Measuring the Southern Forest: 15th Annual Forestry Symposium, 1966

School of Forestry, Louisiana State University, Baton Rouge, Louisiana, USA

Thomas D. Keister
Louisiana State University, Baton Rouge, Louisiana USA

Follow this and additional works at: https://digitalcommons.lsu.edu/pafs

Recommended Citation
Available at: https://digitalcommons.lsu.edu/pafs/vol1/iss14/1
MEASURING THE SOUTHERN FOREST

LOUISIANA STATE UNIVERSITY PRESS
BATON ROUGE, LA.
1966 15th ANNUAL FORESTRY SYMPOSIUM
MEASURING THE SOUTHERN FOREST

PUBLISHED FOR THE SCHOOL OF FORESTRY AND WILDLIFE MANAGEMENT AND THE GENERAL EXTENSION DIVISION

BY

LOUISIANA STATE UNIVERSITY PRESS
BATON ROUGE, LA.
Measuring the forest and its products presents a continuing problem to foresters. Much time and effort have been used in the attempt to find geometric forms that will describe a tree. Many different log rules have been proposed as means of estimating the volume of squared material that can be cut from a cylindrical tree.

The bushel and the pound are standard measures that are widely used with agricultural crops, but few such standard measures have been available to foresters. A cubic foot is a standard in square material, but the number of cubic feet estimated to be in a tree depends on the geometric model used to approximate the form of the tree. The cubic feet estimated to be in a single tree might vary considerably, depending on whether the tree is described as a paraboloid, a neiloid, or a cone.

A board foot is also standard, once it has been cut as lumber from a log, but a board foot estimated in a standing tree must be named Doyle, Scribner, or perhaps International before it is meaningful.

As land and timber become more valuable, and as costs of producing forest products rise, it becomes increasingly important to have accurate measures for forests and their products. Forest managers must assign values to the results of various forestry operations and therefore need to know the quantities involved. Research results usually must be quantified before they can be evaluated properly. Not only must current measurement methods be refined, but new methods also must be devised so that new products may be measured.

Fortunately, foresters are more able now than ever before to measure forests. New equipment has been and is being devised so that faster and more accurate measurements may be taken. New techniques in sampling and statistical design have been developed. Electronic computers now make possible mathematical techniques that were once considered completely impractical. New and improved measures of traditional forest products are being developed, and
methods that were not even needed a few years ago are being devised for measuring tasks.

Unfortunately, many field foresters are only slightly aware of the usefulness of many of these new developments. As it is in many other fields, the communication between those performing the research and those who will need the research findings is not good. The field forester has little time to read all the literature and, in the case of many of the developments of forest mensuration, the forester is afraid to try new techniques because of new and seemingly complicated mathematics involved. Much of the current literature in mensuration seems to be written for other mensurationists and is filled with words like “least-squares solution,” “linear models,” or “quantitative models that satisfactorily simulate living surfaces.” A profusion of such terms might well keep the average field forester from learning a useful new technique.

In view of the many new developments in tools and techniques for measuring the forest, the theme “Measuring the Southern Forest” was selected for the Fifteenth Annual Forestry Symposium. Although the title seems to give a regional connotation to the meeting, the topics discussed were almost universal in application. The primary objective of the symposium was to bridge the gap between the mensurationist who has developed a new technique and the field forester who needs to learn and use this technique. Time permitted only a brief discussion of most of the topics, but hopefully, those who attended the symposium and those who read these proceedings will now be aware of some of the new problems faced by the mensurationist, and of some new answers to some old problems in forest measurement.

Thomas D. Keister
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Editor's Foreword</td>
<td>v</td>
</tr>
<tr>
<td>Measuring the Growth of Trees</td>
<td>3</td>
</tr>
<tr>
<td>S. F. Gingrich</td>
<td></td>
</tr>
<tr>
<td>Construction and Use of Volume and Yield Tables</td>
<td>17</td>
</tr>
<tr>
<td>Frank A. Bennett</td>
<td></td>
</tr>
<tr>
<td>Weight vs. Volume for Use in Measuring Forest Products</td>
<td>30</td>
</tr>
<tr>
<td>W. J. Barton</td>
<td></td>
</tr>
<tr>
<td>Measuring Tree Quality</td>
<td>43</td>
</tr>
<tr>
<td>Kenneth D. Ware</td>
<td></td>
</tr>
<tr>
<td>Computers and Forest Measurements</td>
<td>64</td>
</tr>
<tr>
<td>George M. Furnival</td>
<td></td>
</tr>
<tr>
<td>Use and Misuse of Statistics in Forestry</td>
<td>71</td>
</tr>
<tr>
<td>William Warren Barton</td>
<td></td>
</tr>
<tr>
<td>New Tools and Methods in Forest Mensuration</td>
<td>83</td>
</tr>
<tr>
<td>David Bruce</td>
<td></td>
</tr>
<tr>
<td>Aerial Photos—Tools for Forest Measurement</td>
<td>93</td>
</tr>
<tr>
<td>T. Eugene Avery</td>
<td></td>
</tr>
<tr>
<td>Planning the Inventory to Meet Management Needs</td>
<td>105</td>
</tr>
<tr>
<td>O. F. Hall</td>
<td></td>
</tr>
<tr>
<td>Sampling Methods in Relation to Forest Inventory</td>
<td>121</td>
</tr>
<tr>
<td>C. A. Bickford</td>
<td></td>
</tr>
<tr>
<td>Plantation Measurements</td>
<td>136</td>
</tr>
<tr>
<td>Kenneth R. Swinford</td>
<td></td>
</tr>
<tr>
<td>Measuring the Forest Wildlife Resource</td>
<td>163</td>
</tr>
<tr>
<td>T. H. Ripley and L. K. Halls</td>
<td></td>
</tr>
</tbody>
</table>
LIST OF FIGURES

1. Relation between the number of trees per acre and the average tree diameter for fully stocked, even-aged hardwood stands. Yield trees = 105. 8

2. Relation between the number of trees per acre and the average tree diameter for even-aged upland hardwood stand showing full stocking (broken line) and recommended minimum stocking (solid line). Yield trees = 220. 10

3. Height plotted over diameter. 18

4. Logarithm of height plotted over the reciprocal of diameter. 19

5. Map of Georgia, Florida, Alabama, and Mississippi showing the geographic provinces of the upper, middle, and lower coastal plain, and the distribution of sample plots by counties (shaded) and the number of plots in each county. 22

6. A generalized control system. 107

7. An industrial forest management system. 108

8. Long range forest planning. 117

9. Estimated Standard Error of the mean for one through eight random samples of three units each. 150

10. Comparison of sampling error, estimated on the basis of the range in sampling unit values, and calculated error for progressive sampling cruises of thirteen plantations in Alachua County, Florida. 153

11. Relationship of basal area per acre estimated by progressive sampling and basal area per acre estimated by high-intensity, fixed-acreage row sampling in thirteen slash pine plantations in Alachua County, Florida. 154
12. Comparison of sampling error, estimated on the basis of the range in sampling unit values, and calculated error for independent cruises of a merchantable slash pine plantation in Alachua County, Florida, by fourteen forestry seniors. 156

13. Illustration of tally and computation procedure employed in progressive sampling of plantations. 159
LIST OF TABLES

I. A comparison of volume errors and the associated errors in growth based on successive measurements of the same tree 4

II. Rectangular distribution of sample plots 21

III. Distribution of plots by site and density for the upper coastal plain province 23

IV. An example of variation in board-foot volume as estimated by one-fourth-acre plots 25

V. Board feet Doyle Scale conversion factors per 1,000 pounds of logs of each diameter and log length class 36

VI. Weight per log table 37

VII. Comparative results of several inventories of a fifteen-year-old slash pine plantation in Alachua County, Florida 145

VIII. Multipliers for converting the range in individual sampling unit values into an estimate of the standard deviation and the standard error of the mean 147

IX. Multipliers for converting the mean range in sampling unit values of one through eight sampling sets into an estimate of the standard error of the mean 148

X. Comparison of results of VPR progressive sampling and conventional row sampling in thirteen merchantable plantations in Alachua County, Florida 152

XI. Results of VPR progressive sampling cruises of a slash pine plantation in Alachua County, Florida by fourteen senior forestry students 155

XII. Comparison of random progressive sampling and conventional systematic row sampling in four unmerchantable plantations, Alachua County, Florida 157
1966
15th ANNUAL
FORESTRY SYMPOSIUM
The measurement of growth is a central problem in forest management. The basic concept of the forest as a renewable resource capable of producing a continuous supply of products depends on the ability of the forest to grow. Consequently any planning for the future involves a forecast of future growth.

Historically, crude approximations of growth were quite adequate during the period of custodial management several decades ago when few foresters were recognized for their acumen in forecasting growth. But the situation has changed.

The demands on the forest by a growing and affluent population are greater than ever before. The justification for investments in cultural practices, road construction, and permanent improvements is often based on the capacity of the forest to grow. The need for more reliable growth estimates in forest-management planning is apparent in the light of new and different purposes of the growth estimate. The limitations of cost must also be considered, so that the best method used to obtain an estimate of growth might have to be a compromise between cost and accuracy. In fact, the forester designing the inventory does not really know the required accuracy until he answers at least two questions. What decisions are to be based on the growth information obtained from the inventory? And what are the consequences of making wrong decisions (Dress and Hall, 1965)?

Much work has been done on methods of measuring and predicting growth, and there is a long history of forestry literature on growth. Despite all this, a good deal of confusion still exists even in the definition of growth itself.

First I want to discuss some critical problems that are encountered when measuring and calculating the growth of individual trees. I will
concentrate on the accuracy and precision of measurement rather than on the actual devices of measurement. It is important for the forester to have a general knowledge of error sources, so that he can apply a uniform standard of precision in all of the steps in arriving at a growth estimate—so that he won’t, to use an old cliché, measure his angles with a transit and pace his distances. The second part of my presentation deals with a new and simplified approach to growth sampling where the growth estimate is used as a planning factor in forest management.

Measuring Growth on Individual Trees

Growth is usually considered as a residual or difference between two successive measurements over a given period of time. For example, the volume of a tree at the first remeasurement minus the initial volume is its volume growth. A comparison of the volume-estimation error with the error of the residual or growth (Table I) would indicate that the methods used to obtain volume may be totally inadequate for growth measurements.

Note that a standard error of only 5 percent of the volume estimate at each measurement period results in an 18-percent error in the estimated growth of the individual tree. Some compensation of errors can be expected when working with stand data, or groups of trees, but the standard error of the growth estimate will always exceed the standard error of the volume estimate, whether expressed in percent or actual units of measure.

Table I. A comparison of volume errors and the associated errors in growth, based on successive measurements of the same tree

<table>
<thead>
<tr>
<th>Cubic volume</th>
<th>Standard error of volume growth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cubic feet</td>
<td>Percent</td>
</tr>
<tr>
<td>Initial volume</td>
<td>10</td>
</tr>
<tr>
<td>Volume at first remeasurement</td>
<td>15</td>
</tr>
<tr>
<td>Volume growth</td>
<td>5</td>
</tr>
</tbody>
</table>

Standard error of volume growth = $\sqrt{.50^2 + .75^2}$

$= \pm .90$ or 18%
H. A. Meyer (1953) found that errors due to unavoidable inaccuracies of diameter measurements alone amounted to 3 percent of the volume estimate when all the trees in a thirty-acre experimental tract were measured at a seven-year interval. The corresponding standard error of the growth estimate was 10 percent. Therefore, when growth estimates are obtained from successive volume estimates of the same tree, better measurements are required than those generally needed for volume estimates alone.

Another source of error in the growth estimate occurs when stem measurements are converted to volume or some other unit. The percentage errors in basal area are twice as large as the corresponding errors in diameter. Therefore, estimates of volume will be affected by the same magnitude. Except for the convenience of measurement, the diameter at 4½ feet above ground is not the best place to take a single diameter measurement for volume estimation. The effects of tree-to-tree variation in butt swell, elliptical diameters, and bark distortions near the base of the tree stem result in diameter measurements that are not typical of the solid content of the tree as a whole.

The volume estimate can be improved substantially by taking several upper-stem measurements with a suitable dendrometer. In this way the volume of each tree can be determined independently of any volume table. The use of volume tables can be a source of considerable bias in the growth estimate. Also, the accuracy of a carefully measured d. b. h. can be completely invalidated by a crude estimate of height to a fixed top diameter.

Another obvious source of error is the length of the growth interval. The very nature of tree growth requires years of study and experience to obtain reliable data for long-term growth forecasts. Under certain conditions, a period of four or five years may be needed to wash out all sources of measurement error, not to mention the effects of climatic fluctuations on growth. It is important that the remeasurement interval is consistent with overall measurement precision and the desired accuracy of the growth estimate.

In a special study, three diameters between eight and twenty feet above ground were measured on each of ten trees, first with wooden calipers and then with a Barr and Stroud dendrometer from locations monumented so that the trees were measured on the same face by both methods. A glass vernier was attached to the movable arm of the caliper so that diameters could be read to the nearest 1/20 of
an inch. One year later the same thirty points were remeasured by
the two methods. Diameter growth ranged from 0.25 to 0.45 of an
inch, based on the caliper measurements. Only at three of the thirty
points of measurement was the difference in growth between the two
methods greater than the actual growth at the same point. The
accuracy and cost of this method is probably above many practical
limits, but this limited study shows the feasibility of obtaining
accurate growth measurements on individual trees at short intervals
of time.

In appraising the accuracy of successive diameter measurements
of the same tree, the relative accuracy can be greatly increased if the
measurement is made at a marked point. It has been shown that the
error of a diameter measurement is proportional to diameter and
amounts to about 6 percent of the measured diameter itself. We have
used band dendrometers described by F. G. Liming (1957) that
record changes in circumference as small as \( \frac{1}{1000} \) of an inch. They
are held around the tree by spring tension and, in addition to being
very accurate, are inexpensive and easy to install.

I have discussed only a few of the problems that are encountered
when measuring the growth of individual trees. However, in any
situation there are but two alternatives for obtaining better estimates.
The sampling intensity could be increased by simply measuring more
trees. However, it should be remembered that, once the distribution
of measurement errors around a mean value is established, no amount
of sampling will reduce this range of errors. But an increase in the
sampling intensity will provide a more reliable estimate of the true
mean value of the measured quantity. The other alternative is to
reduce the actual measurement errors by using better measuring
deVICES. The recent trend has been in the direction of better measure­
ment techniques; and, in fact, sampling intensities have generally
been reduced in standard inventories and in timber sale appraisals.

A case in point is the use of 3-P sampling (Grosenbaugh, 1964)
in timber sale appraisals where early trials have shown that, on
large timber sales of several million board feet, estimates of total
volume based on about one hundred sample-tree measurements yielded
a standard error of only 1 or 2 percent. The efficiency of 3-P sampling
can be attributed to better upper-stem measurements, using a den-
drometer, and to a very logical sampling method.
Growth as a Planning Factor

One of the most important reasons for measuring growth is to obtain planning information for regulating the cut; that is, where, when, and how much to cut. In its simplest form, growth as a planning factor is growth per acre by major site and type categories. If the forest is ideally stocked, the cut should equal the growth. Usually the forest is not ideally stocked, and the cut is adjusted so as to reach the desired stocking in some period of time.

The implied purpose of the growth estimate in this context is that the accumulation of growth will ultimately be available as yield. The major problem in growth sampling is to identify those components of the stand that will produce the yield.

Net growth is defined as the volume remaining after natural losses or mortality have been subtracted from gross growth. Furthermore, both ingrowth (volume of trees growing into the lower diameter limit of measurement) and actual yields during the measurement period are part of net growth.

Therefore, an estimate of net growth requires an estimate of mortality. It has been said that we can measure past growth accurately, but we can predict the future only with uncertainty. Without doubt, mortality has been the least predictable of the components of growth. We can, however, assess mortality that is based on long periods of stand development; and, with a possible assist from normal yield tables and some deductive reasoning, we can arrive at average mortality rates for shorter periods. Or, better still, we can develop a sampling procedure whereby the likelihood of a tree’s being selected for growth measurement is proportional to its probability of surviving. This would eliminate any consideration of mortality in the net growth estimate. As will be shown later, the use of point sampling in computing growth at least partially accomplishes this by giving more weight to the larger trees in the plot, or those trees with the highest probability of surviving.

The Yield Tree as a Basis for Sampling Growth

In presenting an approach to net growth estimates based on the yield tree, my discussion is restricted to even-aged stands because the general pattern of ingrowth and mortality is easier to detect than in
all-aged stands. Also, my data come from upland hardwoods stands of the Midwest; but the principles given should apply equally well to the forests of the South.

![Figure 1](image)

**Figure 1.** Relation between the number of trees per acre and the average tree diameter for fully stocked, even-aged upland hardwood stands. Yield trees = 105.

To begin with, consider an even-aged stand in which no cutting is planned until the final harvest cut at the end of the rotation. In the seedling-and-sapling stage, assuming a successful regeneration cut, the new stand will have several thousand stems per acre. After a
period of ten to twenty years of intense competition for growing space, a stand of trees develops. When the average tree diameter reaches 3 inches, a fully stocked stand of upland hardwoods will contain about fourteen hundred trees per acre (Fig. 1). It is obvious, of course, that many of these trees will die simply for lack of elbow room.

As the stand develops, the trees differentiate into a range of diameters even though the trees are of the same age. Depending on the quality of the site, 80 to 120 years after the new stand is established, this uncut stand will have about 105 trees averaging 15 inches in diameter under the same relative stocking condition. In other words, out of every one hundred 3-inch saplings, only seven will survive. Therefore, during any period in the life of this stand, growth should be based on the performance of approximately 105 trees, whether they are the largest trees, some ideal species mix of the same number, or some other category.

For purposes of sampling, only a portion of these would be measured. The accumulated growth of the 105 trees would be about equal to the final yield. The history and temporary growth of the more than 1,300 trees that died during the rotation are of no concern to the forest manager who is scheduling the harvest cuts. This concept might be considered as survival growth on a fixed number of trees where growth is the nonreversible increase in volume, weight, or basal area.

When intermediate cuts are planned, the sampling procedure is somewhat different. In Figure 2 the broken line represents the same stand development as shown in Figure 1, where no cuts are made. The solid line represents our best estimates of minimum stocking for full utilization of the growing space and maximum average diameter growth of individual trees. Periodic cutting is needed to maintain stocking at this level. Even in managed stands some mortality must be expected, especially during the first half of the rotation when the average tree diameter is less than 7 inches. Any cutting made before the average tree diameter is 7 inches is usually a cultural investment, and yet many small trees will die unless an extremely short cutting interval is used. Where there is a market for round wood, a commercial thinning can be made in a managed stand on a medium site when the stand is about thirty-five to forty years old. The stand will have about 220 trees per acre that average 7 inches in diameter, but the range in diameter will vary from 4 to 10 inches.
From this point on mortality will be as low as 5 percent of the cubic-foot growth when cuts are made at intervals of five to ten years. Thus, in a managed stand the stocking is reduced from nearly eight hundred trees when the tree diameters average 3 inches to only sixty trees when they average 15 inches. In this case the 220 yield trees represent the portion of the stand that should provide the net growth estimates.
and, of course, only a portion of these trees would actually be measured in the sampling process.

The actual number of yield trees will depend upon utilization standards, which admittedly could vary and will probably change in time. Some judgment therefore is necessary in setting a threshold diameter limit. Our experience has shown that many of the late arrivals into the ingrowth category—regardless of the lower diameter limit—actually die before they reach merchantable size. The complications of first adding ingrowth volume and a few years later subtracting a larger volume for the same tree as mortality causes obvious difficulties in arriving at an estimate of net growth, yet this has been the usual procedure of handling mortality.

The yield-tree method of measuring growth does not mean that specific yield trees must be identified early in the life of the stand. Rather it provides a basis for sampling the yield components of growth. We do not yet know exact mortality patterns, but we can empirically assign certain survival probabilities based on size-age categories. Mortality occurs in all diameter classes in previously unthinned natural stands because of irregular spacing and the variability of inherent tree vigor. As stands are thinned and spacing and tree vigor become more uniform, most of the mortality occurs in the smallest trees. It then becomes possible to measure growth with the appropriate basal area factor so that the larger trees are sampled in proportion to their survival expectancy.

There are, of course, several possible ways to develop the sampling procedure, but restricting the growth estimate to the portion of the stand that will eventually produce yield should reduce plot work and eliminate the need to mark and number trees to estimate ingrowth and mortality.

I have discussed only a few of the important problems in measuring growth. And perhaps I have over-simplified what has been a tenacious problem in forest measurements. Although I have been somewhat critical of past accomplishments, there has been solid progress in the field of forest measurements. We have gained considerable insight into stand dynamics through research and actual experience, and it seems appropriate to recommend that we assimilate this knowledge to provide a better base for forest management decisions. The limitations of time and costs in forest management require that our methods be based upon a minimum of measurements. There is a great need and potential for more simplification.
Discussion

**Question:** When you are making a diameter measurement to get the variations in growth, how do you account for the soil moisture and relative humidity?

**Mr. Gingrich:** This is rather hard to do, but in research studies we generally consider the site or the soil as a variable, and study the growth on different sites. Researchers have had a pretty rough time trying to determine why a tree grows the way it does, based on these various environmental factors. It’s rather hard to find published results where more than 60 percent of the variation in growth has been accounted for by these site factors. About the only way you can account for these site variables, I believe, is actually to study the performance of the trees on the different sites.

**Question:** You talked about measuring growth of an individual tree, then you went to the growth yield per acre, and the only way you got to the yield per acre of the individual tree, as I remember it, was by multiplying by a specified number of trees per acre. Now is it your supposition here that each tree is going to grow at this same rate?

**Mr. Gingrich:** In answer to your question, you could assume that all the trees are going to grow at the same rate, and that the average diameter will increase a certain amount in ten years—say two inches, for example, but within the stand, of course, there will be a range of growth rates of individual trees. Of course, the two parts of my paper were not meant to coincide. We measure the growth of one tree and we convert this to per-acre basis. This would be a matter of studying the growth of these yield trees through remeasurement, such as on CFI plots, to determine how the yield components of growth are performing; we forget the other 90 percent of the stand, at least during the early years. I feel, if you look at our plot work, we spend too much time on trees that die. We know they’re going to die—we have been around this three
times on some of our inventories, and just from actual experience we know a lot more about mortality than we did twenty years ago. I think we can streamline our growth measurements by accepting mortality as a fact of life and by concentrating on the trees that are going to live. There would be a range in the growth rate of these trees. This is very obvious in even-aged stands, especially with mixed species, where one species may outgrow another.

Question: I think you have a point well taken—that we spend a lot of time on trees that pass out of the picture. However, in mixed stands, we have trees that we know are growing faster than others; their past history indicates it, both genetically and because of their specific location. To make this practical, we have to know which one is growing fastest. Are you making any attempt to approach this problem where you can really apply this knowledge?

Mr. Gingrich: Are you thinking of tree classes?

Comment: Well, we like to fall back on growth involved when we get into a problem. Nevertheless, what you have here is, I think, a very essential problem, in that we can identify mortality, but you led me to believe that some of our CFI work is perhaps useless. I see from your answer that it is really going to be more fundamental than ever.

Mr. Gingrich: Well, I didn’t mean to imply that the CFI work is useless. I think, if I was critical, I was critical of all inventory procedures, where we spend a lot of time on numbering trees, marking trees—and about all this does is determine which trees have died and which trees have grown into an ingrowth category. But, from a pure sampling procedure, you could go back and remeasure a certain component of that stand—the largest one hundred trees per acre or the trees at some spacing—and forget the rest of the stand. I haven’t developed the exact technique of this sampling procedure; I didn’t have the time and it was not my purpose to do it.
Comment: I think one should consider a sampling method which will allow one to pick out which trees one thinks will live. As you've mentioned, point sampling and selecting the largest trees might be one way to do this. In different areas I think you would have to take into consideration what past mortality has shown; for instance, lightning-killed trees—our CFI shows that we lost more sawtimber to lightning than to any other cause. You can't predict which trees are going to be hit by lightning, although larger trees are more apt to be hit. The same would hold true for certain insects. It's hard to predict in certain cases.

Mr. Gingrich: If I were designing an inventory, I would allow a safety factor of 10 percent perhaps. This would still be far less than the total stand has usually been carrying. I mentioned survival growth. This has been a principal component of growth, where measurements are made on the trees that survive from one measurement period to another. Perhaps I was talking about this, but the usual procedure is to readjust the stand table at the second measurement period to include the ingrowth, so that the survival growth base is continually updated, but what it amounts to is that you are carrying an excess of trees in this case. Survival growth over a measurement period is not exactly the same as what I've been talking about here, where you try to recognize the trees that are going to make it until the end.

Question: I think it will be hard to make your predictions proportional to the probability of living, as you had stated. Why couldn't the idea be extended and three-P sampling be used to ascertain this by making your prediction proportional to some measure of tree vigor? Now that would cover a whole lot more of what you are actually trying to measure. This would extend three-P sampling to the other components such as growth, in addition to mortality, and it would still allow you to figure probability of some mortality factor and make some prediction.
Mr. Gingrich: I think there is a similarity in what I’ve said to three-P sampling. Three-P sampling is, I believe, sampling proportional to the volume of the tree.

Comment: No, there would be a difference, and a very important one. You would tend to concentrate your samples in the trees that have the highest probability of growth and therefore are more important.

Mr. Gingrich: Right, I meant to do that. In this case it would perhaps be size that would be the most important basis for sampling. These are the trees that are the most likely to survive.

Question: What variable do you consider in your growth function, and which one contributes most to the shape of the curve? Is it site?

Mr. Gingrich: Well, our experience has been that the growing space or stand density is probably the most important variable in the growth of the individual tree. That is, the diameter growth of a tree can be influenced more by stand density than by site. Now, volume growth is a different thing. Site is perhaps the most important factor from the volume growth standpoint, but diameter growth is very sensitive to growing space.

Question: How do you handle site, when you have a heterogeneous condition such as we have in the South?

Mr. Gingrich: That’s pretty hard to do. We have this problem in our coves. You can use an average site index for a plot; but we have found ½-acre plots that change fifteen feet in site index from one plot to the other, and we cannot dodge this question, because we want to study the growth on these particular stands. We, of course, are studying individual trees, and we have gone so far as to dig soil pits around individual trees and can get fairly precise measurement of site index for that individual tree. But I believe that one of the probable reasons why researchers have accounted for only 60 percent of the growth on work with stand variables is because of this variation in tree to tree growth within a plot, even a small plot.

Question: How would the intensity of silviculture affect the crop tree or the yield tree method of determining
growth—from very extensive silviculture to more intensive silviculture?

Mr. Gingrich: In the examples that I used, there were 220 yield trees in the thinning schedule and 105 trees. Now this may be some measure of the benefit of silviculture, because almost twice as many yield trees are cut in the managed condition. Of course, there is much more to it than that. You will get the sixty yield trees in perhaps \(\frac{3}{4}\) the time. Rotation may be reduced 30 percent and so there is an added benefit from thinning, because you get the large trees faster. So a round figure right now in our best silviculture, as compared with no cutting at all, seems to be about 30 percent gain in wood yield or volume yield. But quality, of course, is another thing, especially in hardwoods, where there may be several hundred times more value added through proper silviculture.

LITERATURE CITED


My subject—the construction and use of volume and yield tables—is a broad one. S. H. Spurr (1952) devotes 110 pages to volume tables alone; my treatment will be a mite briefer and will not be comprehensive. Also, it will pertain primarily to our southern pines.

Most volume tables are now constructed from volume equations developed by the least-squares regression technique; this is the method we will consider here. Tables can be constructed, of course, on the basis of total or merchantable height. I favor the use of total height, especially in even-aged stands, because total height can be more accurately determined than merchantable height. A sample of heights by diameter classes is the only required height measurement for the construction or use of a total height-volume table. A regression solution of the height-diameter curve is quite simple, and if computer analyses are contemplated can be added as a part of the overall program. In our stand density work we have found the following equation form to give an excellent fit:

$$\log \text{ height} = a + b \frac{1}{D}$$

where \( \log \) represents the common logarithm, \( D \) is diameter at breast height, and \( a \) and \( b \) are values computed from the regression solution. Using this model, a height-diameter curve is established for each plot and used in calculating plot volumes. Use of the logarithm of height and the reciprocal of d.b.h. is a necessary transformation of the data in order to produce a curve form about which the range of variation will be minimized and the scale of measurement will be linear and additive. A typical curve of height over diameter is curvilinear, and unit changes in diameter are not accompanied by a uniform pattern of change in height (Fig. 3). However, when the log
of height is plotted over the reciprocal of diameter, a straight line results, variation about the curve is reduced, and for successive changes in diameter a uniform and progressive change in height occurs (Fig. 4).

Sample trees must be measured in a manner to permit determination of volume. Any one of several mathematical formulae—Smalian’s, Huber’s, Newton’s, etc.—may be used to compute cubic volume, or graphic methods may be employed. The graphical approach has certain advantages. It can be used with equal accuracy for all degrees of taper, whereas the formulae establish volumes for specific geometrical forms—paraboloid, cone, or neiloid. By the graphic method, tree measurements can also be made at any odd and convenient interval without complicated volume calculations. Once the tree is graphed, any type volume is available—total cubic, merchantable

![Figure 3. Height plotted over diameter.](image-url)
cubic, board-foot, or topwood. The standard for graphical computation is the U. S. Forest Service Form 558a, developed by L. H. Reineke (1926). Tree measurements, inside and outside bark, are plotted on this form. Any specific volume is determined by planimetering the area under the appropriate section of the curve and multiplying the total by a designated conversion factor. If desired, form class or any other measure of form can be determined from this graph, as well as volume inside or outside bark. Volume determinations by this approach are tedious and time consuming, whereas formula calculations can be handled entirely by a computer.

For the estimation of volume in terms of diameter and height, a number of regression models have been established. One quite commonly used is Spurr's combined-variable model:

\[
\text{Cubic volume} = a + bD^2H
\]
where $D$ stands for diameter at breast height and $H$ for either total or merchantable height. This equation form is really nothing more than a variation of the formula for the volume of a truncated paraboloid, and the regression solution accounts for most of the variation in tree volume—as much as 99 percent in some trials. If this solution does not produce an acceptable fit, a more complex model must be used. As mentioned, there are several established models which might be substituted. However, a standard test can be used to determine what functions of d. b. h. and height, not included in the trial model, show a significant correlation with the dependent variable. The needed variable, or variables, can be added to the regression, and the best possible volume equation for the sample at hand established in this fashion.

The addition of a measure of bole form will invariably increase the efficiency of the prediction model. This does not mean that volume estimates based on form-class tables are always better than estimates from non-form-class tables. In field application they are only better if—and this is a pretty big if—an accurate estimate of form is obtained. If we add form as a third component, our equation becomes:

\[
\text{Cubic volume} = a + bFD^2H
\]

where $F$ represents a measure of form and the other values are as described above.

When using the combined variable model, a specific weighting function may be necessary, since transformations of volume and height have not been used. This is so because the variance of volume increases as tree size increases. To put it simply, big trees vary more than little trees, and, as with the height-diameter curve, we need to reduce this range of variation. A weighting function can be used to stabilize the variance. Theoretically, the true weight for the equation would be the inverse of the volume variance. Since the variance of tree volume is usually a function of $D^2H$, multiplying the equation by the square of the inverse of this factor should effectively reduce the range of variation. However, as G. M. Furnival (1961) and T. Cunia (1964) point out, this factor may not always be the best possible weight, but in general it should give acceptable results. In many cases, use of transformations eliminates the need for weighting.

The discussion so far has pertained to cubic-foot tables. The same approach, in fact the same basic equation forms, can be used for
### Table II. Rectangular distribution of sample plots

<table>
<thead>
<tr>
<th>Age</th>
<th>Site</th>
<th>Basal areas (square feet)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>50</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>80</td>
<td>70</td>
</tr>
<tr>
<td></td>
<td>90</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>70</td>
<td>100</td>
</tr>
<tr>
<td>30</td>
<td>80</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>90</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>70</td>
</tr>
<tr>
<td>40</td>
<td>80</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>90</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>70</td>
</tr>
<tr>
<td>50</td>
<td>70</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>80</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>90</td>
<td>70</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>100</td>
</tr>
</tbody>
</table>
board-foot table construction. The procedure will be the same: if a simple equation form, like the combined-variable model, does not give satisfactory results, additional variables should be tested until an acceptable equation form is produced.

So much for volume tables. Let us now turn our attention to yield tables. The first essential in yield table construction, of course,
that site variation is not pronounced within the species range. In sampling, we merely make a special effort to locate low sites and high sites. I have little experience in the loblolly field, but I am certain that getting a good stratification of the sample for this species is not as difficult as it is for slash pine.

The importance of the sample distribution with respect to the independent variables was illustrated recently in our plantation work at Olustee, Florida, and Cordele, Georgia. We have a growing-space study in slash pine plantations distributed throughout the three geographic provinces—the upper, middle, and lower coastal plain areas (Fig. 5). One objective is to determine if there is a significant difference in growth and yield among these provinces. Site index regressions for the three provinces were first tested. The upper coastal plain regression was significantly different from both the middle and lower province regressions, but no difference was indicated between the middle and lower areas. Since the average density of the upper coastal plain plots was 64 percent greater than that for the other two areas, number of trees per acre was added as a second independent variable to the site index regression for each province. The density variable was highly significant in the upper coastal plain analysis but nonsignificant in the other two areas. To determine if the result in the upper coastal plain was a true density effect, plot distribution in

### Table III. Distribution of plots by site and density for the upper coastal plain province

<table>
<thead>
<tr>
<th>Site</th>
<th>100</th>
<th>200</th>
<th>300</th>
<th>400</th>
<th>500</th>
<th>600</th>
<th>700</th>
<th>800</th>
<th>900</th>
<th>1000</th>
<th>1100</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trees per acre</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Number of plots</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>1</td>
</tr>
<tr>
<td>40</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>1</td>
</tr>
<tr>
<td>50</td>
<td>—</td>
<td>—</td>
<td>2</td>
<td>5</td>
<td>1</td>
<td>2</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>10</td>
</tr>
<tr>
<td>60</td>
<td>—</td>
<td>—</td>
<td>2</td>
<td>6</td>
<td>4</td>
<td>5</td>
<td>7</td>
<td>2</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>26</td>
</tr>
<tr>
<td>70</td>
<td>—</td>
<td>—</td>
<td>1</td>
<td>3</td>
<td>4</td>
<td>8</td>
<td>6</td>
<td>2</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>24</td>
</tr>
<tr>
<td>80</td>
<td>—</td>
<td>—</td>
<td>1</td>
<td>1</td>
<td>—</td>
<td>—</td>
<td>1</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>3</td>
</tr>
<tr>
<td>Total</td>
<td>—</td>
<td>—</td>
<td>3</td>
<td>12</td>
<td>14</td>
<td>14</td>
<td>15</td>
<td>5</td>
<td>1</td>
<td>—</td>
<td>—</td>
<td>65</td>
</tr>
</tbody>
</table>
relation to site and density was determined (Table III). The two highest density plots were on the lowest sites, with no other samples in that portion of the rectangular distribution. With this plot arrangement, a density effect was almost inevitable, although it is not a true density effect, but a site-density interaction resulting from the sample distribution. If these two low-site, high-density plots are deleted from the analysis, or arbitrarily raised to site 60 or 70, the density variable is then nonsignificant in the site index regression, and significant differences among provinces disappear. The point I am making is that to get acceptable results, sample plots must be fairly uniformly distributed with respect to the independent variables being tested. If they are not, unreal effects, such as we have here, may be introduced. The sample should also be rather uniformly distributed over the geographic area for which the tables of yield are to apply.

