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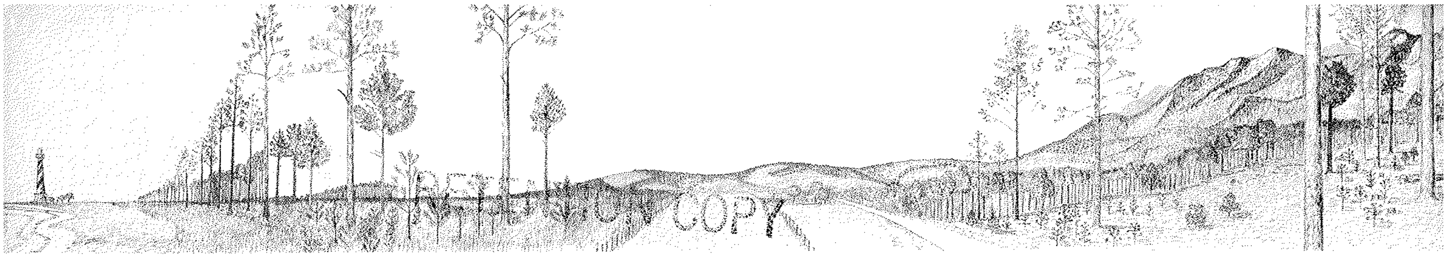

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ESTIMATING THE VOLUME OF HARDWOOD CROWNS, STEMS, AND THE TOTAL TREE

by Douglas R. Phillips, and Noel D. Cost [1]

Abstract.—Forest Survey procedures for estimating crown, stem, and total tree volumes from standing tree measurements are compared with felled tree measurements of 62 northern red oaks. Cubic-foot volumes based on standing tree measurements averaged 8.4 for crowns, 36.3 for stems, and 44.4 for the total tree; whereas cubic-foot volumes for the same trees after felling averaged 11.0, 36.2, and 47.2 cubic feet for these components. Regression equations were developed to predict crown, stem, and total tree volumes for northern red oaks. The squared value for diameter at base of live crown was the best single variable for predicting crown volume. Crown, stem, and total tree volumes can be determined by applying d.b.h. and total height measurements to the equations given.

KEYWORDS: Cubic volume, standing tree measurements, *Quercus rubra* L., prediction equations, volume comparisons.

Accurate estimates of cubic volumes for hardwood crowns, stems, and total trees are needed to determine the potential value of standing and harvested trees for use as solid-wood products and for fuel and fiber. Crown volume estimates are needed to determine forest fire hazards, total stand productivity, nutrient cycling, and even wildlife habitation, but these data are usually lacking. Limited information on hardwood crown volumes has been reported by Keays (1971); Clark and Schroeder (1977); and Phillips (1977). Much information is available on hardwood crown weights, but these data can be used to determine volumes only if reliable weight-volume conversion factors are available.

Since 1975, the Southeastern Station's unit on Renewable Resources Evaluation (Forest Survey) in Asheville, North Carolina, has been working to develop estimates of regional and statewide biomass. In 1975, this unit modified its measurements of standing trees to include all branch material in the crowns of all tree species. This modification allowed the unit, for the first time, to estimate the volume in the total tree above ground. For the past 9 years, the Southeastern Station's unit on Utilization and Technical Characteristics of Southern Timber in Athens, Georgia, has been working to develop biomass data for the major hardwood species in the Southeastern United States.

These two units recently combined their efforts in a cooperative study in North Carolina. Northern red oak (*Quercus rubra* L.) was chosen as the test species because of its commercial importance and great crown variability. In this Note, estimates of the cubic-foot volumes for main stems, crowns, and total trees as based on Forest Survey procedures for standing trees are compared with volumes derived from actual measurements after the trees were felled. Regression equations developed by the Utilization Unit

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to predict crown, stem, and total tree volumes are presented.

CROWN VARIABILITY

Northern red oaks are especially difficult to measure for crown volume. Their crowns are extremely variable and have a large number of branches of all sizes. These branches have varying amounts of bark, foliage, and fruit arranged in an infinite number of patterns. Also, they are not accessible nor always visible when standing trees are measured. Crown dimensions, such as branch diameter and length, must often be determined at distances of 100 feet or more.

