Green and Dry-Weight Equations for Above-ground Components of Planted Loblolly Pine Trees in the West Gulf Region[1]

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*ABSTRACT. Prediction equations based on 130 sample trees from thinned and unthinned loblolly pine (*Pinus taeda L.*) plantations in central Louisiana are presented for the green and dry weights of aboveground tree components. Sample trees ranged from 2 to 21 in. dbh, 18 to 94 ft in height and from 9 to 55 yr in age. Significant differences in partial stem weight between trees from thinned and unthinned stands required development of separate sets of weight ratio equations. The range of the studies' observations increases the predictive applicability of planted loblolly pine biomass equations.*

South. J. Appl. For. 11(4):212–218.

Loblolly pine is the most important commercial softwood species in the South and the most widely planted southern pine. This importance created a need to develop a growth and yield prediction system for loblolly pine plantations in the West Gulf region.[2] It also led to creating new stem profile functions and new volume equations for trees from thinned and unthinned stands. These equations are being published separately.[3] Furthermore, given recent technological advances that make utilization of all tree components feasible and profitable, it was also advisable to develop equations to predict yields of branch and foliage material from these plantations. Weight is the best measure of yield for these nonbole components, and this measure is becoming increasingly popular for bole products, too. Hence, new weight equations were developed to meet this need.

This paper presents equations that predict green and dry weight of boles (ib or ob) to any top diameter limit, branches (ib or ob), or foliage of loblolly pine trees in thinned or unthinned plantations in the West Gulf region. Examples of how to apply the equations are also given.

New weight equations were needed because most existing plantation loblolly pine weight equations were inadequate. Many were developed from trees sampled in the Southeast (e.g., Bailey et al. 1985, Edwards and McNab 1979, Flowers 1978). Their applicability in the West Gulf region is questionable. Clark (1983) has shown that site and geographic differences in tree biomass are significant within a species and that "... biomass estimates for marketing purposes should be made using only locally developed or locally tested species equations... " In this same paper Clark also pointed out that natural pine biomass equations might give acceptable green-weight predictions in plantations, but dry-weight predictions would not be applicable. Thus, the natural loblolly pine equations developed by Matney (1977) or Lenhart et al. (1980) would not be adequate in West Gulf plantations. Furthermore, the plantation loblolly pine biomass equations developed by Hicks et al. (1972) and Hyink et al (1972) only predict bole weights And the Nelson and Switzer (1975) and Shelton et al. (1984) equations may only be accurate when used to predict tree component weights in relatively young unthinned plantations. The Gibson et al. (1985) unthinned plantations biomass equations have somewhat limited application because their loblolly pine data set did not contain planting spacing or age variability.

In all of the studies mentioned above, data were not available for plantation grown trees over 35 yr old, for diameter at breast height (D) generally over 14 in. (there were only 3 trees with D greater than 14 in sample), and total height (H) greater than 75 ft (2 taller trees had been sampled). Furthermore, no publicly available equations have been developed heretofore to predict biomass of tree components in thinned West Gulf loblolly pine plantations.

DATA

Weight data for this study came from 130 felled sample trees. The main sampling objectives were to select trees from both thinned and unthinned study plots or plantations to cover as wide a range as possible of diameters, heights, live crown ratios, and ages. Variability of stand site quality and density was also sought. Within each diameter class, trees were purposely chosen to represent a range of live crown ratios as well as of heights Overall, crown ratio (CR) ranged

[1] Funding for this project was provided through the Southeastern Regional Biomass Energy Program (SERBEP), which is administered by the Tennessee Valley Authority for the U.S. Department of Energy.

[2] Baldwin, V. C., Jr. and D. P. Feduccia. 1987. Loblolly pine growth and yield prediction in West Gulf region plantations. Res. Pap. SO-236. 27 p.

