

Evaluation of the Barr & Stroud FP15 and Criterion 400 Laser Dendrometers for Measuring Upper Stem Diameters and Heights

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ABSTRACT. Calibrated Barr & Stroud FP15 and Criterion 400 laser dendrometers were tested for reliability in measuring upper stem diameters and heights under typical field conditions. Data were collected in the Black Hills National Forest, which covers parts of South Dakota and Wyoming in the United States. Mixed effects models were employed to account for differences between users of the dendrometers and to test for significant differences between the heights and diameters measured indirectly (by dendrometer) and directly (by caliper and linear tape). The location at which measurements were taken on each tree was determined by paint marks along the bole. No significant differences between users were found. The Barr & Stroud consistently overestimated diameters by approximately 0.3 cm (0.1 in). Unbiased estimates of diameter were obtained with the Criterion 400. For height measurements, neither the Barr & Stroud nor the Criterion 400 produced unbiased measurements. The effect of distance to the base of the tree and height of the diameter measurement on the variability of the measurements was also studied. As distance increased, the variability of diameter measurements increased for both dendrometers. For the measurement of height, only the Barr & Stroud exhibited an increase in the variability of measurements with increasing distance. After correcting the data for their biases, taper equations were fitted to them and analyzed. The equations generated from the Barr & Stroud were not significantly different from those generated from direct measurement, unlike the Criterion 400 where taper equations generated were statistically different. A brief study of the effects of familiarity with each dendrometer indicated that the measurement error and variability decreased as the user became more familiar with the Criterion. This was not the case for the Barr & Stroud. *For. Sci.* 45(1):53–61.

Additional Key Words: Mixed effect models, taper equation, instrument familiarity.

MANY OF THE INSTRUMENTS CURRENTLY AVAILABLE for measuring tree height have been thoroughly tested and evaluated (Hummel 1951, Bruce 1975, Rust 1993, Williams et al. 1994). One task that can also be

performed with some of these instruments is estimation of upper stem diameters. The accuracy of the Barr & Stroud dendrometer has been studied by Grosenbaugh (1963), Bell and Groman (1971), and Brickell (1976). The former two publications found the Barr & Stroud to overestimate diameters by 0.7 and 1.2%, respectively. Fairweather (1994) found mean errors for three users ranged from -1.07 to 1.73

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cm (−0.42 to 0.68 in) when measuring upper-stem diameters using a Criterion 400 laser dendrometer. While a number of studies have assessed the ability of instruments to measure diameters or heights, none have addressed the accuracy of pairs of diameter and height measurements, i.e., the diameter at a given height.

The need for accurate upper stem diameter-height measurements has increased in recent years due to the adoption of estimation methods such as taper equations [for recent examples see Flewelling and Raynes (1993) and Flewelling (1993)] and the introduction of sampling methods, such as the centroid method and importance sampling (Gregoire et al. 1986, Wood et al. 1990, Wiant et al. 1996, Williams and Wiant 1998), which require upper stem diameter-height measurements. The need with respect to taper equations is two-fold. First, an upper stem measurement can be used to correct for local bias and improve efficiency [Czaplewski and McClure (1988), Flewelling (1993)]. Second, many of the data sets used to develop taper equations are collected from opportunistic samples using felled trees, thus the data may be nonrepresentative, and it is not possible to determine if the resulting taper equations are representative of the forest population they are supposed to model.

The amount of variability in diameter and height measurements is of particular concern when fitting taper equations because the statistical theory which ensures unbiased and efficient parameter estimates may no longer be valid due to errors in measurement. Two major areas of concern are:

1. The use of diameter squared (d^2) when diameter (d) is the measured attribute can lead to a transformation bias, similar to that noted by Czaplewski and Bruce (1990). To illustrate this bias, assume that the measured diameter ($\hat{d}$) is equal to the true diameter (d) plus some normal random error $\epsilon \sim N(0, \sigma^2)$.

This yields the model

$$\hat{d} = d + \epsilon$$

Squaring both sides and taking the expectation yields

$$E[\hat{d}^2] = d^2 + \sigma^2$$

which indicates an average bias of size σ^2 .

2. Measurement error in both the predictor and response variables, in this case diameter squared and height, respectively, can cause biases in the least squares parameter estimates (Draper and Smith, section 2.14, 1981).

These sources of error can be ignored when the measurement error is small compared to the actual measurement, but we will show later that the magnitude of the diameter and height measurement errors can significantly impact the fit of taper equations.

