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DO DIFFERENT YOUNG PLANTATION-GROWN SPECIES REQUIRE DIFFERENT BIOMASS MODELS?

Bryce E. Schlaegel and Harvey E. Kennedy, Jr.

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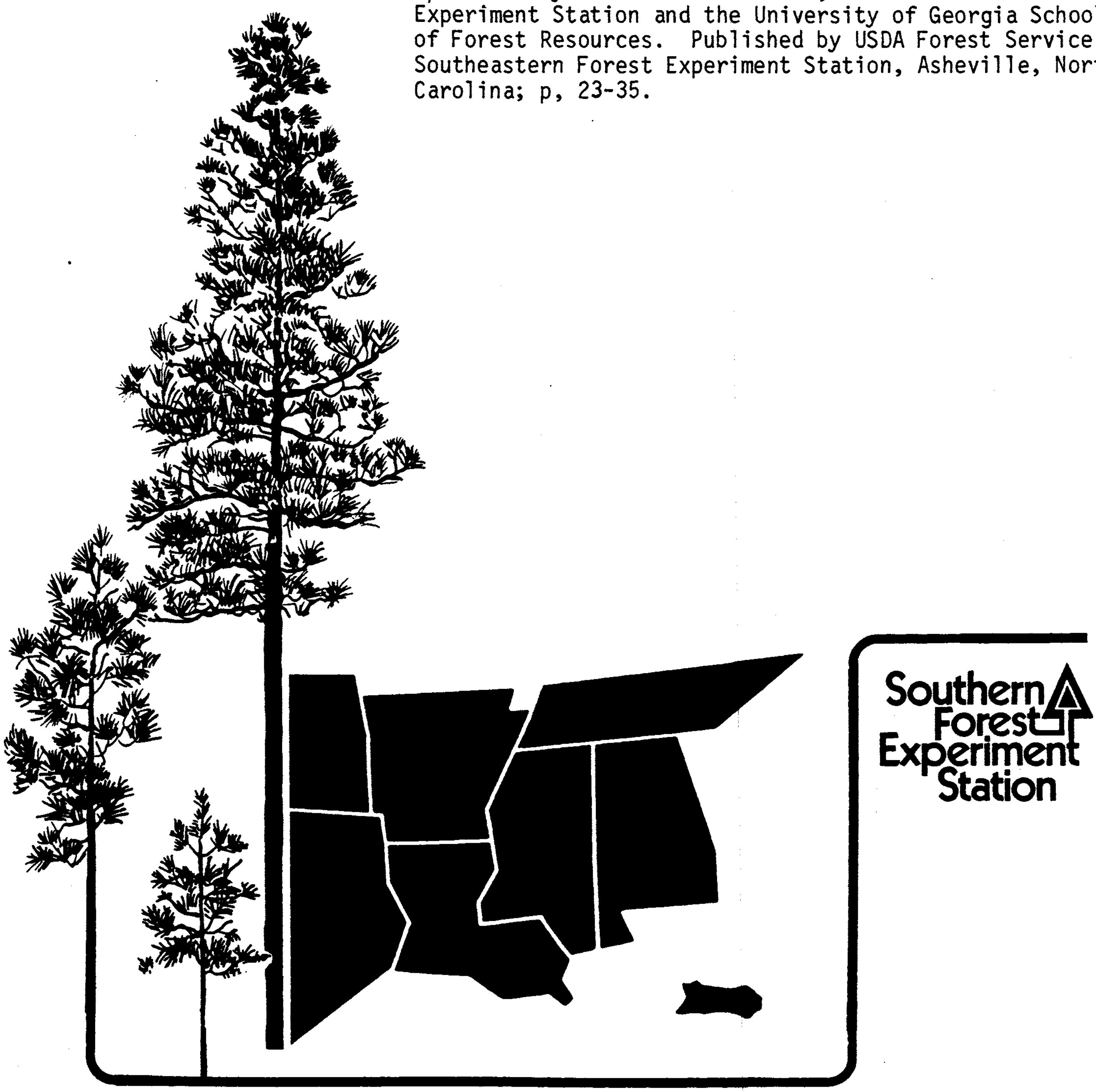

DO DIFFERENT YOUNG PLANTATION-GROWN SPECIES REQUIRE DIFFERENT BIOMASS MODELS?[1]

Bryce E. Schlaegel and Harvey E. Kennedy, Jr.[2]

Abstract.--Sweetgum and water oak trees sampled from a plantation over 7 years were used to test whether primary tree component (bole wood, bole bark, limb wood, limb bark, and leaves) predictions could be summed to estimate total bole, total limb, and total tree values. Estimations by summing primary component predictions were not significantly different from predictions for the totals, but prediction variances were increased for sweetgum and reduced for water oak.

INTRODUCTION

When developing equations to predict tree biomass, the question of which independent variables to include in the prediction equation frequently arises. The allometric model $Ln(Y) = b_0 + b_1 Ln(D^2H)$ has proven to be a simple but accurate estimator for predicting bole volumes and weights for many tree species across a broad range of size classes. This model is useful since it uses an <u>index</u> of bole volume (D^2H) as a <u>predictor</u> of bole <u>volume</u>. Since bole volume and weight are highly correlated, D^2H is also a good predictor of bole weight.

If dbh (D) and either total height (H) or merchantable height (MH) are the only variables available for predicting tree volume or weight, then the choice of predictors to include in the model is limited to these two variables and their transformations. For trees grown in natural stands or in plantations of a single spacing, these variables are adequate for predicting tree boles; R^2 of 0.97 to 0.99 are common and associated standard errors are relatively small. But predictions of tree crowns using these variables alone are usually much less precise. This has caused little problem since the bole is usually the primary variable of interest and usually comprises the primary portion of the tree. In young natural stands or in plantations, competition strongly influences the proportion of crown and bole form, thereby making tree age an important tree volume or weight predictor.

It is a common practice for researchers developing biomass equations to use the same model form to predict primary tree components. Thus bole wood, bole bark, limb wood, limb bark, leaves, and the component totals are predicted using the same model form, such as the allometric model. One reason for this is to be sure all the prediction components can be added if linear models are used to predict an untransformed dependent variable (Kozak 1970). Also, a major effort is required to develop separate models to predict each component, with no assurance the additional effort will result in increased prediction reliability.