[3] Baldwin, V. C., Jr.; Feduccia, D. P. Tree-volume and stem-profile functions for unthinned and thinned plantation grown loblolly pines in the West Gulf region. In review.

from 13 to 78%. Age from planting (A) ranged from 9 to 55 yr and site indices[4] (base age 25) (SI) of the stands from which the trees were taken ranged from 48 to 76 ft. Study plot or plantation densities, at the time of sample tree removal, (TS), ranged from 13 to 1133 stems/ac and from 23 to 200 ft^2 of basal area per acre (BA). Table 1 presents the distributions of the thinned and unthinned stand sample trees by diameter and height classes.

Most of the trees came from within plots being used for growth studies. The others were felled in managed national forest plantations. None of the trees was fork-stemmed, broken-topped, or noticeably diseased. The 12 plantations sampled were located in Beauregard, Grant, Rapides, and Vernon parishes of Central Louisiana.

Sample tree measurement procedures were as follows. Crown class (CC) and diameter outside bark (dob) at heights of 0.5, 2.0, and 4.5 ft were recorded before a sample tree was felled. After felling, 6 live sample branches were selected from along the bole: 2 from the lower 1/3 of the crown, 2 from the middle 1/3 and 2 from the top 1/3. Before any branches were cut from the bole, the height to base of the full live crown (HBLC), dob at base of the full live crown (DBLC), H, height to each sample branch, and dob at each sample branch were measured and recorded.

The 6 sample branches were cut from the bole and their length, diameter, and total green weight with foliage were determined and recorded. The branches were then reweighed each time after their foliage, and consecutively larger portions at 1-in. dob intervals, were removed. Samples of foliage and branches from each 1 in. size class were sealed in polyethylene bags and kept in cold storage until laboratory analyses.

After the six sample branches were weighed, the remaining live branches were cut from the bole

[4] Site indices were predicted from an equation developed by the authors (footnote a).

Table 1. Distribution of sample trees from thinned and unthinned plantations by dbh and total tree height class for West Gulf region loblolly pines.

Dbh	Total height by 10-ft class								
Class	20	30	40	50	60	70	80	90	Totals
2	(1)*								(1)
3	(2)	1	1						2 (2)
4	(1)	1 (2)	2 (1)						3 (4)
5		(1)	1	3 (1)	(1)				4 (3)
6		(2)	2	1 (1)	1 (1)	1			5 (4)
7			(1)	3	5 (1)	(1)			8 (3)
8			(1)	2	5 (2)	2 (1)			9 (4)
9				1	5 (1)	3 (3)	1		10 (4)
10					3	4 (2)			7 (2)
11					4 (1)	5 (1)	2		11 (2)
12						3	4 (2)		7 (2)
13						3	1 (2)		4 (2)
14						2	1 (3)	1	4 (3)
15					1	2	(1)	1	4 (1)
16							2 (1)	1	3 (1)
17								3 (1)	3 (1)
18								2	2
19							1	1	2
20								2	2
21								1	1
Totals	(4)	2 (5)	6 (3)	10 (2)	24 (7)	25 (8)	12 (9)	12 (1)	91 (39)

* Numbers within parentheses are number of trees from unthinned plantations.

and weighed (total combined weight, not individual branches) following the same procedure used for sample branches, except foliage and branches ≤1-in. dob were removed and weighed together rather than separately. Dead branches were also removed and their combined weight recorded.

After all branch measurements were completed, the bole was measured, sectioned, and weighed. Bucking points were marked at 2-ft, 4.5 ft, and every 5-ft interval thereafter. The height and outside-bark diameter were recorded for each point and at the base of the full live crown. Some variability in all the bucking points was necessary to allow for extreme or irregular bole taper or lateral branch swells. After each bolt was weighed, a 1- to 2-in. disk was cut off the bottom end, labeled with the tree and bolt or disk number, sealed in double-thick plastic bags, and kept in cold storage until laboratory analyses.

