree tip coordinates for each tree were stored in a data file. A program was written which, when supplied with this data file, the photo scales, and the blowup factor of the copy machine, calculated the crown diameter (CD) and nine point densities about each of the 484 sample trees.

In addition to the data collected for developing the DBH regression equation, data were collected on 206 trees to serve as the validation data set. These trees were selected on the cruise photos, at a maximum of three per photo, distributed throughout the site. These trees were selected so that, at the time of the photo cruise, they would likely be "in" trees, and therefore a subset of the trees actually used to develop the stand and stock tables. This was accomplished by selecting trees on each photo within one inch of plot center (the approximate photo distance equivalent to a 1/5 acre fixed plot radius) whose crowns intersected either (1) the flight line, or (2) the line perpendicular to the flight line and passing through the plot center. The DBH's and heights of these 206 validation trees were measured in the field. These measurements made it possible to also calculate tree volume and tarif number, which would serve as standards for comparison to predicted values.

The Analysis

Visual analysis of the DBH:CD relationship appeared linear, but heteroscedasticity of the error terms was evident. A weighted least squares approach was deemed necessary. Weights of the form

$$W = .12(CD)^{1.55}$$

were determined appropriate using method a described by Draper and Smith (1981). The dependent and independent variables were divided by the square root of their weights, and the transformed model was fit. Homoscedastic errors were achieved, but their distribution was non-normal.

With this in mind, a log-log transform model was tried. This procedure overcorrected for the increasing variance, thus producing a slighty decreasing trend. Weights of the form

$$W' = \ln(CD)^{-3.1}$$

were determined and applied as described above. This produced stable variance. The distribution of the errors is not significantly different than normal using the Bowman-Shenton omnibus test (Bowman & Shenton 1975).

With these assumptions met, the model was considered adequate for testing the significance of adding the AA density measures. Plots of the density measures over the transformed, weighted dependent variable showed only very weak trends; the most significant density measure, A5C, was significant only at the 0.14 probability level (Figure 2) when crown area was already included in the model. More importantly, this addition had virtually no effect on the mean squared error, indicating that it was of little practical significance. The minor effect of including a density measure is illustrated in Figure 3, where the crown diameter to DBH relationship for the trees in the validation set with the highest A5 density (top 25%) and the lowest A5 density (bottom 25%) are plotted

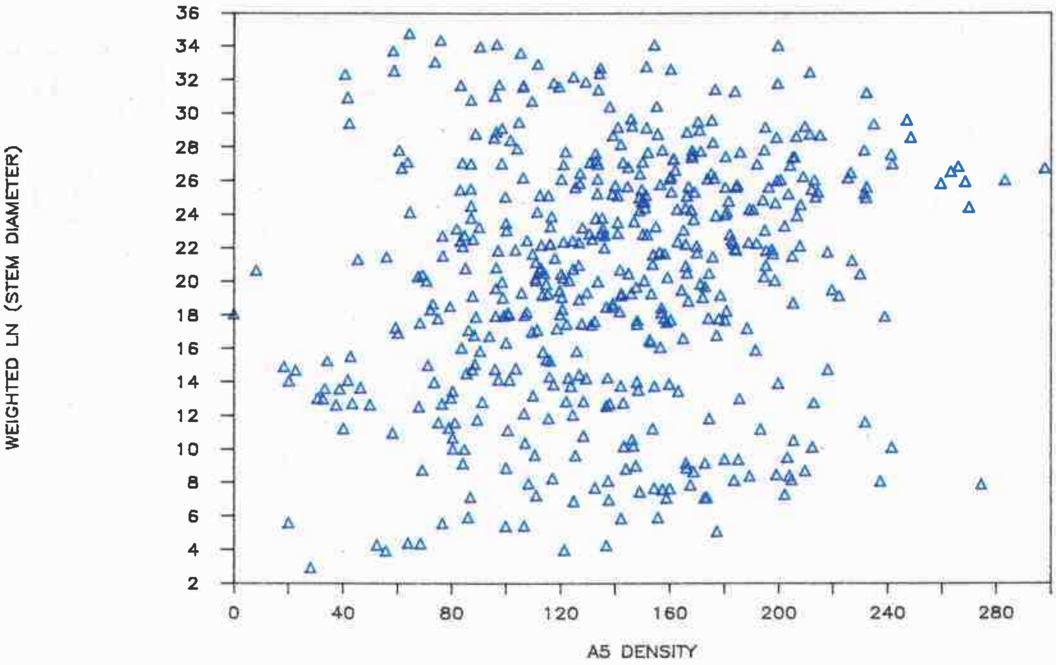


Figure 2. Graphs showing the weak relationships between stem diameter and "adjusted A" point density.

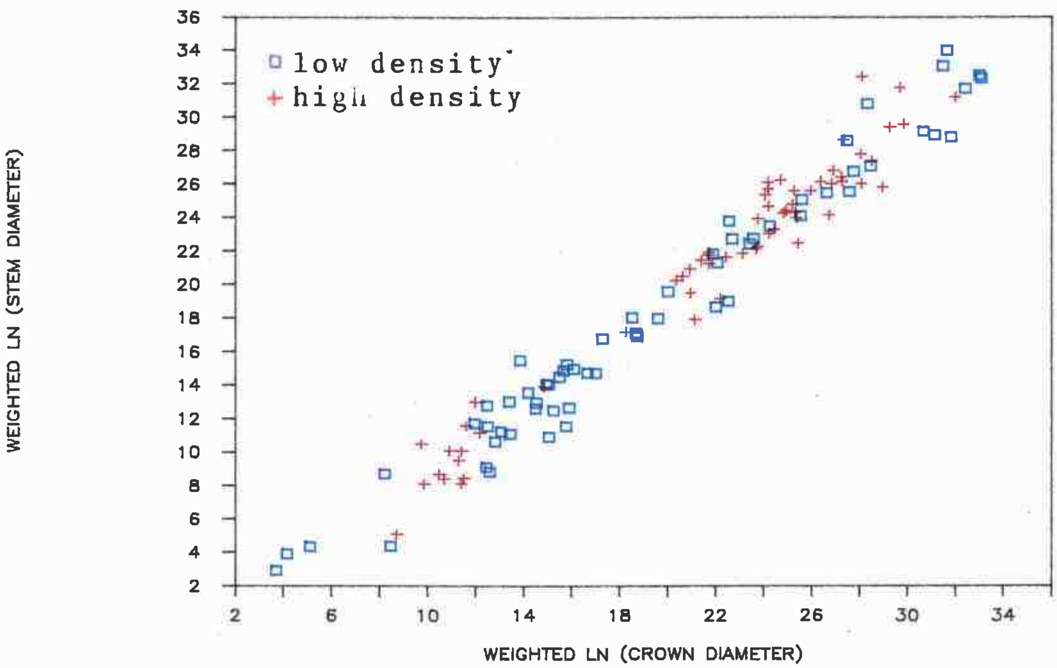


Figure 3. Simultaneous plotting of the crown diameter: stem diameter relationship for the validation trees in the upper and lower 25% A5 density classes.

simultaneously; both data sets, for practical purposes, seem to define the same regression equation. While it is possible that some transformation of density may have improved the "t" test figures slightly, the general poor graphical correlations made this seem a futile course and further testing was abandoned.

Since the major use of the regression model was to be prediction, it was decided that the weighted log-log model was not adequate due to the difficulty of correcting for log bias. The unweighted log-log model suggested that the CD:DBH relationship was slightly cuvilinear, so a weighted nonlinear model of the form

$$DBH = b1(CD)^{b2}$$

where b1 and b2 are model parameters, was fit to the data. Weights were the same as those used in the linear CD:DBH model. Homogeneous variance was obtained, thus achieving best linear unbiased estimates of the parameters. The errors were not normally distributed, but this is not essential for predictive purposes. Furnival's index of fit (Furnival 1961), which is a representation of the mean squared error from various regressions using a common scale, is 4.94 for this nonlinear model, as opposed to 4.77 for the weighted log-log model and 5.51 for a linear, unweighted model.

Stage II: The Photo Cruise

Since the procedures that have been suggested for DBH prediction, tree volume estimation, and sample tree selection are quantitative, they lend themselves to computer application. Also, once these data have been calculated, average gross volume per acre, stand tables, and stock tables can be determined mathematically. A computer program was therefore written to calculate the photo cruise results.

Inputs to the Cruise Program

The cruise program developed requires the following inputs:

1. fixed plot size, crown area factor, and DBH expansion factor, which determine cruise intensity for fixed plot, variable plot, and line transect sampling methods, respectively;

2. digitized crown map data from each of the 153 photo plots, which must include, for each plot, (a) the coordinates of the principal and conjugate principal points and (b) the crown areas, with associated tree tip coordinates, for all potential "in" trees using all three sampling methods;

3. average ground scale at each plot;

4. camera focal length;

5. photographic and photocopy enlargement sizes;

6. the appropriate DBH-predicting equation;

7. an applicable standard volume equation;

8. average tarif number for each plot;

9. average "visible crown ratio".

To make the results of the three sampling methods comparable, the fixed plot size, crown area factor, and diameter expansion factor were selected so that on the average, approximately ten trees would be selected per plot regardless of the sampling method used. A fixed plot size of 1/5 acre, a crown area factor of 2500, and a diameter expansion factor of 2 were selected using a computer program which calculated these values from the digitized crown map data from the regression photo data.

The Bruce-DeMars volume equation (Bruce & DeMars 1974) was selected as the local volume equation for trees with stem diameters less than 32 inches, while the Weyhauser Douglas-fir volume equation (Brackett 1977) was used for larger trees. This combination was used by the OSU ground inventory, and was adopted for use in the photo inventory to make the results comparable.

A single tarif number was determined for each photo inventory plot using the following procedure:

1. An average tarif number was calculated for each of the 206 OSU inventory plots in the test area by determining a mean, weighted by the number of trees per acre represented, for all trees on the variable plot (trees over 8 inches DBH). Only undamaged trees, or those with minor damage, were considered.

2. Each mean plot tarif was transfered to a plot map of the area. The site was then stratified, on the map, into six strata which were fairly homogenous as to tarif number.

3. All mean plot tarif numbers within each stratum were averaged to derive a single tarif number for that stratum.

4. All photo plots within a stratum, and all trees within those plots, were assigned the mean tarif number for that stratum.

Photo observation indicated that the visible crown was about 1/3 of the total crown length. Previous inventory data indicated that the average crown ratio was 43% for the dominant and codominants, so an average visible crown ratio of (.43 * .34) = 14.3% was selected.

The Cruise Program Algorithm

The cruise program, for each of the three tree selection methods, proceeds according to following algorithm:

1. The plot center for each fixed and variable plot is calculated as the coordinate of the point midway between the principal and conjugate principal points. The plot center for the line transect plot is calculated as the line between the principal and conjugate principal points.

2. For each tree crown mapped, its crown area, using ground scale, is calculated. This is used as an independent variable in the regression equation to predict its <u>DBH</u>.

3. Using predicted DBH and the appropriate tarif number, the <u>CVTS</u> volume of each tree is calculated using tarif volume equations. This CVTS volume is transformed mathematically into cubic volume to a four-inch merchantable top (CV4) and Scribner volume

to a six-inch top in 16-foot logs (SV616).

4. Each tree height is estimated using inverse regression of the standard volume equation.

5. Estimated tree height, photo enlargement factor, visible crown ratio, camera focal length, and ground scale are used to determine the photo scale at the tip and visible crown base of each tree.

6. True crown diameter and distance of the tree tip from the plot center are calculated for each tree from the digitized data and appropriate scales. Using this information, each tree is evaluated as to whether it is in the plot.

7. Gross volume per acre estimated by each sample plot is calculated from the volume of all "in" trees on the plot and the appropriate formula.

8. Stand and stock tables in two-inch diameter classes are produced. The mean gross volume per acre is calculated as the sum of the volume per acre estimates in all diameter classes.

