DEVELOPING A SIMPLE LONGLEAF PINE PLANTATION GROWTH AND YIELD MODEL FOR THE GULF REGION

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ABSTRACT

The longleaf pine (*Pinus palustris* P. Mill.) forest ecosystem was one of the most extensive in North America. This species produces valuable wood products but has the stigma of slow growth and hence was often not replanted following harvest. Thus, despite its timber value, only a few growth and yield models have been developed. This study examined the ability of four different modeling approaches to estimate merchantable volume of plantations in the Gulf region. Data used in model development are from the Forest Service, U.S. Department of Agriculture, Forest Inventory and Analysis (FIA) annual surveys conducted in Alabama, Florida, Louisiana, Mississippi, and Texas. Based on independent validation data from four different studies, one each in Mississippi and Alabama and two in Georgia, the approach predicting volume as a function of initial volume and age and the approach that first predicts basal area and then volume produced the best predictive statistics. However, neither approach was consistently best across all four validation studies. Based on these analyses, a single superior modeling approach was not identified.

INTRODUCTION

When using cross-sectional data to estimate future yields per acre (e.g., volume or tons), or using many observations of stands varying in age at the same point of measurement time, one of three growth and yield projection approaches to estimate yields are commonly used. The first is to predict future yield from a single equation based on calibrating the equation using currently observed yields (fig. 1). This is further referred to as Approaches One and Two where the same approach was used but differing in equation form. Fixed-effects regression predicts the average behavior of a dependent variable given regressors. By adjusting the average behavior given current, or local, stand conditions, the future estimate should be more responsive to local site conditions and practices impacting the yield trajectory of a stand through time.

A second method is similar to the first. However, to predict future yield, first another variable is calibrated (e.g., basal area per acre) as described above and then the future value of the other variable is used to predict the future yield. This is further referred to as Approach Three. This approach may be advantageous to One and Two if the equation used to predict basal area has superior model fit statistics relative to simply predicting yield, and then only if basal area has a strong relationship with the yield variable. Since basal area must first be predicted, and then the predicted basal area is used to predict yield, the error involved in predicting basal area is "passed" to the equation to predict yield, and thus the first two approaches will likely be superior predictors of future yields (e.g., volume or tons).

The objective of this study was to examine the ability of these three different modeling approaches to estimate merchantable volume per acre of longleaf pine plantations in the Gulf region. This study will eventually lead to the development of a simple TDSS for longleaf pine plantations in the Gulf region.

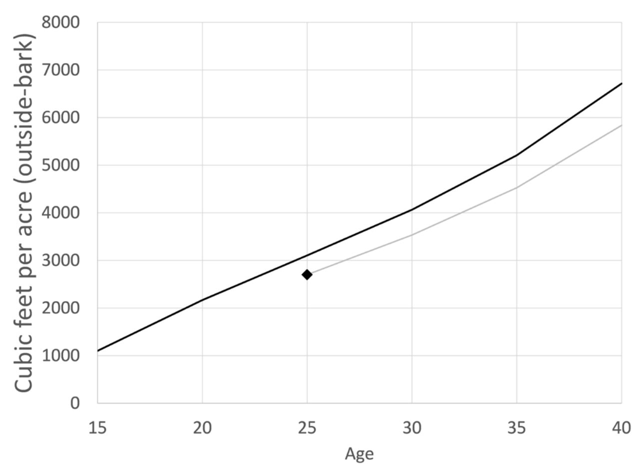

Figure 1—Example of calibrating an individual stand-level growth trajectory of a stand inventoried at age 25. Assuming the black line represents the average behavior for a site of stand conditions, the gray curve is generated by "calibrating" the average trajectory for this individual stand by taking the ratio of the predicted behavior at age 25 from the average curve to the volume based on an inventory at age 25. This ratio is then maintained throughout the rest of the projection.

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Citation for proceedings: Willis, John L.; Self, Andrew B.; Siegert, Courtney M., eds. 2022. Proceedings of the 21st Biennial Southern Silvicultural Research Conference. Gen. Tech. Rep. SRS-268. Asheville, NC: U.S. Department of Agriculture Forest Service, Southern Research Station. 262 p. https://doi.org/10.2737/SRS-GTR-268.

METHODS

The Forest Service, U.S. Department of Agriculture, Forest Inventory and Analysis (FIA) (Miles 2016) plots designated as longleaf pine plantations are located in the Western Gulf but concentrated in the Eastern Gulf region (fig. 2). According to FIA there are 245,227 acres in Alabama, 223,870 acres in Florida, 18,215 acres in Louisiana, 39,868 acres in Mississippi, and 17,761 acres in Texas.

The data used in model development were obtained from FIA annual surveys. The FIA panels used varied by State. Panels from 2006 to 2015, 2010 to 2014, 2001 to 2013, 2006 to 2014, and 2004 to 2012 were used for Alabama, Florida, Louisiana, Mississippi, and Texas, respectively. Data were obtained from the FIA database website (USDA Forest Service 2016).