Measuring crowns on felled trees can also be difficult. Accurate crown volumes cannot be determined by applying diameter and length measurements of each branch and twig to some formula, as is done for stems. The best approach is to weigh the branches and then divide weight by a weight-per-cubic-foot factor determined from wood and bark samples taken from the branches. This procedure was used on the felled trees in this study.

PROCEDURE

Sixty-two northern red oak trees, 6 to 24 inches d.b.h. (diameter at breast height), were selected from natural, even-aged stands in the mountains of North Carolina. Thirty-one pole-size trees 6 to 11 inches d.b.h. were selected from one stand, and 31 sawtimber trees 12 to 24 inches d.b.h. were selected from another.

MEASURING STANDING TREES

Standing trees were measured at 4.5 feet above ground for d.b.h. and double bark thickness. Tree crown class was determined for each tree. Total height was measured by extending 5-foot sectional aluminum poles to the top of each tree. Diameter measurements were taken on the main stem of each tree with a hand-held McClure (1969) Mirror Caliper by taking readings in 4-foot sections to a 9-inch d.o.b. (diameter outside bark) top and in 5-foot sections from 9-inches to a 4-inch d.o.b. top. The volume in these sections from a 0.5-foot stump to a 4-inch d.o.b. top represents standing stem volume.

The crown was measured as follows: (1) Forks, if present, were measured in short sections much as in the main stem—by 4-foot sections to a 9-inch d.o.b. and by 5-foot sections to a 4-inch d.o.b. The portion from 4.0 inches d.o.b. to the tip was measured as one section. (2) All main-stem branches greater than 4.0 inches d.o.b. at the base were measured in 5-foot sections to a 4-inch d.o.b. The portion from 4.0 inches to the tip was measured as one section. (3) Main-stem branches less than 4.0 inches but greater than 1.0 inch were measured as single sections according to basal diameter and branch length. No main-stem branches less than 1.0 inch d.o.b. and no secondary branches and twigs in the crown were measured. All diameter measurements were made outside bark and converted to inside bark according to bark thickness factors developed by Forest Survey.

The volume of each section was determined by Grosenbaugh's (1952) formula:

$$\text{Volume (cubic feet)} = 0.005454154\, L \left[Dd + \frac{(D-d)^2}{K} \right]$$

where: L = length of section in feet,
D = average diameter (inside bark) at *large* end in inches,
d = average diameter (inside bark) at *small* end in inches,
K = constant (2 for paraboloid, 3 for conoid, and 4 for subneiloid).

The stump volume from ground level to approximately 0.5 foot is not included in the volumes reported here, but when it is measured a K-factor of 4 is used. Volume of the main stem, forks, and utilizable limbs to a 4-inch d.o.b. was computed with a K-factor of 3. A K-factor of 2.4 was used for portions from 4.0 inches to the tips of forks, utilizable limbs, and the main stem, as well as for all branches between 1.0 and 4.0 inches d.o.b. For more details on these measurements and volume formulas, see Cost (1978).

MEASURING FELLED TREES

Each tree was felled and measured for total height, height to a 4-inch d.o.b. top, and height to the base of the live crown. Crown width was measured to the nearest foot. Stem d.o.b. measurements were taken at groundline and at the base of the live crown. Crown length and crown ratio were computed from the measurements of stem length.

Individual trees were weighed in the woods to determine green weights of stems, crowns, and total trees. Small trees and crown material were weighed on platform scales; saw logs were weighed with electronically operated load cells.

Cross-sectional disks were cut from the stem and crown of each tree so that weight-per-cubic-foot factors could be determined for these components. Stem disks were taken from each pole-size tree at the butt, at d.b.h., and at quarter points up the stem to a 4-inch d.i.b. (diameter inside bark). Stem disks were taken from sawtimber trees at the butt, at each bucking point between 12- to 16-foot saw logs, and at 8-, 6-, and 4-inches d.i.b. Branch samples of various sizes were taken from each tree crown. All samples were returned to the laboratory for analysis.

