Comparison of Three Methods of Estimating Surface Area and Biomass for a Forest of Young Eastern White Pine

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Abstract. This paper presents estimates of foliage, branch and stem surface area, and ovendry weight, with estimates of precision of these statistics, for a 10-yr-old stand of eastern white pine on a 16-ha watershed at the Coweeta Hydrologic Laboratory in the Southern Appalachians. Three different methods were used to estimate the forest surface area and biomass: (1) stratified two-phase sampling, (2) two-phase sampling with a regression estimator, and (3) two-phase sampling with a ratio-of-means estimator. Stratified two-phase sampling was the most precise and appropriate method; the population was estimated to contain 5.3 ha foliage, 0.76 ha branches, and 0.13 ha stems per hectare of land surface. The estimated ovendry weight of tree components was estimated to be 2.71, 6.83, and 7.01 metric tons per hectare, respectively, for foliage, branches, and stems. The standard error of estimate for surface area and biomass ranged from 5 to 10 percent, depending upon the tree components of interest. ***Forest Sci. 20:91–100.***

Additional key words. *Pinus strobus*, sampling, conifer, foliage, branches, stems.

THE QUANTITY OF TREE SURFACE AREA and tree biomass per unit area of land are inventory data needed to understand the flow of energy, nutrients, and water through forest ecosystems. Surface area, in contrast to biomass, has received little attention. Although Whittaker and Woodwell (1967) described the surface area relations for several deciduous forests in the eastern United States, comparable studies for evergreen forests are lacking.

A deficiency common to surface area and biomass estimates in early studies of forest communities was the lack of statistical statements about the reliability of estimated quantities. The quality of results can vary greatly because a series of sampling steps are involved; thus, the error term for a population estimate depends on the error associated with each sampling step. Attiwill and Ovington (1968) and Satoo (1967) pointed out the need for appraising different methods of determining forest biomass. Ovington *et al.* (1967) and Attiwill (1966) calculated the magnitude of errors which may occur when different methods are used to estimate the biomass on a forest plot. However, forest ecosystem investigations may involve populations considerably larger than a plot, and procedures for assessing the precision of population prediction from sampled values become more complicated.

Our study of surface area and biomass was stimulated by the results of several watershed experiments at the Coweeta Hydrologic Laboratory in western North Carolina. These experiments demonstrated that streamflow reductions of 10 percent occurred 10 yr after watershed cover types were changed from mature hardwoods to

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white pine (Swank and Miner 1968). The results suggested that appropriate vegetative parameters should be measured which logically describe cause and effect relationships when water losses are compared within and between forest ecosystems. Therefore, the immediate objectives of this study were twofold: (1) to estimate the quantity of surface area and biomass for foliage, branches, and stems in a 10-yr-old stand of eastern white pine (*Pinus strobus* L.) at one point in time by several methods, and (2) to derive error terms for these estimates.

Study Area

The study area is Watershed 1, at the Coweeta Hydrologic Laboratory, a 16.1-ha, south-facing catchment. Slopes average 48 percent and elevations range from 706 m at the weir site to 988 m at the top of the catchment. Rainfall averages 1,727 mm, and streamflow averaged 787 mm annually prior to cover type conversion. In 1956, the predominantly oak-hickory forest (19.3 m^2 of basal area/ha) was clearcut; slash was scattered and partially burned; and white pine seedlings (2-0 stock) were planted during the winter of 1957. Initial survival was only 60 percent and much of the area was replanted in 1958. Thereafter, competing hardwood sprouts were cut or sprayed with 2,4,5-T to release the pine.

Methods and Results

Measurements and procedures used to estimate surface area and biomass of the white pine were developed as follows: (1) an inventory of trees was obtained by diameters from plots distributed at random within the population; (2) a method of measuring fascicle area was applied to selected foliage samples, and a regression equation for estimating foliar area was derived; (3) sample trees were cut and separated into foliage, branches, and stem in the laboratory, and specific measurements were made on each component; (4) a technique for measuring branch surface area was applied to selected branch samples, and an equation for estimating surface area was obtained; (5) surface area and biomass of foliage, branches, and stem were calculated for each sample tree and equations for estimating area and biomass of each tree component were computed; and (6) surface area and biomass of each tree component were estimated for the population with several alternative methods, and the error terms for each method were derived.