Additional questions of model form arise when several species with quite different growth characteristics occur in a plantation and tree component predictions are needed for each species. Are separate model forms required to accurately predict each component? If separate models are used, can the component predictions be added to give reliable estimates? Are separate model forms required for each species? The purpose of this paper is to answer these three questions using hardwood plantation data for testing.

THE DATA

The data are from a 7-year-old hardwood plantation growing in a minor stream bottom in southeastern Arkansas, approximately 10 miles

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[2] Bryce E. Schlaegel is Principal Mensurationist and Harvey E. Kennedy, Jr., is Principal Silviculturist at the Southern Hardwoods Laboratory, maintained at Stoneville, Mississippi, by the Southern Forest Experiment Station, Forest Service—USDA, in cooperation with the Mississippi Agricultural and Forestry Experiment Station and the Southern Hardwood Forest Research Group.

south of Monticello. Eight tree species were each planted in a randomized complete block design of four blocks and five spacings. The species were: sycamore (Platanus occidentalis L.), sweetgum (Liquidambar styraciflua L.), cottonwood (Populus deltoides Bartr. ex Marsh.), green ash (Fraxinus pennsylvanica Marsh.), water oak (Quercus nigra L.), cherrybark oak (Q. falcata var. pagodifolia Ell.), Nuttall oak (Q. nuttallii Palmer), and swamp chestnut oak (Q. michauxii Nutt.)

The spacings in feet and respective number of trees per acre (in parentheses) were 2 by 8 (2723), 3 by 8 (1815), 4 by 8 (1361), 8 by 8 (681), and 12 by 12 (303). Spacings were chosen to span from the narrow coppice spacings to the more usual pulpwood and saw log spacings. The 8-foot distance between rows was chosen to allow tending by standard farm equipment.

Each plot consists of 169 trees planted in a rectangular grid of 13 by 13 rows. The interior 5 by 5 rows were designated as permanent remeasurement rows with the outer 4 rows as a buffer.

Beginning in the fall of 1977, two trees representative of the plot from the second and third buffer rows were destructively sampled each fall for a total of seven annual samples. Field measurements included diameter 6 inches above the ground, dbh, total height, crown height, total bole weight, and total crown weight. Individual bole, limb, and leaf samples were taken and sealed in separate polyethylene bags for laboratory determination of green and dry weights and volume. One-inch thick disks were cut from the bole at a 6-inch stump and at intervals of 20, 40, 60, and 80 percent of total tree height. The branch and leaf samples consisted of selecting two representative limbs from each quarter of crown length and consolidating these into an eight-branch tree sample; leaves were detached from the branches in the field and bagged separately. Green weights, dry weights, and volumes of bole and branch components were determined in the laboratory by standard laboratory procedures.

Green weights of bole wood and bark for each tree were obtained by multiplying the proportion of each in the bole sample times the total bole green weight measured in the field. Green weights of branch wood, branch bark, and leaves were derived by adding the leaf and branch sample weights, finding the proportion of each component in the sample and applying the proportions to the total crown weight obtained in the field.

Total dry weights and volumes for each component were calculated using the consolidated sample component moisture contents and specific gravities. Moisture content and specific gravity were assumed to be uniform within each component.

Sweetgum and water oak were chosen to test the model development techniques. Sweetgum is very intolerant with rapid early growth. Young sweetgum have long conical crowns with the branches set at an acute angle to the stem. Water oak, though fairly intolerant, exhibits the slow early growth characteristics of the oaks. The stout, horizontal branches self-prune very slowly.

Only data for trees taller than 4.5 feet were included in the analysis set, giving 207 sweetgum and 175 water oak trees. These sets were reduced in size by one-third due to data set size limitations of the software package used for much of the subsequent analysis. Trees were randomly eliminated, leaving 131 sweetgum and 111 water oak. The following tabulation shows means and ranges of sample tree data.

	Sweetgum		Water oak	
	Mean	Range	Mean	Range
Age (yrs)	4.0	1 - 7	4.5	1 - 7
Dbh (in)	1.7	0.1 - 5.1	1.2	0.1 - 4.2
Total height (ft)	15.5	4.5 - 36.8	12.8	4.5 -23.0
Green bole wood weight (lb)	14.7	0.2 -117.3	8.4	0.2 -72.8
Green bole bark weight (lb)	2.3	0.05- 16.1	1.8	0.05-12.4
Green limb wood weight (lb)	4.8	0.07- 35.3	8.5	0.2 -86.2
Green limb bark weight (lb)	1.9	0.05- 14.8	1.8	0.08-15.6
Green leaf weight (lb)	5.1	0.1 - 34.0	3.8	0.3 -25.8

The tree component percentages for the two species differ due to their different growth characteristics (table 1). Based on dry total tree weight without leaves, both species contain about 85 percent wood and 15 percent bark in the tree, with another 15 percent in the leaves. Each species contains about 8 percent each in bole bark and limb bark. However, sweetgum has 64 percent of wood in the bole and 21 percent in the limbs, while water oak has 40 percent wood in the bole and 43 percent in the limbs. Thus water oak has half its weight in the bole and half in the limbs, while sweetgum is three-fourths bole weight and one-fourth limb weight.

ANALYSIS AND MODEL TESTING

In addition to tree diameter and height, other independent variables are needed when predicting biomass of plantation-grown trees. Tree diameter and height alone, when used as

Table 1.--Sample tree component mean and percent of 131 sweetgum and 111 water oak trees

