VOLUME AND BIOMASS ESTIMATION IN FIA: NATIONAL CONSISTENCY VS. REGIONAL ACCURACY

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ABSTRACT.—Volume and biomass estimates are among the most widely used data produced by the Forest Inventory and Analysis (FIA) program of the USDA Forest Service. This paper documents the various methods used by FIA in the Eastern U.S. and compares those methods for 67 species that cross regional boundaries. Four different methods currently being used by FIA to estimate the gross cubic foot volume, gross board foot volume (International 1/4-inch scale), and total gross biomass are examined. Overall, these four methods produce similar results, but large differences exist for specific species and diameters. I recommend that FIA develop a nationally consistent method for estimating volume and biomass. Users of FIA data are cautioned against making regional comparisons of volume or biomass information for small diameter trees.

Each year FIA field crews visit over ten thousand field plots and measure over one million trees on these plots. For every tree measured, estimates of volume and biomass are calculated based on these tree measurements and regional volume and biomass models. These individual tree volume and biomass estimates are used widely. They contribute to estimates of volume, biomass, growth, mortality, and removals presented in FIA reports and are accessed by many users of the FIA database (FIADB) (Miles and others 2001) via the Internet at www.ncrs.fs.fed.us/4801/fiadb/index.htm.

In recent years national consistency in methods has become a prime concern within FIA. To eliminate regional differences, FIA has adopted a national plot design that calls for taking a core set of common measurements using identical methods on all plots. One database (FIADB) was created for public access to all FIA data. This database contains tree level data including the observed tree attributes collected by the field crews such as species, diameter, height, and crown ratio and computed tree attributes such as volume and biomass.

Methods used to obtain these computed tree attributes currently vary within FIA. Each regional FIA program has its own models for producing estimates of the tree level volume and biomass attributes in the FIADB, and in some cases these methods vary by State within a program. Because of these different methods, an identical tree measured in different locations using the same field procedures may not have the same volume or biomass estimate in the FIADB. For example, the estimated volume of a white oak that is measured to be 23.5 inches d.b.h. in southern Indiana will be different in the FIADB than an identical tree measured on the other side of the Ohio River in Kentucky. These different methods are not well documented, and regional differences are not well understood. Users of FIA volume and biomass estimates want to know how these estimates are made and if regional differences in methods affect the utility of the information.

I have limited this paper to the examination of the four different methods of gross volume and biomass estimation used by the three eastern FIA programs. Only the magnitudes of the differences between the various estimates are compared. I assume that each program selected the best available model for its region although model bias remains a major concern that I do address in this study. An estimate may be unbiased for one population (e.g., estimating total volume in a three-State area) but biased for a different area (e.g., a few counties within that three-State area). Therefore, the purpose of this paper is to simply document the different methods currently in use and to quantify differences between the methods on a set of trees that could be found in the different regions.

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FIA VOLUME AND BIOMASS ESTIMATES

FIA commonly reports seven different estimates of volume and two estimates of biomass for each tree that is sampled. These estimates are stored in the FIADB and are available via the Internet. Only three (gross cubic foot volume, gross board foot volume, and total biomass oven-dry weight) are considered here. The respective names VOLCFGRS, VOLBFGRS, and DRYBIOT are used for these estimates throughout all FIADB documentation and in this paper. These gross volume and biomass estimates form the basis for the other six estimates found in the FIADB. These other estimates are net volumes and biomass where the gross estimates are reduced for excluded portions of the tree.

The models used to compute these three attribute estimates come from various sources. They were originally obtained by fitting various nonlinear models to tree level data sets, which consisted of standard FIA tree measurements (species, diameter, height, …) and "known" volume observations. Typically, the "known" volume observations were calculated based on detailed tree height and upper stem diameter measurements and established regional volume tables or models. Differences exist in the model form, predictor attributes, and nonlinear regression methods used to fit the models. Each model was fit to a different data set, appropriate to the region where it is being used. In general, one model form is used for all species in a region. The model was fit for a specific species (or species group) and parameter estimates were obtained. Species were often grouped together differently in different regions. In some cases, different model forms are used for different species.

The next sections describe each of the three attributes and present the model forms and approaches to estimation used in four regions in the Eastern United States (fig. 1). The regions follow the FIA program regions (the LS and CS regions together make up the North Central FIA program region), which encompass all aspects of FIA operations including data collection, information management, and analysis and reporting of inventory results. Other details such as the fitted parameter values, methods used to fit the models, and characteristics of the data sets used in fitting are not presented here but can be found in the references given for each model.