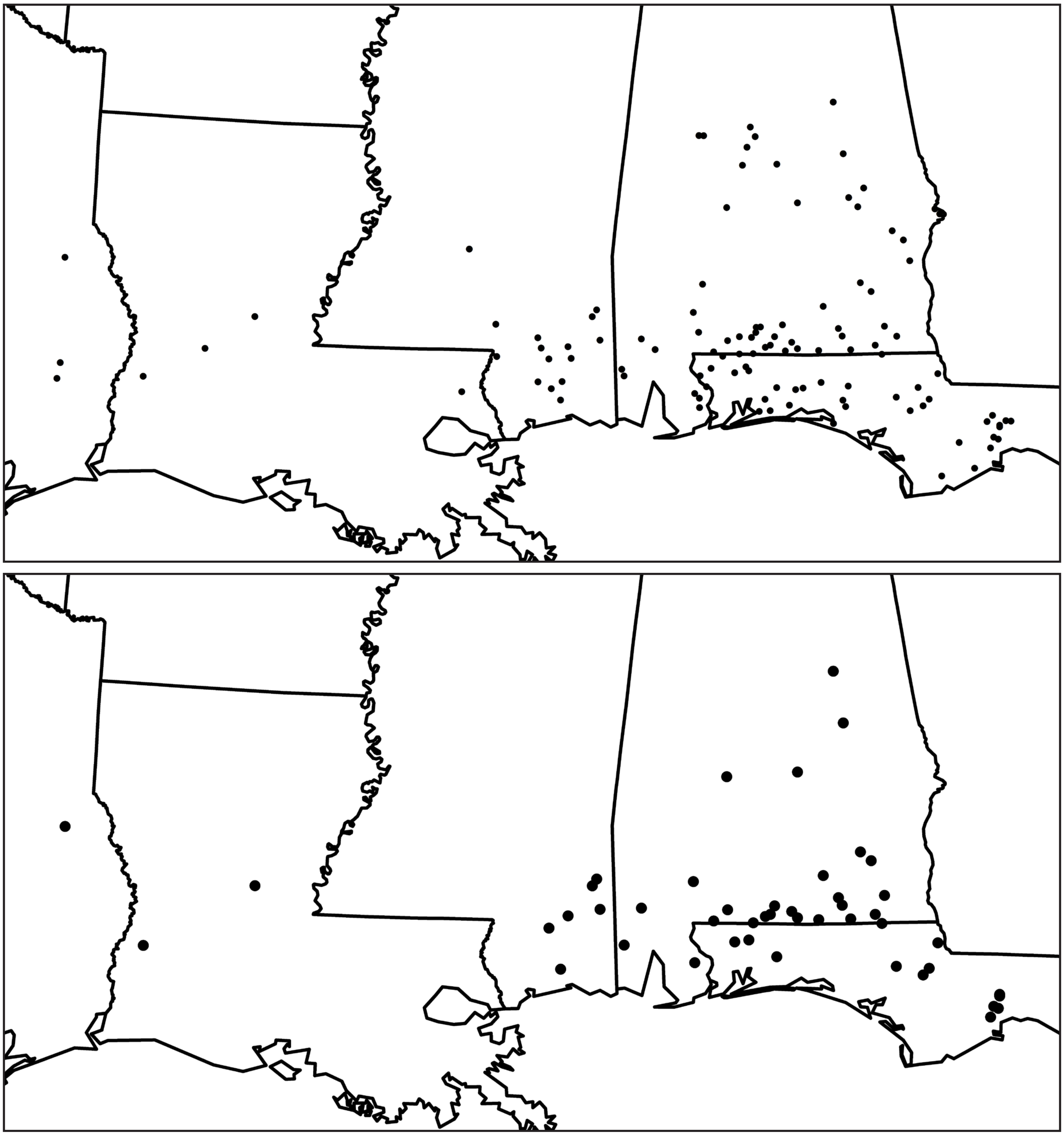

Figure 2—Spatial location of the 116 Forest Inventory and Analysis (FIA) plots designated as longleaf pine plantations (upper). Spatial location of the 47 FIA plots used in model development (lower).

Model Fitting Data

Only those plots considered plantations by FIA (STDORGCD = 1 in the FIA Condition table) were used, as these plots have sufficient evidence to be classified as plantations. Only living trees were included (STATUSCD = 1 in the FIA Tree table), all tree classes were included (TREECLCD within the FIA Tree table was not used to filter the data), all ownerships were included (OWNCD in the FIA Condition table was not used to filter the data), and FIA timberland was used (SITECLCD from 1 to 6 in the FIA Condition table). Table 1 presents summary data for the plots used in model development and figure 2 graphically locates the plots.

Dominant height of a particular plot for model development was defined as the average height of the tallest 50 percent of all surviving longleaf pine trees—consistent with the definition of Boyer (1980). All plots of age less than 5 were removed due to concerns about the reliability of volume estimates and all plots with four or fewer longleaf pine trees used to calculate dominant height were removed because sample sizes are likely too low to provide a reliable estimate of dominant height. Plots that had a ratio of dominant height and stand age (STDAGE in the FIA Condition table) less than 1.22 were removed (two plots), because dominant heights were 30 feet and 46 feet at ages 27 and 38, respectively. One plot greater in age than 70 was deleted. One observation was deleted because after initially calculating site index (base age 25) using equation 2, the estimated site index exceeded 100 feet. The observed dominant height for this stand at age 8 was 45 feet. Following deletion of this observation, the

Table 1—Summary statistics (upper table) by State and across the entire model fitting dataset for the Forest Inventory and Analysis (FIA) plots used in model development (n = 47). Summary statistics (lower table) for the four validation datasets