Component	Sweetgum Mean	Sweetgum Percent of tree	Water oak Mean	Water oak Percent of tree
		Green weight - lb		
Bole wood	14.72	62	8.41	41
Bole bark	2.33	10	1.77	9
Total bole	17.05	72	10.18	50
Limb wood	4.84	20	8.51	42
Limb bark	1.86	8	1.77	8
Total limbs	6.70	28	10.28	50
Tree wood	19.56	82	16.92	83
Tree bark	4.19	18	3.54	17
Tree w/o leaves	23.75	100	20.46	100
Leaves	5.12	22	3.80	19
Tree w/leaves	28.87	122	24.26	119
		Dry weight - lb		
Bole wood	7.65	64	4.83	40
Bole bark	0.97	8	1.10	9
Total bole	8.62	72	5.93	49
Limb wood	2.54	21	5.30	43
Limb bark	0.81	7	0.94	8
Total limbs	3.35	28	6.24	51
Tree wood	10.19	85	10.13	83
Tree bark	1.78	15	2.04	17
Tree w/o leaves	11.97	100	12.17	100
Leaves	1.83	15	1.82	15
Tree w/leaves	13.80	115	13.99	115
		Volume - cubic feet		
Bole wood	0.233	57	0.123	38
Bole bark	0.049	12	0.031	10
Total bole	0.282	69	0.154	48
Limb wood	0.082	20	0.127	40
Limb bark	0.044	11	0.040	12
Total limbs	0.126	31	0.167	52
Tree wood	0.315	77	0.250	78
Tree bark	0.093	23	0.071	22
Tree w/o leaves	0.408	100	0.321	100

biomass predictors, were insufficient descriptors of plantation loblolly (*Pinus taeda* L.) crown biomass (Hepp and Brister 1982), plantation sycamore (*Platanus occidentalis* L.) (Willson et al. 1982), and natural loblolly bay (*Gordonia lasianthus* (L.) Ellis) (Gresham 1982). Earlier results showed that total tree height of plantation sycamore is a function of age, diameter, and initial planting density (Schlaegel 1981). Basic independent variables available for use in the present study are dbh--D, total height--H, tree age--A, and number of trees planted--N. Combinations, transformations, and interactions of these four variables were also used. The dependent variable used was the natural logarithm (Ln) of the component being fitted.

Since the purpose of this paper is to determine whether separate models are required for predicting each tree component for each species, it was assumed that separate models would give the most precise estimates for each component. All subsequent comparisons are against these individual component prediction equations.

Although only four basic independent variables are available, a large number become potentially available if transformations and combinations are considered. Based on scatter plots and past experience, 12 independent variables (table 2) were chosen for testing.

Table 2.--Twelve independent variables used to test the biomass predictors[1/]

Number	Variable	Number	Variable
1	D	7	$1/A^2$
2	H	8	D^2H
3	N	9	$Ln(D^2H)$
4	A	10	$[Ln(D^2H)]^2$
5	Ln(D)	11	[Ln(N)]/A
6	Ln(N)	12	N/A

1/ D = dbh, H = total height, N = number planted per acre, A = age in years, Ln = natural logarithm.

The stepwise procedure of Minitab[3/] was used to fit equations to predict the 31 weights and volumes indicated in table 1. This procedure employs the technique of forward selection/backward elimination, which both adds variables to and eliminates variables from the equation, each variable's contribution to the reduction sum of squares being tested with $\alpha = 0.05$.

As might be expected, no single model form is consistently best for either sweetgum (table 3) or water oak (table 4). The number of variables entering the models ranges from two to eight but is usually four to six for sweetgum and three to five for water oak. With a few exceptions some form of the four basic variables will occur in all prediction equations for both species.

Relative equation precision is evaluated based on fit index, mean residuals, standard error, and coefficient of variation (Schlaegel 1982). These four statistics are calculated by converting the predictions into the units of pounds and cubic feet from their logarithmic form; each equation was corrected for bias as suggested by Baskerville (1972).

No mean residuals (bias) for either sweetgum or water oak predictions were significantly different from zero by the paired t test. The magnitude of bias is small in relation to the component means, ranging from 0.0 to 5.6 percent of the mean. These magnitudes are comparable to earlier sycamore results from this same study (Willson et al. 1982).

Stepwise regression is a suitable method for screening a large number of variables and gaining insight into variables that may be important biomass predictors. But many times automated stepwise routines are not available. Also, it would be desirable to use only a single model form if possible, or two at the most, to predict all biomass components for a single species. In the examples thus far, 62 models (and equations) were used, 31 each for sweetgum and water oak. All comparisons that follow are in relation to estimates from these 31 separate equations for each species.

3/ Minitab Inc., 215 Pond Laboratory, Pennsylvania State University, University Park, PA 16802.

REDUCING THE NUMBER OF MODELS

One of this paper's objectives is to determine if predictions from completely separate model forms could be added to estimate the total bole, total limb, and total tree values. This could possibly reduce the modeling effort from 31 to 14 equations. Willson et al. (1982) showed no significant mean bias when adding predictions using a common logarithmic model fitted to primary sycamore components. It seems logical that predictions from different model forms can also be added to give satisfactory results.

Component predictions using separate model forms can be added with no significant changes in mean residuals (bias) for either species (table 5). However, standard error was significantly increased in 6 of the 17 sweetgum predictions and significantly reduced in 8 of the 17 water oak predictions. Thus, predictions of primary components can be summed with no differences in mean totals, but there is a significant difference in the reliability of the estimate; variance and subsequent standard error can either increase or decrease.

Developing individual models for these 14 components is still a considerable task. Can a single model, or even several models, be selected that will fit the primary components? If so, how can they be selected to minimize modeling effort and still give satisfactory results?

There are several alternatives for choosing one or several model forms that will subsequently be used to fit all primary tree components. One method is to find the model that most accurately describes the tree component of highest proportion. For sweetgum this would be bole wood (64 (percent dry weight). Some precision will probably be lost if this model is used to predict all other components, but for practical purposes this

Table 3.--Significant variables and fit statistics for fitting individual models to sweetgum tree component biomass using stepwise regression

