

CALIBRATING A GROWTH-AND-YIELD MODEL FOR LOBLOLLY PINE IN THE MISIONES/PARANÁ REGION OF SOUTH AMERICA—AN OVERVIEW

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Abstract—Data from permanent remeasurement plots established in loblolly pine (*Pinus taeda* L.) plantations growing in the Misiones/Paraná region of South America were used to develop and test a system of equations for predicting and projecting volume yields for thinned and unthinned stands in that region. Component equations parameterized with the data included dominant height/site index, basal area prediction and projection, survival, and total volume yield prediction. Improved estimates of yield were achieved when geographic coordinates were included in the basal area and total volume yield equation. Yield projections suggest that the system as a whole can be a useful tool for modeling growth and yield in this region of South America.

INTRODUCTION

Loblolly pine (*Pinus taeda* L.), planted extensively across its native range in the Southeastern United States, has proven to grow well as an exotic in other regions including the Misiones/Paraná areas of southern Brazil, northern Uruguay, and Argentina (fig. 1). Under intensive management, internal rates of return can range from 9 percent to 17 percent (Cubbage and others 2007). With a membership that includes cooperators managing land in this very productive area of South America, the Forest Modeling Research Cooperative (FMRC) has been working toward developing tree growth and stand development models to support intensive loblolly pine plantation management in that region. Initial work centered on testing extant dynamic component models of dominant height/site index, survival, and basal area projection equations using permanent inventory plot data from Argentina. Specifically, models from Acerbi and others (2002), Costas and others (2007), and Eisfield and others (2005) were selected because they were developed using data from southern Brazil and northern Uruguay in the Misiones/Paraná region. In addition, a set of models from the Atlantic Coastal Plain areas of the Southeastern United States were also included (Amateis and Burkhart 2017, 2018).

Residual analyses indicated no clear trends for the equations tested across all soil drainage classes and soil textures. The North American models from the Atlantic Coastal Plain generally underpredicted, with basal area and survival having a larger underprediction bias than dominant height. This underprediction bias in basal area translated through to underprediction of the total

volume yield. In summary, no specific set of component equations could be identified as significantly superior using these limited data.

Subsequently, additional data became available that encompassed areas of southern Brazil and northern Uruguay. These data augmented those from Argentina, thus significantly expanding the geographic distribution of plots in this region. They also included geographic coordinates (latitude and longitude in decimal degrees), which have been shown to be significant regressors when used to develop growth-and-yield models in North America (Russell and others 2010, 2012). The purpose of this study was to combine all available data and develop a set of model components and an integrated model system for use in the Misiones/Paraná region of South America.

METHODS

Data

Data from 921 permanent inventory plots in operational loblolly pine plantations located in the Misiones/Paraná region of Argentina, Brazil, and Uruguay (fig. 1) were available for modeling. Some plots received no mid-rotation management treatments. Others were thinned or thinned and pruned once and some received multiple thinning and/or pruning treatments. Plot variables included age (years), dominant height (m), basal area ($\text{m}^2 \text{ ha}^{-1}$), trees surviving (trees per hectare), and total volume yield ($\text{m}^3 \text{ ha}^{-1}$). The precision of all variables, including age, was to one decimal. Of those, 585 plots included geographic coordinates (latitude and longitude in decimal degrees). Most of the plots were remeasured

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Figure 1—Map showing the general location (in red) of the Misiones/Paraná region in South America.

at least once and some multiple times; autocorrelation was not taken into account in model fitting. Remeasurement intervals varied. Table 1 summarizes the combined data for all unthinned and thinned plots.

Models

Dominant height/site index—Because stand dynamic relationships are influenced strongly by site quality, a dominant height/site index equation is a central component equation of most growth-and-yield model systems. For this project, an improved dominant height/

site index equation capable of expressing the height-age relationship across a broad range of ages and growing conditions was needed. While the definition of dominant height in South America is generally expressed as the average height of the 100 trees with the greatest diameter at breast height (d.b.h., 1.37 m) per hectare, there is no standard base age used across the region. Thus, to be broadly applicable, any site index model must have the property of base-age invariance (Burkhart and Tomé 2012).

Table 1—Summary statistics across all measurements for 921 permanent plots in operational loblolly pine plantations in the Misiones/Paraná region of South America

Variable	Mean	SD	Minimum	Maximum
Age (years)	11.6	4.7	3.0	25.8
Dominant height (m)	17.4	5.1	4.2	33.9
Basal area (m ² ha ⁻¹)	30.6	11.0	6.2	81.8
Trees (per hectare)	829.5	422.0	140.0	2486.0
Total volume over bark (m ³ ha ⁻¹)	258.3	151.9	6.5	1159.1
Latitude (decimal degrees) ^a	-28.1778	0.2936	-29.0084	-27.4178
Longitude (decimal degrees) ^a	-56.1309	0.2109	-56.5492	-55.6875

SD = standard deviation.

