Comparison of Field Methods and Models to Estimate Mean Crown Diameter

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ABSTRACT: *The direct measurement of crown diameters with logger's tapes adds significantly to the cost of extensive forest inventories. We undertook a study of 100 trees to compare this measurement method to four alternatives—two field instruments, ocular estimates, and regression models. Using the taping method as the standard of comparison, accuracy of the tested alternatives was adequate for softwood species, but short of the specified measurement quality objective for estimating the mean crown diameter of hardwoods. Due to savings in field costs, ocular estimation and regression models were the best alternatives to direct measurement with logger's tapes. North. J. Appl. For. 19(4):177–182.*

Key Words: Tree crown width, tree crown diameter, crown diameter measurement, crown diameter models.

Tree crown condition can be used as an indicator of general tree health, vigor, and growth potential. Trees with large, full crowns usually have a high potential for carbon fixation and, consequently, net primary production. When natural or anthropogenic stresses impact a forest, the first signs of deterioration may be observed in the tree crowns. Because tree crowns form part of the structural architecture of a forest, they directly influence the composition, processes, and vigor of the ecosystem. The USDA Forest Service Forest Health Monitoring (FHM) program, which is responsible for assessing the health of the nation's forests, uses a variety of tree crown parameters as indicators of forest ecosystem productivity and sustainability. For example, crown diameter is used to calculate composite crown variables such as crown volume, crown surface area, and crown efficiency index (Zarnoch et al. 2001).

FHM field crews traditionally have measured the crown diameters of all live trees 5.0 in. diameter at breast height (dbh) and larger by measuring (with logger's tapes) the horizontal length of the widest axis of each crown, plus the dimension perpendicular to the widest axis. No instruments (e.g., plumb bobs) are used to assist crews align themselves under the crown periphery. The two tape measurements are then averaged to obtain mean crown diameter. Depending on the understory vegetation and percent slope, crown-diameter measurements often average more than 1 minute per tree, and easily can add an hour to a field crew's daily workload. Taping crown diameters also increases foot traffic on the plot, thus increasing exposure to erosion and understory trampling.

Because the cost of measuring crown diameters in the traditional manner is significant for extensive surveys, it is prudent to investigate alternative methods. Our objectives were to develop field methods that require less time and minimize potential damage to the plot, to evaluate the use of regression models for predicting crown diameters, and to test these alternatives against the customary taping method.

Methods

Alternative Field Methods

Three alternative field methods were tested against the traditional method. The first is the calibrated cross (Figure 1), which is based on similar ratios calibrated to total tree length. It consists of a vertical axis scaled from 0 to 100%, with a similarly scaled horizontal axis. The observer visually aligns the vertical axis with total tree length until the vertical scale reads 100% (AB). Crown diameter (in percent) is then read from the scale on the horizontal axis (DC). The result is then multiplied by total tree length (ft) to calculate crown diameter (ft):

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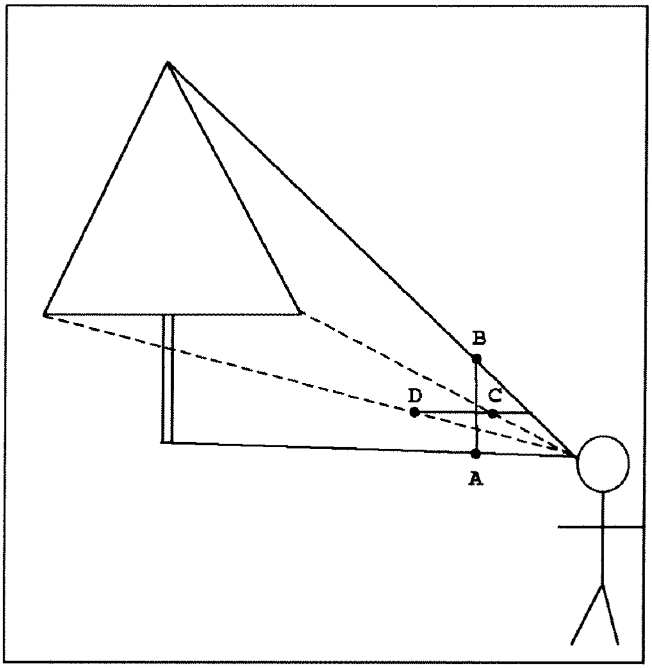

Figure 1. Reading ratios with a calibrated cross.