Component	Sample mean	Significant variables[1/] 1	2	3	4	5	6	7	8	9	10	11	12	Fit index	Bias	Standard error	CV percent
Green weight - lb																	
Bole wood	14.72	X				X	X			X				0.963	-0.353	3.578	24.3
Bole bark	2.33	X								X		X		0.934	-0.047	0.661	28.4
Total bole	17.05						X	X		X	X			0.968	-0.332	3.794	22.3
Limb wood	4.84			X	X	X					X	X	X	0.850	-0.220	2.362	48.8
Limb bark	1.86					X	X	X			X	X		0.854	-0.094	0.833	44.8
Total limbs	6.70	X				X	X	X			X	X		0.899	-0.179	2.613	39.0
Tree wood	19.56	X					X	X		X	X	X		0.973	-0.345	4.031	20.6
Tree bark	4.19				X		X	X		X	X	X		0.934	-0.136	7.199	28.6
Tree w/o leaves	23.75	X			X		X	X		X	X	X		0.972	-0.427	4.876	20.5
Leaves	5.12			X		X	X						X	0.816	-0.001	2.554	49.9
Tree w/leaves	28.87						X			X	X			0.962	-0.566	6.654	23.1
Dry weight - lb																	
Bole wood	7.65					X	X	X		X	X			0.966	-0.188	1.774	23.2
Bole bark	0.97									X	X	X		0.949	-0.023	0.246	25.4
Total bole	8.62	X					X	X		X	X			0.980	-0.106	1.538	17.8
Limb wood	2.54		X	X				X		X	X		X	0.872	-0.098	1.150	45.3
Limb bark	0.81	X		X		X		X					X	0.827	-0.039	0.418	51.6
Total limbs	3.35		X	X		X		X			X		X	0.874	-0.125	1.489	44.5
Tree wood	10.19	X					X	X		X	X	X		0.973	-0.205	2.082	20.4
Tree bark	1.78						X	X		X	X			0.926	-0.059	0.553	31.2
Tree w/o leaves	11.97	X				X	X	X		X	X	X	X	0.968	-0.240	2.641	22.1
Leaves	1.83	X		X			X						X	0.558	-0.153	1.389	75.9
Tree w/leaves	13.80	X			X		X	X		X	X	X	X	0.966	-0.267	3.100	22.5
Volume - cubic feet																	
Bole wood	0.233	X					X	X		X	X			0.982	-0.003	0.038	16.4
Bole bark	0.049									X	X	X		0.948	-0.001	0.012	23.8
Total bole	0.282	X					X	X		X	X			0.984	-0.003	0.042	14.9
Limb wood	0.082		X	X				X		X	X		X	0.883	-0.003	0.034	42.0
Limb bark	0.044	X		X				X	X			X		0.791	-0.002	0.022	50.8
Total limbs	0.126	X				X	X	X			X	X		0.908	-0.004	0.045	35.8
Tree wood	0.315	X					X	X		X	X	X		0.981	-0.006	0.052	16.6
Tree bark	0.093						X	X	X	X	X	X		0.940	-0.003	0.024	25.8
Tree w/o leaves	0.408	X					X	X		X	X	X		0.980	-0.009	0.068	16.6

1/ 1 = D, 2 = H, 3 = N, 4 = A, 5 = Ln(D), 6 = Ln(N), 7 = $1/A^2$, 8 = D^2H, 9 = $Ln(D^2H)$, 10 = $[Ln(D^2H)]^2$, 11 = [Ln(N)]/A, 12 = N/A.

Table 4.--Significant variables and fit statistics for fitting individual models to water oak tree component biomass using stepwise regression

Component	Sample Mean	Significant variables[1/] 1	2	3	4	5	6	7	8	9	10	11	12	Fit index	Bias	Standard error	CV percent
									Green weight - lb								
Bole wood	8.41				X					X	X	X		0.971	0.006	1.798	21.4
Bole bark	1.77							X		X	X			0.881	-0.006	0.670	37.8
Total bole	10.18				X					X	X	X		0.973	-0.006	2.048	20.1
Limb wood	8.51	X					X		X					0.927	-0.406	3.692	43.4
Limb bark	1.77	X					X		X					0.891	-0.039	0.849	47.9
Total limbs	10.28	X					X		X					0.926	-0.403	4.403	42.8
Tree wood	16.92	X								X			X	0.756	-0.923	11.874	70.2
Tree bark	3.54	-						X	X					0.931	-0.058	1.151	32.5
Tree w/o leaves	20.46	x								X			X	0.747	-1.072	14.263	69.7
Leaves	3.80	X			X				X			X		0.757	-0.064	2.025	53.3
Tree w/leaves	24.26	X							X				X	0.941	-0.555	7.804	32.2
									Dry weight - lb								
Bole wood	4.83				X					X	X	X		0.972	-0.022	0.977	20.2
Bole bark	1.10									X	X	X		0.884	-0.020	0.435	39.4
Total bole	5.93				X					X	X	X		0.974	-0.039	1.141	19.2
Limb wood	5.30	X			X		X	X	X					0.892	-0.283	2.814	53.1
Limb bark	0.94	X					X		X					0.899	-0.027	0.430	45.6
Total limbs	6.24	X			X		X	X	X					0.896	-0.297	3.188	51.1
Tree wood	10.13	X								X			X	0.744	-0.564	7.145	70.6
Tree bark	2.04	X								X		X		0.742	-0.094	1.297	63.4
Tree w/o leaves	12.17	X								X			X	0.752	-0.661	8.276	68.0
Leaves	1.82	X			X		X		X					0.768	-0.032	0.919	50.5
Tree w/leaves	13.99	X					X	X	X	X				0.929	-0.330	4.933	35.3
									Volume - cubic feet								
Bole wood	0.123						X	X		X	X		X	0.979	-0.001	0.023	18.3
Bole bark	0.031										X	X	X	0.894	-0.000	0.011	35.2
Total bole	0.154				X					X	X	X		0.977	-0.001	0.029	18.6
Limb wood	0.127	X			X				X				X	0.910	-0.007	0.061	48.1
Limb bark	0.040	X							X					0.900	-0.001	0.017	43.0
Total limbs	0.167	X					X		X					0.936	-0.007	0.065	38.9
Tree wood	0.250	X								X			X	0.752	-0.014	0.176	70.5
Tree bark	0.071	X						X	X					0.942	-0.001	0.021	29.2
Tree w/o leaves	0.321	X								X			X	0.752	-0.017	0.218	68.1

1/ 1 = D, 2 = H, 3 = N, 4 = A, 5 = Ln(D), 6 = Ln(N), 7 = $1/A^2$, 8 = D^2H, 9 = $Ln(D^2H)$, 10 = $[Ln(D^2H)]^2$, 11 = [Ln(N)]/A, 12 = N/A.