In the laboratory, the inside-bark diameters of the stem disks were measured. Green volume, specific gravity, and both green and oven-dry weights were determined for stemwood, stembark, branchwood, and branchbark samples. Green and oven-dry weights were determined for foliage samples based on ratio estimates derived from the appropriate sample branch component weights. All samples were dried in a forced-air oven at 105°C until weight loss was completed.

ANALYSIS OF DATA

The tree weight data were fitted to selected linear and nonlinear model forms. Various combinations of possible predictor variables D, H, A, CR, BA, TS, and DBLC were tried in the models. Statistical Analysis System (SAS Institute 1982) REG and NLIN procedures were used. The resulting equations were evaluated on basis of standard fit statistics, detailed analytical and graphical examinations of the residuals, and anticipated usefulness to forest managers.

Separate sets of coefficients were determined for components of trees from thinned stands, components of trees from unthinned stands, and for the combined data. Then an Analysis of Covariance technique, Freese (1964) for linear models and Milliken (1982) for nonlinear models, was employed to test the null hypothesis that one overall equation (combined data from thinned and unthinned stands) would suffice in place of the alternative hypothesis that separate equations for trees from unthinned stands and for trees from thinned stands would provide better predictions. All decisions in this testing procedure were based on a statistical significance level of $\alpha = 0.05$.

The relatively small sample size restricted validation attempts to a graphical comparison of these equations with similar equations published for other regions. But the results of this comparison are presented and briefly discussed.

RESULTS AND DISCUSSION

Total Bole Weights

A modified Schumacher and Hall (1933) model form was chosen to predict green and dry weight of the bole:

$$W = b_1 D^{b_2} H^{b_3} P^{b_4} \qquad (1)$$

where

W = predicted weight (lb),
D = diameter (ob) (in.) at height 4.5 ft above groundline,
H = total height (ft)
P = any other predictor variable or function specified, and
b_1, b_2, b_3, b_4 = coefficients estimated from the data.

Model 1 was converted to a linear form by logarithmic transformation, and the data were fit to the transformed model:

$$\ln (W) = \ln (b_1)' + b_2 \ln (D) + b_3 \ln (H) + b_4 \ln (P) = b_1' + b_2 \ln (D) + b_3 \ln (H) + b_4 \ln (P). \qquad (2)$$

Utilization of the model in this form easily solved the problem of nonhomogeneous variance in the data, although an adjustment in b_1', to compensate for the small bias that is introduced when transforming $\ln (W)$ back to W, was required (Baskerville 1972).

Bole weight data for 91 trees from thinned stands and 39 trees from unthinned stands were fit to model 2. The overall analysis of covariance test of the residual sums of squares of one combined regression versus separate regressions indicated that separate equations were not statistically justified as long as any one, or a combination of A, DBLC, CR, BA, or TS was included as predictors in addition to D and H to account for the thinning treatment effect on total bole weight. If only D, or D and H were included, as is usually the case, separate equations to predict total bole green weight of trees from unthinned and thinned stands would have been advisable. The simple function $P = EXP(A^2)$ was selected as the additional term to be included in model 2, even though inclusion of DBLC in the model resulted in the greatest decrease in the equation mean square error, because A is usually known for planted stands. DBLC is seldom measured operationally. Thus the final model form was:

$$\ln (W) = b_1' + b_2 \ln (D) + b_3 \ln (H) + b_4 A^2. \qquad (3)$$

Table 2 provides coefficients for use with model 3 for weight prediction of total boles from a 6-in. stump to the tips of trees from thinned or unthinned plantations.

Partial Bole Weights

Bole weights from the stump to any top diameter limit may be predicted from total bole weight and weight ratio equations. Ratio equations predict the proportion of total stem weight below a given upper-stem diameter limit. The model selected was developed by Van Deusen et al. (1981) and modified by Parresol (1983):

$$R = EXP\,[b_1\,(d^{b_2}/D^{b_3})] \qquad (4)$$

where

R = estimated ratio of partial to total weight (lb),
d = upper-stem diameter limit (in),
EXP = exponential function, and
b_1, b_2, b_3 = coefficients estimated from the data.