		Stand age				Basal area per acre *(square feet)*				Cubic feet per acre				Dominant height *(feet)*				Site index *(feet, base age 25)*			
State	*n*	M	S	Min.	Max.	M	S	Min.	Max.	M	S	Min.	Max.	M	S	Min.	Max.	M	S	Min.	Max.
Alabama	25	18	8	10	45	88	40	40	236	1,185	804	188	3,217	48	13	27	80	59	7	43	70
Florida	13	23	10	11	40	61	29	27	113	786	636	210	2,058	49	12	34	69	54	9	38	66
Louisiana	2	34	10	27	41	111	17	99	123	2,489	341	2,248	2,730	73	3	71	75	67	9	61	73
Mississippi	6	26	6	17	32	108	41	56	167	1,859	712	605	2,670	59	7	46	66	59	4	55	66
Texas	1	28	–	28	28	100	–	100	100	1,989	–	1,989	1,989	65	–	65	65	62	–	62	62
All	47	21	9	10	45	84	39	27	236	1,233	831	188	3,217	51	13	27	80	58	8	38	73

		Stand age	Basal area per acre *(square feet)*				Cubic feet per acre				Dominant height *(feet)*			
State	*n*		M	SD	Min.	Max.	M	SD	Min.	Max.	M	SD	Min.	Max.
Mississippi	40	8	17	11	1	35	38	51	0	192	22	7	8	30
	40	25	48	21	8	98	963	486	142	2163	60	6	47	69
	40	39	69	28	17	133	1,782	784	407	3,799	74	6	58	85
Alabama	6	7, 8, 10, 11	33	11	19	46	130	128	8	285	22.8	5.1	17.0	29.0
Cuthbert, GA	5	7	19	5	12	23	240	82	112	313	.	.	.	.
	5	9	32	6	24	38	460	101	315	561	20.6	1.6	18.3	22.2
Tift, GA	3	17	118	8	113	127	3,368	414	3,096	3,845	56.9[a]	0.4	56.4	57.3
	3	21	134	11	126	146	4,634	532	4,261	5,243	66.5[a]	0.1	66.4	66.5

M = mean; SD = standard deviation; Min. = minimum; Max. = maximum; .= no reported height.

[a]For Tift, GA, dominant height was calculated by multiplying reported average height by 1.0939390541.

parameters of equation 2 were then re-estimated. The final sample size used in model fitting was n = 47 observations.

Merchantable volume as defined by FIA (VOLCFNET within the FIA Tree table) was used as the dependent variable. Essentially, this is the merchantable volume of trees with diameter at breast height (d.b.h.) of 5.0 inches and greater, from a 1-foot stump to a minimum 4.0 inches top diameter.

Stand-Level Model Development

Equations were selected based on both biological and statistical considerations. Parameter estimates were checked to make sure they were consistent with biological theory (e.g., with age volume per acre should increase). Additionally, predicted values of stand development were examined to determine whether a particular equation or sets of equations produced reasonable estimates across a range of ages and values of the regressors. After accounting for biologically meaningful variables, the function with the highest Adjusted R^2(s) was selected. Residuals were examined for trends. Proc Model (SAS 1989) and the Gauss-Newton algorithm were used to estimate parameters of all equations.

Dominant Height Equation

A widely accepted site index equation for longleaf pine plantations does not exist. Hence, an equation was developed. A simple anamorphic guide curve approach was selected using equation 1:

$$Ht_D = e^{\beta_0 + \beta_1 A^{-1}} \qquad (1)$$

where

Ht_D = dominant height (feet), defined as the average height of the tallest 50 percent of surviving longleaf pine trees (other species were not selected), within a FIA plot

A = plot age (STDAGE in the FIA Condition table)

β_0, β_1 = parameters to be estimated

After removing plots of young ages and low numbers of trees, a total of 47 FIA plots were used in model development. After fitting (Adjusted R^2 = 0.7312) and algebraic manipulation, equation 1 becomes:

$$SI = Ht_D e^{(25^{-1} - A^{-1})^{-10.7364}} \qquad (2)$$

where

SI = dominant height at a reference base age of 25 years, and others as previously defined.

Equation 3 is used to predict dominant height:

$$Ht_D = SIe^{(25^{-1} - A^{-1})^{10.7364}} \qquad (3)$$

Predicting Volume

Approach One—For Approach One, equation 4 was used to estimate volume per acre:

$$Vol = \beta_2 (1-e^{-\beta_3 A})^{[1-\beta_4]^{-1}} \qquad (4)$$

where

Vol = volume of trees of d.b.h. 5.0 inches and greater from a 1-foot stump to a 4-inch top diameter outside-bark (essentially trees merchantable for pulpwood, sawtimber, veneer, etc.). Within FIADB, the variables VOLCFNET and TPA_UNADJ are used to estimate individual tree volume on a plot basis, merchantable trees of all species,

β_2, β_3, β_4 = parameters to be estimated, and others as previously defined.

Approach Two—Alternatively, equation 5 contains an estimate of site quality–dominant height:

$$Vol = \beta_5 (1-e^{-\beta_6 A})^{[1-\beta_7 Ht_D]} \qquad (5)$$

where

β_5, β_6, β_7 = parameters to be estimated, and others as previously defined.

To project a stand trajectory forward, after algebraic manipulation, equation 4 becomes:

$$Vol_2 = Vol_1 \left[\frac{1-e^{-\beta 3A2}}{1-e^{-\beta 3A1}}\right]^{[1-\beta_4]^{-1}} \qquad (6)$$

where

A_1 = plot age at the current time; A_2 = desired future plot age, and others as previously defined.