The need for representative data prompted this study in which pairs of diameter and height measurements were taken on a large number of standing trees as part of the data collection process for the construction of taper equations for the Black Hills National Forest. Measurements of true diam-

eter and height were taken using calipers and a linear tape (Husch et al. 1982, sections 2-1.3 and 3-1.2) respectively. Measurements of diameter and height were also collected using a Barr & Stroud dendrometer (Bell and Groman 1971) and a Criterion 400 laser dendrometer (Carr 1992). These instruments will be referred to as the caliper, tape, Barr & Stroud, and Criterion respectively. Using these data we test the following:

1. Can the Barr & Stroud or Criterion accurately measure upper stem diameters and heights under realistic field conditions?
2. Does the instrument operator have a significant effect on accuracy of the measurement and what portion of the variability can be attributed to differences among operators?
3. Does tree height, diameter, or distance from the measuring device have any effect on the accuracy of the dendrometers?
4. Does familiarity with the dendrometers and measurement techniques reduce the bias or variability over time?
5. How do measurements taken with each dendrometer affect the taper equations generated from them and are differences in the equations significant?

Data Description and Collection Methods

A representative probability proportional to size sample of ponderosa pine (*Pinus ponderosa* Laws) from the Black Hills National Forest in South Dakota and Eastern Wyoming was taken for constructing new taper equations. The sample was based on a permanent grid already existing in the area and used for ongoing stand inventories. The grid was chosen because it offered a substantial saving in time and effort. It comprised approximately 300 locations at each of which a five-point cluster of variable radius plots had been established. From these locations, 30 five-point clusters were chosen at random, and all trees on the first three points were chosen for measurement. A total of 369 trees were selected. Each tree was marked with a ribbon at 1.47 m (4.5 ft), a paint gun was used to mark measurement points approximately every 2.4 m (8 ft) up the bole, these marks serving as reference points where diameter and height measurements would be taken with the caliper, tape, Barr & Stroud, and Criterion. Each tree was then climbed, and diameter and height measurements were taken using the caliper and linear tape, respectively. For safety reasons, trees were not climbed to the top. Thus, measurements of true height and diameter were available for only a subset (1187 measurements) of all the measurements. The maximum height climbed up the bole was about 11 m (35 ft). In terms of relative height (height of the measurement point as a percentage of the total height) a number of trees were climbed to approximately 60–65% of their total height, but the majority were climbed to approximately 30–40 %.

The Barr & Stroud and Criterion measurements were taken to the top of the tree using the paint marks as reference points. For each tree, a location was selected to

place a tripod, which was used to steady the instruments. Great care was taken to ensure that the caliper measurements were taken perpendicular to the line of sight from the dendrometers. Any error incurred would have been accidental and free of intentional bias. The number of measurements taken with each dendrometer was 1788.

Funding was not available to assign a special field crew to collect the data, so the collection was performed by 17 different users with varying degrees of field experience. To make sure that the collection process was consistent, at least one member of a three person "core" crew was present for all measurements. Before the study was begun, the "core" crew spent one day using both dendrometers and testing field protocols. The analysis methods used in the paper take user differences into account.

Most of the analysis described below was based on the smaller data set of 1187 composite measurements where true diameter and height were paired with corresponding measurements by dendrometer.

Evaluation Methods

Both visual and analytic methods were used to determine dendrometer accuracy. The caliper and tape measurements were assumed to be true measurements of tree diameter and height respectively. The diameter measurement error for the Barr & Stroud and Criterion were defined as

$$e(d)^{Barr} = d^{Barr} - d$$

and

$$e(d)^{Crit} = d^{Crit} - d$$

where d , d^{Barr} , and d^{Crit} are the diameter measurements produced by the caliper, Barr & Stroud, and Criterion, respectively. Errors for the height measurements were defined similarly with

$$e(h)^{Barr} = h^{Barr} - h$$

and

$$e(h)^{Crit} = h^{Crit} - h$$

where h , h^{Barr} , and h^{Crit} are the height measurements produced by the tape, Barr & Stroud and Criterion respectively.

The first test was a visual comparison where box plots of measurement errors for each user were graphed for both the Criterion and Barr & Stroud.

To illustrate the size of the overall bias and variability of the measurements, the mean error and standard deviation were calculated for the diameter and height measurements. Mean error was given by

$$\bar{e}(.)^* = \frac{1}{n} \sum_{i=1}^n e(.)_i^*$$

where $*$ = *Crit* or *Barr* for the Criterion and Barr & Stroud, respectively, and $(.)$ = (d) or (h) indicates whether diam-

eters or heights were being considered. The standard deviation of the mean error was given by

$$\sqrt{\frac{1}{n-1} \sum_{i=1}^n (e(.)_i^* - \bar{e}(.)^*)^2}$$

with $*$ and $(.)$ defined similarly. Errors expressed as a percentage were also calculated for the diameter and height measurements. Tests of significance of the bias based on these average errors could be misleading as explained below.

Two problems were encountered when trying to determine if either of the dendrometers produced unbiased measurements. The first problem was that a number of different users collected the data. The second problem was that the variance of the diameter measurements increased with the size of the tree. The commonly used accuracy tests, such as those proposed by Freese (1960) and Reynolds (1984), require constant variance and make no provisions for multiple data collectors. Thus, a different approach needed to be taken to determine the accuracy of the dendrometers.