^a585 plots had latitude and longitude data.

To model the height-age trend in these data, several base-age invariant candidate models were examined. The model developed by Bailey and Clutter (1974) and tested by Cao (1993) was found to be superior for these data:

$$HD_2 = \exp\{b_1 + (\ln(HD_1) - b_1)(A_1/A_2)^{b_2}\} \quad (1)$$

where A_1, A_2 = age (years); HD_1, HD_2 = average height (m) of the 100 thickest trees per hectare at ages A_1 and A_2 , respectively; and b_1, b_2 = parameters. By substituting a site index value, S , for HD_1 at A_1 and solving for S , equation (2) can be used to estimate site index from dominant height and age:

$$S = \exp\{b_1 + (\ln(HD) - b_1)(A/A_1)^{b_2}\} \quad (2)$$

where A_1 is index age and b_1 and b_2 are the same as in equation (1).

Basal area prediction—When basal area for an existing stand is not available or when initiating a plantation at young ages, an estimate of initial basal area is needed. Equation (3) was found to be suitable for this purpose:

$$\ln(BA) = b_0 + b_1 \ln(N) + b_2 \ln(HD) + b_3 \ln(A) + b_4 \text{ LONG} \quad (3)$$

where BA is basal area (m² ha⁻¹); N =trees per hectare; LONG =longitude expressed in decimal degrees; and b_0 - b_4 are parameters.

Basal area projection—Basal area projection equations suitable for unthinned and thinned stands for the area are required. The model of Clutter and Jones (1980),

modified with variables that account for the effects of thinning and geographic locale (equation (4)), was found to be appropriate for these data:

$$\ln(BA_2) = (HD_1/HD_2)^{b_1} (\ln(BA_1))^{(b_{21} + b_{22} \text{ THIN} + b_{23} \text{ LONG})} + b_3 (N_1^{b_4}) (1 - HD_1/HD_2)^{b_1} \quad (4)$$

where BA_1 and BA_2 are basal area (m² ha⁻¹) at time 1 and time 2, respectively; N_1 =trees per hectare at time 1; THIN =1 if the stand has been previously thinned, 0 otherwise; and b_1 - b_4 are parameters.

Survival projection—Projections of trees per hectare surviving are obtained using the baseline equation from Clutter and Jones (1980) modified with a variable that accounts for the effects of thinning. Efforts to improve the model by including geographic coordinates were not successful. Therefore, equation 5 was accepted:

$$N_2 = [N_1^{(b_{11} + b_{12} * \text{THIN})} + b_2 ((A_2/10)^{b_3}) - (A_1/10)^{b_3}]^{(1/(b_{11} + b_{12} * \text{THIN}))} \quad (5)$$

where N_1 and N_2 are trees per hectare at time A_1 and A_2 , respectively, and other variables as previously defined.

Total yield—A total volume yield outside bark model that can be viewed as a stand-level analog to the individual tree combined variable equation (Burkhart and Tomé 2012) was selected to predict total volume (m³ ha⁻¹) for all plots 5 years of age or older.

$$\text{TVob} = (b_{01} + b_{02} \text{ THIN} + b_{03} \text{ LAT}) BA^{b_1} HD^{b_2} \quad (6)$$

where TVob is total volume yield (m³ ha⁻¹) outside bark; and LAT = latitude expressed in decimal degrees. The variable THIN takes on a value of 1 for a stand previously thinned or 0 for an unthinned stand and b_{01} - b_{02} are parameters.

RESULTS

Equations 1-6 were fitted to the data and fit statistics are shown in table 2. Because equation (1) is not indexed to any specific base age, it can be used with equation (2) to determine dominant height/site index for any specified base age. For the basal area prediction and projection equations, including geographic coordinates reduced the mean squared error (MSE) only minimally. However, including geographic coordinates in the total volume yield equation reduced MSE considerably. Including a switch for thinned or unthinned stands was significant for the basal area projection model, the survival projection model, and the total volume yield model.

The fitted equations were compiled into a dynamically linked library and installed into the FMRC's growth-and-yield software shell for projection. Three hundred and three unthinned plots and 442 thinned plots with initial age of at least 5.0 years were projected to each remeasurement age where the projected dominant

height, basal area, and total volume yield outside bark were compared to the observed values. Percent residuals [(observed – predicted)/observed*100] for these variables are shown in table 3 and figures 2 and 3.