And, to project a stand trajectory forward, after algebraic manipulation, equation 5 becomes:

$$Vol_2 = Vol_1 \left[\frac{1-e^{-\beta 6A2}}{1-e^{-\beta 6A1}}\right]^{[1-\beta_7 Ht_D]^{-1}} \qquad (7)$$

Hence, we can "calibrate" equations 4 or 5 to local site conditions and practices such as site preparation, herbaceous weed control treatments, planting density, etc., through the use of Vol_1.

Approach Three—For this approach the following equation was used to first estimate basal area per acre:

$$BA = e^{\beta_8 + \beta_9 A^{-1}} \qquad (8)$$

where

BA = square feet of basal area per acre of all surviving trees (trees of all species, and whether the trees are merchantable or not) within the plot; β_8, β_9 = parameters to be estimated, and others as previously defined.

After algebraic manipulation of equation 8 similarly to equation 1, equation 9 is produced:

$$BA_2 = BA_1 e^{(A_2^{-1} - A_1^{-1})^{\beta_9}} \qquad (9)$$

Equation 10 is then used to predict volume:

$$Vol = \beta_{10} BA{*}Ht_D \qquad (10)$$

For Approach Three, to avoid potential simultaneous equation bias and to account for potential cross-equation correlation of the residuals, a simultaneous parameter estimation methodology (Borders 1989) was used to estimate parameters of equations 8 and 10.

Validation Data

To gain insight into which approach will produce the most accurate and precise estimates of future growth and yield, predictions were made using unthinned plantations established in southern Mississippi (Schmidtling 1987). All individual tree data were obtained from longleaf pine growing on the Harrison Experimental Forest near Saucier, MS. This study consisted of testing whether plowing and discing combined with a single application of NPK fertilizer disced into the soil 1 year after planting increased yield. Seed sources differing in whether specific gravity was low or high were also tested. Cultivated plots were cleared of all stumps and slash, then plowed and disced. Cultivation consisted of discing 3 times each season for 3 years after planting and mowing in the 4th and 5th seasons. All seedlings were 1-0 bareroot stock of a local seed source planted in 1960 at a 10 feet by 10 feet spacing. There were four replications consisting of 10 plots. Each plot contained 100 trees. Total tree height and d.b.h. measurements were conducted at ages 8, 25, and 39, and volumes were predicted for ages 8, 25, and 39. Dead trees after the first growing season were replanted.

The definition of volume was consistent with FIA's definition as defined for Vol in equation 4. Volume of trees of d.b.h. 5.0 inches and greater from a 1-foot stump to a 4-inch top diameter outside-bark (essentially trees merchantable for pulpwood, chip-n-saw, sawtimber, etc.). Individual tree volumes were estimated using equations found in Gonzalez-Benecke and others (2014). For this study, age 8 data were used as the initial measurement for predictions at age 25 and age 25 data were used as the initial measurement for predictions at age 39. These long predictive intervals will likely impact predictive ability. For Approaches Two and Three, the observed dominant heights at ages 25 and 39 were used. In practice, these dominant heights would need to be predicted using equation 3. This study is further referred to as the Mississippi study. Table 1 presents summary data for the plots used in model validation.

Farrar and White (1983) provided the second unthinned validation dataset. They state that all site preparation treatments essentially resulted in complete destruction of woody vegetation and thus removal of all sources of brownspot needle blight (*Scirrhia acicola* Dearn. Siggers) infection. All planting stock was 1-0 bareroot, machine-planted, and densities ranged from 1,132 to 1,271 seedlings per acre. No additional cultural treatments were conducted beyond site preparation, thus there was no first-year herbaceous weed control treatment. Study sites were located within Escambia County, AL. Initial measurement data at sites were ages 7 and 8 while the predictive ages were either 10 or 11, respectively. For Approaches Two and Three, the observed dominant heights at ages 10 or 11 were used. In practice, these dominant heights would need to be predicted using equation 3. This study is further referred to as the Alabama study.

The second published source was obtained from an unthinned plantation established near Cuthbert, GA (Creighton 1987, Knowe 1982, Lauer 1990). Previous land use was a 20-year-old slash pine plantation and site preparation consisted of chopping and discing. Planting density was 726 seedlings per acre (5 feet by 12 feet), machine planted (likely bareroot stock). This study examined how varying number and application method (either banded or broadcast) of annual herbaceous weed control treatments affected yield. Treatments consisted of no control, first-year, or first- and second-year herbicide applications to control herbaceous weeds. The initial measurements were conducted at age 7 while age 9 measurements were predicted. For Approaches Two and Three, the observed dominant heights at age 9 were used. In practice, these dominant heights would need to be predicted using equation 3. This study is further referred to as the Cuthbert, GA study.

The third published source was obtained from an unthinned plantation established on a former old-field in Tift County, GA (Dickens and others 2012). Site preparation consisted of chisel plowing, followed by Oust sprayed in years 1 and 2 post-plant and the site was burned in year 2. Planting density was 605 bareroot seedlings per acre (6 feet by 12 feet). This study examined how NPK fertilization would impact growth rates. Measurements were conducted at ages 17 and 21. The initial measurement age was 17 and the predictive age was 21. Dominant height was not reported, but average height was presented. To estimate dominant height, dominant height was calculated using the reported average heights and the ratio between the average and dominant heights at age 25 from the Mississippi study, a value of 1.0939390541. Dominant height was defined as the average height of the tallest 50 percent of surviving longleaf pine trees, consistent with equation 3. The value of 1.0939390541 (used for internal calculations) is similar to the ratio between reported dominant height and average height at age 9 in the Cuthbert, GA study of 1.114031. The Mississippi ratio was used since the data was similar in age and to some degree planting density to the Tift, GA study. This study is further referred to as the Tift, GA study.