In addition to doing the actual photo cruise, the cruise program takes, as input, the field measured DBH's and tree heights of the 206 validation trees (which are a subset of the trees in the photo cruise). It calculates the "true" (field-measured) CV4 volume of these trees using the appropriate volume equation. The true volume, predicted volume, true DBH, predicted DBH, true height, and predicted height are all output to data file for further analysis.

EVALUATION OF RESULTS OF THE EMPIRICAL TEST: MEETING THE SECOND OBJECTIVE

The stand tables, stock tables, and gross volume estimates using each of the three sampling methods, are the desired end-products of the empirical test. These results will be influenced by the net effect of all cumulative biases occuring in the steps used in their development. Because of this, it is useful to examine the biases associated with some of these steps in addition to displaying the final results. To this end, the following section will examine the results of predicting the diameters, tarif numbers , volumes, and heights of the trees in the validation data set. Following this, the results of the aerial photo stand tables, stock tables, and gross volume will be presented, in conjunction with comparative data from the OSU ground inventory.

Examining Individual Tree Measurement Predictions Using the Validation Data Set

Prediction of DBH

Figure 4a shows the error in estimating the the stem diameters of the validation trees, expressed as a percentage of their true diameters, over the range of their crown diameters[1]. A slight downward trend appears to exist because most points at the far left side of the graph fall above the horizontal "zero line" (signifying

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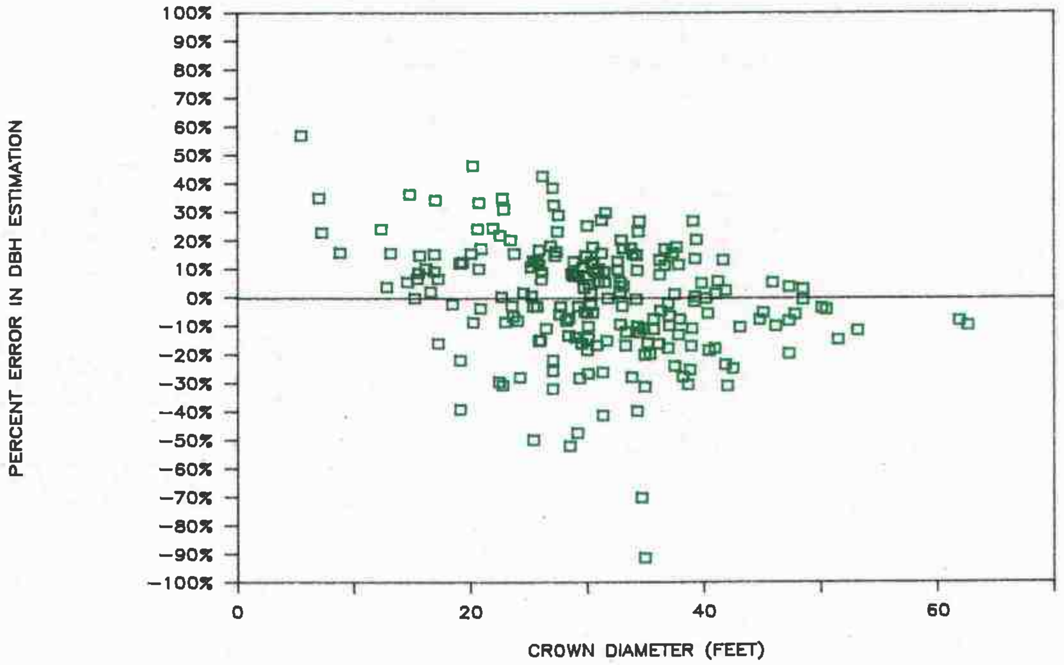
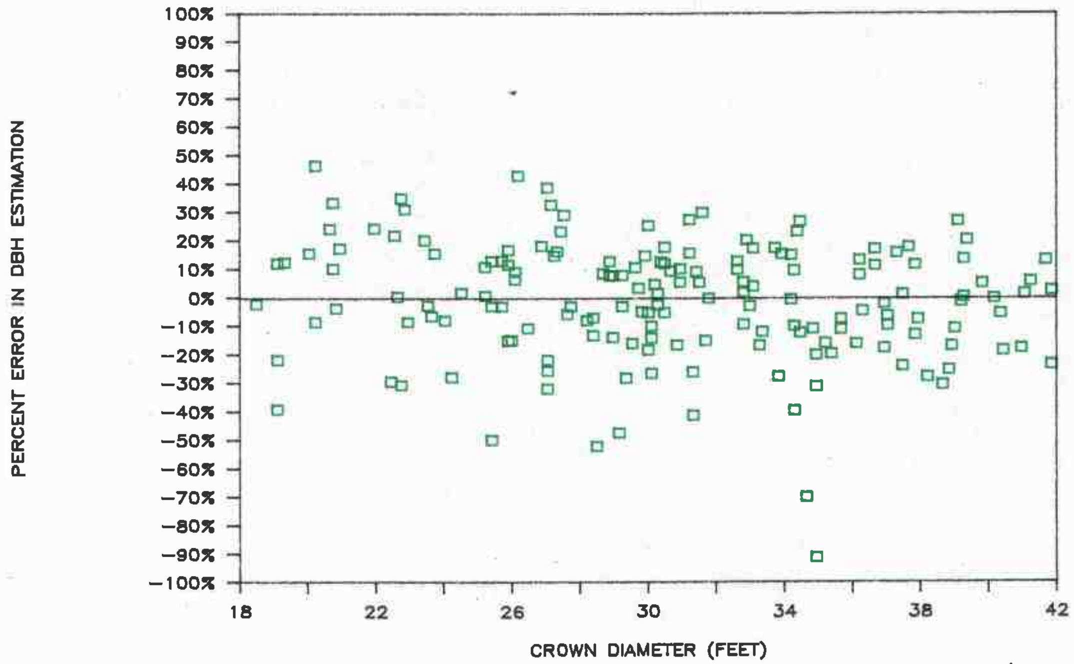
[1] Residuals are expressed as percentages to homogenize variance and allow for more convenient interpretation than would graphs of weighted residuals.



4a. Relationship graphed over the Entire Crown Diameter Range



4b. Relationship graphed over the Restricted Crown Diameter Range

Figure 4. Residual plots resulting from the prediction of the stem diameters of the trees in the validation data set, with residuals expressed as a percentage of the true stem diameter.

underprediction), and most points at the far right fall below the line (overprediction). An examination of Figure 5 reveals that this trend is not due to a misspecified model, as might be suspected, but rather to a failure of the validation data set to include: (1) trees having crown diameters larger than 42 feet and DBH's greater than 48 inches, and (2) trees having crown diameters less that 18 feet and DBH's less than 11 inches. If an examination of residuals is made only for that portion of the population adequately represented by the validation set (crown diameters from 18 to 42 feet), as in Figure 4b (residuals are expressed as percentages), a trend is less evident. Although a very weak, downward sloping trend can be envisioned, an attempt to verify it statistically was considered pointless due to the large variability in the data.

The average residual is 0.37 inches, which is not significantly different from zero (t=1.02). Because the "t" test uses the precision of the regression equation to test for bias, however, it does not guarantee that bias is nonexistant; only that an average residual of this size is not an unlikely event for this sample (Freese 1960).

The validation data indicate that the DBH regression model, at least within the range of crown diameters from 18 to 42 feet, is performing adequately. It is possible that small biases exist, undetectable because of the large variability in the data.

Prediction of Tarif Number

Examination of Figure 6, which shows the percent error in estimation tarif number over the range of crown diameters, reveals that there was a tendency to underestimate the tarif number of the validation trees.

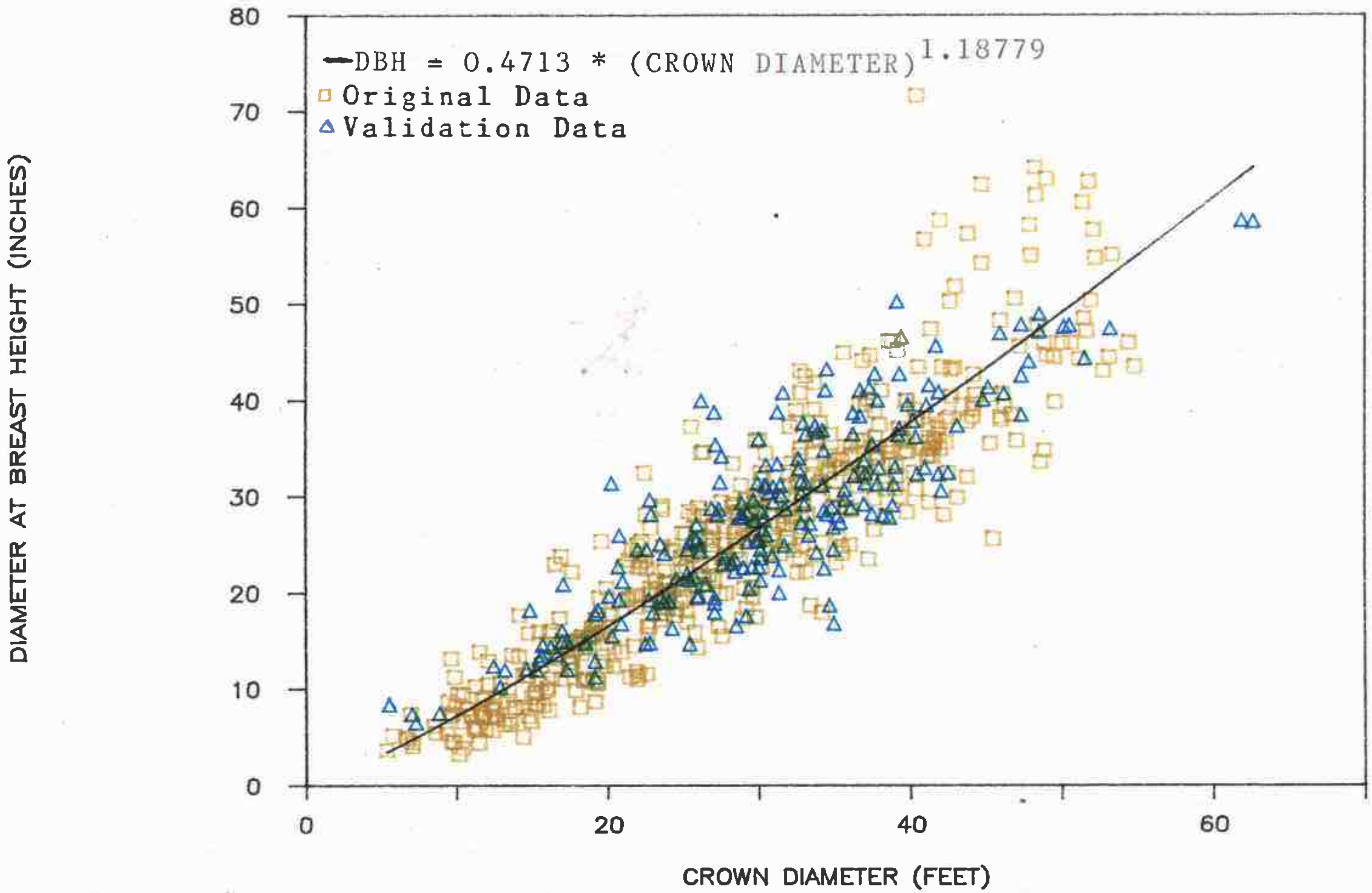
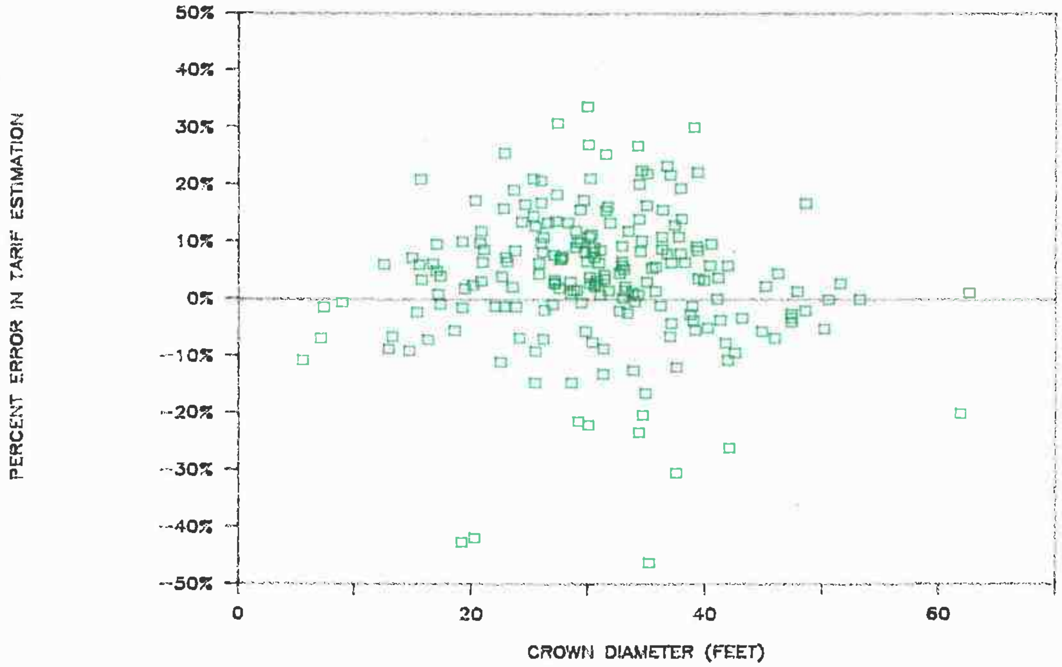
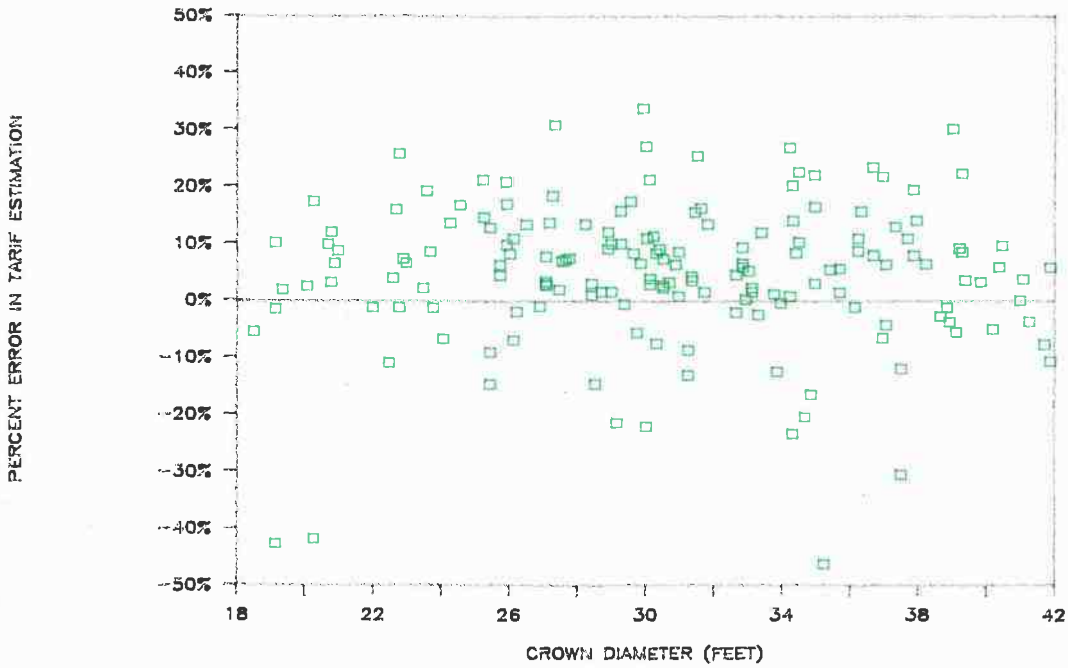


