Differences in Computed Individual-Tree Volumes Caused by Differences in Field Measurements

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ABSTRACT

Individual-tree volumes are primarily predicted using volume equations that rely on measured tree attributes. In the northeastern United States, the Forest Inventory and Analysis program determines tree volume using dbh, bole height, proportion of cull, and species information. These measurements are subject to variability due to a host of factors. The sensitivity of the volume equations were assessed in relation to changes in each of the input variables. Additionally, data from 3,345 trees that were independently remeasured were used to assess differences in gross and net volumes between operational and audit measurements. Evaluations were conducted for dbh, bole height, and proportion of cull classes, across 18 different species groups. Differences in bole height and proportion cull measurements were found to contribute the most to volume differences. Surprisingly, trees with relatively short bole heights were affected more than trees having taller bole heights. Differences in dbh and species identification contributed little to the volume differences. An analysis of the full data set across all realized volume differences showed no statistical bias in either gross or net volume. These results show the influence that specific field measurements have on accurate estimation of volume, which may be useful for targeting specific attributes where additional training or refined measurement protocols could improve consistency.

Keywords: quality assurance, measurement error, forest inventory, estimation

In many forest inventories, tree volumes are computed using a regression model. Direct prediction results from the fitted equation having volume as the dependent variable (Edminster et al. 1980, Hahn and Hansen 1991), while indirect prediction may be performed, e.g., via integration of a tree taper model (Martin 1981, Avery and Burkhart 2002). In either case, the prediction relies on independent variables that include some measure(s) of tree attributes (Clutter et al. 1983). For traditional sample-based inventories, these values are obtained from field measurements. These field measurements are subject to measurement error, disparity in perception, inconsistent instrument calibration, mistakes reading an instrument, and/or faulty data recording such that differing values may be obtained on repeated measurement of the same tree. The contribution of these differences to the overall uncertainty of population estimates is often ignored but has been studied by some researchers (Gertner 1990; Westfall and Patterson 2007). These studies provide a good assessment of this error source but are not specific on variation in computed volume for individual trees. This article examines the variation in individual tree volumes in terms of the sensitivity of a volume equation to changes in predictor values and evaluates a realized distribution of volume differences arising from repeated field measurements.

Methods

Two data sets were used in the analysis. Both data sets consist of tree measurements taken in Ohio, Pennsylvania, New York, Maine, New Hampshire, Connecticut, and Massachusetts by the Forest Inventory and Analysis (FIA) program of the US Forest Service. The first set of data is from regular inventory plots that were selected to receive a quality assurance (QA) audit. The second data set are data from these same plots, but measured a short time later (within 2 weeks) by a different field crew as part of a QA program. The remeasurement crew had no knowledge of the results from the initial regular inventory measurement—thus, the term "blind check." There were 3,345 measured trees encompassing 72 species on 140 sample plots that were approximately ⅙ ac in size. The plots were measured between 2002 and 2005.

Attributes of interest for this study include dbh, bole height (height associated with 4-in. top diameter, outside bark), proportion of cull, and species. Operational and audit measurements are taken in the following manner: (1) dbh (nearest 0.1 in.), d-tape; (2) bole height (nearest 1 ft), clinometer, laser, or ocular estimate; and (3) proportion cull (nearest 0.01) and species, visual assessment. Gross cubic foot volumes for these trees are computed from the equations developed by Scott (1981):

$$\hat{V}_{\mathrm{g}} = \hat{\beta}_0 + \hat{\beta}_1 D^{\hat{\beta}_2} + \hat{\beta}_3 D^{\hat{\beta}_4} H^{\hat{\beta}_5}, \tag{1}$$

where $\hat{V}_{\mathrm{g}}$ = predicted gross merchantable volume (cubic feet); D = dbh (inches); H =bole height (feet); and $\hat{\beta}_0$–$\hat{\beta}_5$ = estimated coefficients (species group specific).

Net merchantable volumes are obtained by subtracting any unmerchantable portion of the stem volume, which is derived from the proportion cull measurement:

$$\hat{V}_{\mathrm{n}} = \hat{V}_{\mathrm{g}} \times (1 - C), \tag{2}$$

where $\hat{V}_{\mathrm{n}}$ = predicted net merchantable volume (cubic feet); and C = proportion cull. A summary of dbh (D), bole height (B), proportion of cull (C), and net merchantable volume $\hat{V}_{\mathrm{n}}$ by softwood/hardwood species classification is given in Table 1.