Validation Analyses

Validation analyses follow those presented in Trincado and others (2007). The difference between the predicted (Vol_{pred}) and observed volumes (Vol_{obs}) for the four modeling approaches was calculated ($e = Vol_{pred} - Vol_{obs}$) for each validation plot/observation within a particular study. The mean residual ($\bar{e}$) and the sample variance (v) of residuals were computed by study and age for each modeling approach and considered to be estimates of bias and precision, respectively. An estimate of mean square error (MSE) was obtained by study for each modeling approach by combining the bias and precision measures using the following formula:

$$MSE = \bar{e}^2 + v \quad (11)$$

RESULTS AND DISCUSSION

Parameter estimates and model fitting results are presented in table 2. For the Mississippi study, all modeling approaches underpredicted volumes (figs. 3 and 4, table 3). In some cases, predictions were consistently severely low. Once again this is likely in part due to the extremely long prediction intervals. All modeling approaches use current inventory data to in a sense "calibrate" the models for that plots specific growing conditions. Hence, it may be that 3- or 5-year intervals would produce better predictions. Additionally, volumes on this site are inherently low. Perhaps the model fitting data in general will not produce adequate predictions for this site. However, that is the purpose of the initial measurement—to help "calibrate" the models. Modeling Approach Three, although not satisfactory, clearly produced the best predictive statistics. A problem with Approaches One and Two is that if the previous volume was 0, there will be no predicted future volume, this can be seen for $n = 16$ observations in figure 3. This is an advantage of Approach Three, when applying this model to most stands at ages 5 and older, some amount of basal area will exist, and hence some amount of volume will be predicted since volume is predicted (equation 10) as a function of basal area from equation 9 and the dominant height.

Similarly, Approach Three produced the best predictive results in the Alabama study (fig. 5, table 3). Approach Three actually produced reasonable predictions that may be acceptable by users. The predictive intervals were only 3 years which may have resulted in the better predictive ability relative to the Mississippi study.

For the two Georgia studies of common approaches, Approach One produced the best predictive statistics by meaningful amounts. Approach Three did not produce acceptable results. The Tift, GA site is an old-field, this could have had some impact on predictions.