In this case nonlinear regression methods were used to fit the data to model 4. Again, three sets of equations were developed based on tree bole data from unthinned stands, thinned stands, and the combined data. The test results were highly significant in this case for both ib and ob ratios of either green or dry bole weights.

Because the resulting separate-treatment equations always predicted higher ratios for trees from thinned stands than from the same sized trees (e.g., equal d and D) from unthinned stands, it was surmised that the main effect of thinning on the tree bole was due to the changes in stem form that occur when stands are thinned (Smith 1962). Meng (1981) summarized results of others regarding stem form change after thinning or fertilization and presented a method to statistically verify this change. The results of Baldwin and Feduccia[5] also veri-

[5] Ibid.

Table 2. Regression Coefficients for total bole weight equations.[1]

Dependent variable[2]	Parameter estimates				Statistics		
	b_1'	b_2	b_3	b_4	FI	SE	CV
BGWob	−2.06033	1.93926	1.05077	0.000061	0.99	153.4	11.4
BGWib	−2.53232	1.96524	1.12691	0.000060	0.99	152.9	12.4
BDWob	−3.31353	1.91029	1.19118	0.000076	0.99	70.1	10 5
BDWib	−4.20913	1.87667	1.38064	0.000088	0.99	69.0	11.8

[1] The model is:

$$\ln(W) = b_1' + b_2\ln(D) + b_3\ln(H) + b_4A^2$$

where:

W = predicted bole weight (lb) from a 6-in. stump to the bole tip,
D = diameter outside bark (in.) at 4.5 ft
H = total tree height (ft)
A = age from planting, and
b_1', b_2, b_3, b_4 = coefficients estimated from the data.

[2] *BGWob* = bole green weight outside bark,
BGWib = bole green weight inside bark,
BDWob = bole dry weight outside bark,
BDWib = bole dry weight inside bark.

[3] Fit Index (FI) = $\{1 - [\Sigma(Y_i - \hat{Y}_i)^2]/[\Sigma(Y_i - \bar{Y}_i)^2]\}$,
SE = Standard error of the estimate in original units,
CV = Coefficient of variation in percent.

fied this thinning response. They found the thinning effect on tree boles is a stem form change resulting in more taper in the lower bole and relatively less upper-stem taper in trees within thinned stands as compared to the same size trees (equal D and H) in unthinned stands.

An attempt was made to find a measured variable that, when added to model 4, would account for the treatment effect. Only *DBLC* came close as a strong contender, but it was not a strong enough predictor to allow one combined treatment regression to account for all the treatment differences. Therefore, the most practical option was chosen—to keep separate ratio equations for thinned and unthinned stands.

The unthinned stand equations are used in predicting tree component weights in unthinned plantations of any age. They should also be used for predictions in thinned plantations for up to 5 yr after the first commercial thinning. In all other cases the thinned stand equations should be applied. Table 3 provides the separate coefficients for application of model 4 to predict bole weight ratios of trees from either thinned or unthinned stands according to these rules.

These decision rules were adopted because all thinned stands, from which samples were drawn, had been commercially thinned at least 5 yr previously and were at least 20 yr old. Many had been thinned repeatedly at 5-yr intervals for 15 yr or more (4 or more thinnings).