To compare differences in individual-tree measurements and computed volumes, these two data sets were combined by matching

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Received January 11, 2008; accepted September 11, 2008.

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Table 1. Summary statistics for dbh (D), bole height (B), proportion of cull (C) and net merchantable volume ($\hat{V}_n$) by softwood/hardwood species classification.

Quantile	Hardwood dbh	Softwood dbh	Hardwood bole height	Softwood bole height	Hardwood proportion of cull	Softwood proportion of cull	Hardwood net volume	Softwood net volume
	. . . . (in)		. . . . (ft)				. . . . (ft^3)	
100% Maximum	41.5	30.3	93	80	0.99	0.99	157.84	136.07
99%	23.5	18.6	74	70	0.99	0.71	69.59	47.28
95%	16.5	13.4	62	52	0.40	0.29	36.38	21.23
90%	14.5	11.8	55	44	0.26	0.15	26.48	14.44
75% Q3	10.9	8.8	44	34	0.15	0.05	13.78	7.71
50% Median	8.0	7.0	31	24	0.08	0.00	5.88	4.09
25% Q1	6.1	5.7	21	17	0.00	0.00	2.66	2.52
10%	5.4	5.2	14	13	0.00	0.00	1.54	1.79
5%	5.2	5.1	10	11	0.00	0.00	1.08	1.52
1%	5.0	5.0	6	8	0.00	0.00	0.07	1.01
0% Minimum	5.0	5.0	4	5	0.00	0.00	0.01	0.04

trees on each plot. The procedure is designed to be conservative, ensuring that only unambiguous matches are created. Additional manual matching resulted in roughly 99% of trees being matched. The method is outlined in more detail by Pollard et al. (2006).

Statistical tests for differences by various categorizations of the data (dbh, bole height, and cull classes; species groups; and hardwood/softwood) were based on values resulting from subtracting the tree volume as determined from the regular inventory measurements from the volume obtained from the QA measurements. Paired *t*-tests were conducted and differences were considered to be statistically different from 0 at the 95% confidence level, i.e., when the value of $P < 0.05$.

Analysis and Results

Volume Equation Sensitivity

Computation of gross volume relies on three field measurements—dbh, bole height, and species. The dbh and bole height are predictor variables in the volume equation and species determines the set of coefficients to be used. Because the coefficients of Equation 1 are similar across all species groups (Scott 1981), the response surfaces for computed volumes exhibit similar behavior, i.e., trees with large dbh exhibit a larger change in volume for a given change in bole height (and vice versa) than smaller trees. Thus, measurement variation is potentially more of a concern as tree size increases.

To assess the effects of species differences, gross volumes were computed for each species group across a range of dbh/bole height combinations (dbh, 5–25 in. by 1 in. class; bole height, 5–90 ft by 5 ft class). Assuming that species would be correctly identified as either a hardwood or softwood species, *maximum* absolute differences in volumes were computed among the species groups within the hardwood/softwood categories. The maximum absolute differences among the hardwood species groups were larger than the maximum absolute differences among the softwood groups (Figures 1 and 2). The differences increase with increasing dbh and bole height, such that species identification (within the softwood/hardwood groups) has a bigger impact on volume determination for larger trees.

Volume Difference Distributions

Individual-tree volume differences arise from differences in measurements of dbh, bole height, and proportion cull, as well as species determination. Statistics related to the variation in these individual measurements are reported by Pollard et al. (2006). The combined effect of variation across these four measurement sources can be examined by comparing differences in computed volumes between the regular inventory measurements and the QA blind check results. The distribution of percent volume differences (using the audit volumes as the basis) by hardwood/softwood classification are shown in Table 2. The spread of the softwood differences is somewhat less than that of the hardwood distribution. The extreme values seen in both softwood and hardwood categories result from large differences in the proportion of cull between the operational and audit crews.