Figure 5. Simultaneous plot of the relationship between crown diameter and stem diameter for all observations in the original and validation data sets.



6a. Relationship graphed over the Entire Crown Diameter Range



6b. Relationship graphed over the Restricted Crown Diameter Range

Figure 6. Residual plots resulting from the prediction of the tarif numbers of the trees in the validation data set, with residuals expressed as a percentage of the true tarif number.

The predicted mean tarif number is 4.8% below the true value. Figure 7 gives the breakdown of the errors in tarif prediction by tarif strata (validation trees fell in only five of the six strata, missing one small stratum about 7 acres in size).

No single source of error capable of causing this difference between the average tarif number determined from the existing OSU inventory data and the average tarif number of the validation trees could be identified. Multiple sources are suspected. The two sources which are believed to be the major contributors are:

1. Methodological differences in selecting the trees used for average tarif calculation. The average strata tarifs were determined from trees included in the existing OSU inventory data, and were weighted proportional to tree frequency (see page 42). This is not strictly true for the validation trees, since these trees were selected proportional to crown diameter (see page 37), and tarif number may vary by diameter class (McCadden 1983, Peavy, 1984).

2. Sampling error. Although the sample size of the validation data set was large, these 206 trees came from about 65 clusters which were distributed systematically within the study site. The majority of validation trees in any stratum came from a single strip through that stratum; the strata populations may not have been adequately represented.

Differences in field measurement techniques and mathematical calcultions were examined and eliminated as potential sources of bias. It is possible that other sources, which could not be identified, also contribute.

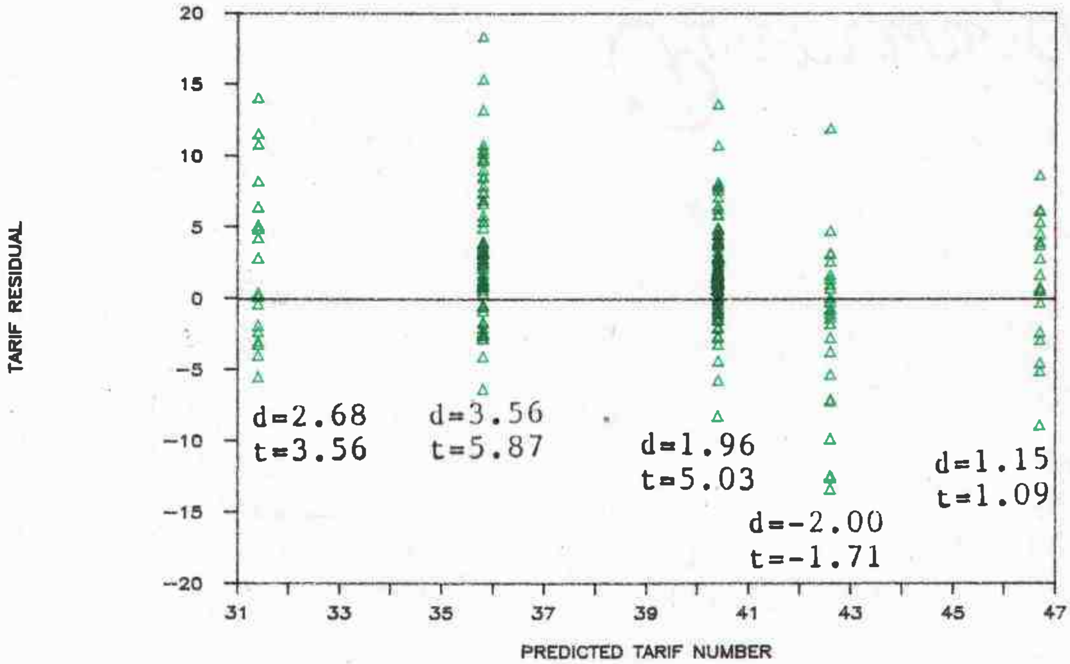


Figure 7. Summary of the errors in estimating the tarif numbers of the trees in the validation data set by tarif strata.

Prediction of Tree Volume

The average residuals resulting from the prediction of volume for those trees in the validation set are 14.7 cubic feet (CV4) and 107.1 board feet (SV616). These values represent underpredictions of 6.8% and 7.8% of the volume of the average tree in the validation set in CV4 and SV616 units, respectively. Such an underprediction is not surprizing since volume is calculated from predicted DBH and tarif number and, for this validation set, these values were both underpredicted. For example, tarif number is known to have been underpredicted by an average of 4.8% for the trees in the validation set; this would create an average underprediction of approximately the same relative magnitude in the estimation of volume. Additionally, DBH was underpredicted by an average of 0.37 inches, which is expected to cause an average underestimate of volume of approximately 1 to 2% (depending on how the bias in DBH is distributed among diameter classes).

Another possible source of error in the determination of tree volume, mentioned earlier, arises from the use of a predicted (stochastic) value of DBH in the tarif volume equation. A detailed discussion of this procedure is beyond the scope of this paper. A brief examination of this situation, however, indicates that the result would be an underprediction of tree volume. The following reasoning is used:

1. Since a DBH regression equation was developed, the sum of the DBH residuals would, ideally, be zero.

2. Because basal area is a function of squared diameter, the sum of the residual basal areas should be some positive number, assuming the distribution of

the DBH residuals is not badly skewed (skewnes could actually increase <u>or</u> decrease this effect.

3. Volume is calculated as a constant (tarif number) times basal area, therefore the sum of the residual volumes should also be a positive number, which corresponds to an underprediction in tree volume.

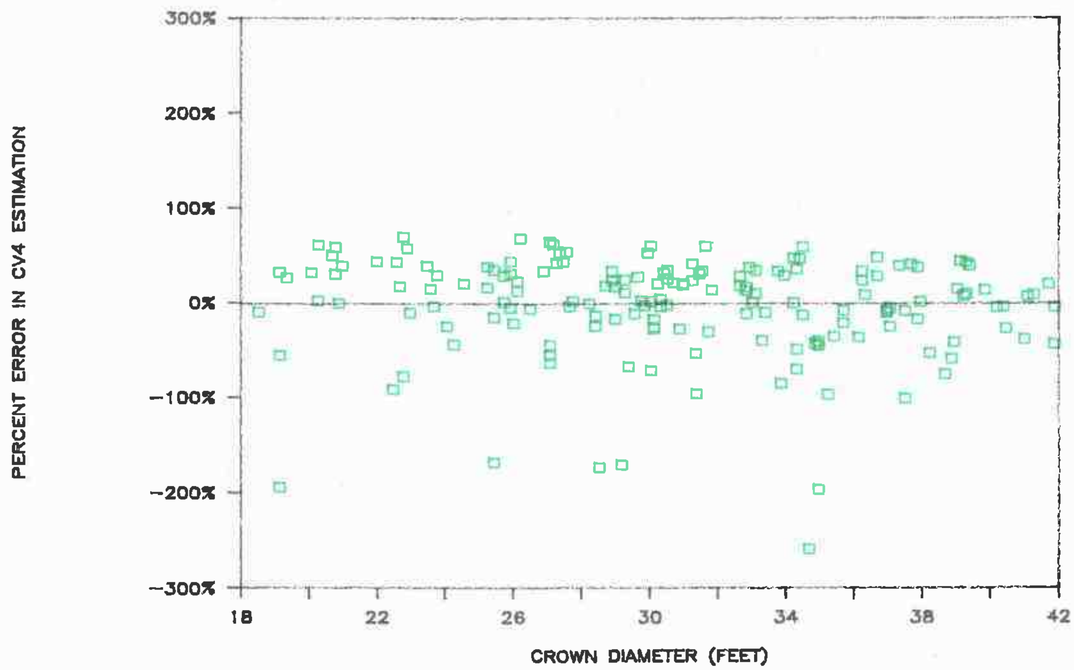
This suggests that the underprediction of volume observed for the validation set may be due, in part, by the use of a stochastic measure of DBH. It also provides a reason to believe that the prediction of basal area, instead of DBH, would lead to a less biased estimate of tree volume.

Residual percentage plots for the predicted CV4 and SV616 volumes per tree are shown in Figures 8a and 8b. A slight downward-sloping trend is suspected, but it is minor as compared to the total variability in the data, indicating that statistical testing would not provide a means for verification of the trend.