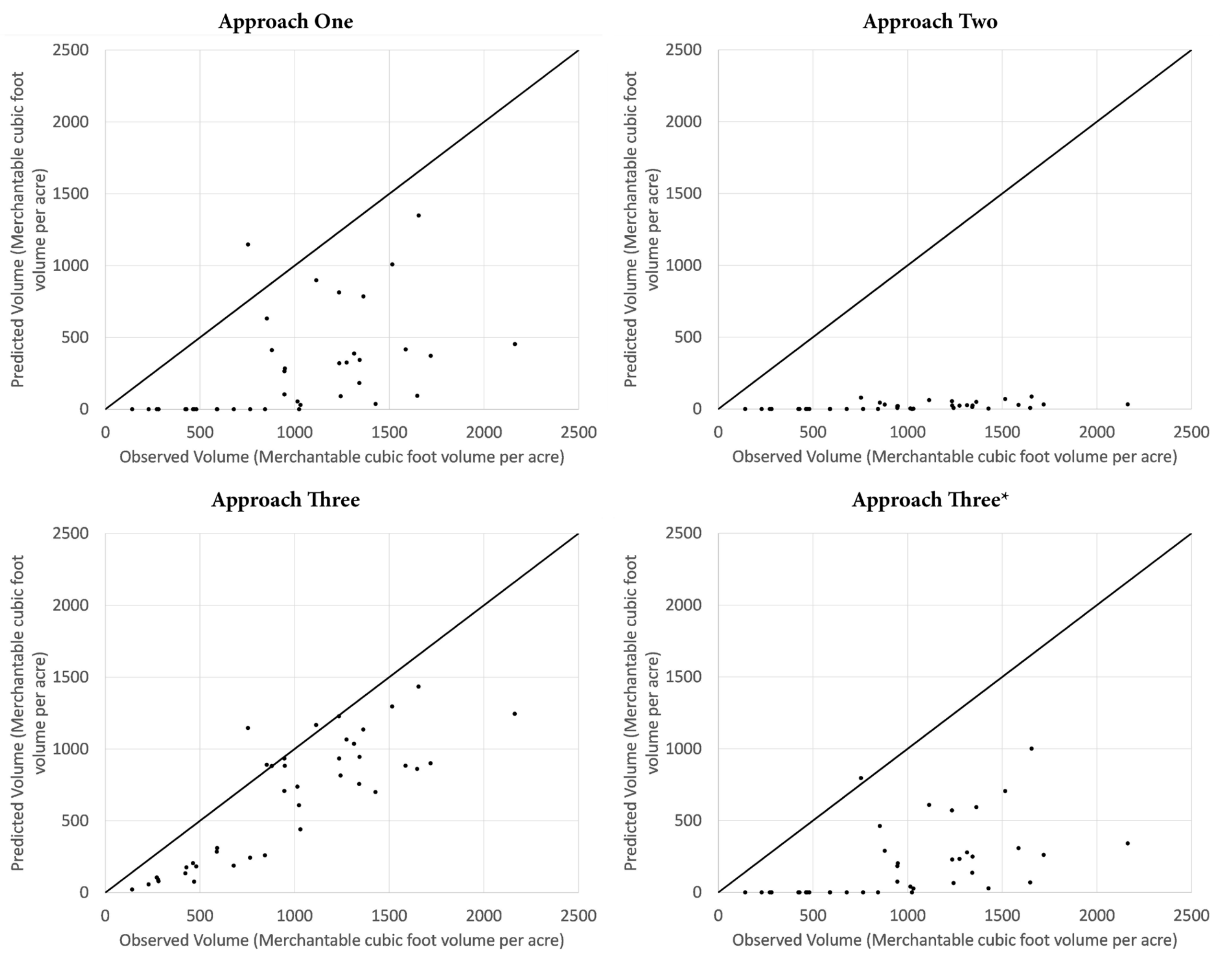

Figure 3—Model validation results of the four approaches from the Mississippi study at age 25. Black lines are one-to-one predictions. $n = 40$.

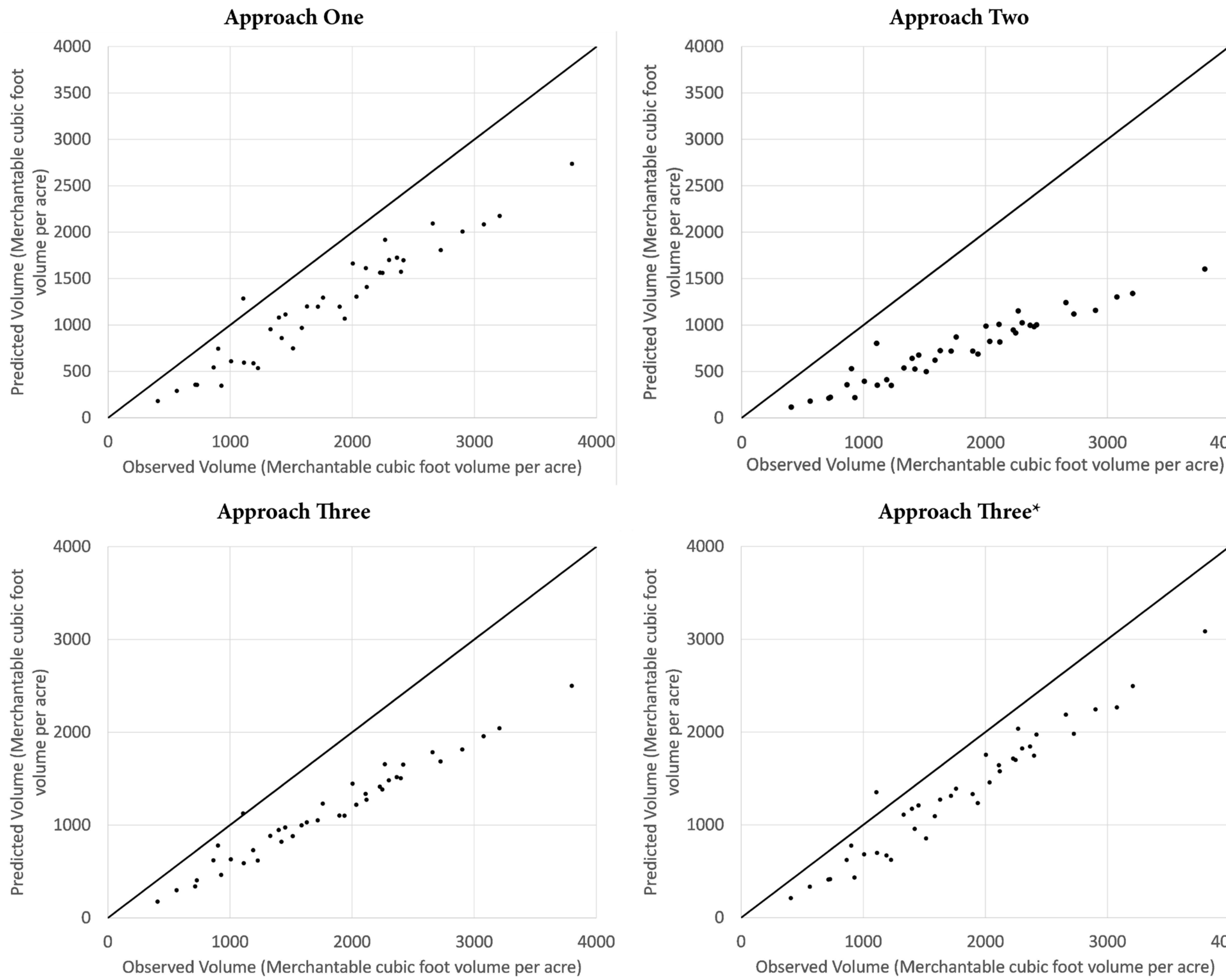

Figure 4—Model validation results of the four approaches from the Mississippi study at age 39. Black lines are one-to-one predictions. *n* = 40.