Evaluation of the effects of differences in species determination that result in different volume equation coefficients was difficult because a particular combination usually only occurred once, which precluded variance estimation and subsequent tests for differences. Overall, 42 trees (1.3%) had conflicting species data that caused a change in model coefficients. These trees were grouped by softwood and hardwood classification for testing purposes. No statistically significant volume differences were produced from changing model coefficients due to disagreements in species identification.

A more detailed look into the hardwood/softwood classifications was accomplished by examining the mean differences in gross and net volume for each of the 18 species groups (Table 3). Within the softwoods, the only group having a significant deviation from zero was balsam fir (*Abies balsamea*). This result applied to both gross and net volumes. Hardwood species having significant volume differences were black cherry (*Prunus serotina*) and chestnut oak (*Quercus prinus*). Similar to balsam fir, both gross and net volume differences were nonzero for black cherry. Only the net volume differences were significantly nonzero for chestnut oak.

A more comprehensive evaluation of the volume differences was performed by grouping the data into dbh, bole height, and proportion cull classes (based on audit measurements). Mean differences in gross and net volume were computed by softwood/hardwood species within each class (Table 4). For hardwoods, there are no dbh classes exhibiting a mean difference that is statistically different from zero, except for the 17.0- to 18.9-in. category. In this category, both gross and net volume differences are positive (audit volume greater than operational volume) and different from zero. For softwoods, there were statistically nonzero positive mean differences for both gross and net volume in the dbh

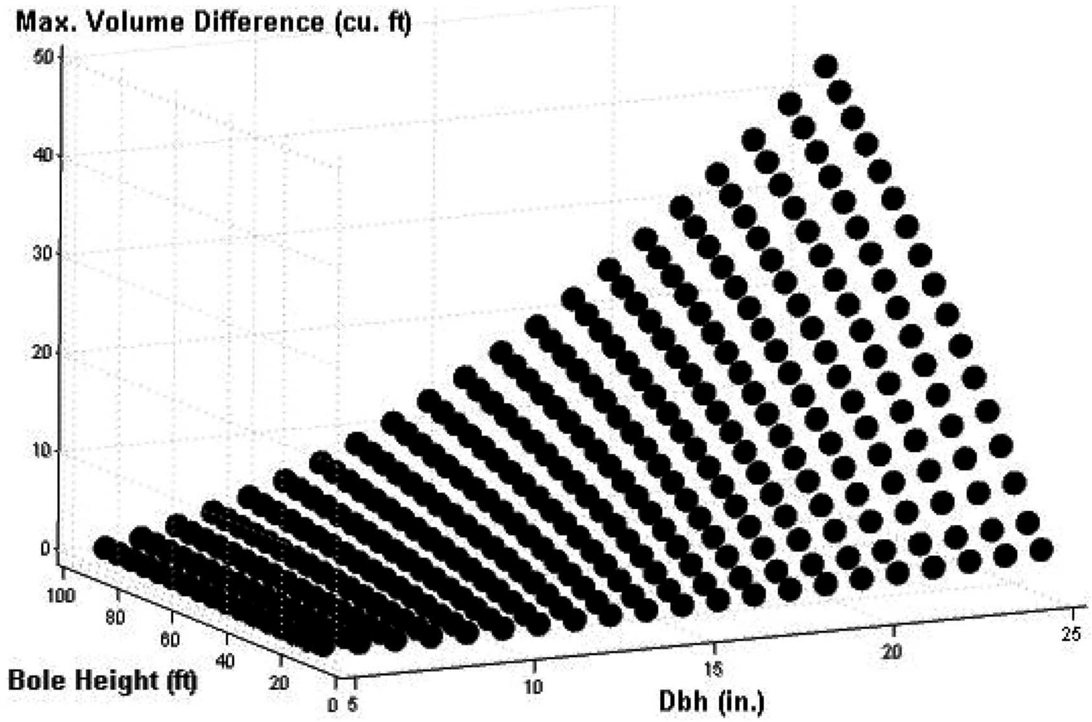

Figure 1. Maximum absolute differences in individual-tree volumes by bole height and dbh for hardwood species.