We normally wish to predict yields for stands that have not been unduly affected by destructive agencies, such as fire, insects, disease, ice, etc. For this reason, a purely random sample is not permissible. For example, thinned stands obviously should be excluded. Fair to good distribution of the stand is also essential. In general, we can say stands are suitable for sampling when there are no recognizable factors measurably affecting growth other than those being evaluated—that is, age, site, and stand density.

Yield tables developed from sample data taken in the manner described will overestimate yields for a good portion of our existing stands, both natural and planted. This is true because the purpose of a yield table is to estimate productive potential, not production based purely on stand history. If the latter type of information is desired, an inventory is the answer. To evaluate productive potential, we must specify the type of stands we will sample: that is, stands with fair to good distribution in which growth has been essentially unaffected by factors other than those being measured. These facts must be kept in mind by those applying any empirical yield table. An exception to this might be yield tables developed for stands that are maintained at specified densities by periodic cuttings. Such tables will evaluate both periodic annual growth and total yield under a given density regime and for a particular thinning method.

In my experience, relatively small plots may be used for sampling cubic yields in plantations. However, with the same number of plots and for the same relative degree of efficiency, larger plots seem to be
necessary for evaluating board-foot yields. This is most decidedly true if the stands are relatively young with fairly wide spacing—the situation on most of our plantations that show appreciable board-foot production. In such stands, a quarter-acre plot does not give a good sample of the diameter distribution, and board-foot yield is quite sensitive to this deficiency. Consider the example of two quarter-acre plots in the same plantation (Table IV). These plots are the

Table IV. An example of variation in board-foot volume as estimated by quarter-acre plots

<table>
<thead>
<tr>
<th>Plot number</th>
<th>Age</th>
<th>Site index</th>
<th>Trees per acre</th>
<th>Volume per acre</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Years</td>
<td>Feet</td>
<td>Number</td>
<td>Board feet</td>
</tr>
<tr>
<td>14</td>
<td>26</td>
<td>55</td>
<td>163</td>
<td>3262</td>
</tr>
<tr>
<td>15</td>
<td>26</td>
<td>55</td>
<td>168</td>
<td>1306</td>
</tr>
</tbody>
</table>

same age, have the same exact site classification, one has 163 trees per acre and the other 168, and yet one plot has twice as many sawtimber trees as the other and two and a half times the board-foot volume. A larger plot size would have greatly reduced the variation between these two plots. This problem will be eliminated once most of the trees reach sawtimber size.

In all of our plantation work we have used variable-size plots. It is impractical to specify an exact plot size in plantations because the plot outline and shape will be determined by the plantation spacing. Our only specification relative to shape merely stipulates a minimum width for rectangular plots. In fact, we admit other plot shapes, such as parallelograms, if the spacing pattern requires it. Circular plots are not used in plantations because other designs are more practical.

In natural stands twenty years of age and older, a quarter-acre circular plot seems entirely adequate for sampling both cubic and board-foot yields.

As to plot data, the usual measurements are made: a complete plot inventory by 1-inch diameter classes, a sample of heights by diameter classes, determination of average dominant height, and age of the stand. After the routine job of volume calculations, we are ready for the analysis. From the yield equations that have been published, we have good background information for developing a preliminary model.
Thus it is purely a matter of writing a program for the computer and including the variables we wish to test. A rather simple regression model will sometimes satisfactorily express the relationship between cubic yield and the age-site-density combinations encompassed by the sample data:

\[
\text{Log cubic volume} = 2.70584 - \frac{10.2041}{\text{age}} + 0.872664 \left( \log \text{basal area} \right) - \frac{51.0506}{\text{site}}
\]

For example, this equation accounts for 94 percent of the variation in the cubic yield of unthinned, natural slash pine stands in north Florida and south Georgia. The sample included stands averaging thirty-two years of age, with a range from 20 to 60, and densities from 40 to 170 square feet of basal area. The range in number of trees per acre was sixty to fourteen hundred. Basal area was the most highly significant variable in this regression and accounted for 53 percent of the total variation the equation removed. Number of trees per acre was tried as a density measure, but was not as effective as basal area. Basal area, of course, is a predictor for only one point in time, whereas space per tree or number of trees per acre can be used for any and all points in time. However, the main purpose of a yield table is an estimate of productive potential, and for that we need the most efficient prediction equation we can establish.

Cubic yields for young slash pine plantations seem to react differently:

\[
\text{Log} \frac{\text{CFV}}{1000} = 2.65878 - 0.12940 \left( \frac{N}{100} \right) - \frac{16.08665}{A} - 0.81454 \left( \frac{100}{S} \right) \\
- 0.01838 \left( A \times \frac{S}{100} \right) + 0.02083 \left[ A \times \text{Log} \left( \frac{N}{100} \right) \right] \\
+ 1.71705 \left\{ \frac{S}{100} \times \left[ \text{Log} \left( \frac{N}{100} \right) \right]^2 \right\}
\]

For example, this equation (developed by J. L. Clutter, University of Georgia) removes 88 percent of the variation in cubic yields for slash pine plantations, but the density variable (number of trees per acre) did not enter the equation until the fourth variable, and then as an interaction term. In fact, age, site, and the interaction of these two
variables accounted for better than 96 percent of the total variation the equation removed. In a preliminary analysis, basal area was used as the density measure, but the overall equation was not quite as effective as the one with number of trees. The sample for this analysis ranged from eight to thirty years of age, with an average of sixteen. Density ranged from one hundred to twelve hundred trees per acre.

The varying effect of density between natural stands averaging thirty-two years of age and planted stands averaging sixteen years is not surprising. Age and site are the dominant factors affecting unthinned merchantable cubic yields during the period of heavy ingrowth and good height growth. For example, during the period from fifteen to twenty years, periodic annual growth may amount to four cords on the better sites. Much of this is ingrowth, but an annual average of 2.5 to 3.0 feet in height growth (a total increase in height of 12 to 15 feet during the five-year period) adds considerably to the volume increase. As a simple illustration, a 6-inch slash pine tree 55 feet tall has, according to our volume table, 51 percent more volume than a 6-inch tree only 40 feet in height. The relative weakness of the density variable in the young plantation equation is explained by the fact that within plantations ingrowth and height growth are influenced much more by age and site than by density.

In contrast, most of the plots in the natural stand analysis were at an age where height growth, as well as ingrowth, had influenced yield but little for several years (Bennett, 1960). As a result, density became the dominant factor affecting yields, since volume increase was primarily through diameter growth. This being true, basal area itself became a rather precise expression of volume and influenced yields accordingly. If you recall, for example, no interaction terms between age and density or site and density were required in the natural stand equation. This is an indication that basal area is, to an extent, an expression of the effect of both age and site on total yield. This situation does not hold nearly so well as long as yields are materially influenced by either ingrowth or height growth.

Discussion

Question: Mr. Bennett, were you using a reference age of twenty-five?

Mr. Bennett: In plantations, yes.
Comment: I think some of the people here were worried about those terribly low sites you mentioned. They are accustomed to thinking in terms of age fifty, so a 30-foot site up to an 80-foot site did not sound very good for your situation.

Mr. Bennett: Yes, I failed to indicate that, I guess, but that was the reference index age. We use age twenty-five for plantations. I think whenever you find anyone speaking of site indexes for plantations, slash pine plantations, at least, they are referring to an index age of twenty-five, simply because we do not have plantations fifty years of age to measure.

Question: Mr. Bennett, you mentioned the possibility of constructing yield tables from managed plantations handled to some specified density. If I am not mistaken, this original work which you did with the yield of unthinned plantations included the possibility of doing a little bit of this through permanent plot remeasurement. Has work progressed along this line?

Mr. Bennett: Yes, we are doing some spacing studies and growing space studies in both natural slash pine stands, and plantations. Within a few weeks we will have completed the first five-year remeasurement of our plantation stand density study. We will be ready to analyze the first five-year growth data—now we have been working for two years on analyzing the first five-year growth data from our natural-stand plots, but we have had some difficulties. We lost about a third of our plots, and we have obtained growth remeasurements on, say, only two-thirds of our plots. We have had some mortality, and the loss of these plots upset our plot distribution in reference to the variables being tested. We have had a hard time trying to come out with anything on this, and we may have to wait until we complete the second five-year remeasurement on these natural-stand plots before we can get growth measurements on the natural stands. I am very hopeful that we will get something meaningful in the plantations from the first five-year growth data. If you get 60 percent of the variation
in the growth analysis, you are doing pretty well. In the first five years growth, I think that the best that anybody has come up with in southern pines has been maybe 40 percent. So don't expect anything tremendous from these five-year results.

LITERATURE CITED

Naval stores people were the first users of wood products in this country and have worked out a sensible method of buying and selling raw gum—they trade on the basis of weight. Although they talk in terms of barrels, everyone in this ancient industry knows that a standard barrel is a firm 435 pounds, regardless of how much gum is actually in the container. They think in terms of pounds of crude gum converted to pounds of rosin and gallons of turpentine. The grader, who is also the weighmaster, determines, by experience and knowledge, grade, rosin and turpentine content for each standard barrel. The 435-pound barrel probably evolved over long years of averaging thousands and thousands of containers of crude gum.

The sale and purchase of such products as pulpwood, sawlogs, veneer logs, and poles have an equally interesting history. Many years ago, the usual method was buying by the “boundary.” This could include land, or only the standing timber. Prices paid depended almost entirely on negotiation, and often the buyer or the seller, or both, did not really know what, or how much, he was buying or selling. Volumes at that time did not mean quite as much as they do now because the product involved was relatively inexpensive.

With the passage of time, the timber cruiser became valuable for his ability to advise the parties of how much timber was available for sale. In the early days this involved a woodsman’s walking through the timber and estimating how many board feet of lumber could be sawed from a particular place. My own grandfather claimed he could do this with great accuracy, though I doubt he ever saw a volume table. He was a sawmill man and always said, “I know what a tree will saw out.”

Today, with the aid of improved cruising techniques and reliable, professional estimators, and with knowledgeable and reputable busi-
nessmen in competition for forest products, bulk or boundary trades continue to be satisfactory from both the buying and selling points of view. These are good methods of transacting timber sales, but they do not suit all sets of conditions. Certain tax law interpretations prevent repeated bulk sales, in a number of instances, unless the seller is willing to forego capital gains. Individuals and organizations making repeated timber sales must retain an economic interest in the timber in order to qualify for capital gain treatment. One way to retain an economic interest is to sell by the unit on a “pay as cut” concept.

This brings us to the point where, because of tax laws, custom, reduction of risk, and other factors, it is often agreed between the seller and the buyer that measurement of and settlement for forest products are made after the material is cut and hauled to the mill yard or woodyard. With the material at the yard, the buyer is faced with a number of questions relating to the fairest, cheapest, most equitable way of measuring the product.

Let’s think about logs first. The layman and, at times, the forester think volume scaling is an easy job—merely measure the diameter and length. Surely anyone can do such a simple mechanical task. But is it really simple? Logs usually are not perfectly straight, or perfectly round, or perfectly sound. What about mud or dirt on the little end of the log? Can one tell exactly where the bark ends and the wood begins? Are scaling practices so uniform that all scalers perform in exactly the same manner? What about tree length material? What about indifference? What about honest differences of opinion, or interpretation of the facts? Very rarely do two men scale the same load of logs and get the same result. Loads and partial loads get lost and misplaced because trucks from numerous contractors come in at the same time. What about the variance of different log rules? A 14-inch log, 18 feet long, scaled according to the Scribner Decimal “C” Rule, contains 130 board feet, according to the Doyle Rule, 112 board feet, and according to the International ⅓” Rule, 155 board feet. It is little wonder, even with good intentions on the part of buyers, that sellers of forest products are confused. The point I am trying to make is that there are numerous reasons why conventional scaling is not simple, easy, or foolproof.

Volume scaling of pulpwood is easier, because piece-by-piece measurements are not made. However, scaling pulpwood is not as
easy and trouble free as one might think. The 128-cubic-foot cord is fairly standard throughout the industry, but even this is clouded by the 160-cubic-foot unit, the 168-cubic-foot unit and goodness knows how many other “units.” It is fortunate that the unit has not caught on too well as it would serve only to confuse further an already confused group.

How many times have all of us seen discouraged wood suppliers disgruntled and simmering because they think the man reading the stick is measuring incorrectly? The scaler may be accused of (a) placing the stick at improper places for vertical measurements, (b) picking out short sticks for horizontal measurements, (c) unfairly deducting for large voids, (d) doing any number of “sinister” things. There are very real problems connected with stick-scaling round wood on trucks or rail cars. For example, “shakedown” often happens when wood racks are loosely loaded. It is rare when wood scaled on a truck, reloaded on a rail car, and rescalled at a receiving yard, scales out the same. Here again, volume scaling is not easy, simple or foolproof.

The pulpwood industry, so far as I know, was the first to begin weighing wood. I am sure there were numerous obstacles—legal, practical and otherwise—placed in the way of the first man who wanted to try it, but it was a good idea. It was practical and fast. It saved time and money. The problem of how much a standard cord weighs has not been too difficult to solve. Most paper companies carefully stick scaled and weighed loads of wood for a period of time and then struck an average. This has worked out exceptionally well, and although conditions such as dried-out tops and cull wood pose problems, they have not been of a serious nature. A bulk product is being measured and, from a labor and utilization standpoint, pounds of material are more satisfactory as a basis of measurement than cubic feet of fibre, bark, and air space. The number of pounds per 128 cubic feet of stacked wood does vary, but the variations are rather minor within reasonable geographical limitations. M. A. Tarras (1956) in his study on buying wood by weight, pointed out that weight factors used by different segments of the industry in the South varied from about 4,800 pounds to about 5,600 pounds per cord for pine and from about 5,000 pounds to over 6,000 pounds for hardwood. He stated that these variations may be justified because of species and location differences. According to Tarras, slash pine is heaviest, followed by longleaf, loblolly, and shortleaf.
One of the real weighing problems occurs when a mill draws wood from a territory with several hundreds of miles between the northernmost point and the southernmost point. Weights per standard cord differ in such instances, usually due to species change. Variation in amount of money per ton at different buying points should do much to solve this problem. This is a satisfactory refinement so long as everybody wants only to arrive at a fair method of measurement.

Weight measurement is favorable to the seller, the wood harvesting personnel, and the buyer. Fresh green wood weighs more than old dry wood. Quite naturally, landowners and wood suppliers are interested in delivering newly cut, heavy wood since they will realize more money for their product and effort. This is a happy situation since the pulp and paper industry is equally interested in receiving fresh green wood since it yields more usable fibre. Buying by weight is a good method and washes out the possibility of human error or indifference. A printed record is available to the buyer and seller. Weight measurement is a very satisfactory way of doing business in connection with a bulk product.

Logs are a different matter. The sale of logs is based on the sale of lumber measured in board feet. How many board feet can be sawed from a given log? How many board feet can be sawed from "X" pounds of logs? This is difficult, if not impossible, to answer since the board foot volume that may be sawed from a given number of pounds or tons of logs can vary considerably. If we have this variance to contend with, why try to weigh logs? The major reasons are that log rules are estimated and are often incorrectly applied; weighing is accurate. A pound is a pound the world around. With this fact firmly in mind, it behooves us to search for a workable method of relating weight to volume. Initially, some fortitude is necessary. Unless the relationship is close to being right, either side could lose a substantial sum of money, since the stumpage price of logs is relatively high. Human nature makes it seem easier to go along with an imperfect "custom of the business" method instead of trying something new that might hurt us, our companies, or our customers. However, man has always sought improvement and has always been willing to take some degree of risk for this improvement.

I would like to discuss a method which, while not perfect, is workable. The method is so simple, I am almost embarrassed to explain it. It was conceived as a way to "break the ice" and make a log sale
on a weight basis for the sake of experience. Apparently it worked pretty well for it is still being used. We selected for the sale an even-aged stand of slash. It was agreed that the buyer would buy from a designated area all of the pine logs 14 inches and larger in diameter, measured at a point 12 inches above the groundline utilized to at least an 8-inch top. The buyer agreed to pay a certain price per MBF for logs on the area. A contract covering the above points was drawn. We further agreed that approximately fifty MBF, or one week's cut, would be stick scaled jointly by a representative of the seller and a representative of the buyer. This was very carefully done with any difference of opinion being rather easily resolved. Each load of logs was weighed on the seller's scales which were used primarily for pulpwood. Each truck was weighed—loaded and empty. The net weight was the actual weight of the logs on the load. At the end of the week, the board foot volume was totaled and the weight of the logs was also totaled. The board foot total was divided into the weight and a weight factor was determined. We had found what an average one thousand board feet weighed for this specific fifty MBF.

We were confident that this sample was sufficient to give us a factor that was accurate for all designated timber on the sale area. We could not, from a legal standpoint, write another contract saying that one MBF of logs weighed "X" pounds. We merely found the number of tons in the weight factor and divided this number into the previously agreed price. This gave us a price per ton. We then terminated the stick-scale contract and prepared a new contract for the same area on the basis of a certain number of dollars per ton, leaving out any reference to board feet. For our information, we continued to stick scale a number of loads each week. There was variation for specific loads, but the averages fell into line. The sale occurred on a forest of some 170,000 acres and although we went through the same procedure on subsequent sales, the weight factor for this particular forest did not change very much.

The experiment resulted in a few interesting statistics. During the first week's test, we scaled 40,790 BF in seventeen loads. The 1,297 logs involved weighed 612,970 pounds. The average log was only 7.8" in diameter inside the bark at the little end, was 15.02' long, and contained 31.46 board feet (Scribner Decimal "C" Log Rule). It weighed 472 pounds. We were surprised that such small logs weighed 15,030 pounds per MBF, but it is interesting to note that R. H. Page and P. J. Bois (1961) reported that 8-inch green slash pine logs weighed
15,200 pounds per MBF. Loads from the higher, better-drained sites averaged 14,772 pounds per MBF, while wood from low, wet sites averaged 15,388 pounds per MBF. We weighed and stick scaled for an additional week, and the factor for the two-week period for 99,890 MBF was 15,060 pounds. This is information relative to a particular tract of timber in Atkinson County, Georgia.

After this initial effort we made a number of sales on other forest areas, all of which were made on the same general basis. The weight factors varied from 15,030 to 12,400 pounds per MBF. The lower factors were for relatively larger loblolly and pond pine timber. Check scales revealed that weight factors remained reasonably constant within given sale areas. None of our customers objected to the results and we were satisfied. While we did not attempt to conduct a precise experiment, we were very interested in the reasons for the variation in the weight factors. Slash will give the highest weight factor, followed by longleaf, loblolly, and pond pine of comparable size. Large logs will weigh less per MBF than small logs of the same species. In our experience, we found that tree size was the most important factor.

Our method worked well for our specific set of circumstances. I believe there were several reasons for this. We were merely trying to find a more efficient way to measure a product. We were not interested in any selling advantage. We were not looking for an overall factor that would guarantee "X" pounds equal 1 MBF for all sales. We were interested in a fair factor for a specific sale, all the while looking for an inexpensive and accurate way of arriving at weight factors for specific sales. We were equating weight against one log scale—the Scribner Decimal "C." In the beginning our sale chances were modest, involving about 200 MBF, and were small enough so that the timber sold was fairly uniform. In this connection, however, if the timber was not uniform, we did not let this discourage us from making weight sales. We simply negotiated with the logger to scatter his test loads to cover a more extensive sample of the area. In all cases, we required loads to be hauled from both hill and pond areas in proportion to the volume to be cut from hill or pond when determining weight factors. As we gained experience we made weight sales in excess of 22,500 tons (3,000 MBF) of logs from areas well over a thousand acres in size. I realize all this sounds simple, and it is. I strongly suggest that its strength lies in its simplicity and in the fact that the method was devised for one specific situation and set of conditions.
Our method was one we initiated as sellers of logs. James W. Martin (1965), reporting in *Alabama Forest Products*, tells of a method used by Olon Belcher Lumber Company as buyers of logs. The objective was to devise a way to scale logs by weight that would give results

<table>
<thead>
<tr>
<th>Diameter</th>
<th>14'</th>
<th>16'</th>
<th>14'</th>
<th>16'</th>
<th>14'</th>
<th>16'</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.5&quot;</td>
<td>44.4</td>
<td>51.8</td>
<td>50.7</td>
<td>52.1</td>
<td>53.6</td>
<td>54.5</td>
</tr>
<tr>
<td>9.0&quot;</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12'</td>
<td>50.0</td>
<td>52.4</td>
<td>55.4</td>
<td>53.5</td>
<td>57.5</td>
<td>60.6</td>
</tr>
<tr>
<td>11&quot;</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12'</td>
<td>58.0</td>
<td>63.8</td>
<td>66.5</td>
<td>64.0</td>
<td>70.0</td>
<td>72.1</td>
</tr>
<tr>
<td>13&quot;</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12'</td>
<td>69.5</td>
<td>76.4</td>
<td>78.0</td>
<td>75.0</td>
<td>82.5</td>
<td>83.8</td>
</tr>
<tr>
<td>15&quot;</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12'</td>
<td>80.2</td>
<td>88.8</td>
<td>89.5</td>
<td>85.6</td>
<td>95.0</td>
<td>95.3</td>
</tr>
<tr>
<td>17&quot;</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12'</td>
<td>102.0</td>
<td>99.8</td>
<td></td>
<td>107.5</td>
<td>107.0</td>
<td></td>
</tr>
</tbody>
</table>

*This merely tells how many board feet are in (for example) one thousand pounds of logs 10 inches in diameter, 14 feet long (or for any other size log).*

equivalent to stick scaling by the Doyle Rule. Martin has worked out a very good system. What he actually does is weigh the logs and then convert back to board feet. This gives the advantages of weight scaling and leaves him with a familiar unit of measurement—the board
foot—as a final result. For his study, Martin weighed and stick scaled six hundred loads of logs. From the scale tickets he arrived at the average diameter and average length of each load. Next, the number of one thousand pounds of logs was divided into the board foot volume. This figure represented the Doyle volume for each one thousand pounds of logs for that specific average log diameter and length. The six hundred loads gave weight conversion factor data for all possible log diameters and lengths, which were recorded, averaged, and plotted on a graph. With this data, Martin devised a table which gives the board foot Doyle Scale conversion factor per one thousand pounds of logs for each possible diameter and log length class. See Table V.

Then Martin encountered a problem—how to arrive at the average size log on each load without having to go through the laborious process of measuring each log, for if he had to measure each log there would be no advantage. Page and Bois (1961) had done some excellent work on weight, and Martin found that some of the information they had worked out could be adapted to his set of conditions. He used this information to work out his own table which gave the average weight of logs by diameter and length. This table follows:

### Table VI. Weight per log table

<table>
<thead>
<tr>
<th>Average Diameter of Logs on Load</th>
<th>Average Length of Load</th>
<th>12'</th>
<th>14'</th>
<th>16'</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.5</td>
<td>261-300</td>
<td>313-358</td>
<td>365-418</td>
<td></td>
</tr>
<tr>
<td>8.0</td>
<td>301-340</td>
<td>359-405</td>
<td>418-474</td>
<td></td>
</tr>
<tr>
<td>8.5</td>
<td>341-380</td>
<td>406-455</td>
<td>475-531</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>381-450</td>
<td>456-540</td>
<td>532-630</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>451-550</td>
<td>541-660</td>
<td>631-770</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>551-658</td>
<td>661-790</td>
<td>771-920</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>659-778</td>
<td>791-933</td>
<td>921-1088</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>779-905</td>
<td>934-1085</td>
<td>1089-1268</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>906-1040</td>
<td>1089-1253</td>
<td>1269-1460</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>1041-1185</td>
<td>1253-1430</td>
<td>1461-1665</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>1186-1335</td>
<td>1431-1610</td>
<td>1666-1875</td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>1336-1565</td>
<td>1611-1800</td>
<td>1876-2085</td>
<td></td>
</tr>
</tbody>
</table>
Using these two tables, he proceeds in the following manner: (1) The weight of the load of logs is determined. (2) The logs on the load are counted. (3) The weighmaster determines the length class under which the load is to be categorized. (4) The weighmaster divides the number of logs into the net weight and gets the average weight per log. (5) With the average length and average weight, he goes to his table and determines the average diameter. (6) With the average diameter and average length he goes to the conversion factor table and gets the number of board feet per one thousand pounds for this specific average diameter and length. (7) He then multiplies the number of one thousand pounds on the load by the conversion factor and comes up with the board foot volume for the load.

Martin uses a similar method for tree length material in which he follows nearly the same procedure and uses the same table. He works on the basis of 14-foot logs. He determines the number of linear feet on the load and then determines the number of theoretical 14-foot logs on the load by dividing 14 into the total linear footage. This is a fine workable method and one of its real advantages is that consideration is given to the influence of log size by load. For instance, a contract logger could bring in twenty thousand pounds of small logs having a relatively small board foot content, while the next truckload could be twenty thousand pounds of large logs having a relatively high board foot content. Mr. Martin’s system largely satisfies this general disadvantage to weight scaling.

The Del-Cook Lumber Company of Adel, Georgia, was one of the pioneers in weight scaling. It sought a workable method of buying on a weight basis because a large volume of logs moved through their mill. Its buyers purchased tree length material and had neither the time nor space to stick scale. Del-Cook concluded that for its area and system an average factor of sixteen thousand pounds per MBF was equitable. It recognized that variations due to size and species existed and worked from this basic sixteen thousand pound factor generally by varying stumpage. We had a number of contracts with the company at specified sums per ton of logs, leaving the firm free to continue with its sixteen thousand pound factor.

There are several advantages and disadvantages to weight scaling. S. Guttenberg et al. (1960) point out several potential advantages: (1) a single objective measurement that can supplant scaling by timber growers, loggers, haulers, and mill men; (2) the elimination of
stick scaling's log-by-log computations and opportunities for error; (3) shorter truck turnaround time at the mill; (4) feasibility of uncontested spot payment for delivered logs; (5) a stimulus for delivery of green logs, free from stain; (6) lessening of the risk of physical injury to scalers.

Tarras (1956) points out the following: (1) Positive records of a transaction can be made without human judgment entering the picture. (2) The method is quick, requiring no special handling, and saves time for both the buyer and seller. (3) It provides an incentive for better piling of wood on trucks and thus increases volume handled by the supplier. (4) A greater volume of wood can be handled with less time and personnel. (5) It encourages prompt delivery of green wood to the mill, which is desirable from the standpoint of pulping. (6) Inventories are more easily maintained. Personally, I believe the use of weight scaling almost forces a better job in the woods. Certainly it does with logs. For instance, we constantly had trouble with trim allowance. We permitted a 6-inch trim, but in a great many instances the trim was 14, 16, and 18 inches. With the use of weight, a buyer pays for this over-trim at the regular log prices. After a few weeks, he brings his trim into line. Also, a contract logger or pulpwood man is apt to pick up his wood or logs and get it to the scales quicker since loss of weight is considerable if the material is left in the woods for any appreciable length of time.

There are some disadvantages to weighing logs. The prime problem is the change from a volumetric system to a weight system. For years we have been thinking in terms of cords, units, and board feet. The industry is more or less geared to the volumetric system and a considerable change involving legal, accounting, and sales matters must occur. Change is difficult and slow. At times, it is difficult for the buyer to weigh logs if a truck must be routed out of its way in order to cross a scale. Of course, this is something that can be cured by purchase of scales, but it can handicap early efforts toward making weight sales.

G. R. Trimble (1965) observes that weight scaling is not too well adapted to scaling hardwood logs when grade is a factor. Mr. Trimble has a valid point, especially since grade involves both size and log quality, or absence of knots. It is impractical to think that weight scaling is the answer to all problems involving measurement. I do not see how a satisfactory system could be devised for all hardwood
log sales. For instance, we have had sales under which we received $45 per MBF Scribner Decimal "C" for Prime and #1 Redgum, $36 per MBF Scribner Decimal "C" for Prime and #1 Sap Gum, and $22 per MBF for everything else. I do not believe a sale such as this on a weight basis is practical. There are certain sales that simply do not lend themselves to weight scaling. I do feel that under a number of conditions hardwood log sales are practical. The U.S. Army at Fort Stewart has made a number of hardwood sales on a weight basis and as far as I know all have been satisfactory.

With regard to the future of weight scaling, I believe it is firmly established. A great percentage of roundwood, both pine and hardwood, as well as chips, are weight measured. More and more sawmills are buying on a weight basis. As time goes on and as experience is gained, most pulpwood and logs will be bought and sold by weight. The procedures are new and in many cases somewhat rough. Knowledge is limited, but more and more research is being done on weight. One very helpful project could be the assembling and condensing into usable form the available weight information. Also, I feel that an inexpensive method of arriving at reliable weight factors for logs is a problem on which much work is needed. W. J. Richter, R. V. Malecki (mensurationists of considerable ability), and I were working on such a method. It seemed to us that with enough data on log size, species, and location, coupled with knowledge of timber to be sold, tree size, species, volumes in ponds and on hills, we could project a reasonably accurate factor for specific sales. Most of the needed information would be gathered during routine cruises made for cutting budgets on annual harvest compartments. We did not intend to get one overall factor for all sales. Because, with regard to weight sales, nothing can take the place of accurate information regarding size, species, and quality. This information is necessary and personal knowledge of the timber to be bought or sold, as the case may be, has never been more essential.

To summarize, there are important advantages to weight scaling. The major one is accuracy. It is efficient and overcomes the problem of human error. From a technical point of view, weight factors are simple to determine for bulk products such as pulpwood. Within reasonable geographical limits pulpwood weight factors are generally constant, but do change over wide areas. Factor variation, or pricing per ton, at different buying points should solve this problem. It is
also feasible to buy or sell logs on a weight basis. One weight factor for all logs is impractical. Variation in size and species requires varying weight factors. Accurate factors for specific sales are practical and can be determined easily. Here again, variation in price per ton might be an acceptable solution.

The word "agreement" is a wonderful word. It indicates peace, cooperation, progress, and prosperity. True agreements are reached when two parties, with full knowledge of the facts, decide that a specific course of action is of mutual benefit. Weight scaling is not the answer to all scaling problems, but if buyers and sellers can agree that the objective is only to find a better way of measuring forest products, then, undoubtedly, weight scaling will assume and hold a most prominent place in the field of wood product measurement.

Discussion

**Question:** Has mud been a problem in your weight scaling?

**Mr. Barton:** Yes. Let me explain this. We were not sophisticated enough, and our system was not refined enough for us to worry about the mud. We did recognize that this was some problem, but we just hoped that the truck was rough enough to knock the mud off before it got to the scales. I'm sorry that I can't give you a better answer.

**Question:** Did you find any variations in your weights in different seasons of the year?

**Mr. Barton:** No, sir, we did not. There was very little difference. We were afraid that there would be some difference; we thought logs might weigh more in the spring than in the summer when the sap was up, but we really found no difference.

**Question:** Union Bag apparently has set a price per thousand pounds for logs. Are there any plans for using this in the woods in the form of making weight tables in place of volume tables, and keeping cruising records in place of the weight?

**Mr. Barton:** I wish you hadn't brought that up. It is a problem. All of our own wood is bought on the basis of weight; yet all of our field work is done on a volume basis.
The volume tables in our CFI program are based on cord equivalent. We measured enough trees and weighed them so that we were able to put pounds per cubic foot back into our volume tables. So our volume tables actually are based on rate weight, although we still call it cords.

LITERATURE CITED


It seems unnecessary to develop a justification for our consideration of tree quality. It is common knowledge that the average quality of our timber supply is low (U. S. For. Serv., 1965) and that this creates a significant difficulty for the industry and for the nation. Certainly, in our more intensive forest management and more efficient production, we shall find it necessary to be able to assess the quality of our resource. Below, we can only sketch a conceptual framework upon which to support our thoughts about the problem of measuring tree quality. Let us see if we can isolate the most important supporting members in the framework. Perhaps we then can see some order in what must now appear a chaotic mass of unrelated details.

There is no shortage of written materials about log and tree quality—fifty pages were required for the bibliography five years ago (Flick, et al., 1961), and it is still growing. Many of these papers were written about the various log-grading systems and do not relate directly to tree quality; some of the older ones were released through inaccessible media; some were simply communications among log-and tree-grade researchers describing their research difficulties; and others are quite general or out of date. Consequently, the practicing forester may believe that the research done in measuring tree quality has not been directly useful to him. Some foresters view the problem as a trivial one; they say, for example, that tree diameter is a sufficient index of quality. Others view the question as a very complex one. They would like to estimate, with high precision, the potential yield and value of individual trees for a whole set of end products and various kinds of mill technology.

Mensurationists, even though they are the experts at measuring things, generally have left the measurement of tree quality to the people working in forest utilization. This approach has some shortcomings, and it seems quite irrational to consider the problems of
measuring quality and volume as separate ones (Ware, 1965). The solution to these difficulties will require communication between the practicing foresters and researchers, and among the various research specialists.

In our consideration of the problem of measuring tree quality, let us attempt to answer a series of questions:

1. What is tree quality?
2. Can tree quality be measured directly in practice? If not, can sufficient precision be achieved by estimating indirectly?
3. What are the objectives in estimating tree quality?
4. What are the characteristics of a good procedure for estimating tree quality?
5. How may the practicing forester estimate tree quality now?
6. How shall we estimate tree quality in the future?