Hereafter, in text references to branches and stems, the term surface area includes both wood and bark. Our terminology thus is synonymous with the definition of bark surface area by Whittaker and Woodwell (1967).

Tree Inventory

During the winter of 1967, after 10 growing seasons, the pine stand was inventoried by measuring dbh (1.37 m) of every tree on 20 randomly located, 0.08-ha plots. Mean basal area was 7.3 m^2/ha; mean stocking, 1,780 trees/ha; and mean tree diameter, 7.4 cm. The frequency distribution of trees by 2.5-cm diameter classes (Fig. 1) indicates a slight positive skewness. Trees averaged 8 m in height; the stand was not fully closed and even the lowermost nodes on most trees supported foliage.

Fascicle Area Determination

In transverse section, needles of eastern white pine are approximately triangular in shape, with two straight (radial) surfaces with stomata and one slightly convex surface without stomata. Individual fascicles of five needles are a convenient and logical unit of foliage to use in determining surface area because the needles can be oriented to form a solid geometric figure (Kozlowski and Schumacher 1943, Cable 1958). The problem then is to measure and define the geometric shape accurately. It is also desirable to relate surface area to a more easily measured characteristic of the fascicle, such as dry weight or volume.

Our measurement technique was similar to the method Kozlowski and Schumacher (1943) used to measure the surface area

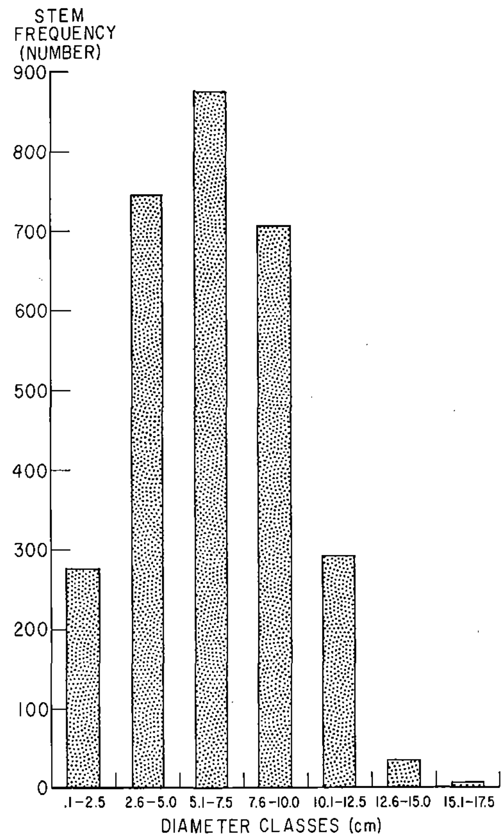

FIGURE 1. *Distribution of trees by 2.5-cm diameter classes for the white pine stand on Watershed 1.*

of loblolly pine (*Pinus taeda* L.) and eastern white pine fascicles. We chose ovendry fascicle weight as a measurement related to area. The needles in each fascicle were oriented and spirally wrapped with a light thread from base to apex so that the radial sides of the needles were in tight contact along the entire fascicle length. The fascicle was then immersed in water and stored in a refrigerator for several hours prior to measurement. Fascicle diameter was measured with a micrometer caliper to the nearest 0.01 mm at four approximately equidistant points along the length of the fascicle. The point of measurement was examined under 10× magnification and the micrometer contact surface was adjusted until the needles formed a tight fit, as evidenced by the extrusion of water between the needle edges. Repeated diameter measurements on a fascicle by the same person and by different individuals showed precision within 2 percent. Fascicle length was measured to the nearest millimeter from the junction of the petiole and needles to the tip of average needle length (within most fascicles, needles were uniform in length). Following the measurements, fascicles were ovendried at 70°C and weighed to the nearest milligram.

These techniques were applied to 485 fascicles collected during February and March of 1967 from 10 randomly selected trees that were distributed among the 3-, 8-, and 13-cm diameter classes. Five to 10 fascicles were selected from every node within each tree. Fascicle length ranged from 50 to 142 mm and fascicle dry weight ranged from 18 to 167 mg.