Crown Weights

Weight data for the crowns (lateral branches and foliage) were fit to model 2. For these components the variable A was not significant in any of the regressions. Of the other predictor variables tried (*DBLC, CR, BA, TS*), only *DBLC* significantly improved the weight prediction of the crown components. However, the *DBLC* influence was not strong enough to cause rejection of the hypothesis that one pooled data equation for trees from either thinned or unthinned stands was satisfactory. Even though the addition of *DBLC* was significant statistically in the combined regression for each component, the improvement in weight prediction was negligible, considering the inherent variability in the weight of crown components. Therefore, given these facts, and the difficulty of measuring *DBLC* accurately in practice, the variable was dropped and the final combined data regressions were of the form:

$$\ln(W) = b_1' + b_2 \ln(D) + b_3 \ln(H). \quad (5)$$

The crown weight component coefficients for model 5 are given in Table 4. These equations can be used to predict green or dry weight of the tree crown components in thinned or unthinned plantations.

Table 3. Regression coefficients for weight ratio equations.[1]

Dependent variable[2]	Parameter estimates b_1	b_2	b_3	Statistics[3] FI	SE
		Unthinned Stands			
PGWob/BGWob	−1.153726	4.911545	4.723876	0.97	0.050
PGWib/BGWib	−1.171351	4.957184	4.772917	0.97	0.055
PDWob/BDWob	−0.842507	5.128205	4.854891	0.97	0.060
PDWib/BDWib	−0.932732	5.101845	4.857451	0.96	0.059
		Thinned Stands			
PGWob/BGWob	−2.058914	5.124867	5.170415	0.97	0.050
PGWib/BGWib	−2.075039	5.171997	5.218171	0.97	0.056
PDWob/BDWob	−1.875204	5.346034	5.397755	0.96	0.060
PDWib/BDWib	−2.020278	5.367307	5.436636	0.97	0.057

[1] The ratio model is:

$$R = \exp[b_1(d^{b_2}/D^{b_3})]$$

where:

R = predicted ratio of partial to total weight (lb)
d = upper bole diameter limit (in., ib for ib ratios, ob for ob ratios),
D = diameter ob (in. at 4.5 ft), and
b_1, b_2, b_3 = coefficients estimated from the data.

[2] *PGWob* = partial bole green weight outside bark,
BGWob = bole green weight outside bark,
PGWib = partial bole green weight inside bark,
BGWib = bole green weight inside bark,
PDWob = partial bole dry weight outside bark,
BDWob = bole dry weight outside bark,
PDWib = partial bole dry weight inside bark,
BDWib = bole dry weight inside bark.

[3] Fit Index (FI) = $\{1 - [\Sigma(Y_i - \hat{Y}_i)^2]/[\Sigma(Y_i - \bar{Y}_i)^2]\}$,
SE = Standard error of the estimate in original units

Table 4. Regression coefficients for crown green and dry weight equations.[1]

Dependent variable[2]	Parameter estimates b_1	b_2	b_3	Statistics[3] FI	SE	CV
		Thinned or unthinned stands				
CGWW	1.735217	3.492293	−1.243386	0.90	61.5	41.2
CDWW	0.379049	3.454388	−1.088445	0.90	28.5	41.3
CGWB	1.203148	3.023912	−1.136030	0.85	14.6	36.9
CDWB	0.264828	3.033934	−1.109824	0.86	6.9	38.2
CGWF	3.652443	2.864732	−1.454774	0.86	25.1	32.4
CDWF	2.796233	2.912819	−1.474651	0.85	11.4	33.5

[1] The model is:

$$\ln(W) = b_1' + b_2\ln(D) + b_3\ln(H)$$

where:

W = predicted weight (lb) of crown component,
D = bole diameter outside bark (in.) at 4.5 ft,
H = total tree height (ft), and
b_1', b_2, b_3 = coefficients estimated from the data.

[2] *CGWW* = crown green weight of wood,
CDWW = crown dry weight of wood,
CGWB = crown green weight of bark,
CDWB = crown dry weight of bark,
CGWF = crown green weight of foliage,
CDWF = crown dry weight of foliage.

[3] Fit Index (FI) = $\{1 - [\Sigma(Y_i - \hat{Y}_i)^2]/[\Sigma(Y_i - \bar{Y}_i)^2]\}$,
SE = Standard error of the estimate in original units,
CV = Coefficient of variation in percent.