Table 2—Parameter estimates of equations 4, 5, 8, and 10 (*n* = 47)

Equation	Adj. R_2	Parameters	Estimate	Approximate Standard Error	*t*-value	Pr > |t|
4	0.3806	β_2	2178.996	480.3	4.54	<.0001
		β_3	0.104124	0.0675	1.54	0.1298
		β_4	0.746766	0.2465	3.03	0.0041
5	0.6809	β_5	650.7229	293.5	2.22	0.0318
		β_6	0.007	0.00163	4.30	<.0001
		β_7	0.025319	0.00448	5.65	<.0001
8	0.1055	β_8	4.905399	0.1652	29.70	<.0001
		β_9	-9.00891	3.1934	-2.82	0.0071
10	0.8463	β_{10}	0.277065	0.00880	31.49	<.0001

Table 3—Model validation results of cubic foot volume and square feet of basal area per acre using the three modeling approaches for the four validation datasets

Mississippi, Schmidtling (1987), *n* = 80, *n* = 40 within parentheses				
	Error			MSE
Approach	ē	v	ē%	
One	-628 (-693 & -564)	128581	-45.8 (-72.0 & -31.6)	523255 (665552 & 384042)
Two	-1028 (-944 & -1113)	233584	-74.9 (-98.0 & -62.5)	1291260 (1115083 & 1473062)
Three	-478 (-312 & -645)	105535	-34.9 (-32.4 & -36.2)	334462 (167983 & 502220)
Three*	-604 (-769 & -440)	132919	-44.0 (-79.9 & -24.7)	498178 (761742 & 236634)

Alabama, Farrar and White (1983), *n* = 3				
	Error			MSE
Approach	ē	v	ē%	
One	-211	1436	-86.2%	45917
Two	-229	1357	-93.6%	53688
Three	19	2911	7.8%	3264
Three*	-214	1480	-87.5%	47122

Cuthbert, GA, Knowe (1982), Creighton (1987), Lauer (1990), *n* = 5				
	Error			MSE
Approach	ē	v	ē%	
One	-7	3289	-1.5%	3336
Two	-192	386	-41.7%	37104
Three	-313	3078	-68.0%	101355

Tift, GA, Dickens and others (2012), *n* = 3				
	Error			MSE
Approach	ē	v	ē%	
One	-236	13003	-5.1%	68492
Two	-1691	37115	-36.5%	2897480
Three	-2230	143684	-48.1%	5117889
Three*	-285	9449	-6.1%	90851

Basal area per acre study	Error			MSE
	ē	v	ē%	
Mississippi (*n* = 80)	-12.3 (-10.6 & -14.0)	147	-21.1 (-22.2 & -20.3)	298 (349 & 250)
Alabama (*n* = 3)	-7.7	25	-18.2%	85
Cuthbert, GA (*n* = 5)	-6.7	2	-21.0%	47
Tift, GA (*n* = 3)	-3.1	8	-2.3%	18

ē, v, ē%, and MSE are the mean error, variance of the errors, percent mean error, and mean square error, respectively, for a particular study and approach, as expressed in equation 11. For Approach Three* rather than using the parameter estimate for β_{10} of 0.277065 in equation 10, an observation-specific ratio using equation 12 was used, calculated using data from the previous (or current) measurement. For the Mississippi study, the first number in parentheses corresponds to age 25 results and the second number corresponds to age 39 results.