Fascicle diameter measurements revealed that the majority of the fascicles were tapered toward the base and the apex. Thus, to define the geometric form of an average fascicle, we averaged diameter measurements for similar positions on the 485 fascicles and determined the average fascicle length. When considered as a solid geometric figure, the fascicle of average dimensions is a truncated prolate spheroid. Generally, a cylindrical shape is assumed. Comparison of total surface area estimates for the two geometric forms shows that the cylindrical shape overestimates the area by 2 percent. Similarly, Madgwick (1964) found that the assumption of a cylindrical form for fascicles of red pine (*Pinus resinosa* Ait.) overestimated surface area by an average of 5.6 percent when compared to values derived by the repeated Simpson's rule.

The cylindrical shape assumption requires fewer measurements than does the truncated prolate spheroid. Therefore, fascicle area was calculated for the cylinder formula and the small bias in surface area estimate can be corrected at a later time if needed. The curved surface is estimated by the formula

$$S_1 = \pi dh \qquad (1)$$

where d is the mean diameter of the fascicle based on four measurements and h is total fascicle length. The formula for the total surface of the 10 radial surfaces is therefore

$$S_2 = 5\,hd. \quad (2)$$

A scatter diagram showed that total fascicle area was linearly related to fascicle weight, expressed as

$$Y_1 = 3.61709 + 0.10588\,X_1 \quad (3)$$

where $18 \text{ mg} \leqslant X_1 \leqslant 167 \text{ mg}$, Y_1 is estimated fascicle area (cm^2), and X_1 is ovendry fascicle weight (mg). Fascicle weight accounts for 92 percent of the variation in fascicle area, and the standard deviation about the regression is 0.75 cm^2. Equation (3) includes all measured fascicles because, in a prior analysis, a test for common regressions by covariance analysis for the three tree diameter classes sampled showed that little precision was lost by pooling the data. Additional examination of the data indicated that a weighted regression analysis would not be better than the unweighted analysis.

Other investigators have suggested that fascicle area is curvilinearly related to fascicle weight (Madgwick 1964). The relationship for white pine fascicles showed a curvilinear tendency at the lowest range of data. Thus, 10 additional fascicles, ranging from 4 to 11 mg but from a population of natural seedlings, were collected and measured. These additional data verified the curvilinear relationship which was expressed as

$$\log_{10} Y_1 = 0.61353 \log_{10} X_1 - 0.08491 \quad (4)$$

where Y_1 and X_1 are the same as in equation (3). Log fascicle weight again accounts for 92 percent of the variation in log fascicle area. Direct comparison of regression error terms for transformations of the dependent variables is not valid. The common procedure is to compare correlation coefficients (Cox 1968). This comparison indicates that the linear fit is as good as or even better than the curvilinear fit for the range of data considered. Based on this comparison and simplicity of the relationship between variables, equation (3) is used in this paper to estimate foliage area.

Sample Tree Collection, Laboratory Separation, and Measurement

Seven diameter classes (strata) were designated, based on the tree diameter distribution obtained from the inventory plots. Twenty trees were selected by stratified random sampling from these diameter classes over the entire watershed during February 1968. This sampling time was chosen because biomass is probably most static during late winter and this period provides a base time for comparative measurements in succeeding years.

Trees were measured for dbh, stem diameter at 1-m intervals, total tree height, and the height of each node above the ground. Branches were cut flush with the stem and bundled by node for transport to the laboratory and cool storage. The stem was divided into three equal-length sections and a disk (bark included) approximately 4 cm thick was removed from the middle of each section for subsequent analysis.

In the laboratory, foliage of each node was manually separated from the branches. The separation was accomplished as rapidly as possible (a 50-day period) to minimize weight losses by respiration (Forrest 1968). The basal diameter of every branch was measured and the number of branches per node was recorded. Foliage and branches were dried at 70°C and weighed.