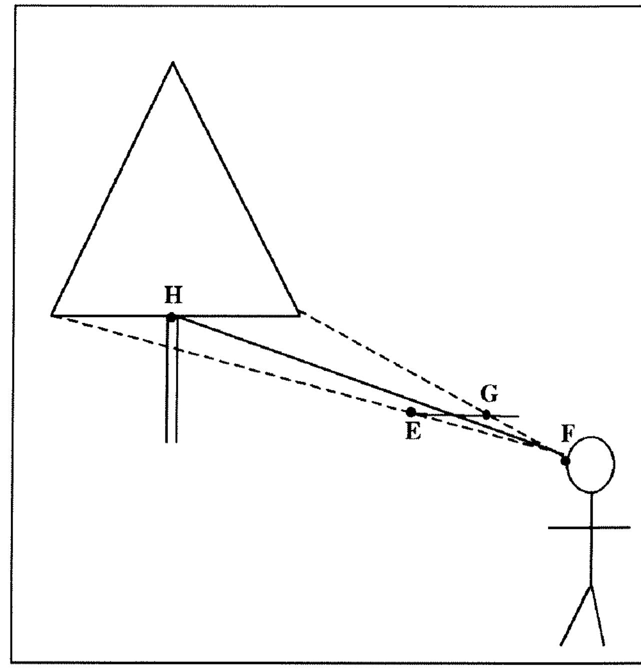

Figure 2. Reading an angle and slope distance for the optical fork method.

$$D = R_h(L) \quad (1)$$

where

R_h = the horizontal ratio (in percent) read from the calibrated cross when the vertical ratio is aligned with total tree length (L) at 100 percent, and

L = total tree length (ft).

The second alternative is an optical fork (Grosenbaugh 1963). This version of the optical fork is simplified in that direct measurement of slope distance with a laser allows all measurements to be made in the same plane. With the observer's eye as the vertex (F), the angle formed by the left and right edge of a tree crown (EFG) is read from an angle gauge (Figure 2). Slope distance from the observer to the point on the bole where the angle was viewed (FH) is then measured with a laser. Assuming the axis of the crown is perpendicular to the slope distance (forming a right angle), crown diameter is computed as:

$$D = 2(\tan(\theta / 2))S \quad (2)$$

where

θ = the angle read from an angle gauge, and

S = the slope distance (ft) from the observer to the point on the bole where the angle was read.

The third alternative is the ocular method, where crown diameters are visually estimated (without instrumentation) to the nearest foot.

For all three field alternatives, observations were taken from the two perspectives that offered the best view of each tree crown, as opposed to the traditional method, which requires the widest axis and its perpendicular. Each method thus produced a crown-diameter estimate for each tree that was averaged from two perspectives.

The Data

Two datasets were used for this analysis. All observations were made during the "leaf-on" growing season:

1. 100-tree Special Study. One hundred trees 5.0 in. dbh and larger were measured at five different sites in and around the Bent Creek Experimental Forest near Asheville, NC. These sites varied from 6 to 55% slope, with crown visibility ranging from good to poor. Three two-person crews took part in the study, each of which measured about one-third of the trees. All measurements obtained for a given tree were obtained from a single crew. "Ground truth" was obtained by measuring crowns with logger's tapes in the traditional manner after all other readings were recorded. Seventeen different tree species were encountered.