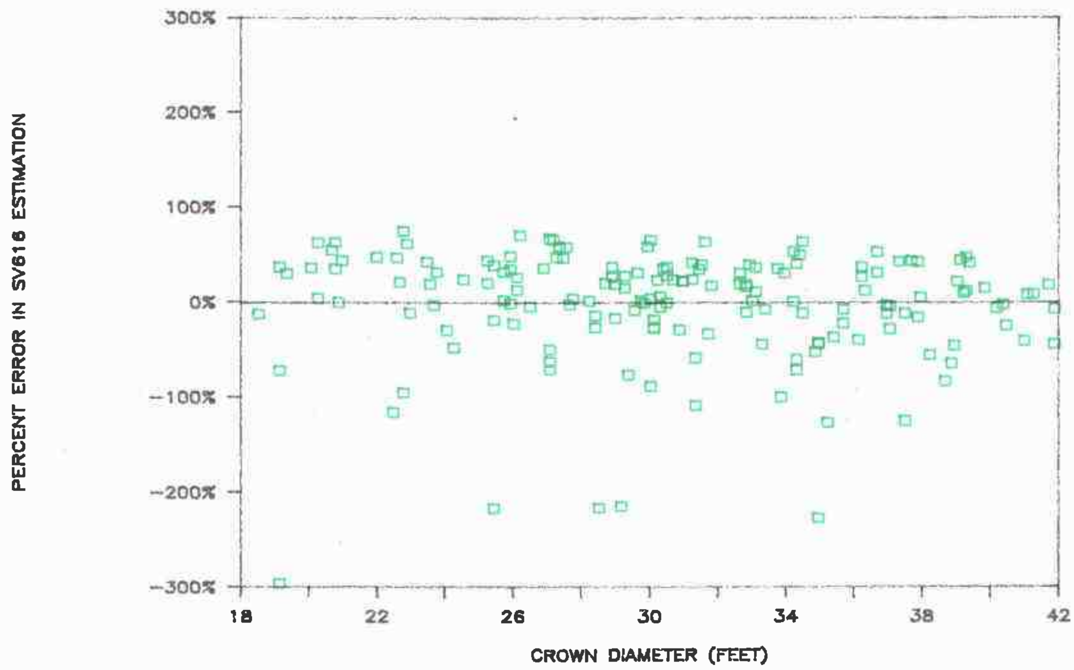
Prediction of Tree Height

The accuracy with which tree height is estimated is important since it is influential in the determination of tree frequency. The average residual resulting from height prediction of the validation trees is an underprediction of 6.9 feet. This bias is a consequence of (1) biases in the estimates of tree tarif number and DBH and (2) bias introduced from the use of stochastic variables and the inverse regression procedure used for calculation (see page 25).

The observed average underestimate in tree tarif number by about 5% is believed to be the major cause of the underprediction of tree height. In general, if



8a. Cubic Volume to a Four-inch Top



8b. Scribner Volume to a Six-inch Top in 32' Logs

Figure 8. Residual plots resulting from the prediction of CV4 and SV616 volume for the trees in the validation data set, with residuals expressed as a percentage of the true volume.

average tarif number is underpredicted by 5% then average underestimates of tree height from about four feet (10-inch DBH tree) up to a maximum of ten feet (60-inch tree) for the trees in the validation data set would occur.

A small average bias in the prediction of DBH has relatively little effect on the determination of tree height. An average underestimate of DBH by .37 inches, as was observed for the validation set, results in an average underprediction of tree height of less than one foot. An investigation of the errors introduced through the use of inverse regression and stochastic independent variables was not undertaken since the biases in tarif number and DBH seemed to account for the majority of bias observed in predicting the height of the trees in the validation data set.

Summary of Individual Tree Measurement Results

Although the predicted individual tree measurements investigated show high variability from their true values, the biases involved are small. The major source of bias uncovered is that arising from the underprediction of tarif number. This, in turn, introduces bias into the estimation of tree volume and height.

Examination of the Results of the Photo Cruise In Comparison to the Results from an Independent Ground Sample

Prediction of Total Gross Volume

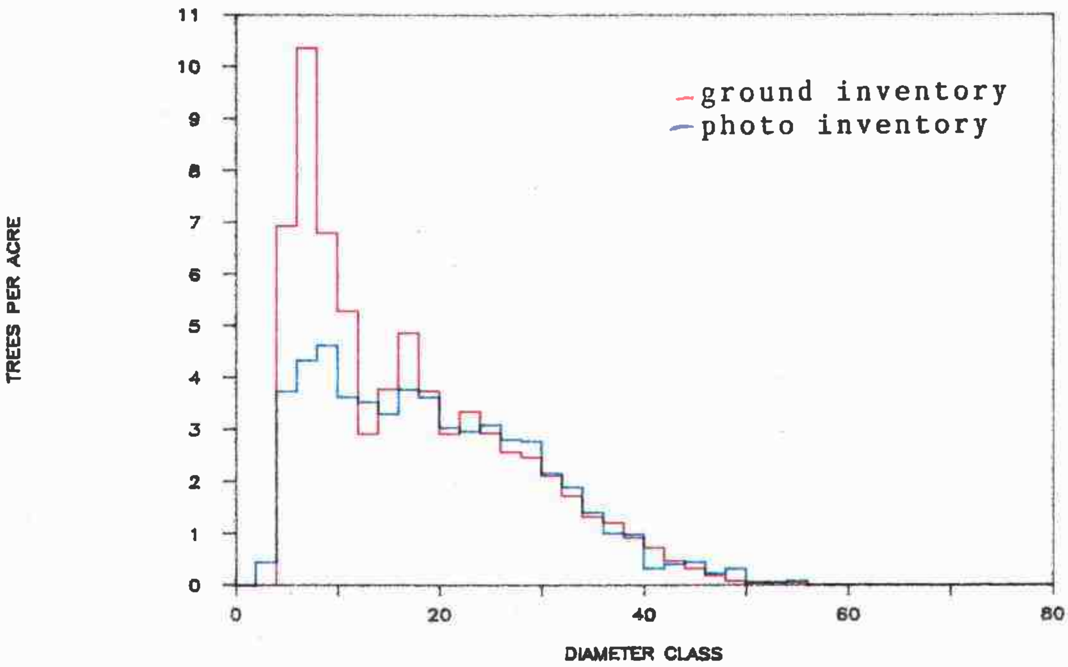
The results of predicting the mean gross volume per acre of the test site, including the associated standard errors of these means (see appendix D), are presented in Table 1. All photo sampling methods produced mean volume estimates within 5% of the mean obtained by the OSU ground inventory. Except in in the case of predicting CV4 using fixed plot sampling, the photo estimates are within one standard deviation of the mean of the OSU estimate; in all cases the 68% confidence intervals for the OSU and photo inventory estimates overlap.

TABLE 1. The Results Of Gross Volume Per Acre Estimation Using the Aerial Photo Timber Inventory System in Conjunction with the DBH-predicting Regression Equation.

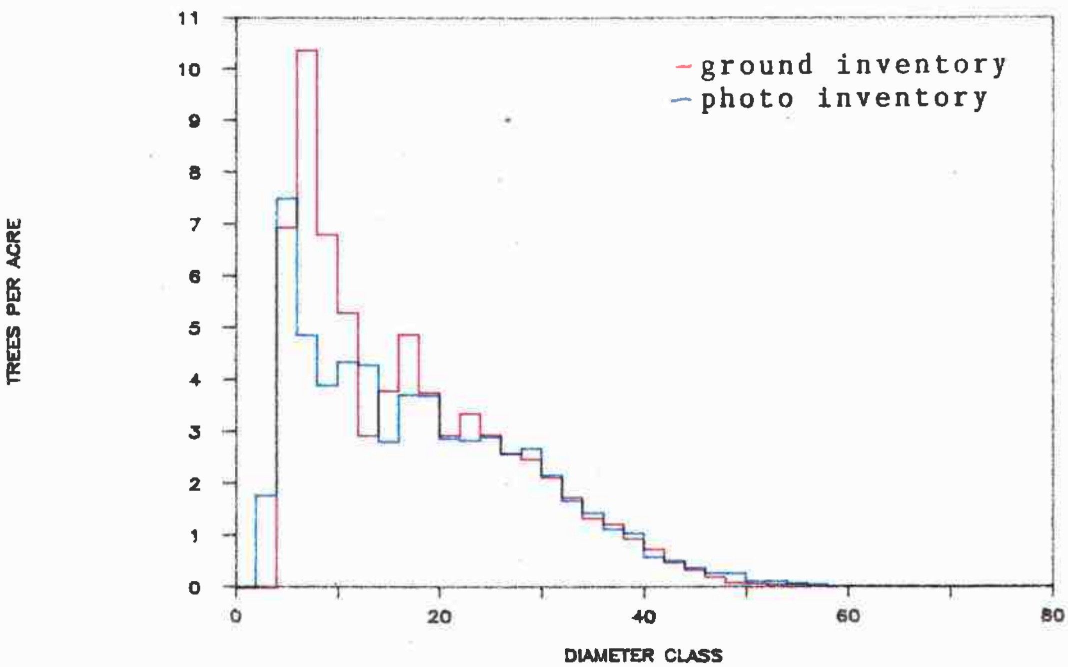
MEAN VOLUME PER ACRE	OSU INVENTORY	FIXED PLOT	VARIABLE PLOT	LINE PLOT
CV4	6,378	6,071	6,176	6,420
STD.DEV.	284	263	236	242
SV616	38,259	36,461	37,149	38,593
STD.DEV.	1,805	1,723	1,554	1,588

Production of Stand Tables

Aerial photo stand tables, in two-inch diameter classes, are shown graphically in Figures 9a, 9b, and 9c for fixed plot, variable plot, and line transect sampling methods, respectively (in red). The stand table produced using the OSU inventory data (appendix A) is shown also (in blue). The following general trends are evident:

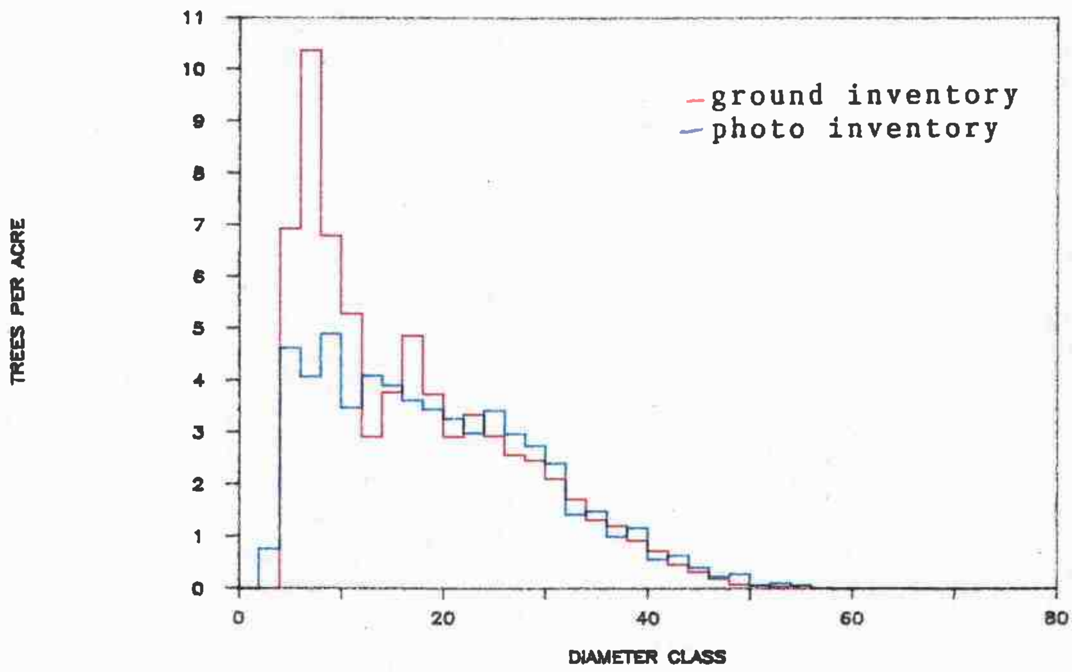


9a. Fixed Plot Sampling



9b. Variable Plot Sampling

Figure 9. Graphic stand tables resulting from the photo cruise in conjuncton with the DBH-predicting regression equation for fixed, variable, and line transect tree selection methods.