To calculate tree foliar surface area with equation (3), the number of fascicles on each sample tree must be known. The number of fascicles can be derived by dividing foliage weight by mean fascicle weight. Thus, samples containing 100 fascicles each were selected at random from 157 nodes (14 nodes had no foliage), and an additional subsample containing 100 fascicles each was taken from 44 of these nodes. The weight difference of the two independent subsamples taken from 44 nodes was generally less than one percent of the mean of the two samples, but a large gradient in mean fascicle weight

TABLE 1. Regression coefficients, R values and standard deviation about the regression (n = 171) for estimating white pine branch area and branch weight using untransformed and transformed relationships.

Dependent variable *Y*	Independent variable *X*	*a*	*b*	*r*	Standard deviation about the regression[1]
Branch area (cm^2)	Branch weight (g)	228.55	7.8343	.977	369
Branch area ($\log_e$) (cm^2)	Branch weight ($\log_e$) (g)	2.5353	.9508	.962	.4087
Branch area (cm^2)	Branch basal diameter squared (mm^2)	–257.61	6.0999	.946	564
Branch area ($\log_e$) (cm^2)	Branch basal diameter ($\log_e$) (mm)	–.4023	2.6545	.902	.6486
Branch weight (g)	Branch basal diameter squared (mm^2)	–59.79	.7713	.959	61.65
Branch weight ($\log_e$) (g)	Branch basal diameter ($\log_e$) (mm)	–3.2913	2.8681	.963	.4108

[1] For log–log equations, the standard deviation about the regression is in log units.

within trees was found. For example, mean fascicle weight within a 16.7-cm tree decreased from 99 mg for the uppermost node to 84, 64, 43, 46, 41, 37, 35, and 26 mg for successively lower nodes. Therefore, fascicle numbers were calculated by node from the mean fascicle weight and total foliage weight of each node.

The ends of the fresh stem disks were leveled and smoothed, diameter and length measurements for volume determinations were taken, and the disks were dried at 70°C. The density of each disk was determined for later use in calculating stem weight from stem volume.

Estimation of Branch Area

The surface area of a branch segment can be computed by simple geometric formulas if the taper within the segment is negligible. A segment refers to the internodal portions of the branch. Diameter measurements for segments showed their maximum taper was only 3 percent, even for the larger branches with diameters up to 35 mm. Thus, it is logical to assume a cylindrical shape for a segment, and the surface area can be readily calculated from the formula for a cylinder as $S_b = \pi dh$, where S_b is outer surface area of the branch segment, d is the diameter at midpoint, and h is length.

In the laboratory, one branch was selected at random from every node for each sample tree for a total of 171 sample branches. Each sample branch was cut into segments and the segments were separated into 2-mm diameter classes using a slotted form. Segment lengths were measured to the nearest millimeter and the surface area of each diameter group was calculated. Total surface area of the sample branch was obtained by summing surface area values of segments.

Sample branch surface area and weight were related to several branch measurements by regression analysis (Table 1). Sample branch weights ranged from 2 g to 835 g, and basal diameter of branches ranged from 3 mm to 35 mm. The analysis showed that all independent variables listed are closely correlated with branch area and that branch weight is the most reliable predictor of branch area. The equation used in subsequent calculations of branch area can then be stated as

$$Y_2 = 228.55 + 7.8343\, X_2 \qquad (5)$$

where $2 \leqslant X_2 \leqslant 835$, Y_2 is estimated fresh area of a branch (cm^2), and X_2 is ovendry weight of a branch (g). In studies where destructive sampling is undesirable, branch area and weight can be estimated from branch diameters, although the equations are valid only for branches that have not undergone deterioration following death.

Sample Tree Surface Area and Biomass Computations and Equations

Thus far, the analysis has given basic equations for estimating fascicle area and branch area. The next step is computation

TABLE 2. *Sample tree regression coefficients, R values and standard deviation about the regression (n = 20) for estimating surface area and biomass of various components for eastern white pine.*