In the laboratory, wood samples were processed to determine moisture content, specific gravity, and weight per cubic foot. Moisture content was determined after samples were ovendried to a constant weight at 103°C. Specific gravity was determined on a green volume and ovendry weight basis. Moisture content and specific gravity data were used to compute green wood weight per cubic foot values. Felled tree volumes (stem, crown, and total tree) were determined by dividing the green weight of each tree section by a computed green weight per cubic foot for that section.

RESULTS AND DISCUSSION

STANDING VS. FELLED TREE VOLUMES

The use of sectional aluminum poles to measure the height of standing trees is extremely accurate. Total height of standing trees averaged 83.2 feet, whereas the same trees measured 83.4 feet on the ground (table 1). In each d.b.h. class, estimated total height was very close to the actual height of the felled trees. Similar results were reported by McClure (1968).

Forest Survey's estimates of crown volume of standing trees were too conservative. Average crown volume was estimated at 8.4 cubic feet; the average for felled trees was 11.0 (table 1). Crown estimates were below actual values for felled trees in each d.b.h. class, with the largest difference occurring in the larger trees.

Crown volume estimates were low primarily because not all branch material was measured. As noted earlier, none of the main-stem branches less than 1 inch d.o.b. and none of the secondary branches and twigs in the crown were measured. We had hoped that the secondary branches would be compensated for by applying the parabolic form of the volume equation to all main-stem branches at least 1 inch d.o.b. As it turned out, such was not the case. To help correct this prob-

Table 1.—Comparisons of heights and average wood volumes for northern red oak trees while standing and after felling

D.b.h. (inches)	Sample trees	Total height		Average volume					
				Crown		Stem		Total tree	
		Standing	Felled	Standing	Felled	Standing	Felled	Standing	Felled
	No.	.... *Feet*		.... *Cubic feet*					
6	4	61	60	1.2	1.4	4.5	4.5	5.7	5.9
7	6	68	66	1.4	1.8	6.9	6.7	8.3	8.5
8	7	69	69	1.9	2.4	9.3	9.4	11.2	11.8
9	5	77	75	2.4	3.2	12.2	12.2	14.6	15.4
10	5	75	74	3.6	4.0	15.7	15.4	19.3	19.4
11	4	84	80	4.1	4.4	20.0	20.5	24.1	24.9
12	5	85	83	5.4	6.9	24.3	25.6	29.7	32.5
14	5	92	94	9.7	12.1	37.9	39.2	48.8	51.3
16	6	94	96	10.6	13.4	45.9	47.3	56.6	60.7
18	4	94	96	12.7	16.6	58.4	59.8	71.1	76.5
20	4	100	101	15.7	21.0	77.5	77.8	93.2	98.8
22	5	101	106	26.4	36.2	106.8	104.6	133.2	140.8
24	2	97	96	32.4	46.2	111.5	109.9	143.9	156.1
Weighted study average	62	83.2	83.4	8.4	11.0	36.3	36.2	44.4	47.2

lem, future measurements will be taken on all lateral branches 0.5 inch d.o.b. and larger rather than on branches 1 inch d.o.b. and larger.

Forest Survey's estimates of stem volume of standing trees were quite accurate. Average stem volume for the 62 standing trees was 36.3 cubic feet, whereas that for felled trees was 36.2 cubic feet (table 1). Within each d.b.h. class from 6 to 24 inches, estimates for standing trees varied less than 5 percent from those for felled trees.

Estimates of total tree volume in standing trees averaged 44.4 cubic feet, whereas felled trees measured 47.2 cubic feet (table 1). The low estimates for total volume of standing trees were due to the low estimates of crown volumes.