By attempting to answer these questions, we should be able to gain an impression of the outlines of the problem. Hopefully too, we may gain some useful insights about applications that are feasible now or in the near future.

**What is tree quality?**

What is tree quality? This important question has been seriously considered by many researchers: wood technologists, forest geneticists, silviculture physiologists, and mensurationists (see, e.g., Englerth, 1966). All these specialists seem to have had different objectives in mind, and there has been relatively poor communication about the differences. And the objectives have often seemed quite different from those that one might expect the practicing forester to have. Unless we look at measurement of quality as an end in itself (something quite difficult to imagine!), then the only rational objective and definition is that of the decision-maker who will be the ultimate user of the methods for measuring tree quality and the user of the information gained from the measurement.

Timber quality has been defined by G. H. Englerth (1966) as “that combination of physical and chemical characteristics of a tree or its parts that permits the best utilization of the wood for the intended use.” This definition leaves us with many difficulties in quantification. How shall we decide what the “intended use” should
be? What is "best utilization" even for a given intended use? Should we be content with knowing what will "permit" the utilization? This implies that we consider only what minimum characteristics will permit a given use. Is there any rational way to define "best utilization" and "intended use" other than through a value criterion?

Let us therefore define a quality measure as a measure of the relative value of a tree or log for the various end products that might be produced from it. Ideally, this measure would be an index that effectively combined all the factors that determine product value in a specific situation. However, we usually settle for less than the ideal (even in our search for quality measures!). Thus, quality has in practice frequently been a measure, not of the relative value of a product, but of the relative abundance of one of the [groups of] factors that influence the product value (such as the independent factors that indirectly relate to percentage of high-grade lumber that can be cut, or to the specific gravity). Such measures are related to quality as we have defined it. However, there are serious difficulties with them because they have been estimated separately and independently of the other value determinants such as volume, price, production technology, yet they are inextricably tied to these other factors, and therefore it is difficult to know how to use such partial measures.

Any really useful definition of tree quality must relate directly to the characteristics which determine the value of the tree for producing various end products (Ware, 1965). Quality must then be defined separately in terms of each of several possible end-product uses for the tree, or in terms of an optimum (highest dollar value) mix of various end-product uses for each tree. So defined, the emphasis is on the use of the quality measurement and upon the major groups of factors that influence value and hence must be considered in measuring quality. These factors logically divide into three groups: (1) factors that determine the total volume of end products that may be produced from the tree; (2) factors that determine how this total volume is distributed by quality classes of end product (e.g., lumber or veneer grades); (3) factors that determine the price per unit of volume by quality classes of end product.

The first two groups include both (a) factors that are related to the inherent characteristics of the tree and (b) factors that are related to the production technology and the quality classes recognized in the trade.
Most of the traditional emphasis has been concentrated on a part of this overall problem of measuring quality and value. The emphasis has been on a particular subgroup of the factors that influence the distribution of volume by quality class of end product (such as, for example, the percentage of the tree that will be in grade 1 lumber). This subgroup of factors includes those inherent characteristics of the tree, such as the amount and distribution of various external defect indicators (knots, worm holes, etc.). We have been mainly concerned with the way these translate into lesser yield of the high-value end products. There is not space here for an expansive discussion of the importance and relevance of the factors related to total volume, production technology, and price. Some of the consequences of ignoring these factors have been set out elsewhere (Ware, 1965).

Can tree quality be measured?

If we accept a definition of tree quality such as has just been suggested, then we are led to conclude that tree quality cannot be measured directly in the standing tree. Certain of the variables that influence quality might conceivably be measured directly, but most cannot. Or we might directly measure certain indices of quality that would be based entirely on observable inherent characteristics. In the first place, not even the total volume of a given end product (such as lumber) can be measured, it can only be indirectly estimated (think of volume tables, log rules, overrun percentages, etc.). The distribution of volume by quality class of end product (as, e.g., percentage of lumber by lumber grade) is even further from being measurable. This is so because it depends so much on internal defects that may be very obscure on the standing tree and also on differences among production technologies at various mills. Price varies with quality class of end product, and with place, time, product technology, market structures, etc.

This does not mean that we must abandon our attempts to quantify quality. We have always had to live with a similar situation for board-foot (and even cubic-foot) volume of standing trees. There, we have developed procedures for indirectly estimating the volume of standing trees. When the volume-table procedure is stripped of the details so we can see the essence of the estimation problem in its stark simplicity, we see that it is a double-sampling approach, with the rela-
tionship derived from an independent sample. Unfortunately, foresters have not recognized the volume-table method by that name.

Because this point is fairly important to a consideration of quality estimation, let us more closely examine our estimation procedure for volume. The variable that we are interested in estimating, tree volume, is difficult (volume yield in board feet is literally impossible) to measure in the standing tree. However, we know from the theory of the volume of geometric solids and from much experience and empirical data, that tree volume has a quite consistent relationship to easier-to-measure variables such as diameter and height of the standing tree. Consequently we take a relatively small sample of trees from our population, and on this sample, we measure both the volume (by felling the trees) and the easy-to-measure dimensions such as diameter and height. From this small sample, we estimate the relationship of volume to the dimensions. We take the results we get from estimating this relationship, put them into tabular form, and we have what we call a volume table.

Then, to estimate the volume of standing trees (in the population to which the estimated relationship applies), we take a larger sample of trees and we measure the dimensions directly for each tree. We then use the estimated relationship of volume to these dimensions to estimate the volume indirectly. We usually are not careful to assure ourselves that the relationship really does apply to our forest population. Also we have generally failed to try to evaluate objectively the error that arises from the estimated relationship. Mending of these procedures is long overdue in general mensurational practice.

However, we are not now concerned with volume estimation, except as it is relevant to quality estimation. It is quite relevant though because volume and quality are inextricably related. These details about double sampling for volume simply show the relevance of the same approach to estimating quality. Though tree quality cannot be measured in the standing tree, it can be estimated indirectly through such double sampling. Some of the same predictor variables (such as diameter and height) would be involved, along with several other more complex variables such as defect-indicator counts or grade of the butt-log. There are many relevant questions about what relationships can be used and about the efficiency and costs of alternative ways of achieving the necessary precision in the final estimate.

There are several places in this kind of double sampling and estimating procedure where we can allocate effort to control the precision
of the final estimate. First, we can control the size of the sample used to estimate the relationship of tree quality to the characteristics measured on the standing tree. We would also try to use the best sampling design to choose the sample so that it adequately represents the true population relationship and gives estimates with a small residual error. Second, we can seek the model or form of relationship that best estimates the true relationship and gives tree quality estimates with a small residual error. Third, we can control the size of the sample on which we measure the characteristics in the standing trees. And we can choose an efficient sampling design to select those trees.

Notice that we may achieve a specified sampling precision either by applying a simpler relationship with larger residual error to a large sample of trees or by applying a more complex relationship with smaller residual error to a small sample of trees. The optimum balance point between these is simply a question of sampling efficiency and costs, and the optimum allocation of effort will vary with local circumstances. Methods are available for calculating such optima. But this is perhaps more properly a question of sampling designs and estimators for forest inventory, so we shall pursue it no further here.

What are the objectives in estimating tree quality?

One of the most serious difficulties is that of specifying our objectives in estimating tree quality (Newport, 1960; Ware, 1965). A quotation from a very recent publication may illustrate the point. Englerth (1966) says: “Two aspects should be considered in timber quality research. One is the recognition and evaluation of the tree and wood characteristics as they affect end uses, and the other is growing trees for these products. [italics mine]” When timber quality and timber-quality research are so defined, we can see that they are all-encompassing. We all are concerned with “growing trees for these products.” But are we all timber-quality researchers? The objective implied by this statement has such breadth as to be useless as a guide for our attempts to measure tree quality. We will have to be far more specific than this about the relevance of quality measures to the solution of the problems we have in growing the raw material and converting it into wood products.

Clearly, different users of quality estimates will have different uses
and hence will have different objectives. It is therefore impossible to specify general objectives (or definitions) that are acceptable to all users. Presumably, however, each forester who has a need of estimates of quality can specify detailed objectives for his own circumstances.

The only person who can possibly specify the objectives is the decision-maker who will use the information and who has thought about how much it is worth to him. However, we often have failed to think about whether quality estimates would be useful to us or have assumed that the estimates are too costly. The conventional practice is to do what has traditionally been done without really seriously reexamining our needs or specifying our objectives.

The objective (in its most simplified form) might be to achieve, at lowest total cost, a specified precision level in an estimate of the value of lumber (or other end products) that might be produced from the timber on a given area of forest. There would undoubtedly be subobjectives related to value by species, size classes, etc., and even predicted future value. And there would probably be need of estimates of some index of quality that depended only on inherent characteristics of the tree and that was relatively free of influence of current prices, current specifications of quality-classes of end product, and current production technology.

There is not space here to elaborate or to give more specific examples, but certainly the forester can, with some thought, specify his objectives just as he must do for inventory generally.

What is a good procedure for estimating tree quality?

How are we to know a good procedure for estimating tree quality? How can we recognize a good one provided for us by someone else? How might we go about deriving a good one? These are broad and profound questions, and there can be no ideal answer. We do know, however, that a good estimating procedure must have several specific properties.

First, the method should be as efficient as our current knowledge can make it. The most efficient one is the one that will, at the lowest possible total cost, give us estimates of tree quality within our specified precision for our forest, our mill, our end-product mix, and our market situation.
Second, it must be possible to apply the measuring and estimating procedure consistently so that different observers will reach the same estimate time after time. This is particularly important when we want to assess growth and change in volume and quality.

Third, the procedure must be simple enough to permit its being carried out by the available timber cruisers and data analyzers. Insofar as lack of simplicity can be overcome by incurring added costs, this last property is related to the first one about cost and efficiency considerations. Such costs include, for example, the cost of observing a larger number of more detailed defect indicators on each tree, cost of training observers, and cost of observer "fatigue" and non-sampling errors from getting "fed-up" with complicated field procedures.

Fourth, the procedure should yield estimates for which the sampling error and reliability can be objectively evaluated. This depends upon the ways in which samples are taken, predictor variables are observed, and final estimates are made and also involves the question of whether the relationships used in the indirect estimation are applicable to the forest at hand.

How may the practicing forester estimate tree quality now?

Many foresters are currently faced with the problem of estimating tree quality to some precision level or other. The problem exists even if only a very low precision is required but becomes difficult when high precision is required. Foresters have two main alternative ways of approaching the problem and many alternative combinations between these two extremes.

**Estimating your own relationship**

The first of these alternatives is to estimate, by appropriate statistical procedures, the relationship of value (or some other useful index of quality) to the characteristics observed on the standing tree. Then, having done this for the forest for which estimates are required, the straightforward double-sampling procedure could be applied in whatever sampling design is most efficient. This requires us to select sample trees in some appropriate way, to observe appropriate independent variables on the standing sample trees, and then to harvest the trees and record yields (volumes, grades of end product, etc.) as they are milled. This alternative obviously requires much time and
highly trained, expensive talent, and calls for a sizable research task.

Consequently, this surely will not be the best alternative for most small forestry enterprises now. However, it is now possible for some foresters to take a much more unified and efficient approach to estimation of volume, quality, and growth in volume and quality. This is largely because of increasingly better mensuration training for foresters. But we also have many new and efficient methods of sampling, measurement, computation, and estimation—such, for example, as unequal probability methods based on extensions of point sampling and three-P sampling.

Using a relationship developed by someone else

Most foresters will find it necessary to use one of the more general types of relationship of quality to tree characteristics, like those derived by some research agency with broad responsibilities. Such general relationships have been and continue to be derived by the U.S. Forest Service, Tennessee Valley Authority (Cummings and Zarger, 1953; Ellertsen and Lane, 1953), forestry schools (Herrick, 1946; Worley, et al. 1958; Ward, 1964) and some large industrial research agencies (Weyerhaeuser Co., 1965).

In applying these relationships, the user has no choice of what characteristics (predictor variables) to observe on the standing tree. He must observe those specific variables for which the relationship was derived and observe them as specified by the developer of the relationship; otherwise, he will obtain useless estimates. The user will be able to select the sample trees on which the predictor variables are to be observed. But that is the common matter of sampling design in forest inventory.

Let us now turn our attention to a more detailed consideration of the essential features of those relationships that are now available and how they may be used. Suppose we take the simple ones first—even if they are simpler only because few or no relationships are available. We will begin with veneer as the end product, then consider pulp, and finally, lumber. Hardwoods and softwoods must be considered separately, particularly for veneer and lumber, because of the basic differences in the end product and the quality classes of end products.

Veneer We can, unfortunately, dispense rather quickly with the
problem of estimating quality of trees for producing veneer. Research on standard bolt grades for veneer is under way. But there are no general or standard relationships now available for estimating quality of hardwood veneer bolts—to say nothing of estimating quality of standing trees. Such bolt grades as exist are either local grades, based on subjective judgments, or grades for which the performance in veneer yields is not known. The hardwood-veneer industry has not settled on a generally applicable set of specifications for quality classes or grades of the end product. (Most of the trade is based on bidding on individual flitches after cutting.) The quality of a hardwood tree for veneer depends heavily upon the size and clearness of the surface of the lower bole, so that we should be able to “make a stab at it” indirectly through such variables. However, the many other important factors that influence color, figure, and grain pattern are often unknown and not yet quantifiable.

The rapidly expanding industry in southern pine veneer and plywood will make it necessary to be able to evaluate the quality of logs and trees for veneer. Here, we should be able to use to advantage the kinds of estimators, grades, etc., that have worked best for western softwoods. Changing technology and prices cause some drastic variations in effectiveness of our present grades.

Pulp The quality of trees for pulp is dependent upon several internal factors that are not easy to observe on the surface—fiber length, specific gravity and other characteristics indirectly related to it such as species, growth rate, spring-wood/summer-wood ratio, age, and diameter. There now is much interest in this topic, and some relationships are being developed. The wood density surveys may lead to some useful relationships for estimating tree quality for pulp, even though the objectives seemingly pertain more directly to estimating strength properties, etc. (Bendtsen, 1966). These relationships are expected to be useful for stress-graded lumber.

At present, the markets for pulpwood do not really reflect quality differences. There is some indirect reflection through differences between species and through purchasing by weight. Purchasing by weight assigns the higher price to the wood with higher specific gravity and hence more pulp (assuming moisture content, and other factors, constant). Until the prices (or value at the mill, for integrated-product firms) reflect quality differentials, there seems rela-
tively little need, in the usual forestry operation, for precise measures of tree quality in pulpwood trees.

**Lumber** What relationships might we use to estimate tree quality for lumber? Most available relationships are for estimating in logs with both ends visible and with defect indicators visible at close range. These relationships are typically in the form of log grades differing between hardwoods and softwoods and among groups of softwoods.

The relationships for estimating tree quality are mostly based on using the log grades and their performance (yield) data as an intermediate step in deriving the relationship and in using it. When this procedure is used to estimate tree quality, the only additional sources of variation accounted for, beyond those accounted for by the log grades, are those associated with the distribution of logs by log grade within the tree. Suppose, for example, that we have two 16-inch d.b.h. trees of a given species; one having three logs of grades 1, 2, and 3, respectively, and the other three logs of grade 1. Some of the relationships would estimate the same yield for these two trees. To be most precise for estimating the quality of these trees, however, the relationship would have to be based on the observable characteristics of the tree that account for the difference in this distribution of volume by log grades. Many of the available relationships are also based on assigning the same average yield to logs of a given grade, regardless of position in tree (except for butt logs) or associated quality of other logs in the tree. We must give up some precision in our estimate and sacrifice the possibility of evaluating all the sources of sampling errors when we use such relationships. The alternative to deriving relationships on the basis of the log grades, however, would have been to discard the voluminous and extremely costly performance (yield) data that have been collected for some of the log grades.

There are many log-and tree-grading systems for hardwoods (Newport, Lockard, and Vaughan, 1958). However, most of those that seem to have any general applicability or that have been tested and adopted over other than local areas are based on the U.S. Forest Service Standard Hardwood Log Grades for Factory Lumber (Forest Products Laboratory, 1959). There has been a great deal written about how to apply these log grades (Ostrander et al. 1965; Lockard, Putnam, and Carpenter, 1963).
There also is information available relative to how the log grades may be applied to estimate tree quality through tree grades based upon them (Whitmore and Jackson, 1957; Bulgrin and Walters, 1959; Campbell, 1951, 1955, 1959a). Consequently, we will turn most of our attention to the tree-grading systems based upon this broad foundation of data.

There are several ways to use these log grades as an intermediate step in estimating tree quality. We may proceed directly to estimates of average percentage yields in each lumber grade by applying the log grades and performance data given in the latest revisions of “Report D-1737” (Forest Products Laboratory, 1959). The value of each log can then be obtained by multiplying these performance data by total volume and then by price per board foot for each lumber grade. Alternatively, we may estimate value indirectly through the quality index. Quality index is first estimated, either log by log or for the whole tree. Then it is multiplied by total volume and the price per board foot of lumber in the grade that is the base for the quality index. It is often advantageous to use quality index (Beazley and Herrick, 1954; Martens, 1963; Ware, 1965).

The most complex procedure for estimating the quality for a given tree is one based on log grades and using the average performance data directly, log by log. In this procedure, we first select sample trees for which the quality is to be estimated and estimate total board-foot volume in the usual way. Then each log (usually standard sixteen-foot lengths) in the standing tree would be “graded” by applying the standard log grade specifications (Ostrander, et al. 1965). By multiplying the total volume of the tree by the proportion of its volume that falls in each log (given with many volume tables) we can get an estimate of the volume of each log. (Alternatively, we could use taper rules or dendrometers to get an estimate or a measurement of scaling diameter of each log—and obtain volume from a log rule.) The estimates of average percentages of volume in each lumber grade for logs of that species and grade can then be obtained from the Forest Products Laboratory (1959) performance data for the appropriate average log diameter. The yield percentages would then be multiplied by price per board foot for each lumber grade, and then by total volume of the log. These products would then be summed to get total value for each log, and the tree value would be the sum of these for all logs in the tree. A. M. Gilbert (1959) and
M. D. Ostrander et al. (1965) gave examples of the use of this procedure and a discussion of it.

This procedure is clearly quite tedious both in field and office, and all the burdensome field work and arithmetic may lead to overconfidence in a spurious precision. In addition to the labor involved, this procedure has several other shortcomings—some inherent in the log grades and some arising from their application to standing trees. Some of the shortcomings are: (1) It is not possible to get an objective evaluation of the reliability because the variation inherent in the performance data is unknown (and for other reasons listed below). (2) The performance data are based on purposively selected mills of “average efficiency” so that the yield percentages and overruns do not apply to any given mill. (3) The performance data for some diameter classes are based on very small numbers of logs and involve several thicknesses of lumber. (4) The performance data are for logs of various lengths, graded after felling and with both ends observed, and graded with surface defect indicators examined at close range. We do not know how the performance will change for logs of standard length (16-feet or 8-feet) graded in standing trees. (5) It is difficult to see some kinds of surface defect indicators and to estimate scaling diameter and, consequently, to grade logs in tall, standing trees. (6) It is difficult to get consistent grading of the upper logs of tall trees—either consistent among observers or at different times with the same observer. This leads to serious problems in production control and estimating growth.

Are there alternative ways to use the large amount of performance data for the log grades without grading every log in the standing tree? There are procedures based upon “tree grades”; but “tree grades” are not yet available for most species and areas. The U.S. Forest Service is working to develop such tree grades. New techniques are also being investigated for future application (Marden, 1965).

For current applications, however, we must use the tree grades that have already been developed. These include the grades by W. H. Cummings and T. G. Zarger (1953) for the Tennessee Valley area, by R. A. Campbell (1951, 1955, 1959a, 1959b) for the Southeast, by J. G. Schroeder (1964) for yellow-poplar in the central states, or by various workers for oaks in the central states (Herrick and Jackson, 1957; Whitmore and Jackson, 1957; Bulgrin and Walters, 1959). These tree grades are based on application of the standard log grade to a
section of the 16-foot butt-log and measuring the diameter and merchantable length of the tree. Researchers have provided relationships (or more precisely, tables based upon relationships) from which the percentage yield of lumber by lumber grade or the quality index and, hence, the tree value can be obtained. These tree grades are based on the standard log grades, and for any local situation, they have some of the shortcomings mentioned, but they are certainly better than no relationship. They provide an example, too, of one way that the forester might estimate a relationship for his specific problem of tree quality estimation.

We have only mentioned quality index, but we should consider it in more detail because it is involved in so many of the quality estimators. The quality index of a tree is a single number that is an aggregate index of the quality and value of the tree. It is obtained by first forming, for each lumber grade, the ratio of the price of lumber of that grade to the price of lumber of a base grade (usually #1 common for hardwoods). Then this price ratio for each lumber grade is multiplied by the corresponding yield percentage in that grade, and the products are summed over all lumber grades. The resulting sum is the quality index; a weighted average price ratio. When we multiply the quality index by the price per board foot of lumber of the base grade and then by total volume of the tree, we obtain the value of the tree directly. Consequently if we could find relationships to estimate quality index from measurable characteristics of the tree, the estimation of the value would then be a simple matter.

The concept of the quality index has been with us for a long time (Herrick, 1946; Purdue University, 1952; Ellertsen and Lane, 1958; Beazley and Herrick, 1954; Whitmore and Thornton, 1955), but is still poorly understood (Ware, 1965). However, it has several advantages. It is particularly convenient and useful for value estimation if the price ratios remain relatively stable or change predictably over time.

An estimating procedure based on having current prices inherent in the value estimator will become outdated (or inefficient, or both) quickly as prices change. And one developed without regard to prices and value will be inefficient from the start. But the quality index will remain a useful index of tree quality and value even if prices change, so long as the price ratios change slowly or predictably. Relationships based upon the index would be relatively easy to recalculate.
if price ratios changed drastically. Those seriously interested in esti-
mating tree quality should certainly make themselves familiar with 
the quality index.

Most of our discussion about measuring tree quality for lumber 
has been centered around hardwoods. The problem of estimating tree 
quality for southern softwoods is not different in principle from the 
problem for hardwoods. However, softwood lumber has widely dif-
ferent uses, and, hence, different lumber grade specifications. Conse-
quently, the relationships and surface defect indicators used to esti-
mate quality are quite different (Putnam, 1960). Standard Forest 
Service Log Grades are now available for southern pine (U.S. Forest 
Service, 1953; Campbell, 1962, 1964), and these may be applied to 
each log in the standing tree just as for hardwoods. Relationships that 
permit more direct estimation of tree quality and value are not yet 
available for the southern softwoods.

How shall we estimate tree quality in the future?

We have seen that it is difficult to obtain an appropriate relation-
ship for estimating tree quality—particularly if the user must develop 
his own relationships, and there are so few available that he will 
sometimes have no choice. Will we ever have relationships that will 
be applicable to a wide range of conditions in the forests and mills 
and that will, at the same time, give adequate precision and accuracy 
and be efficient for estimates in a local context? There are good 
reasons to doubt that we will.

We must begin now to think about whether we should not, as part 
of our regular inventory procedures, use double sampling and thereby 
develop relationships for estimating volume and quality that we know 
will be applicable to our forest. It will not be wise to wait for gener-
ally applicable relationships only to learn, perhaps, that those we can 
get are not generally applicable, or that those with any broad applica-
bility are extremely complex and inefficient. Why not develop your 
own relationship? You could derive it to satisfy your specific objec-
tives to be of assured applicability to your forest and mill, to be com-
patible with your volume definitions and volume estimators, to suit 
your tastes of complexity or simplicity, and to permit optimum alloca-
tion among various phases of the estimation procedure.

If your environment and objectives are such as to make this un-
feasible, then what may you expect in general relationships? To answer that for the long run would require clairvoyance, but perhaps we can get a useful preview of what is likely to be available within the next ten years.

To review briefly, we recall that there are four major groups of factors or sources of variation in the conversion value of trees. These are: (1) the inherent physical characteristics of the tree which determine the yield and its distribution by quality class of end product; (2) the characteristics of the manufacturing process (production technology) which determine the yield and its distribution by quality class of end product; (3) the characteristics of the market which determine the specifications for quality classes of the end product and the prices per unit of volume by quality classes; (4) the characteristics of the harvesting, production, and manufacturing process which determine the costs of production.

These groups are clearly interrelated, so it is not fruitful to push the categorization too far. However, we can see that a system of quality quantification will have major shortcomings if, somehow, it fails to account for each group. In the past, we have not included costs of production in the general estimating process because they are too variable. Every local situation would have different cost relationships; therefore, this is treated as a separate step to be taken last by each user. We also have either ignored or attempted to average out production technology and factors related to price (categories 2 and 3).

We are beginning to give—and in the future we must give—more attention to these latter sources of variation. (This is not to imply that we will not also probably need indices of quality that are based only on the inherent characteristics of the tree—for long-run forest management planning and evaluation of change in the resource.) Almost all research now being conducted takes some account of price in the development of the relationships—either through quality index or value based on current prices. This is true for the research program of the U. S. Forest Service where such research is continuing in many locations. The effort in hardwood-quality research is directed from Columbus by R. D. Carpenter, but it involves several of the experiment stations. Also, we at Iowa State are cooperating with the Forest Service in research on quantification of tree quality. We expect soon to make available the results of our joint efforts to derive regression-
type estimators of quality index for several species of hardwood trees.

In the western softwood areas, the Forest Service researchers are making the first major efforts to bring production technology into the relationships. They are attempting to use methods of econometrics and operations research to derive grading systems and control systems for optimum log and tree input and product output mixes (Gaines, 1965; Moody, 1963). If these attempts are successful in setting relationships that account for most of the variation, then we may expect rather striking changes in our approaches to measuring tree quality. One of the most likely changes is that the U. S. Forest Service research would provide guides as to what the predictor variables and form of relationship should be but would leave the actual coefficients in these relationships to be derived from production studies conducted at the user's mill. This is certainly a sensible approach for the large western softwood mills, but it is somewhat less attractive for the small mills in the southern hardwoods and softwoods.

Lest we misunderstand, let's think more specifically about the implications of bringing in this production technology. The relationship and procedure would have its simplest form if "average" production technology could be assumed and if changing technology could be ignored. In that case, the researchers would determine the form of relationships from data taken in a sample of "average" mills. The researcher would then be able to tell the user what predictor variables to observe (e.g., log grades, diameter, height, count of knots and defect indicators on butt-log), however, because of variability among users, would leave to the user the development of the actual performance data or coefficients in the relationship for estimating from these predictor variables for a particular locality and particular mill. This would require the forester to conduct mill-yield studies at the site where the relationship is to be used.

If this simple form was inadequate, then the research results would have to include additional predictor variables related to production technology—input mix, kind and efficiency of mill, potential end-product mix, prices. But the user would again need to derive his own estimates of performance and coefficients in the production function.

He would then use this in a larger system of production control, through some form of mathematical programming—linear programming, for example—to control the operation from tree to end product. Using such a system, the forester could estimate not only value for
a fixed input mix but also could estimate value for the joint optimum input (tree, log, bolt) and output (end product) mixes, and could control the process to achieve this. This would provide a production control well beyond anything we now have generally operating, and well beyond the classic viewpoints of the various research specialists and foresters in general. To develop such relationships and systems and apply them so as to make them really work will require teamwork among practicing foresters, economists, management scientists, mensurationists, and forest and wood utilization experts. It is certainly possible that one day we foresters may have this worked out nearly to the point where it now is in the petro-chemical industries. There the production control has reached a nearly unbelievable efficiency.

However, for our forestry context, we might take as a definition of an out-of-control optimist that he is one who thinks that this problem of measuring tree quality and producing the best product mix can all be wrapped up in one big general equation or production model, or even one who thinks that we now have in forestry the average level of technical training to make it go even if we had it. We can learn much by generalizing our models for treating these problems and by deduction from these general abstractions. In this way we undoubtedly will learn a lot about quality estimation in the next few years. Watch for it! But don’t wait for it if you need tree-quality estimates now!

Discussion

Question: Don’t you think that, with the increased mechanization that we are trying here in the South, tree size far outweighs tree quality in most of our pricing situations?

Dr. Ware: You have asked me a question that I cannot comment on very well, because I do not know your local situation quite as well as I should. If the trees have different values for different sizes, then I would have to disagree with you on principle. If, however, the efficiency considerations in production are such that you cannot afford to sort into value classes, or if the market place does not recognize any price differential, then, you see, you will be using my argument to say, “No, you should not.” Because if there is no price differential, then it is an artificial distinction. It is an
artificial distinction, I think, to talk about quality in cases where there is no value distinction. Now I will readily agree that there are cases where a price differential does not exist. There may be other differentials that should be taken into account so that price, for one reason or another, does not really reflect the differences of value between two trees for producing products. If your situation is such that you do not have to recognize quality, or your methods of harvesting and production are such that it is inefficient to keep track of these things, then I would say that you are operating efficiently to use size as your criterion of quality. I don't know the answer to your question in that I don't know your situation well enough.

LITERATURE CITED


KENNETH D. WARE

The association of computers and foresters is only about ten years old, but the effect on forest measurements has been truly revolutionary. Most of our new techniques depend heavily on computers. C.F.I., sampling with partial replacement, dendrometers, and 3-P sampling would all be impractical without some quick and inexpensive means of processing masses of data. Similarly, the new tools of forest management—systems analysis, simulation, linear programming, and dynamic programming—all would be useless without the modern electronic computer.

I do not propose to describe these specific uses of computers in any great detail. I will give a rather general outline of the kind of work to which computers are presently being applied, but I propose to discuss what I believe are promising opportunities for new and more intensive applications with particular attention to some of the difficulties involved.

The present uses of computers can be divided in three broad classes:

1. The compilation of a statistical description of a forest.
2. The prediction of change.
3. The analysis of management alternatives.

Of course, these three classes are not mutually exclusive. In any given application, elements of two or even all three may be involved, but this overlapping will not handicap our discussion. Furthermore, the classes are not exhaustive; there is no mention of the use of computers in research. For the purposes of this paper, I am adopting a rather restricted definition of forest measurements and will be concerned only with data collected for decision-making in the management of a real forest.
The use of computers to compile forest inventory statistics is the oldest and best developed application in forestry. We have now advanced to the point where computers are employed in practically every large inventory, at least to calculate volumes and to compile tables. In other areas of forest inventory, progress has not been so rapid. Two such areas that I would like to discuss are (1) the editing of field records and (2) the retrieval of information for special, unanticipated reports after the completion of the main job of data processing.

It is difficult to overemphasize the importance of careful editing and checking of field records. Errors undetected here can make it necessary to repeat the whole job of data processing. Checking by hand is a slow, tedious, and error-prone procedure, but a large computer is ideally suited for the job. Hundreds of logical checks can be made rapidly and inexpensively on every plot or tree record.

The writing of an editing program makes heavy demands on the time, foresight, and skill of a programmer. Perhaps this is why so few have been written. Fortunately, at least one general purpose editing program is available. It is called, reasonably enough, EDIT, and is a part of a general data processing system developed at the Northeastern Forest Experiment Station by R. W. Wilson and R. C. Peters (1965). The program is not simple to use. A complicated set of control cards must be prepared and some knowledge of programming is required for this job. However, the program is very flexible and can be applied to almost any kind of data. Preparing the control cards takes time but not nearly as much time as writing an editing program from scratch.

The second aspect of data processing that I wish to discuss—the retrieval of information needed for special reports—has not received the attention in forestry that it has in other fields where elaborate and costly electronic systems are being employed to make information available when needed. Flexibility is the keynote of these systems; they are designed to retrieve exactly what is wanted when it is wanted. In forestry, on the other hand, the approach has been the preparation of a huge mass of tables in an attempt to anticipate every possible demand for information. Such a procedure is self-defeating. The mass of reports buries the very information that is supposed to be made available. In addition, the rigid, complex programs employed are unsuitable for the quick reprocessing of data to obtain some simple but needed bit of information.
At one time I regarded the basic plot and tree records from a forest inventory as something to be processed once, in a single pass through a computer, and then packed away in dead storage. It has become increasingly evident that such a philosophy is fundamentally wrong. Information not incorporated in summary tables is frequently needed and should be available without a massive job of reprogramming and reprocessing. A more fruitful approach, and one that is being adopted by Forest Survey, is to regard inventory records as a kind of data bank that can be tapped for special reports by a flexible retrieval program. It is quite likely that such a system will also turn out to be highly efficient for the preparation of standard tables and reports since these "standards" have a way of changing from year to year.

The data processing system developed at the Northeastern Station, which I have mentioned previously, is designed to cope with changing standards and with special reports. Table formats and contents are specified by the user and can be readily changed. However, there are still some problems in producing estimates which involve unforeseen subdivision and breakdowns of the data. These difficulties arise primarily in sophisticated sampling designs such as double sampling, multi-stage sampling, and sampling with partial replacement. The root of the trouble appears to be that these sampling designs were developed for the purpose of estimating a single overall mean or grand total. The theory for dealing with subdivisions of a population is not well developed even when the subdivisions are defined before sampling begins; the difficulties are compounded when unexpected breakdowns are required.

The second of my three broad classes of computer applications, the prediction of change in the forest, probably is as well developed as our current mensurational techniques permit. Most of the programs I am familiar with employ either yield tables or stand-table projection. Both of these methods have shortcomings that are too well-known to warrant discussion here, but, despite these limitations, both can produce reasonably good estimates of growth, at least over short periods of time.

At present most predictions of change appear to be oriented toward future growth and production but the use of computers to update old inventories is receiving increased attention. The amount of field work involved in a large scale inventory makes some form of scheduling in which part of the work is done each year an extremely attractive
proposition. The drawback is that part of the inventory is always out of date but short-term projections can remedy this deficiency.

The near future will, I believe, see systematic and regular updating incorporated as an integral part of most management inventory systems. Such an approach has obvious advantages. The addition of an updating procedure to a data bank tapped by a flexible retrieval program promises to provide the forest manager with current, up-to-date information on the status of his property. Instead of a static mass of dated reports and old field records buried in dead storage, we now can at least visualize a dynamic system that accepts and processes new data, brings old data up to date and produces standard or special reports upon request. We can also visualize a system with the ability to correct its own mistakes; that is, one that will compare updated records with new data and modify future predictions accordingly.