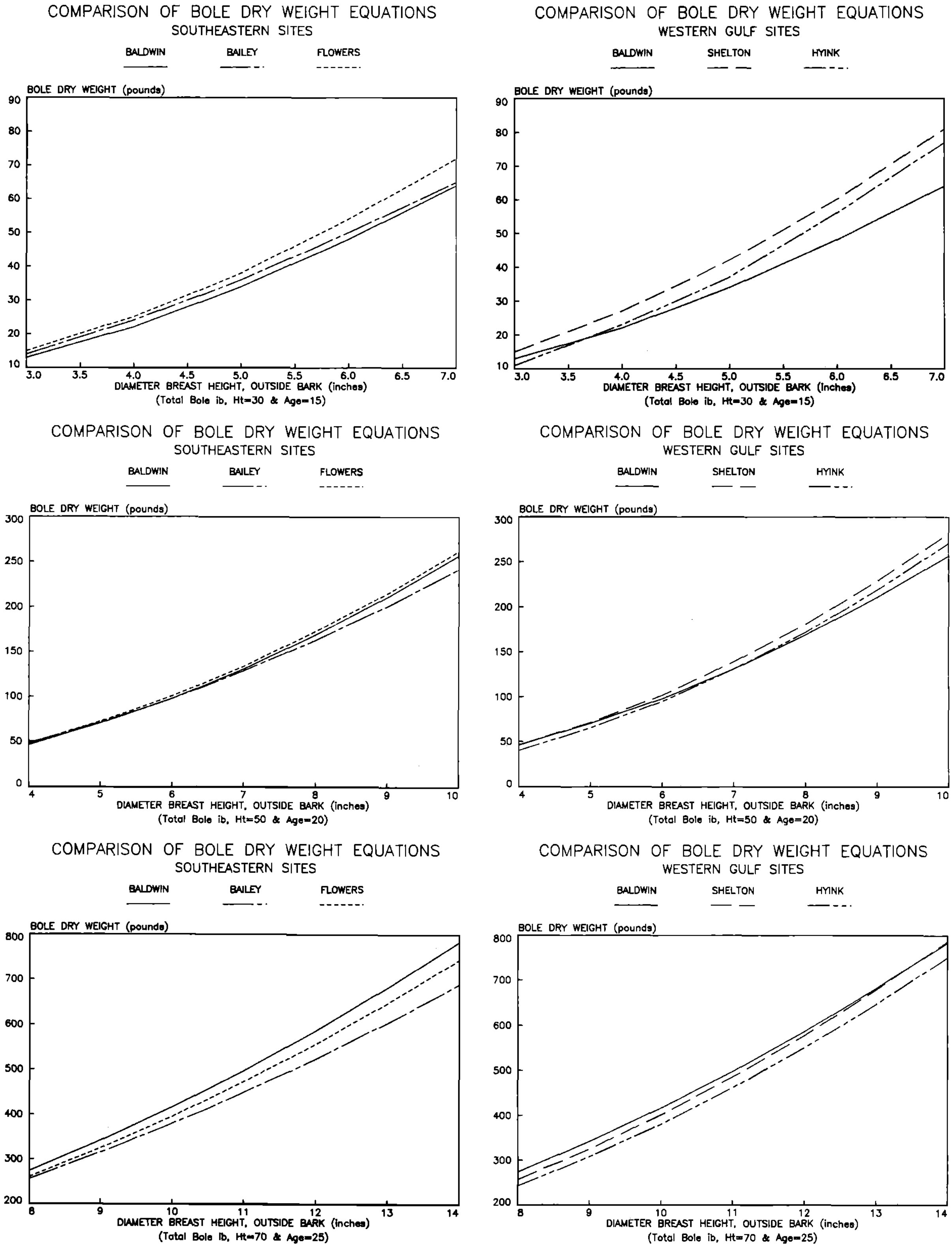

Figure 1. Comparison of total bole-wood dry-weight predictions for the new West Gulf equations, two Southeast Area equations, and two other West Gulf equations.