9c. Line Transect Sampling

Figure 9. (continued from previous page)

1. No sampling method produced good estimates of tree frequency for diameter classes below ten inches. These smaller trees may be understory trees which were missed in the crown mapping process due to the presence of shadows and dominating tree crowns.

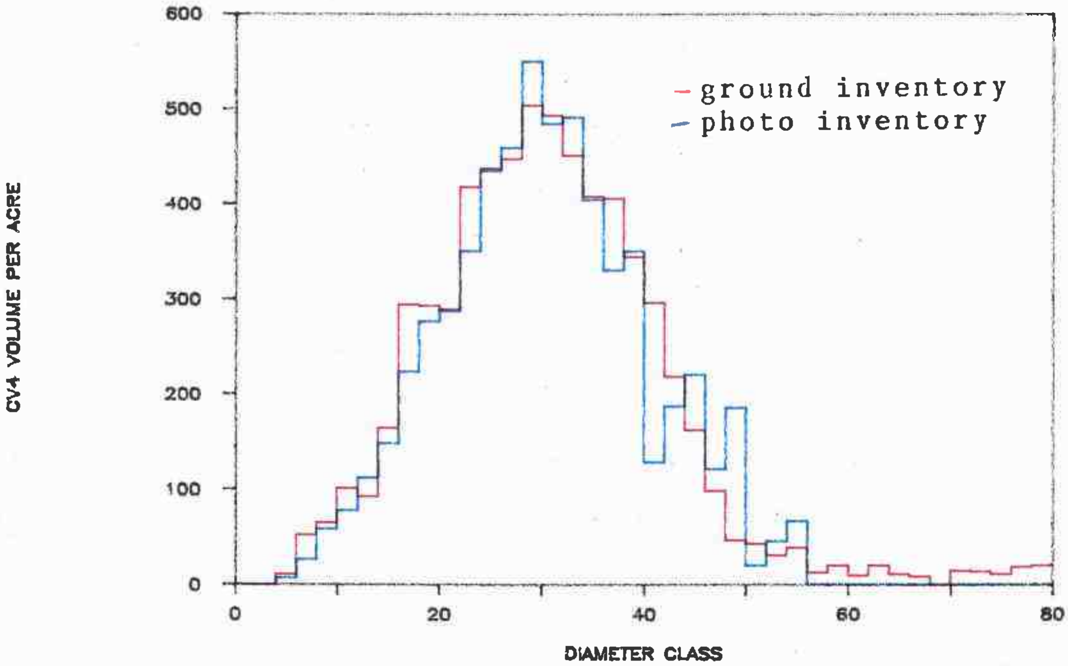
2. The aerial photo stand table distribution follows the ground-obtained distribution closely above the 12-inch diameter class. There is a tendency for the photo-obtained distibution to approach a "smoothed" curve (averaging of highs and lows) as compared to the ground-obtained distribution; this is particularly noticable in the 10 to 22 inch DBH classes.

Production of Stock Tables

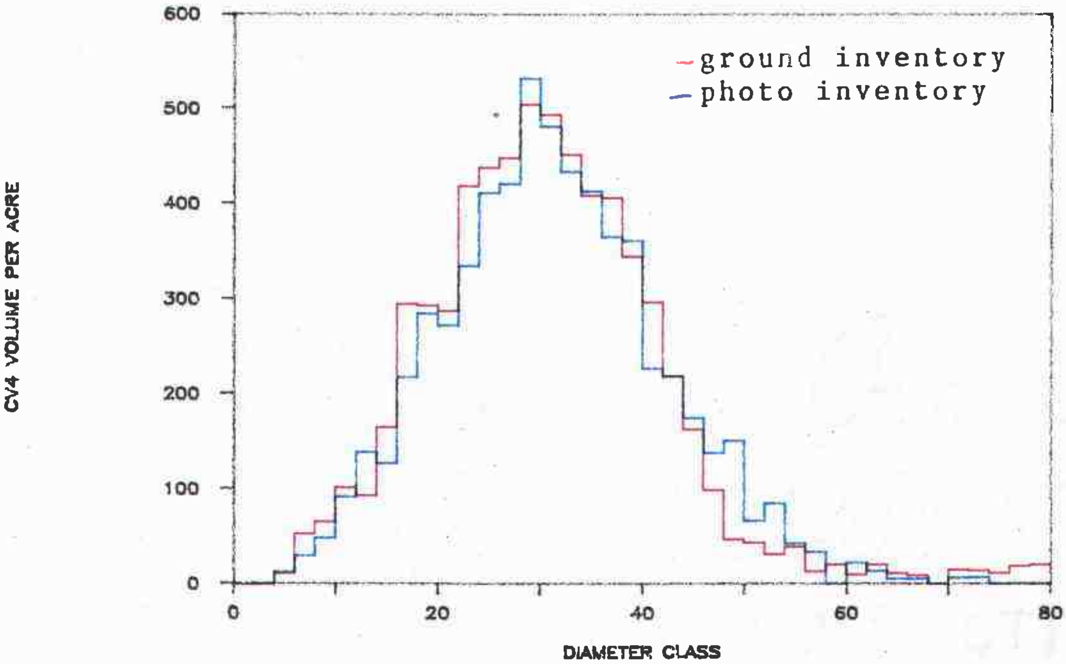
Aerial photo stock tables, also in two-inch diameter classes, are shown graphically (in red) in Figures 10 and 11 for CV4 and SV616 units using each of the three sampling methods. The stock tables developed from the OSU ground inventory data are plotted simultaneously (in blue). Although the ground and photo inventory methods show some large differences for specific diameter classes, the overall stocking distibutions are quite similar. The following points are observable:

1. The photo stock table produced using line transect sampling does the poorest job of tracking (following the rising and falling trend) of the distributions produced through the ground inventory (i.e. defining the mode).

2. All methods show some overprediction of volume in the

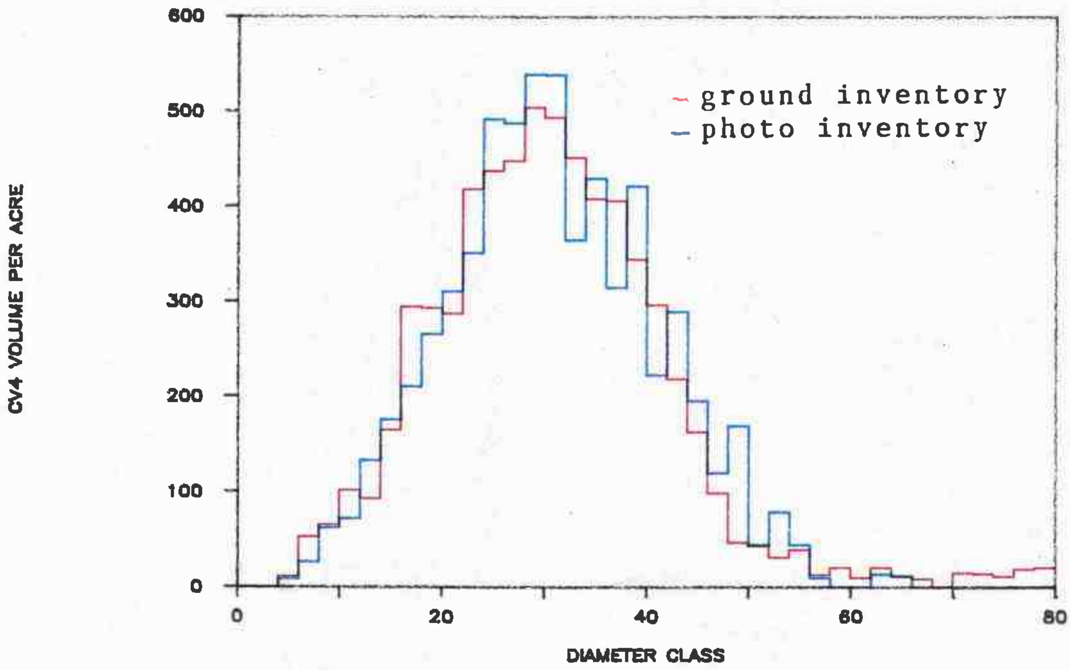


10a. Fixed Plot Sampling



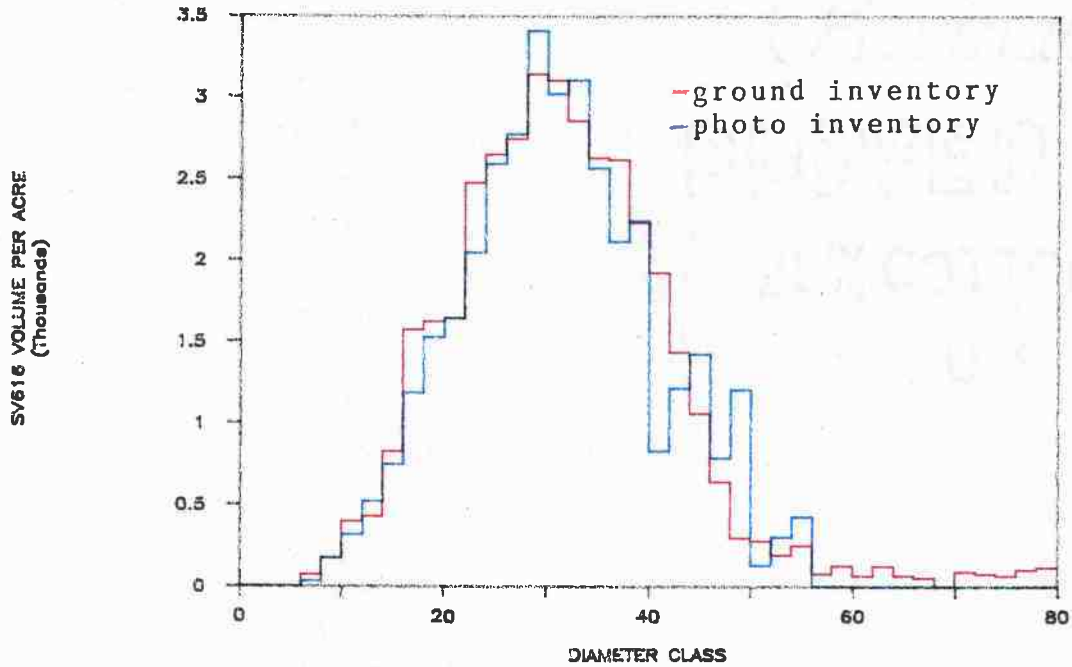
10b. Variable Plot Sampling

Figure 10. Graphic CV4 stock tables resulting from the photo cruise in conjunction with the DBH-predicting regresssion equation for fixed, variable, and line transect tree selection methods.

