Calibration of the STEMS Diameter Growth Model Using FIA Data

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Abstract.—The diameter growth model used in STEMS, the Stand and Tree Evaluation and Modeling System, was originally calibrated using data from permanent growth plots in Minnesota, Wisconsin, and Michigan. Because the model has been applied in predicting growth using Forest Inventory and Analysis (FIA) data, it was appropriate to refit the model to FIA data. The model was calibrated for four species—quaking aspen, balsam fir, paper birch, and red pine—using FIA data from the Aspen-Birch and Northern Pine Units of northeastern Minnesota. To compare the new and original calibrations of the model, it was important to use the same formulation and methodology in refitting the model. In this way differences due to the data sets would not be confounded with differences in model form or approach. Although STEMS was originally calibrated on permanent growth plot data, when applied to FIA data it produced estimates that were equivalent to those of the STEMS model that was refit to FIA data. Both models produced biased estimates that had large variation. Efforts to improve model performance should focus on improving the model form.

Inventories of forest stands and information about how these stands are growing are crucial elements for making wise forest management decisions. The Forest and Rangeland Renewable Resources Planning Act of 1974 and the McSweeney-McNary Forest Research Act of 1928 for the collection of forest inventory data were enacted by Congress to address the first of these elements. STEMS, the Stand and Tree Evaluation System (Belcher *et al.* 1982), is a system of models designed to meet the second element. STEMS was developed to analyze current forest resource information and to predict future resources levels. The STEMS tree growth model is composed of three components: (1) a potential diameter growth model that estimates the potential diameter growth of a tree; (2) a modifier model that reduces the potential diameter growth based on stand competition; and (3) a mortality model. Together the potential diameter growth and modifier models produce the predicted diameter growth of a tree.

Although the current STEMS diameter growth model has performed adequately (Guertin and Ramm 1996, Holdaway and Brand 1986), several concerns remain: (1) the potential and modifier models were calibrated as separate models, which makes reporting of confidence intervals for the mean predicted values intractable; (2) climate-related variables, which may improve precision of the predicted values, are not included in STEMS; (3) estimates of the variability of the predictor variables and their impact on the variability of the predictions of the model have not been analyzed; and (4) the current diameter growth model was originally calibrated on data from permanent growth plots, while many applications of the model have been on FIA data. These concerns are currently being addressed. First, Holdaway (2000) has developed a new model form, referred to as the Annual Forest Inventory System (AFIS) model, built on average growth and calibrated on FIA data as a single model, allowing confidence intervals to be reported. Second, although the AFIS model does not currently include climate-related variables, analysis for their incorporation is ongoing. Third, McRoberts (2000) has examined how uncertainty in the independent variables affects the precision of model predictions. He found that although inclusion of certain independent variables improves R^2 values for the model, the confidence band about the predicted values may be much wider as a result.

In this paper, the effect of the fourth of these concerns is investigated. The STEMS growth model, composed of the potential and modifier models, was initially calibrated on data from permanent growth plots from various locations in the Lake States (Michigan, Wisconsin, and Minnesota). Although it was the most complete Lake States data set available at the time, we now have complete coverage of the Lake States with repeated measurements of FIA data to calibrate the model on a data set similar to that on which the model is being applied. The objectives of this study are: (1) to calibrate the potential and modifier models for four species using FIA data from the northeast portion of Minnesota (MN FIA Units 1 and 2); and (2) to compare the bias and precision in predictions using the new versus the original calibrations of the STEMS growth model. The new and original calibrations of the STEMS growth model will be referred to as STEMS-FIA and STEMS, respectively, throughout the

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rest of the paper. Because the purpose of the study is to see if the predictive ability of STEMS increases when applied to the FIA data set, no attempt was made to improve the model form, and the same methodology used to fit STEMS was used when fitting STEMS-FIA. In this way, differences due to the data set were not confounded with differences in model form or methodology. STEMS-FIA was calibrated for the following species: quaking aspen (*Populus tremuloides* Michx.), balsam fir (*Abies balsamea* (L.) Mill.), paper birch (*Betula papyrifera* Marsh.), and red pine (*Pinus resinosa* Ait.).