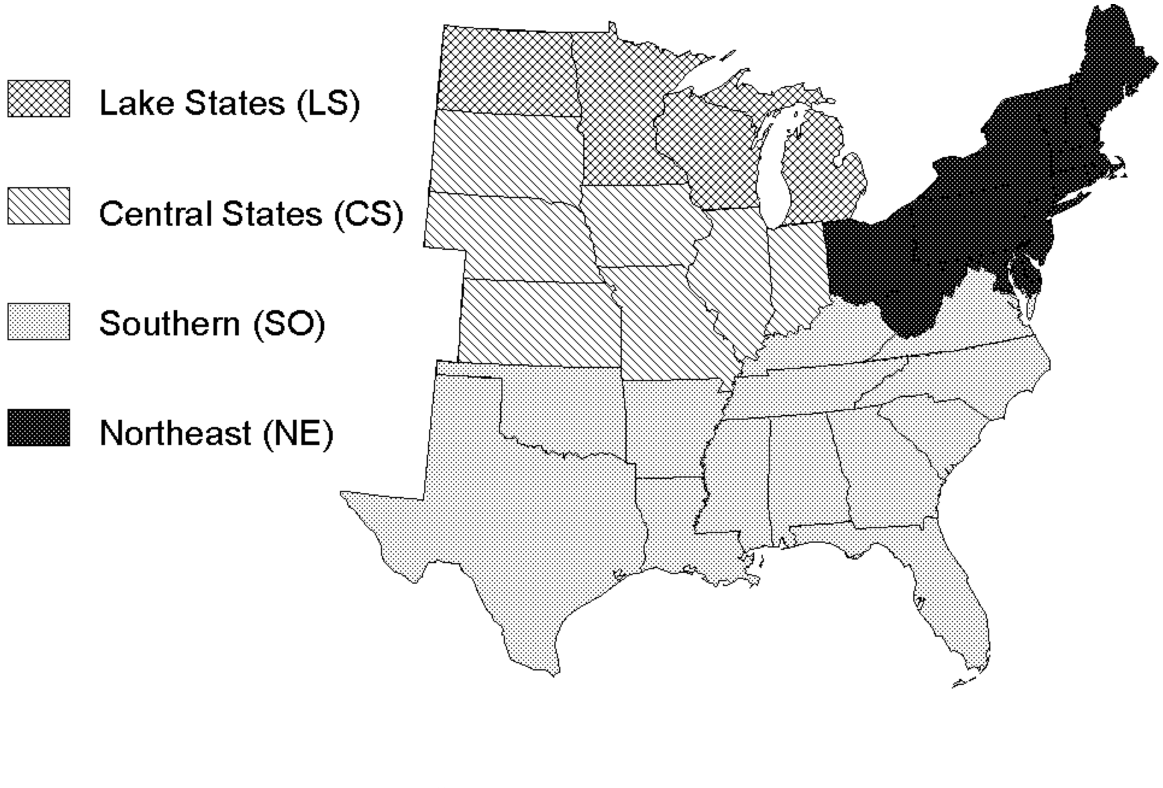

Figure 1.—*Regions in the Eastern U.S. where different volume and biomass estimation methods are used.*

Gross Cubic Foot Volume

Gross cubic foot volume (VOLCFGRS) is defined as the total volume inside bark of the central stem from a 1-foot stump to a minimum 4-inch top diameter-outside-bark (d.o.b.) or to where the central stem breaks into limbs all of which are less than 4.0 inches d.o.b. Although gross cubic foot volume estimates are not commonly presented in most FIA reports, this variable forms the basis for the most widely used FIA volume attribute, net cubic foot volume, reported in many core FIA tables.

In all of the models shown in this paper, the error term has been excluded for presentation purposes only. The model forms used to estimate VOLCFGRS in each of the four regions are shown in table 1. The NE and SO regions have different model forms, but both use observed diameter at breast height (d.b.h.) and bole length (BL, distance from a 1-foot stump to a 4-inch top d.o.b.) as predictor variables. In the CS region, d.b.h. and site index (SI) are used to predict VOLCFGRS. In the LS region, a combined model approach is used. First, BL is predicted based on a model that uses observed values of d.b.h., SI, and all live stand basal area (BA) as predictor variables of height to any specified d.o.b. (in this case 4 inches). A second model that uses BL (in this case predicted BL) and d.b.h. is used to make the final estimate of VOLCFGRS.

Gross Board Foot Volume

Gross board foot volume (VOLBFGRS) is defined as the total volume inside bark (International 1/4-inch rule) of the central stem of a commercial species tree of sawtimber size (9.0 inches d.b.h. minimum for softwoods, 11.0 inches d.b.h. minimum for hardwoods) from a 1-foot stump to a minimum top d.o.b. (7.0 inches for softwoods, 9.0 inches for hardwoods) or to where the central stem breaks into limbs that are all less than the minimum top d.o.b. Again, this is a gross volume with no deduction for cull and is therefore not commonly reported by FIA. VOLBFGRS forms the basis for net board foot volume, another widely used FIA attribute.

The model forms used to estimate VOLBFGRS in each of the four regions are shown in table 2. In the CS region the same model form is used for VOLCFGRS and VOLBFGRS, but of course, the parameter estimates are different. The NE region also uses the same model form for VOLCFGRS and VOLBFGRS, but in this case observed d.b.h. and saw log length (SL, distance from a 1-foot stump to a 7 (softwoods)- or 9 (hardwoods)-inch top d.o.b.) rather than observed d.b.h. and BL are the predictor variables. The approach in the LS region for VOLBFGRS is very similar to the combined model approach used to predict VOLCFGRS in that region. Initially, SL is estimated based on the same height model used in VOLCFGRS

Table 1.—*Gross cubic foot volume models used by FIA*

Region	**Form of the model:** **VOLCFGRS =** $f(x_1, x_2, ...x_n)$	**Observed items:** $(x_1, x_2, ...x_n)$	**Citation**
NE	VOLCFGRS = $b_1 + b_2 x_1^{b_3} + b_4 x_1^{b_5} x_2^{b_6}$	x_1 = DBH x_2 = BL	Scott 1981
SO	VOLCFGRS = $b_1 + b_2(x_1^2 x_2)$	x_1 = DBH x_2 = BL	Royer 2001
CS	VOLCFGRS = $b_1(x_2)^{b_2}(1 - e^{b_3 x_1^{b_4}})$	x_1 = DBH x_2 = SI	Hahn and Hansen 1991
LS	VOLCFGRS = $(b_0 + b_1 x_1 + b_2 4 + b_3 x_1^2 + b_4 x_1^2 h_4 + b_5 h_4^2 + b_6 h_4 4^2 +$ $b_7 x_1^2 h_4^3 + b_8 x_1^2 h_4^2 4)(b_9 + b_{10} x_1)$ where h_4 = predicted BL = $4.5 + b_{11}(1 - e^{(-b_{12} x_1)})^{b_{13}} x_2^{b_{14}} \left(1.00001 - \frac{4.0}{x_1}\right)^{b_{15}} x_3^{b_{16}}$	x_1 = DBH x_2 = SI x_3 = BA	Hahn 1984