2. FHM Production Plots. Crown diameters were measured from trees on 1,413 FHM plots distributed across 32 states in 1999. Data from a subset of these plots (i.e., plots with the species of interest) were used to develop models to predict crown diameters for the 17 species encountered in the Special Study. The locations of plots from which the models were derived span the ranges of the species involved. The resulting models were then applied to the trees measured in the 100-tree Special Study and compared with other alternatives.

Crown-Diameter Models

Tree dbh, stand density, and stand age have been shown to be correlated with crown diameter (Krajicek et al. 1961, Bonner 1964, Holdaway 1986, Sprinz and Burkhart 1987, Smith et al. 1992, Bragg 2001). Tree dbh, stand age, and various stand-level measures of stand density were thus used as candidate variables in stepwise linear regressions fitted to 1999 FHM production data, by species, for the 17 species encountered in the 100-tree Special Study. Vertical crown ratio, a measure of crown length, was also included in the stepwise solutions because preliminary investigation indicated a significant correlation between crown ratio and crown diameter. This particular crown ratio is the "uncompacted" measure implemented by FHM (USDA Forest Service 1999).

Tree dbh and vertical crown ratio were highly significant in most models. Parameter estimates for stand density and stand age did not improve the models, probably because crown ratio is correlated with stand density for many species (Holdaway 1986). Examinations of model residuals did not reveal any problems with model specification or indicate the need for transformations, so the following linear model was selected:

$$D = b_0 + b_1(dbh) + b_2(R_v) \tag{3}$$

where

D = mean crown diameter (ft),

dbh = tree diameter (in.) at breast height (minimum 5.0 in.),

R_v = uncompacted vertical crown ratio (i.e. percentage of tree length with live crown), and

b_i = regression parameters estimated from the data.

Nonlinear power functions are often used to model crown diameters (Bragg 2001), so we checked to see if any improvement might be gained with the following equation form:

$$D = b_0 + b_1(dbh)^{b_2} + b_3(R_v) \tag{4}$$

Equation (4), when fit to the FHM production data set, did not exhibit any noticeable improvement over Equation (3), so we decided to use the simpler linear model.

Evaluation Statistics

Statistics used to evaluate the three alternative field methods and model predictions are defined as follows:

Bias

Bias, the difference between the mean alternative value and the mean measured (true) value (Cochran 1977), is defined as:

$$Bias = \sum (\hat{Y}_i - Y_i) / N \tag{5}$$

where

$\hat{Y}_i$ = the alternative measurement or prediction of crown diameter for the *i*th value of the dataset,

Y_i = the measured (true) crown diameter for the *i*th value of the data set (as defined by the traditional method), and

N = the number of observations in the data set.

Root Mean Squared Error (RMSE)

Mean squared error (MSE) is a relative measure of overall accuracy. The closer it is to zero, the greater the accuracy. MSE has two components—variance and squared bias (Cochran 1977). Differences among MSE's are thus the result of differences in the variance and/or bias of model predictions. This analysis utilizes the square root of MSE as an evaluation statistic:

$$RMSE = \left(\sum (\hat{Y}_i - Y_i)^2 / N\right)^{0.5} \tag{6}$$

If one is interested in variance, it is easily obtained by subtracting Bias squared from MSE.

Absolute Deviation (AD)

AD is the mean absolute difference between the alternative values and the true values. It is the average amount that an alternative method deviates from the true value (disregarding sign):

$$AD = \sum (|\hat{Y}_i - Y_i|) / N \tag{7}$$

Percent Absolute Deviation (PAD)

PAD is the mean absolute difference between the alternative values and the true values, expressed as a percentage of the true values. It is the average percentage that an alternative method deviates from the measured value (disregarding sign), and is computed as:

$$PAD = \left(\sum (|\hat{Y}_i - Y_i| / Y_i) / N\right)100 \tag{8}$$

Within Measurement Quality Objective (WMQO)