DISCUSSION

The set of models presented here can be used for predicting and projecting stand characteristics for managed loblolly pine plantations growing in the Misiones/Paraná area of South America. Loblolly pine growth in this region slows during the winter months but never enters a true dormant season. Therefore, it is important to specify stand age to tenths of a year. Due to a lack of individual tree data for these plots it was not possible to directly extend these stand-level component equations and obtain diameter class or merchantable yields for these plots.

Because equation (1) is not indexed to any specific base age, it can be used with equation (2) to determine

Table 2—Fit statistics for equations 1-6 applied to data from 921 permanent plots in operational loblolly pine plantations in the Misiones/Paraná region of South America using all observations and only observations with geographic coordinates

Equations	All plot observations		Observations with geographic coordinates		
	<i>n</i>	MSE	<i>n</i>	MSE with geographic coordinates	MSE without geographic coordinates
1 and 2	1926	0.9733			
3	2804	0.0166	2007	0.0126	0.0133
4	1260	0.00357	802	0.0033	0.0034
5	1223	1043.7			
6	2679	95.01	1949	43.53	55.1

n = number of observations, some plots were measured multiple times; MSE = mean squared error.

Table 3—Summary statistics for mean percent residuals [(observed-predicted)/observed*100] for dominant height, basal area, and total volume yield outside bark of 442 thinned and 303 unthinned plots following projection from plot establishment to subsequent remeasurement ages

Variable	Unthinned				Thinned			
	Mean	SD	Minimum	Maximum	Mean	SD	Minimum	Maximum
HD	-0.3	6.4	-18.1	20.9	-0.3	3.4	-29.9	10.5
BA	-4.3	14.0	-64.2	22.0	-1.3	13.4	-55.2	26.8
TVob	-7.3	19.5	-58.1	29.0	-1.5	15.4	-61.7	31.2

SD = standard deviation, HD = average height (m) of 100 thickest trees by diameter at breast height (cm) per hectare, BA = basal area (m² ha⁻¹), TVob = total volume outside bark (m³ ha⁻¹).

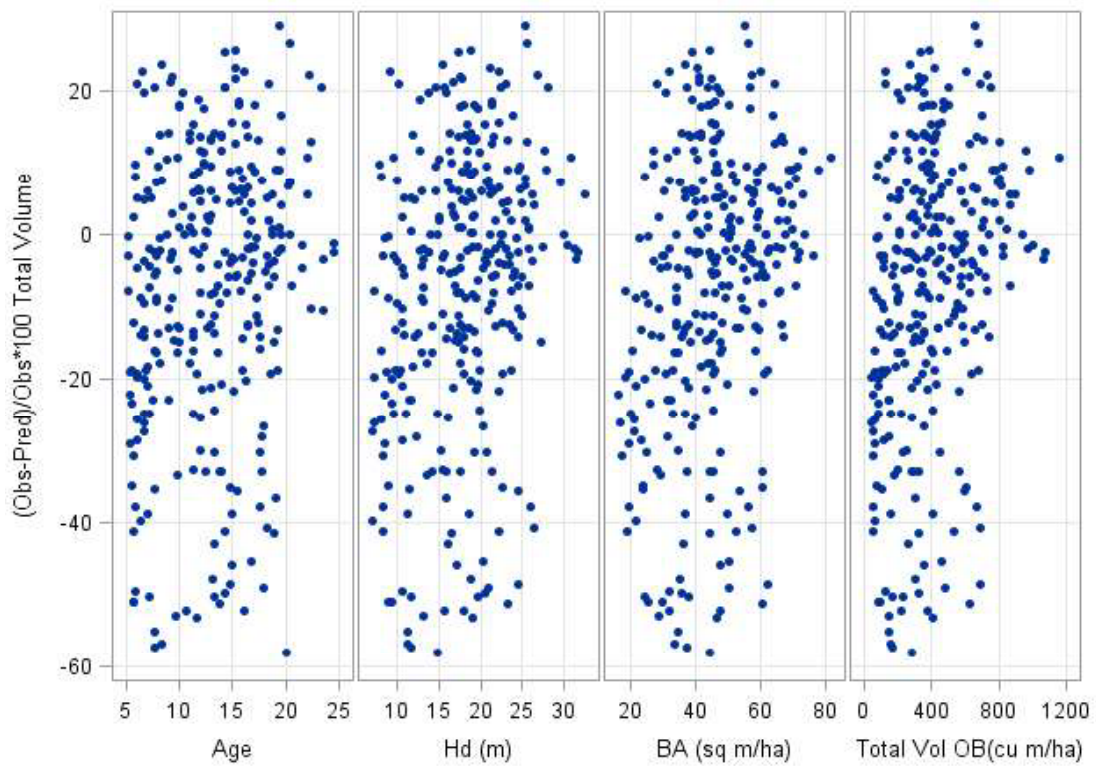


Figure 2—Percent residuals of total volume yield outside bark (observed – predicted)/observed*100 for 303 unthinned plot observations in the Misiones/Paraná region of South America.