Table 2.—*Gross board foot volume models used by FIA*

Region	**Form of the model:** **VOLBFGRS =** $f(x_1, x_2, \ldots x_n)$	**Observed items:** $(x_1, x_2, \ldots x_n)$	**Citation**
NE	VOLBFGRS = $b_1 + b_2 x_1^{b_3} + b_4 x_1^{b_5} x_2^{b_6}$	x_1 = DBH x_2 =SL	Scott 1979
SO	VOLBFGRS = VOLCFGRS= $\left(b_3 + b_4(1 - 1/x_1)\right)$ = $\left(b_1 + b_2(x_1^2 x_2)\right)\left(b_3 + b_4(1 - 1/x_1)\right)$	x_1 = DBH x_2 = BL	Royer 2001
CS	VOLBFGRS = $b_1(x_2)^{b_2}(1 - e^{b_3 x_1^{b_4}})$	x_1 = DBH x_2 = SI	Hahn and Hansen 1991
LS	VOLBFGRS = $\left[\begin{array}{l}(b_0 + b_1 x_1 + b_2 h_s + b_3 x_1^2 + b_4 x_1^2 h_s + \\ b_5 h_s^2 + b_6 h_s x_3^2 + b_7 x_1^2 h_s^3 + \\ b_8 x_1^2 h_s^2 x_3)(b_9 + b_{10} x_1)\end{array}\right] b_{17}$ $+ b_{18} x_1 + b_{19} h_s + b_{20} x_3 + b_{21}$ where h_s = estimated SL = $4.5 + b_{11}(1 - e^{(b_{12} x_1)})^{b_{13}} x_2^{b_{14}} \left(1.00001 - \frac{x_3}{x_1}\right)^{b_{15}} x_4^{b_{16}}$	x_1 = DBH x_2 = SI x_3 = 7; Sfwd x_3 = 9; Hdwd x_4 = BA	Hahn 1984

and observed values of d.b.h., SI, and BA. This predicted SL, together with d.b.h., is then used to predict VOLCFGRS in the final model, which is a modification of the final model for VOLCFGRS used in that region. In the SO region, a combined model approach is also used. Here, a BF/CF ratio model that uses d.b.h. as the predictor variable is multiplied by the estimated VOLCFGRS value to obtain an estimate of VOLBFGRS.

Total Biomass Oven-dry Weight

Total biomass oven-dry weight (DRYBIOT) is defined as the total oven-dry weight (pounds) of the aboveground portion of a tree 1.0 inch d.b.h. or larger, including the stump, bark, bole, top, and limbs, but excluding foliage. FIA also produces estimates of merchantable biomass, which is defined only for trees 5.0 inches d.b.h. and larger and does not include the stump, top, and limbs. In some older FIA publications, these biomass estimates were reported as green weight rather than oven-dry weight.

In all regions, model forms used for trees less than 5 inches d.b.h. differ from those used for trees 5 inches d.b.h. and larger. In the NE region, there are four different model forms, but all use d.b.h. alone to predict total biomass. One model form is used for all trees less than 5 inches d.b.h. For larger trees, one of three models is used depending on the species. For trees less than 5 inches d.b.h., the SO region has two different species dependent models that use observed d.b.h. and total length (TL, distance from a 1-foot stump to the top of the tree) to predict DRYBIOT, and for larger trees, it has two different species dependent models, but these use observed d.b.h. and BL to predict total biomass. The approach used in both the LS and CS regions is a single combined approach. In the two regions, estimates of DRYBIOMT for trees 5 inches d.b.h. and larger are based on a model that uses VOLCFGRS (in this case predicted VOLCFGRS) as the predictor variable. For trees less than 5 inches d.b.h., a model based on d.b.h. is used, but it is adjusted by a factor so that at 5 inches both methods produce the same biomass. These models are all presented in table 3.

Table 3.—*Total biomass oven-dry weight models used by FIA*

Region	Form of the model: DRYBIOT = $f(x_1, x_2, ...x_n)$	Observed items: $(x_1, x_2, ...x_n)$	Citation
NE	For DBH ≥ 5.0” DRYBIOT $= e^{(.b_1 + b_2 \ln(x_1))} b_4$ or $= 10^{(.\log_{10}(b_1) + b_2 \log_{10}(x_1))} b_4$ or $= 2.2046 \left(b_1 + b_2 25.4x_1 + b_3 (25.4x_1)^2\right) b_4$ model form is species dependent b_4 is DBH class dependent	x_1 = DBH	Wharton and Griffith 1998
	For DBH < 5.0” DRYBIOT = $e^{(.95595 + 2.42640 \ln(x_1))}$		
SO	For DBH ≥ 5.0” DRYBIOT $= b_1 + b_2 x_1^2 \left(b_3 + b_4 x_2 + \frac{b_5}{x_1^2}\right)$ or $= b_1 \left(x_1^2 \left(b_2 + b_3 x_2 + \frac{b_4}{x_1^2}\right)\right)^{b_5}$ model form is species dependent	x_1 = DBH x_2 = BL x_3 = TL	Royer 2001
	For DBH < 5.0” DRYBIOT $= b_1 + b_2 x_1^2 x_3$ or $= b_1 (x_1^2 x_3)^{b_2}$ model form is species dependent		
CS & LS	For DBH ≥ 5.0” DRYBIOT $= x_2 b_4 + (b_1 + x_1 b_2) x_2 b_5 + b_3 x_1^2 b_4$	x_1 = DBH x_2 = VOLCFGRS x_3 = VOLCFGRS of a 5” DBH tree	Hahn 1984 and Smith 1985
	For DBH < 5.0” DRYBIOT $= \frac{(x_3 b_4 + (b_1 + 5 b_2) x_3 b_5 + b_3 5^2 b_4)}{b_6 5^{b_7}} b_6 x_1^{b_7}$		

METHODS AND DATA

Sixty-seven species were considered in this study. Only species common to the three regions that share a common border (CS, SO, NE) were selected. A species was included in the study only if there were at least 25 live tally trees 5.0 inches d.b.h. or larger of that species in each of the three regions in the FIADB, and only if the species occurred on at least three inventory plots in each of the three regions. The average BA and SI of FIA ground plots where the species occurred were also computed. These data are shown in table 4 along with the mean d.b.h., maximum d.b.h., and third quartile of d.b.h. for trees 5.0 inches d.b.h. and larger.