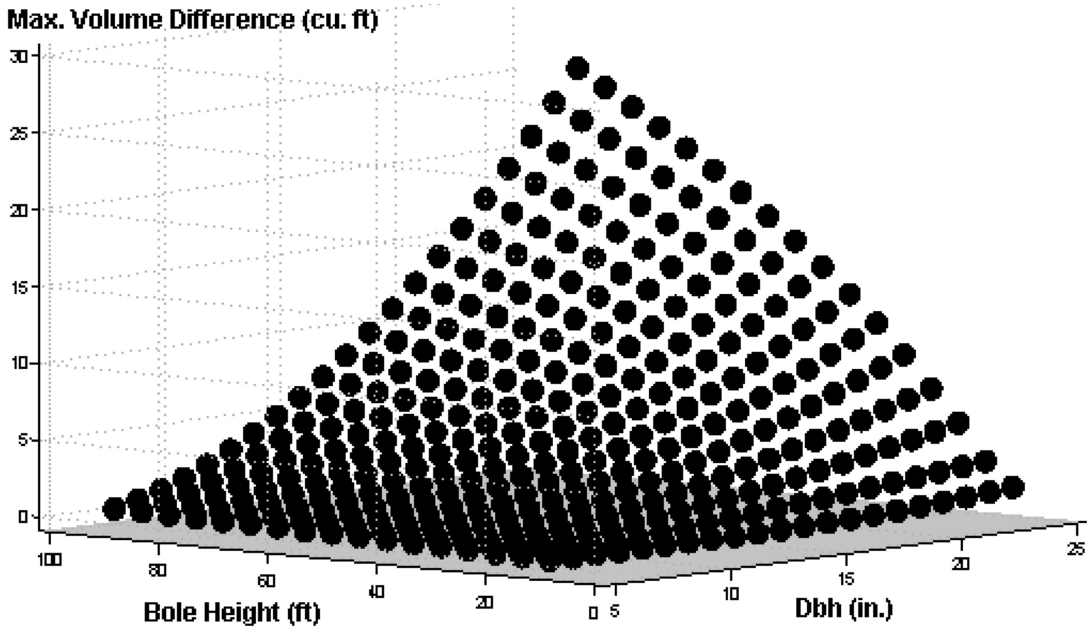

Figure 2. Maximum absolute differences in individual-tree volumes by bole height and dbh for softwood species.

classes covering 5.0–8.9 in. The mean difference for net volume in the 9.0- to 10.9-in. class was also nonzero but negatively valued. This suggests there is substantial variation in determination of both bole height and proportion cull for smaller softwood trees.

The results of the analysis by bole height classes also show there is considerable measurement variation for bole height in smaller trees (Table 4). There are significant nonzero negative mean differences in gross volume for hardwood bole heights ranging from 0 to 39 ft and nonzero positive mean difference for 40–59 ft. There were also nonzero differences for softwood bole heights that were 0–39 ft, where the difference was negative for the 0-to 19-ft height class and positive for the 20- to 39-ft class. The problem is alleviated somewhat for hardwoods by the introduction of proportion of cull (net volume), where the 40- to 59-ft class no longer shows a significant difference. However, the net volumes for the hardwood 60- to 79-ft class exhibit a significant positive volume difference, showing that cull produces a discrepancy in these size trees. For softwoods, results for net volume were similar to those for gross volume, where significant differences were found for bole heights from 0 to 39 ft.

Table 2. Quantiles of distributions of percent volume (%) differences for hardwood and softwood classifications.

Quantile	Hardwood volume differences	Softwood volume differences
	(%)	
100% Maximum	99.20	99.34
99%	97.00	98.02
95%	35.98	28.81
90%	24.65	21.21
75% Q3	11.54	10.52
50% Median	−0.06	1.48
25% Q1	−12.64	−6.65
10%	−29.67	−18.94
5%	−50.86	−27.75
1%	−175.75	−86.34
0% Minimum	−16,796.20	−11,076.80

When the differences are evaluated by proportion cull class, the most notable results are associated with trees that have little cull or are mostly cull. For hardwoods, significant nonzero mean differences in net volume were found for the 0.00–0.19 (positive difference) and 0.80+ (negative difference) classes. The differences in gross volume for these two classes did not statistically deviate from zero, indicating the differences in volume were primarily caused by differences in proportion of cull. However, for softwoods, both the gross and the net volume differences for the 0.00–0.19 class were positive and nonzero—suggesting that volume differences do not arise from cull differences for smaller softwood trees. Other softwood cull classes exhibiting significant differences were 0.60–0.79 for gross volume (positive) and 0.80+ for net volume (negative). Across all trees in the data set, both gross and net volume differences were not significantly different from zero at the 95% confidence level.