DATABASE

The original STEMS calibration used individual tree record data from permanent growth plots distributed across the Lake States. These plot records came from cutting experiments, demonstration woodlots, industrial, continuous forest inventory, and other records of forest growth. All plots were fixed size, ranging from 0.1 to 0.5 acres for square plots and 0.1 to 0.2 acres for circular plots. The minimum diameter at breast height (dbh) recorded on these plots ranged from 0.6 to 9 inches (Christensen *et al.* 1979).

FIA data for the STEMS-FIA diameter growth model came from land classified as forestland over all ownership categories in the Minnesota Aspen-Birch and Northern Pine Units (MN FIA Units 1 and 2). These data were systematically split into two data sets: 75 percent for calibration and 25 percent for validation. Inventory data were collected for trees of dbh greater than 5 inches on 10-point clusters using variable-radius point sampling, with a basal area factor (BAF) of 37.5 square feet per acre for the cluster. Data for trees 1 to 5 inches in diameter were obtained from 6.8-foot fixed-radius sample plots (approximately 1/300 acre) located at each point in the cluster. Before 1986, the fixed-radius plots were sampled at only the first three cluster points. Due to the sampling design, there were more trees of both the larger and smaller diameter classes for each species in the FIA data than in the original calibration data. Except for red pine, the total number of trees per species was greater in the FIA calibration database than in the permanent growth plot database (table 1). FIA data for the calibration of STEMS-FIA were extracted from undisturbed plots at two measurements. Only trees that were alive both at the beginning and end of the time interval were included. The first measurement for each plot in the data set was taken around either 1977 or 1990. The second measurement was recorded on the first subsequent date at which that plot was revisited. The average time interval was close to 9 years, with a range of approximately 2 to 21 years.

METHODS

The STEMS potential diameter growth (Hahn and Leary 1979) and corresponding modifier models (Holdaway 1984) were developed as species-specific, individual tree

Table 1.—*The number of trees in the databases used to calibrate STEMS. Data from the Lake States permanent growth plots were used in the original STEMS calibration, while Minnesota FIA data from the Aspen-Birch and Northern Pine Units (FIA Units 1 and 2, respectively) were used in the STEMS-FIA calibration.*

Species	Number of trees of each species in each data set	Lake States permanent growth plots	MN FIA Unit 1	MN FIA Unit 2	MN FIA Units 1 & 2 Totals
All species	All trees	51,149	34,225	25,822	60,047
Quaking aspen	All trees	2,547	8,190	7,193	15,383
Dominant and codominant trees	2,124 (83%)	7,028 (86%)	6,263 (87%)	13,291 (86%)	
Balsam fir	All trees	2,515	4,453	1,456	5,909
Dominant and codominant trees	1,277 (51%)	1,808 (41%)	607 (42%)	2,415 (41%)	
Paper birch	All trees	1,125	3,584	1,854	5,438
Dominant and codominant trees	748 (66%)	2,941 (82%)	1,561 (84%)	4,502 (83%)	
Red pine	All trees	NA	516	844	1,360
Dominant and codominant trees	11,663	452 (88%)	760 (90%)	1,212 (89%)	

based models to predict the increase in diameter for the Lake States tree species. The predicted average annual change in diameter for a tree is calculated as the product of its potential growth and a modifier based on the competition in the stand of which it is a member (Holdaway 1984). The potential diameter growth model portrays the growth rate that a tree of a given species could attain under optimal conditions. The modifier model accounts for stand competition. It is designed to allow a tree to reach a portion of the rate of growth predicted by the potential diameter growth model.

Potential Diameter Growth Model

The potential diameter growth represents an upper bound for the growth rate that may be attained by a tree of a given species based on its diameter (D), crown ratio (CR), and plot site index (SI). The following methods, used to develop the potential growth model (Hahn and Leary 1979), were followed as closely as possible when refitting the potential diameter growth model to FIA data. Only dominant and co-dominant trees were used in modeling the potential diameter growth model. Two measurements, approximately 10 years apart, were taken for each tree included in the database. The model uses average annual change in diameter (ΔD), calculated as the average positive difference in dbh measurements for trees within a cell on the two sampling dates divided by the number of years in the interval between measurements.