Equation No.	Dependent variable *Y*	Independent variable *X*	*a*	*b*	*r*	Standard deviation about the regression[1]
(1)	Foliage area (m^2)	Basal area (cm^2)	3.716	0.70351	.988	9.406
(2)	Foliage area ($\log_e$) (m^2)	DBH ($\log_e$) (cm)	–.6662	2.0541	.989	.1884
(3)	Branch area (m^2)	Basal area (cm^2)	.04944	.11122	.983	1.8072
(4)	Branch area ($\log_e$) (m^2)	DBH ($\log_e$) (cm)	–2.01831	1.82289	.988	.1683
(5)	Stem area (dm^2)	Basal area (cm^2)	31.29	1.09327	.984	17.18
(6)	Stem area ($\log_e$) (dm^2)	DBH ($\log_e$) (cm)	1.663	1.3856	.994	.0883
(7)	Foliage weight (g)	Basal area (cm^2)	221.1	35.067	.979	625.1
(8)	Foliage weight ($\log_e$) (g)	DBH ($\log_e$) (cm)	3.051	2.1354	.985	.2250
(9)	Branch weight (g)	Basal area (cm^2)	–1332.	133.79	.980	2360.
(10)	Branch weight ($\log_e$) (g)	DBH ($\log_e$) (cm)	3.158	2.5328	.990	.1728
(11)	Stem weight (kg)	Basal area (cm^2)	–.3292	.11570	.990	1.415
(12)	Stem weight ($\log_e$) (kg)	DBH ($\log_e$) (cm)	–2.788	2.1338	.994	.1439

[1] For log–log equations, the standard deviation about the regression is in log units.

of area and biomass for foliage, branches, and stem of each sample tree.

Sample tree foliage area and branch area were calculated using equations (3) and (5) with the appropriate number and oven-dry weight of fascicles and branches. The biomass of these two components was measured directly and contains only a small error, due primarily to respiration loss between collection and drying. Stem biomass and surface area of sample trees were calculated after first determining the geometric form of the stems. A plotting of diameters taken along the length of the stems showed that a conic shape was the best approximation for the stems of these young trees. Thus, the surface area of stems was computed using the formula for the curved surface of a right cone

$$S_s = \pi r \sqrt{r^2 + h^2} \qquad (6)$$

where h is tree height and r is the stem radius at ground level. The three sample sections from each sample tree showed a density gradient within most trees. Therefore, stem weight for a sample tree was calculated by applying the density measurement to the appropriate stem volume.

Sample tree area and biomass data were plotted and related to expressions of stem dimensions at breast height. Regression statistics for the relations between area, biomass, and stem dimensions are summarized in Table 2. The analysis shows a strong relationship between the logarithm of tree diameter and the logarithm of various tree components, a fact reported by many investigators for other forest tree species. However, there is also a good untransformed relation between tree basal area and the area and biomass of tree components. The problem then is to determine which equation is most appropriate for subsequent application to the population. Since variances from several sampling steps must be combined to obtain error terms for population estimates, untransformed dependent variables offer the fewest operational difficulties. But the choice between untransformed and logarithmic equations also rests upon a comparison of correlation coefficients. Since this comparison indicates that little precision is lost using the untransformed relationship, equations (1), (3), (5), (7), (9), and (11) in Table 2 are used below to obtain population estimates.

Watershed Surface Area and Biomass Estimates and Error Terms

The flow diagram in Figure 2 illustrates the relationship between previous sampling steps and three different methods used to

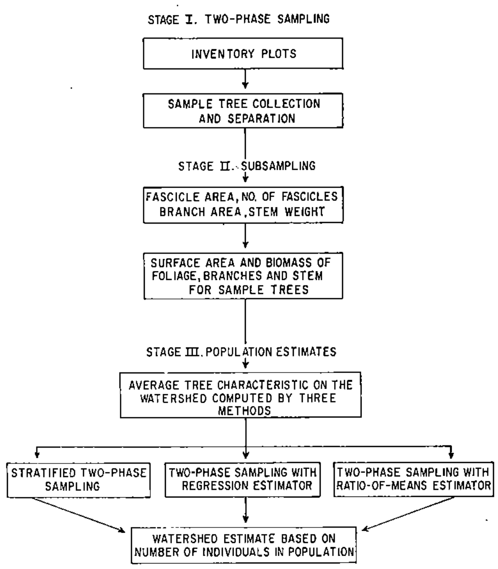

FIGURE 2. *Diagram illustrates the relationship between sampling stages and three methods of estimating tree characteristics for a watershed.*

estimate watershed parameters. Formulas for estimates and variances for each sampling method are too lengthy to be included in this report, but they can be obtained from the authors upon request.