Using the mean BA and SI in table 4 and the height model portion of the LS volume model, I generated a data set consisting of 30 tree records for each species with d.b.h. values of 1 through 30 inches. These tree records consisted of simulated observations of species, d.b.h., BA, SI, BL, SL, and TL. I then applied each of the four estimation procedures for VOLCFGRS, VOLBFGRS, and DRYBIOT to this data set. The LS procedures were applied only to species found to occur (at least

Table 4.—*Mean BA (square feet per acre), mean SI (feet, base age 50 years), mean DBH (in.), third quartile DBH (in.), and maximum DBH (in.) of tree species common to all three eastern regions in the FIADB*

Species	**Mean BA**	**Mean SI**	**Mean DBH**	**3rd qu. DBH**	**Max DBH**	**Species**	**Mean BA**	**Mean SI**	**Mean DBH**	**3rd qu. DBH**	**Max DBH**
Eastern Redcedar	89.1	59.4	8.1	9.4	51.0	Yellow-Poplar	122.1	68.6	13.6	17.1	59.1
Shortleaf Pine	112.7	59.2	10.0	12.0	32.8	Osage-Orange	89.5	67.8	10.1	12.0	50.0
Eastern White Pine	118.0	59.7	13.9	17.9	48.1	Apple Sp.	77.3	69.6	8.1	9.0	34.7
Loblolly Pine	125.2	68.4	9.9	12.2	43.1	Water Tupelo	251.5	63.6	15.6	18.9	89.5
Virginia Pine	119.1	51.9	9.3	11.2	45.4	Blackgum	112.7	63.2	10.0	12.4	35.7
Eastern Hemlock	132.9	57.8	12.7	16.0	41.5	Ironwood	109.4	65.9	7.2	8.0	28.0
Boxelder	98.5	70.8	11.4	14.0	43.1	Sycamore	100.7	76.5	16.9	21.6	66.9
Black Maple	92.1	73.9	13.3	16.6	40.1	Balsam Poplar	96.5	62.6	10.6	12.8	47.2
Striped Maple	112.6	46.5	6.2	6.7	14.7	East.ern Cottonwood	106.9	73.5	21.2	26.9	83.9
Red Maple	117.2	62.3	10.3	12.5	59.0	Bigtooth Aspen	109.5	69.9	10.9	13.0	50.8
Silver Maple	114.9	81.4	16.3	20.4	75.0	Black Cherry	122.9	70.8	9.9	11.9	53.3
Sugar Maple	113.9	66.5	11.5	14.4	55.0	White Oak	100.4	61.3	13.3	16.5	72.0
Ohio Buckeye	97.7	76.4	9.8	11.8	26.1	Swamp White Oak	100.7	74.1	16.2	21.2	49.3
Ailanthus	103.5	56.8	8.4	9.7	21.3	Scarlet Oak	101.3	54.8	12.3	15.3	48.1
Yellow Birch	121.2	57.5	12.5	15.6	49.1	Southern Red Oak	102.1	61.0	12.0	15.0	46.5
River Birch	106.0	78.6	11.5	14.1	47.6	Cherrybark Oak	111.3	68.2	16.6	20.9	55.5
Musclewood	110.9	66.7	7.3	8.2	21.9	Shingle Oak	89.7	72.4	12.0	15.1	51.7
Bitternut Hickory	97.4	75.4	10.8	13.1	42.6	Bur Oak	94.2	58.6	13.8	17.3	63.1
Pignut Hickory	96.6	72.0	10.9	13.4	68.2	Swamp Chestnut Oak	113.1	64.3	14.9	19.0	55.8
Shagbark Hickory	94.1	70.5	11.0	13.5	50.4	Chinkapin Oak	90.3	60.6	12.5	15.4	41.0
Mockernut Hickory	94.0	71.9	10.3	12.7	37.2	Pin Oak	100.7	78.7	16.5	21.0	57.0
Hackberry	101.7	72.6	12.2	15.2	53.5	Willow Oak	113.6	64.1	14.4	18.2	52.8
Eastern Redbud	93.2	70.1	6.8	7.4	29.1	Chestnut Oak	113.9	50.1	13.0	16.2	52.7
Flowering Dogwood	114.3	67.9	6.2	6.6	49.1	Northern Red Oak	105.8	63.7	14.1	17.4	76.8
Hawthorn	95.9	80.3	6.9	7.6	21.7	Post Oak	91.0	57.5	11.0	13.5	53.4
Common Persimmon	103.9	71.0	7.8	8.9	28.1	Black Oak	94.8	63.7	13.6	16.7	84.0
American Beech	110.3	60.7	13.3	17.3	87.0	Black Locust	107.3	64.8	10.8	13.1	47.2
White Ash	105.1	73.0	11.5	14.2	56.2	Black Willow	98.6	75.6	14.1	17.3	88.9
Green Ash	100.4	68.9	11.5	14.2	52.4	Sassafras	107.8	77.5	8.4	9.8	40.0
Blue Ash	96.9	68.6	9.9	11.4	32.4	American Basswood	115.4	67.9	12.2	14.8	58.8
Honeylocust	86.7	72.0	12.8	15.9	48.6	American Elm	92.9	68.3	11.9	14.7	61.9
Butternut	91.8	70.1	12.2	15.0	31.7	Slippery Elm	96.9	74.4	11.1	13.5	55.2
Black Walnut	92.1	70.7	12.0	14.7	45.5	Rock Elm	95.6	66.4	11.2	14.3	37.3
Sweetgum	158.4	69.5	10.4	12.9	50.2						

25 trees and 3 plots) in States in that region. VOLBFGRS estimation was not done for species where the FIADB did not contain at least 25 live tally sawtimber size trees in each of the three regions. This reduced the number of species from the 67 available for the analysis of VOLCFGRS and DRYBIOT to 55 used to compare VOLBFGRS among the regions.