Table 5.—Statistics produced by adding individual tree component predictions to produce total bole, total limbs, and total tree estimations for sweetgum and water oak

Component	Sweetgum						Water oak					
	Fit index	Bias	t for bias	(df)	Std. error	Coef. var.	Fit index	Bias	t for bias	(df)	Std. error	Coef. var.
Green weight - lb												
Total bole	0.962	-0.399	-1.14	(122)	4.173	24.5	0.972	0.000	0.00	(102)	2.124	20.8
Total limbs	0.865	-0.315	-1.22	(118)	3.105+	46.4	0.927	-0.445	-1.09	(103)	4.483	43.6
Tree wood	0.956	-0.573	-1.33	(119)	5.196+	26.6	0.958	-0.400	-0.87	(102)	5.064*	29.9
Tree bark	0.921	-0.141	-1.26	(120)	1.328	31.7	0.929	-0.045	-0.41	(103)	1.194	33.7
Tree w/o leaves	0.955	-0.714	-1.37	(109)	6.565+	27.6	0.959	-0.445	-0.83	(94)	6.109*	29.8
Tree w/leaves	0.956	-0.715	-1.16	(104)	7.911+	27.4	0.949	-0.509	-0.75	(89)	7.950	32.8
Dry weight - lb												
Total bole	0.966	-0.212	-1.26	(121)	2.005+	23.3	0.974	-0.042	-0.39	(102)	1.164	19.6
Total limbs	0.874	-0.136	-1.07	(118)	1.529	45.7	0.898	-0.309	-1.06	(101)	3.219	51.6
Tree wood	0.965	-0.286	-1.42	(118)	2.429	23.8	0.941	-0.305	-0.96	(100)	3.541*	35.0
Tree bark	0.917	-0.062	-1.24	(121)	0.597	33.6	0.935	-0.046	-0.76	(103)	0.664*	32.4
Tree w/o leaves	0.962	-0.348	-1.43	(108)	3.072	25.7	0.948	-0.351	-1.00	(92)	4.066*	33.4
Tree w/leaves	0.944	-0.501	-1.52	(103)	4.283+	31.1	0.939	-0.383	-0.91	(87)	5.003	35.8
Volume - cubic feet												
Total bole	0.982	-0.004	-1.02	(121)	0.045	16.0	0.979	-0.002	-0.72	(101)	0.028.	18.1
Total limbs	0.874	-0.005	-1.21	(118)	0.054+	42.9	0.917	-0.008	-1.18	(103)	0.075	44.9
Tree wood	0.981	-0.006	-1.33	(118)	0.054	17.0	0.955	-0.008	-1.21	(100)	0.078*	31.0
Tree bark	0.933	-0.003	-1.57	(121)	0.026	27.5	0.928	-0.001	-0.66	(104)	0.023*	33.1
Tree w/o leaves	0.979	-0.009	-1.61	(108)	0.073	17.8	0.958	-0.010	-1.18	(93)	0.096*	30.0

+ Standard error significantly ($\alpha = 0.05$) larger using the two-sided F test than that produced by separate prediction equation.

* Standard error significantly ($\alpha = 0.05$) smaller using the two-side F test than that produced by separate prediction equation.

makes little difference due to the relatively small proportions of these other components.

Should this single model be fitted to green weight, dry weight, or volume? Fitting to dry bole wood weight eliminates variation due to moisture content. Fitting to bole wood volume would be acceptable, since this also reduces variation due to wood density—but in biomass work, weight is the usual measurement unit of interest.

Water oak has no component of highest proportion; bole wood is 40 percent and limb wood 43 percent of the total tree. The options in this case are: (1) Develop a bole wood model and use it for all primary tree components, (2) develop a limb wood model and use it to fit all primary components, or (3) develop individual bole wood and limb wood models and fit each to their respective components.

To test this idea, the model was selected for sweetgum that best described dry bole wood weight:

$$Ln(Y) = b_0 + b_1 Ln(D) + b_2 Ln(N) + b_3 1/A^2 + b_4 Ln(D^2H) + b_5 [Ln(D^2H)]^2 \quad (1)$$

This model was subsequently fit to each of the 10 tree weights (5 green and 5 dry) and 4 tree volume components; total bole, total limb, and total tree values were estimated by summing the predictions of the primary components. The component estimations and summed predictions were tested against predictions from the individual models shown in table 3. Prediction differences were compared using the paired t test; variances of the predictions were compared using the two-sided F test (table 6).

Table 6.—Comparing a bole wood model to individual component prediction models for predicting sweetgum biomass components

Component	Predicted mean[1/]	(df)	Estimated variance	Predicted means and summed predictions[2/]	(df)	Estimated variance	Mean difference	Variance ratio (largest/smallest)
				Green weight - lb				
Bole wood	15.07	(126)	12.80	15.02	(125)	10.44	0.05	1.23
Bole bark	2.38	(127)	0.44	2.35	(125)	0.24	0.03	1.83 *
Total bole	17.38	(126)	14.39	17.37	(119)	13.41	0.01	1.07
Limb wood	5.06	(124)	5.57	5.03	(125)	4.77	0.03	1.17
Limb bark	1.95	(125)	0.69	1.92	(125)	0.57	0.03	1.21
Total limbs	6.88	(124)	6.83	6.95	(119)	8.12	-0.07	1.19
Tree wood	19.90	(124)	16.25	20.05	(119)	22.80	-0.15	1.40 +
Tree bark	4.33	(124)	1.44	4.27	(119)	1.14	0.06	1.26
Tree w/o leaves	24.17	(123)	23.78	24.32	(107)	33.97	-0.15	1.43 +
Leaves	5.12	(126)	6.51	5.15	(125)	6.78	-0.03	1.04
Tree w/leaves	29.43	(127)	44.28	29.47	(101)	59.01	-0.04	1.33
				Dry weight - lb				
Bole wood	7.84	(125)	3.15	7.84	(125)	3.15	0.00	1.00
Bole bark	0.99	(127)	0.06	0.99	(125)	0.08	0.00	1.33
Total bole	8.72	(125)	2.36	8.83	(119)	4.22	-0.11	1.79 +
Limb wood	2.64	(124)	1.32	2.66	(125)	1.28	-0.02	1.03
Limb bark	0.85	(125)	0.17	0.84	(125)	0.14	0.01	1.21
Total limbs	3.47	(124)	2.22	3.50	(119)	2.21	-0.03	1.00
Tree wood	10.39	(124)	4.33	10.49	(119)	6.86	-0.10	1.58 +
Tree bark	1.83	(126)	0.31	1.83	(119)	0.32	0.00	1.03
Tree w/o leaves	12.20	(122)	6.97	12.32	(107)	10.67	-0.12	1.53 +
Leaves	1.98	(126)	1.93	1.84	(125)	0.82	0.14	2.35 *
Tree w/leaves	14.06	(122)	9.60	14.16	(101)	14.15	-0.10	1.47 +
				Volume - cubic feet				
Bole wood	0.236	(125)	0.00145	0.239	(125)	0.00302	-0.003	2.08 +
Bole bark	0.051	(127)	0.00014	0.051	(125)	0.00018	0.000	1.28
Total bole	0.286	(125)	0.00177	0.290	(119)	0.00450	-0.004	2.54 +
Limb wood	0.085	(124)	0.00118	0.086	(125)	0.00117	-0.001	1.01
Limb bark	0.046	(125)	0.00049	0.045	(125)	0.00031	0.001	1.58 +
Total limbs	0.130	(124)	0.00202	0.131	(119)	0.00240	-0.001	1.19
Tree wood	0.321	(124)	0.00273	0.325	(119)	0.00560	-0.004	2.05 +
Tree bark	0.096	(124)	0.00058	0.096	(119)	0.00070	0.000	1.21
Tree w/o leaves	0.417	(124)	0.00458	0.421	(107)	0.00970	-0.004	2.12 +