The overall contribution of each factor to the variability in computed net volumes was assessed by isolating the measurement differences, i.e., only allow a single factor to vary while holding the others constant. Examination of the standard errors of the mean net volume difference reveals the relative contribution of each factor. Table 5 lists the standard errors of the mean net volume differences for dbh, bole height, cull, and species determination by softwood/hardwood classification. The results were fairly consistent within the two species groups, where cull proportion was the factor that contributed the most to variability in computed volumes. Bole height and dbh contributed lesser amounts and had similar values within each group. Species identification differences contributed little to the volume difference variation.

To evaluate how the differences in individual-tree volumes affect estimation, differences in plot-level volume totals were investigated. Specifically, the per-plot gross and net volumes were compared between the regular production values and the QA results. Mean differences between plot volumes were 1.8 and 1.9 ft^3 for gross and net volume, respectively. Neither of these statistics was significantly different from zero with 95% confidence.

Discussion/Conclusion

Volume Equations

For a given change in predictor variable values, the volume equations used in this study produce bigger changes in volume for larger trees. This behavior is consistent with volume being correlated to the cross-sectional area of the stem (i.e., diameter squared; Husch et al. 1982) and nonlinear diameter/height relationships (Colbert et al. 2002). The exact relationships between volume and dbh/bole height differed among the 18 species groups (owing to different model coefficients) and particularly between hardwood and softwood species. The largest differences in individual-tree volume due to species within the softwood groups were substantially smaller than the largest differences among the hardwood groups. This is attributable to the more consistent excurrent tree form found in softwood species.

Within softwood species, the largest differences between groups were between cedars (*Chamaecyparis thyoides*, *Juniperus virginiana*, and *Thuja occidentalis*) and spruces (*Picea* sp.) and between cedars and balsam fir. This result stems from the differences in tree taper between the spruce/fir and cedar species. Similarly, the largest differences within the hardwood groups were between beech (*Fagus grandifolia*) and chestnut oak, where notable differences in tree form produce disparate amounts of tree volume at the same dbh and height.

Mean Volume Differences

Comparisons of net volumes for the same tree measured independently by the regular inventory crew and the QA crew indicated

Table 3. Mean differences and *P*-values for two-sided paired *t*-tests against zero for gross and net volume across species groups.

Group	No. trees	Mean difference V_g (ft^3)	*P*-value	Mean difference V_n (ft^3)	*P*-value
White/red pine	114	0.12	0.370	−0.33	0.180
Red/white/black spruce	274	0.02	0.850	0.04	0.639
Balsam fir	288	0.24	**0.000**	0.34	**0.008**
Eastern hemlock	153	0.02	0.840	−0.11	0.472
Hard pines/tamarack/Norway spruce	21	−0.01	0.967	1.07	0.353
Cedar spp.	128	0.13	0.208	0.35	0.080
Sugar maple	256	0.02	0.894	−0.11	0.624
Yellow-poplar	17	0.38	0.698	−1.00	0.426
Ash spp./aspen spp.	268	−0.10	0.574	0.14	0.434
Black cherry	132	0.53	**0.026**	0.76	**0.006**
Birch spp.	263	0.17	0.123	0.21	0.072
Beech	109	−0.41	0.150	−0.36	0.246
Basswood	39	−0.21	0.463	−0.68	0.228
Red oaks/sweetgum/blackgum	255	−0.33	0.055	−0.09	0.625
Chestnut oak	44	−0.02	0.948	0.75	**0.037**
Hickory spp.	38	0.57	0.087	−0.01	0.981
Other hardwoods	266	0.60	0.172	−0.13	0.788
Red maple	680	0.00	0.996	0.13	0.465

Significant differences ($\alpha = 0.05$) are shown in bold font.

Table 4. Mean differences and *P*-values for two-sided paired *t*-tests against zero for dbh, bole height, and proportion cull classes by softwood/hardwood classification.