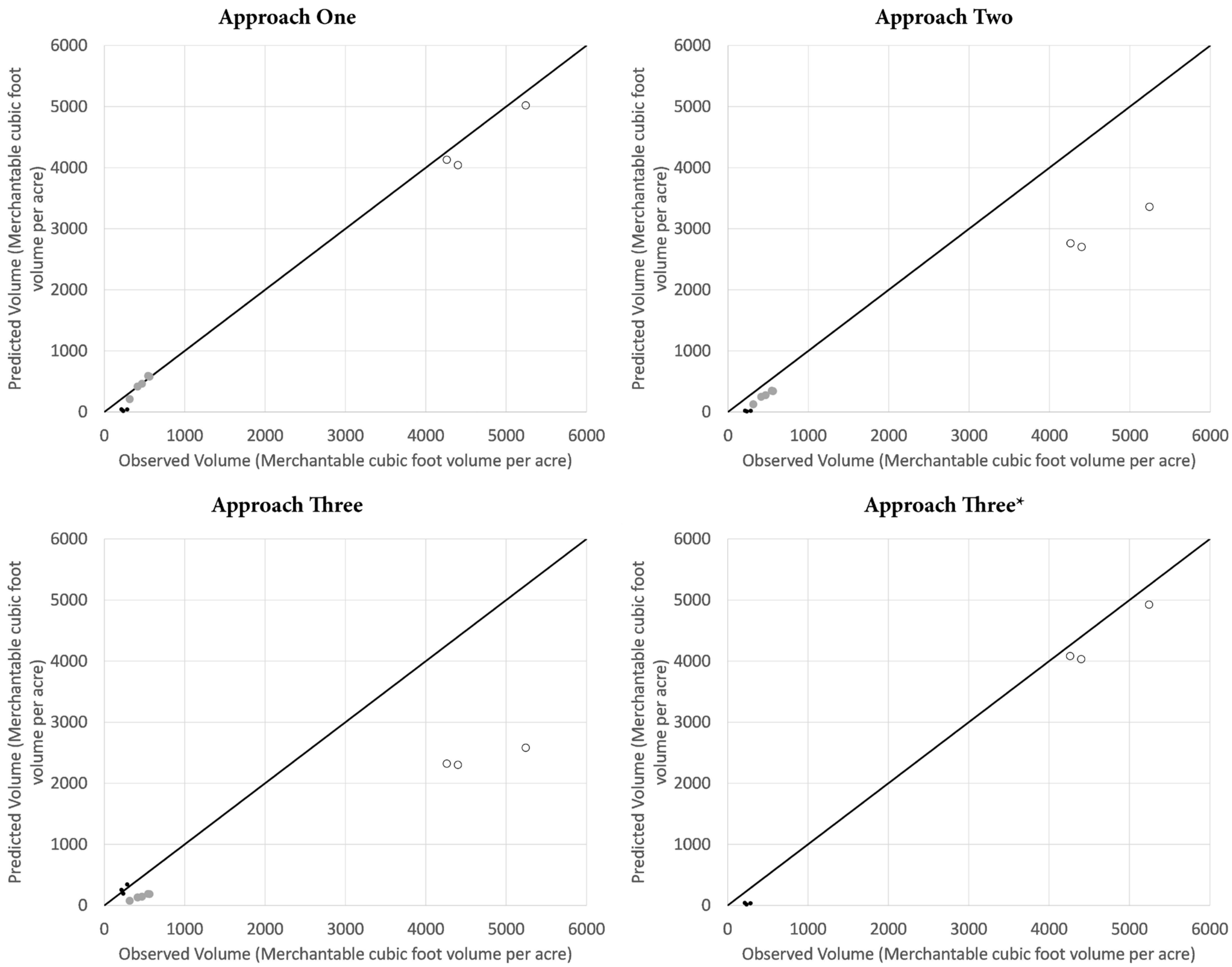

Figure 5—Model validation results of the four approaches from the Alabama (black circles *n* = 3), Cuthbert, GA (gray circles *n* = 5), and Tift, GA (unfilled circles *n* = 3) studies. Black lines are one-to-one predictions.

Equation 9 produced good estimates of basal area for the Tift, GA site (table 3), a percent error of 2.3 percent. However, Approach Three did not produce very good volume estimates, likely because the estimated value of β_{10} is not appropriate for the Tift, GA dataset. Therefore, equation 12 was used to determine a mathematically-derived value of β_{10} using previous measurement age observations. This allows a user to produce an estimate of β_{10} that is more indicative of the local genetic stock, stand densities, and their impacts on form and taper rates when estimating merchantable volume.

$$Vol_{A_1} / [BA_{A_1} * Ht_{DA_1}] = \beta_{10i} \quad (12)$$

where

β_{10i}= parameter mathematically-derived for each stand/plot (*i*) at a particular age using the previous (or current) measurement age (A_1) volume, basal area per acre, and dominant height.

This approach, further referred to as Approach Three*, substantially improved volume estimates at the Tift, GA site relative to Approach Three, but they were still not as good as Approach One. Approach Three* did not produce acceptable results at the Mississippi site as a whole and the Alabama site. At the Mississippi site, overall, this likely resulted in part from the long prediction intervals, making the previous value of β_{10i} not applicable for the estimated age. However, for volume, when predicting from age 25 to 39 the lowest percent error at the Mississippi site was observed (-24.7 percent). At both the Mississippi and Alabama sites, basal area was not accurately predicted, equation 9 produced percent errors of 21.1 percent and 18.2 percent at the Mississippi and Alabama sites, respectively. These relatively poor results likely were produced at the Mississippi site because of the long prediction intervals and the sporadic survival, producing in some cases low basal areas, and the young previous ages (ages 7 or 8) and low productivities, likely due to minimal vegetation control after establishment, at the Alabama site. There was no reported previous dominant height (at age 7) at the Cuthbert, GA site. Similar to Approaches One and Two, a problem with Approach Three* is that if the previous volume was 0 there will be no predicted future volume (see equations 10 and 12). This can be seen for n = 16 observations in figure 3.

Validation analyses show substantial variability. Based on these results it is difficult to suggest a particular prediction approach across all four validation studies. Approach One produced the best results for two studies, while Approach Three produced the best results at the two other studies. And while Approach Three* never produced the best results, it was second, or nearly so, in the three studies where the approach was used. Additionally, it produced the lowest percent error when predicting from age 25 to age 39 at the Mississippi site. Approach One, since it has a means to in a sense "calibrate" the volume predictions to that site's specific characteristics through Vol_1, is likely the method that should be suggested. However, the use of equation 12 to produce a stand-specific estimate of β_{10}, or β_{10i}, produced solid predictions when using Approach Three* for initial measurement ages greater than 10, which were the Tift, GA study and when predicting volume at age 39 using age 25 observed volumes at the Mississippi study. For younger initial ages, it often did not produce satisfactory results. Approaches Three and Three* also have an advantage of providing a basal area per acre estimate. Approach Two consistently produced unsatisfactory prediction statistics.

These validation studies were purposefully chosen because they vary widely in their ages, site conditions (e.g., old-field versus cutover), planting densities, and prediction intervals. Young ages, such as those less than 10 years old, seem to have relatively poorer prediction results. This is particularly true of low productivity sites such as the Alabama study. Vegetation control is essential for longleaf survival and productivity during the first year or two following establishment (Lauer 1990, Nelson and others 1985). The Alabama study only consisted of site preparation treatments (Farrar and White 1983) and that likely contributed to the low productivity, and likely the poor prediction results. In general, relatively poorer results were observed for the Mississippi study when predicting from age 8 to 25 than from age 25 to 39 (figs. 3 and 4, table 3). It appears that when young previous measurement age data (e.g., less than 10) is used to estimate β_{10i} (equation 12), that the ratios are not applicable to older ages and hence generally result in poor prediction results when using Approach Three*.

Projection intervals should be no greater than 5 years. Longer projection intervals will likely result in poor predictions. Unfortunately, at this time, a consistently best modeling approach was not identified. If these equations are used, managers should use these tools along with other available tools when making management decisions.

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