The FHM measurement quality objective (MQO) for crown diameter is ±5 ft, or 10% (whichever is larger). WMQO is the percentage of alternative estimates within ±5 ft of measured (true) crown diameter (or within ±10% for trees with crown diameters >50 ft):

$$WMQO = \left(\sum W_i / N\right)100 \tag{9}$$

where

W_i =

1 $\quad if (|\hat{Y}_i - Y_i| \leq 5) \; or \; (|\hat{Y}_i - Y_i| / Y)100 \leq 10 \; and \; (Y_i > 50)$

0 $\quad otherwise$

The target WMQO for crown diameter in the FHM Program is 90%. Upper and lower 95% confidence intervals for WMQO can be calculated with the normal approximation (Hollander and Wolfe 1973) as follows

$$WMQO \pm 1.96\left(\frac{WMQO(100 - WMQO)}{N}\right)^{0.5} \tag{10}$$

Results and Discussion

Comparison of Alternative Field Methods

Each of the three field alternatives reduced the amount of foot traffic on the plot because crown diameters could be obtained from the same position where field crews measure other crown parameters (e.g., vertical crown ratio). None of the alternatives required extra walking to measure crown diameters, as does the traditional method.

The time required for the traditional method averaged 52 sec/tree, which increased to 66 sec if the time it took to walk from tree to tree was included. The latter figure is more realistic because crews prefer to obtain crown-diameter measurements all at once (after all other tree measurements are completed), thus requiring an extra trip between trees. Across all species, the alternative field methods averaged between 16 and 57 sec per tree (Table 1). The optical fork took about the same amount of time as the traditional method because two variables were required (θ and S), and the process occasionally was hampered by difficulty finding a clear laser shot to the upper stem. Although two variables also were required for the calibrated cross (R_h and L), the time required to measure L was not counted because this variable was already available and not obtained exclusively for the purpose of estimating crown diameter. Had the time to measure L been included, the calibrated cross would have taken about the same amount of time as the optical fork. Ocular estimation was by far the quickest field method, averaging about one-fourth the time necessary for the traditional method.

Across all species, evaluation statistics show that all three field alternatives are approximately equivalent (Table 1). The optical fork attained the desired measurement quality objective 80% of the time, compared to 79% for ocular estimates and 74% for the calibrated cross. The 95% confidence intervals for WMQO overlap for all three methods. The two instruments exhibited a slight negative bias. Considering accuracy, bias, and measurement time, ocular estimation proved to be the best field alternative tested. Ocular estimation also has the advantage of requiring no additional field equipment.

A few negative influences explain the inability of the two instruments to outperform ocular estimation. The optical fork exhibited sensitivity at longer distances because small errors in the angle reading are multiplied by a longer slope distance. In cases where it was difficult to obtain a clear shot to the upper stem, the laser may have underestimated S by reflecting from crown foliage in front of the bole. Estimates from both instruments were calculated from two independent variables, each of which contributes variance to the estimate. Of most significance, the effectiveness of both instruments was compromised by difficulty viewing crown outlines obscured by brush and other trees while simultaneously attempting to read an instrument. This likely contributed to the negative bias.

Hardwood crowns are generally larger, more likely to be intermingled with other trees, and more variable than softwood crowns. As a result, all three field alternatives performed better for softwoods than hardwoods. For softwood species, the percentage of measurements that achieved the desired measurement quality was 89% with the calibrated cross, 95% with the optical fork, and 87% with ocular estimation. For softwoods, the confidence intervals associated with the WMQO's of all alternatives include 90%, suggesting that all alternatives are adequate for coniferous species. In contrast, none of the WMQO confidence intervals for hardwoods include the 90% quality objective.

Taped crown diameters were used as the standard of comparison in this analysis, but there is also measurement error associated with this method. A national quality-assurance (QA) study of 1999 FHM data that includes blind checks of 1,376 taped crown measurements (Pollard and Smith 2001) indicates that field crews using the traditional method attained the desired WMQO 83 of the time—88% for softwoods and 76% for hardwoods. Results from the QA study reveal that hardwood crown diameters are difficult to measure with the traditional method, and that a target WMQO of 90% may be unrealistic for hardwood species, regardless of method.