PREDICTED VOLUMES

In the development of prediction equations, a number of independent variables (tree physical characteristics) should be screened. The importance of a variable depends on the accuracy it provides, the needs of the user, and the resources required to measure the variable. In this study, we examined d.b.h. (D), total height (Th), diameter at base of live crown (DCr), crown ratio (CR), crown length (CLn), crown width (CWd), and crown class (CCls) as independent variables. We then examined the relationship between these independent variables and actual cubic volumes of felled trees by computing correlation coefficients (r). Crown volume was most strongly correlated with the squared value for stem d.o.b. at base of crown $(DCR)^2$ and the squared value for d.o.b. at base of crown times crown length $(DCR)^2(CLn)$; both had r values of 0.95 (table 2). A strong correlation between crown weight and diameter at base of crown was reported for several hardwood species by Storey and Pong (1957) and for two pine species by Loomis and others (1966) and Ralston (1973).

Crown volume was also strongly correlated with d.b.h. squared (D^2), which had an r value of 0.93, and with d.b.h. squared times total height (D^2Th), which had an r value of 0.92 (table 2). Other variables—crown length (CLn), crown width (CWd), crown ratio (CR), and crown class (CCls)—had successively poorer correlations with crown volumes.

The variable most highly correlated with stem and total tree volume was D^2Th, which had an r value of 0.99 in each case. The second best variable was D^2, with an r value of 0.98. The choice as to whether D^2 or D^2Th should be used in the prediction equations depends on the objectives. If predictions are to be made in more than one stand, D^2Th should be used. If predictions are to be made in only one stand, height would probably be closely related to d.b.h., and the extra time required to measure total height (Th) would not be worth the effort (Madgwick 1971).

With the correlations in table 2, we developed regression equations to predict crown, stem, and total tree volumes. We then used these equations to predict volume yields by 1-inch d.b.h. classes so that we could determine the accuracy of each equation. Predicted and actual volumes of felled trees as well as the equations used for the predictions are given in table 3.

Table 2.—Correlation coefficients (r) for various tree dimensions and crown, stem, and total tree volumes of northern red oaks

Component volume	Tree dimension[1]									
	D	D^2	D^2Th	DCr	$(DCr)^2$	CLn	$(DCr)^2CLn$	CWd	CR	CCls
	Correlation coefficients (r)									
Crown	0.90	0.93	0.92	0.91	0.95	0.84	0.95	0.83	0.66	−0.61
Stem	.97	.98	.99	.93	.95	.84	.93	.83	.55	− .64
Total tree	.97	.98	.99	.94	.97	.85	.95	.85	.59	− .64

[1] D = d.b.h. (diameter at 4.5 feet) in inches.
Th = total height in feet.
DCr = d.o.b. (diameter outside bark) at base of crown in inches.
CLn = crown length in feet.
CWd = crown width in feet.
CR = crown ratio in percent.
CCls = crown class (1 = open grown, 2 = dominant, 3 = codominant, 4 = intermediate, and 5 = suppressed).

Table 3.—Comparison of actual felled-tree and predicted volumes of wood in northern red oak trees

D.b.h. (inches)	Sample trees	Total height	Average volume						
			Crown			Stem		Total tree	
			Actual	Predicted[1] $(DCr)^2$	Predicted[2] $(Log_{10}\ D^2Th)$	Actual	Predicted[3] $(Log_{10}\ D^2Th)$	Actual	Predicted[4] $(Log_{10}\ D^2Th)$
	No.	*Feet*	.... *Cubic feet*						
6	4	60	1.4	1.5	1.1	4.5	4.5	5.9	5.6
7	6	66	1.8	1.5	1.7	6.7	6.7	8.5	8.4
8	7	69	2.4	2.6	2.4	9.4	9.4	11.8	11.8
9	5	75	3.2	3.1	3.2	12.2	12.4	15.4	15.8
10	5	74	4.0	4.6	4.0	15.4	15.4	19.4	19.6
11	4	80	4.4	5.0	5.3	20.5	20.0	24.9	25.5
12	5	83	6.9	7.1	6.8	25.6	24.7	32.5	31.7
14	5	94	12.1	12.2	10.7	39.2	38.7	51.3	49.9
16	6	96	13.4	14.1	13.0	47.3	46.7	60.7	60.4
18	4	96	16.6	17.2	17.0	59.8	59.9	76.5	77.7
20	4	101	21.0	25.9	23.6	77.8	81.7	98.8	106.4
22	5	106	36.2	35.3	30.3	104.6	103.3	140.8	135.0
24	2	96	46.2	40.4	33.1	109.9	112.0	156.1	146.5
Weighted study average	62	83.4	11.0	11.3	10.2	36.2	36.3	47.2	46.9