1/ Means predicted from individual models; these are slightly different from sample means presented in tables 1 and 3.

2/ Estimated from $Ln(Y) = b_0 + b_1 Ln(D) + b_2 Ln(N) + b_3 1/A^2 + b_4 Ln(D^2H) + b_5 [Ln(D^2H)]^2$.

* Variance of bole wood model equation significantly ($\alpha = 0.05$) smaller than variance of individual component equation using the two-sided F test.

\+ Variance of bole wood model equation significantly ($\alpha = 0.05$) larger than variance of individual prediction equation using the two-sided F test.

No significant differences in mean component predictions were found in estimating component biomass for sweetgum when using a single model fit to the primary tree components and then summing component predictions to estimate tree totals. However, prediction variance was significantly increased in 11 cases. Thus, while a component average of a large number of trees can be accurately determined using a single model form fit to all tree components, there is a significant lack of confidence in predicting the biomass of a specific tree.

Similar tests were also done for water oak. Since bole wood and limb wood occurred in about equal proportions, the best dry bole wood model:

$$Ln(Y) = b_0 + b_1A + b_2Ln(D^2H) + b_3[Ln(D^2H)]^2 + b_4[Ln(N)]/A, \quad (2)$$

and dry limb wood model:

$$Ln(Y) = b_0 + b_1D + b_2A + b_3Ln(N) + b_4(1/A^2) + b_5D^2H, \quad (3)$$

were each fit to the 10 tree weight components and 4 volume components. Predictions from each model were again compared to predictions from individual component models (given in table 4 for water oak). Individual tree predictions and mean bias were tested using the paired t test and variances compared with the F test.

Fitting the best dry bole wood model (eq. 2) to primary tree components, then summing predictions to estimate total bole, limb, and tree values, showed no significant differences in predicting the average tree component (table 7). But, as with sweetgum, prediction variance increased in nine cases and decreased in seven cases. Six of the nine increases are directly attributable to errors in using the bole wood model to predict limb components, indicating the bole wood model is not the "correct" model for predicting limbs. Variance for total tree predictions was significantly reduced.

Fitting the best dry limb wood model to the primary components gives no significant differences in estimating the average tree component, but some variances are significantly different from those individual component prediction models (table 8). Six of eight variance increases are for bole estimates, indicating that a limb model may not be "best" for predicting bole components. However, total limb variance is still significantly increased for green weight and volume.

Since limb prediction variance was increased using the bole model and bole prediction variance was increased using the limb model, the logical next step is to fit the bole model to bole components, the limb model to limb components, and a dry leaf model to the leaf components. This would give three separate model forms to fit to the three main tree components: boles, limbs, and leaves. Total bole, total limbs, and total tree estimates are obtained by summing individual predictions. These results are given in table 9.

No significant differences in estimating component means were noted. Although total limb green weight and volume prediction variances are still significantly larger than if a separate total limb prediction model had been used, all other variances are either unchanged or are significantly reduced.

SUMMARY AND CONCLUSIONS

Sweetgum and water oak trees sampled from a plantation over 7 years were used to test whether primary tree component predictions could be summed to estimate total bole, total limb, and total tree values. The primary predictors are: volume—bole wood, bole bark, limb wood, and limb bark; and green and dry weight—bole wood, bole bark, limb wood, limb bark, and leaves. Twelve independent variables were fitted using stepwise regression to give a separate prediction model for each primary component and each total bole, limb, and tree value. Mean tree estimates by summing primary component predictions were not significantly different from mean predictions for the total tree model, but prediction variances were increased for sweetgum and reduced for water oak.

An attempt was made to find a single model form for each species that would satisfactorily fit all primary components for each species. Fitting a bole wood model to all sweetgum components gave satisfactory estimates of component means, but prediction variance was significantly increased in a number of cases. Satisfactory results were obtained for water oak by fitting a bole wood model to primary bole components, a limb wood model to primary limb components, and a leaf model to leaf weights. Primary predictions and summations of these models showed no significant bias with prediction variance generally unchanged or reduced.

Due to the quite different results from these two species, it is not possible to infer results to other species. Growth characteristics seem to play an important role in these young plantations, particularly when estimating limb biomass.

The 12 independent variables used for model building and testing were screened from a larger set specifically for these 2 species. This was due to the limitations of the available computer hardware and software. Other species may require additional transformations or combinations of the four basic variables to give reliable component predictions. It appears that biomass prediction models for the other species in this plantation will have to be developed for each separate species to give the most reliable estimates.