RESULTS AND ANALYSIS

Figures 2 and 3 show the VOLCFGS data for black cherry and chestnut oak. For each simulated tree, the estimated volume using each of the four regional models is plotted against d.b.h. In black cherry, the differences between methods were among the largest I found, and in chestnut oak, the differences were about as small as I found. These graphs show the range of the values FIA would report for VOLCFGRS of sampled trees with identical measurements but occurring in four different States. In figure 2, at 20 inches d.b.h. the four values for black cherry range from 58.4 to 76.8 cubic feet, a range of 28 percent of the average of the four values, and in figure 3, the range for a 20-inch chestnut oak is 46.3 to 53.7 or 12.7 percent. Similar graphs were examined for all species and estimators.

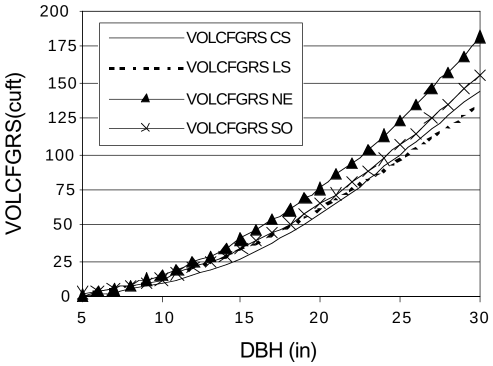

Figure 2.—*Estimated gross cubic foot volume of black cherry (BA = 122.9, SI = 70.8) using the four different regional FIA approaches to volume estimation.*

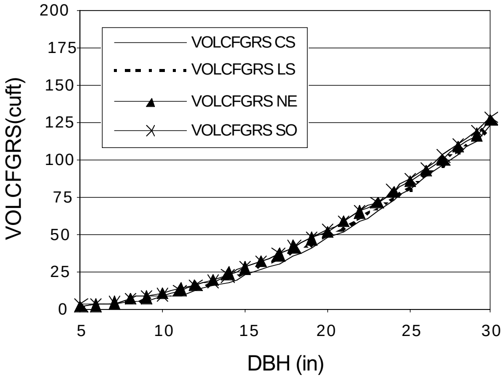

Figure 3.—*Estimated gross cubic foot volume of chestnut oak (BA = 113.9, SI = 50.1) using the four different regional FIA approaches to volume estimation.*

The results shown in figures 2 and 3 are typical of the ranges seen in other species and for VOLBFGRS and DRYBIOT. Range observations, expressed as a percentage of the mean of the four estimates (or mean of the three estimates in the case of species that do not occur in the LS region) are presented in table 5 for selected diameters. Ranges of over 50 percent are not uncommon, especially for small diameter values.

Examination of graphs similar to figures 2 and 3 for all species indicated some regional trends that are also apparent in table 6. The table summarizes the number of species where each regional approach produced the maximum or minimum value for identical trees. For example, the top row of table 6 indicates that for 6-inch-d.b.h. trees, in 60 of the 67 species the SO models produced values greater than the other three regional models, and in 60 of the 67 species the CS model produced values less than the other three regional models.

For almost all species, the CS VOLCFGRS model produced the lowest value of the four methods for small diameter trees. For larger diameter trees, the LS VOLCFGRS model most frequently produced the lowest values. In very few species did either the NE or SO models produce the minimum of the four values. The SO model almost always produced the largest value for 6-inch diameter trees. Above 6 inches, the NE model most frequently produced the maximum value, but the dominance of the NE model was most pronounced in the middle diameters (9-21 inches). For very large trees, all the models except the LS model had a fair number of species where they produced the maximum value.

For VOLBFGRS, the trend is totally different. For smaller diameter sawtimber trees (12 and 15 inches d.b.h.), the LS and CS models most frequently produced the maximum values and the NE and SO most frequently produced the minimum value. In the larger diameter classes, the LS model most often produced the minimum value. The largest values were most often produced by the NE model, which seldom produced the largest value in smaller sawtimber trees.

For DRYBIOT, there is a different trend than in either VOLCFGRS or VOLBFGRS. For small diameter trees, the SO model most often produced the maximum values and the NE model most often produced the minimum values. For larger diameter trees no single model dominated either the minimum or maximum values, but the NE and SO produced most of the maximums and the LS produced most of the minimums.

Table 5.—*Range of FIA volume and biomass estimates expressed as a percent of the mean among the different volume estimation methods for species common to at least three regions*