Site index was recorded in different ways for the permanent growth plot and FIA data sets. In the data set used for the STEMS calibration of the potential model, site index values for two species were generally recorded on a single sampling date. If the site index existed for the species being modeled, it was selected as the variable. Otherwise, the site index for another species was used. In the FIA data set, site index and site index species were recorded at each sampling date. The following rule was devised to handle site index when refitting the STEMS-FIA potential growth model:

1. If two different site index species are recorded on the two sampling dates and if one of these is the species of interest, use the site index for the species of interest.

2. If two different site index species are recorded on the two sampling dates and neither is the species of interest, take the average of the two site index values.

3. If the same site index species is recorded in both time periods, use the average of the two site index values.

As with the original STEMS calibration, the data for each species were grouped into cells by 1-inch diameter classes, 10-foot site index classes, and 10-percent crown ratio classes. The dependent variable (POT) for the potential diameter growth model was calculated as the mean plus 1.65 times the standard deviation of average annual diameter growth for trees in each cell ($\overline{\Delta D} + 1.65 s_{\Delta D}$). This diameter growth represents the 95th percentile of dominant and co-dominant diameter growth. To calculate a cell standard deviation for average annual diameter growth, at least two observations are needed per cell. If a cell contained a single tree, Hahn and Leary (1979) included it in "the most appropriate adjacent class." In the calibration of the STEMS-FIA potential model, three passes were made through the data to reassign single-observation trees to a new cell. At each pass, the value of one variable (SI, CR, or D) for the observation in cells containing a single tree was moved one class toward the center of the range of class values for that variable. After three passes, any remaining cells with single observations were dropped. The numbers of trees and cells used in fitting the STEMS and STEMS-FIA potential diameter growth models are given in table 2. The form of the potential diameter growth model (Hahn and Leary 1979) is:

$$POT = b_1 + b_2 D^{b_3} + b_4 SI \cdot CR \cdot D^{b_5} \qquad (1)$$

Marquardt's method of weighted nonlinear least squares regression was used to fit the model. The inverse of the squared standard error was used as the weighting scheme when fitting the STEMS-FIA potential model.

Modifier Model

The modifier model limits the predicted growth for trees by taking into account the competition within the stand (plot) surrounding each tree. The modifier model was calibrated on all trees of each species in the data set. The data set used to calibrate the STEMS modifier model was made up of two measurements, approximately 10 years apart, from undisturbed plots using trees that were alive at both measurements (Holdaway 1984).

In keeping with the methodology used for the original calibration of STEMS, the modifier value (MOD) for each tree is calculated as the ratio of the actual observed growth to the potential growth for that tree calculated by (1). Data were sorted by the independent variables into 2-inch average stand diameter (AD) classes, 25-ft^2 basal area (BA) classes, and 10-percent relative diameter (REL), the ratio of individual tree dbh to AD, classes. The cell mean modifier value was used as the dependent variable in fitting the nonlinear modifier model. The resulting number of cells used to calibrate the modifier on FIA data is given in table 2.

Table 2.—*The number of trees and number of cells used in calibrating the potential diameter growth and modifier models for the four species are given in the table below. The number of cells used in the original calibration of the modifier model is not available in the literature.*

Model	Species	STEMS		STEMS-FIA	
		Trees	Cells	Trees	Cells
		Number			
Potential					
	Balsam fir	1,277	121	2,376	387
	Quaking aspen	2,124	201	13,256	576
	Paper birch	748	112	4,467	426
	Red pine	11,663	282	1,177	239
Modifier					
	Balsam fir	4,376	NA	5,909	773
	Quaking aspen	2,944	NA	15,383	1,209
	Paper birch	1,214	NA	5,438	884
	Red pine	6,067-N[1]	NA	1,360	579
		20,224-P[1]			

[1] N and P denote natural stands and plantations of red pine, respectively. Because so few red pine trees existed in the MN FIA Units 1 and 2 data set, red pines were not separated by this distinction.