The sample selection procedures consisted of two-phase sampling with subsampling (Stages I and II), which are common to all three methods. The first phase of two-phase sampling consists of an inventory of trees obtained from sample plots, giving estimates of the total number of trees, the total basal area, number of trees in each of seven strata, or other useful parameters for the watershed. The second phase of two-phase sampling consists of sample tree data obtained either directly in the case of biomass and stem area or in combination with subsampling in the case of foliage and branch area. This phase provides estimates of average (per tree) stem, branch and foliage biomass, and surface area.

The information obtained from Stages I and II can be combined in several ways (Figure 2) to provide estimates of average and total surface area and biomass of foliage, branches, and stems on the watershed. The three basic estimation methods used in this study (with and without subsampling) are: (1) stratified two-phase sampling, (2) two-phase sampling with a regression estimator, and (3) two-phase sampling with a ratio estimator.

In the stratified estimation method, the independent variable (diameter) is used to stratify the population into seven strata. The variance of the estimator and an estimator of this variance were derived by standard procedures used in stratified sampling (Cochran 1963), under the assumption that random plot sampling can be treated as random sampling of trees. This method provides essentially unbiased estimation of watershed averages and efficient error estimates. The method is particularly efficient when allocation of sample trees to the different strata is based on prior knowledge of strata sizes and within-strata variability of the dependent variable.

The regression estimation method uses basal area as the independent regression variable. Unbiased estimation using this estimator requires linearity between the dependent and independent variables. Moreover, for efficient estimation and for unbiased error estimation, the variance of the dependent variable at each given value of the independent variable should be a constant value (that is, homogeneity of variance needs to be assumed). It was necessary to treat the random plot sampling as random tree selection in deriving the variance of the estimator and in deriving an estimator of this variance. In addition, $1/n$ (n is number of sample trees) should be a negligible term for the variance formula to be a satisfactory approximation of the true variance.

Two-phase sampling with subsampling with a ratio estimator is unbiased if linearity through the origin can be assumed for the regression relationship between the variables. This estimator is most efficient if, in addition to the above condition, the variance of the dependent variable is proportional to each value of the independent variable (basal area). The standard variance estimation formula is a satisfactory approximation only if the second-phase sample size is large enough so that the

TABLE 3. Estimates and standard error of estimates (shown in parentheses in percent) for surface area and biomass of a white pine stand using three different estimation methods.

	Surface area (ha/ha)			Biomass (tons/ha)		
Estimation method	Foliage	Branches	Stems	Foliage	Branches	Stems
Stratified two-phase sampling	5.3 (8.7)	0.76 (7.1)	0.126 (5.3)	2.71 (10.2)	6.83 (8.2)	7.01 (8.4)
Two-phase sampling with regression	5.8 (8.6)	.82 (11.2)	.135 (6.7)	2.95 (10.7)	7.35 (16.0)	7.87 (9.6)
Two-phase sampling with ratio-of-means	5.4 (10.1)	.82 (11.1)	.104 (14.3)	2.74 (11.7)	8.72 (13.8)	8.19 (9.9)

ratio of sample means can be replaced by the corresponding ratio of population means.

The final estimates, with standard errors of estimates expressed in percent, are shown in Table 3.

Discussion

Since the primary interest of the study was the estimation of surface area and biomass for the watershed, this discussion will be restricted to estimates given in Table 3. One basic assumption is required for unbiased estimation and valid variance estimation. It states that the estimate of the number of trees on the watershed is independent of the estimates of mean tree surface area and biomass. An analysis of inventory plots revealed there was no apparent correlation between number of trees and average tree basal area. Hence, in this study unbiased estimation up to this point of analysis can be safely assumed.