Table 7.--Comparing a bole wood model to individual component prediction models for predicting water oak biomass components

Component	Predicted mean[1/] (df)	Estimated variance	Predicted means and summed predictions[2/] (df)	Estimated variance	Mean difference	Variance ratio (largest/ smallest)	
			Green weight - lb				
Bole wood	8.41 (106)	3.23	8.41 (106)	3.23	0.00	1.00	
Bole bark	1.78 (107)	0.45	1.78 (106)	0.43	0.00	1.05	
Total bole	10.19 (106)	4.19	10.19 (101)	4.43	0.00	1.06	
Limb wood	8.92 (107)	13.63	8.56 (106)	20.20	0.36	1.48	+
Limb bark	1.81 (107)	0.72	1.77 (106)	1.07	0.04	1.49	+
Total limbs	10.69 (107)	19.39	10.33 (101)	31.10	0.36	1.60	+
Tree wood	17.85 (107)	140.99	16.96 (101)	37.03	0.87	3.81	*
Tree bark	3.60 (107)	1.32	3.56 (101)	1.99	0.04	1.51	+
Tree w/o leaves	21.54 (107)	203.43	20.52 (91)	57.37	1.02	3.55	*
Leaves	3.86 (106)	4.10	3.83 (106)	4.73	0.03	1.15	
Tree w/leaves	24.83 (107)	60.90	24.35 (86)	94.85	0.48	1.55	+
			Dry weight - lb				
Bole wood	4.85 (106)	0.95	4.85 (106)	0.95	0.00	1.00	
Bole bark	1.12 (107)	0.19	1.12 (106)	0.19	0.00	1.00	
Total bole	5.97 (106)	1.30	5.97 (101)	1.37	0.00	1.05	
Limb wood	5.58 (105)	7.92	5.32 (106)	8.87	0.26	1.12	
Limb bark	0.97 (107)	0.18	0.95 (106)	0.30	0.02	1.67	+
Total limbs	6.54 (105)	10.16	6.27 (101)	12.68	0.27	1.25	
Tree wood	10.69 (107)	51.05	10.17 (101)	14.58	0.52	3.50	*
Tree bark	2.14 (107)	1.68	2.07 (101)	0.64	0.07	2.62	*
Tree w/o leaves	12.83 (107)	68.49	12.24 (91)	21.35	0.59	3.21	*
Leaves	1.85 (106)	0.84	1.84 (106)	1.14	0.01	1.36	
Tree w/leaves	14.32 (105)	24.33	14.08 (86)	32.87	0.24	1.35	
			Volume - cubic feet				
Bole wood	0.125 (105)	0.00051	0.123 (106)	0.00060	0.002	1.18	
Bole bark	0.031 (107)	0.00012	0.032 (106)	0.00011	-0.001	1.06	
Total bole	0.155 (106)	0.00083	0.155 (101)	0.00090	0.000	1.08	
Limb wood	0.134 (106)	0.00373	0.128 (106)	0.00407	0.006	1.09	
Limb bark	0.041 (108)	0.00029	0.041 (106)	0.00042	0.000	1.45	+
Total limbs	0.174 (107)	0.00422	0.169 (101)	0.00700	0.005	1.66	+
Tree wood	0.264 (107)	0.03105	0.251 (101)	0.00730	0.013	4.25	*
Tree bark	0.072 (107)	0.00043	0.073 (101)	0.00070	-0.001	1.63	+
Tree w/o leaves	0.339 (107)	0.04774	0.324 (91)	0.01250	0.015	3.82	*

1/ Means predicted from individual models; these are slightly different from sample means presented in tables 1 and 4.

2/ Predicted from $Ln(Y) = b_0 + b_1A + b_2Ln(D^2H) + b_3[Ln(D^2H)]^2 + b_4[Ln(N)]/A$.

\+ Variance of bole wood model equation significantly ($\alpha = 0.05$) larger than variance of individual component equation using the two-sided F test.

* Variance of bole wood model equation significantly ($\alpha = 0.05$) smaller than variance of individual component equation using the two-sided F test.

Table 8.--Comparing a limb wood model to individual component prediction models for predicting water oak biomass components

Component	Predicted mean[1/]	(df)	Estimated variance	Predicted means and summed predictions[2/]	(df)	Estimated variance	Mean difference	Variance ratio (largest/smallest)	
				Green weight - lb					
Bole wood	8.41	(106)	3.23	8.70	(105)	5.29	-0.29	1.64	+
Bole bark	1.78	(107)	0.45	1.81	(105)	0.38	-0.03	1.18	
Total bole	10.19	(106)	4.19	10.51	(99)	6.73	-0.32	1.61	+
Limb wood	8.92	(107)	13.63	8.97	(105)	18.58	-0.05	1.36	
Limb bark	1.81	(107)	0.72	1.82	(105)	0.83	-0.01	1.15	
Total limbs	10.69	(107)	19.39	10.79	(99)	30.01	-0.10	1.55	+
Tree wood	17.85	(107)	140.99	17.67	(99)	33.42	0.18	4.21	*
Tree bark	3.60	(107)	1.32	3.63	(99)	1.34	-0.03	1.02	
Tree w/o leaves	21.54	(107)	203.43	21.30	(87)	51.33	0.24	3.96	*
Leaves	3.86	(106)	4.10	3.87	(105)	3.68	-0.01	1.11	
Tree w/leaves	24.83	(107)	60.90	25.17	(81)	83.25	-0.34	1.37	
				Dry weight - lb					
Bole wood	4.85	(106)	0.95	5.01	(105)	1.80	-0.16	1.89	+
Bole bark	1.12	(107)	0.19	1.16	(105)	0.21	-0.04	1.10	
Total bole	5.97	(106)	1.30	6.17	(99)	2.57	-0.20	1.98	+
Limb wood	5.58	(105)	7.92	5.58	(105)	7.92	0.00	1.00	
Limb bark	0.97	(107)	0.18	0.98	(105)	0.21	-0.01	1.17	
Total limbs	6.54	(105)	10.16	6.56	(99)	10.94	-0.02	1.08	
Tree wood	10.69	(107)	51.05	10.59	(99)	13.97	0.10	3.65	*
Tree bark	2.14	(107)	1.68	2.14	(99)	0.42	0.00	4.00	*
Tree w/o leaves	12.83	(107)	68.49	12.73	(87)	19.39	0.10	3.53	*
Leaves	1.85	(106)	0.84	1.85	(105)	0.89	0.00	1.06	
Tree w/leaves	14.32	(105)	24.33	14.58	(81)	29.26	-0.26	1.20	
				Volume - cubic feet					
Bole wood	0.125	(105)	0.00051	0.127	(105)	0.00107	-0.002	2.10	+
Bole bark	0.031	(107)	0.00012	0.032	(105)	0.00012	-0.001	1.00	
Total bole	0.155	(106)	0.00083	0.159	(99)	0.00150	-0.004	1.81	+
Limb wood	0.134	(106)	0.00373	0.134	(105)	0.00385	0.000	1.03	
Limb bark	0.041	(108)	0.00029	0.041	(105)	0.00027	0.000	1.07	
Total limbs	0.174	(107)	0.00422	0.175	(99)	0.00610	-0.001	1.45	+
Tree wood	0.264	(107)	0.03105	0.261	(99)	0.00730	0.003	4.25	*
Tree bark	0.072	(107)	0.00043	0.073	(99)	0.00040	-0.001	1.07	
Tree w/o leaves	0.339	(107)	0.04774	0.334	(87)	0.01140	0.005	4.19	*