Table 1. Comparison of traditional crown-diameter measurements to alternative methods for 100-tree Special Study, by species group.

Species group/method	N	Bias[a]	RMSE[b]	AD[c]	PAD[d]	WMQO[e,f]	Time[g] (sec)
		Evaluation statistics					
		(ft)			(%)		
Hardwood species							
Calibrated cross	62	−2.9	5.4	4.1	18	65 (53–76)	31
Optical fork	62	−2.1	6.0	4.5	19	71 (60–82)	53
Ocular estimate	62	−0.4	5.0	3.7	17	74 (63–85)	18
Regression model	62	−2.4	5.2	4.0	19	68 (56–79)	0
Softwood species							
Calibrated cross	38	−1.6	3.4	2.7	21	89 (80–99)	33
Optical fork	38	−0.5	2.7	2.2	19	95 (88–100)	64
Ocular estimate	38	2.0	3.5	2.9	27	87 (76–98)	12
Regression model	38	−0.1	3.0	2.3	19	92 (84–100)	0
All species							
Calibrated cross	100	−2.4	4.7	3.6	19	74 (65–83)	32
Optical fork	100	−1.5	5.0	3.6	19	80 (72–88)	57
Ocular estimate	100	0.5	4.5	3.4	21	79 (71–87)	16
Regression model	100	−1.5	4.5	3.4	19	77 (69–85)	0

[a] Mean deviation.
[b] Square root of mean squared deviation.
[c] Mean absolute deviation.
[d] Mean percent absolute deviation.
[e] Percent of observations within the ±5 ft (or 10%) measurement quality objective.
[f] 95% confidence interval for WMQO is in parentheses.
[g] Mean measurement time per tree.

Table 2. Model statistics and parameter estimates resulting from crown-diameter prediction models[a] fit to 1999 FHM production data, by species. (Note: * is $P < 0.05$.)

Species	N	Model statistics: Adjusted R-square	RMSE[b]	CV[c]	Parameter estimates: b_0	b_1	b_2
Bitternut hickory (*Carya cordiformis*)	70	0.64	4.1	20.4	4.332	1.743 *	0.019
Black cherry (*Prunus serotina*)	367	0.53	4.7	25.4	1.981 *	1.171 *	0.121 *
Black locust (*Robinia pseudoacacia*)	89	0.39	5.3	33.1	2.682	0.946 *	0.121 *
Black oak (*Quercus velutina*)	497	0.68	4.5	21.3	1.324	1.523 *	0.072 *
Blackgum (*Nyssa sylvatica*)	287	0.32	4.6	24.5	7.434 *	0.927 *	0.062 *
Chestnut oak (*Quercus prinus*)	471	0.60	4.9	23.9	4.358 *	1.366 *	0.047 *
Eastern white pine (*Pinus strobus*)	645	0.69	3.9	23.7	0.104	0.967 *	0.123 *
Mockernut hickory (*Carya tomentosa*)	146	0.67	4.6	22.2	1.390	1.736 *	0.064 *
Pitch pine (*Pinus rigida*)	71	0.47	4.4	26.1	0.272	1.040 *	0.167 *
Red maple (*Acer rubrum*)	2265	0.41	4.8	25.9	4.757 *	1.021 *	0.098 *
Scarlet oak (*Quercus coccinea*)	199	0.66	5.3	22.6	1.430	1.730 *	0.049
Shortleaf pine (*Pinus echinata*)	234	0.70	3.1	22.7	–3.041 *	1.334 *	0.113 *
Sourwood (*Oxydendrum arboreum*)	144	0.16	4.6	27.3	6.870 *	0.843 *	0.087 *
Southern red oak (*Quercus falcata*)	103	0.64	4.6	21.4	5.953 *	1.501 *	0.008
Table mountain pine (*Pinus pungens*)	9	0.67	3.5	18.1	–1.543	2.008 *	0.047
White oak (*Quercus alba*)	915	0.68	4.7	22.0	3.247 *	1.570 *	0.048 *
Yellow poplar (*Liriodendron tulipifera*)	512	0.60	4.6	22.7	4.788 *	1.031 *	0.079 *