	Softwood/ hardwood	No. trees	Mean difference V_g (ft^3)	*P*-value	Mean difference V_n (ft^3)	*P*-value
dbh Class (in.)						
5.0–6.9	H	898	−0.02	0.231	−0.02	0.309
7.0–8.9	H	493	0.03	0.572	−0.03	0.545
9.0–10.9	H	396	0.12	0.163	0.18	0.074
11.0–12.9	H	220	−0.06	0.715	0.06	0.769
13.0–14.9	H	160	0.18	0.542	0.32	0.372
15.0–16.9	H	94	−0.26	0.596	0.68	0.207
17.0–18.9	H	41	2.16	**0.022**	2.98	**0.048**
19.0–20.9	H	28	−0.09	0.947	−0.71	0.725
21.0 +	H	37	0.69	0.877	−3.28	0.453
5.0–6.9	S	489	0.13	**0.000**	0.14	**0.000**
7.0–8.9	S	258	0.10	**0.019**	0.10	**0.047**
9.0–10.9	S	106	−0.31	0.193	−0.54	**0.023**
11.0–12.9	S	62	0.06	0.762	0.48	0.186
13.0–14.9	S	37	0.71	0.054	−0.25	0.723
15.0–16.9	S	13	0.92	0.291	5.33	0.116
17.0–18.9	S	7	0.57	0.540	0.06	0.956
19.0–20.9	S	3	2.33	0.471	−0.56	0.937
21.0 +	S	3	−1.00	0.558	−1.43	0.822
Bole height class (ft)						
00–19	H	582	−0.32	**0.000**	−0.24	**0.000**
20–39	H	1,073	−0.13	**0.019**	−0.08	0.176
40–59	H	585	0.49	**0.021**	0.04	0.878
60–79	H	117	1.19	0.276	2.95	**0.007**
80 +	H	10	4.13	0.111	0.95	0.763
00–19	S	363	−0.07	**0.005**	−0.08	**0.015**
20–39	S	477	0.16	**0.000**	0.13	**0.022**
40–59	S	117	0.39	0.119	0.55	0.141
60–79	S	21	0.51	0.358	1.25	0.541
Proportion cull class						
0.00–0.19	H	1,965	0.02	0.749	0.22	**0.004**
0.20–0. 39	H	276	−0.02	0.937	0.20	0.469
0.40–0.59	H	62	−0.16	0.632	−2.25	0.089
0.60–0.79	H	32	3.69	0.272	−3.89	0.158
0.80 +	H	32	−0.29	0.341	−2.25	**0.028**
0.00–0.19	S	904	0.14	**0.000**	0.20	**0.000**
0.20–0. 39	S	40	−0.34	0.589	0.06	0.962
0.40–0.59	S	15	−0.66	0.079	−1.32	0.190
0.60–0.79	S	12	0.49	**0.013**	−2.08	0.083
0.80 +	S	7	−1.00	0.102	−2.91	**0.036**
All		3,345	0.07	0.203	0.08	0.220

Significant differences ($\alpha = 0.05$) in bold font.

that differences were more variable for hardwood species. Tree characteristics, particularly bole height and proportion cull, are generally more difficult to accurately measure on hardwood species because of their deliquescent form. Bole height is further complicated by data collection protocols that generally pertain to hardwood trees. The desired height is to a 4-in. top diameter, which must be ocularly estimated. Additionally, the 4-in. top diameter is often not achieved due to merchantability rules regarding minimum log lengths (4 ft) and maximum number of forks (generally 3). These factors present additional variability as the judgment of the crew becomes paramount in determining the point at which bole height is measured. This uncertainty can propagate into the proportion cull measurement as well, because the proportion is based on the volume below bole height.

The analysis of differences by species groups showed significant nonzero differences in gross and net volume for balsam fir and black cherry and in net volume for chestnut oak. Additional investigation into balsam fir showed that volume differences in bole height class 20–39 ft were significantly different from zero ($P < 1\text{E–}10$). However, the gross volume and net volume mean differences were of similar magnitude, suggesting that proportion cull measurements were contributing little to the volume differences. The mean gross and net volume differences for black cherry bole height classes 0–19 and 60–79 ft were nonzero and of similar amount, indicating that bole height variation primarily contributed to the volume differences for these size trees. For chestnut oak, mean differences between gross and net volumes by bole height and proportion cull classes showed dissimilar magnitudes that reveal proportion cull measurements are the primary contributor to the net volume differences.