Of course, some problems still remain to be solved; the most serious appears to be the rather mundane task of keeping track of timber cut. Difficulties exist even when reasonably detailed scaling records are available. Lack of precision in our volume estimates combined with variations in utilization make it almost certain that a cord of standing timber will not be a cord when cut and stacked on a truck. This discrepancy is often ignored or its importance minimized but the errors arising here can be larger than those due to sampling variation or biased growth predictions. Another source of difficulty is the near impossibility of allocating cut volumes back to stand components. Scaling records cannot ordinarily be broken down by tree diameter or by other similar descriptors employed in management inventories. Therefore, an updated inventory must suffer some loss of detail when any appreciable amount of cutting has occurred. About all that can be expected to survive is a breakdown of volume by species and compartments. If greater detail is desired, the only solution I know of requires inventories of the affected areas before and possibly after cutting.

My third group of computer applications, the analysis of management alternatives, encompasses a variety of techniques. Terms frequently heard include: linear programming, dynamic programming, and computer simulation. I will discuss only the last of these because I believe that with our present state of knowledge only simulation can cope with the multitude of factors involved in the management of a large forest property. It has been said that a resort to simulation is
a confession of ignorance; if so, I stand ready to be indicted for I can visualize no other course of action.

At present two forest simulators approach operational status. One is the Harvard Forest Simulator, developed by E. M. Gould and W. G. O'Regan (1965); the other is the University of Georgia program, FOPS, prepared by J. L. Clutter and J. H. Bamping (1966). Both employ yield tables and suffer from the weaknesses thereof. Furthermore, both require that stands rather than compartments serve as the basic units for record keeping and the disadvantages here are serious. Boundaries are vague and change with time. Remapping is necessary at frequent intervals and keeping track of the cut by stands is practically impossible.

Unfortunately, however, I have nothing better to suggest. Furthermore, I am convinced that these simulators or others like them will receive intensive use in the near future because they offer at least a partial solution to an important problem. The most elaborate forest inventory, no matter how current or how detailed, can answer only the question, “What is the present condition of the forest?” A reply, while certainly useful, tells us nothing directly about what to do. A simulator, on the other hand, can respond to the more pointed query: “Given the present condition of the forest, what will be the economic consequences of a particular management decision?” If we question many possible decisions, we can approach an answer to the question we would really like to ask: “What should the management practices be on a given forest property?” The process is purely and simply trial and error, but trial and error in a computer is a great deal cheaper than trial and error in the woods.

Discussion

**Question:**

What kind of errors can be detected with the EDIT program?

**Dr. Furnival:**

Any error you specify can be checked, such as check for impossible values, unreasonable values, or something like this.

**Question:**

Just how many variables are we going to have to measure and find the significance of before we can make practical use of computer simulation?
Dr. Furnival: It depends on how good you want the answers to be. I think we have been doing simulations for years on backs of old envelopes—you know, economic analysis, checking the possibility of reasonable alternatives, and this sort of thing.

Question: We have not been using any expensive IBM 360 machines to do this though, so we have to get value returns per cost of the output. How well are we going to have to know our results from the measurable elements of the stand before we can afford to go into it?

Dr. Furnival: That I do not know. I think that if you want to ask questions where the differences can be rather broad, you can use rather crude means; in other words, if you wanted to ask a question whether to grow pulpwood or sawtimber on a certain market, and it comes out clearly that one is highly more valuable than the other, then you can probably trust the answer. On the other hand, if you want to know whether rotation age of thirty-one years is better than twenty-nine years, I think you are going to have to get very precise models.

Question: Do you know of a cure model that will schedule the cutting of $N$ number of units over $R$ rotation period that have an $M$ number of products—not a single product, but a multitude of products—while maximizing cash flow?

Dr. Furnival: No!

Question: Do you know of any that are being developed?

Dr. Furnival: I would prefer to introduce you to Jerry Clutter. Jerry, would you like to answer that question? Are you working on this?

Dr. Jerome Clutter
University of Georgia: We are working on it, but only on single products right now. When you translate the multiple product to the common money I'm not sure it creates any problem. I think several people are working on the rest of it.
LITERATURE CITED


USE AND MISUSE OF
STATISTICS IN FORESTRY

WILLIAM WARREN BARTON
U. S. Forest Service
Upper Darby, Pennsylvania

Unless you are an old, old-timer, at some time in your education you were exposed to the theory and use of statistics. Thirty-five years ago we were not using statistics very much; only a few experts knew how. Today, many of us use statistics in our everyday work. Accordingly, there are many opportunities to use properly and quite a few opportunities to misuse statistics. Misuse is usually unintentional. It is principally due to lack of clear understanding of the underlying principles of statistical theory which show us what statistics can and cannot do.

Today, the libraries are full of textbooks and bulletins which cover statistics from A to Z. Donald Bruce and Francis Schumacher (1935) were among the first to write about the use of statistics in forestry. In 1942, Roy Chapman, who had critically reviewed Forest Mensuration for the authors, and Francis Schumacher published again on the use of statistics in forestry. This was the Duke University School of Forestry Bulletin No. 7. Another early publication with a section on statistics was Timber Cruising by Jim Gerard and S. R. Gevorkiantz (1939). Others, like George Snedecor of Iowa State College wrote complete text books on statistics alone. Many of these complete texts used examples with a biological research background. The first edition of Snedecor's Statistical Methods was printed in 1937. One of the most recent publications dealing with the application of statistics specifically to forestry is Frank Freese's Elementary Forest Sampling 1962. This he calls a cook book, and it is a good one. It was published in 1962 as U. S. D. A. Agricultural Handbook No. 232.

In these books you will find a lot of information on the theory and proper use of statistics and some cautionary notes to help you keep away from pitfalls. Over a period of years, there have been some changes in the symbols used by various writers, but there has been
little change in the basic theory. There have developed some complex uses of these basic theories resulting in some complicated equations and some tricky logic. If you contemplate getting into some of these complexities, such as double sampling, you may want to consult not only the textbooks, but also the statistical experts themselves. Even in complicated applications, once the proper equations have been worked out, you will be all set to get on with your project.

For a moment let us look back at the foundations of the science of statistics. Statistics is based on laws of chance. The occurrence of a certain condition tends to show up in direct relationship to the number of ways in which it can occur. If we arrange ten coins in the 1,024 different ways that it is possible to do, in how many ways can we have all ten heads facing up? There is only one such arrangement. Accordingly, if we tossed the coins many times we would expect according to the laws of chance that the all-heads combination would come up once out of every 1,024 tosses. The probability of all heads coming up is about one in a thousand.

There are 252 combinations of the coins that have five heads and five tails—the average condition. The chance of tossing a five heads—five tails combination is about one in four. Three heads and seven tails should appear at a frequency of about one time in every twenty-three tosses, or forty-five times in 1,024 tosses. If we plot the number of combinations (occurrences) over the number of heads we shall get a picture of a binomial frequency distribution. The binomial frequency distribution was described by Bernoulli in 1712. This is the type of distribution we have when we estimate forest type acreages from a count of grid dots falling within or without a type on aerial photographs, or from the number of sample plots falling in or outside a type in a cruise. Counts of individual samples possessing or not possessing a specific attribute are known as discrete—or non-continuous—variables.

Let us imagine that we increase the number of coins infinitely and the number of tosses infinitely. We would expect to get the same pattern of distribution but the number of points would become so close together that we would have a continuous curve instead of a jointed line. At this infinite limit the binomial curve has become transformed into a normal frequency distribution curve. De Moivre published an equation for this continuous curve in 1737. It begins to look as if statistics were pretty old stuff. As you might surmise, the
normal frequency distribution curve is used with continuous variables—those that result from measurements. Both the binomial and the normal frequency distributions are defined by algebraic equations which involve only individual sample values, the number of samples and constants.

From your experience with stock and stand tables developed from cruise data, you know that there are many shapes of frequency distribution curves. Many skewed distributions have resulted from some drastic disturbance to a more or less normal situation. Some are natural distributions. The arithmetic averages (means) of most of these odd distributions have been observed to follow a normal distribution pattern. This is fortunate because it allows us to use the mathematics of the normal curve to analyze these means as well as those from the truly normal distributions.

These are some of the things we know about the normal frequency distribution curve. It is completely described by the true mean and the standard deviation of this mean. Means calculated from a hundred similar random sample surveys of a particular population would cluster about the true mean so that about 68 percent of them would lie within plus or minus one standard deviation and about 95 percent would lie within plus or minus two standard deviations of the true mean. This leaves a one out of twenty chance (or .05 probability) that the mean from a single random sample survey will fall beyond the limits of plus or minus two standard deviations from the true mean. These limits above and below the mean are called confidence limits and must show the associated probability.

Since in sampling surveys we never know the true mean, we shall state the proposition more truly if we reverse the statement above and conclude that there is the stated probability that the true mean will exceed the distance of the confidence limits from the sample mean which we have used as an estimator of the true mean. The standard deviation of the true mean is also estimated and not actual since it is also derived from sample data. The standard deviation of the mean is usually called the standard error of estimate, or just standard error.

The estimated mean (\(\bar{x}\)) and the estimated standard error (\(s_{\bar{x}}\)) are both quite easily calculated from the individual sample records (X) and the number of samples (n).

The mean:

\[
\bar{x} = \frac{\sum X}{n}
\]
The Standard Error:

\[ s_x = \sqrt{\frac{n\sum X^2 - (\sum X)^2}{n^2(n-1)}} \]

Derived from these two estimated parameters are the coefficient of variation (c), the confidence interval (E), and the confidence limits (CL).

The coefficient of variation squared:

\[ c^2 = \frac{n(s_x)^2}{(\bar{x})^2} \]

The confidence interval:

\[ E_{.05} = \pm 2.0 \ (s_x) \]

The confidence limits:

\[ CL = \bar{x} \pm E_{.05} \]

There are two special conditions which are important. When the number of samples examined (n) make up more than one-twentieth (0.05) of the total number of similar samples (N) that exist in the population, a finite population correction (fpc) is applied to the standard error. The finite population correction is:

\[ fpc = \sqrt{1 - \frac{n}{N}} \]

When there are only a few samples a large error will be introduced if the number of standard errors multiplier we earlier associated with the various probabilities (2.0 for 0.05 probability, for instance) is used to determine the confidence interval (E_{op}). To take care of the small number of samples situation, special multipliers called (Student’s) t factors are used. The distribution of t for various probabilities and degrees of freedom was worked out by W. S. Gosset in 1908. A table showing this distribution is essential when less than thirty samples are used. This table will be found in all major publications on statistics. The applicable t factor is read from the table on the line opposite the number of degrees of freedom in the column for the desired probability. For a simple random survey, the degree of freedom is the number of samples minus one (n—1).

To demonstrate the importance of using this factor for very small numbers of samples, one might study a table of t distribution which
may be found in any standard statistical text. The value of $t$ drops rapidly from 12.7 for one degree of freedom to 2.6 at five degrees of freedom. From this point on, the value of $t$ decreases gradually until at 28 degrees of freedom it reaches and stabilizes at 2.0—the number of standard errors multiplier used for the many sample survey.

There are a great many uses for statistics in forestry. Many of these fall into one or another of the categories: (1) estimating populations, (2) testing the probable truth of an assumption or hypotheses, and (3) looking for significant differences or correlations. Probably the most common example of population estimating is that of cruising timber for volumes to use in forest management planning, resource situation reporting, or forest operations.

Over the past fifty years, cruising has progressed from strip and line-plot to random and square-grid (or equi-spaced) plot systems. Because there is just one sample, it is obvious that the strip cruise cannot be analyzed by statistical procedures. Let us consider the line-plot cruise. This is usually too far away from a random selection of samples to expect statistics to give a dependable measure of the probability of error. The random sample selection is tailor-made for use of statistical analysis.

Cruises made with equally-spaced samples cannot be exactly analyzed by random sample equations, but these equations do give a useful approximation of the limits of error. Because reason says that it should give good coverage of the population, the square grid pattern is much used, and because of this, statisticians are trying to derive equations that will develop true values for its limit of error and associated parameters. When the random sample equations are applied to equi-spaced sample data, standard errors tend to be exaggerated—the estimated mean is probably closer to the true mean than the figures show. Several explorations have indicated that the standard error for equi-spaced sample surveys may be about 80 percent of that calculated by the random equations. From the practical point of view, the equi-spaced sample survey will continue to be tested with random equations until acceptable equations are developed for the design. Before a statistical test is made, it should appear reasonable to make it, and any limitations to be expected in the answers should be recognized.

With strip and line-plot cruising, timber types are frequently 100 percent mapped on the ground. With random and grid-spaced samples, areas within types are frequently determined from counts of
grid-spaced points on aerial photographs. Sometimes the type into which each sample plot falls is used to estimate the proportion of area falling within the type and this proportion used to expand the type acreage for the whole tract. These are binomial frequency distribution problems. Formulae that apply to random counts of attributes are:

Mean (P) (for percent)
\[
P = \frac{\text{number possessing the attribute (n)}}{\text{total number examined (N)}}
\]

Standard error (E%) in percent of P:
\[
E\% = \pm t \sqrt{\frac{1}{n} - \frac{1}{N}}
\]

Coefficient of variation squared (c²) :
\[
c^2 = \frac{1-P}{P}
\]

Number of points (n) to examine for a planned survey:
\[
n = \frac{t^2 c^2}{(E\%)^2}
\]

Where counts are taken of items possessing a certain attribute within a number of samples which may not be of the same size, the proportion of each sample possessing the attribute is usually transformed into a continuous variable so that the data may be analyzed by the normal curve equations. Such transformations are frequently to percent, logarithm, or arcsin of the percent. The arcsin is the angle in degrees and decimals of degrees which has a sine equal to the square root of the percent. After the calculations, the result is transformed back to the original units. Examples of data which might be handled in this way are twig counts in browse surveys or counts of insects infesting cones.

Sometimes we may think certain proportionate conditions exist. To test the hypothesis that there are 55 percent doe (F₁) and 45 percent buck (F₂) in the herd of deer on Black Mountain we take a sample count. Is our count of 52 doe (f₁) and 48 buck (f₂) sufficient evidence to disprove our hypothesis? This is a typical job for chi-square (χ)², invented and described by Karl Pearson in 1899.
Chi-square ($\chi^2$):

$$\chi^2 = \frac{(f_1 - F_1)^2}{F_1} + \frac{(f_2 - F_2)^2}{F_2}$$

$$\chi^2 = \frac{(52 - 55)^2}{55} + \frac{(48 - 45)^2}{45} = .36$$

This calculated chi-square value is compared with values in Karl Pearson's table of chi-square limits for the usual probabilities and degrees of freedom. On page 28 in the fifth edition of Snedecor's *Statistical Methods*, this table shows that for a .05 probability and one degree of freedom (such as we have) a chi-square value up to 3.84 could still be due to chance. Our observation would be that the value .36 is so deeply contained within this limit that our count is not sufficient evidence to disprove our original hypothesis. If we had counted a thousand head with the same proportions resulting, the chi-square would have calculated 3.54. Since this is getting pretty close to the 3.84 borderline we may wish to exercise our own judgment and disbelieve our original hypothesis.

Had we counted ten thousand head, still with the same proportions resulting, the calculated chi-square would be 38.36. This is so far outside the 3.84 limit that there would be little doubt that our original hypothesis was incorrect and that a better estimate would be obtained from the test count.

Chi-square has some application in forestry, but not nearly as much as the more familiar statistical analyses. Its use should be confined to the situations it fits, principally that of testing hypotheses. A somewhat similar, and highly useful, test of the significance of a difference is the paired t test. It is useful for testing the effect of treatments where one situation is treated and another is kept as a check. The test may be accomplished in two ways with the result the same.

Two sets of data, the treatment and the check for instance, are paired either at random or by selection and their differences calculated. For the differences, the mean ($\bar{d}$), and the standard error ($s_d$) are calculated in the usual way. To test the result, "$t$" for the probability desired and the degrees of freedom in the data may be applied to the standard error to obtain the confidence limits. If there is no difference
in the treatment and check, the mean of differences will be zero; therefore if the confidence limits include zero, it is concluded that there is no significant difference resulting from the treatment.

Another way to test the result is to put the values into the formula:

\[ t = \frac{d}{s_d} \]

and then to scan the position of this calculated "t" in the distribution table for (Student's) "t" on the line for the number of degrees of freedom involved. If the calculated "t" is larger than "t" shown for the probability chosen for reference, the result is not significant. Results by either method of testing are identical. Should the test show that there is a real difference, it is said that there is a difference significant at the stated probability level. Frequently the probable level used is .01, which is the 99 to 1 chance that there is a real difference.

The test for linear correlation also involves paired data. Before such a test is made it should be ascertained that there is a logical reason to believe there is some degree of correlation between values assumed by the two variables. The estimated coefficient of linear correlation (r) is easily calculated from the variances of the two variables X and Y, the covariance of XY, and the number of record pairs (n).

**Variance of X, \( (s_x^2) \):**

\[ s_x^2 = \frac{n (\sum X^2) - (\sum X)^2}{n(n-1)} \]

**Variance of Y, \( (s_y^2) \):**

\[ s_y^2 = \frac{n (\sum Y^2) - (\sum Y)^2}{n(n-1)} \]

**Covariance of XY, \( (s_{XY}) \):**

\[ s_{XY} = \frac{n (\sum XY) - (\sum X)(\sum Y)}{n(n-1)} \]

The estimated coefficient of correlation (r);

\[ r = \frac{s_{XY}}{\sqrt{(s_x^2)(s_y^2)}} \]
The value of r varies from 0—indicating no linear correlation—to ±1—indicating close linear correlation. The chief abuse of this statistic is to calculate a meaningless relationship between two variables which have no real relationship to one another. This is sometimes called nonsense correlation.

Some of the general types of work which can be done better with the aid of statistics are: cruising (all kinds); testing results of experiments; estimating number and quality of seedlings in seedbeds; germination counts for seed; survival of trees in plantations; timber sales; pest detection surveys. To these can be added many jobs that can not even be done without statistics. These are the jobs where 100 percent testing would be completely destructive, where the amount of work would otherwise be prohibitive, where there would not be time to do the work without using a sampling technique, and where the job must be kept within a stated cost.

As I pointed out in the beginning, there are also some ways to misuse statistics and that misuse, usually unintentional, is principally due to lack of understanding. It is a misuse to choose the wrong statistical method for a particular situation, but this may sometimes be recognized and corrected after the sample data has been gathered. The most common and, very serious, misuse of statistics occurs in connection with securing the sample data—this misuse is expecting statistical calculations to compensate for inaccurate sample data. With statistics, as with any computer program, it is garbage in—garbage out.

There are three words which concern the value of the results of a sampling survey. These are precision, bias, and accuracy. Statistical formulae can examine only the precision attained in sampling—how close the samples fed into the system group around the estimated mean. This is sometimes called the error due to sampling.

Statistical formulae can never correct for unknown bias or slipshod work. Both of these destroy the accuracy—the true value—of the samples. Bias is a systematic, non-compensating error. It may be introduced by improper weighting of samples in a complex survey, by using volume tables that do not fit, by improper use of an instrument so that the reading is consistently too large, or by using tools that are improperly adjusted. Bias is also introduced by such personal habits as a tendency to overestimate heights, or to take diameter breast-high measurements consistently too low.
To achieve a high level of accuracy, it is necessary to plan, train and supervise the work done in any sampling survey. First, you must define your objective in full detail. From this you will be able to determine what will constitute a sample and how it will be selected. Both the constitution and selection of the sample must be fully specified. For efficiency and better workmanship you should avoid gathering any information not needed to fulfill your objective. All of these things should be carefully written out in a detailed manual of instructions.

Training in locating and in collecting data on satisfactory crew proficiency should precede collection of the data to be used. Supervision of the work should be immediate and at the field level. Laxness in supervision allows measurement bias to develop and editable errors to creep into the work. Editable errors are those that can be detected, but must be corrected, before calculations can proceed. On page 77 in *Elementary Forest Sampling*, Frank Freese puts it this way: “The greatest single stumbling block is the common failure of supervisors to continue training and checking field crews or to provide for editing of field forms.”

There are several other kinds of abuses of statistics that I would like to mention briefly. Not all factual information requires a statistical analysis to support its findings. Once in a while something is so obviously true that statistical defense is superfluous. The converse is also true; occasionally the statistical data available is obviously too weak to justify its use in support of an observation. There are good articles on important ideas and observations which do not lend themselves to statistical explanation, at least at the moment of discovery. There are instances where an author feels that his work is being suppressed by an apparent publication editorial policy requiring all articles to be supported by statistical analyses. Most of the time this may be a figment of an author’s imagination, yet there may be some real cases. The individuals who set the editorial policies may sometimes have just recently awakened to statistics and put more store in it than makes good sense. Suppressing an otherwise good article just because it is not accompanied by statistical calculations would amount to an abuse of statistics.

Sometimes I wonder why it is still necessary to print with an article the whole run of calculations leading up to the confidence limits involved. I feel it would be sufficient to print the confidence
limits; I shall assume that the work has been done correctly and has been checked as necessary. Is it not an abuse of statistics to waste printing space for unnecessarily detailed calculations of standard processes? Sometimes such a practice detracts so much attention from the real conclusions that the paper seems mostly to try to overawe the reader with its mathematics. I am sure there is a tendency for some foresters to skip reading some excellent articles just because they are associated with lengthy statistical calculations.

The results of the statistical analysis of data should be intelligently interpreted. It should be remembered that all statistical parameters are estimates; that their errors are not real, just probable. A confidence interval of ±12 percent does not mean there is a real error of this amount, just a possible one of this magnitude at the outside edge of the probability chosen. The chances are much greater that the estimated mean is very close to the true mean than that it approaches the outer limit of the confidence interval. A second survey, redesigned to change a confidence limit of ±12 percent to ±6 percent would require four times the work, yet might yield an estimate with a real (but still unknown) error greater than the first survey. You may have run into this problem with a supervisor who did not understand statistics. Trying to make statistics into more than it really is, is a type of abuse. Statistics is a tool to provide its masters with decision-supporting information. It should not be allowed automatically to dictate a decision on its own.

There are many jobs in forestry where efficiency can be improved or optimized by statistics. Anytime sampling can save time or money, avoid destruction in testing, or bolster confidence in results of experiments, there is probably a way to do it efficiently with statistics. If the situation is complex, seek help from an expert. Plan every detail of every step; write complete instructions meticulously as though you had to program a robot to do the work; and carefully train and supervise all personnel all along the line. Then you need not worry about abusing statistics. Make it work for you every chance you get.

LITERATURE CITED

Since the general theme of the 1966 symposium is "Measuring the Southern Forest," I expect many of the other participants to describe new methods, and a few of them to mention new tools. I hope they do, because it is difficult to find much that is really new in forest mensuration. However, before preparing my contribution, I tried to identify some new things that would not be better covered by other speakers.

To find these things, I conducted an informal mail survey of selected foresters in the South, describing my subject and asking for suggestions about a few important new tools and methods in mensuration. This was a most successful survey. I received an 83-percent response and, without too much finagling with the results, found that each of the same three categories was mentioned by 80 percent of the respondents. Each of another three categories received 20 percent of the votes.

The three important categories of new tools and methods in forest mensuration were: (1) instruments for measuring upper stems of standing trees; (2) three-P sampling or other statistically designed cruising methods; (3) use of digital computers or automatic data processing.

These three categories may overlap what other speakers are covering. However, the list of topics showed that no one else was assigned instruments as a specific subject. I checked with Al Bickford to see what he planned to say about "Sampling Methods," and with George Furnival to see what he was going to cover under "Computer Applications." Neither of them had in mind the same aspects of these subject that I want to describe, so I was quite happy with the outcome of my survey.
Most of these instruments can measure upper stem diameters from a distance. This suggests a strong concern with the measurement of trees before they are scheduled for felling. This, in turn, implies a recognized need for better presale volume or value estimates, improved inventories of stands not scheduled for early felling, or for repeated measurements of trees or stands from which accurate estimates of growth can be made.

The capabilities of the instruments vary. Unfortunately, and almost predictably, the most accurate is the most expensive. However, I feel that the expressed need for such instruments will eventually lead to the development of new devices. These won’t be as expensive as the highest cost ones today—but don’t expect to buy a good one in a dime store.

These instruments measure in the field the actual dimensions of all parts of each sample stem. This allows direct estimates of volume in each of several value or product classes. These direct estimates avoid the bias of volume tables prepared by measurement of trees that are often not representative of the stand being measured. Furthermore, volume tables seldom permit breakdown into value or product class.

The most accurate instrument for measuring upper stems that I have used is the Barr & Stroud rangefinder dendrometer. Last fall, five of us at the Pacific Northwest Experiment Station tested its accuracy. For eight trees 15 to 26 inches in diameter, at distances of 66 to 144 feet, the average coefficient of variation (CV) of diameter was 0.88 percent. A single instrument setup was used for each tree and a small tag was put on the front of the tree to indicate point of measurement. Each observer measured each tree twice. The CV includes observer, repetition, and tree interactions with these. On the same trees, the CV of extremely careful caliper measurements, taken in the same direction as the dendrometer readings, was 0.42 percent. The difference between the means of eighty dendrometer measurements and forty caliper measurements was 0.07 inch. The CV of basal area for the dendrometer, including difference between instruments, was 2.5 percent. Grosenbaugh (1963) reported 3.9 percent CV of basal area measurement on some pines at Crossett, but he included aspect as a variable, which would increase variation somewhat.

In our test, we got a CV of 0.90 percent for slope distance measure-
ments against 0.18 percent for steel tape. The CV for dendrometer height determinations was 1.16 percent. This was not compared with other height measurements; however, this CV and that for basal area suggest that volume will be predicted within the 4 percent found by Grosenbaugh at Crossett.

In another test last summer, using the dendrometer in an eighty-year-old Douglas-fir, permanent sample plot, we measured seventeen trees. Excluding one tree with a broken top, we found that our standard volume table was overestimating the volume of small trees by 12 percent and underestimating the volume of big trees by 10 percent. (Tree diameters were from 11 inches to 24 inches.) For the tree with a broken top, direct measurement was much easier than using the volume table. This volume would be the total for a tree whose height included the fifty-foot (more or less) missing tip, with a deduction for the tip volume based on this guessed length and the estimated diameter at the break (13 inches).

A comparison of dendrometer-measured gross volumes of over a hundred trees with those based on the local volume tables actually used in one Oregon timber sales appraisal showed an overestimate of 9 percent for the volume tables.

These few examples are cited to indicate the gains in accuracy that may be expected when upper stems are measured. Instruments other than the Barr & Stroud dendrometer, mentioned by my respondents and others, include Wheeler’s optical calipers, McClure’s mirror caliper, Bitterlich’s Spiegel-Relascope, and the Zeiss Teletop. I probably should add a couple: mil-scale binoculars and the Liljenstrom dendrometer. Some of these instruments aren’t exactly new.

I do not have data from comparable tests showing the relative accuracy of all these different instruments. These tests are not necessary to rank them in probable order of relative accuracy, since their operating principles can be used for this purpose.

For two reasons, instruments that displace the image of one side of a tree so that it can be aligned with the other side will be more accurate than those that require alignment of two reference marks with the two sides of the tree. The first reason is that there are only two lines to bring into coincidence instead of four. The second advantage for displaced images is that slight movement of the instrument, or the tree, will not interfere with alignment.

An instrument that adjusts the displaced image so that amount
of adjustment can be read after the two images are brought into coincidence will be more accurate than one which needs to be read while the two sides of the tree are aligned.

Magnification will improve accuracy of alignment. However, the wrong telescope might do as much harm as good. Some defects that could be introduced through poor optical design are: too small a field of view, reduced illumination of image, and too small an exit pupil for optimum resolution of the image.

A telescopic instrument has an advantage other than magnification, if it is desired to use an internal scale to measure relative width of a tree—the reference marks and image of the tree are both in the focal plane of the eye lens. This does away with the nearly impossible job of clearly seeing a tree at a distance and reference marks close to the eye. Such a telescopic instrument must be mounted on a staff or tripod to eliminate instrument movement, but even so, movement of the tree by wind will reduce accuracy.

How then, would I rank these other instruments in order of probable accuracy? There are two parts to this: repeatability of measurements (or precision) and lack of bias. Precise instruments are not necessarily accurate because they may be biased.

First in rank would be Wheeler's telescopic optical calipers, which about equal the Barr & Stroud dendrometer in overall accuracy. First models of the telescopic calipers lacked a sharp separation of the two images. Despite this problem, repeated readings on the same point on a tree by different observers fell in a narrow range.

The Zeiss Teletop should be equally accurate for trees under 12 inches and not quite so accurate for trees 12 inches to 24 inches since two separate readings are required.

Wheeler's simple penta-prism calipers, which have been in use in the South for about three years, would probably rank next. The use of penta prisms practically eliminates bias. These calipers probably would be better than mil-scale binoculars for swaying upper stems but not so accurate for form class determinations, provided a tripod was used with the binoculars and a reticle with a suitable scale was substituted for the mil-scale.

I have not examined a Liljenstrom dendrometer, but I suppose it would be about as accurate as a modified binocular. These last two instruments require careful calibration and accurate determination of slope distance to eliminate bias.
McClure’s mirror caliper should be a trifle less accurate than the prism calipers because the reading is made while the two sides of the tree are lined up and, also, any deviation from parallelism of the mirrors will introduce bias. The Spiegel-Relascope would rank next because it requires four-way alignment and accurate distance determinations.

These accuracy ratings do not necessarily rank the instruments in order of utility for practical field measurement. Further, the differences in accuracy may be relatively small. A test, similar to the one we made of the rangefinder dendrometer, would probably find a CV of diameter measurement of about 2 percent or a little more for the Spiegel-Relascope—although a recent article in Malayan Forester (Brunig, 1964) suggests a CV closer to 1 percent. However, the Spiegel-Relascope has the advantage of automatic slope correction and can also be used as a clinometer. These features make it a very useful field instrument.

I would expect CV’s of 0.75 to 2.5 percent for most of these instruments in determining diameters. Some would have to be used at fairly short distances to stay in this range. Because of stem irregularities, telescopic instruments are not likely to demonstrate much greater accuracy than 0.75 percent, unless measurements are made on telephone poles or repeated measurements are made by people with exceptionally good memories. The easiest trees to measure accurately are probably those with smooth bark, and possibly the hardest are trees with large plates of bark. With Douglas-fir, plates of bark six to twelve inches long can stand out on the silhouette one-quarter to one-half inch. If the approximate level of measurement is at the top or bottom of one of these plates, large discrepancies in successive readings can occur.

Diameter measurement is only one part of upper stem measurement. The only new gadget for height measurement, mentioned by my respondents, was the fiber glass extension pole. I think this is significant, because I have yet to find a really good clinometer. Something like the Suunto, with a drum at least twice the size, a well-illuminated, easily read scale, and a better sighting arrangement should not be too expensive and would be an improvement over what is now available. The World War II Navy Position Angle Finder was such an instrument, but apparently is no longer manufactured.

Brendemuehl and Baker, 1965, of the Southern Station, recently
described a sectional aluminum pole which they claimed was more convenient than the telescoping fiber glass pole. I can think of several advantages which were not mentioned. After we used the fiber glass pole in the rain, it took about a week to dry the inside of it. Also, in the rain, one of the top sections occasionally unlocked while the pole was being extended vertically—if not noticed, this could cause errors.

Three-P Sampling

All I want to say about sampling methods is to report briefly on the gain in accuracy found in one test of three-P sampling (Grosenbaugh, 1964), plus dendrometer measurements, in the Northwest (Johnson, et al.). "Three-P" means probability proportional to prediction, so three-P is a form of variable probability sampling. It is used in sales appraisals where an ocular estimate (prediction) can be made of each tree, not in inventories where only a small fraction of the population is examined. It is most efficient when the prediction is actually proportional to the variable of interest, whether the latter be dollars of stumpage or volume of wood. In effect, it is a kind of nearly continuous stratification, where each level of prediction is a stratum. The number of units in the sample and error of estimate can be estimated fairly closely, but number in the sample cannot be specified exactly in advance. Since the outcome of samplings can be a useful guide to design of other similar sampling, results of this Northwest trial may be useful to some of you.

In a presale cruise of 1-1/2 million board feet of old-growth ponderosa pine, three-P sampling had a standard error of estimate of 4 percent against 9 percent for a standard one-in-twenty tree cruise. This is not a real measure of relative accuracy, since the standard errors measure different kinds of variation. The three-P error is based on the variation of the ratio of actual volume measured by the dendrometer to a local volume table estimate based on measured diameter. This diameter measurement was substituted for volume estimates to get more uniformity than we could expect from ocular estimates of two markers. Thus, three-P error measures the deviation of measured from estimated volume and gives limits within which total volume would be expected to fall if all trees were measured.

In the one-in-twenty cruise, the 9-percent error of estimate is based on the variation of estimated volumes within the sample. These
estimates were based on taped diameters, ocularly estimated number of logs, an average form class, and a volume table. The error of estimate includes no allowance for possible systematic bias in height or form class estimates, no consideration of possible differences in average upper-stem form of trees in the volume table and those on the sale area, and no measure of the variation in volume of the trees on which the volume table was based. Thus, the error of the standard cruise will give an estimate of the limits within which total volume would fall, if all trees had been estimated the same as sample trees.

One other difference between the two samplings was that there were thirty-six three-P sample trees and eighty-eight in the standard cruise. Of course, it took longer to measure the thirty-six trees than to tape diameters and eyeball heights on the eighty-eight trees. However, it would have required 336 trees by the standard cruise method to get an error of estimate as low as that for three-P.

Three-P gross volume estimate was 1,498,000 board feet and standard cruise estimate was 1,860,000 board feet. Gross scale for the sale was 1,508,000 board feet. Of course, scaling is not an accurate means of estimating volume; but its close correspondence to results of dendrometer measurements is encouraging and suggests doing away with the high cost of scaling.

Use of Digital Computers

The computer capability most familiar to research foresters is multiple regression analysis. It used to take many hours to fit by least squares a multiple regression involving four or more variables. Machine programs are available that will screen thirty or forty variables in stepwise or controlled deletion programs to find one or more combinations of the few independent variables that account for most of the variation in the dependent variable. Since few people measure this many variables, the thirty to forty or fewer usually consist of transformations or combinations of measured variables that seem likely to be better related than untransformed measurements. These programs have been used in soil-site studies, in growth studies, and in other studies to identify transformations of measured variables in a sample with highest coefficient of determination and, hence, with good promise of being the most useful predictors.

A similar computer capability is the production of kinds of multi-
variate analyses used in econometric and sociological studies. An early application in forestry was discriminant function analysis. However, more and more of these techniques are being applied to forestry data.