	DRYBIOT					VOLCFGRS				VOLBFGRS		
	DBH					DBH				DBH		
Species	**1 in.**	**6 in.**	**11 in.**	**16 in.**	**26 in.**	**6 in.**	**11 in.**	**16 in.**	**26 in.**	**11in.**	**16 in.**	**26 in.**
Eastern Redcedar	15.1	49.3	47.5	45.6	36.3	35.4	33.6	33.8	34.3	60.2	55.0	73.3
Shortleaf Pine	26.1	35.6	71.1	82.6	87.8	22.4	18.5	19.2	25.6	22.4	35.7	51.8
Eastern White Pine	38.9	58.7	54.3	49.8	39.1	56.8	32.8	30.7	27.4	15.6	32.1	40.6
Loblolly Pine	24.9	57.2	72.1	79.5	82.6	21.4	16.1	12.2	19.2	23.8	30.6	47.9
Virginia Pine	77.6	70.2	56.7	59.2	57.5	41.4	27.4	27.5	33.4	19.9	33.0	45.5
Eastern Hemlock	54.0	44.5	49.5	47.5	32.3	32.0	22.5	12.5	8.0	21.4	8.3	15.5
Boxelder	103.3	51.1	32.2	28.6	51.5	62.7	25.7	18.2	17.7	26.1	8.6	13.0
Black Maple	53.5	41.3	46.2	47.1	44.8	33.2	22.6	16.0	13.4			
Striped Maple	85.3	46.2	39.4	43.1	45.3	56.7	23.6	20.6	24.0			
Red Maple	16.8	27.2	26.7	20.8	19.3	51.0	27.9	18.6	16.8	30.8	12.5	15.0
Silver Maple	22.0	22.3	24.0	14.7	7.4	42.9	33.6	24.5	13.1	31.0	11.9	11.7
Sugar Maple	75.3	10.7	13.0	21.2	30.5	32.7	27.5	18.4	15.7	26.0	8.5	14.3
Ohio Buckeye	98.4	31.2	31.7	24.3	26.3	46.1	25.6	17.4	15.6	21.1	4.7	13.4
Ailanthus	103.1	29.0	11.1	38.0	73.5	52.6	24.7	18.7	20.3			
Yellow Birch	19.3	19.7	34.6	34.3	30.7	48.6	34.8	26.6	27.9	23.8	8.3	17.8
River Birch	85.9	40.6	55.3	53.4	47.9	75.5	43.5	29.6	15.5	9.5	14.7	16.0
Musclewood	123.4	28.7	7.5	37.5	77.8	52.1	25.3	16.6	16.6			
Bitternut Hickory	72.4	19.5	23.3	22.5	18.4	15.7	27.5	18.7	13.5	47.3	16.0	11.2
Pignut Hickory	78.5	12.4	11.4	7.3	11.8	15.9	27.6	19.4	13.5	46.9	16.3	11.9
Shagbark Hickory	74.7	20.4	17.1	10.8	7.3	14.8	29.1	20.8	14.4	43.2	11.5	12.4
Mockernut Hickory	75.1	20.9	17.8	11.2	6.8	14.8	29.1	20.9	14.5	43.1	11.2	12.1
Hackberry	15.3	33.3	31.5	22.3	15.5	57.4	31.3	20.6	8.9	32.4	11.0	8.8
Eastern Redbud	82.0	27.7	4.3	22.9	44.2	51.9	25.3	16.1	15.8			
Flowering Dogwood	118.1	33.9	39.6	52.0	74.8	40.0	25.5	18.6	18.2			
Hawthorn	128.0	31.2	4.1	32.0	71.6	51.7	25.8	14.2	12.5			
Common Persimmon	107.3	43.6	37.1	50.8	73.8	35.5	26.2	18.5	17.8	29.0	20.8	23.1
American Beech	28.0	22.2	19.1	19.3	26.9	55.7	39.5	29.8	26.7	18.5	31.5	50.4
White Ash	22.8	12.9	16.8	25.9	38.9	60.9	36.8	25.3	18.8	24.2	6.6	12.4
Green Ash	22.8	25.1	30.4	25.7	36.9	61.2	36.6	25.1	18.5	24.8	6.1	11.8
Blue Ash	14.8	26.3	24.9	17.2	22.8	59.7	35.9	25.1	19.1			
Honeylocust	110.1	58.1	47.0	51.5	55.1	40.0	25.5	17.9	17.3	21.6	11.5	13.4
Butternut	34.3	35.0	38.1	32.5	57.1	58.8	30.1	17.8	15.1	44.1	16.1	14.4
Black Walnut	19.6	34.0	45.2	45.1	41.4	34.3	30.3	23.4	16.8	41.6	27.8	28.3
Sweetgum	39.9	20.1	22.9	18.0	14.9	43.5	36.2	22.7	8.6	23.1	12.8	18.9
Yellow-Poplar	39.1	30.0	32.8	25.1	22.5	34.4	27.0	19.6	24.4	34.2	13.4	17.1
Osage-Orange	123.5	28.5	7.3	37.2	77.5	52.0	25.2	16.5	16.6	23.8	8.9	12.0
Apple Sp.	80.9	26.6	16.8	36.4	62.2	51.8	25.1	16.2	16.2			
Water Tupelo	77.6	22.0	18.9	12.9	10.6	79.3	35.6	23.6	25.3	62.7	30.0	25.8
Blackgum	74.2	18.2	10.8	7.0	15.4	66.1	34.6	20.9	10.6	22.5	1.7	6.6
Ironwood	91.5	27.0	31.0	58.6	95.3	52.2	25.2	16.8	16.9	24.1	9.3	12.4
Sycamore	29.7	9.9	13.2	10.6	13.6	65.6	12.9	1.6	16.8	40.2	20.7	19.7
Balsam Poplar	53.2	11.9	22.3	23.7	49.3	43.8	34.0	28.0	25.5	33.3	9.8	31.1
Eastern Cottonwood	52.6	22.0	32.8	28.9	28.5	45.6	28.7	23.5	14.9	35.1	20.7	22.3
Bigtooth Aspen	92.1	18.4	27.5	27.2	45.5	46.2	35.4	28.7	25.8			
Black Cherry	49.5	40.0	27.7	12.2	18.4	58.1	48.2	36.0	27.2	36.2	19.8	29.8
White Oak	101.5	40.1	31.3	19.2	14.2	32.9	24.7	17.9	11.8	33.2	2.4	10.7
Swamp White Oak	85.0	20.9	14.5	8.2	23.5	36.7	24.9	17.5	10.0	34.2	2.8	10.4
Scarlet Oak	31.1	19.2	23.7	19.5	18.4	28.3	26.4	20.3	16.5	35.7	13.6	18.7
Southern Red Oak	32.1	21.4	11.5	22.2	35.8	27.7	27.4	19.0	13.8	35.2	13.2	15.7
Cherrybark Oak	106.0	40.9	36.7	27.4	16.5	48.6	25.9	19.8	9.3			
Shingle Oak	41.1	13.6	25.1	20.4	16.3	35.6	27.5	16.5	10.0	34.4	11.2	11.5
Bur Oak	41.4	13.5	7.8	15.4	23.4	36.9	24.3	16.8	11.7	33.4	3.6	10.4

Table 5 (continued)

Table 5 (continued)