Differences in individual-tree volumes were evaluated for hardwood species by dbh, bole height, and proportion cull classes. For analyses by dbh class, the only class within hardwoods that showed statistically significant differences was 17.0–18.9 in. A review of the data reveals that the bole heights measured by the QA crew for the trees in this class were about 3 ft higher, on average, than the regular inventory crew. It is not clear why this trend in height differences was found for these size trees, but not in any of the other dbh classes. The 41 trees in this diameter class occurred on 27 different sample plots scattered across 5 states; so, perhaps the differences were a random event.

Table 5. Standard errors of mean net volume differences for factors that affect volume prediction.

	dbh	Bole height	Cull proportion	Species
Hardwood	0.0461	0.0421	0.0746	0.0024
Softwood	0.0202	0.0251	0.0603	0.0041

Examination of hardwood species volume differences categorized by bole height classes detected nonzero differences in gross volume from 0 to 59 ft. For the 0- to 19-ft class, net volume differences were also nonzero, which suggests a counterintuitive finding of substantial differences in bole height determination for smaller trees. In the 20- to 59-ft range, net volumes showed no statistical disparity. The combination of nonzero gross volume differences but nonsignificant net volume differences illustrates the interdependence of the bole height and proportion cull measurements. For instance, there may be a propensity for some field personnel to judge relatively low bole heights and corresponding low proportion cull values. Others may do the opposite and tend to have high bole heights with more proportion cull. The differences in bole height manifests itself in the gross volume comparisons; however, the differences in cull tend to equal out the net volumes such that no significant difference exists when proportion cull is accounted for.

Net volume differences for hardwoods were nonzero for proportion cull classes 0.00–0.19 and 0.80+, while there were no gross volume differences for the same two classes. This exemplifies the uncertainty in proportion cull associated with trees that have little/no cull or are mostly cull. The lack of significant differences in net volume for the midrange cull classes suggests that between-crew variability is lessened when cull proportions are not near the minimum or maximum values. Given that the QA measurement is used as the basis for comparison, this result also implies that regular inventory crews are less likely to assign extremely high or low cull values. This outcome may be caused by the tendency for QA crews to have more field experience than the regular field crews during the time period in which the plots were measured.

Examination of mean differences by classes for softwood species also revealed underlying patterns in volume differences. In the dbh class analysis, there were nonzero differences for both gross and net volume in the 5.0- to 8.9-in. classes and for net volume in the 9.0- to 10.9-in. class. As dbh class increased, the differences became nonsignificant. Similarly, the bole height classes 0–39 ft also showed nonzero differences for gross and net volume. Because trees in lower dbh classes also tend to be in the lower bole height classes, this outcome was expected. As with hardwoods, the QA crew had a tendency to record higher bole heights for these classes than the regular production crew. There were also nonzero differences for gross and net volume for the 0.00–0.19 proportion cull class. Because small trees tend to have little cull, many of the trees in this class are the same as those in the lower dbh and bole height classes. Thus, it may be concluded that differences in bole height determination result in significant volume differences on smaller softwood trees. Additionally, there were also some nonzero differences in the upper classes, which indicates the difficulty in determining bole height and/or proportion cull when the tree is mostly cull.

The evaluation of the contribution from each factor to the net volume differences variation showed the cull proportion was the most problematic. Determination of proportion of cull depends on a host of factors, including type of defect and location on the bole, which contributes to high variability between repeated assessments of the same tree. This is problematic in that this variable can more dramatically affect the net volume than the other factors because it is a proportion that is directly multiplied against the gross volume. The fact that dbh and bole height contributed similarly to the variability is primarily because of their relative influences in the volume equations. The dbh is the primary driver of individual-tree volume prediction, so even though it is measured quite consistently, minor deviations can notably affect the prediction. Contrarily, species identification is also a very consistent field attribute, and the differences in volume equation coefficients is relatively small—so differences have little effect on the volume prediction.