The form of the modifier model is (Holdaway 1984):

$$MOD = 1 - \exp\{-f(REL) \cdot g(AD) \cdot [(BA_{max} - BA)/BA]^{\frac{1}{2}}\} \quad (2)$$

where

$$f(REL) = b_1 [1 - \exp(b_2 \cdot REL)]^{b_3} + b_4 , \quad (3)$$

and

$$g(AD) = c_1 (AD+1)^{c2} . \quad (4)$$

In keeping with the methodology used in the original calibration, the nonlinear modifier model was fit in two steps. First, parameter values, c_1 and c_2, were obtained for g(AD) by fitting equation 2, while setting f(R) = 1.0. These parameter values were substituted into (2), and equation 2 was refit to obtain values for the four parameters in equation 3. At both steps Marquardt's method of nonlinear regression, weighted by the number of observations per cell, was used.

Verification and Validation

The models were verified in separate runs of the STEMS growth projection system using the parameters of the STEMS and STEMS-FIA growth and modifier models on the calibration data. The two models were evaluated on their ability to predict tree diameter and basal area per acre growth when applied to the data set on which STEMS-FIA was calibrated. The STEMS and STEMS-FIA growth models were then tested for their performance on the validation data.

The STEMS growth projection system contains adjustments applied to the STEMS. The adjustment factors are ratio of means multipliers, calculated for each of five dbh classes, to adjust the growth predictions of this regional STEMS model for local conditions (Holdaway 1985, Smith 1983). Because STEMS-FIA was calibrated on local data (MN FIA Units 1 and 2), the adjustment factors were not applied to the STEMS-FIA potential growth model when running the STEMS system to predict diameter and basal area per acre growth. The adjustments were applied to the STEMS model when predicting diameter and basal area per acre growth.

Using the calibration and validation data sets in separate runs, each tree was grown for the number of years in the interval between its first and second measurement. The residuals, calculated as the observed minus predicted dbh for each tree (or stand basal area per acre for each plot), were annualized by dividing by the number of years in the interval over which each tree or plot was grown. Shapiro-Wilk ($n < 2000$) and Kolmogorov ($n \geq 2000$) tests of normality conducted on the sets of annualized residuals from both diameter and stand basal area predictions indicated that most of these data sets were not normally distributed. Annualized residual medians, median ratios, size ratios, standard deviations, and r^2 values were calculated to examine the prediction differences in diameter and stand basal area growth by species for

Table 3.—*The median annualized diameter prediction residuals (inches/year) are given for the STEMS and STEMS-FIA diameter growth models. Negative values for residuals and median ratios indicate an overprediction by the model.*

Species	Model	Number of trees	Median residual	Standard deviation	Median ratio	Size ratio	Wilcoxon H_0:M_i=0	Wilcoxon H_0:M_1=M_2	Box's test H_0:σ_1^2=σ_2^2	r^2
			- - - In/yr - - -		- Percent -		- - - - - P-value - - - - -			
CALIBRATION										
Red pine	STEMS	1,360	-0.009	0.0696	-7.0	32.7	0.0028			0.418
Red pine	STEMS-FIA	1,360	-0.005	0.0689	-3.9	30.3	0.2007	0.1533	0.9695	0.437
Balsam fir	STEMS	5,909	-0.011	0.0620	-13.8	47.5	0.0001			0.199
Balsam fir	STEMS-FIA	5,909	-0.008	0.0573	-10.0	41.3	0.0001	0.0022	0.0540	0.304
Quaking aspen	STEMS	15,383	-0.006	0.0703	-4.8	35.2	0.1148			0.157
Quaking aspen	STEMS-FIA	15,383	-0.004	0.0717	-3.2	34.4	0.4224	0.4757	0.1786	0.172
Paper birch	STEMS	5,461	-0.007	0.0496	-11.4	48.8	0.0001			0.101
Paper birch	STEMS-FIA	5,461	-0.006	0.0486	-9.8	47.1	0.0001	0.3089	0.5688	0.117
VALIDATION										
Red pine	STEMS	501	0.004	0.0796	3.1	31.9	0.0561			0.480
Red pine	STEMS-FIA	501	0.006	0.0721	4.7	29.6	0.0085	0.6247	0.0969	0.560
Balsam fir	STEMS	1,924	-0.012	0.0656	-16.0	50.7	0.0001			0.201
Balsam fir	STEMS-FIA	1,924	-0.011	0.0599	-14.7	43.3	0.0001	0.0495	0.0722	0.328
Quaking aspen	STEMS	5,348	-0.005	0.0708	-4.2	35.8	0.4931			0.133
Quaking aspen	STEMS-FIA	5,348	-0.003	0.0724	-2.5	35.0	0.3731	0.1626	0.1163	0.156
Paper birch	STEMS	1,708	-0.005	0.0672	-7.9	48.7	0.1056			0.066
Paper birch	STEMS-FIA	1,708	-0.005	0.0665	-7.9	50.3	0.0997	0.9686	0.8187	0.074