Comparisons with Other Equations

As explained in the introduction, several other loblolly pine plantation tree component weight prediction equations have been developed, but they may not be widely applicable in the Western Gulf Region for various reasons. Some kind of comparison between these and those developed in this study seemed in order. Only a graphical comparison was possible because different model forms

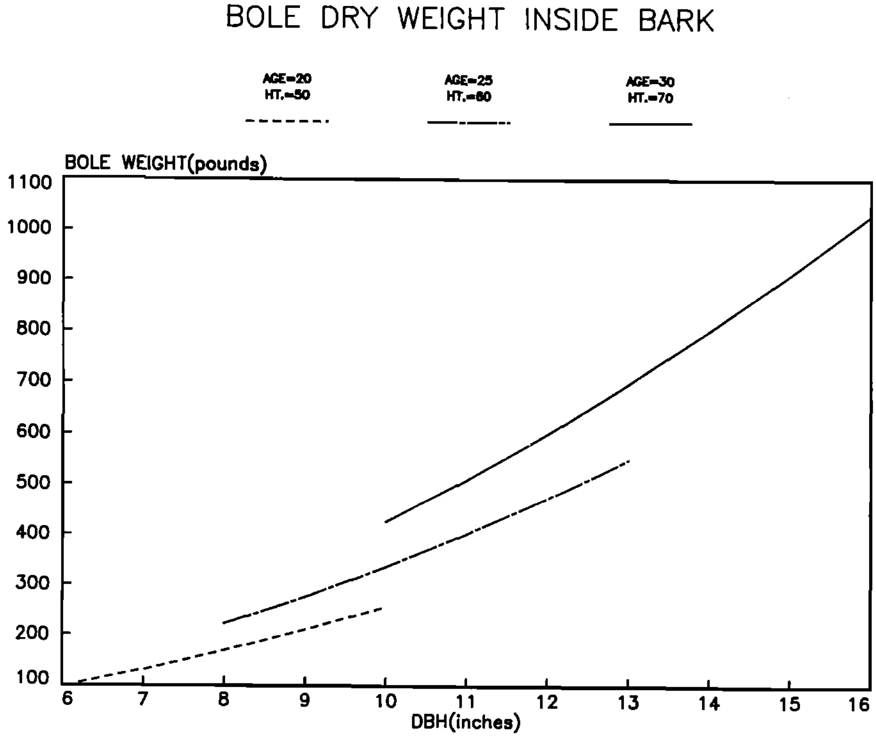

Figure 2. New West Gulf equation prediction for total bole inside bark dry weight, showing the influence of age from planting and of total tree height on the weight estimates.

were used and no other data were available. Dry weight of total bole wood was the only universally predicted tree component in the following representative studies: Bailey et al. (1985), Flowers (1978), Hyink et al. (1972), and Shelton et al. (1984). Their predictions of dry bole-wood weight, and the predictions made from the equations in this paper are compared graphically in Figure 1 for the specific inputs of D, H, and A given. The southeastern states equations are compared with the new West Gulf equations in one series, and the West Gulf equations are compared with the new West Gulf equations in the other series. The measurement values were chosen to fall within the range of data used in the development of all the equations to make the comparisons as reasonable as possible, given that other possible sources of variation, such as laboratory procedure differences, were unknown.

The results show the relative magnitude of differences in prediction that may be expected through use of any of these equations in stands having the characteristics specified. The maximum percentage difference in either region occurred between the new West Gulf equation and the Shelton et al. equation when predicting dry bole weight of small younger trees. At $D = 7$ the new equation prediction was 21% less than the Shelton et al. prediction (a 17-lb difference). The largest actual weight difference was in older stands—a 95-lb greater difference at $D = 14$ in. between the new West Gulf equation prediction and the Bailey et al. prediction. This was a 12% difference.