From an estimation standpoint, interest is primarily in potential biases of population parameter estimates. Generally, this does not appear to be a problem because gross and net volume differences were statistically not different from zero when analyzed across all trees in the data. Similarly, aggregations to plot-level volume totals also showed no significant difference. However, certain queries may be directed at specific problem areas such that bias may be of concern (e.g., volume of balsam fir). Additionally, inventories of smaller acreages would likely have a more restricted range of tree characteristics, e.g., a tract considered for harvest may consist primarily of trees having large dbh and bole height with low proportion of cull. In such cases, the rows of Table 4 corresponding to the attributes of the trees of interest may provide better insight into potential bias than the test for differences across a wide range of forest conditions. In this study, it is impossible to determine the magnitude and extent of any latent bias because the true values of the tree attributes are unknown.

The volume equations used here may be more complex than other formulations currently in use and, thus, more variation in computed volumes may be incurred. Inventories that use less complex formulations, such as local volume equations (based on dbh alone), would exhibit less variation in tree volumes. However, this approach assumes an underlying tree form, which, if not satisfied, may result in poorer prediction (and potential bias) for individual trees. There is a tradeoff between using more complex models that rely on multiple tree measurements to better estimate the volume of individual trees and implementing simpler equations that likely provide less accuracy in volume prediction for a given tree. However, the more complex models likely exhibit more variation in volume than the simpler equations because of the additional sources of measurement variability. Quantifying these differences is a topic for further investigation.

It was expected that bole height determination would contribute to most of the discrepancies in computed volume because of the difficulties encountered when collecting these data. However, it was surprising to find that many of the statistically nonzero differences were associated with the smaller tree-size classes. Another finding of note was the differences in volume for hardwood trees that had either little/no proportion cull or were mostly/all cull. This could be attributed to simple differences in perception of proportion cull or, more likely, to a more complex interaction between proportion cull and bole height. Differences in dbh and species determination also have the potential to substantially affect tree volume estimates, but there was no evidence that these sources contributed significantly to the volume variation in this study.

These findings have two primary applications: (1) provide users of FIA data with information on the influence that field measurements have on the estimation of volume at the tree-, plot- and population-level; and (2) inform other entities, such as forestry consultants, state agencies etc., of likely areas where field measurements may be contributing to inaccuracies in volume estimates. This information may be useful for targeting specific attributes on which to focus additional training or adapt measurement protocols to improve consistency.

Literature Cited

Avery, T.E., and H.E. Burkhart. 2002. *Forest measurements*, 5th ed. McGraw-Hill, New York. 456 p.

Clutter, J.L., J.C. Fortson, L.V. Pienaar, G.H. Brister, and R.L. Bailey. 1983. *Timber management: A quantitative approach.* John Wiley & Sons, New York. 333 p.

Colbert, K.C., D.R. Larsen, and J.R. Lootens. 2002. Height-diameter equations for thirteen midwestern bottomland hardwood species. *North. J. Appl. For.* 19(4):171–176.

Edminster, C.B., Beeson, R.T. and Metcalf, G.B. 1980. *Volume tables and point-sampling factors for ponderosa pine in the front range of Colorado.* US For. Serv. Res. Pap. RM-218. 14 p.

Gertner, G.Z. 1990. The sensitivity of measurement error in stand volume estimation. *Can. J. For. Res.* 20:800–804.

Hahn, J.T., and M.H. Hansen. 1991. Cubic and board foot volume models for the Central States. *North. J. Appl. For.* 8:47–57.

Husch B., C.I. Miller, and T.W. Beers. 1982. *Forest mensuration*, 3rd ed. John Wiley & Sons, New York. 402 p.

Martin, A.J. 1981. *Taper and volume equations for selected Appalachian hardwood species.* US For. Serv. Res. Pap. NE-490. 22 p.

Pollard, J.E., J.A. Westfall, P.L. Patterson, D.L. Gartner, M.H. Hansen, and O. Kuegler. 2006. *Forest inventory and analysis national data quality assessment report for 2000 to 2003.* US For. Serv. Gen. Tech. Rep. RMRS-181. 43 p.

Scott, C.T. 1981. *Northeastern forest survey revised cubic-foot volume equations.* US For. Serv. Res. Note NE-304. 3 p.

Westfall, J.A., and P.L. Patterson. 2007. Measurement variability error for estimates of volume change. *Can. J. For. Res.* 37:2201–2210.