Ideally, the relationship between the caliper and tape measurements and the dendrometer measurements would be one-to-one, thus linear models can be used to test this assumption. The models used for testing were

$$y = \beta x + \epsilon$$

and

$$y = \alpha + \beta x + \epsilon$$

where x was the assumed true measurement, y was the instrument measurement, and ϵ is the measurement error. The first model assumes a zero intercept and indicates a bias which changes with the size of the measurement whenever the slope coefficient (β) differs significantly from one. For the second model, if the instrument gives an unbiased measurement of the true value then the intercept coefficient (α) is expected to equal zero and the slope coefficient (β) to equal one. A calibration model was used to remove the bias whenever it was determined that one of the dendrometers produced biased diameter or height measurements. The model used was

$$x = \frac{y - \hat{\alpha}}{\hat{\beta}}$$

(Neter et al. 1989).

To account for differences in users, mixed effects models (Searle 1971) were used where the diameter or height measurements were treated as fixed effects and the different users were random effects. This random effects model assumes that the users constitute a random sample of possible users. This type of model is appropriate whenever the primary concern is to account for the variability of different users rather than study a particular group of users. To account for nonconstant variance, weights were applied as needed to the caliper and instrument measurements to achieve constant variance. Appropriate weights were determined using maximum likelihood methods as described in Williams and Gregoire (1993). The two mixed effects models used to test the diameter measurements were

$$d_{ij} = \alpha + \beta d_{ij}^* + \delta_j + \varepsilon_{ij} \quad (1)$$

and

$$d_{ij} = \beta d_{ij}^* + \delta_j + \varepsilon_{ij} \quad (2)$$

where * = *Barr* or *Crit* if the Barr & Stroud or Criterion, respectively, was being tested, i indexes measurements and δ_j indicates the effect of user j who took the measurement. These mixed effects models assume $\varepsilon_{ij} \sim (0, \sigma_\varepsilon^2)$ and $\delta_j \sim (0, \sigma_\delta^2)$.

Confidence intervals for the α and β from models (1) and (2) allowed the hypotheses

$$H_0: \alpha = 0, \beta = 1$$

for (1) and

$$H_0: \beta = 1$$

for (2) to be tested. Since the first hypothesis tests both parameters simultaneously, Bonferroni simultaneous confidence intervals (Neter et al. 1989) were used.

To determine if differences between users were significant, we tested whether the estimated variance component for the difference between users was equal to zero, i.e.,

$$\sigma_\delta^2 = 0$$

The relationship between height measurements derived by linear tape and dendrometer was tested by replacing diameter with height in (1) and (2). This gives

$$h_{ij} = \alpha + \beta h_{ij}^* + \delta_j + \varepsilon_{ij} \quad (3)$$

and

$$h_{ij} = \beta h_{ij}^* + \delta_j + \varepsilon_{ij} \quad (4)$$

where h indicates the height measurement taken using the tape and *, i , and j are defined as before.

We were also interested in determining if either the distance from the instrument to the tree or the height of the measurement up the tree had any effect on measurement accuracy. To perform this analysis, the absolute error was regressed on the distance to the tree and the height of the measurement up the stem, i.e.

$$|e(d_{ij})^*| = \alpha + \beta r_{ij} + \delta_j + \varepsilon_{ij}$$

and

$$|e(d_{ij})^*| = \alpha + \beta h_{ij} + \delta_j + \varepsilon_{ij}$$

where r_{ij} and h_{ij} are the distance (range) to the base of the tree and height above ground respectively and $e(d_{ij})^*$ is defined as before. When determining the accuracy of the height measurements, it was only meaningful to test measurement error as a function of distance. When β was not significantly different from zero, we concluded that neither the height nor distance at which the measurement was taken had a significant effect on measurement error.

The aim of collecting the original data was to determine if either dendrometer could collect pairs of diameter and height measurements which were accurate enough to produce taper equations using standard regression techniques. Testing the data by diameter and height pairs is important because a dendrometer could systematically under- or overestimate pairs of measurements which would not be detected by testing diameter and height measurements individually. A preliminary analysis used Spearman's rank correlation coefficient (Siegel and Castellan 1988) to test for a significant correlation ρ between the diameter and height errors. While this test is straightforward, it does not account for the effects of multiple users and unequal variances. This problem was addressed by fitting taper equations to the data collected by the two instruments and comparing the models. To test the accuracy of pairs of measurements, the diameter and height measurements taken by both instruments were corrected with linear calibration models with coefficients derived from Equations (1) and (3). The corrected data were then used to fit the taper equations. For comparison, a taper equation was also fitted to the true diameters and heights derived by caliper and tape. The taper equation used was proposed by Max and Burkhart (1976) and requires six parameters, two of which (J_1 and J_2) are fixed before the fitting process is begun. The form of the model is:

$$\frac{d(h_{ij})^{2*}}{D_k^2} = b_1 \left(\frac{h_{ij}}{H_k} - 1 \right) + b_2 \left(\frac{h_{ij}^2}{H_k^2} - 1 \right) + b_3 \left(J_1 - \frac{h_{ij}}{H_k} \right)^2 I_1 + b_4 \left(J_2 - \frac{h_{ij}}{H_k} \right)^2 I_2 + \delta_j + \varepsilon_{ij}$$

where

i = diameter and height measurement index

j = user index $j = 1, \dots, 17$

k = tree index $k = 1, \dots, 369$

l = parameter index $l = 1, \dots, 4$

m = join point index $m = 1, 2$

$d(h_{ij})$ = upper stem diameter at height h_{ij}

D_k = calipered diameter at breast height outside bark for tree k

h_{ij} = i th height taken by observer j

H_k = total tree height of tree k

δ_j = random effect of user j

b_l = model parameter

J_m = model join points; upper = 1, lower = 2

* = *Cal&Tape*, *Barr*, or *Crit* indicating use of the caliper, Barr & Stroud, or Criterion

$I_m = \begin{cases} 1, & \text{if } h_{ij} / H_k < J_m \\ 0, & \text{otherwise.} \end{cases}$

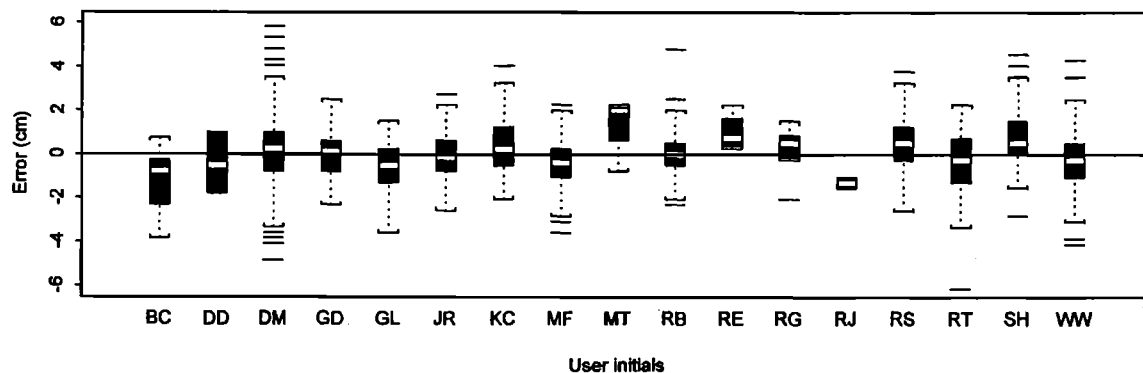


Figure 1. Criterion 400 diameter measurement errors for each observer.

Note that the random effects term δ_j was included to account for user differences. After fitting the taper equations for all three sets of measurements, the estimated relative diameter squared ($\hat{d}(h_{ij})^2 / D_k^2$) generated for each of these were then tested to see if a one-to-one relationship existed between the taper equations using the model

$$\frac{\hat{d}(h_{ij})^2{}^{Cal\&Tape}}{D_k^2} = \alpha + \beta \frac{\hat{d}(h_{ij})^2}{D_k^2} + \varepsilon \quad (5)$$

where * and *Cal&Tape* indicate the use measurement by the Barr & Stroud, Criterion, and caliper and tape, respectively.

If the confidence interval for α and β contained zero and one respectively, then the taper equation generated from the instrument measurements was assumed to be unbiased. One additional problem encountered with this method was that total height measurements by linear tape were not available because the trees could not be climbed to the top. Instead, calibrated measurements made with the Criterion were substituted for the true heights because this dendrometer proved to be slightly more precise than the Barr & Stroud for measuring height.

The final topic of interest was whether familiarity with the dendrometer had any effect on measurement bias or variability. Since the data collection methods did not lend themselves to this type of analysis, only anecdotal comparisons could be made. We speculate that if familiarity with an instrument had any effect on measurement error, then the bias or variability would decrease as more measurements were taken. One of the users in the study had little previous experience with both dendrometers. This

user took 120 and 113 measurements with the Barr & Stroud and Criterion respectively. The diameter errors, $e(d)^{Barr}$ and $e(d)^{Crit}$, for each day were graphed, and nonlinear smoothing approximations of the mean and variance were overlaid. The user was not made aware of his previous day's performance, so any reduction in bias or variability could be attributed to user familiarity with the instrument rather than an adjustment in measurement technique or interpretation. If the smoothed mean or variance of the errors shows a pattern of reduction in bias or variability then we may conclude that there is some evidence that familiarity with the instrument improves measurement accuracy.