Species	DRYBIOT DBH 1 in.	DRYBIOT DBH 6 in.	DRYBIOT DBH 11 in.	DRYBIOT DBH 16 in.	DRYBIOT DBH 26 in.	VOLCFGRS DBH 6 in.	VOLCFGRS DBH 11 in.	VOLCFGRS DBH 16 in.	VOLCFGRS DBH 26 in.	VOLBFGRS DBH 11in.	VOLBFGRS DBH 16 in.	VOLBFGRS DBH 26 in.
Swamp Chestnut Oak	58.0	20.1	24.1	20.9	12.5	50.2	25.7	18.3	10.5	32.9	3.6	15.5
Chinkapin Oak	80.7	21.1	6.6	10.2	31.4	36.5	24.1	16.6	11.5	33.9	3.9	10.0
Pin Oak	62.4	22.0	21.8	12.7	26.9	36.1	28.5	17.3	8.1	33.1	9.6	7.7
Willow Oak	78.4	38.0	33.9	19.5	22.4	46.7	27.8	17.7	11.3	33.8	11.9	16.3
Chestnut Oak	65.6	22.1	14.8	2.8	14.4	34.1	26.4	18.0	6.9	33.2	15.7	6.7
Northern Red Oak	94.7	25.9	18.1	10.7	26.5	25.1	25.8	19.6	7.6	36.3	10.0	7.2
Post Oak	45.0	17.2	17.6	14.4	10.1	41.2	28.4	21.0	11.8	29.0	6.3	12.8
Black Oak	36.7	31.7	28.4	16.8	15.5	16.8	27.5	18.7	13.4	42.5	20.9	18.9
Black Locust	136.9	49.0	48.9	51.0	60.2	35.1	26.3	20.5	24.9	28.9	39.4	51.8
Black Willow	54.4	23.1	29.3	32.1	50.0	46.9	18.5	14.8	8.4	47.1	17.2	12.6
Sassafras	66.8	24.4	17.2	22.7	34.9	55.2	26.4	17.1	15.5	26.3	4.4	10.4
American Basswood	26.9	25.3	37.6	34.3	55.0	41.1	36.5	25.5	19.6	28.5	10.9	18.1
American Elm	28.1	13.4	15.1	14.0	16.7	51.6	31.5	25.9	19.2	30.2	6.7	10.6
Slippery Elm	26.5	14.2	15.9	16.1	15.8	51.6	33.1	27.7	19.0	30.3	7.8	10.5
Rock Elm	25.4	17.7	27.1	36.4	62.5	51.8	31.4	25.8	19.2			

Table 6.—*Number of common eastern species where each regional model produces the largest or smallest estimated volume or biomass on identical trees*

MODEL	DBH	Number of species with maximum value CS	LS	NE	SO	Number of species with minimum value CS	LS	NE	SO
	Inches								
VOLCFGRS 67 species	6	0	1	6	60	60	7	0	0
	9	0	2	53	12	61	6	0	0
	12	0	0	58	9	61	6	0	0
	15	0	0	54	13	42	23	0	2
	18	1	0	52	14	28	34	1	4
	21	13	0	39	15	22	38	3	4
	24	18	0	33	16	18	42	3	4
	27	24	0	27	16	20	38	3	6
VOLBFGRS 55 species	12	26	26	0	3	1	0	30	24
	15	28	14	5	8	7	6	18	24
	18	20	5	12	18	12	19	7	17
	21	21	1	16	17	15	23	4	13
	24	16	1	22	16	13	27	4	11
	27	14	1	26	14	15	27	4	9
DRYBIOT 67 species	3	8	2	2	55	19	10	36	2
	6	6	15	8	38	26	3	34	4
	9	0	21	3	43	29	1	37	0
	12	3	9	10	45	13	8	38	8
	15	5	7	11	44	11	11	37	8
	18	7	4	18	38	6	19	31	11
	21	11	1	22	33	2	28	26	11
	24	8	2	26	31	4	33	19	11
	27	7	4	32	24	7	35	14	11

Figure 4 also points out these regional trends for this data set. Here I have averaged the estimates for each region across all species and plotted the regional deviation (as a percent of the average across all regions) against d.b.h. for each of the three estimates. For example, figure 4c indicates that the lines for the CS and LS models for VOLBFGRS closely follow each other and the lines for the NE and SO models follow each other. The NE and SO models are low for small diameters and high for the large diameters. All four models produce similar estimates for d.b.h. values of 15 to 20 inches, a typical diameter for a sawtimber tree.

There are definite differences in the estimates of gross volume and biomass by region for this particular set of “typical” tree measurements. Because the generated data set does not contain true values of volume and biomass, it is not possible to comment on the bias of these estimates. This brief analysis simply demonstrates that regional differences do exist and that these differences can be large.

DISCUSSION AND RECOMMENDATIONS

There are a number of possible causes of the regional trends in the volume and biomass models that have been demonstrated here. All of these models were developed independently. Typically a data set consisting of tree volume and biomass measurements along with predictor variable measurements was created. Nonlinear regression methods were used to fit estimated parameter values for the selected model form.

The data sets used to develop these models are all independent and created using different methods. Some data sets came from FIA data where additional tree height and upper stem diameter measurements were taken on standing trees. Other data sets came from felled tree data where measurements were taken on cut trees. In some cases both types of data were combined. Methods used to obtain the “known” volume and biomass values of these trees are not consistent across regions.