1/ Predicted from individual models.

2/ Predicted from $Ln(Y) = b_0 + b_1D + b_2A + b_3Ln(N) + b_4(1/A^2) + b_5D^2H$.

+ Variance of limb wood model equation significantly ($\alpha = 0.05$) larger than variance of individual component equation using the two-sided F test.

* Variance of limb wood model equation significantly ($\alpha = 0.05$) smaller than variance of individual component equation using the two-sided F test.

Table 9.—Comparing predictions from bole wood model plus limb wood model to individual component prediction models for predicting water oak biomass components

Component	Predicted mean[1/] (df)	Estimated variance	Predicted means and summed predictions[2/] (df)	Estimated variance	Mean difference	Variance ratio (largest/smallest)
			Green weight - lb			
Bole wood	8.41 (106)	3.23	8.41 (106)	3.23	0.00	1.00
Bole bark	1.78 (107)	0.45	1.78 (106)	0.43	0.00	1.05
Total bole	10.19 (106)	4.19	10.19 (101)	4.43	0.00	1.06
Limb wood	8.92 (107)	13.63	8.97 (105)	18.58	-0.05	1.36
Limb bark	1.81 (107)	0.72	1.82 (105)	0.83	-0.01	1.15
Total limbs	10.69 (107)	19.39	10.79 (99)	30.01	-0.10	1.55 +
Tree wood	17.85 (107)	140.99	17.38 (100)	31.33	0.47	4.50 *
Tree bark	3.60 (107)	1.32	3.60 (100)	1.52	0.00	1.15
Tree w/o leaves	21.54 (107)	203.43	20.98 (89)	47.33	-0.44	4.30 *
Leaves	3.86 (106)	4.10	3.88 (106)	3.43	-0.02	1.20
Tree w/leaves	24.83 (107)	60.90	24.86 (84)	76.21	-0.03	1.25
			Dry weight - lb			
Bole wood	4.85 (106)	0.95	4.85 (106)	0.95	0.00	1.00
Bole bark	1.12 (107)	0.19	1.12 (106)	0.19	0.00	1.00
Total bole	5.97 (106)	1.30	5.97 (101)	1.37	0.00	1.05
Limb wood	5.58 (105)	7.92	5.58 (105)	7.92	0.00	1.00
Limb bark	0.97 (107)	0.18	0.98 (105)	0.21	-0.01	1.17
Total limbs	6.54 (105)	10.16	6.56 (99)	10.94	-0.02	1.08
Tree wood	10.69 (107)	51.05	10.43 (100)	12.54	0.26	4.07 *
Tree bark	2.14 (107)	1.68	2.10 (100)	0.46	0.04	3.65 *
Tree w/o leaves	12.83 (107)	68.49	12.53 (89)	17.52	0.30	3.91 *
Leaves	1.85 (106)	0.84	1.85 (106)	0.84	0.00	1.00
Tree w/leaves	14.32 (105)	24.33	14.38 (84)	26.48	-0.06	1.09
			Volume - cubic feet			
Bole wood	0.125 (105)	0.00051	0.123 (106)	0.00060	0.002	1.18
Bole bark	0.031 (107)	0.00012	0.032 (106)	0.00011	-0.001	1.09
Total bole	0.155 (106)	0.00083	0.155 (101)	0.00090	0.000	1.08
Limb wood	0.134 (106)	0.00373	0.134 (105)	0.00385	0.000	1.03
Limb bark	0.041 (108)	0.00029	0.041 (105)	0.00027	0.000	1.07
Total limbs	0.174 (107)	0.00422	0.175 (99)	0.00610	-0.001	1.45 +
Tree wood	0.264 (107)	0.03105	0.257 (100)	0.00640	0.007	4.85 *
Tree bark	0.072 (107)	0.00043	0.073 (100)	0.00050	-0.001	1.16
Tree w/o leaves	0.339 (107)	0.04774	0.330 (89)	0.01040	0.009	4.59 *

1/ Predicted from individual models.

2/ Bole components predicted from: $Ln(Y) = b_0 + b_1 A + b_2 Ln(D^2H) + b_3[Ln(D^2H)]^2 + b_4[Ln(N)]/A$.
Limb components predicted from: $Ln(Y) = b_0 + b_1 D + b_2 A + b_3 Ln(N) + b_4(1/A^2) + b_5 D^2H$.
Leaf components predicted from: $Ln(Y) = b_0 + b_1 D + b_2 A + b_3 Ln(N) + b_4 D^2H$.

+ Variance significantly ($\alpha = 0.05$) larger than variance of individual component equation using the two-sided F test.

* Variance significantly ($\alpha = 0.05$) smaller than variance of individual component equation using the two-sided F test.

Although no significant prediction bias was noted, mean residuals for both species were all negative. This suggests the Baskerville bias correction technique consistently overcorrected. Though these overcorrections are small, their effects are increased as components increase in size. This adds to prediction variance when converting from logarithmic units back to measured units. Perhaps more precise predictions could be obtained by correcting the bias for each equation so as to give a zero bias as suggested by Hepp and Brister (1982).

We would expect that as the plantation ages, the models for each species will become more similar. Crowns will close, limb mortality will become more rapid, and tree boles will increase in proportion. But in young plantations, different species will undoubtedly require different model forms to reliably estimate biomass.

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