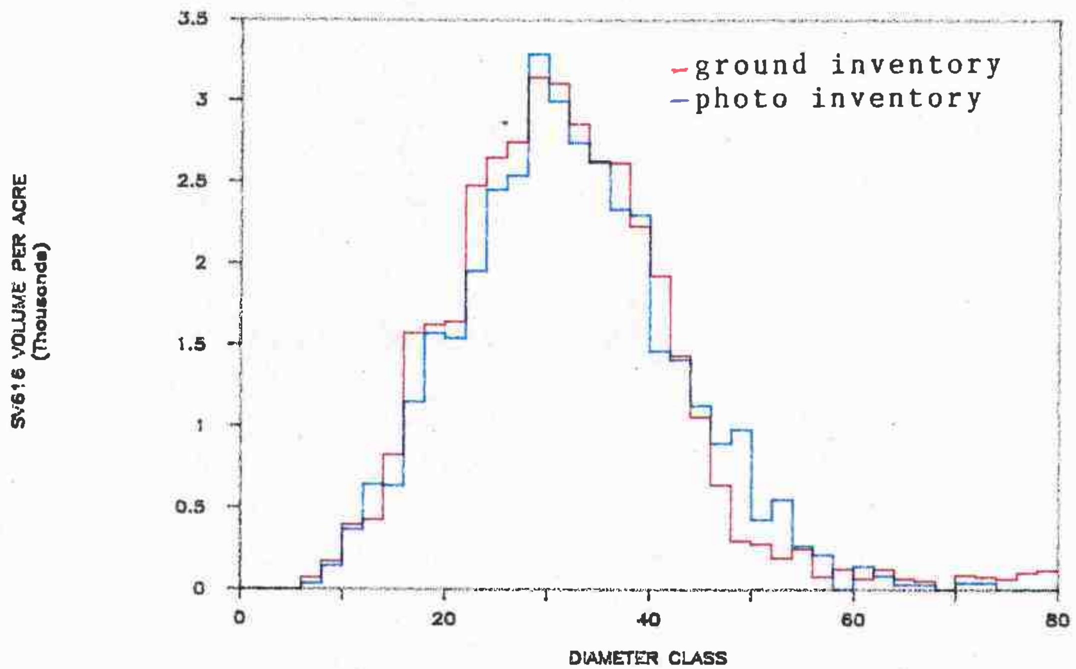


10c. Line Transect Sampling

Figure 10. (continued from previous page)

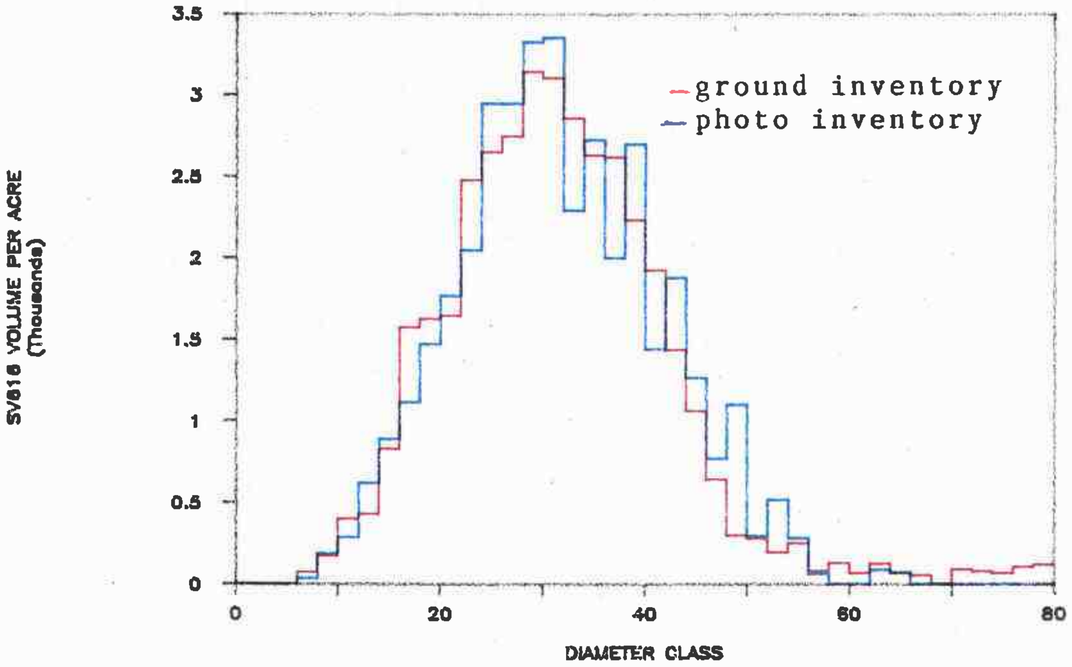


11a. Fixed Plot Sampling



11b. Variable Plot Sampling

Figure 11. Graphic SV616 stock tables resulting from the photo cruise in conjunction with the DBH-predicting regresssion equation for fixed, variable, and line transect tree selection methods.



11c. Line Transect Sampling

Figure 11. (continued from previous page)

diameter classes between 46 and 54 inches.

3. The underprediction of the ground-obtained volume by the fixed and variable plot photo methods appears to occur throughout the diameter class range, aside from the exception noted in (2) above.

4. Variable plot sampling was the most successful method for obtaining information on the large, rare trees above 55 inches in DBH, while fixed plot sampling was the least effective.

5. Although the stock tables showed an underprediction of the frequency of trees with DBH's less than 12 inches, this has relatively little impact on the stand tables. This is due partly to the low volume of these smaller trees and partly to a tendency to overpredict the tarif of the trees included.

Influence of the Choice of Dependent Regression Variable On the Photo Cruise Results

Concern over the use of a stochastic DBH value as an independent variable for predicting tree volume (see page 25). arose as a result of the photo cruise. The final results looked good, but what would have happened if basal area had been used as the dependent variable for regression development and, in turn, this stochastic basal area had been used to predict volume? Would the mean volume prediction be larger, as hypothesized (page 47), and, if so, by what magnitude?

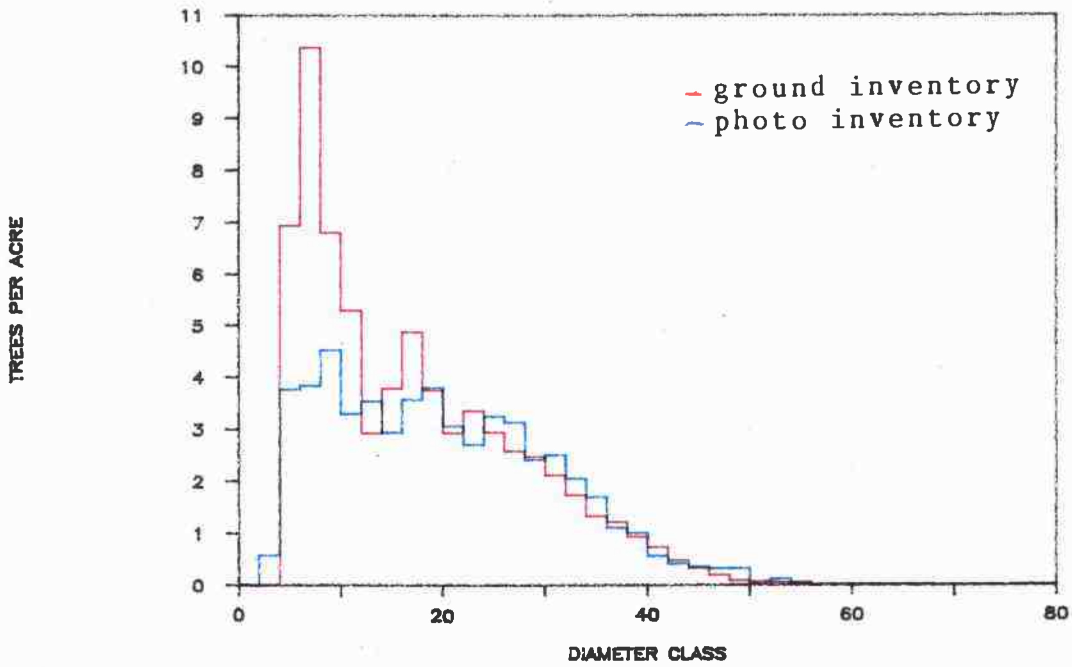
To acquire an answer to these questions a linear, weighted, basal area-predicting equation was developed from the same data used to develop the original, DBH-predicting equation. The basal area equation was incorporated into the photo cruise (everything else remained the same) and the program was rerun. New gross volumes, stand tables, and stock tables were developed.

The results of the volume prediction are shown in Table 2. All results are higher than those obtained using the DBH equation, as expected, by about five percent. Statistically, it is not possible to determine whether these estimates are "better" than previous estimates, but the fixed and variable plot mean volume estimates <u>are</u> closer to the ground estimate.

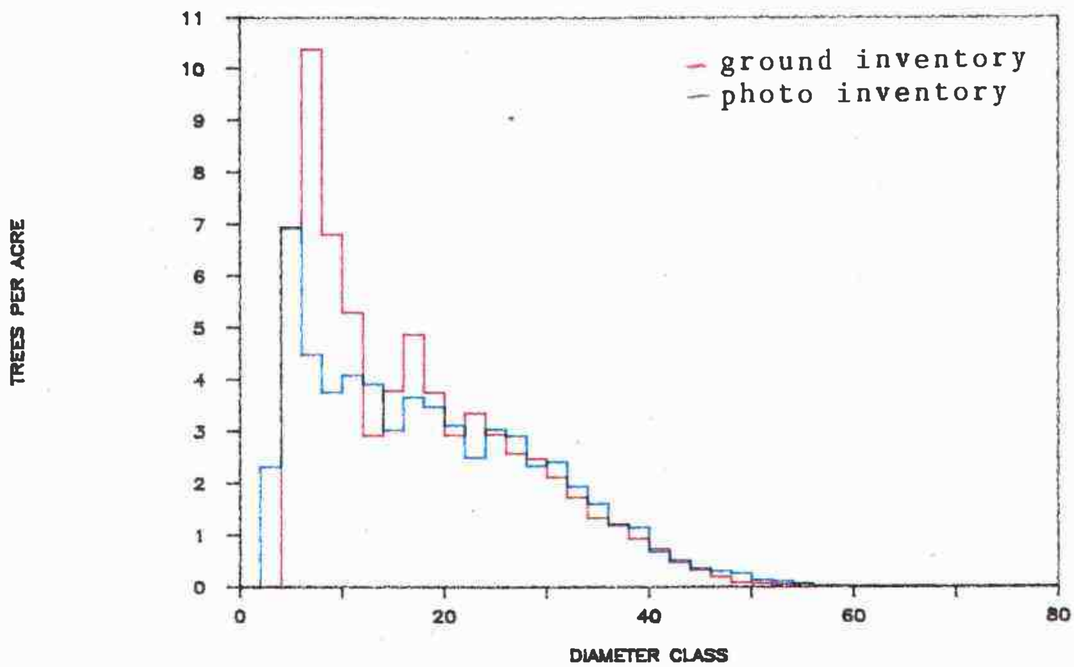
TABLE 2. The Results Of Gross Volume Per Acre Estimation Using the Aerial Photo Timber Inventory System in Conjunction with the Basal Area-predicting Regression Equation.