[a] $D = b_0 + b_1(dbh) + b_2(R_v)$; where D = crown diameter (ft), dbh = diameter (in.) at 4.5 ft, and R_v = vertical crown ratio.
[b] *RMSE* = root mean squared error from the regression solution.
[c] *CV* = coefficient of variation from the regression solution: $(RMSE / \bar{Y}) * 100$.

Crown-Diameter Models

Parameter estimates and fit statistics for Equation (3) are listed in Table 2. Adjusted R-squares range from 0.16 for sourwood to 0.70 for shortleaf pine. In general, the models performed especially well for shade-intolerant overstory species such as pines, oaks, and hickories; but relatively poorly for shade-tolerant understory hardwoods such as red maple, sourwood, and blackgum.

Regression models derived from the FHM production data set produced results that were approximately equivalent to the three alternative field methods. For the 100-tree Special Study, models attained the target measurement quality 77% of the time (Table 1). As with the field alternatives, model predictions were noticeably better for softwoods than hardwoods (92% WMQO vs. 68%, respectively). The confidence interval for the softwood models contains the 90% measurement quality objective, whereas the confidence interval for the hardwood models does not.

A closer look at the 1999 FHM production data indicates that a model performance of 77% WMQO is consistent with general model performance over a broader area and range of trees (Table 3). Applying evaluation statistics to the 7,024 trees from which the 17 models were derived, 75% attained the desired measurement quality (85% for softwoods and 74% for hardwoods).

Upon further investigation of model performance using all data from the 1999 production dataset and fitting regressions to all available species (31,911 trees and 117 species),

Table 3. Comparison of traditional crown-diameter measurements to model predictions for 1999 FHM production data and 100-tree Special Study, by species.

Species	1999 FHM production data: N	Bias[a] (ft)	RMSE[b] (ft)	AD[c] (ft)	PAD[d] (%)	WMQO[e] (%)	100-tree special study: N	Bias[a] (ft)	RMSE[b] (ft)	AD[c] (ft)	PAD[d] (%)	WMQO[e] (%)
Bitternut hickory	70	0	4.0	3.4	19	76	1	4.1	4.1	4.1	24	100
Black cherry	367	0	4.7	3.5	22	76	1	–0.3	0.3	0.3	2	100
Black locust	89	0	5.3	3.7	27	82	4	3.1	4.2	3.1	64	50
Black oak	497	0	4.5	3.5	19	73	3	–2.4	2.6	2.4	15	100
Blackgum	287	0	4.6	3.6	21	74	2	2.2	3.9	3.3	27	50
Chestnut oak	471	0	4.9	3.7	21	73	8	–4.6	5.4	5.1	17	50
Eastern white pine	645	0	3.9	2.9	22	84	30	0.0	2.6	2.2	21	97
Mockernut hickory	146	0	4.6	3.3	18	84	1	–3.9	3.9	3.9	18	100
Pitch pine	71	0	4.3	3.3	25	80	4	0.1	1.2	1.0	7	100
Red maple	2,265	0	4.8	3.7	23	73	6	–1.8	2.9	2.2	11	83
Scarlet oak	199	0	5.3	4.0	19	68	1	3.8	3.8	3.8	20	100
Shortleaf pine	234	0	3.1	2.3	19	89	3	–3.6	4.6	3.9	14	67
Sourwood	144	0	4.5	3.5	24	77	14	–1.3	4.6	3.1	15	79
Southern red oak	103	0	4.6	3.6	17	75	1	–2.8	2.8	2.8	13	100
Table Mountain pine	9	0	2.8	2.2	11	89	1	8.6	8.6	8.6	50	0
White oak	915	0	4.7	3.6	19	73	8	–5.2	7.7	6.3	16	50
Yellow-poplar	512	0	4.5	3.5	19	74	12	–4.2	6.3	5.1	18	58
All hardwoods	6,065	0	4.7	3.6	21	74	62	–2.4	5.2	4.0	19	68
All softwoods	959	0	3.7	2.8	22	85	38	–0.1	3.0	2.3	19	92
All species	7,024	0	4.6	3.5	21	75	100	–1.5	4.5	3.4	19	77