[1] To calculate the size ratios (percent), the absolute values of annualized growth residuals and annualized observed growth were taken. The median values for each were foun,d and the ratio of the median annual residual magnitude to the median annual observed growth magnitude was multiplied by 100 percent. Median ratios (percent) were calculated as 100 percent times the ratio of the median annualized residual to the median annual observed growth magnitude. One-sample Wilcoxon Signed Rank tests were used to test if the median residual was different from zero (a = 0.05). Two-sample Wilcoxon Rank Sum (Mann-Whitney-Wilcoxon) tests were used to test if the median residual of STEMS-FIA was different from that of STEMS (a = 0.05). Box's test was used to test for homogeneity in residual variances of STEMS-FIA and STEMS (a = 0.10). The r^2 values were computed as the square of the correlation coefficient between the observed and predicted annual diameter growth.

STEMS and STEMS-FIA (tables 3 and 4). Median ratios present the median bias as a percent of the magnitude of observed growth and give a perspective of the importance of this bias from a biological standpoint. By contrast, the size ratios give a biological perspective to the size of the residuals relative to the size of actual growth. Median ratios are calculated as 100 percent times the ratio of the median annualized growth residual to the median of absolute values of annualized observed growth. To calculate the size ratios, the absolute values of annualized growth residuals and annualized reserved growth were taken. The median values for each were found, and the ratio of the median growth residual to the median observed growth was multiplied by 100 percent. The r^2 values are calculated as the square of the coefficient of correlation between the annualized predicted and observed values of diameter or basal area per acre growth. The Wilcoxon Signed Rank one-sample test was used to test if the prediction residuals for each model were significantly different from zero. Two-sample Wilcoxon Rank Sum (Mann-Whitney-Wilcoxon) tests were used to test for overall differences between the annualized prediction residuals of STEMS-FIA and STEMS. Box's test was used to test for differences in the precision of STEMS-FIA and STEMS.

RESULTS

Verification

DBH Estimates

Both models were applied to the data set used to calibrate STEMS-FIA. In general, STEMS-FIA performed as well or better than STEMS, the regional model with local adjustments. When using the calibration data, both STEMS-FIA and STEMS generally overpredicted dbh growth. The magnitude of the median residual values by

Table 4.—*The median annualized stand basal area per acre (feet²/acre/year) prediction residuals are given for the STEMS and STEMS-FIA diameter growth models. Negative values for residuals and median ratios indicate an overprediction by the model.*