In stratified sampling, only one additional assumption has been made; that is, random plot sampling is treated as random sampling of trees. A check of plots showed that the within-plot variability in tree basal area was larger than the variability between plot means. This comparison indicates that plot sampling is efficient relative to random sampling of trees so that the above assumption may lead to overestimates of the actual precision of the estimates. The estimates of the strata weights are biased, but the bias should be negligible because of the large sample of trees from the plots. Stratified sampling appears to be the best method because only the above additional assumption is needed and the method generally provides estimates with the best precision (Table 3). Therefore, stratified two-phase sampling will be used as a standard with which the two other estimation methods are compared.

The superior performance of the stratified sampling is due to the large number of strata that eliminated as much variability as would the use of the same independent variable in regression analysis. Also, allocation of the 20 sample trees to the strata happened to be favorable. As can be seen in Table 4, strata variances fluctuate considerably; generally larger sample sizes were assigned to the more variable strata. The large differences between strata variances indicate that improvement in precision could be achieved by optimum allocation of sample sizes to the strata. Estimates of stem and branch areas and weights were more precise than the same foliage variables in stratified two-phase sampling. Differences in the within-tree sampling procedure (subsampling) do not contribute significantly to the error estimation for any variable, and the two-phase sampling procedure was exactly the same for all variables. Thus, the differences in the precision of estimates must be due to the inherently larger variability in foliage. The greater variability of foliage estimates can probably be attributed to foliar fluctuations caused by diseases, insects, and the microenvironment, factors which affect branches and stems to a lesser degree.

The large differences between stratified sampling and regression estimation may be due primarily to sampling error. Confi-

TABLE 4. Within stratum variances for tree components expressed as a percentage of the smallest within stratum variance.[1]

Tree component	Stratum 1	2	3	4	5	6	7
Foliage area	145	145	100	4,164	2,114	1,141	13,873
Branch area	100	100	343	766	1,541	4,813	7,134
Stem area	100	100	369	142	592	1,878	808
Foliage weight	124	124	100	5,531	5,010	1,406	15,906
Branch weight	100	100	406	2,773	3,344	8,314	17,017
Stem weight	100	100	1,361	5,077	23,257	34,386	9,258

[1] Only one sample tree was obtained from stratum 1, hence we used the within-stratum-2 variance estimate for the stratum-1 variance estimate.

dence bounds at the 95 percent level constructed around any of the point estimates contained all point estimates. Two-phase sampling with a regression estimator is essentially unbiased in all six cases, since the assumption of linearity seems reasonable in all cases. The results in Table 4 were used to check the assumption of homogeneity of variance. It is clear that the assumption was not contradicted in the case of foliage area, stem area, and foliage weight in the sense that the variance within each stratum was not an obvious function of the independent variable. The assumption was clearly violated in the case of branch area, branch weight, and, to a lesser extent, stem weight. Thus, the regression estimates may be efficient in the case of foliar area, stem area, and foliage weight, but are inefficient with unreliable estimates of precision in the other cases. Although homogeneity of variance has not been refuted, neither has it been accepted; and where regression estimation may be appropriate, it is only slightly better than stratified sampling in one case and poorer in the other two cases. Even if the variance estimates were appropriate for branch area, branch weight, and stem weight, regression estimation would clearly be inferior to stratified sampling estimation in these cases. The highly inefficient regression estimation in the case of branch biomass is probably due to some curvilinearity in the relationship between the variables.

In two-phase sampling with a ratio estimator, the assumption of linearity through the origin is necessary for an essentially unbiased estimation. Although theoretically reasonable for all variables, the data indicate this assumption seems reasonable only for branch area and stem weight. An assumption necessary for efficient estimation is that the variance of the dependent variable at each value of the independent variable be proportional to the value of the independent variable. This assumption is best met for branch area, branch weight, and stem weight, as reflected in the error estimation (Table 3) where ratio estimation is slightly better than regression estimation for branch area, considerably better for branch weight, and slightly poorer for stem weight. In all cases ratio estimation is much poorer than stratified sampling estimation.

Conclusion

It appears that stratified two-phase sampling is the preferred estimation method because of the efficiency and minimum assumptions. Two-phase sampling with a regression estimator is second best, although results were quite erratic in the case of branch biomass. Two-phase sampling with a ratio estimator was always poorer than stratified two-phase sampling but better than regression estimation in two out of six cases.

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