MEAN VOLUME PER ACRE	OSU INVENTORY	FIXED PLOT	VARIABLE PLOT	LINE PLOT
CV4	6,378	6,357	6,455	6,746
STD.DEV.	284	273	246	252
SV616	38,259	38,323	38,974	40,680
STD.DEV.	1,805	1,785	1,617	1,652

The revised stand tables are presented in Figure 12. The new stock tables are shown in Figures 13 and 14. Examination of these stock tables reveals an expected result: the photo-derived stocking distributions do not track the ground-derived distributions as well as with the

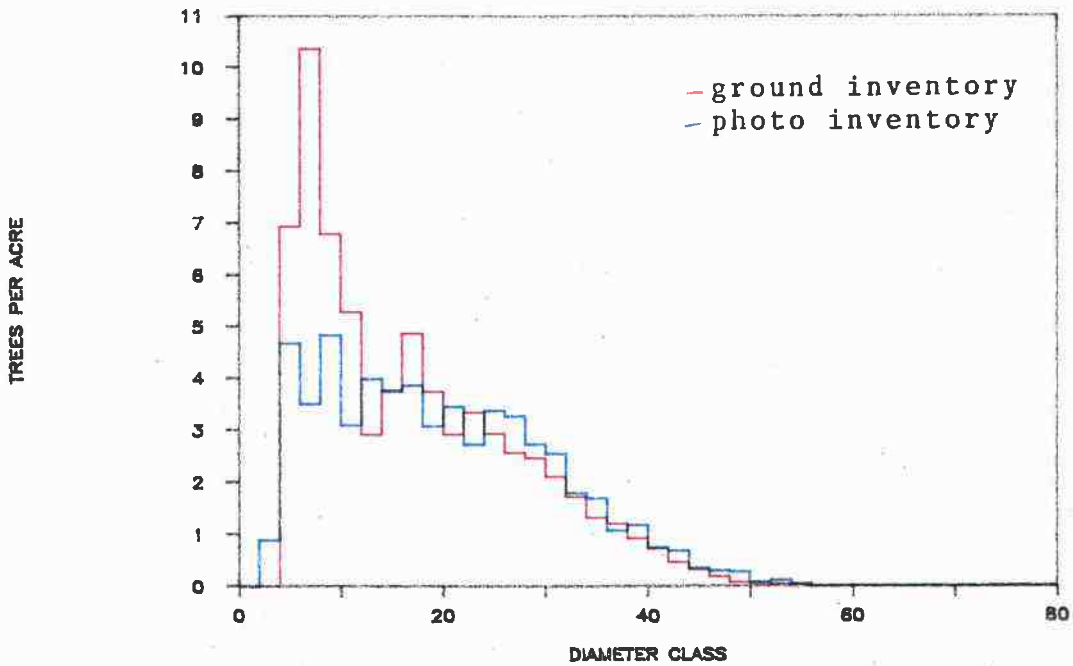


12a. Fixed Plot Sampling



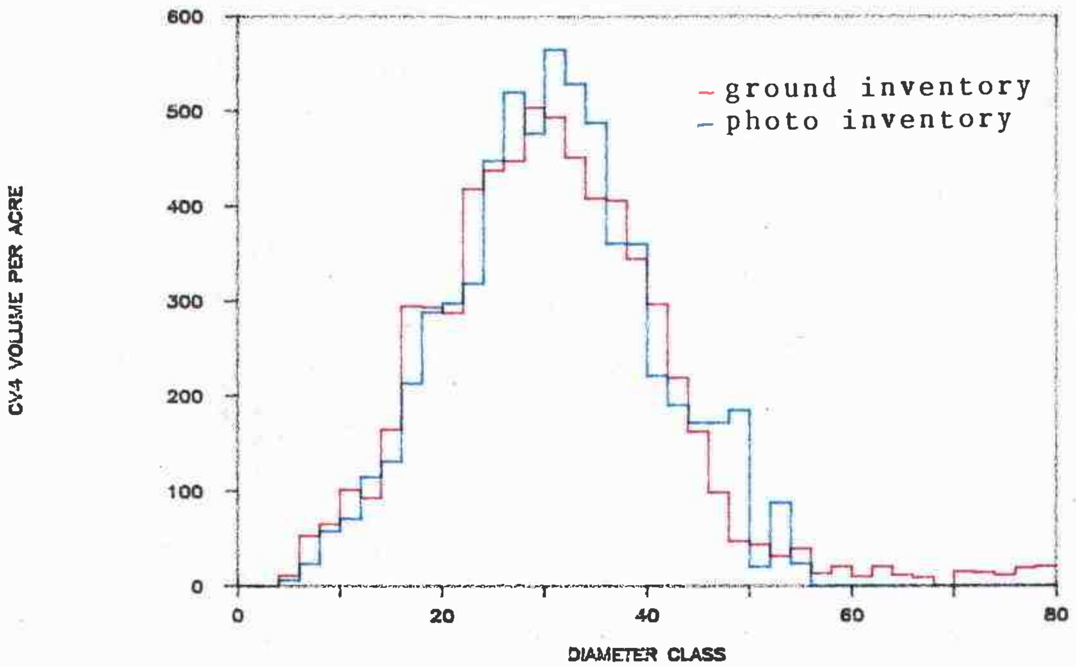
12b. Variable Plot Sampling

Figure 12. Graphic stand tables resulting from the photo cruise in conjunction with the basal area-predicting regresssion equation for fixed, variable, and line transect tree selection methods.

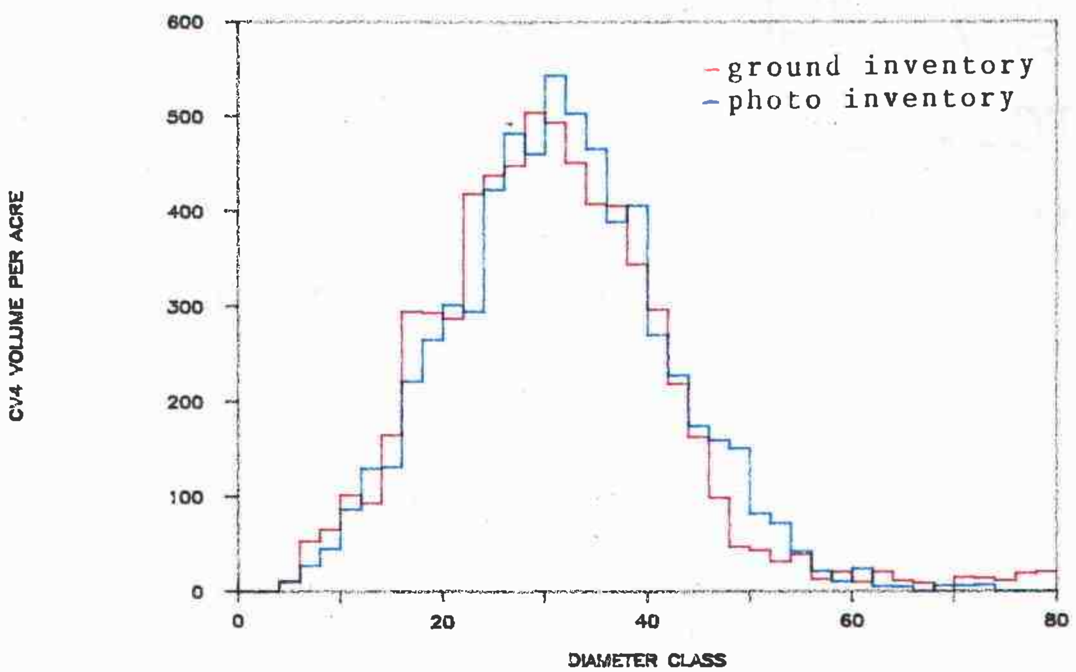


12c. Line Transect Sampling

Figure 12. (continued from previous page)

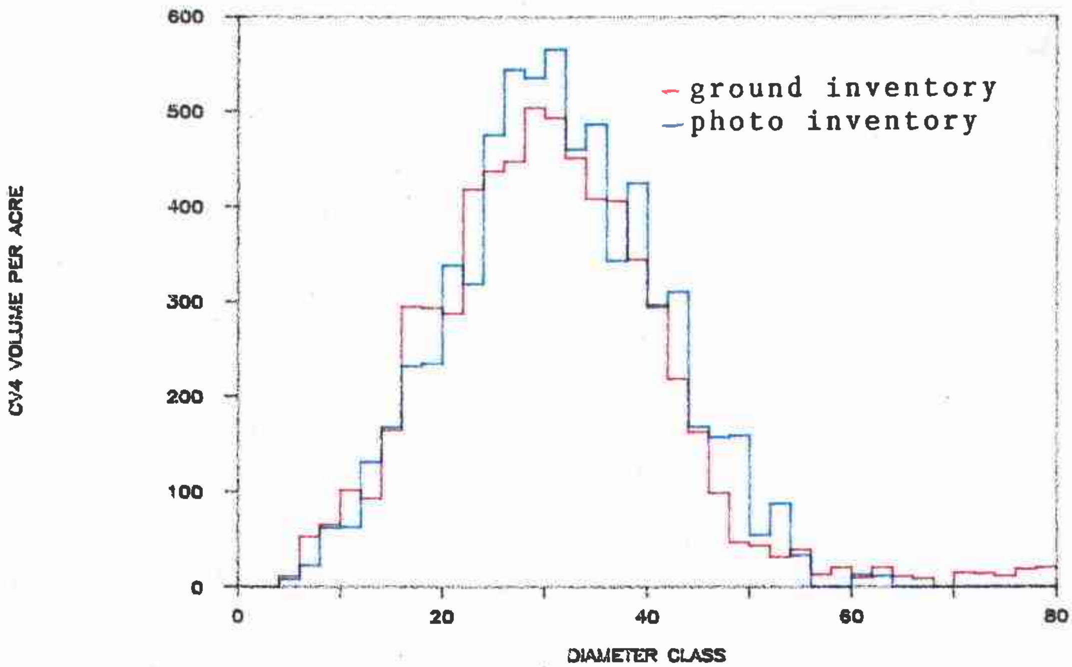


13a. Fixed Plot Sampling



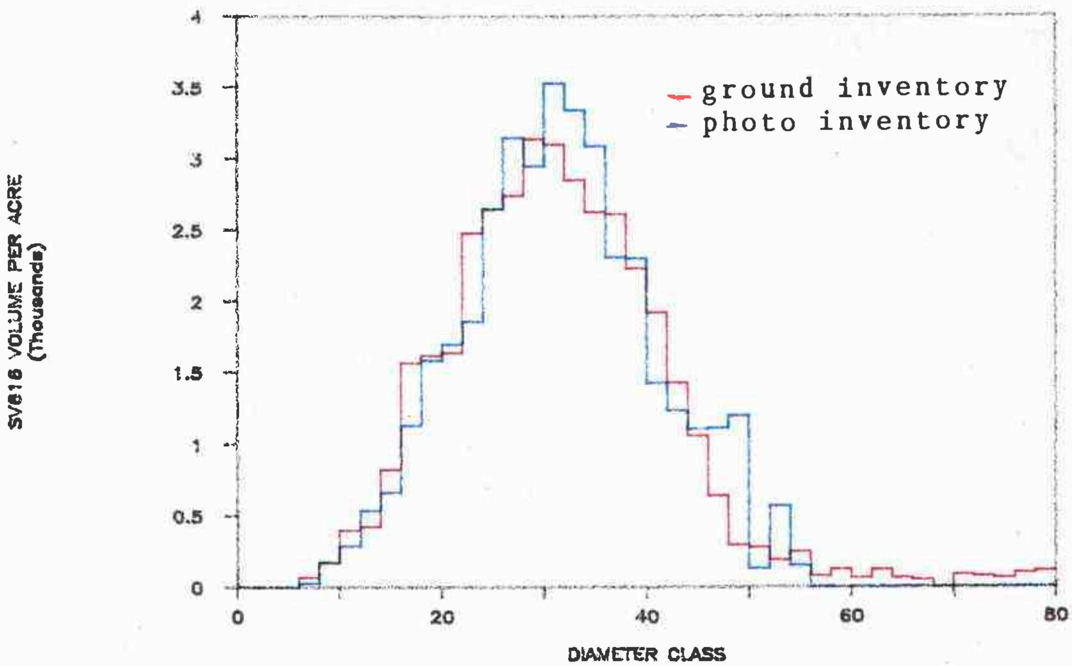
13b. Variable Plot Sampling

Figure 13. Graphic CV4 stock tables resulting from the photo cruise in conjunction with the basal area-predicting regresssion equation for fixed, variable, and line transect tree selection methods.