Results and Discussion

Figures 1 through 4 show the distribution of diameter and height measurement errors by user for both dendrometers. The most prominent feature is the consistent overestimate of the diameter and height measurements by nearly every user of the Barr & Stroud (Figures 2 and 4). For the Criterion, the variability was noticeably higher than the Barr & Stroud for the diameter measurements, as indicated by the lengths of the box plots (Figures 1 and 2). There was no visual difference in the precision of the two dendrometers (Figures 3 and 4) when measuring heights. With the Criterion, some users produced underestimates and others overestimates. Thus, any attempt to calibrate the Criterion would require a separate calibration equation for each user. The same may not be true for the Barr & Stroud because every user produced overestimates of nearly the same magnitude. These results are not surprising,

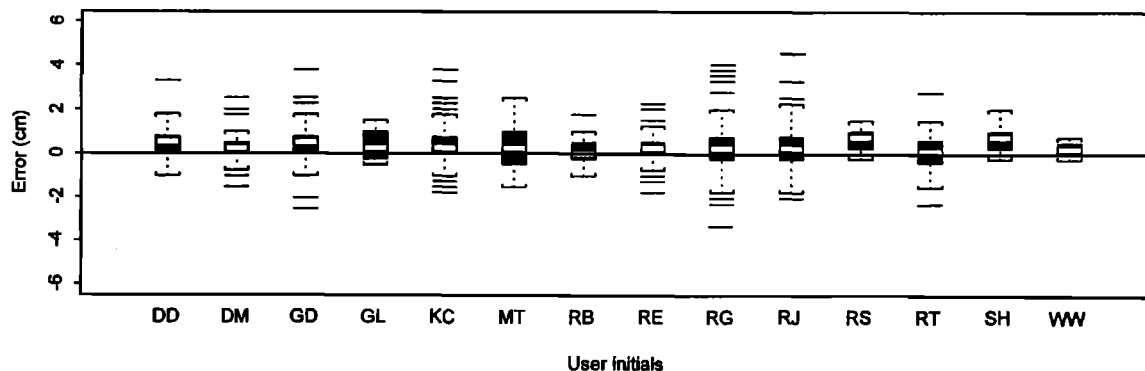


Figure 2. Barr & Stroud diameter measurement errors for each observer.

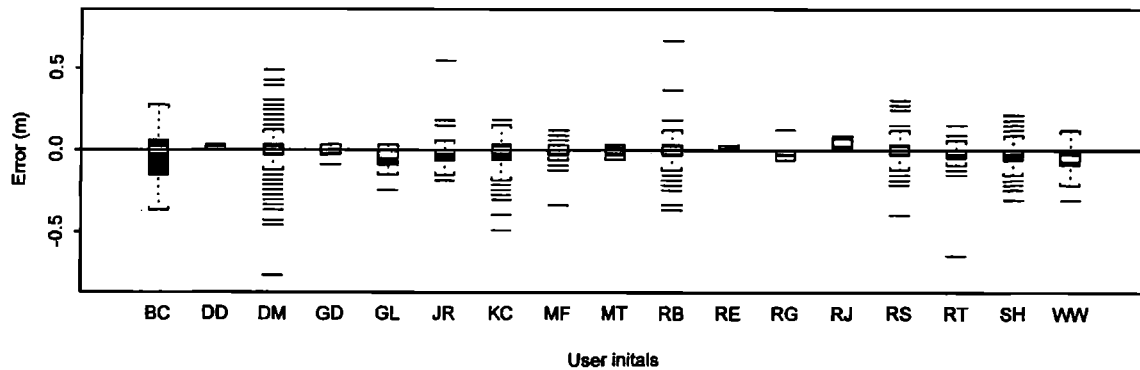


Figure 3. Errors in height measurements for the Criterion 400 for each observer.

because the Criterion requires the user to count the number of hash marks seen through the scope. It involves a personal judgment on irregularly shaped boles and whenever borderline situations occur. This dendrometer is more error prone than the split-image of the Barr & Stroud as indicated by the increased width of the box plots. Some calibration must be applied with the Barr & Stroud because there appears to be a systematic overestimate of diameters and heights. This overestimate is consistent with the results reported by Bell and Groman (1971) and Grosenbaugh (1963).

The mean error and percent errors are listed in Table 1 and indicate that both dendrometers overestimate the true diameter, with an average overestimate of 0.34 cm (0.13 in.) and 0.12 cm (0.05 in.) for the Barr & Stroud and Criterion respectively. When the errors are expressed as a percentage of the true measurement, the means are 1.34 and 0.40% overestimate for the Barr & Stroud and Criterion, respectively. When the height measurements were tested, the Criterion produced average biases of -0.01 m (-0.03 ft) and -0.18% . The Barr & Stroud overestimated heights by 0.03 m (0.09 ft) and 0.65%. Standard errors indicate that the Criterion was substantially less efficient when estimating diameters and about equally efficient at estimating heights.

Coefficients for mixed models (1) and (2) indicate that the Barr & Stroud consistently overestimated the true diameter (Table 2). An analysis of the residuals indicated that the Barr & Stroud consistently overestimated diameter by about 0.3 cm (0.1 in.) and that forcing the intercept term through the origin [model (2)] was inappropriate. For the Criterion, both models indicate that this dendrometer measured upper stem diameters without bias. When estimating height, neither

instrument was unbiased, with the Criterion underestimating the height and the Barr & Stroud overestimating the heights as indicated by model (4).