The usual least squares methods of fitting equations cannot be used for some of the more flexible growth curves. These require repeated fitting of equations with nonlinear coefficients which can be done quickly on a computer. The simple growth curves that can be fitted by usual least squares methods may have high coefficients of determination but may have no logical interpretation in terms of how trees really grow.

Some mensurationists are old-fashioned enough to want to see their data plotted. This is painless if you use an X-Y plotter. In fact, it’s more accurate than hand plotting, and one can plot the dependent variable against all the independent variables, or plot the residuals against the variables in an equation or other variables. These plots quickly reveal correlation of residuals with independent variables and the possible need for weighting. They also can suggest untried functions of independent variables that will fit better than those already tried.

Computers with large memories can digest stem maps with trees located by X-Y coordinates and identified by variables of interest, such as diameter, height, volume, crown size, and growth rate. Such maps can be used in a number of different types of studies. These can be used to study the errors of systematic and other sampling designs, to model stand growth and development, to study effects of clumping and density on growth, and to study alternative intermediate cutting systems.

Tree growth can be simulated in other ways than by this stem mapping procedure. For example, a stand can be broken down into groups of trees that are expected to die or to be removed in intermediate cuts at different stages in stand history. Rules governing progressive changes in competition and growth rates among groups can be developed empirically or theoretically. This model can then be used to predict probable stand growth and yield. Tests against actual stand remeasurements will demonstrate validity of the model.

Detailed tree measurement data from stands representative of sites and management practices on a large area can be placed on punch cards or on magnetic tape. These become a universal volume table.
Whenever a question arises about the potential yield of the property for any product mix, a set of cutting rules can be drawn up specifying which parts of which size trees will go into each product. The stem measurement data are then used to get yields for trees of varying size and these, in turn, are applied to stand tables for the various sites and ages involved.

A new procedure for consistent volume table compilation is feasible. Equations describing average stem profiles and the changes in stem profile related to d.b.h., total height, crown height, and, possibly, other factors can be fitted to tree measurement data. These equations can be integrated between appropriate limits to get cubic volume to any desired top diameter, including or excluding the stump. These equations can also be used to produce taper tables showing for selected tree heights and diameters the d.i.b at intervals of two feet plus a fraction of trim allowance above stump. Board-foot volume tables can be prepared by giving the machine scaling rules and board-foot equations or tables to apply to these taper tables.

This brief review far from exhausts the ways electronic computers can help in forest mensuration. However, I may have exhausted the patience of those readers not already introduced to analysis methods and computing techniques. Nevertheless, I would like to mention some current general changes in mensuration due to the use of computers.

I think this facility in computing encourages foresters to measure more variables in their site, growth, or other studies. Also, I believe there are more attempts to quantify factors formerly described in qualitative terms. A further quite evident trend is found in field forms, which are now designed for ease of transcription to punch card or tape. Also, there are systems for recording data on cards or tape in the field, most of which will require improvement in means of field editing to detect erroneous records before they become generally useful.

I believe there is a continuing change in regression analysis, from the use of functions that fit batches of data to a search for functions that have biological meaning. Finally, I expect to see more and more different analysis techniques borrowed from econometrics, engineering, and the social sciences.

This look at what is new in tools and methods in forest measurement suggests that we are a long way from having the instruments we need. However, trials and tests of the few new ones demonstrate
both the gains that can be expected when better instruments are available and the need for development of such instruments.

Electronic computers have opened new opportunities for mensuration and silviculture studies which will eventually produce explanations of the complicated processes controlling growth and yield in the forest. The practical outcome of all this will be the ability to forecast with greater certainty the yield of managed forests and to evaluate more precisely the economic feasibility of proposed cultural treatments.

LITERATURE CITED


AERIAL PHOTOS—TOOLS
FOR FOREST MEASUREMENT

T. EUGENE AVERY
School of Forestry
University of Georgia

Forest Photo Interpretation

How photographs can help

With a minimum of training, the forester can use aerial photographs to locate inventory plots and property boundaries, determine bearings and distances, identify classes of vegetation, and compile timber type maps. Additional experience will enable him to improve the efficiency of forest inventories by distributing field samples on the basis of photo stratifications. On certain occasions, the forester may be able to estimate timber volumes directly from aerial photographs. In brief, the principal uses for which aerial photographs are currently adapted are (1) to identify or classify trees and stands, (2) to count trees and other objects, and (3) to measure or assess forests and range vegetation.

The first part of this discussion is comprised of a brief review of these techniques; in part II, future possibilities in "infrared sensing" of forest areas are explored.

Tree identifications

The degree to which forest types and tree species can be recognized depends on the quality, scale, and season of photography, the type of film used, and the interpreter's background and ability. The shape, texture, and tone of tree crowns as seen on vertical photographs may be influenced by stand age or topographic site. Furthermore, such images may be distorted by time of day, sun angle, atmospheric haze, clouds, or inconsistent processing of negatives and prints. In spite of insistence on rigid specifications, it is often impossible to
obtain uniform imagery of extensive timber holdings. Nevertheless, experienced interpreters can reliably distinguish types in diverse forest regions when photographic flights are carefully planned to minimize the foregoing limitations.

When available, a generalized forest cover map provides the first step in the identification process, i.e., the elimination of those cover types not likely to occur in a given locality. The second step is to establish which types may logically be encountered. Here, a general knowledge of forest ecology is helpful, and field experience in the specific area to be mapped is even more valuable. Recognition of an individual species, often feasible only on large-scale photography, is normally the culmination of intensive study. It is obvious that the forest interpreter must be familiar with branching patterns and crown shapes of all important species in his particular region. Mature conifers in sparsely stocked stands can often be recognized by the configuration of their crowns or from shadows that fall in open areas of the stand.

Aside from shadows, crown shapes, and branching patterns, the chief diagnostic features to be considered in recognizing tree species are photographic texture (smoothness or coarseness of images), tonal contrast, relative sizes of tree images at a given photo scale, and topographic location or site. Most of these characteristics constitute rather weak clues when observed singly, but together they may comprise the final link in the chain of identification by elimination.

Vegetation keys

A photo interpretation key may be defined as an aid for identifying and judging the significance of objects from the study of their photographic images. Most vegetation keys may be conveniently classed as being of the selective or elimination type. Selective keys are made up principally of stereograms, illustrations, and diagrams showing the typical appearance of the object or condition to be identified. Maps showing distribution of vegetation types are also frequently included. Illustrations may be supplemented by descriptions of species characteristics such as photographic tone, texture, crown shapes, tree branching habits, shadow patterns, topographic site, and geographic location.

All of the foregoing features may not be distinguishable on a given photograph, of course. Morphological characteristics such as crown
shape and branching habit are primary recognition features on very large-scale photos. On medium-and small-scale photos, tone and texture become more important in identifying forest types. In using an elimination or dichotomous type of key, objects are identified through successive selections of alternatives until the final identifying characteristic is reached. While some authorities prefer elimination keys to the selective type, actual tests of their effectiveness indicate that there is no real advantage of one over the other. The choice of type of key and method or organization to be used ordinarily depends on (1) the number of objects or conditions to be recognized, and (2) the variability normally encountered within each classification.

Object counts

For certain photo interpretation activities, the ability to distinguish and count individual objects is of prime importance. In evaluating the survival of forest plantations or in estimating timber volumes, counts of individual trees may be required. Similar tallies are often needed for assessing trees damaged or killed by forest fires, insects, or diseases. As a rule, widely dispersed trees having some degree of uniformity (orchards and plantations) are more easily counted than those characterized by "clumping" as in natural stands. The principal factors affecting counting accuracy are: (1) actual size and shape of objects; (2) scale and resolution of photography; (3) spatial arrangements of objects; (4) tonal contrast between objects and associated backgrounds; (5) type of film (e.g., infrared or camouflage-detection); (6) use of stereo-pairs versus single prints for making counts.

Where large numbers of objects are closely spaced, counts are commonly made on sample plots of predetermined size. Tallies are expanded on the basis of the total area involved. For example, counts made on several one-acre plots randomly located in a woodland area might indicate an average of fifty trees per acre. If the woodland area is 160 acres, the estimated total number of standing trees is 50 x 160 or 800. Actually, the difficulty of separating such items as individual tree crowns may result in unreliable counts, even on small sample plots. In such instances, measures of crown density or crown closure percent may be substituted for stem counts.

Crown closure percent, also referred to as crown density, is the proportion of the forest canopy occupied by the trees. The term may refer to all crowns in the stand regardless of canopy level or only to
the dominants. Estimates are purely ocular, and stands are commonly grouped into 10-percent density classes. Evaluation of crown closure is much more subjective than the determination of tree height or crown diameter. Actual measurement is virtually impossible on small-scale photographs, and accuracy is thus largely dependent on the interpreter’s judgment. Crown closure is useful because of its relation to stand volume per acre. It is applied in lieu of basal area or number of trees per acre, because these variables cannot often be determined directly from available photography.

**Individual tree volumes**

Ordinary tree volume tables can be easily converted to aerial volume tables when correlations can be established between tree crown diameters and stem diameters. In applying this technique, photo determinations of crown diameter and total tree height are merely substituted for the usual field measures of stem diameter (d.b.h.) and merchantable height, respectively. Photographic measurements are usually limited to well-defined, open-grown trees, and crown counts are required to obtain total volume for a given stand of timber.

Tree crowns are rarely circular, but, because individual limbs are often invisible on aerial photos, they usually appear roughly circular or elliptical. As only the portions visible from above can be evaluated, photo measures of crown diameter are often lower than ground checks of the same trees. Nevertheless, most interpreters can determine average crown diameter with reasonable precision if they take several readings and avoid bias in measurement.

In making an aerial cruise, photo measurements may include all trees on 0.2-to 1-acre circular plots, or stands may be delineated according to height classes for determination of the average tree per unit area. In the latter instance, a tree count must be made for obtaining the total stand volume. As a rule, the individual-tree approach to aerial cruising is of limited value unless large-scale photographs are available. When scales are smaller than 1:12,000 (1,000 feet per inch) images are usually too small to permit accurate assessment of individual trees.

**Aerial stand volume tables**

If recent photographs and reliable aerial stand-volume tables can be obtained, average stand volume per acre can be estimated with
a minimum of field work. Estimates are made in terms of gross volume, as amount of cull or defect cannot be adequately evaluated. Even-aged stands of simple species structure are best suited for this type of estimating, especially if gross and net volumes are essentially identical. All-aged stands of mixed hardwoods are more difficult to assess, but satisfactory results can be obtained where field checks are made to adjust the photo estimate of stand volume per acre and to determine allowance for defect. Though photo volumes cannot be expressed by species and diameter classes, total gross volumes for areas as small as forty acres can be estimated within 10 to 15 percent of volumes derived from conventional ground cruises.

Most aerial stand-volume tables for mixed species are constructed in terms of cubic feet per acre. Tables for species occurring naturally in pure stands, such as longleaf pine, may be expressed either in board feet or cubic feet per acre. Three photographic measurements of the dominant stand are generally required for entering an aerial stand volume table: average total height, crown diameter, and crown closure percent. With some tables, crown diameter may be eliminated as a variable, and only measurements of stand height and crown closure required. Stand-volume tables have been published for several important timber types in the United States and Canada.

Stand volume estimates

One of several procedures for making aerial volume estimates is as follows:

1. Outline tract boundaries on the photographs, utilizing the effective area of every other print in each flight line. This assures stereoscopic coverage of the area on a minimum number of photographs and avoids duplication of measurements by the interpreter.

2. Delineate important forest types. Except where type lines define stands of relatively uniform stocking and total height, they should be further broken down into homogeneous units so that measures of height, density, and crown diameter will apply to the entire unit. Generally, it is unnecessary to recognize stands smaller than five to ten acres.

3. Determine the acreage of each condition class with dot grids. This determination can sometimes be made on contact prints.
4. By stereoscopic examination, measure the variables for entering the aerial stand volume table. From the table, obtain the average volume per acre for each condition class.

5. Multiply gross volumes per acre from the table by condition class areas to determine gross volumes of each stand.

6. Add class volumes for the total gross volume on the tract.

Adjusting photo volumes by field checks

When aerial volume tables are not sufficiently reliable for pure photo estimates and allowance must be made for defective trees, some of the plots interpreted should be selected for field measurement. For example, if 350 plots were interpreted and every tenth plot selected, thirty-five plots would be visited in the field. If the field volumes averaged 600 cubic feet per acre as opposed to 800 cubic feet per acre for the photo plots, the adjustment ratio would be $600 \div 800$ or 0.75. If the thirty-five field plots are representative of the total, the ratio can be applied to the average photo volume per acre to determine the adjusted volume. It is desirable to compute ratios by forest types, because hardwoods are likely to require larger adjustments than conifers.

The accuracy of aerial cruises depends not only upon the volume tables but on the availability of recent photographs and the interpreter’s ability to make photo measurements correctly. This last item may be the greatest single source of error. It is advisable to measure each photo variable twice for an average, or to have two interpreters assess each plot.

Remote Sensing of Forest Areas

What is remote sensing?
The detection and recognition of objects by means of a distant sensing device is referred to as remote sensing. An astronomical telescope, an aerial camera in a supersonic jet aircraft, and a sonar installation in a submarine are all forms of remote sensors. The nocturnal bat employs a remote sensing technique to guide its flight in darkness; a similar principle is embodied in radar equipment. Recent types of remote sensors include the various earth-orbiting satellites—the TIROS or Television Infra-Red Orbiting Satellite—that are rapidly becoming commonplace.
Because new and sophisticated techniques in remote sensing have a high strategic value, military and defense agencies have been largely responsible for their development and operational use. As a result, many aspects of remote sensing—and the images produced therefrom—have been screened from civilian scrutiny by security classifications. Some of these security regulations have become more relaxed during the past year or two, and foresters have begun to take special interest in a relatively new technique known as infrared sensing. In simple terms, this refers to the detection of remote objects by recording the amount of infrared energy (heat radiation) emitted from various surfaces.

The nature of infrared radiation

Infrared radiation is electromagnetic radiation having wavelengths between 0.7 and 1,000 microns [a micron is equal to one-millionth of a meter]. By contrast, the visible portion of the electromagnetic spectrum falls within the relatively narrow limits of 0.4 to 0.7 microns. Ordinary panchromatic black-and-white film has a light sensitivity approximating the range of the visible spectrum; thus the tones in which objects register on such film are determined by the amount of visible light reflected from different surfaces. The common infrared photography familiar to many foresters utilizes a portion of the visible spectrum and some of the shorter wavelengths in the infrared region (approximately 0.7 to 1.0 micron). The tonal contrasts produced on this type of film are thus derived from a combination of visible light reflectance and absorption (or reflectance) of infrared radiation; hence the sharp tonal differences between broad-leaved and coniferous trees.

Although the shorter infrared wavelengths can be recorded by conventional photography, highly specialized sensing devices are required for registration of infrared wavelengths longer than 1.0 micron. An infrared sensor is a scanning device that functions somewhat like a television receiver by producing a near-continuous image from a series of line scans. The key component of the scanning device, a “detector,” senses the incoming infrared radiation and converts changes in the radiation into an electrical signal. This signal is electronically amplified and then converted to a visible image by a device known as a “glow tube.” The image can subsequently be focused and recorded on photographic film.
Infrared images bear strong resemblances to conventional photographs, but they have inherent geometric distortions due to the nature of line scanning. Because the scale along the line of flight may differ appreciably from that across the flight path, accurate measurements of images are not usually feasible. Thus infrared images are more suitable for making identifications than for purely mensurational uses, and they should be regarded as supplements to, rather than replacements for, conventional aerial photographs.

Emission of infrared energy
Operational use of infrared sensors is necessarily based on a sensor's capability to distinguish between different objects, surfaces, or backgrounds. This requires, in turn, that objects must exhibit some differences in the magnitude or distribution of emitted infrared energy. Infrared energy is emitted by any material substance having a temperature above absolute zero (−273°C). Therefore all solid objects from animal life to trees and rocks are sources of infrared radiations. Temperature and surface characteristics are the primary factors that govern the emission of infrared radiation. The theoretical ideal emitter is called the "black body" radiator, and the total energy given off by a perfect emitter increases with higher temperatures; at the same time, the wavelength of maximum emission decreases as the temperature rises. If an object is sufficiently heated, it will begin to glow and produce visible light (Olson, 1965). With respect to surface characteristics, objects with polished or silvered surfaces are poorer emitters of infrared radiation than matte-surfaced objects. Some materials, such as silicon, that are opaque to visible light are relatively transparent to infrared; conversely, bodies of water act as screens that block infrared radiation.

Detection of forest fires
Many vegetative and terrain features of interest to foresters produce relatively low surface temperatures and are therefore rather weak emitters of infrared radiation. Although it is possible to design an infrared sensor that can distinguish between an object and its background when the temperature difference is less than 1 degree centigrade, greater temperature contrasts will obviously permit easier distinctions to be made. Thus an immediate application that comes to mind is the detection of forest fires.
Studies at the Northern Forest Fire Laboratory (Hirsch, 1966) indicate the utility of infrared line scanners for detection of spot fires. Infrared images obtained during hours of total darkness clearly indicated the positions of eight incipient fires, some of which were located beneath a forest overstory. In another instance, the perimeter and relative intensity of a fire, along with the locations of separated spot fires, were discernible in daylight when normal vision from the air was obscured by heavy smoke. Distinct patterns of water courses on infrared images are also worthy of mention, because such knowledge might become a critical factor in organizing the suppression of wildfires.

**Detection of mobile populations**

Could infrared scanners be employed to detect forest insect infestations, or to make a reliable census of wildlife, or to count visitors in recreation areas? Certainly these and other applications are within the realm of feasibility, though they are not currently practicable. First, we will need to know what temperature and radiation changes occur when healthy trees are attacked by insects, or when animals, including humans, "bed down" on various background surfaces.

It becomes clear that maximum utilization of infrared sensors will be heavily dependent on the acquisition of knowledge relating to temperature variations in the forest community. When existing national security regulations are eased to the point where these sensors are readily available, the forester will likely find that infrared imagery comprises a valuable addition to his mensurational tool kit. Coupled with conventional aerial cameras, infrared sensors will provide a second "eye in the sky."

**Discussion**

**Question:** Does the military actually publish sets of these infrared sensing photographs?

**Dr. Avery:** I can't answer that, for good reason, as this is classified matter. Some of the aspects of it have obviously been published and you can get quite a bit of information from two sources of reading. One of these sources is the last three or four years of Photogrammetric Engineering, and the other is the Infrared Laboratories at the Uni-
versity of Michigan in Ann Arbor, where they have a large project financed by the Office of Naval Research. They have been running a symposium for the last three or four years and publishing proceedings, so much of this information is available. There is no question that you can get information on how the system works, what it will do, what the resolution potentialities are, and what the prototypes of the equipment look like, but the big problem, up to now, has been that the researchers have published very little imagery which has been obtained with this equipment. There has been very little implied, written, or published on how you can go about interpreting it once you get it. So we know all about the equipment and how to use it. Manufacturers, such as Bendix, among others, are making this equipment, but we haven’t seen much in imagery and we don’t know exactly what we can do with it. We do know that the more we know about the surface emission characteristics, the better the interpretation will be.

*Question:* Will insect attacks show up on infrared before the crown itself starts to change color?

*Dr. Avery:* Are you speaking of conventional infrared photography—or one of these special sensors?

*Comment:* Well, I was speaking, more or less, of the conventional infrared.

*Dr. Avery:* I do not believe it would, on conventional black and white infrared. However, with this camouflage detection film, there are some kinds of damages that can apparently be picked up earlier than could be picked up on the ground. Now, this could be because you suspect the damage is there and you study these photographs quite carefully, or maybe it is because you actually pick them up earlier on the photograph. I’m not sure. How early in the process damage can be discovered is a little bit tough to say. Now, Bob Caldwell in California has found that, with certain types of rust that get on cereal crops, the infestation can be discovered with this kind of film before the average person could see it if he were walking through that field. Now this could be a combination of
the fact that the film is more sensitive than the eye, and the fact that visual perception is not as good when you just walk around and look at things, as it is when you study a photograph.

**Question:** Dr. Avery, would you make a comment or two about the future of color aerial film in commercial forestry?

**Dr. Avery:** Well, I'll try. Again, I think that the available color films—largely Kodachrome or Ektachrome film, that everybody is familiar with from 35 mm. slides—have a real place for certain types of things with real color differences, that you and I can perceive every day. I think probably there is greater potential for some of these specialized films, like camouflage detection or infrared color for detecting diseased trees, or for trying to pick up some of these things early enough to make it more beneficial. Now there is quite a bit of research being done on a project, formerly in Beltsville, and is now in Berkeley, with Heller, Aldrich, Caldwell, and that group at the Pacific Southwest Station. They are doing quite a bit of work with color films, large scale, with healthy vegetation and with disease- and insect-infested vegetation. I think there is a lot to be said for this, but it is really not the answer to all the problems, and is relatively expensive right now. This expense is going to always be at least one of the factors.

**Question:** Has anything significant been developed in stereoscopic photography? Has there been any major breakthrough or is it any better now than it was—say, ten, twenty years ago?

**Dr. Avery:** Well, I think we have better lenses than we ever had before, and usually the resolution and the film is better.

**Question:** Is there a single film, for example, that can be used for stereoscopic purpose?

**Dr. Avery:** You mean, can we get a sort of pseudo-stereoscopic image from really one view rather than two? I am not familiar with that particular technique. There have been some great improvements in both cameras and viewing equipment, but in general I think the kinds of problems that foresters have been concerned with have not really been ones of resolution, as such. I think that
resolutions have always been good enough for us. Often there will be developments that we do not hear about for five years because they may be classified until the military agencies have checked them out. So I couldn’t say there is not something, but I just don’t know that particular technique.

REFERENCES


The appearance of this title in a symposium devoted to forest measurement is very gratifying, because it shows an awareness that measurement is a means toward satisfying some larger requirement—that it is not merely an end in itself. While it is recognized that measurement as a scientific technique has many other ramifications of significance in forest research, here I wish to discuss it primarily as the major information-gathering tool of the forest manager.

Forest inventory is the collection of measurement techniques by which the forest manager gathers information about the physical production aspects of the process under his control and the tract of forest land on which this process takes place. Inventory must work in conjunction with other information-gathering procedures, of which the accounting system for getting economic information is perhaps the most significant, or at least the best formulated. Other less formal procedures are community and professional contact for knowledge of social relationships, market surveys of various formal and informal types, reading, and attending meetings for information on research findings. Therefore, for this paper, forest inventory will be considered as limited to its functioning as eyes and ears in the woods for the forest manager.

I doubt that there would be very much dissension from this viewpoint of the purpose of inventory, but the big question is how to make management needs operative during the planning stages of forest inventory. This is the problem on which I will concentrate. So often in the planning of inventory, attention focuses very quickly on the details of sampling design, volume estimation, and measurement tools, so that the overall objectives of the inventory are lost to sight, resulting in elaborate collections of data that are not as useful in management decisions as had been hoped.
Written Statement of Management Needs

The top foresters of an organization should put an appreciable amount of effort in the early planning stages for an inventory. The end point of their efforts should be some sort of written statement on exactly what they feel to be the operational objectives of the organization and the management needs from inventory. The main point of my discussion will be suggestions on how to get this statement.

It should consist of three main parts. First, there should be a statement of objectives of land ownership. Second, there should be an exposition in some form of the most important decisions to be made on the basis of inventory information. Third, there should be a set of tables outlining the final form in which the immediate results of the inventory will be presented.

Before going further let us agree on the kind of organization to which I am referring. Primarily it is one which has the job of actively managing forested lands. It could be either a wood-using industry, a governmental agency, or a landowner selling stumpage, but it has an ongoing interest in the production of the land. There would be some differences in approach depending on whether it is a new organization with newly acquired land and the need to establish a control system, or an already operating organization wishing to improve its management controls. In either case it is an organization planning to engage in active management, not merely custodial care or statistical accumulation. The basic problem of management control is the same, whether this is a privately owned or publicly owned property. If the owner is a wood-using industry, the relationships with wood procurement must be recognized, but the basic problem will be that of land management. In short we are concerned with more than just an accurate count of standing trees and volume.

Management Is Development of a Control System

The modern view of management sets as its major responsibility the development and operation of a control system for whatever productive process it is responsible. This view implies a conscious effort to recognize and regularize the procedures of information gathering and decision, as well as simply to make decisions whenever the need for them arrives. In theory, at least, the control system
A GENERALIZED CONTROL SYSTEM

INPUT

CONTROL

PROCESSOR

MONITOR

OUTPUT

FEEDBACK

Figure 6
should be set up so the process can "run itself." The system is so organized that the need for decisions is anticipated and information is available to help make the decisions when the need arises.

In abstract form a control system may be shown as in Figure 6. Here is seen a Processor, or a productive process, receiving certain inputs and yielding outputs. The efficiency with which this process
operates is determined by the Control which we see in the box between the Input and the Processor. In this diagram Control represents the function of management decisions. To operate, this controlling manager must have information on how well the output satisfies the goals of the organization. This information he gets from the Monitor, which is some method of observing, recording, and transmitting information about the success of the entire process. In the forest production process, this monitor is the forest inventory.

I have tried many times to diagram the forest production process and the control system needed for it. Figure 7 illustrates one such attempt (Hall, 1961). The function of the Processor in the previous diagram has shrunk to the little box showing Supervision of Operations, and the rest of the diagram is the expanded parts of the control system. The diamond-shaped boxes are decision points, at which the information from the monitor is put to use controlling the process. The entire chart may be considered a map of the flow of information. Once the entire production process is in operation, forest inventory and accounting operate together as the monitor to collect information and feed it back to decision points.

With this viewpoint, inventory is part of a continuing process whose purpose is the production of a flow of goods and services, of which wood may be the predominating one. The objective is more than just to grow a tree, or grow a lot of trees, so the inventory must do more than just count trees. It is also more than simply gathering of data that will be used to write a one-time management plan. It is recognized that there are some types of inventory that do essentially only count, such as the cruise for the sale of standing timber, or possibly a governmental forest survey of all standing timber in a state or region for prospective industrial development. Even in the latter case, some thought should be given to the decisions of public policy or private industrial development which will be based upon the survey results. The major task of management, then, is the implementation of a control system for a continuously operating and highly complex seminatural process.

Managerial Steps Toward a Statement of Needs

How can the forest management team of an organization work toward getting this written statement of inventory needs? Some
rather definite steps are needed to get from the acknowledgment of the desire for such a statement to the accomplishment of it. A series of meetings of the top management men should be the initial step in inventory planning. At first the group should be small, perhaps two to four, and it should try to get down on paper a statement of the forest ownership objectives and the anatomy of the control system. At one meeting shortly after the first, an outsider might be invited to inject new approaches, but essentially this series of meetings should be held by the members of the organization who try to describe and systematize their own activities.

Should a statistician or computation expert be present at these first meetings? I have mixed feelings on this, but I feel he should not be present for the purpose of contributing from his professional expertise. His presence is desirable at some point so that when the time comes to develop a sampling scheme and computation methodology, he will be familiar with objectives and considerations of cost. His entry should not be delayed too long; however, if he comes to these first meetings in his official capacity, it should be merely as an observer until a solid statement of objectives has been completed.

Four or more such meetings may be held. Suggestions for their conduct are:

1. A broad-view, imaginative session, bringing into the open some of the most optimistic objectives and items of information most to be desired, even if they are seemingly impractical of achievement at first. More or less a brainstorming session, recording the most definite ideas as they arise, without trying to evaluate them.

2. Preparation of a brief statement, one or two pages, of the objectives of land ownership. It should be realistic, without vague generalities or rose-tinted, unattainable objectives. John M. Reed (1964), director of business planning for North American Aviation, said: "To be most useful, objectives should be stated in such a way as to make it possible to measure progress toward them and the more quantitative the better."

There may be fear of committing objectives to writing, from a feeling that the organization may become bound to fixed objectives under changes in circumstances. However, all organizations need to be ready to admit to the necessity of changes in objectives in the modern, dynamic economy, even after they are formally stated.
The statement should also face squarely the demands of secondary land uses and their impact upon management objectives.

3. One or more sessions devoted to building a descriptive diagram or flow chart of the management control information system that is in existence. A beginning may be made by charting the flow of paperwork. In this flow chart carefully designate all the points at which decisions are made, and try to phrase these decisions as definitely as possible.

4. One or more sessions devoted to building a diagram of the management control system the group believes should be established. The diagram may come from revision of the previously made chart of existing procedures, or it may be entirely different. For a forest management organization that has been running smoothly for a long time, the existing system and the desired one may be very similar. The important outcome is a chart which carefully distinguishes the important decisions that must be made, for which the inventory must provide information.

Some questions that might be used to initiate discussion in the course of these meetings in an effort focus on objectives are: What is the function of the woodland in the organization? If raw material for a wood-using industry owner is a primary objective, is the desire to minimize cost on a set amount of wood each year, or is it to yield a maximum return on invested capital? Is capital available for investment, or must the woodland operate out of the income generated? What is the permissible amount of inequality in annual output. Is the woodland understocked or overstocked for its major function? What will be the long-term sustained yield level of production? Are logging, regeneration and other silvicultural practices settled, or are they still developing? What will be the impact of new types of harvesting equipment? (It must be remembered that these are questions which may be very significant in long-term planning, but that cannot be answered by inventory [Hawes, 1948]).

When answers to some of these questions are not found, the discussion may help to indicate certain needs for the data from the inventory that would not otherwise be obtained. This may also indicate that in view of the stage of development of management, obtaining certain data may be premature; it would be out of date by the time it could be used.
Decisions for Which Inventory Can Provide Help

It might be helpful to have some other questions to use as starting places for bringing into sharp focus the important decisions for which inventory must provide data. Decisions can be separated into two general types, those which must be made in the central office for the direction of the entire property, and those which must be made by the district and field men.

Central Office Decisions

1. What important decisions were made during the past year? Was there sufficient information for those decisions?
2. What important decisions are anticipated during the next year? During the next five years?
3. For private concerns, what values should be entered into accounts for volume, growth, and basis for depletion?
4. What depletion policy should be followed, where the Internal Revenue Code permits some latitude in election of method?
5. How may units of inventory volume be related to volumes scaled as removed?
6. What is the magnitude of losses due to fire, insects, disease, and wind?
7. How much should be budgeted for protection from these losses?
8. What should be acquisition policy? How much more land should be purchased, and at what price?
9. What return is being received on the investment in land? This may call for some new methods of bookkeeping, to bring in unrealized values from growth and capital accretion.
10. What are relative volumes of species? Do these indicate any changes in utilization policy, or in utilization research?
11. Can we place some kind of a value on recreation, wildlife, or other non-commodity land uses? (The use of opportunity cost of timber income that is foregone might be used here.)
12. What are desirable growing stock levels for stands that might be ready for thinning or selection cutting?
13. What total allowable cut is desirable, considering growth rates?
14. How should scheduling of individual compartments for cutting,
planting, and other operations be accomplished? (More on this below.)

15. How can projections of annual income and cost be made to a planning horizon of ten to twenty years, or perhaps one rotation?

Field Decisions

1. Are the marking guides being used correct for all growing conditions? Thinning guides? Tree quality guides?
2. Are correct instructions available for evaluating insect and disease incidence?
3. Is there adequate information for prescription decisions on timber stand improvement and site preparation?
4. Are field men properly assessing marketability of trees and stands?

Evaluation of Past Operations

With the greater intensity of management effort, one question that is of great interest to foresters at all levels is, "How successful have our silvicultural practices been?" Evaluation of investments in planting, natural regeneration, hardwood control by herbicides, controlled burning, and site preparation calls for some sort of feedback information system. Perhaps the inventory system can contribute to this. The need for this information indicates that inventory records should include, at least, data on the date of each treatment of a plot or block. Observations should be recorded of the current degree of success and apparent reasons for failures. It is most important that this phase of the feedback cycle operate as rapidly as possible, for each year of investment in unsuccessful treatments is not only an avoidable loss, but also another year of growth loss from unsuccessful treatment.

Scheduling—The Basic Management Job

The more one studies the overall job of management control, as forest land emerges from the natural state toward more managed stands, the more one realizes that the job is essentially one of scheduling—one of ordering in time. It is the task of deciding in which year
each stand will receive the next treatment that is logical for it. Inventory must provide the basic data for carrying out this process.

The designation of boundaries for areas to be scheduled is one of the important matters that must be settled in advance of inventory. Subdivision into basic compartments with permanent boundaries locatable on the ground is an essential step in developing the control system. Grosenbaugh (1955) has called these record units. They may vary in size from forty to five hundred or more acres, and they may be smaller for less extensive land holdings. It is desirable to have some tendency toward uniformity of size, and it may be possible to administer disconnected areas together, if they are too small. Such designation of areas by permanent boundaries does not mean that site differences which divide compartments will be ignored. It simply means that if site boundaries are difficult to designate accurately on the ground, they may not be serviceable as compartment boundaries.

While these compartments are being discussed, it is well to direct attention to one important and frequently overlooked phase of inventory work—the need for accurate determination of area. Too often, area figures are taken from erroneous land records or rough, uncorrected maps or aerial photographs, so that the error in area may largely counteract much care in getting a very accurate volume estimate on sample plots or points.

**Outlines for Tables of Results**

From the discussions of the questions listed above should come a clear idea of the information management will need from inventory to make its most important decisions. Much of this information will be desired in the form of tables, so the group of managers should try to produce a set of outline tables of the information that is desired from the inventory. These would be blank tables as far as the data in the body of the table are concerned, but the subclasses of the variables along the edges should be specified in as much detail as is possible. These will be the classes of tree and plot variables which will be used in the field inventory. They will be the independent variables, by which the dependent variables in the body of the tables will be classified. The dependent variables will be such factors as volumes, in cords and board feet or cubic feet, acres of land, and growth rates in volume units per acre and total.
The use of prepared blank tables of special design can facilitate the preparation of these outline tables. An effort should be made to keep the number of these requested to a minimum, for two reasons. First, if the number becomes too great, no one will take time to analyze them and apply the results in the decision situations for which they were prepared. Second, with the availability of tape and disc storage on computers, it is so easy to go back to the basic data and bring out specific tabular analyses as needed; thus it is not necessary to anticipate all needed output at a single analysis.

Composition of Written Statement of Management Needs

Thus we can now present some rather concrete suggestions about the form which the written statement of management needs might take. It might be in four parts: (1) list of the main objectives of forest ownership; (2) diagram of the management control system, with significant decision points highlighted; (3) set of outline tables for which the inventory should provide data for completion; (4) the figure of approximately how much money is available for establishing and operating the inventory system.