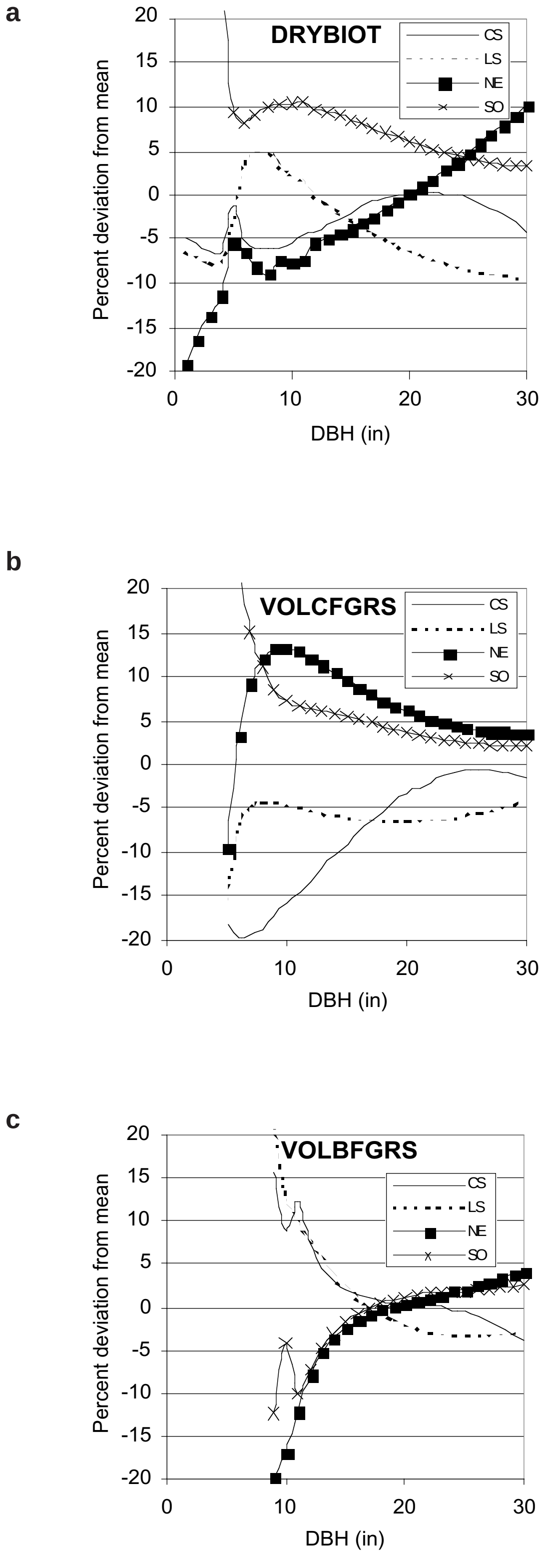

Figure 4.—*Average deviation (over all common species) of the four regional estimates from the average of all four regional estimates by diameter.*

Differences in model form that exist between regions could account for some of these differences. The basic shapes of these models are somewhat different. The LS and CS models for both VOLCFGRS and VOLBFGRS have an inflection point whereas the SO and NE models do not. The specific nonlinear regression methods used to fit the model and weighting factors applied can have major impacts on the parameter values selected. Several of these models, such as the LS cubic foot volume models, the LS and SO board foot volume models, and the LS and CS biomass models, are combined models, where two different models are involved. The combined effect of the two models is difficult to assess.

FIA is currently making considerable efforts to move to consistency throughout all of its operations. Across the country, a common plot design is used and common plot and tree attributes are measured. These common data are available to all users. It seems reasonable to assume that when two trees measured in two different locations have identical measure-ments, they should have identical volume and biomass values, not values as different as 100 percent or more. FIA needs to move to a consistent method to estimate tree volume and biomass nationwide that uses common measurement data to estimate the volume and biomass of sample trees.

What would it take to develop a consistent system for volume and biomass estimation? This would be a major project for FIA. An approach that I would recommend is to base volume and biomass estimates on predicted stem profile or taper models. Such a system would predict the bole diameter at any height. This would enable the user to predict the gross volume of any specified segment of a tree. Associated cull estimates would be needed to make net volume estimates. Biomass estimates could be based on an allometric approach in which models for the various components of biomass (bole, bark, branches, stump, roots) are based on the gross volume in the bole plus other attributes. Such a system would eliminate the need for separate VOLCFGRS, VOLBFGRS, and DRYBIOT models that currently are in use. Inconsistencies between estimates currently exist because separate models are being used. For example, ratios like DRYBIOT:VOLCFGRS or VOLBFGRS:VOLCFGRS are often inconsistent.

Demand for biomass information is increasing. A stem profile based system with an allometric model for biomass components would have more biological basis than the empirical models now being used. All of the biomass models currently in use attempt to estimate various biomass components such as biomass in branches, primarily through percentage estimates from published information. These estimates are all very simplistic. None of the estimates of branch biomass used by FIA utilize any of the crown measurement data such as crown ratio or crown class that are being taken. Currently the ratio of branch biomass to bole biomass for a dominant tree with a large crown ratio is equal to the same ratio for a suppressed tree with a small crown ratio given both trees have the same species and diameter.

The development of a consistent approach to volume and biomass estimation would require the construction of a database consisting of candidate predictor variables (core FIA attributes such as d.b.h., total height, crown ratio, crown class, and species taken to FIA standards) along with sufficient height and upper stem diameter measurements needed to adequately fit a good stem profile model. FIA has recently moved to a core set of common measurement attributes and not all of the core attributes (particularly total tree height) have been collected on most older FIA plots. Also, older FIA data were limited to trees measured on timberland. FIA has expanded its volume and biomass estimation to include all forest land and is currently investigating expanding estimation to include trees on nonforest lands such as urban areas. Existing FIA data would not be adequate for developing such a model.

Phase 3 (P3) plots are a small subset of the FIA field plots on which many additional attributes are being measured. By adding several upper stem diameter and height measurements to the suite of data currently being taken on these P3 plots, FIA could begin to construct the nationwide data set necessary to develop a comprehensive approach to volume and biomass estimates. Other candidate predictor measurements could also be added to the P3 suite of data for consideration as additional core attributes if they were shown to improve volume estimates. Much information is currently available for P3 plots. Most of these plots have already been measured at least once. It would be possible to stratify these P3 plots before measurement to determine which plots and trees would need to be measured in order to construct a data set with adequate representation across species, diameters, regions, and stand conditions. Most likely it would not be necessary to make additional measurements on every tree on all P3 plots.

A number of things must be considered in the development of a new system for volume and biomass estimation. Consistency over time is an important consideration. It would be necessary to apply the new system to old FIA data in all regions in order to recompute existing estimates using the new system for comparison purposes and for estimation of components of change such as growth, removals, and mortality. If the new system uses predictor variables not previously collected, then it would be necessary to estimate these new predictor variables on old plots where they were not measured.

Until FIA adopts a consistent method of volume and biomass estimation, I would caution users of FIA data to make detailed regional comparisons of volume and biomass, particularly for smaller diameter trees. With the increasing demands placed on our timber supply, the utilization and value of smaller diameter trees is increasing. Comparisons of the volume in small diameter trees between States where different volume models are being used should be avoided. If this type of information is necessary, I suggest that users compare FIA estimates of number of trees by diameter class estimates. These estimates are not affected by volume models and should be consistent across regional boundaries.

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