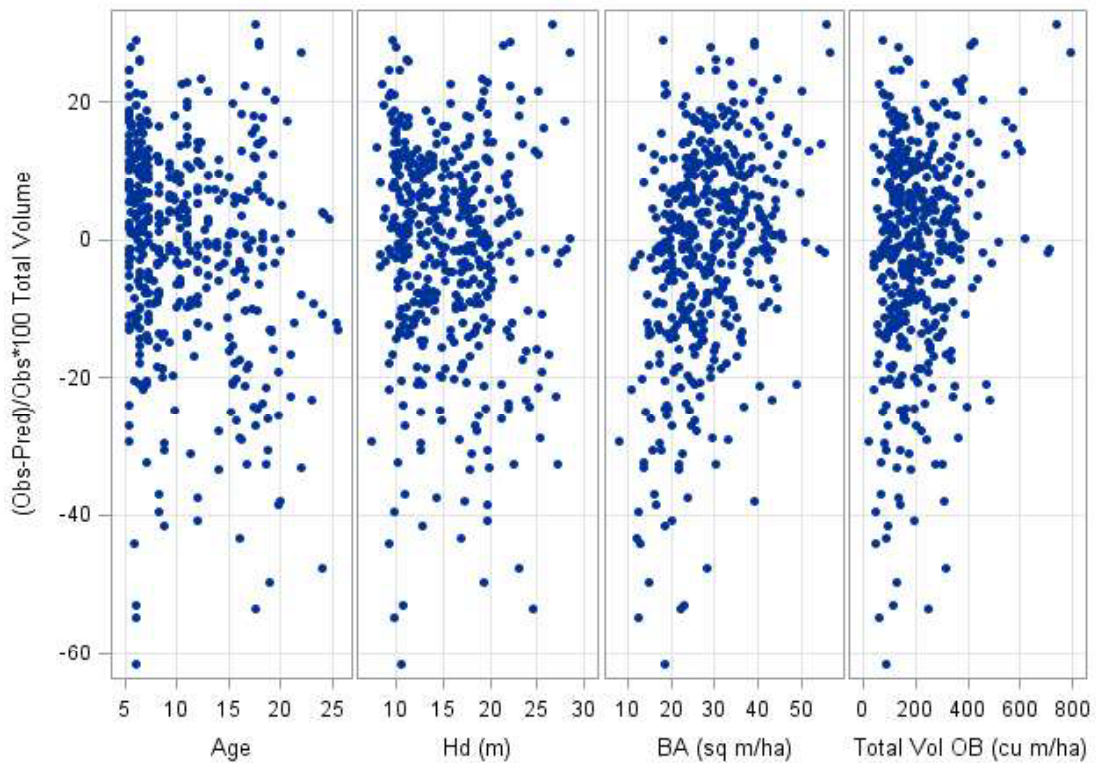


Figure 3—Percent residuals of total volume yield outside bark (observed – predicted)/observed*100 for 442 thinned plot observations in the Misiones/Paraná region of South America.

site index at any desired base age from a given height-age pair. This is desirable because there are several commonly used base ages for this particular region.

When predicting and projecting basal area and total volume yield, including geographic coordinates in equations (3), (4), and (6) significantly reduced the MSE over the same equations fitted without including geographic coordinates. The use of geographic coordinates improves predictions for specific locales within a large region such as the Misiones/Paraná just as it does within the natural loblolly pine growing area of North America.

Thinning type and intensity in terms of basal area per hectare or trees per hectare removed was not available for these plots. Therefore, the effects of thinning were incorporated into equations (3), (4), and (6) by including a parameter to “switch” from unthinned to thinned stands. No attempt was made to distinguish between the effects of first and subsequent thinnings on these plots. Therefore, when implementing thinnings during stand projection or when starting projections with a previously thinned stand, the thinning parameter should be set to 1.

Pruning selected crop trees at time of thinning is a common silvicultural practice in this region. Since no information was available on the number of trees pruned or the intensity of pruning, it was not feasible to include the effects of pruning in this study. However, results from a pruning study established in North America suggest that removing up to one-half the live crown in young loblolly pine plantations has minimal effect on subsequent height and diameter growth (Amateis and Burkhart 2011). Therefore, the pruned and thinned plots were combined with the thinned only plots for this study.

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