At about the time the preparation of outline tables begins, the inventory supervisory team can be organized. This team will take the specifications for the inventory, presented in the written statement, work out the details of field procedure, supervise the gathering of field data, and make the final analyses. This team may well be composed of a management representative, a mensurationist, a statistician, and a computer programmer. Perhaps two of these areas of competence can be covered by one person. For continuity of effort it is helpful if the management man and perhaps the statistician can be one of those working in the management group during its planning.

The part of the written statement of specifications that will be the most difficult to obtain is the outline tables. It may be necessary for the inventory team to prepare a set of them according to their best estimates and familiarity with other forest inventories, and then ask the management group for approval, additions, or revisions. If the makeup and contents of these desired tables can be given considerable attention prior to inventory, they can not only give specific guidelines to what measurements must be taken in the field, but also greatly speed up the later analysis summarization, and reporting of the results of inventory.
Two Coordinated Inventory Systems

As specific planning for inventory begins, or as one examines inventory systems which have gradually evolved, it becomes apparent that actually two coordinated but separate inventory systems are necessary. One is the management control inventory based upon a light sample repeated at intervals of three to five years or possibly longer. The use of relocatable plots or points for this type of inventory is widespread and has maintained itself in favor long enough to indicate that it has real value. This inventory provides the basis for the following purposes and decisions: (1) following the trend in supply of standing timber, including the components of growth—survivor growth, mortality, and ingrowth; (2) accounting values for standing volume, growth, and, perhaps, cut; (3) setting land acquisition policy; (4) setting utilization policy, as to species, quality, and sizes, and, perhaps, salvage operations for damaged timber; (5) determining total allowable cut; (6) setting desired target growing stock levels, both per acre and total; (7) developing yield functions for the prediction of future growth; (8) setting scheduling controls, either by volume or by area; (9) assessing and reconstructing marketing guides.

The other inventory is the intensive stand description for operational direction of cutting and other treatments. It calls for detailed ground examination of a proportion of the compartments every year, for purposes of marking, prescription of treatments, road layout, and detailed planning for the next few years. Regular reinspection of all stands may be done on a five to ten-year cycle. This inventory is for the purpose of: (1) providing an accurate estimate of timber volumes on particular compartments; (2) prescription of treatments for individual stands; (3) data for scheduling of compartments to specific years; (4) allocation of funds to be entered in the annual budget; (5) locating areas of incipient loss, so that salvage and protective measures may be taken; (6) determining accessibility and marketability of particular trees and stands.

To suggest the way in which some inventory information will be tied into management control, let us look at another flow chart of the planning process, as seen in Figure 8. For long range planning it is necessary to estimate volumes for considerable times into the future. This projection requires, first, estimates of present stand volumes and conditions, and, second, yield functions with which to
LONG RANGE FOREST PLANNING

Figure 8
estimate future volumes. Providing growth data, to be used in the formulation of these yield functions, is one of the major purposes to be served by the permanent plots of the management control inventory. Methodology for deriving these functions from inventory measurements is one of the most rapidly growing and important areas of mensuration research today, and it deserves increasing attention. It is important for statisticians to give some immediate attention to this, recognizing the realistic problems of data gathering, because eventually these yield equations will be presented to them for evaluation. It will be unfortunate if they are overly critical and undermine confidence in them because of difficulties in obtaining statistically ideal sampling procedures. Desirable sampling methods for growth and yield analyses should be specified as soon as possible.

In this chart can also be seen the part played by statement of objectives. They become the “Quantitative and Qualitative Decision Criteria.”

Economic factors are brought in through cost and returns information. In this connection should be mentioned the desirability in the inventory of classification of areas by (1) property taxation levels; (2) transportation costs to owner-operated mills or other marketing points; (3) land values—especially in view of probability of pressure toward conversion to other land uses.

This chart shows that all these factors are brought together in the preparation of the annual operating budget. Short range factors, gathered from the stand description inventory, are also used.

Plan Computer Programming as Far Ahead as Possible

One other area of inventory planning in which early and close management consideration is required is in arrangements for preparation of computer programs and for access to computers for data summarization. It is too easy to assume that established data-handling centers in and out of the organization will take care of these problems quickly when the data are available. Experience with these assumptions has been disappointing. Realistic planning should begin as soon as the inventory team is assembled, and preparation of programs should begin immediately, with the objective of having tested programs ready for operation at the time field work begins. This will seem overly ambitious, but unanticipated delays will probably mean
that the organization is indeed fortunate to have operating programs when all the field data are in, and without such preparation field data may remain unused for months or even years.

Consideration should be given to using standard summarization programs as such become available, to eliminate the cost and time involved in preparation of special programs for this most difficult of the data processing steps.

Summary

In conclusion, then, I have tried to make the following points:

1. That inventory should be recognized as the information-gathering portion of a continuing management control system.

2. That, in advance of inventory planning, the top management of the organization should give as much thought as possible and provide as concrete a statement as possible of the objectives and important decision situations of the organization. This statement should be in the form of: a listing of objectives; a flow chart or other diagram of the forest management control system, showing important decision points; a set of outline tables of the specific results desired from inventory in the immediate future; a specific figure on the amount of money available for conduct of the inventory system.

3. That the inventory planning team should derive its procedures from the written statement of guidelines set up by the management group.

Discussion

Question: Dr. Hall, could you give some specific horrible examples of foresters who did not properly plan their management inventory?

Dr. Hall: Nobody ever does this job as well as the ideal I have set up here. I think this is a goal we are shooting at. I, personally, have known organizations that have had data coming out of the field that is a year and a half old, and it is not worked up yet. I have also known organizations which have very extensive inventories, and they get piles
of tab sheets, with the idea that someone is going to read these and use them in their management decision. These computers can turn out data much faster than anyone can read it. I remember talking to a man who is a computer programmer for the Michigan state highway system. They were using computers in their planning, and they had it figured out that if the whole management group, planning the highway system for the State of Michigan, did nothing but read the computer output that was supposed to come to them, they would fall behind. They could do nothing but read computer output. Well, this is the kind of horrible example that does exist, and I think that pre-planning can do a lot for it. This is one reason I say that the managers need to control the system as much as they can. It is very easy to say, "Well, let’s get a statistician; let’s get a computer programmer; and let’s get a mensurationist," and have them take an inventory, without giving them guides. I do not think they should be blamed if they come up with something that is not what management wants. There is one other point here I think comes out of this—I mentioned that John Reed had spoken out for the need for quantitative statements of objectives, but really we used to think that the only people who needed to be quantitative were our mensurationists and our statisticians. I think things are changing. Management has got to be number-conscious; its people have to be a little bit at ease with numbers.

LITERATURE CITED

Any series of repeated inventories has a beginning and what is done initially affects the relative efficiency of the sampling alternatives that come afterwards. Thus continuous forest inventory is a special case and better understanding of principles should come from a broader treatment. The remarks which follow are concerned with the principles of sampling to obtain the data needed for a forest inventory rather than the techniques of sampling or the planning of an inventory.

What is a forest inventory?

Forest inventories are made to obtain objective data as a basis for a decision. In the simplest case, the information required concerns a single variable such as total volume. More commonly a forest inventory will provide information concerning several variables—volumes, areas, numbers of trees—sometimes in two units and frequently with multiple classifications in the form of several two way tables. Few go as far as the forest survey which currently requires data for thirty-three standard tables.

The required data may be obtained by measuring and counting every tree in the forest and by putting every square yard into an appropriate area class. Or estimates may be obtained by sampling (observing the variable, or variables, on only part of the forest). If the forested area is small enough, a complete tally of all trees, areas, etc., is the appropriate way to conduct the inventory. Usually, the cost of this method is prohibitive and we are compelled to sample.

* This paper was read by Dr. Jerome Clutter, University of Georgia.
What is sampling and a sampling method?

Sampling means that some part of the forest is selected, appropriate variables are observed, and these data are used to calculate an estimate of the desired quantities. When we do this, we realize that the resultant estimate will not agree exactly with what we would have obtained without sampling. If there are no measurement errors, no omissions or duplications, and no mistakes, the difference in the two quantities is the error due to sampling, or sampling error. When planning our forest inventory, we must recognize this error and choose our sampling method accordingly.

One solution to the problem is to take a large sample but this alone is not enough, as the managers of the Literary Digest learned to their sorrow in 1936. A better solution is to calculate the sample size required, based upon the error you are willing to accept, combined with the risk of an error of this size. This is not an easy quantity to derive. You would like to minimize total cost, which is the sum of the cost of the inventory and the cost of making a particular error times the risk of this error. I will grant it is much easier to minimize error for a particular budget, but this cannot tell you if you spent too much or too little. And if you can not answer this question, how can you justify a sample size greater than one, or possibly two? I know of no easy answer to this problem but will assume a maximum error that can be tolerated and its associated risk; call this $\varepsilon$ for future reference.

Many sampling methods are possible and I would like to consider next what is meant by sampling method. A sampling method is a combination of techniques with as many kinds of sampling units as these techniques require (Cochran 1963). Techniques include simple random, stratified random, regression, multiple stage, and several others. These will be considered in more detail later. A sampling unit for purposes of forest inventory is a point or area defined by some rule which identifies the particular trees to measure at a particular location in the forest. In this sense, a sampling unit may be a plot of fixed area, a strip of given width, or a point with a particular critical angle. It could also be a group, or cluster, of these units. Problems of specifying the optimum sampling unit have been studied by H. F. Smith (1938), F. A. Johnson and H. T. Hixon (1959), W. G. O’Regan and M. N. Palley (1965), and C. J. Anagnostopoulos (1966), among others. I shall not dwell further on sampling units, but I ask the
question: is it likely, or even necessary, that the same sampling unit be best for all forest inventories?

Why foresters sample

An inventory is made to provide some specific information about the forest. This information is commonly requested to provide management with the basis for a decision. I am sure the information would be obtained from a complete enumeration if it were not so time consuming and so expensive to examine and measure every tree in the forest. Sampling becomes a reasonable alternative when the consequences of the error introduced by sampling cost less than the added effort of a complete enumeration.

When estimates, based upon a sample, serve as the basis for a decision it becomes imperative to provide some sort of measure of the trustworthiness of the estimates. The standard deviation (or standard error) of the mean is generally recognized as the best objective measure of the reliability of any estimate based upon a sample. As there is an associated probability distribution, it enables one to make a confidence statement with reference to the population mean or total that is impossible otherwise. And the interval can be made as narrow as desired by appropriate choice of sample size. This is the logical basis for calculating sample size in advance.

An efficient forest inventory

As forests for which an inventory is sought are commonly extensive in area, the usual forest inventory will use some form of sampling. And the more costly the method, the more important it becomes to identify and use the most efficient method available under the circumstances. I presume most readers would prefer to obtain requisite data at least cost, if you knew how.

There is a best way to do any given task. Furthermore, this best way is frequently the easiest way, or the lazy man’s way. In relation to sampling for a forest inventory it is chiefly a matter of choosing the appropriate sampling design; a simple-minded, inefficient design may cost four to eight times as much as a more complex but efficient design. There is, of course, no advantage to a complex design that does not result in less cost.
It turns out that the design which results in minimum cost for a fixed error is the same design which minimizes error for a fixed cost. Which then should be specified: minimum sampling error or total cost? Minimizing cost to achieve a specified precision is the usual criterion of an efficient sampling design as this means saving money. The alternative of minimizing sampling error for a fixed cost is inferior as it does not tell you when you have spent too much, or too little. If you should be uncertain of the values you have used in the formula and should encounter difficulty in obtaining as much money as you think you need, it may be expedient to accept what you can get at the moment and try harder next time. The principle of minimizing cost is still the way to do it, when you can.

When estimates of more than one variable are sought, as is commonly the case with forest inventories, sample size, for a fixed error should be calculated for each variable. It is evident these calculated sample sizes will not agree; solution of the dilemma will depend upon particular circumstances: if you can afford to use the largest number you will probably do so. If not, there will be a reexamination of the assumed values and of the arithmetic, possibly followed by some compromise.

If you are looking for some panacea, you will be disappointed, as there is no one best way of making a forest inventory. Instead, this best way depends upon the particular forest, what it is you want to know, and what is already available. We shall examine some of these particulars presently.

Fuller and more appropriate use of known sampling methods and techniques leads to better forest inventory procedures. I am sure foresters generally are well aware of the basic sampling methods, but I suspect many of you know so little of the capabilities of more complex methods that you are reluctant to even try out these more intricate procedures. There is no particular virtue in complexity of itself but if the simple procedure costs four to eight times as much as the more complicated design, I think this should be of interest to you, especially those of you working in an organization which seeks profits. I hope I can dispel some of your apprehensions concerning these more complex designs.

The best inventory method is that which provides the information desired at least cost. As you are unlikely to repeat such an inventory right away, you may be expected to choose the one which promises to provide the data at least cost.
The best method is the result of careful advance planning which includes a comparison of the estimated efficiencies of the methods that might provide the estimates required. Earl Rogers (1964) in planning the FAO Preinvestment Survey of Greece, compared seven alternatives in design before choosing one of them. Estimated costs ranged from 265,000 to 1,900,000 drachmas for nearly 2,000,000 hectares (a difference of 1,635,000 drachmas or $54,500). The method chosen was an adaptation of the design for the initial Forest Survey of the Northeast which I described about fifteen years ago in the Journal of Forestry (Bickford, 1952). The most expensive was a simple design without the use of photographs and without use of strata.

This advance planning means:

1. Specification of requirements—the forest to be sampled, the quantities to be estimated, and required precision for each estimated quantity in terms of both size of error and its risk;
2. A marshalling of available information and facilities, relevant to the conduct of the inventory;
3. Choosing the sampling design that promises to meet the objective at least cost followed by specification of pertinent procedural details.

How to obtain a better forest inventory

The best forest inventory method is that which attains its objective at least cost. This is easily said but not so easily achieved. Many sampling methods are available for obtaining the data sought for a forest inventory. When properly carried out, many of them provide unbiased estimates of the information that management desires. In any given situation, however, not all are equally efficient and we should consider the problems that arise in choosing the best method. This choice requires a knowledge of the methods that might be used, their relative efficiencies in a statistical sense, and their relevant costs. It seems self-evident that there is no one method that is best for all situations; if this is granted, it then follows that identification of the one that is best in a particular situation will usually require careful study of what is involved, what is available, and what is sought.

I shall briefly describe two simple sampling alternatives in making a forest inventory. Then two situations will be examined in enough
detail to show how efficient more complex designs may be, and why. The first will center on the Northeastern forest survey; the second will examine problems of resurvey.

The simple methods

The two simple methods are systematic sampling and simple random sampling. Foresters have used systematic sampling for a long time, and I am sure you know approximately what is meant: a sample of size, n, in a particular arrangement involving equal intervals is selected from the forest. When the desirability of random sampling was recognized, a random start was added which meant that every possible sample of this size and arrangement had an equal chance of being selected. The various units of either sample are not independent, however, and this lack means there is no completely valid estimate of the sampling error. A relatively large sample is commonly used in the hope that the estimate will be correct; probability and confidence statements are impossible. Estimates of the mean and total are unbiased and for some purposes this may suffice. As C. J. Shuie (1960) pointed out, one such set of units may be regarded as a cluster and with multiple random starts, a valid estimate of sampling error is possible.

A simple random sample is one of size, n, such that every possible sample of this size has an equal chance of being selected. The result is a random arrangement of sampling units in the forest which has very serious practical disadvantages that may outweigh the advantages of unbiased estimates of the mean, total, and sampling error. Although seldom used in forest inventories the simple random sample is useful as a point of reference for more complex designs. Empirical evidence suggests that the simple random sample may be less efficient than a systematic sample of equal size but the difference is not substantial.

Situation I. Stratified random sampling

To illustrate stratified sampling, let’s begin with an assumed situation—a second-growth forest of 700,000 acres in the Northeast with trees of twenty to twenty-five commercially important species ranging up to about 3 feet in diameter. In 1946 an inventory was undertaken to provide the basis for a revision of the management plan.
Aerial photographs were available and the sampling method chosen was stratified random sampling where the strata, defined in terms of estimated volume per acre by forest type, were completely delineated on the photographs. Delineation was chosen to provide information on location of stands as well as total volumes, areas, etc. Ground plots, randomly located within each stratum, were used to obtain requisite data on numbers of trees, volume, increment, etc.

This kind of a situation identifies stratification where stratum weights (areas or proportions) are known and have no sampling error. This is the simplest way of using stratified random sampling. In the form so far described, it may or may not be more efficient than simple random sampling. There must be real differences among the stratum means of the estimated variables and there must be an appropriate distribution of ground plots by strata. Under proportional allocation, numbers of ground plots are proportional to stratum areas while according to optimum allocation numbers of ground plots are proportional to the product of stratum weight and stratum standard deviation (Neyman 1934). You can find appropriate formulae in any standard text but we don’t need them here.

Under what circumstances is this procedure likely to be more efficient than a simple random sample, or a systematic sample, and by how much? W. G. Cochran (1963) answers the first part of the question by pointing out that:

\[ V_r = V_p + \frac{\sum P_i (Y_i - \bar{Y})^2}{n} \]

and the

\[ V_p = V_o + \frac{\sum P_i (S_i - \bar{S})^2}{n} \]

Where:

- \( V_r \) — Variance of a simple random sample
- \( V_p \) — Variance of a stratified sample with proportional allocation
- \( V_o \) — Variance of a stratified sample with optimum allocation
- \( Y_i \) — Mean of the \( i \) th stratum mean
- \( S_i \) — Standard deviation of \( i \) th stratum
- \( \bar{Y} \) and \( \bar{S} \) — The grand mean and standard deviation respectively
- \( P_i \) — The stratum weight of the \( i \) th stratum
- \( n \) — Number of units in sample

Thus \( V_r > V_p \) whenever there are differences among the stratum means, and \( V_p > V_o \) whenever there are differences among the stratum variances. Practically, the gain in efficiency is small unless these dif-
ferences in means and variances are of the order of two to one, or greater. Experience with stratification in the northeast based upon estimated volume, shows that differences of these magnitudes and greater are common.

As photographs age and forests change these differences will become smaller and there is less advantage to stratified sampling. Stratification may be less advantageous for smaller areas although, of course, smaller areas also are less likely to have usable strata. It should be remembered that significant differences between strata, rather than agreement with volume estimated from the photographs, is the crucial factor in determining if stratification is an efficient sampling procedure.

This has been an artificial illustration, so far as 1946 is concerned because no delineations were done in the northeast until later, and because it is simpler than the design actually used in the initial survey of the northeast. In the beginning, stratum weights were estimated from photo plots, each of which had an estimated volume class based upon careful study of the photograph under a stereoscope: stratum weight was the proportion defined by number of photo plots in the stratum divided by total number of photo plots. Because this weight was determined from a sample there was an associated sampling error. And the sampling error of total volume must include the effect of these errors in stratum weights, as may be seen by comparing formulae in Cochran:

\[ \sum \frac{P_i S_i^2}{n_i} \text{ vs } \sum \frac{P_i S_i^2}{n_i} + \frac{\sum P_i (\bar{Y_i} - \bar{Y})^2}{n} \]

This design provided for an optimum distribution of effort between photo plots and ground plots, as well as by the several strata, recognizing differences in cost, relative contributions to error, variances within strata, and differences in means among strata. Use of the design formula required estimates of these parameters which were frequently in error, and the resulting design was only approximately optimum. This is the design selected for the Greek survey by Rogers. This plan for initial forest survey in the northeast also included a technique known as double sampling: photo plots were first stage units from which a randomly selected subsample was drawn to use as ground plots, or second stage units. It would have been possible to use an independent sample for the ground plots, but this would have been less efficient when stratum weights are subject to sampling error.

Data recorded on the ground plots are the same whether stratum
weights are determined by sampling or by complete delineation. Even though strata are defined on the basis of estimated volume per acre, unbiased estimates for other variables including number of trees, and areas, and their corresponding variances are obtained. It is evident that all these estimates cannot be obtained at maximum efficiency. Experience on the forest survey in the northeast showed that if required precision in net cubic foot volume was attained, the other standards were also met. This might not be true in other areas with relatively less forest land.

For this first situation, still another technique might have been used, and I know it was considered for the FAO project in Greece before Earl Rogers chose to use the design I have described above. This other possibility was regression sampling with or without double sampling. For a relatively small sample, ground measurements of volume plus photogrammetric measurement of certain stand variables provide the basis for a regression equation that will estimate ground volume from what may be observed on aerial photographs. This equation, together with a much larger sample of photo plots alone, will also provide unbiased estimates of mean and total volume, and their sampling errors. This procedure would have been superior and more efficient, with the right combination of correlation and costs per sampling unit. An approximate guide is provided by the relative magnitudes of:

\[(1-r^2) \frac{S_a^2}{n} \text{ or } (1-R^2) \frac{S_a^2}{n_i} \text{ and } \sum \frac{P_i S_i^2}{n_i} \text{ or } \sum \frac{P_i S_i^2}{n_i} + \frac{\sum P_i (\bar{Y}_i - \bar{Y})^2}{N}\]

where \(n = \sum n_i\) for the same sample size.

Regression sampling assumes a linear relationship. If this is true, and if \(r\) or \(R\) is 0.9 or higher, regression sampling is at least promising. Cases involving photogrammetric measurements with which I am familiar have had correlations of 0.6 or less, and stratification has been more attractive. When plots are remeasured, regression sampling is usable for the one estimate, as we shall see presently.

**Situation II. Combined estimates in problems of resurvey**

In some circumstances, two or more estimates of the same quantity may be available. If there is an associated sampling error for each, these estimates may be combined by a weighted average, where
variance reciprocals are used as weights. This combined estimate procedure is particularly important when successive inventories are made of the same forest. The procedure has been described with reference to the resurvey of the northeast (Bickford et al. 1963). Some of the plots from the initial survey are remeasured, thus providing data at the two occasions that may be linked by a regression equation. This equation, using all of the data from initial survey, provides estimates of current volume. A new independent sample is used to obtain a second estimate, and the two are combined.

In previous articles this has been called sampling with partial replacement, and it is so labelled in standard statistical texts on sampling. This label calls attention to a nonessential feature, without reference to combining. It is important from the point of view of successive forest inventories to realize that two quite different designs may be used for the two estimates, without any material revision of basic concepts. Thus an initially less efficient simple design may provide the first estimate, and the sophisticated double sampling with optimum allocation may be used for the second. Furthermore, it is easy to change sampling units, if desired, to incorporate local intensification, and many other variations, as long as the multiple estimates are independent and have acceptable estimates of sampling error. New Hampshire, West Virginia, Maryland, Pennsylvania, and Vermont have been resurveyed under this general procedure, and plans for proceeding in other states are well under way. In each state, upon completion of the resurvey, there has been local intensification, including cooperation with included national forests and state forestry organizations. A very general program has been written for the IBM 7094, which obtains required entries for every cell of nearly thirty standard tables and a sampling error for each entry (U.S. Dept. Agri., 1966). The method is admittedly complex but so is the 1966 automobile.

Other methods are available for obtaining successive estimates of volume and other variables. Repeated independent surveys will provide such estimates, as well as associated sampling errors. Remeasurement of all the plots of a fixed sample will also provide such estimates. As I pointed out, at the national meeting of the SAF in Boston in 1963 (Bickford, 1964) either of these alternatives require more plots to obtain the same accuracy on the basis of experience values for correlation and pertinent costs.
Efficiency of the combined estimate procedure that has been described above, relative to a fixed sample or two independent estimates, will increase as correlation between successive observations increases or as cost of remeasured plot is reduced. It is possible that extenuating cost of new plot circumstances may favor one of the less efficient alternatives. The efficiency of combining two independent estimates is likely to vanish for small areas. If small enough, sampling ceases to be a better method than complete enumeration, as has been noted.

Choosing a better sampling method

It has been pointed out before that the best sampling method to use for a forest inventory is the one which satisfies the objective at least cost. You are no doubt wondering how to identify this method. Two procedures are available and I shall describe first a relatively clumsy method which may be easier for most of you to carry out. In essence it is this: (1) List all sampling procedures you can think of that might be most efficient under your particular circumstances. (2) Obtain the appropriate formula for calculating the sampling error for each method. (3) Calculate sample size required to satisfy $\varepsilon$ for each method. (4) Calculate cost for each method to obtain an array of costs that satisfy a common $\varepsilon$. The best method is that which costs least.

For a clearer understanding, let's examine each step a little closer. I have repeatedly pointed out that many sampling methods are available which provide unbiased estimates of the desired quantities: simple random, stratified, regression, etc. List all that promise efficiency; but there is seldom need to list all that are in the book. Rogers examined seven alternatives; two or three may be enough. Every design that provides unbiased estimates, and that need concern you now, will have an appropriate sampling error formula published somewhere. A text, such as Cochran (1963) will provide all that you would need.

A formula for sample size is simply a rearrangement of the sampling error formula, solved for sample size, replacing sampling error by required precision. You will also find formulae for computing sample size in several articles and texts. The actual calculation of sample size may encounter a minor problem: estimates of unknown means and
variances may be necessary. Use other experience if you can; if none is available draw a preliminary sample. Remember that the risk of an error of this size is needed in the formula. Total cost is obtained by multiplying numbers of units by costs per unit, and summing when two or more kinds of units are involved. The remaining steps are obvious.

A more elegant way to obtain what should be the same answer is available to those who can use calculus. Develop a mathematical statement in the form of an equation which relates the relevant components; differentiate this equation with respect to cost; equate the derivative (or partial derivatives) to zero and solve for sample size. J. Neyman did this to arrive at optimum allocation in 1938 and K. D. Ware did this in his doctoral dissertation in 1960.

Earlier I gave as my aim increasing your understanding of some sampling methods which would help you select the best method for your particular forest inventory. I hope you have a better appreciation of what to look for. In closing I shall quote from a famous poem by Robert Frost which I was privileged to hear him read more than forty years ago as a Dartmouth undergraduate. "Good fences make good neighbors," he quotes his neighbor as saying. And he goes on to remark that the truth of that statement depends upon the need for fences. In a somewhat parallel sense this is also what I have been saying. A forest inventory is made to answer one or more questions; an efficient inventory is one which answers these questions at least expense, and the way to achieve it depends upon particular circumstances, not a formula. Those readers in private industry must be concerned with meeting inventory objectives as efficiently as you can. I hope all of you have found these pages interesting and helpful.

Discussion

Comment: Dr. Clutter, I would like your comments on two statements made by Dr. Bickford in his paper that do not ring true to me. The first statement is in connection with the systematic sample, with or without a random start—I don't think that it makes any difference. I believe Dr. Bickford stated that you could not make any probability statement whatsoever about a systematic sample. I do not think that is true. Second, I
would like your comments on the comparison that Dr. Bickford made between the systematic sample and the simple random sample, when I believe, he stated that in most cases, or in many cases, there would be no difference in efficiency. This, again, doesn't seem right to me. It seems that in most cases the systematic sample would be the more efficient.

Dr. Clutter: Well, this has been a popular subject for debate for many years. The problem, I think, boils down to the fact that any answer to the question involves some assumptions. Questions arising out of the comparisons of efficiency between systematic and random, and whether or not you can estimate sampling error, have been answered only by results of empirical sampling studies. Most of them, I guess, have come from two forests that were, essentially, completely mapped—the Dehra Dun in India and the Black Mountain in California. This was done for simple random, for various other procedures, and also systematic sampling. If I recall, the results showed first of all that your estimate of the error, calculated from systematic samples, was not too far from being correct; that is, it was reasonably good. But, of course, just because we have demonstrated in certain cases that this is true does not furnish general proof that it will always be so. I believe the point that Dr. Bickford is trying to make here is that there is no way that one can argue from statistical theory to prove that we can quote our experience and say it worked pretty well for us; that this is not putting it on the same basis with the other parts of sampling theory. With respect to the relative efficiency, I believe his statement was that systematic sampling is usually somewhat more efficient, but the differences are not large. Again, I think he is probably speaking largely from his own experience, and any statement about whether or not there is a difference depends on what kind of population one would be sampling. To my recollection this is about the sort of thing that has come up in these comparisons from empirical data.
Comment: There has been a discussion about systematic cruising and random sampling, and I want to speak as a teacher of mensuration and as one who has had field experience in timber cruising. It is my opinion (and this is an opinion) that systematic cruising is superior to most cruising work in forestry. If you’re doing that type of cruising, I would recommend that you continue to do it—stratify your cruise lines, do good field work, and have confidence in your work.

LITERATURE CITED


BICKFORD, C. ALLEN. 1952. The sampling design used in the forest survey of the northeast. Jour. For. 50:290–293.


PLANTATION MEASUREMENTS

KENNETH R. SWINFORD
University of Florida

During the past fifteen years timberland owners have given top priority to the planting of young pines on idle farm land. Cut-over forests and extensive areas of adverse sites containing inferior and non-merchantable scrubby trees have also been planted. The continuation of this program and the regeneration of timbered areas that have reached rotation age, soon will lead to the prevalence of pine plantations on virtually all managed forest holdings.

Established timber cruising techniques, developed primarily for the sampling of natural stands, are also applicable in plantations. However, uniformity in the spatial arrangement of individual trees and size-class distribution in plantations permits modification and simplification of conventional practices. The following discussion deals with some of the possibilities in this regard.

Required Measurements

Unmerchantable Plantations

Determination of planting density and survival are the principal reasons for measuring young, unmerchantable plantations. Other information, such as early height growth, incidence and extent of disease and insects, and the nutritional condition of surviving trees, may be collected in conjunction with survival counts.

Measurements for such purposes are usually made one or two years following planting. They may include low intensity survival counts, direct height measurements using graduated measuring rods, and general observations of seedling appearance and condition.

In nutritional experiments, some workers have measured seedling diameters at the ground line, using finely calibrated calipers. The product of the square of this diameter and total seedling height provides a volumetric estimate closely correlated with actual volume. This may provide a more sensitive index of comparative response to
early cultural treatment than tree height alone. Change in dimensions over time, rather than dimensions at any given time, should be used to measure treatment response. Non-uniformity in size of planting stock and the effect of initial size on subsequent growth and survival makes this consideration important.

Survival counts from aerial photographs of appropriate scale are a distinct possibility after the second season following planting. Techniques and procedures for such measurements are covered in a previous paper by K. Swinford (1965).

**Merchantable Plantations**

Merchantable plantations may be surveyed or examined a number of times during the rotation to obtain needed management information, such as basal area, volume, total and/or merchantable height, growth rate, live-crown ratio, form class, d.b.h. distribution, extent of fusiform cankers and other defects, and insect and disease activity. Various measurements of diameter and height serve as the basis for most of this information.

Routine measurements of d.b.h. are usually made with a well-adjusted tree caliper or diameter tape, the latter being preferred for precise scientific work. For recurring inventories the d.b.h. point should be marked on the tree so that all future measurements can be taken at the same point.

Diameter above d.b.h. is usually estimated. However, various devices, such as the Spiegel-Relascope and extension calipers, may be used as aids.

Height measurements up to thirty feet can be taken accurately and conveniently with graduated, jointed or telescoping poles. Above this height some form of hypsometer is usually required. One that can be used accurately at distances less than 0.5 chains from the base of the tree, such as the Spiegel-Relascope, will be required in dense plantations.

**Applicable Sampling Principles**

Nearly all data collection in plantations involves some form of sampling, therefore a brief review of pertinent sampling principles may be appropriate at this point. Complete coverage of this subject is
beyond the scope of this article. Standard texts on mensuration and statistics should be referred to for specific details.

**Sampling Intensity**

Determination of the appropriate intensity of sampling in order to achieve an acceptable degree of accuracy of the sample mean is a perpetual problem for timber cruisers. The use of constant-percentage cruises for all plantations is inadvisable. The relatively high values represented usually demand greater attention to accuracy using statistical procedures to determine sampling intensity. In practice this approach is essential to efficiency in cruising.

Population variability is the key to accuracy of the sample mean. With a good estimate of expected variability—usually expressed as the coefficient of variation—it is possible to design a cruise that will meet any desired limit of accuracy. The required number of sampling units is easily obtained by applying any of several sampling formulae, such as the following one proposed by J. W. Girard and S. R. Gevorkiantz (1939):

\[
n = \frac{(N t^2 c^2)}{(Na^2 + t^2 c^2)}
\]

In which:  
- \( N \) = Total number of sampling units in the population.  
- \( a \) = The limit of the allowable error as a decimal fraction of the mean.  
- \( n \) = The required number of sampling units.  
- \( t \) = The multiple of the standard error for the limit of error selected.  
- \( c \) = The expected coefficient of variation for the size and shape of sampling unit employed-expressed as decimal fraction of the mean.

Determination of the number of sampling units in the population when using the variable plot radius (VPR) system of cruising is facilitated by a procedure suggested by M. Afanasiev (1958).

Selection of an appropriate coefficient of variation for the sampling intensity equation should be guided by experience in similar stands or based upon a partial sample of the plantation made prior to the cruise. The paper on plantation sampling referred to previously (Swinford, 1965) covers methods of estimating variability and cites examples of coefficients of variation that have been obtained in various cruises of slash pine plantations in Florida.
The following well-known formulae may be used to estimate the coefficient of variation based upon preliminary, partial sampling of the plantation in question.

\[
SD = \sqrt{\frac{\sum X^2 - (\sum X)^2}{n}} \quad CV = \left( \frac{SD}{Mean} \right) \cdot 100
\]

In which:  
SD = The standard deviation in terms of unit values of X.  
X = Values per plot for the parameter being considered.  
\(\sum X^2\) = Sum of the squares of the individual plot values.  
n = Number of plots or points in the sample.  
CV = Coefficient of Variation.

For fixed acreage samples the values of X in the preceding formula would be plot basal area or plot volume, which would require considerable computation after preliminary sampling was completed. In VPR cruising, tree count per plot may be used as the basic statistic for determining the SD of basal area per acre. The CV is then calculated by dividing the SD by the mean tree count. This value, obtained rather quickly from eight to ten preliminary sampling points, can be substituted for the CV of volume. This permits an immediate field computation of the required number of sampling points for the population.

**Stratification**

Despite the fact that plantations tend to be much more uniform than natural stands, a certain amount of variation in number and size of trees from place to place within the plantation frequently will be encountered. This will result from variation in site quality, often indicated by topography, and the effects of destructive agents such as fire, insects, and disease.