Species	Model	Number of plots	Median residual	Standard deviation	Median ratio	Size ratio	Wilcoxon H_0:M_i=0	Wilcoxon H_0:M_1=M_2	Box's test H_0:σ_1^2=σ_2^2	r^2
			- - ft²/ac/yr - -		- Percent -		- - - - - P-value - - - - -			
CALIBRATION										
Red pine	STEMS	62	0.097	2.0590	5.2	48.6	0.9503			0.588
Red pine	STEMS-FIA	62	0.003	1.9723	0.2	44.5	0.7843	0.8710	0.5982	0.621
Balsam fir	STEMS	228	-0.505	1.8993	-41.7	83.0	0.0001			0.395
Balsam fir	STEMS-FIA	228	-0.386	1.9344	-31.8	76.4	0.0001	0.6074	0.9558	0.370
Quaking aspen	STEMS	1,296	-0.297	2.0160	-22.8	75.1	0.0001			0.512
Quaking aspen	STEMS-FIA	1,296	-0.281	2.1004	-21.6	82.3	0.0001	0.4379	0.2606	0.471
Paper birch	STEMS	247	-0.375	1.7699	-35.0	104.8	0.0011			0.169
Paper birch	STEMS-FIA	247	-0.351	1.7336	-32.8	102.0	0.0002	0.8249	0.9807	0.177
VALIDATION										
Red pine	STEMS	25	0.497	1.5805	26.2	40.4	0.0340			0.836
Red pine	STEMS-FIA	25	0.285	1.3085	15.0	85.5	0.0523	0.7124	0.4117	0.888
Balsam fir	STEMS	62	0.046	2.2645	2.9	68.2	0.6398			0.282
Balsam fir	STEMS-FIA	62	0.054	2.2393	3.4	67.6	0.6649	0.9641	0.8614	0.288
Quaking aspen	STEMS	443	-0.293	1.9084	-24.4	82.0	0.0003			0.483
Quaking aspen	STEMS-FIA	443	-0.327	2.0027	-27.2	78.5	0.0015	0.7850	0.4653	0.424
Paper birch	STEMS	71	-0.466	1.9104	-40.1	81.6	0.0215			0.221
Paper birch	STEMS-FIA	71	-0.391	1.8684	-33.7	91.1	0.0075	0.8736	0.8494	0.234

[1] To calculate the size ratios (percent), the absolute values of annualized growth residuals and annualized observed growth were taken. The median values for each were found, and the ratio of the median annual residual magnitude to the median annual observed growth magnitude was multiplied by 100 percent. Median ratios (percent) were calculated as 100 percent times the ratio of the median annualized residual to the median annual observed growth magnitude. One-sample Wilcoxon Signed Rank tests were used to test if the median residual was different from zero (a= 0.05). Two-sample Wilcoxon Rank Sum (Mann-Whitney-Wilcoxon) tests were used to test if the median residual of STEMS-FIA was different from that of STEMS (a = 0.05). Box's test was used to test for homogeneity in residual variances of STEMS-FIA and STEMS (a = 0.10). The r^2 values were computed as the square of the correlation coefficient between the observed and predicted annual diameter growth

species and model ranged from 0.004 to 0.011 inches per year (table 3). These overpredictions were greater than zero (P < 0.05) for both STEMS-FIA and STEMS for balsam fir (P = 0.0001) and paper birch (P = 0.0001) and for STEMS for red pine (P = 0.0028). For those median residuals found to be different from zero, the corresponding median ratio values ranged from -7.0 to -13.8 percent. The median residuals were greater in magnitude for STEMS than for STEMS-FIA over all species.

To test if the differences in residuals for STEMS-FIA and STEMS were significant, two-sample Wilcoxon Rank Sums tests were used on all four species. The balsam fir annualized residuals were different (P = 0.0022) for the two models. STEMS overestimated dbh by a median value of 0.011 inches per year, while STEMS-FIA overestimated dbh by a median value of 0.008 inches per year. This difference, approximately 0.03 inches over a 10-year prediction period, is relatively small from a biological viewpoint. The differences in the dbh residuals of the two models were not statistically significant for the other species.

The size ratios, each given as the percent of the median observed growth magnitude represented by the median growth residual magnitude, ranged from 30.3 to 48.8 percent. The values of r^2 were highest for red pine (0.418 and 0.437) and lowest for paper birch (0.101 and 0.117) for STEMS and STEMS-FIA, respectively. In all cases, the r^2 value was at least as high for STEMS-FIA as it was for STEMS, although again all r^2 values were low.

The variance of dbh estimates from the two models was compared using Box's test at a 0.10 level of significance. The variation of balsam fir growth residuals was different between the two models (P = 0.0540). The standard deviation of balsam fir dbh residuals was 0.0573 inches for STEMS-FIA and 0.0620 inches for STEMS. No differences in variance for the diameter residuals were found for the other species.