Figure 2 illustrates how age, total height, and diameter relate to total dry wood weight. Note at $D = 10$ in. that, depending on the A, H combinations, there can be as much as 200 lb difference in predicted weight. This clearly shows that, even though diameter alone accounts for most of the variation in bole weight, the influence of A and H can be highly significant.

The comparisons illustrated in Figure 1 were done within the A, H, and D range of all the data sets compared. As mentioned earlier, the data for the new West Gulf equations was much more extensive, especially in terms of age and tree size. The new West Gulf equation predictions should be more accurate at the large diameters, ages, and heights because 25% of the trees sampled were in diameter classes 13 in. and larger and height classes 70 ft and larger. And 19 (15%) of the trees were at least 25 yr old (13 were 55 yr old).

EXAMPLES

The following examples illustrate use of the equation coefficients presented above.

Suppose one wants to estimate the total tree green-weight, total weight of the bole wood and bark, and the weight of the bole wood and bark to a top diameter (ob) of 4 in. of a loblolly pine tree in a 25-yr old plantation thinned once at age 18. The tree has a dbh of 10 in. and total height of 70 ft.

The total green-weight of the bole is predicted using the equation and coefficients from Table 2:

$$
\begin{aligned}
BGWob &= EXP\,[b'_1 + b_2 \ln (D) + b_3 \ln (H) + b_4 A^2] \\
&= EXP\,[-2.06033 + 1.93926 \ln (10) + 1.05077 \ln (70) + .000061\,(25)^2] \\
&= EXP\,[-2.06033 + 4.46531 + 4.46531 + 4.46419 + .038125] \\
&= EXP\,[6.907298] = 1000 \text{ lb}
\end{aligned}
$$

The ratio of partial to total green-weight of the bole, R is estimated using thinned stand coefficients from Table 3:

$$
\begin{aligned}
R &= EXP\,[b_1\,(d^{b_2}/D^{b_3})] \\
&= EXP\,[-2.058914\,(4^{5.124867}/10^{5.170415})] \\
&= EXP\,[-2.058914\,(1218/148{,}052)] \\
&= EXP\,[-.01694] = .9832.
\end{aligned}
$$

The partial green-weight ($PGWob$) of wood and bark to a 4-in. ob top is then obtained by multiplying R times the total green weight of the bole:

$$
\begin{aligned}
PGWob &= R \times BGWob = .9832\,(1000) \\
&= 983 \text{ lb.}
\end{aligned}
$$

The crown green-weight is estimated by using the coefficients in Table 4 to obtain the green weight of the branch wood ($CGWW$), branch bark (*CGWB*) and foliage (*CGWF*):

$$CGWW = EXP\,[b'_1 + b_2\ln(D) + b_3\ln(H)]$$
$$= EXP\,[1.735217 + 3.492293\ln(10) - 1.243386\ln(70)]$$
$$= EXP\,[1.735217 + 8.041302 - 5.282520] = EXP\,[4.493999] = 89 \text{ lb},$$

$$CGWB = EXP\,[1.203148 + 3.023912\ln(10) - 1.136030\ln(70)]$$
$$= EXP\,[1.203148 + 6.962815 - 4.826418] = EXP\,[3.339545] = 28 \text{ lb}$$

$$CGWF = EXP\,[3.652443 + 2.864732\ln(10) - 1.454774\ln(70)]$$
$$= EXP\,[3.652443 + 6.596289 - 6.180600] = EXP\,[4.068131] = 58 \text{ lb}.$$

Therefore, the total tree green weight (*TTGW*) is the sum of the green weights of the bole and crown components:

$$TTGW = BGWob + CGWW + CGWB + CGWF$$
$$= 1000 + 89 + 28 + 58$$
$$= 1175 \text{ lb}.$$ □

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