Data must be recorded separately for such strata and the average volume for the total plantation computed by weighting each individual strata average by the individual strata acreage.

Even if different strata are not readily recognizable it may be worthwhile to divide the plantation arbitrarily into blocks of approximately equal acreage and treat each block as a separate stratum. The weighting process is considerably simplified if blocks are of identical acreage.
Location of Sampling Units

Regardless of the sampling method employed, care should be taken to eliminate bias in locating individual sampling units. Plots or points may be located systematically at uniform intervals or at random. However, statistical procedures should not be applied to systematic samples without a thorough understanding of the various implications of such practice. S. H. Spurr’s text on forest inventory (1952) covers this in a rather thorough treatment of systematic versus random selection of sampling units.

Plots of systematic surveys should be located in a uniform grid pattern. Where this is not feasible, such as in low intensity sampling of large areas, it will be best to use closely spaced plots along widely spaced lines perpendicular to the topography. The same applies to the location of sampling points for systematic VPR cruises.

Random location of sample plots or points is practical for plantation cruising. Using tables of random numbers available in most any statistical text, a two- or three-digit number, depending on the total number of rows in the plantation, can be selected as the row number for each individual sample. A second series can be selected to indicate the distance—in feet or chains, or number of trees—along the row to the plot center or sampling point. A constant offset of a few feet in a given direction may be used at each location to avoid having sampling points fall directly on the trees. Field location of random plots will be facilitated if the distances for all plots are preselected and their relative locations are marked on cross-section paper in advance of the field work.

Sampling Error Determination

With the increasing value of forest land and timber, and the comparatively high volumes represented in merchantable plantations, an estimate of sampling error is rapidly becoming an essential part of a basal area or volume estimate.

In order to compute the sampling error it is necessary to maintain a separate tally of each sampling unit. Special tally forms can be devised to facilitate this practice.

The sampling error formula is as follows:

$$SE = \sqrt{\frac{(SD)^2}{n}}$$
PLANTATION MEASUREMENTS

In which: SE = Sampling error in the same unit in which the SD is expressed.

SD = Standard deviation, computed from the variation among the various sampling units as indicated in a previously described formula.

n = Number of sampling units.

If the sampling intensity is relatively high and the population finite, a better estimate of the SE will result from the following modified formula:

$$SE = \sqrt{\frac{(SD)^2}{n}} \cdot (1 - \text{proportion sampled})$$

Since most plantation samples will be of a relatively low intensity, the difference in the values obtained by the two equations will usually be insignificant.

Where estimates of several different strata of a plantation are to be combined to obtain an overall average for the total plantation, computations should be weighed by individual strata acreages as illustrated in the following example (Meyer 1953):

<table>
<thead>
<tr>
<th>Type</th>
<th>Area (acres)</th>
<th>Stand Per Acre with Error</th>
<th>Total Stand with Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>30</td>
<td>400 ± 70</td>
<td>12000 ± 2100</td>
</tr>
<tr>
<td>2</td>
<td>20</td>
<td>500 ± 50</td>
<td>10000 ± 1000</td>
</tr>
<tr>
<td>3</td>
<td>10</td>
<td>600 ± 40</td>
<td>6000 ± 400</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td></td>
<td>28000</td>
</tr>
</tbody>
</table>

SE for the total plantation = $$\sqrt{2100^2 + 1000^2 + 400^2}$$

$$= \pm 2360$$

Thus, the total stand, with its error = 28000 ± 2360, and the average stand per acre, with its error will be:

$$(28000 \pm 2360)/60 \text{ or }$$

approximately 467 ± 39
Sampling Methods

Conventional Procedures

Among the several sampling techniques adaptable in plantations are the following: fixed-acreage plot sampling, variable plot radius or point sampling, and row sampling.

As indicated by Swinford (1965), the first two methods have been used equally well by the pulpwood industry and state and federal forest services in the southeast. Row sampling apparently has had little application by these organizations.

Row Sampling Due to its apparent unfamiliarity, a brief discussion of row sampling seems appropriate at this point. This is an efficient method for plantation inventory.

This is essentially a fixed-acreage sampling method employing rectangular plots one or more rows of trees in width and one to five or more chains in length. The length used is arbitrary. Assuming a between-row spacing of ten feet, a length of 3.3 chains will form a \( \frac{1}{10} \)-acre area for a two-row width. This should be satisfactory for young, well-stocked plantations. In older plantations which have had several thinnings, and in others in which the timber is scattered, it may be preferable to use plots up to \( \frac{1}{4} \)-acre in size. Here it may be advantageous to use a four-row plot, 4.12 chains long, rather than a two-row plot of twice this length. Long, narrow plots will give good results where tree rows are oriented at right-angles to zones of site quality, or if there is little apparent stratification. Sometimes it will be desirable to extend the plots across the entire plantation, resulting in what amounts to a strip cruise. However, if rows tend to parallel topography or existing site quality boundaries, a better sample will result from the use of a greater number of comparatively short, row-sampling units.

A measurement of plot width is necessary to determine the sample acreage. For management cruises of plantations of uniform spacing, a single, average value may be used for all plots. This can be obtained from one or more randomly located distance measurements across twenty to forty rows. If spacing varies from place to place, or if great accuracy is desired, it will be preferable to determine a separate average width for each pair of rows along which plots are located. If it is desirable that plots be some exact fraction of an acre in size,
average between-row spacing can govern plot length and be determined prior to plot establishment, but this is not an essential requirement. Some cruisers may prefer to use a convenient plot length, such as two chains, and then accept whatever plot acreage results from the average between-row spacing.

If the data are to be analyzed statistically for error determination, it will be necessary to keep a separate tally for each plot. Should plots differ in size owing to variation in between-row spacing, it will be well to expand plot data to a per-acre basis prior to the analysis. Where plots extend entirely across the plantation, the length of each strip must be determined as well as average width. If this varies appreciably, as in plantations with irregular boundaries, data must be weighted by length or acreage. Appropriate procedures for this are covered by F. X. Schumacher and R. A. Chapman (1942).

Row sampling is efficient for a single cruiser. Plot boundaries are clearly defined, except for volunteer trees and the few residuals of the original natural stand. In practical application of the system, the cruiser drops a handkerchief or other marker between the tree rows at one end of the selected plot. After pacing the required length of the plot, he then tallies the two rows simultaneously as he returns to the marker. To determine average plot width he uses a similar procedure, only this time he removes himself twenty to thirty rows from the marked row and then paces the distance back.

Results with Row Sampling

The author and his associates have had excellent results with row sampling in several different trials. J. W. Willingham and D. A. Graves (1961) compared this system with plot and VPR sampling in a twenty-acre, twenty-three-year old slash pine plantation in Alachua County, Florida. Using a 100 percent cruise as a basis for comparison, they completed twenty-eight separate random samplings of the area with each VPR and Plot system and thirty-five separate sampling units located systematically rather than at random. In both experiments, row sampling showed less variability among means and provided the most accurate estimate of average basal area per acre.

Several different variations of row sampling were recently tested in a fifteen-year-old plantation located in Alachua County, Florida. Detailed 100 percent inventories had been made of sixteen 1-acre thinning study plots in this uniformly spaced plantation (trees care-
fully planted seven feet apart in rows ten feet apart). Using these data it was possible to reconstruct a rectangular plantation eighty rows in width and 16.4 chains in length (19.926 acres total). This was necessary because the individual plots were separated by border zones which were not inventoried. Also, plots were not aligned in a manner which permitted systematic sampling.

Basal area in square feet and volume in cords were available for each tree of the reconstructed plantation. These volumes were based upon individual d.b.h. measurements to the nearest 1/10-inch and a separate local volume table for each of the thinning plots.

The results of several different inventories of relatively equal intensity in the reconstructed plantation are shown in Table VII. Sampling units in all cases consisted of row samples of varying width and length. Estimates of basal area and volume per acre were within 5 percent of actual values in all but two inventories; the maximum error was 7.6 percent. Only one inventory showed an error greater than 5 percent in estimates of the number of trees per acre.

Unfortunately, estimates by the VPR method of sampling could not be obtained for comparison. Time did not permit actual field sampling of the plantation by this method and no suitable means could be devised for applying the method to the 100 percent plot inventory data.

**Progressive Sampling**

The high degree of uniformity in plantations permits a much lower intensity of sampling for a given accuracy than is usually possible in natural stands. Samples of as little as 3 to 5 percent of the total area may yield errors of less than 10 percent even in plantations less than ten acres in size. Most natural stands of such small acreage would require sampling 50 percent or more of the area for comparable accuracy. In plantation inventory, therefore, considerable saving in time and expense is possible through limiting the sample to that needed to achieve the desired accuracy.

As discussed previously, cruises can be designed to meet any stated accuracy if a good estimate of the expected variability is available. Estimates can be made by observation, based upon prior experience, but these are often subject to considerable error. As a result, when the cruise error is calculated additional sampling may be required to meet the accuracy specifications. Superimposing these additional plots on
Inventor;  
1 Total area of plantation = 19.93 acres.
2 Errors expressed as percentages of values obtained by 100% cruise of the plantation; Basal area/acre = 141.978 sq. ft. Volume per acre of trees 5" d. b. h. and larger = 35.207 cords. Number of stems per acre, all live trees = 485,685.

<table>
<thead>
<tr>
<th>Inventory Number</th>
<th>Total area cruised</th>
<th>Error in basal area estimate</th>
<th>Error in cordwood vol. est.</th>
<th>Error in Estimated trees/acre</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>9.73</td>
<td>-4.80</td>
<td>-5.86</td>
<td>-3.18</td>
</tr>
<tr>
<td>2</td>
<td>9.73</td>
<td>-7.60</td>
<td>-6.15</td>
<td>-10.50</td>
</tr>
<tr>
<td>3</td>
<td>9.68</td>
<td>+0.88</td>
<td>+0.99</td>
<td>+0.16</td>
</tr>
<tr>
<td>4</td>
<td>10.16</td>
<td>+1.32</td>
<td>+1.34</td>
<td>+2.09</td>
</tr>
<tr>
<td>5</td>
<td>9.73</td>
<td>-2.91</td>
<td>-3.83</td>
<td>-0.31</td>
</tr>
<tr>
<td>6</td>
<td>9.73</td>
<td>-3.15</td>
<td>-3.57</td>
<td>-4.98</td>
</tr>
<tr>
<td>7</td>
<td>9.73</td>
<td>-1.34</td>
<td>-2.16</td>
<td>-0.21</td>
</tr>
</tbody>
</table>

Systematic row-sample with 8 lines, 8 plots/line. (Plots 1-chain long and 2 rows wide—.0303 acres/plot). 
Systematic row-sample with 8 lines, 4 plots/line. (Plots 2-chains long and 2 rows wide—.0606 acres/plot). 
Systematic row-sample with 5 lines, 6 plots/line. (Plots 56-feet long and 5 rows wide—.0643 acres/plot). 
Systematic row-sample with 5 lines, 4 plots/line. (Plots 63-feet long and 7 rows wide—.1012 acres/plot). 
Systematic row-sample with 8 lines, 2 plots/line. (Plots 4-chains long and 2 rows wide—.1212 acres/plot). 
Random row-samples with 32 plots. (Plots 2-chains long and 2 rows wide—.0606 acres/plot) 
Representative random row-sample with 2 plots at random from each of 20 blocks of dimensions 210-feet with rows and 200-feet across rows. (Plots 1.6 chains long and 2 rows wide—.0485 acres/plot).
the sampling pattern of the completed cruise is procedurally awkward if not statistically unsound. Such additional sampling may be quite time consuming, particularly if the cruiser waits until he has access to his office calculator to compute the accuracy of his work.

Estimates of variability may also be obtained by preliminary sampling of the area concerned. This, too, may yield an uncertain estimate of the coefficient of variation. Also, the cruiser faces the question of whether or not to include the preliminary samples with those subsequently taken. If they are made a part of the regular sampling scheme, they usually do not fit the adopted plot location pattern. If they are disregarded, the time required to obtain them has essentially been wasted.

During the past five to six years a form of sequential sampling has been tested in plantations. The basic idea was to check accuracy as the cruise progressed, continuing sampling until the desired accuracy was reached.

The major problem in such a procedure is the large amount of computational work required in the calculation of the standard error. Conventional procedure for doing this is complicated and time consuming, thus precluding its use in the field at the time the individual plots are sampled.

Before his untimely death in a plane crash two years ago this past February, Dr. J. W. Willingham developed a procedure for the rapid, and reasonably accurate, field estimation of the standard error of the mean. He, Donald H. Graves (one of his graduate students), and I made limited tests of the system about four years ago. Initial results were not too promising, however, and the system was abandoned in favor of other, more pressing work. The reasons for its apparent failure seemed to be in the VPR point location scheme employed. This was a systematic scheme, starting at the center of the plantation and continuing with sampling points at uniformly spaced intervals along a circuitous path of gradually increasing radii until the required accuracy had been obtained. Since this was usually achieved with comparatively few points, the outer portions of the plantation seldom were sampled. This did not always provide an accurate estimate of the entire plantation, despite the accuracy achieved for the portion sampled.

Further investigation into sampling procedures that would permit a continuous assay of the sampling error lead to a satisfactory appli-
cation of the original idea. For lack of a more descriptive term the method has been named "Progressive Sampling." This seems quite an appropriate title; in practice, random sampling of the plantation progresses until a desired level of accuracy of the mean is obtained.

**Basis of the System** Statisticians have long recognized the possibility of estimating the standard deviation of the mean on the basis of the range in the values of the individual sampling units. R. Ferber (1949), for example, discusses this and presents tabular multipliers called $a_n$, for converting the range into an estimate of the standard deviation. Table VIII gives Ferber's values of $a_n$ for samples consisting of from 2 to 20 sampling units.

**Table VIII.** Multipliers for converting the range in individual sampling unit values into an estimate of the standard deviation and the standard error of the mean.

<table>
<thead>
<tr>
<th>Sample Size (n)</th>
<th>$a_n$</th>
<th>$\frac{a_n}{\sqrt{n}}$</th>
<th>Sample Size (n)</th>
<th>$a_n$</th>
<th>$\frac{a_n}{\sqrt{n}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.8862</td>
<td>0.6263</td>
<td>11</td>
<td>0.3152</td>
<td>0.0951</td>
</tr>
<tr>
<td>3</td>
<td>0.5908</td>
<td>0.3411</td>
<td>12</td>
<td>0.3069</td>
<td>0.0886</td>
</tr>
<tr>
<td>4</td>
<td>0.4857</td>
<td>0.2428</td>
<td>13</td>
<td>0.2998</td>
<td>0.0832</td>
</tr>
<tr>
<td>5</td>
<td>0.4299</td>
<td>0.1922</td>
<td>14</td>
<td>0.2935</td>
<td>0.0789</td>
</tr>
<tr>
<td>6</td>
<td>0.3946</td>
<td>0.1611</td>
<td>15</td>
<td>0.2880</td>
<td>0.0744</td>
</tr>
<tr>
<td>7</td>
<td>0.3698</td>
<td>0.1397</td>
<td>16</td>
<td>0.2831</td>
<td>0.0708</td>
</tr>
<tr>
<td>8</td>
<td>0.3512</td>
<td>0.1241</td>
<td>17</td>
<td>0.2787</td>
<td>0.0676</td>
</tr>
<tr>
<td>9</td>
<td>0.3367</td>
<td>0.1122</td>
<td>18</td>
<td>0.2747</td>
<td>0.0647</td>
</tr>
<tr>
<td>10</td>
<td>0.3249</td>
<td>0.1027</td>
<td>19</td>
<td>0.2711</td>
<td>0.0623</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>20</td>
<td>0.2677</td>
<td>0.0598</td>
</tr>
</tbody>
</table>

1 Tabular value $a_n \times \text{Range} = \text{Estimate of standard deviation of sample. Values of } a_n \text{ from Ferber (1949)}$.

2 Since standard error of the mean = standard deviation $\div \sqrt{n}$; then $a_n$ multiplied by the range will give an an estimate of the SE. $\sqrt{n}$

Carrying this idea one step further and applying the formula for
the standard error of the mean \( \frac{SD}{\sqrt{n}} \), a set of multipliers for converting the range into an estimate of the standard error was developed by dividing each \( a_n \) by the square root of the number of sampling units employed. Appropriate multipliers for samples of two to twenty units are shown in Table VIII.

The values for \( a_n \) do not change significantly beyond the point where a sample size of four or five is reached. Thus, the tabular values would have little utility where the range is based upon more than five sampling units.

Fortunately, the \( a_n \) values apply to the mean range in several sets of samples containing the same number of sampling units. Thus, after having taken a series of three samples, each containing four sampling units, an estimate of the SE can be obtained by multiplying the mean of the range within the three samples by the basic \( a_n \) for four sampling units divided by the square root of the total number of sampling units involved. In this case, \( SE = \text{Mean Range} \cdot \left( \frac{.4857}{\sqrt{12}} \right) \) or .1402.

### Table IX. Multipliers for converting the mean range in sampling unit values of one through eight sampling sets into an estimate of the standard error of the mean.

<table>
<thead>
<tr>
<th>No. of separate sets of samples taken from the population</th>
<th>Numbers of individual sampling units per set ¹</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2</td>
</tr>
<tr>
<td>1</td>
<td>0.6263</td>
</tr>
<tr>
<td>2</td>
<td>0.4431</td>
</tr>
<tr>
<td>3</td>
<td>0.3619</td>
</tr>
<tr>
<td>4</td>
<td>0.3134</td>
</tr>
<tr>
<td>5</td>
<td>0.2803</td>
</tr>
<tr>
<td>6</td>
<td>0.2558</td>
</tr>
<tr>
<td>7</td>
<td>0.2368</td>
</tr>
<tr>
<td>8</td>
<td>0.2216</td>
</tr>
</tbody>
</table>

¹To obtain an estimate of the value of SE, multiply appropriate tabular value by the mean set range at the end of the particular sampling set concerned.
Table IX gives separate values of $\frac{a_n}{\sqrt{n}}$ for one through eight separate sets of samples consisting of two through five sampling units each.

The following example illustrates the procedure: Assume that samples containing three units each were drawn, with the following results after four sets:

<table>
<thead>
<tr>
<th>Set No.</th>
<th>Unit Values</th>
<th>Cumulative Mean</th>
<th>Set Mean Range</th>
<th>Set Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7, 3, 1</td>
<td>3.67</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>2</td>
<td>3, 1, 6</td>
<td>3.50</td>
<td>5</td>
<td>5.5</td>
</tr>
<tr>
<td>3</td>
<td>8, 6, 3</td>
<td>4.22</td>
<td>5</td>
<td>5.33</td>
</tr>
<tr>
<td>4</td>
<td>7, 4, 5</td>
<td>4.50</td>
<td>3</td>
<td>4.75</td>
</tr>
</tbody>
</table>

An estimate of the SE can be made at the end of each set as follows:

1. After first set—$6 \times 0.3411 = 2.047$, which is 54 percent of 3.67, the mean value.
2. After second set—$5.5 \times 0.2412 = 1.3267$, which is 38 percent of 3.50, the mean value.
3. After third set—$5.33 \times 0.1969 = 1.0495$, which is 25 percent of 4.22, the mean value.
4. After fourth set—$4.75 \times 0.1706 = 0.810$, which is 18 percent of 4.50, the mean value.

A linear relationship exists between the estimated SE and mean range for any given number of sampling sets (assuming that each set contains the same number of individual sampling units). It is then possible to prepare graphical solutions to the computations, such as the one illustrated in Figure 9, which may be used in the field to read the estimated SE directly. Regression lines can be located by solving the value of the SE for any two values of the mean range for each number of sampling sets that are expected to be needed during field sampling. Lines for one to eight sets are shown in the example. Additional lines may be constructed, if needed. Based upon experience with the system, it is doubtful if more than four or five sets will be required except in plantations of an extremely variable nature. Figure 9 was prepared for samples consisting of three units each. Separate graphs, of course, will be necessary for each different
Figure 9. Estimated Standard Error of the mean for 1 through 8 random samples of 3 units each.
number of sampling units employed per set. Both three-and four-unit sets were tested. Based upon preliminary findings, three-unit sets are recommended for small sampling strata (less than four acres in size) with four-unit sets employed in larger strata.

**Field Results with the System** The system is applicable to both merchantable and unmerchantable plantations.

**Merchantable Plantations**—Sampling may be done by the VPR method, employing the basal area factor 10 optical fork of a Spiegel-Relascope. A step-by-step application of the method is discussed in detail in the Appendix. Essentially, each plantation is stratified into two or three sampling blocks of equal acreage, and each block separately sampled until a predetermined sampling error is achieved. Within each block, individual sampling units are located at random, applying values drawn from a table of random numbers to determine a distance parallel to the rows and a distance at right angles to the rows from a selected corner of the block for each individual sampling point.

Movement from point to point is facilitated by plotting individual point locations on a sketch map of each block, conveniently prepared on graph paper. Computations are simplified by using a special tally sheet (see Fig. 13) and a 6-inch pocket slide rule.

Results of the use of the system in thirteen merchantable plantations in Alachua County, Florida are shown in Table X. In all cases, sampling progressed until the estimate of the standard error was 8 percent or less of the mean VPR point count. At each sampling point, count trees were recorded by 1-inch d.b.h. classes (based upon estimation, supplemented by occasional diameter tape measurements).

The actual error in count was computed later in the office using the conventional sums of squares procedure. Agreement between the estimated and actual errors was very close in practically all cases (see Fig. 10).

Time did not permit a 100 percent cruise of each plantation to check the accuracy of the VPR estimates. However, conventional row-sampling cruises, using systematically spaced strips, were made in each plantations. Sampling intensity and the results of each of these cruises are shown in Table X. The agreement between VPR sampling
Table X. Comparison of results of VPR progressive sampling and conventional row sampling in thirteen merchantable plantations in Alachua County, Florida

<table>
<thead>
<tr>
<th>Plantation number</th>
<th>Total area of plantation (acres)</th>
<th>Fixed acreage cruise using row sampling</th>
<th>Variable plot radius cruise using a BAF 10 factor Spiegel Relascope—progressive sampling to a given accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>% of area sampled</td>
<td>Trees per acre</td>
<td>Basal area per acre</td>
</tr>
<tr>
<td>1</td>
<td>15.4</td>
<td>14.9</td>
<td>338</td>
</tr>
<tr>
<td>2</td>
<td>11.4</td>
<td>13.7</td>
<td>178</td>
</tr>
<tr>
<td>3</td>
<td>3.2</td>
<td>25.0</td>
<td>474</td>
</tr>
<tr>
<td>4</td>
<td>15.9</td>
<td>20.0</td>
<td>65</td>
</tr>
<tr>
<td>5</td>
<td>12.1</td>
<td>17.8</td>
<td>150</td>
</tr>
<tr>
<td>6</td>
<td>11.9</td>
<td>16.9</td>
<td>138</td>
</tr>
<tr>
<td>7</td>
<td>13.7</td>
<td>18.6</td>
<td>144</td>
</tr>
<tr>
<td>8</td>
<td>6.5</td>
<td>11.4</td>
<td>514</td>
</tr>
<tr>
<td>9</td>
<td>4.7</td>
<td>20.6</td>
<td>461</td>
</tr>
<tr>
<td>10</td>
<td>3.2</td>
<td>46.0</td>
<td>585</td>
</tr>
<tr>
<td>11</td>
<td>2.1</td>
<td>63.0</td>
<td>258</td>
</tr>
<tr>
<td>12</td>
<td>10.0</td>
<td>18.4</td>
<td>278</td>
</tr>
<tr>
<td>13</td>
<td>5.4</td>
<td>16.7</td>
<td>192</td>
</tr>
</tbody>
</table>

1 Data from 2-row sampling units extending entirely across the plantation at systematically-spaced intervals.
2 Progressively sampled, using sets of 4 units each, until the estimated error was 5% or less in uniform plantation; 10% or less in variable plantations.
3 Includes all live trees 3-inches and larger in d. b. h. 4 Includes all live trees 5-inches and larger in d. b. h.
5 Based upon an estimate of the average acreage cruised per sampling point—this was taken as the area of a circle, the radius of which was equivalent to the maximum distance that the tree of average d. b. h. would be accepted as a count tree by the sampling device.
6 Deviation of the VPR cruise from the fixed-acreage cruise in per cent of the latter.
and row sampling was very good in all but a few of the smaller, quite variable plantations (see Fig. 11). Through oversight, data for the row-sampling cruises were not kept in a fashion that permitted the computation of their sampling errors. It is likely that the VPR cruises gave results as close to the true mean of each plantation as did row sampling, even in plantations 3, 6, and 9 where VPR results varied from those of row-sampling by 15 percent or more.

The system was further tested in plantation No. 1 by independent cruises by fourteen members of the author’s senior class in forest management. Individually calibrated wedge prisms were used for

![Graph](image-url)
this work (see Table XI). Cruise intensities varied from 2.50 percent to 4.10 percent.

Considering that this was the first or second encounter with VPR cruising for most of these students, results were surprisingly accurate.

The close agreement between their estimated sampling errors and calculated errors is indicated by Figure 12.

Progressive sampling was also tested in the previously mentioned thinning study area where a 100 percent inventory was available. In
this instance, individual sampling units consisted of two rows of trees, two chains in length. Units were located at random throughout the entire 19.9 acres with no attempt at stratification. Sample sets consisted of four plots each and the error was set at 4 percent or less.

Eight separate cruises, ranging from 2.43 to 3.65 percent in intensity, were completed. Basal area, which was available for each tree of each plot, was the only information recorded.

Table XI. Results of VPR progressive sampling cruises of a slash pine plantation in Alachua County, Florida by fourteen senior forestry students

<table>
<thead>
<tr>
<th>Basal Area per acre estimate—error from fixed-acreage cruise</th>
<th>Frequency (Number of students)</th>
<th>Cords per acre estimate—error from fixed acreage cruise</th>
<th>Frequency (Number of students)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Less than 1</td>
<td>2</td>
<td>1-5</td>
<td>6</td>
</tr>
<tr>
<td>1-5</td>
<td>2</td>
<td>6-10</td>
<td>2</td>
</tr>
<tr>
<td>6-10</td>
<td>5</td>
<td>11-15</td>
<td>1</td>
</tr>
<tr>
<td>11-15</td>
<td>2</td>
<td>16-20</td>
<td>1</td>
</tr>
<tr>
<td>16-20</td>
<td>2</td>
<td>21-25</td>
<td>1</td>
</tr>
<tr>
<td>21+</td>
<td>1</td>
<td>26-30</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>31+</td>
<td>1</td>
</tr>
</tbody>
</table>

1 Deviation from a 15 percent, fixed-acreage, row-sampling cruise expressed as a percentage. Row-sample mean values: Basal area—122.71 sq. ft. per acre Volume—39.334 cords per acre.

Average basal area per acre values of the individual cruises were very close to the 100 percent cruise data. Deviation percentages ranged from a high of 7.32 to a low of 0.19 with only three of the cruises showing errors greater than 4 percent. Since basal area is closely related to volume, it is probable that volume estimates also would have been close to the accuracy desired.

Unmerchantable Plantations—Application of progressive sampling in unmerchantable plantations is similar to the random row-sampling
procedure used in the thinning study plantation referred to in the previous section. Samples consisting of three or four sets of individual sample plots are located at random throughout the entire plantation

or in individual strata. Number of surviving seedlings or saplings per plot is the usual parameter.

Four separate plantations, varying in age from four to seven years, were used to test progressive sampling procedure. Individual plots were two chains in length and two rows in width. The average between row spacing, as computed by a distance measurement over

![Graph showing comparison of sampling error](image-url)
**Table XII.** Comparison of random progressive sampling and conventional, systematic row sampling in four unmerchantable plantations, Alachua County, Florida

<table>
<thead>
<tr>
<th>Item</th>
<th>Plantation Number</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Plantation area (acres)</td>
<td>9.60</td>
</tr>
<tr>
<td>Percent of area sampled by conventional row sampling.¹</td>
<td>22.0</td>
</tr>
<tr>
<td>Number of trees per acre by row samplings.</td>
<td>454</td>
</tr>
<tr>
<td>Number of sets of four unit samples required to achieve a satisfactory accuracy level.²</td>
<td>8</td>
</tr>
<tr>
<td>Percent of area sampled by progressive sampling.</td>
<td>4.9</td>
</tr>
<tr>
<td>Error in number of trees per acre by progressive sampling. (%)³</td>
<td>—1.39</td>
</tr>
<tr>
<td>Error estimated on the basis of the range in measured values. (%)</td>
<td>4.60</td>
</tr>
<tr>
<td>Computed error. (%)</td>
<td>4.30</td>
</tr>
</tbody>
</table>

¹ Data from two row-sampling units extending entirely across the plantation at stentially-spaced intervals.

² An error of .5 percent or less was the objective. However, in plantations No. 2 and No. 4 it soon became obvious that this could not be reached and a higher error was accepted.

³ Deviation of progressive sampling mean from conventional mean, expressed as a percentage of the latter.
forty or fifty rows in the central portion of the plantation, was the basis for plot width. Sets consisting of four sampling units each were employed.

Table XII compares the results of random progressive sampling with high-intensity, systematically spaced conventional inventories of the four plantations. Estimates of the average number of stems per acre by the two methods were in close agreement, although progressive sampling was consistently on the low side. Sampling intensities necessary to achieve accuracies less than 8 to 10 percent were two to three times greater than those required in VPR applications of the system in merchantable plantations.

Recommended Procedure for VPR Progressive Sampling in Plantations

Application of this system should follow a well-organized procedure, otherwise the data will be difficult to handle efficiently. The following procedure, developed during preliminary trials in several different plantations, was found to be efficient and practical. It is best described in steps as follows:

1. Based upon a brief reconnaissance, using aerial photographs if possible, sub-divide the plantation into several strata or blocks, the number depending upon total acreage and variability. This should be done in all plantations over four or five acres in size even though different strata are not readily visible. Make all the blocks the same size if possible, ignoring minor irregularities in plantation boundaries. This will greatly simplify later computations of basal area and volume. Experience will indicate the number of blocks to employ. As a guide, it is recommended that at least two blocks be used in all plantations in excess of five acres. In large plantations, individual blocks probably should not exceed five acres in area.

2. Using graph paper, sketch the boundaries of each block at some convenient scale. Then determine the dimensions of each block, both parallel to the rows and at right angles to the rows. Enter this information on the tally sheet (Fig. 13). If blocks are of equal dimensions, a single tally sheet will suffice for the entire plantation. If not, a separate sheet will be needed for each block.

3. Determine the maximum sampling distance parallel to the rows and at right angles to the rows and enter this in the appropriate place on the tally sheet. This distance can be computed for each dimension by the following formula:
PLANTATION MEASUREMENTS

MSD = TD – 2 • (Max. d. b. h. x PRF). In which:
- MSD = Maximum sampling distance parallel to rows (or at right angles to the rows).
- TD = Total distance parallel to the rows (or at right angles to the rows).
- Max. d. b. h. = d. b. h. in inches of largest tree anticipated.
- PRF = Plot radius factor for the prism or angle gage used in the cruising.

**PLANTATION SAMPLING STUDY**

<table>
<thead>
<tr>
<th>Plantation No.</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type or Strata</td>
<td>2 Strata</td>
</tr>
<tr>
<td>Date</td>
<td>2/12/66</td>
</tr>
<tr>
<td>Dimensions of Sampling Area: With rows:</td>
<td>4.0 chains</td>
</tr>
<tr>
<td>Across rows:</td>
<td>4.0 chains</td>
</tr>
<tr>
<td>Est. D.H.H. Largest Tree</td>
<td>10</td>
</tr>
<tr>
<td>Max. D.H.H. Test</td>
<td>0.5 ch Multipliers: With: 3.0 ch Access: 3.0 ch</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Point No.</th>
<th>Location from Corner</th>
<th>Tally (count tries by D.H.H. class)</th>
<th>Total Point Count</th>
<th>Cumulative Count for Strata</th>
<th>Average Count per Print</th>
<th>Range and Mean Range</th>
<th>Tabular Error</th>
<th>% Error</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>With Across rows: 5</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
<td>10</td>
<td>11</td>
<td>12</td>
</tr>
<tr>
<td>1</td>
<td>0.7 2.3</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>2.5 2.4</td>
<td>4</td>
<td>1</td>
<td>2</td>
<td>7</td>
<td>4</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>1.0 2.5</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>5</td>
<td>2</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>1.0 1.4</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>2</td>
<td>13</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>3.0 2.2</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>2.9 3.4</td>
<td>2</td>
<td>2</td>
<td>4</td>
<td>2</td>
<td>1</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>0.9 1.7</td>
<td>2</td>
<td>4</td>
<td>5</td>
<td>3</td>
<td>1</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>2.8 3.2</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>6</td>
<td>1</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>0</td>
<td>8</td>
<td>0.5</td>
<td>2</td>
<td>2.3</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>1</td>
<td>6</td>
<td>0.6</td>
<td>2</td>
<td>2.6</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>1.0</td>
<td>1</td>
<td>1.0</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>0</td>
<td>3</td>
<td>0.6</td>
<td>1</td>
<td>1.6</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5</td>
<td>1</td>
<td>6</td>
<td>1.1</td>
<td>1</td>
<td>1.4</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6</td>
<td>2</td>
<td>6</td>
<td>1.5</td>
<td>1</td>
<td>1.3</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7</td>
<td>0</td>
<td>8</td>
<td>2.3</td>
<td>1</td>
<td>1.4</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>8</td>
<td>0</td>
<td>8</td>
<td>0.9</td>
<td>1</td>
<td>1.3</td>
<td>6</td>
</tr>
</tbody>
</table>

**TOTAL**

<table>
<thead>
<tr>
<th>Count</th>
<th>4 20 31 41 77 9 6</th>
<th>1</th>
<th>199</th>
<th>$\times \frac{1}{25} = 124.375$ Sq. Ft./Acre</th>
</tr>
</thead>
<tbody>
<tr>
<td>38.041</td>
<td>Vol./Acre in (Cds)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Figure 13.** Illustration of tally and computation procedure employed in progressive sampling of plantations.
4. Using a table of random numbers, determine the grid locations of several sets of sampling points and enter the distances on the tally sheet. Also plot the location of each point on the grid map of the plantation. The number of sets required in each block will be determined as cruising progresses. Where blocks are larger than three acres in size it is recommended that a minimum of two sets be used regardless of the set range that results during cruising.