[1]Crown volume (cubic feet) = $-0.88554 + 0.10874\ (DCr)^2$ — $R^2 = 0.90$ — $Sy{\cdot}x = 3.87$ cubic feet

[2]Log_{10} crown volume (cubic feet) = $-3.48231 + 1.05295\ Log_{10}\ (D^2Th)$ — $R^2 = 0.92$ — $Sy{\cdot}x = 5.10$ cubic feet

[3]Log_{10} stem volume (cubic feet) = $-2.67736 + 0.99529\ Log_{10}\ (D^2Th)$ — $R^2 = 0.99$ — $Sy{\cdot}x = 2.94$ cubic feet

[4]Log_{10} total-tree volume (cubic feet) = $-2.62944 + 1.00979\ Log_{10}\ (D^2Th)$ — $R^2 = 0.99$ — $Sy{\cdot}x = 6.08$ cubic feet

Crown volumes predicted from the squared value for diameter at base of crown $(DCr)^2$ averaged 11.3 cubic feet, whereas those from felled trees averaged 11.0 (table 3). Predictions ranged from 1.5 cubic feet for 6-inch trees to 40.4 cubic feet for 24-inch trees—close to the actual values of 1.4 and 46.2 cubic feet. Crown volumes predicted from d.b.h. squared times total height (D^2Th) averaged 10.2 cubic feet, whereas those from felled trees averaged 11.0 cubic feet. This equation was transformed to the logarithmic scale in order to correct for a slight curvilinearity in the data, but it still failed to produce the accuracy of the equation based on $(DCr)^2$.

Stem and total tree volumes were predicted accurately at all levels of d.b.h. with D^2Th as the independent variable (table 3). Stem volume predictions averaged 36.3 cubic feet, whereas actual stem volumes averaged 36.2. Total tree predictions averaged 46.9 cubic feet, whereas actual total tree volume averaged 47.2. Again, the logarithmic form of the equation was used to correct for curvilinearity in the data. When predicted values on the logarithmic scale are transformed back to the original units, a slight bias occurs that can be corrected with a procedure developed by Baskerville (1972). In our data, the adjustment was so small that it was ignored. Standard errors of the estimate $(Sy{\cdot}x)$ were computed in cubic feet for each logarithmic equation according to a procedure described by Johnstone (1971). These standard errors are given in the footnotes to table 3.

SUMMARY

Procedures developed by Forest Survey for standing trees and by the Utilization Unit for felled trees were used to estimate the cubic-foot volume of wood in 62 northern red oaks. Results showed that stems and total trees were quite accurate but that estimated crown volumes were low. Forest Survey's procedures for crown measurement have been changed to include smaller branches; this change should improve the accuracy of the measurements. Regression equations based on measurements of the diameter and total height (D^2Th) of felled trees gave good predictions of the cubic volumes of stems and total trees. Crown volumes were best predicted by using the squared value for diameter at base of crown $(DCr)^2$ as the independent variable. Crown volumes, which are the most difficult to estimate, were poorly predicted with equations which included crown ratio, crown class, or crown length. Either approach described in the report can provide data which are suitable for developing volume equations. Once volume equations are developed by species or geographic regions, they provide an accurate method of estimating the volume of standing trees with a minimum of measurements. Such equations should be applied within the region in which they were developed.

This cooperative study identified some areas where further research is needed. Volume yields reported are for wood only; the outside bark diameters in standing trees had to be converted to inside bark diameters. In the crown, assumptions on bark thickness had to be made, because such data were not available. Therefore, bark thickness of various sizes of tree branches should be determined for all species. Because the Utilization Unit collects data on the weight of each sample tree, other information such as tree component weight and weight-per-cubic-foot values can be generated. With such information, Forest Survey can express its inventories in tons as well as cubic feet.

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