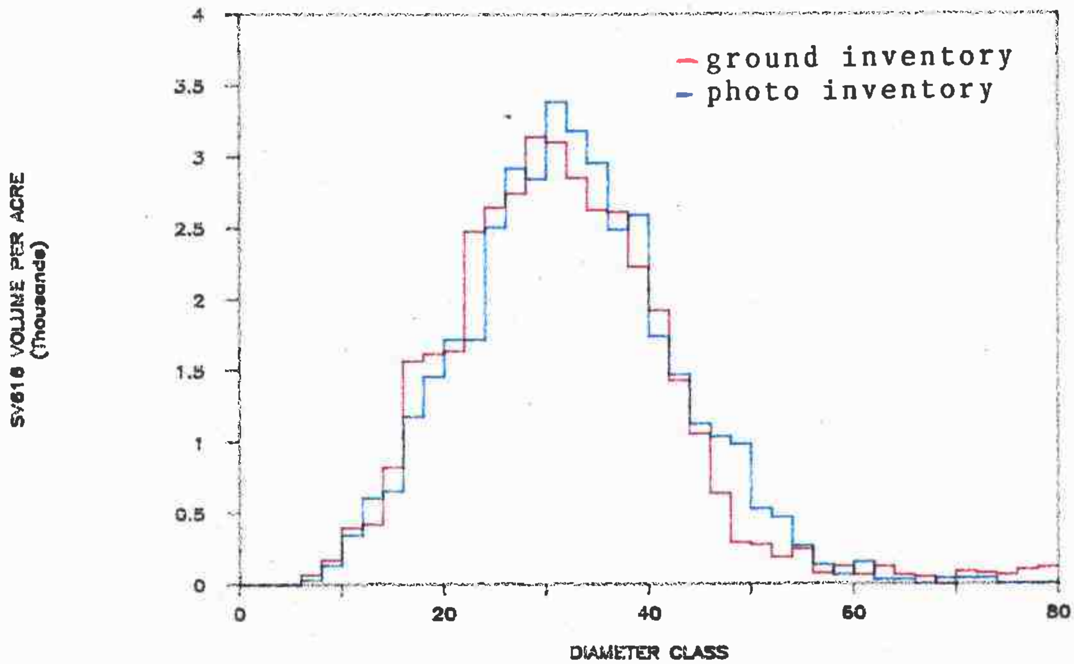


13c. Line Transect Sampling

Figure 13. (continued from previous page)

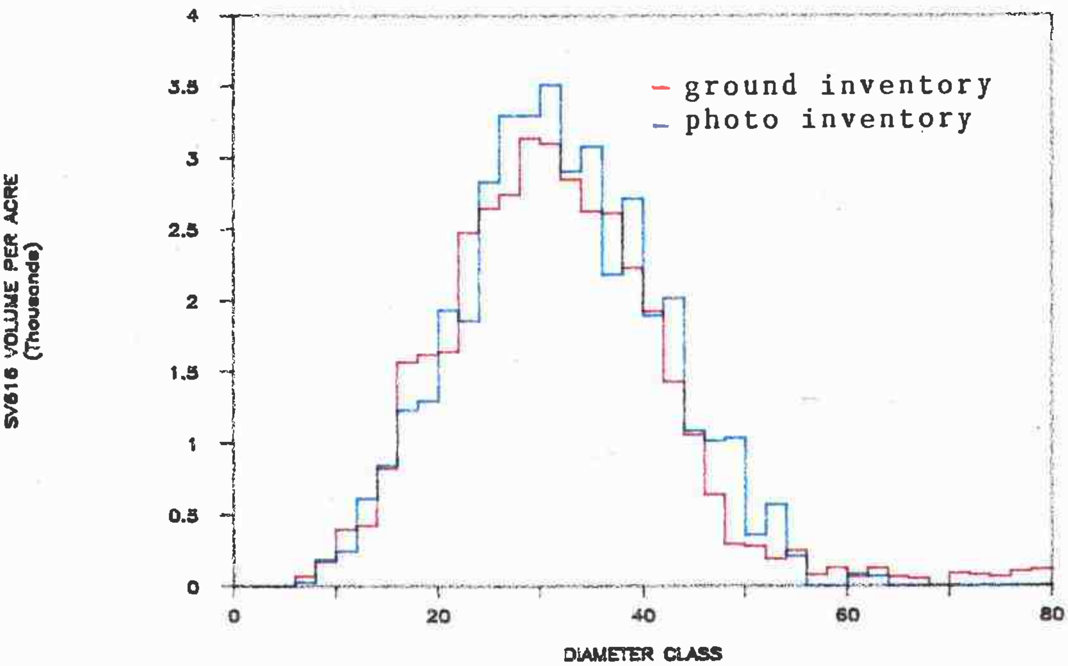


14a. Fixed Plot Sampling



14b. Variable Plot Sampling

Figure 14. Graphic SV616 stock tables resulting from the photo cruise in conjunction with the basal area-predicting regresssion equation for fixed, variable, and line transect tree selection methods.



14c. Line Transect Sampling

Figure 14. (continued from previous page)

use of the DBH regression equation. This is understandable because (using the same logic as on page 47) a basal area-predicting equation would tend to overpredict DBH (again, this would be influenced by the distribution of the error terms.

Summary of Photo Cruise Results

The aerial photo inventory system developed as part of this project, using all three sampling methods, proved to be effective in the empirical test: the aerial photo stand and stock tables produced are similar to those developed usng conventional ground inventory methods, with the exception of the apparent inability of the photo inventory to accurately predict the frequency of trees in diameter classes less than 12 inches. The photo estimates of gross volume per acre for the study site differ by no more than 5% from the independently-derived ground inventory estimates.

IMPLICATIONS AND RECOMMENDATIONS: MEETING THE THIRD OBJECTIVE

Although the success of the aerial photo inventory system in this case study is encouraging, caution should be exercised in the extrapolation of these results to other situations. Many processes, such as the development of the DBH regression equation, choice of the standard volume equation, determination of photo scales, crown mapping/digitizing procedure, and the acquisition of photography are critical to the overall system, and little attempt has been made to investigate how minor changes in these processes might affect the final results. If small changes bring about disproportionately large changes in the final results, then the reliability of the system would be questionable. (This did not occur in the one instance when a basal area-predicting equation was used in place of a DBH-predicting equation.)

In light of the results obtained in this case study, however, further research is recommended. Aside from investigation of the system response to minor changes, as just discussed, experience with this project leads to the following suggested research needs:

1. A further investigation into the effect of using stochastic DBH and tarif variables as inputs to the tarif volume equation is recommended. Although no major repercussions from this procedure were reflected in the results of this empirical test, the full potential for such complications remains unknown.

2. The use of two separate regression equations: a DBH predictor for the determination of diameter class and a basal-area-predictor for the determination of volume should be explored.

3. The system should be tested in other areas, with different stand conditions or, perhaps, different species. The effectiveness of the system on larger land areas could be evaluated.

4. An investigation into an effective method for obtaining average tarif numbers for large forest areas, with emphasis on how to stratify, sample, and calculate and appropriate sample size would be useful.

If, after these areas have been explored, the system still appears effective, the next logical step would evaluation and improvement on the cost efficiency of the system.

CONCLUSIONS

Stand tables, stock tables, and gross volume estimates, which closely approximate results obtained using conventional ground inventory techniques, were produced using the proprosed aerial photo inventory system. The results of this case study, though not necessarily indicative of the performance of this system in other situations, do provide the impetus to recommend further research and evaluation.

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APPENDICES

APPENDIX A
THE GROUND INVENTORY AND UPDATE PROCEDURE

The current study site is located on the Oregon State University Forest Properties, a 12,000 acre forest administered by the Oregon State University College of Forestry. An intensive forest inventory of this property was completed in 1984. Over 5000 ground inventory plots were taken, 206 of which were located in the current study site. The intensity of this cruise varied: 32% of the current project site was inventoried at an intensity of one plot per acre, 44% at two plots per acre, and 24% at one plot per four acres. These plots, which were field-measured during the winter of 1981, consisted of A 20 BAF variable plot and two nested fixed plots. For the fixed plots, radii of 15.56 feet and 7.76 feet were used to tally trees 4.1 to 8.0 inches and 0.0 to 4.0 inches in diameter, respectively. (All trees were measured to the nearest 1/10 inch.) The field plots were heavily check-cruised and allowable error tolerance levels were stringent. A complete descrption of this inventory can be found in the reference by Garver (1981).

Because there was a three-growing-season time lag between the dates of the ground and photo inventories, it was necessary to update the OSU inventory data so that the stand tables, stock tables, and total volume estimates would be comparable. The following procedure was used for updating the ground inventory:

1. Past 5-year radial growth data, which was available for each tallied tree greater than 4.1 inches in DBH, was converted to a 5-year basal area growth increment per tree. An updated DBH was calculated for each tally tree by assuming that basal area growth equal to 3/5 of the

5-year basal area increment had occured since the ground inventory.

2. Past 5-year height growth and radial growth data from 146 felled Douglas-fir trees, representative of the age classes present on the study site, were obtained. These data had been gathered throughout the OSU Forest Properties as part of another project (Ritchie 1983). From these height and radial growth data it was determined that tarif number had increased by approximately 0.18 number per year throughout the previous five years. The same average yearly increase was projected for all trees in the study site throughout the three-year update period, and updated tarif numbers were calculated.

3. Using the updated DBH's and tarif numbers of the tally trees, in conjunction with the tree frequency estimates from the ground inventory (trees per acre represented by each "in" tree <u>before</u> updating), updated stand and stock tables were produced.

Since no radial growth data were available for trees less than 4.1 inches in DBH, the upgrowth of these trees is ignored in the updating procedure. Stand and stock table estimates for the updated OSU inventory, which are presented in 2-inch diameter classes, are, therefore, inaccuarate for the 4.1 - 6.0 inch diameter class.

APPENDIX B
NOTES ON TARIF NUMBER DETERMINATION

Literature on the tarif system (Turnbull et.al. 1980) suggests that an average tarif number should be calculated from a sample of approximately 20 trees representative of the range of diameter classes for each "group" of interest, where the "group" can be a stand, portion of a stand, age class, etc. As the area of interest becomes increasingly large, however, this guideline becomes increasingly nebulous. Evidence indicates that tree height (Turnbull & Hoyer 1965), tree diameter, and site index (McCadden 1983) all influence tarif number, suggesting that more rigorous guidlines are needed to insure a representative tarif number. For example, a better estimate of volume per acre may result if tarif measurement trees are selected with a probability proportional to basal area rather than subjectively choosing them to represent the "range of diameter classes" - especially if variable plots are being used to select the trees for the actual inventory.

In addition, average tarif number changes with geographic location, and this becomes important when the area being inventoried is large. Stratification offers a theoretical solution, but no guidelines for how to accomplish effective tarif stratification, without prior field data, have been developed. Also, once stratified, procedures for the determination of sample size and the subsequent distribution of this sample among strata, are lacking.

Solutions to these problems are not presented as part of this preliminary project, but are identified as concerns which must be addressed before the procedures in this report can be put into practical use.

APPENDIX C
INFLUENCE OF SCALE ON VARIABLE PLOT SAMPLING

The determination of whether a tree is included in a variable plot tally is based on the equation

$$CAF = 43560/(1+4(R/W)^2)$$

as defined on page 28. This being the case, it is evident that the ratio of R/W is the critical variable for determining whether a tree is "in" a plot; the actual values of R and W are unimportant. The selection of variable plot tally trees on aerial photos would, therefore, be independent of scale if the ratio of the scale at the base of the visible crown (elevation where W is measured on the photo) to the scale at the tree tip (elevation where R is measured on the photo) was a constant for all trees on a plot. This is not generally true, so these two scales are both estimated for use in the variable plot selection procedure described on page 28.

Another consequence of the fact that variable plot tally trees are selected based on the ratio of R/W arises when considering errors in determining ground scale. If, for example, ground scale is underestimated, then both R and W will also be underestimated, leaving R/W relatively unchanged. (This ratio will not be exactly correct due to the manner in which R and W are calculated from ground scale.) As a result, the correct selection of tally trees on a variable plot is not as dependent on the correct determination of scale as is the use of a fixed plot, which depends on the exact magnitude of R.

APPENDIX D
NOTES ON SAMPLING ERROR CALCULATION

The sampling error for in the determination of gross volume per acre, using each of the three tree selection methods, was calculated as:

$$\frac{\sum^{n} (Vi-V)^2}{n*(n-1)}$$

where: Vi = the gross volume per acre estimate from a single plot,

V = the mean gross volume per acre estimate from all plots,

n = the total number of plots.

For this formula to be strictly applicable to line transect sampling it is necessary for the distance between all photo principal points to be a constant. In reality, however, this distance varied due to changes in photo scale and endlap. The standard error of the volume estimate, as calculated above, reflects this additional variability, and is therefore overestimated. This overestimation of the standard error is not expected to be greater than 1% of the mean.