[a] Mean deviation.
[b] Square root of mean squared deviation.
[c] Mean absolute deviation.
[d] Mean percent absolute deviation.
[e] % of observations within the ±5 ft (or 10%) measurement quality objective.

we found that 83% of the model predictions attained the desired measurement quality—90% for softwoods and 76% for hardwoods. Model performance ranged from a low of 58% WMQO for bigleaf maple (*Acer macrophyllum*) to a high of 100% for jack pine (*Pinus banksiana*). Of the 117 species for which regressions were solved, models for 32 species achieved the target 90% WMQO. Model performance for some species would likely be improved by calibration to local conditions (by allowing parameter estimates to vary by state or region).

In some situations, especially for some species, crown-diameter models offer an attractive alternative to the traditional method. However, they must be used cautiously. In monitoring applications such as FHM, sole reliance on models to predict crown diameter and associated attributes (e.g., crown volume) has the potential to mask spatial or temporal trends involving these attributes. Models should be applied with the understanding that the same functional relationship between dependent and independent variables must be assumed for the predicted trees as for the trees from which the models were developed. If this functional relationship is altered by a change in forest health, poor predictions could result in the failure to detect a problem. For example, models developed from healthy trees would overestimate the crown diameters of trees with crowns stunted by gypsy moth (*Lymantria dispar*) attacks. Acceptance of predictions from such models at face value would underestimate the impact of a gypsy moth infestation on tree crowns. A more appropriate use of models for monitoring applications would be to generate residuals (predicted minus observed values) for the purpose of isolating and examining trees with crown attributes that are worse than expected (i.e., extreme residuals). Thus, in situations where the functional relationships among model variables may not be stable, one of the field methods should be used.

Potential Propagation of Error

When considering alternatives to the taping method, the effects of reduced measurement quality on additional parameters that may be calculated with crown diameter should also be considered. In some cases, the effects of reduced measurement quality may be exaggerated. For example, crown diameter is used in the following calculation of crown volume:

$$V = 0.5\pi(D/2)^2 \; L_c \qquad (11)$$

where

D = crown diameter (ft), and

L_C = crown length (ft)= $(L^* R_v) / 100$.

Squaring the crown diameter term in Equation (11) compounds any error associated with it. To illustrate, measured crown diameters and ocular estimates from the 100-tree Special Study were used to solve Equation (11). By themselves, estimated crown diameters exhibit a mean percent absolute deviation (PAD) of 21% when compared to measured crown diameters (Table 1). When a similar comparison is made between crown volumes calculated with estimated and measured crown diameters, the PAD for volumes derived from estimated diameters increases to 48%.

Conclusions

When measurement of crown diameters with logger's tapes is the standard of comparison, all of the tested alternatives are adequate for softwood species, but none achieve the 90% measurement quality objective for hardwoods. If crown diameters are important to the goal of an inventory or monitoring program, the most prudent course of action is direct measurement with logger's tapes—unless quality objectives can be relaxed (particularly for hardwood species). FHM QA data suggest that the 90% target may not be realistic for hardwood species, even when the taping method is used. Due to reduced field costs, regression models and ocular estimation are the most appealing alternatives to measurement with logger's tapes. For monitoring applications, the possibility that models may mask a temporal or spatial trend involving crown diameters should be considered. Because reductions in measurement quality can be exaggerated when estimated crown diameters are used in the derivation of other variables, the decision to use measured, predicted, or field-estimated crown diameters should also include the impact on derived variables.

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