Basal Area Per Acre Estimates

The two models overestimated annual basal area per acre for balsam fir (P = 0.0001), quaking aspen (P = 0.0001), and paper birch (P = 0.0011 and P = 0.0002 for STEMS and STEMS FIA, respectively) by median values ranging from 0.281 to 0.505 ft^2 per acre per year (table 4). The median ratios for overprediction for these three species ranged from 21.6 to 41.7 percent, while the corresponding size ratios ranged from 75.1 to 104.8. As with diameter, the correlation between predicted and observed basal area growth was highest for red pine, with r^2 values of 0.588 and 0.621, and lowest for paper birch, with r^2 values of 0.169 and 0.177 for STEMS and STEMS-FIA, respectively. The r^2 values for STEMS were slightly higher than those for STEMS-FIA in balsam fir and quaking aspen, but lower in red pine and paper birch. No differences were found between the median residuals for the predictions of basal area per acre for any of the species (Wilcoxon Signed Rank, (a = 0.05). The variation of the basal area per acre growth residuals was equivalent for both models in all four species (Box's test, (a = 0.10).

Validation

Dbh Estimates

Validation is used to test model performance on a data set similar to, but separate from the data with which the model was calibrated. Both STEMS-FIA and STEMS were applied to the validation data to compare performance. The models overestimated average annual dbh growth in balsam fir by median values of 0.012 and 0.011 inches and median ratios of 16.0 and 14.7 percent for STEMS (P = 0.0001) and STEMS-FIA (P = 0.0001), respectively (table 3). In red pine, STEMS-FIA underestimated average annual change in dbh by a median value of 0.006 inches (P = 0.0085) and a median ratio of 4.7 percent, while STEMS underestimated it by a median value of 0.004 inches (P = 0.0561) and a median ratio of 3.1 percent. The size ratios for all four species ranged from 29.6 percent for the STEMS FIA prediction residuals for red pine to 50.7 percent for the STEMS prediction residuals for balsam fir. Again, the correlation between the predicted and observed diameter growth for the interval was highest for red pine, with r^2 values of 0.480 and 0.560, and lowest for paper birch, with r^2 values of 0.066 and 0.074 for STEMS and STEMS-FIA, respectively. There was a difference in residuals of the two models only in balsam fir (P = 0.0495), but this difference is only about 0.01 inches over a 10-year projection period. There was a difference in variance of the residuals for STEMS and STEMS-FIA only in red pine (Box's test; P = 0.0969) and balsam fir (Box's test; P = 0.0722). In both cases, the standard deviation for STEMS was greater than for STEMS-FIA.

Basal Area Per Acre Estimates

Both STEMS and STEMS-FIA overestimated average annual stand basal area per acre change by median values of 0.293 and 0.327 ft^2 per acre for quaking aspen (P = 0.0003 and P = 0.0015) and by 0.466 and 0.391 ft^2 per acre for paper birch (P = 0.0215 and P = 0.0075), respectively (table 4). STEMS underestimated annual basal area per acre change by a median value of 0.497 square feet (P = 0.0340) in red pine. The models overestimated basal area growth for quaking aspen and paper birch by median ratio values between 24.4 to 40.1 percent and underestimated annual basal area per acre growth for red pine by median ratio values of 26.2 and 15.0 percent for STEMS and STEMS FIA, respectively. The size ratios ranged from 40.4 percent for the STEMS residuals for red pine to 91.1 percent for the STEMS-FIA residuals for paper birch. The r^2 values were highest for red pine (0.836 and 0.888 for STEMS and STEMS-FIA, respectively). For balsam fir, quaking aspen, and paper birch, the r^2 values ranged from 0.221 to 0.483. No differences were found in either medians or variation of residuals for the two models within any species (table 4).

CONCLUSIONS

In general, the performances of STEMS-FIA and STEMS in predicting annual diameter and basal area change were nearly equivalent. The direction of overprediction or underprediction was the same for the two models within a species of a data set. While there is very little difference in the predictive ability of the two models, the bias of both diameter and basal area per acre growth predictions, the relative size of these residuals, and the lack of fit indicated by the low r^2 values are causes for concern with both models.

Although STEMS was calibrated on permanent growth data, when applied to FIA data it performs about as well as STEMS-FIA. While the model form appears to be robust in the sense that results from different estimation procedures are equivalent, the model form is limiting in the sense that it does only so well. There seems to be no need to try to refine STEMS through further recalibration. Future work should focus on improving the form of model and possible inclusion of climate-related variables (Holdaway 2000).

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