The grid distance parallel to the rows for each point is determined by multiplying the appropriate MSD by a two-digit random number treated as a percentage. The value \((\text{Max d.b.h. x PRF})\) should be added to this to give the distance parallel to the rows from a selected corner of the plantation to the sampling point in question. By similar procedures the distance right angles to the rows is computed for each sampling point. Using a slide rule these values can be computed quickly, even in the field.

5. Using the grid map as a guide, proceed in an orderly fashion to each sampling point of the first two sampling sets, entering the tree count for each point in the appropriate space on the tally sheet.

6. After the two sets have been sampled, the estimated error is computed. This is done as follows:

a Determine the total count and the range in count for the first set.
b Determine the total count and range in count for the second set.
c Determine the mean count and the mean range for the first two sets.
d Enter the error estimation graph and read the estimated error opposite the intersection of the vertical line representing the mean range and the diagonal line representing two sets.
e Express the error as a percentage of the mean count.

7. If the error is within the accuracy limits desired, sampling can proceed into the next block. If not, another set of samples must be taken and the error again computed. This time, the mean range of the three sets serves as the basis for entering the graph and the error is read opposite the three-set diagonal. This process is continued, progressively adding an additional set of samples, until a satisfactory error is reached or until it is impractical to continue sampling.

In setting the accuracy limit for each block it is well to remember that the overall error will be less than the average of the individual
block errors. Where blocks are equal in size and have approximately equal individual errors, the total error will vary according to the number of blocks involved. With five blocks, the total error will be approximately 45 percent of the average of the individual block errors. Accordingly the total error will approximate 50 percent of the average block error with four blocks, 60 percent with three blocks, and about 70 percent with two blocks. Thus, if an overall error of 5 percent is desired for a plantation that has been divided into three blocks, an 8 percent error should be set as the limit from the individual blocks. This can be reduced somewhat as the number of blocks is increased.

8. Basal area and volume are computed after sampling is finished in all blocks. If all blocks are the same size, total average per acre values for the plantation as a whole can be determined by the following formulae:

**a** Basal area per acre = \( \frac{(\Sigma MC) \times BAF}{N} \) in which:

- \( MC \) = Mean count for each block
- \( BAF \) = Basal area factor of the VPR instrument employed
- \( N \) = Number of blocks

**b** Volume per acre =

\[ \frac{[\Sigma MC_1 VF_1 + (\Sigma MC_2) VF_2 + \ldots + (\Sigma MC_n) VF_n] BAF}{N} \]

In which:

- \( MC_1, MC_2, \ldots, MC_n \) = Mean count of individual d.b.h. classes for each block.
- \( VF_1, VF_2, \ldots, VF_n \) = Volume factor for the individual d.b.h. classes.
- \( BAF \) and \( N \) = same as in foregoing equation.

In situations where the same number of sets were taken in each block, the volume equation simplifies to the following form:

\[ \text{Vol} = \frac{[\Sigma TC_1 VF_1 + (\Sigma TC_2) VF_2 + \ldots + (\Sigma TC_n) VF_n] BAF}{n} \]

In which:

- \( TC_1, TC_2, \ldots, TC_n \) = Total count for individual d.b.h. classes
- \( VF_1, VF_2, \ldots, VF_n \) = Volume factor as before
- \( n \) = Total sampling points employed
Wild animals are an integral part of commercial forests. The variety and number of animals are directly, and often very sensitively, controlled by type, type interspersion, and successional stage of the land that collectively controls the capacity of the ever-changing habitat. The effects of change are powerful, rapid, and in some cases devastating to game and nongame species.

So-called virgin forests that exist in a state of vegetal climax usually exhibit great stability in animal composition and numbers, but population densities are rather low. Generally, this is not true in wide areas of commercial forests. These forests are subject to frequent and extensive disturbance which results in large numbers of a few species. Often these are prized game animals. How this disturbance affects wildlife is largely controlled by our ability to meet the requirements of specific species in this dynamic complex.

The first step toward effective management is to determine the wildlife potential of major types in various states of succession and the stage and direction of vegetal trend. A manager should interpret each situation as it effects important species in the faunal complex. He should assess the general population levels of important wildlife species, and gauge the direction these populations will go under a full range of alternative management programs. Finally, he must specify his goals, that is, determine which game and nongame species he will stress in harmony with other resource production goals.

The manager of a commercial forest must be able to assess the state of the plant and animal complex; what its capacities are; where it is going; and how, when, and where to treat, alter, or supplement
the existing community to increase wildlife species that have a high economic or important aesthetic value. Furthermore, he must be able to do this quickly, skillfully, and cheaply.

Inventory of the commercial land complex to determine plant-animal population, composition, density, and change can provide the base information for effective management. For the most part, however, elaborate recurring measurement of forest habitat and wildlife populations is neither practical nor profitable. On the other hand, the days of viewing wildlife as a nuisance are over. The importance of both game and nongame species has assumed economic and aesthetic proportions which cannot be denied by forest managers seeking maximum resource outputs from commercial wild lands. Full realization of wildlife resource benefits will not come by chance or providence—it will result only from skilled, knowledgeable management. Apparently, a very high percentage of rural people depend on commercial forests for their recreation activities and this may be particularly true of the influential, voting male (Maddock et al., 1965). What these people think of commercial forests and the way in which they are managed can bear directly on local commercial programs (namely, taxes). Thus, the measurement of habitat and wildlife populations assumes a critical role. We must caution, however, that very often, when we recognize the importance of a sometimes neglected resource, we are prone to overdo the measurement aspects of the problem, wasting energy which might be profitably directed to learning how to work with the environment. All the inventory information in the world will not do us a particle of good if we do not know how to use it. Our plea is—determine carefully the information differences that limit effective decision-making for increased wildlife production through adjustments in cultural activities, before we start counting.

Once we know our objectives, we must determine what is to be measured. The central need for effective wildlife management is to develop a clear picture of what is happening to key habitat elements and wildlife populations; both of these are vital in providing the manager with base knowledge for effective planning. The balance of our discussion is an attempt to give you some limited idea of what information to collect, when and how to collect it, and what to do with it once you have it.

We have limited our treatment to commercial forests, and the animals and plants we discuss are typically found in natural stands and plantations of the South and Southeast. Most of our discussion
is confined to upland game, but we recognize that many of the managerial activities undertaken on commercial forests have a profound effect on numerous other forms of wildlife. Our discussions cover habitat and population measurements of deer, turkey, grouse, quail, squirrels, and nongame birds (largely passerines).

**Measurement of Key Habitat Elements**

Vegetation measurements in the forest habitat are usually made for any one or all of the following reasons: to find how much food is available (yield); to find how much and what kind of plants are being eaten (utilization); to determine the condition of the range and whether it is getting better or worse (condition and trend); and to describe interrelations between plants, animals, and the environment (habitat relations).

**Yields**

Yields are good expressions of range productiveness and, when correlated with animal requirements, serve as indicators of animal carrying capacity. Two broad classes of food we are most concerned with are forage and fruits. Forage includes all browse and herbaceous growth that is available to game. Fruit includes acorns, nuts, seeds, and fleshy fruits.

**Forage** Forage yields are estimated by harvesting and weighing forage from a series of plots; by visual estimates; by combinations or modifications of these methods; and by indirect comparison with other measurable, but closely correlated, plant characters.

*Clipping and weighing:* In this direct approach, the current season’s growth is clipped from a series of plots of known dimensions. The green weight is usually converted to dry weight at some specified drying temperature until weight is stable. The data are objective and therefore subject to statistical analysis, but the method is very time consuming and laborious. Simplified instructions for field application of this method are outlined by R. S. Campbell and J. T. Cassady (1955) and by L. K. Halls *et al.* (1964). Both papers include recommendations of 3.1-foot-square plots in which grams per plot can be
converted to pounds per acre by multiplying by 10. The most efficient plot size will vary with differing vegetal types, but the 3.1-foot-square plot seems suitable for herbaceous vegetation. Milacre plots may be better for browse. The number of plots needed to meet a specified accuracy can, of course, be calculated with limited presurvey sampling. In nearly all cases the sampling variation is so large that the number of plots needed to properly characterize a range or measure a treatment effect is economically prohibitive by clipping and weighing techniques.

The "rank set" method offers promise in decreasing the number of clipped plots, or increasing sampling precision without increasing the number of plots.

For example, suppose nine sets of three random samples are defined and ranked by ocular judgment on the basis of forage yields. Forage from the highest ranking sample in the first set is clipped and weighed, in the second set the second ranked sample is measured, and the third ranking sample from the third set is clipped and weighed. The sequence is then repeated for the remaining sets and the nine samples clipped out of the twenty-seven samples inspected would include three samples in each of the three ranks. The average of the sample estimates of the means in each stratum (rank) is the unbiased estimate of the population mean.

In a browse and herbage sampling test in a loblolly and shortleaf pine-hardwood forest near Nacogdoches, Texas, we found that sampling variation was reduced nearly one half by use of "rank sets," and we concluded that precision equal to that from simple random sampling could be achieved with about half the number of clipped plots.

Visual Estimates: This method consists simply of estimating the weight of current annual growth on a plot of specified dimensions. It is rapid, and a large number of plots can be examined in a short time. The big disadvantage is that the data are totally subjective, and variation and degree of approximation to actual values are not known. With adequate training and frequent checking, however, the estimator can arrive at good approximations of actual weight, and the method has been used to advantage by J. F. Pechanec and G. D. Pickford (1937), A. H. Carhart and H. Means (1941), W. P. Dasmann (1948), and H. E. Schwan and L. Swift (1941).
This method was recently used to sample deer forage (browse) in Georgia by T. H. Ripley and J. P. McClure (1963). In the Georgia survey, plots were located by Forest Survey crews and browse weights were estimated at twenty systematically clustered cylindrical plots that were one milacre in area and 4½ feet high. In order to assist in crew training and control of weight estimates, a series of photo standards was developed to show forage samples of known weight and dimensions. Data from this survey, when correlated with other measured habitat factors, gave good estimates of the wildlife resource potential and provided basic information for management decisions.

Weight Estimate-Clipping Combination: In this method, often referred to as double sampling, forage weight is estimated on a large number of plots and, in addition, forage on a small number of the plots is clipped and weighed. Using the small-sample data, the relation between actual forage weight and estimated forage weight is determined. This relation, or regression, is then used to correct the estimate of forage weight obtained from the larger sample. The method saves considerable field time compared with clipping methods, and, as an advantage over the weight estimate method, it gives quantitative data that can be examined for statistical variability. With the job of calculating ratios and regressions now simplified through the use of computers, this method may be very useful. Examples of successful double sampling are reported for south Florida ranges by J. B. Hilmon (1959). Here, the optimum ratio of clipped to estimated plots was 1:11. Browse inventories we have taken in Louisiana and Arkansas suggest that the clipped to estimated plot ratio may be about 1:8.

Correlation of Weight with Other Plant Measurements: This method requires correlation of easily measured plant characters with forage weight. Twig numbers and length measurements, for example, offer several advantages: they are representative of the growth potential of a browse plant; measurements are not destructive, and repeat measurements are possible; and the data can be collected rapidly and analyzed statistically.

J. V. Basile and S. S. Hutchings (1966) found that twig characters were sufficiently consistent for predicting weight in western browse plants. In Pennsylvania, E. L. Shafer, Jr., (1963) converted twig
counts to browse weight by use of an average weight per twig for each species and found that this was nearly twice as fast as a weight-estimation method and comparable in accuracy to the more tedious clip-and-weigh method.

J. L. Schuster (1965), in pine-hardwoods forests of East Texas, found good correlations between twig numbers and weight, but they were not as good as total twig length-weight relations. Additional data for several browse species of the southern pine-hardwood forests show that twig length is consistently more closely correlated with weight than either twig diameter or twig number. The variation in weight accounted for by twig length was consistently above 80 percent and quite often more than 90. So far, the twig length-weight relations have been tested for the more important browse plants at a particular time and location. Whether these regressions and ratios can reliably predict weights at other sites and times is yet to be tested. From data already accumulated, it appears that the method will prove useful in making browse surveys.

**Fruits**  Fruits, as a whole, are probably the most important source of food for wildlife, yet methods of measuring fruit yields are generally unsatisfactory. Complicating factors, such as spacial location or variation, time of ripening and period of availability, and progressive use or removal are troublesome.

To date, efforts to evaluate woody plant fruit yields in relation to wildlife have been confined mainly to acorns. Sampling is by individual trees or by area. Individual tree samples are taken by setting traps beneath the crowns or by counting fruit in the tree. In trap samples, the number of acorns per trap is expanded to the number of acorns for the total crown area. The recommended number of traps per tree varies from one to sixteen, but four to six are commonly used. Total counts of attacked fruits are tedious and often require felling the tree. Frequently, the numbers of fruits on sample branches are used to estimate tree totals. Tree data can then be expanded by determining yields from various classes of tree size, form, and species for stands of known composition and density. Area sampling consists of collecting data from small plots distributed over the entire stand. Open, unprotected plots on the ground may be useful if samples can be taken frequently during the fruiting season. Most trapping is preferable to protect against loss of fruit from animal consumption.
Funnel-type traps with a small collection device at the bottom are desirable. Generally, large numbers of traps are required to get good area yield data. Sampling restrictions usually permit only crude yield determinations for year-to-year differences.

Measurement of seed disseminated from low-growing plants has received recent attention, T. H. Ripley and C. J. Perkins (1965). We found that number and weight of seed could be estimated with reasonable accuracy from twelve composites of ten samples of soil 3 inches in diameter and 1 inch thick. To date, this seems the best means of measuring small fruits that do not rapidly deteriorate, such as legume and grass seeds used by quail and turkey.

It is important to remember that yield measurements represent only one period of time, and important ephemeral plants and fruits may be easily overlooked.

**Utilization**

Utilization measurements tell us the amount and kind of food eaten by animals. They are useful in describing the degree of grazing or browsing pressure on plants or ranges, and for rating the relative palatability of plant foods. Utilization can be expressed as the percentage of food consumed in relation to that produced, or as an actual measure of food removed. Utilization data are timely judgments representing conditions at a particular point in time.

There are many ways of measuring utilization. One widely used approach compares yields of protected and unprotected plots or ranges, with the differences representing forage utilization. This method is often used on livestock ranges for measuring herbage utilization, but it is of limited use in assessing wildlife habitat situations. Most wildlife forage utilization estimates are, and have been, concerned with deer browse and are made by selecting a series of plots that is observed at regular time intervals to determine use. For browsed twigs the observer estimates the amount or percentage of material removed—it is presumed, of course, that with training and a good knowledge of plant form the observer can closely approach the actual value. To get some idea of how well estimated weights approach actual weights of forage removed, several browse species were clipped to various degrees, closely simulating deer browsing. Later, four men independently estimated the weight of browse removed.
Each observer estimated actual browse removed for all species within 20 percent. Estimates for most species were within 30 percent of actual weights, but they varied as much as 57 percent for some observers and plants. We suspect these results are typical where browse is actually eaten by deer.

A more objective approach, using measured characteristics, is preferable. Methods involving twig numbers and length have proved practical in western studies by D. Smith and P. J. Urness (1962), and J. V. Basile and S. S. Hutchings (1966). These methods involve establishment of twig length-weight ratios for ungrazed twigs. Then, by counting the number of grazed and ungrazed twigs and measuring differences in their length, a figure for lineal length removed can be calculated which in turn can be converted to weight. The basic assumption is that there is a consistent and definite relation in length and weight for twigs of the same species. Because length is highly correlated with weight for southern browse, we think that the system would be quite workable in this area.

**Condition and Trend**

Condition is the state of health of a range or habitat complex. It is classified on the basis of kind, quantity, age, and vigor of plants present, and also on the condition of soil and litter cover. Trend tells us whether conditions are becoming better or worse. Rarely are restrictions in management needed when the trend is upward, but ranges showing a downward trend usually require immediate and considerable adjustments. Although the condition and trend of a habitat reflects animal use (largely for cervids), rapid and very obvious changes in the habitat as a result of natural plant succession are also documented with these techniques.

Condition and trend measurements have long been of great concern to public land administrators in the West, and the Forest Service relies mainly on Parker’s three-step method, K. W. Parker and R. W. Harris (1959), in making managerial decisions. Parker’s method consists of measuring and observing essential features of vegetation and soil along permanently established transects. Observations are taken with a ¾-inch loop at one hundred points along a stretched tape as a basis for rating site condition at specified times. Documentation of trend or change is supplemented using general and close-up photos.
Using a modification of R. H. Canfield's (1941) line intercept and Parker's three-step, Ripley et al. (1963) devised a system more applicable to the dense understory shrubs, vines, and small trees of southern forests. In this method, all woody plant parts intercepted by a vertical plane of specified height and length are recorded. The plane is quickly and easily defined by running a vertical rod along the edge of the chain. A summarization of intercepts, recorded by species, measures the existing composition and density of food-bearing twigs in woody understories. Repeat measurements along the same plane serve as a basis for measuring change. By implication the system indicates changes in food production.

Equally as important as the actual measurement of changes in plant composition is an explanation of why the changes occur. In southern forests the rapid change in timber stand conditions, whether natural or artificially imposed, may be the most important factor influencing the understory vegetation. Thus, any condition and trend study should also document changing timber conditions.

**Habitat Relations**

We earlier indicated the desirability of developing some concept of why certain phenomena occur in order that better use may be made of survey data. One of the main problems concerning habitat-wildlife relations is how to tell when game numbers and food are approximately in balance. The question would be simple, of course, if food quantities were constant, but they aren't. Acorns may be abundant one year, but scarce the next. Even more important, there may be alternate periods of scarcity and abundance within a year or even a season. One of the best indicators of food sufficiency, for deer at least, is the extent to which the forage plants are eaten. A keen observer can usually see signs of trouble, but the need for definitive guides in judging the degree of the problem is obvious. Some preliminary work by D. W. Lay (1965) in pine-hardwood forests of East Texas indicates that the optimum level of utilization for most browse species is probably close to 25 percent, although he suggests that there are a great many factors that may alter this figure. The kind, number, size, and spacing of trees have a tremendous impact on understory foods, and may operate entirely independently of animal pressure. The degree to which forage declines as timber stand density increases in loblolly pine-hardwood forests has been noted by L. K. Halls and J. L. Schuster (1965) and by E. N. Gaines et al. (1954) in longleaf pines.
Crown cover appears to be a good index to stand conditions governing forage availability. Crown cover can be measured by changing the mirror in an Abney level so that line of sight is directed upward. If the cross hairs intercept a portion of the tree crown above five feet, a hit is recorded. A ratio of hits to misses from fifty or more sightings at one sample location has been used to determine percentage of cover. It has consistently been found more closely correlated with forage yields and better understood than basal area.

In taking tree measurements it is well to distinguish between pines and hardwoods, because the latter are more restrictive to understory growth than pines, at least in stands of pole size or larger. Descriptions of stands can also be useful in predicting future trends in forage conditions. For example, forage conditions are likely to get worse in young stands but improve at stand maturity with increase in forage production, particularly if commercial thinnings are planned. A stand scheduled for final harvest will be most productive during the first four to five years after regeneration, but young vigorous browse will quickly grow beyond reach of deer unless subsequent treatment keeps it near the ground.

**Measurement of Wildlife Populations**

With the exception of deer, our discussion of techniques will be concerned solely with determining animal numbers. Turkeys, squirrels, grouse, and quail, and many species of passerine birds will respond quickly to changes in the habitat. Unlike deer, these species are not beset with long-term, gradual reduction in fecundity and general animal condition due to long-term adverse habitat changes or deterioration from overuse. In order to use population census data effectively, one must have an understanding of the life history, including adaptability and mobility of individual animals and populations under any given set of environmental conditions. All of the harvestable game populations that we will discuss are nonmigratory, and (except for turkeys) all display low mobility. Contrary to widely held misconception, white-tail deer have a restricted home range, and with the exception of fairly extensive seasonal movement of adult males, home ranges probably are in the neighborhood of two hundred to three hundred acres.
Deer

The two basic approaches to censusing eastern white-tails—direct and indirect—have serious limitations. Of the direct method, a drive-and-count census, properly conducted, is probably the most accurate form of counting deer in small tracts. The big disadvantages are problems in projection of sample area counts and high manpower requirements. All partial, strip, or cruise methods have similar difficulties. Several good references on the subject of direct census are available and are recommended to those concerned with these problems (Hazzard, 1958; Downing et al., 1965; Hahn, 1949; and Longhurst et al., 1952).

Several indirect methods are available and have utility under specific conditions. Track and fecal counts are the two most widely used. Track counts have been used with varying success, largely because of extreme day-to-day variability in deer movement. A good account of the problems can be found in the paper by Downing et al. and accounts of success were reported by E. L. Tyson (1959). Except in the South, where dung beetle activity is virtually continuous, the use of the pellet group technique has wide application. It requires considerable field time and care to assure that sample plots are properly located and cleared before the period of enumeration. Pellet group counts have been successful on northern ranges, especially in winter yards. Probably the best account of this method is reported from years of accumulated experience in Michigan by L. Eberhardt and R. C. Van Etten (1956). A good critical discussion of the fecal count technique can also be found in papers by W. L. Robinette et al. (1958), G. Rogers et al. (1958), and Downing.

Obviously, we do not have a really good census technique, but perhaps the best method of maintaining surveillance over deer herds is to keep records of pressure and kill. The use of pressure and kill statistics as population density indices shows some promise; see R. L. Downing (1965), G. H. Kelker (1940), and L. K. Hazzard (1958). General treatments of the subject can be found in Kelker (1940), J. B. Lauckhart (1950), and R. H. Baker and H. R. Siegler's work, (1943).

Fortunately, a great deal of work done on white-tails indicates that excessive population density can be detected by animal condition. This approach probably offers the cheapest and most realistic means of maintaining some knowledge of herd density and harvest require-
ments (Petrides, 1949). Animal condition, as it reflects population density, habitat capacity, and use was discussed by M. M. Alexander (1958). Aging techniques are well developed for white-tails and examination of ovarian and uterine materials can be used to determine herd structure in relation to fecundity and fawning rates (Cheatum, 1949a; Severinghaus, 1949, Armstrong, 1950; Gill, 1956; Park and Day, 1942). In extreme cases of malnutrition on northern ranges, examination of long bone marrow can give a very good picture of herd stress. Cheatum's work (1949b) in New York is authoritative in this area.

The main things for practicing foresters to remember are that the white-tailed deer is a long-lived animal, it has a small home range, its active breeding years extend over ten or more years, and the fawning rate (depending upon condition of the range) may vary from half a fawn per adult doe on very poor ranges up to two fawns on excellent range. Fawning rate, condition and weight, antler development, and other characteristics are sensitive and useful as a management tool. For the extensive forested areas of the South, we think that a modest but continuing effort to maintain information on animal condition, plus periodic sampling for condition and use of key forage species, provides a reasonably good base for white-tail management.

**Turkeys**

The wild turkey is a highly prized but poorly understood game animal. We do know, however, that once wild strains of turkeys have been established and populations have been nourished into reasonably solid numbers, the wild turkey will hold tenaciously to its habitat and exhibit remarkable recovery following periods of adversity. Its populations seem little affected by heavy gunning pressure, and with reasonable protection from baiting and poaching, turkeys apparently can be maintained indefinitely.

Direct measurement of turkey populations is probably the only effective means of determining turkey numbers. Hen, poult, and flock counts on areas which are reasonably accessible can be maintained and give a pretty good picture of turkey population density. Good discussions of this problem can be found in papers by W. R. Bailey *et al.* (1951), D. M. Hoffman (1962), J. A. Powell (1965), and project reports by M. L. Burget (1957) and E. A. Walker (1951). Full treatment of the subject was covered in papers presented at the Wild
Turkey Symposium held in Memphis, Tennessee, in 1959 (in press). Selected references from this compendium by W. R. Bailey (1959) would be especially useful to forest managers.

Apparently, the principal factors affecting turkeys are rainfall during the nesting season and, possibly on some ranges, human disturbance. As with other game birds, the wild turkey has a high turnover rate, but fall populations or shootable surpluses of birds are controlled to a large extent by the nesting success and productivity of the preceding summer. Reasonably frequent observations maintained by resident foresters on hen-poult ratios may give a good index to fall population numbers, and papers by D. DeArment (1959) and C. E. Knoder (1959) are good references for hen-poult indices.

For the practicing forester, direct observations represent the best means of "keeping track" of wild turkey populations. Where possible, resident managers can maintain records of hen-poult ratios, and year-to-year shooting records certainly are useful to forest managers dealing with large areas of commercial forests.

**Ruffed Grouse**

Although interest in the ruffed grouse is probably limited with this group, we want to cover the species because it is important in the Southern Appalachians (Edwards, 1957). Some of the best work on grouse has been done with northern birds. G. Bump *et al.* (1947), F. C. Edminster (1947), and the compendium of papers on grouse in the *Journal of Wildlife Management* (1963) provide excellent background for anyone interested in this subject.

There are two general approaches to censusing grouse—although both are weak. The first involves strip counts or census of belt transects where either broods or grown birds are counted. One of the most widely used of these procedures was developed by R. T. King (1937). Brood censuses based on a modification of techniques described by King were developed and used successfully by F. F. Fogg (1956) in New Hampshire. The strip count of adult birds or broods can be used with a varying or fixed-width belt and is theoretically capable of yielding good estimates of population density. All other techniques are at best indices to grouse populations. The second approach involves counting drumming males (Palmer, 1961). This has been widely tested, and is used by several state game agencies. A very good discussion of the drumming count method and numerous
other inventory procedures was reported by F. C. Hardy (1952), R. S. Dorney et al. (1958), and G. A. Ammann and L. A. Ryel (1963).

By and large, grouse are little affected by gunning pressure and managers of commercial forests should be well satisfied if they can maintain grouse populations using common-sense approaches, such as increasing edge and cover diversification. The only possible exception to this would be smaller selected areas of commercial forest land which consistently support high grouse populations and where grouse hunting is a major objective. Under these conditions it may be justifiable to indulge the appetite for population information to predict the level of hunting success.

Quail

The bobwhite quail is one of the most important game animals on commercial forests in the South, where it is an economic crop on millions of acres of pinelands. Fortunately, there is a good body of knowledge on this species which is directly applicable to commercial forests, and quail are very responsive to skillful management.

The bobwhite is a short-lived species with an annual turnover of about 80 percent, extremely low mobility, and strong territorial instincts. Population density is very closely linked with active land disturbance, for the bobwhite feeds heavily on seeds and plants which are typically found where land is subject to continued and heavy disturbance. The bobwhite occurs most abundantly in two distinctly different types of ecosystems—diversified farm economics and burned pinelands.

The census of bobwhite numbers, while interesting, is usually of value for a very short period of time, and unless the manager intends to make immediate use of population figures, he is apt to find them completely outdated within a few months. Because quail are so responsive to habitat manipulation and disturbance, we think that keeping track of key elements in the habitat may be more useful than bird counts. In fact, an extensive but skilled look at understory annuals will give a good picture of the range condition for quail. As we have noted, the high occurrence of legume flora, Panicums, Paspalums, and fruit-producing shrubs is associated with high quail populations.

There are two fairly useful techniques for censusing bobwhites. Again, one is an indirect method that involves counts of singing males.
Bobwhite males sing from vantage points in the early summer, and the system of routes which can be traveled by automobiles can be used to count total numbers of birds heard from various stops. Annual records can be compared to determine general trends in quail populations. This technique has been widely used and we have had considerable experience with the method. Probably the best discussion of the subject can be found in papers by R. Bennitt (1951) and W. Rosene (1957).

The literature is full of references on the second basic technique of direct census. By repeatedly covering large blocks of land with finished bird dogs, fairly accurate inventories of coveys and total birds can be established. On northern ranges populations have been censused "virtually to the last bird" by snow track counts, as reported by P. L. Errington and F. N. Hamerstrom (1936) in their classic study. Earl Frye (1954), working in south Florida, had excellent success with strip count flushing techniques similar to those used for grouse inventory work, and was able to keep good records on quail population on the Cecil Webb Area in Charlotte County, Florida. Another good reference is a paper by H. S. Mosby and Q. A. Overton (1950).

As with other species, kill records can be most useful where they can be maintained with limited effort. Except under unusual conditions, where intensive management of the species is practiced, we think that careful reconnaissance of disturbed understories may be the best approach to the problem.

**Squirrels**

Squirrels (gray and fox) are among the most important small game animals in many of the commercial forests of the South, especially in mixed pine-hardwood stands and hardwood stands where mast production is fairly abundant (Bertram and Gault, 1952). Managers of many commercial forests will be concerned with obtaining maximum hunting use from squirrel populations. Squirrels, like many other species of small game, seldom suffer from excessive gunning pressure under a reasonable management program and realistic shooting regulations. Good, general references are the squirrel symposium edited by V. Flyger (1959) and the gray squirrel analysis by H. R. Redmond (undated).

Several techniques for censusing squirrels have been developed, but
only two seem worthy of discussion here. The first is direct, and involves time-lapse counts of squirrels in sample plots. Limited experience in Georgia with insular populations suggests this may be useful.* An indirect method of counting leaf nests, although of doubtful value in comparing different ranges, may be useful for determining year-to-year changes in squirrel populations. H. G. Uhlig (1956a) found that most of the leaf nests were constructed by juveniles approximately eighteen weeks of age. Presumably, then, the more leaf nests there are in any year for any given area, the higher the squirrel population. Uhlig’s work (1955, 1956b) and that by L. L. Baumgartner (1940) dealing with production and other life history considerations in the gray and fox squirrel may be helpful. D. L. Allen’s papers (1942, 1943) on the population and habits of fox squirrels may also provide useful information. Studies by P. P. D. Kline (1964), and D. N. Danilov (1941) have shown that highly variable squirrel populations are closely associated with the production of mast in antecedent years, and that highs in population usually follow periods of high mast production. We think that census of squirrels will be of use only to people concerned with determining squirrel population response to specific land management treatments. Again, simple bag checks and the knowledge of forest composition and mast production probably will suffice.

Census of Nongame Birdlife

Although wild land managers often recognize the importance of game species, it is increasingly evident that the great bulk of people have an attraction for nongame birdlife. Failure to recognize the needs of important passerine and other nongame species (many of which have important economic roles) may have a profound, adverse effect on local attitude toward an otherwise effective and responsive policy of land management. An excellent example of progress has been made by the Forest Service in maintaining Kirtland’s warbler habitats in jack pine stands.

Although practicing foresters normally have little contact with vanishing or endangered species, commercial forests of the South and East provide the habitat for millions of breeding pairs of nongame

* The authors have contacted biologists in Georgia working with this technique and learned that the method produces highly variable results but offers some promise.
MEASURING THE FOREST WILDLIFE RESOURCE

birds, ranging from tiny nuthatches to pileated woodpeckers, numerous raptors, and a host of insectivorous warblers, thrushes, and the like. It is interesting that Roger Tory Peterson (1963) estimated that there were no less than five billion, and probably closer to six billion, land birds in the United States at the beginning of this decade.

Although the practicing land manager normally has little direct interest in maintaining census of important nongame birds, he may have occasion to plan and carry out at least partial population surveys in his forest domain. Probably the most widely used technique, and one which is successfully employed by the Audubon Society, involves enumerating singing males in their breeding territories. This gives an index to the number of pairs per acre in different types of habitat. (Birdlife in the United States varies from an estimated low of one bird per acre on prairie and short grass plains to fifteen or sixteen birds per acre in bogs, swamp-bordered hardwood lands, and southern hardwood forests.) Land managers having occasion to enumerate forms of birdlife probably will find that the method used by the Audubon Society in counting singing males is one of the most effective, and can be applied to sample counts for expansion (Wallace, 1959).

We have suggested that both game and nongame wildlife species represent an important resource on commercial lands. It is clear that these lands usually support highly dynamic communities that are primarily used for the production of some other resource—usually timber. It is equally clear, however, that the production of wildlife is not only a desirable aesthetic and sociopolitical adjunct, but it may be an important economic addition in commercial forests. The fact that the author was invited to prepare this article is evidence, apparently, that there is a rapidly growing concern “to do something for wildlife.” This something, we are assured, must be a planned, orderly program of wildlife management.

We have stressed that effective management of commercial lands for wildlife production must be grounded in a fairly sophisticated understanding of the wildlife habitat complex—its potential and degree of use by animal life. We have indicated that in some cases it may be desirable for the manager to census game and nongame species, but that by and large (with the possible exception of deer) a simple record of kill may suffice.

In the case of nongame birdlife, recognition of unusual forms and special habitat situations may meet most needs. We have tried to
emphasize those things which we think are important to the land
owner as he approaches the problem of measuring wildlife popula-
tions, and we have urged that managers exercise care in the selection
of techniques that they can apply judiciously. Finally, managers of
commercial forest lands are in a much better position to regulate
hunting than are most public land managing agencies. They can take
advantage of new findings and incorporate new techniques much more
rapidly than can public agencies, generally. It is heartening, then, to
see industry taking a vital interest in the wildlife complex. It would
seem to be only a matter of time before commercial forest interests
will assume a leadership role in the management of wildlife resources.

LITERATURE CITED

ALEXANDER, M. M. 1958. The place of aging in wildlife management.
Amer. Sci. 46 (3): 123–137.

ALLEN, D. L. 1942. Populations and habits of the fox squirrel in Allegan

Game Div., Pub. 100. 404 pp.

ALLEN, J. M. 1952. Gray and fox squirrel management in Indiana. Dept. of


ARMSTRONG, R. A. 1950. Fetal development of the northern white-tailed
deer (Odocoileus virginianus borealis Miller). Amer. Midland Naturalist

BAILEY, R. W. 1956. Sex determination of adult wild turkeys by means

BAILEY, R. W. 1959. Preliminary report on wild turkey banding studies
as applicable to management in West Virginia. Conserv. Comm. of West
Va. (Paper presented at the Wild Turkey Symposium. Memphis, Tenn.,
Feb. 13–15, 1959.)


BAKER, R. H., and H. R. SIEGLER. 1943. Use of bag record of big game
to determine sex ratios and population densities. Jour. Wildl. Mgmt. 7 (1):
11–13.


BAUMGARTNER, L. L. 1940. Trapping, handling, and marking fox squirrels.

BENNITT, RUDOLF. 1951. Some aspects of Missouri quail and quail


FOGG, F. F. 1956. Results of a study of ruffed grouse population trends in New Hampshire for the past eight years. New Hampshire Fish and Game Dept. 7 pp.
———, R. B. FERGUSON, and J. S. GASHWILER. 1958. Problems involved