The mixed model divides the measurement variability into two components. One component for error in measurement (σ_e^2), and one associated with the differences between observers (σ_g^2). For every model tested the size of σ_e^2 was approximately an order of magnitude larger than σ_g^2 (Table 3). The confidence intervals for σ_g^2 all contain zero indicating that the differences between users were not significant for the measurement of both diameter and height. The one exception was when evaluating the measurement of heights using the Criterion in conjunction with model (4). These results indicate that most of the variability in measurement was due to the instrument and only a small portion to the differences between users. Comparing σ_e^2 values between the Barr & Stroud and Criterion indicated that the latter is less efficient at measuring diameters and both dendrometers are about equally efficient at measuring heights. This is consistent with the results of the mean error analysis.

Tests of the relationship between absolute error and the distance to the tree and height of the measurement showed that only distance significantly increased errors in measurement. Table 4 contains the estimates of the β coefficients and confidence intervals. The models for both dendrometers show that the error in the diameter measurements increased with distance between the instrument and the tree. Since β is larger for the Criterion, we conclude that measurement error increases more rapidly with increases in distance for the Criterion than the Barr & Stroud. The models for the error in height measurement showed that only the Barr & Stroud

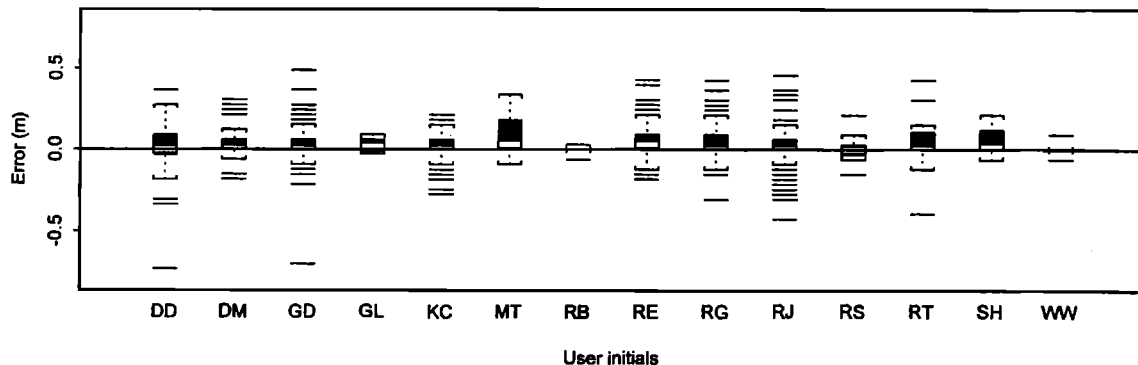


Figure 4. Errors in height measurements for the Barr & Stroud for each observer.

Table 1. Mean errors and % errors listed with their standard deviations. Values for the mean errors are given in centimeters for the diameter measurements and meters for the height measurements.

Relationship tested	Instrument	Mean error, SD	% error, SD
Diameter	Barr & Stroud	0.34, 0.88	1.34, 3.09
Diameter	Criterion	0.12, 1.43	0.40, 5.30
Height	Barr & Stroud	0.03, 0.11	0.65, 3.17
Height	Criterion	-0.01, 0.11	-0.18, 3.08

Table 2. Model coefficients and confidence intervals for the tests of bias for diameter and height measurements.

Test	Instrument	Model no.	α	C.I.	β	C.I.
Diameter	Barr & Stroud	[1]	0.295	(0.164, 0.426)	1.002	(0.997, 1.007)
Diameter	Barr & Stroud	[2]			1.012	(1.009, 1.014)
Diameter	Criterion	[1]	-0.004	(-0.293, 0.285)	0.998	(0.993, 1.011)
Diameter	Criterion	[2]			0.998	(-0.989, 1.007)
Height	Barr & Stroud	[3]	-0.004	(-0.024, 0.015)	1.009	(1.006, 1.012)
Height	Barr & Stroud	[4]			1.009	(1.006, 1.011)
Height	Criterion	[3]	0.017	(0.001, 0.034)	0.990	(0.987, 0.993)
Height	Criterion	[4]			0.992	(0.990, 0.994)

Table 3. Estimated variances and confidence intervals for the mixed models.

Test	Instrument	Model no.	σ_e^2	C.I.	σ_e^2	C.I.
Diameter	Barr & Stroud	[1]	0.0091	(0.0084, 0.0097)	0.0001	(-0.0006, 0.0009)
Diameter	Barr & Stroud	[2]	0.0092	(0.0008, 0.0099)	0.0002	(-0.0003, 0.0008)
Diameter	Criterion	[1]	0.0266	(0.0244, 0.0287)	0.0033	(-0.0000, 0.0066)
Diameter	Criterion	[2]	0.0265	(0.0244, 0.0287)	0.0032	(0.0001, 0.0064)
Height	Barr & Stroud	[3]	0.1231	(0.1130, 0.1331)	0.0038	(-0.0012, 0.0090)
Height	Barr & Stroud	[4]	0.1230	(0.1131, 0.1330)	0.0036	(-0.0011, 0.0083)
Height	Criterion	[3]	0.1131	(0.1131, 0.1131)	0.0030	(0.0030, 0.0030)
Height	Criterion	[4]	0.1132	(0.1039, 0.1224)	0.0040	(-0.0006, 0.0086)

Table 4. Beta coefficients and confidence intervals for testing the relationship between absolute error and distance and height of the measurement.

Dependent variable	Explanatory variable	Instrument	β	C.I.
Diameter	Height	Barr & Stroud	0.0096	(-0.0085, 0.0277)
Diameter	Height	Criterion	0.0083	(-0.0209, 0.0375)
Diameter	Distance	Barr & Stroud	0.0187	(0.0106, 0.0267)
Diameter	Distance	Criterion	0.0385	(0.0256, 0.0514)
Height	Distance	Barr & Stroud	0.0015	(0.0004, 0.0026)
Height	Distance	Criterion	0.0003	(-0.0007, 0.0014)

showed a significant increase in measurement errors with distance. Visual tests showed no increase in the variability of the measurement errors as a function of distance or height of the measurements.

The results of the Spearman's rank correlation test indicated no systematic correlation between the errors in diameter and height measurement. The estimated correlation between diameter and height errors was $\rho = -0.022$ and 0.016 for the Criterion and the Barr & Stroud, respectively.

When the taper equations were fitted to the calibrated data, the equation based on the measurements of the Criterion was

significantly different from the taper equation generated by the caliper and linear tape measurements (true values). The form of Equation (5) was

$$\frac{\hat{d}(h_{ij})^{2^{Cal\&Tape}}}{D_k^2} = -0.083 + 1.117 \frac{\hat{d}(h_{ij})^{2^{Cri}}}{D_k^2}$$

with confidence intervals of $(-0.091, -0.076)$ and $(1.108, 1.127)$ for α and β , respectively. Fitting a quadratic model indicated significant curvature in the relations between the

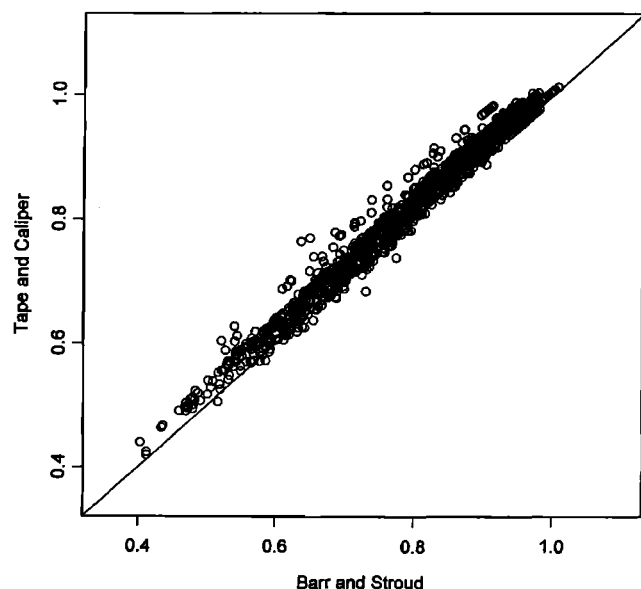


Figure 5. Predicted relative diameter squared for Caliper and Tape vs. Barr & Stroud.

two models. Agreement between the taper equations generated with the calibrated Barr & Stroud measurements, and true values was very good. The form of Equation (5) was

$$\frac{\hat{d}(h_{ij})^{2^{Cal\&Tape}}}{D_k^2} = -0.004 + 1.003 \frac{\hat{d}(h_{ij})^{2^{Barr}}}{D_k^2}$$

with confidence intervals of $(-0.012, 0.004)$ and $(0.996, 1.012)$ for α and β , respectively.

Predicted relative diameters squared

$$\left(\frac{\hat{d}(h_{ij})^2}{D_k^2} \right)$$

were generated using taper equations derived from the dendrometers and caliper and linear tape measurements. The

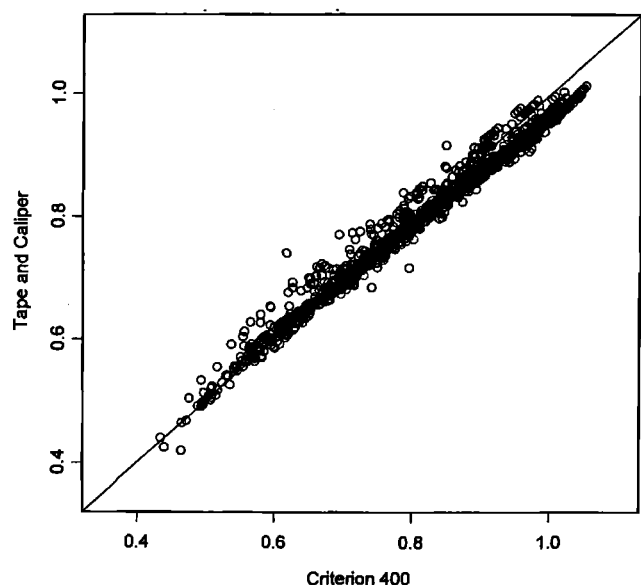


Figure 6. Predicted relative diameter squared for Caliper and Tape vs. Criterion 400.

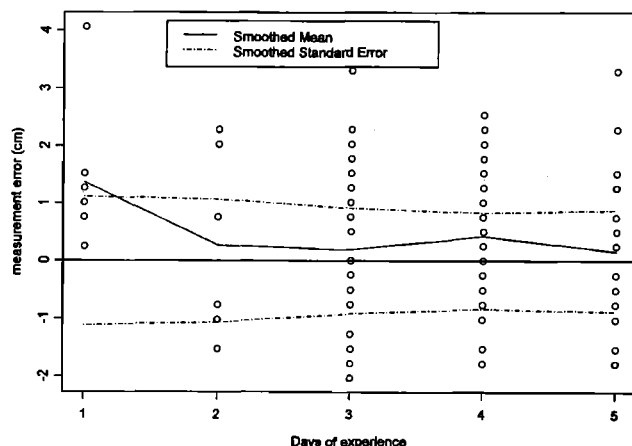


Figure 7. Measurement errors by days of experience for the Criterion 400.

values derived from the dendrometers were graphed against those derived by true diameters and heights. Those generated by the Barr & Stroud (Figure 5) taper equation showed nearly perfect agreement with those derived from the caliper and linear tape. Results for the Criterion show poor agreement (Figure 6) between the predicted values with a substantial degree of curvature in the data. An analysis of residuals failed to indicate any lack of fit or influence of outliers. Further investigation showed that while there is a one-to-one correspondence between the caliper and calibrated Criterion diameter measurements, when these measurements are squared to produce $d(h)^2 / D_k^2$ values, there is a significant degree of curvature in the relationship. Two possible explanations are.

1. The relationship between caliper and Criterion diameter measurements is not truly one-to-one, but the sample size is insufficient to reach this conclusion.
2. The diameter squared measurements for the laser are influenced by a significant transformation bias, similar to that discussed by Czaplewski and Bruce (1990).

The first explanation seems rather unlikely due to the large number of observations.

Figures 7 and 8 were used to determine if there was any evidence of a reduction in bias or measurement error once a user became familiar with an instrument. The graphs display

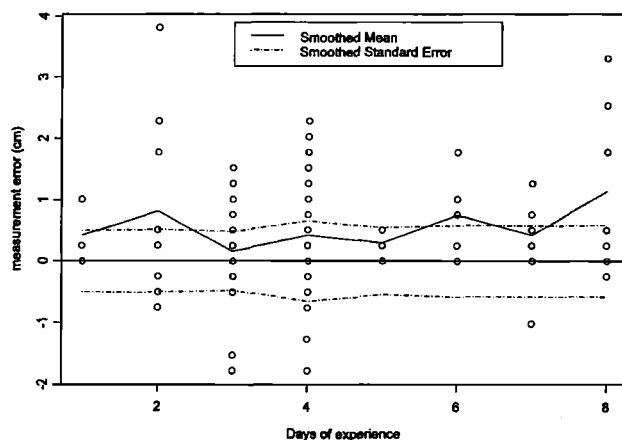


Figure 8. Measurement errors by days of experience for the Barr & Stroud.

measurement errors for a single user plotted against the day each measurement was collected. For the Criterion (Figure 7), the smoothed mean shows some decrease in both bias and variability over the time of the study. Note that during the first day, all measurements were overestimates of the true diameter. The graph for the Barr & Stroud (Figure 8) shows no pattern except for the tendency to overestimate the diameter. Figure 7 suggests a potential problem for calibrating the Criterion, namely, if bias and variability change over a short "training" period, then the data for this "training" period should not be included in any calibration model because they do not accurately reflect the long-term performance of the instrument.

Conclusions

The results of this study indicate that neither the Criterion nor Barr & Stroud dendrometers are capable of producing both unbiased upper stem measurements of both diameter and height without calibration. Measurements of diameter made by the Barr & Stroud were more precise than those made by the Criterion. Height measurements were about equally efficient for both dendrometers. When calibrated, only the Barr & Stroud generated a taper equation which agreed well with the one derived from true diameter and height measurements. It is not possible to determine the exact cause of the taper equation bias reported for the Criterion, but a transformation bias and the propagation of measurement error through the fitting process are the most likely causes.

The only factor influencing the magnitude of the measurement error is the distance between the point of measurement and the base of the tree. Measurement errors for both height and diameter increased with increasing distance for the Criterion. Only measurements of height were affected for the Barr & Stroud.

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