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Equations for Predicting Biomass in 2- to 6-year-old *Eucalyptus saligna* in Hawaii

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Eucalyptus saligna trees grown in short-rotation plantations on the island of Hawaii were measured, harvested, and weighed to provide data for developing regression equations using non-destructive stand measurements. Regression analysis of the data from 190 trees in the 2.0- to 3.5-year range and 96 trees in the 4- to 6-year range related stem-only and total above-ground biomass to diameter at breast height and total height. Equations developed for each age class are recommended over equations developed for the combined data base (286 trees). For younger stands (<4-years) recommended equations include one based on diameter measurements only, thus simplifying field measurements.

Retrieval Terms: biomass equations, prediction equations, short rotation silviculture, Hawaii, *Eucalyptus saligna*

Wood fiber, when available, is used to supplement bagasse (sugarcane residue) as fuel for generating electricity in Hawaii. In recent years, wood chips have supplied power on the islands of Hawaii, Maui, Molokai, and Kauai. Several high-yielding eucalyptus species have been planted in intensively-cultured, short-rotation (3- to 7-years) plantations in Hawaii.[1] One is saligna (*Eucalyptus saligna* Sm.). It provides wood with a high BTU content,[2] grows rapidly, is adapted to a wide range of site conditions, and is relatively free from insects and diseases.

To assess the growth and yield of *eucalyptus* plantations, land managers need estimates of above-ground biomass. Such data are useful if they can be obtained cheaply—especially without destructive sampling. Biomass equations that predict individual tree weights from diameter and height measurements can estimate stand biomass by summation. Equations to estimate biomass of individual trees have been derived for other species of *Eucalyptus*; e.g., *E. grandis* in Australia[3] and in South Africa;[4] and *E. globulus* in Australia[5] and in South Africa.[6] But similar equations for *E. saligna* are lacking. Estimates of biomass production rate were published for *E. saligna* in New Zealand[7] but without prediction equations.

Plantations along the Hamakua Coast north of Hilo on the island of Hawaii (lat. 19°50' N, long. 155°09' W) were sampled. Elevations range from 420- to 480-m. At this locale, the annual rainfall often exceeds 6,000 mm, and is usually distributed fairly even throughout the year, although any given month may be the wettest. The soil is Akaka silty clay loam formed in volcanic ash, and classified as a thixotropic isomesic Typic Hydrandept. Tree growth increases on these wet soils during dry periods.

A plantation at 540 m elevation at Ninole, Ka'u District, about 10 km southwest of Pahala town (lat. 19°10' N, long. 155°33' W), was also sampled. Annual rainfall is about 1,800 mm, with the wettest period occurring between December and April. Extended dry periods may occur during summer. The two soils on this site are Kiloa, an extremely stony muck derived from organic matter overlying a'a lava rock (classified as a dysic isothermic Typic Tropofolist), and an extremely stony silty clay loam, Alapai series, formed from volcanic ash (classified as a thixotropic isothermic Typic Hydrandept). These soils are rocky and very shallow.[8]

This note provides biomass equations for 2- to 6-year-old *E. saligna* sapling and pole-size trees, based upon biomass data obtained by destructive sampling.

METHODS

Sample Tree—Selection and Measurement

From these two sites, 190 *Eucalyptus saligna* trees ranging in age from 2- to 3.5-years were sampled, and their individual green weights determined. Two years later, 96 trees ranging from 4- to 6-years-old were also sampled and their weights determined.

Table 1—*Number of trees, diameter, and height for three sample tree data bases*, Eucalyptus saligna, *island of Hawaii, 1988*

Data base	Trees	Mean		Minimum		Maximum	
		D.b.h.	Height	D.b.h.	Height	D.b.h.	Height
		cm	*m*	*cm*	*m*	*cm*	*m*
Younger	190	8.3	9.8	1.7	2.3	14.4	16.8
Older	96	12.6	17.5	4.1	7.8	24.7	27.9
Combined	286	9.7	12.4	1.7	2.3	24.7	27.9

Diameter breast height (d.b.h.) of the combined data base ranged from 1.7- to 24.7-cm, with total tree height ranging from 2.3- to 27.9-m (*table 1*). An additional 12 trees were sampled from 5- and 6-year-old plantations on the Hamakua Coast to provide an equation check. One tree's d.b.h. fell outside the data-base range, while two trees were taller (28.6 m and 29.1 m) than the tallest data-base tree (27.9 m).

Felled trees were separated into two components: stems, and a combined leaf and branch total. Green weights of these components were determined by using a Chatillon scale (accuracy: ± 0.23 kg). Wood disks (2.5 cm thick) were extracted at d.b.h. and at 5 m for the calculation of moisture content. Subsamples of the leaves and branches, and wood disks were taken to the laboratory for dry weighing.

Data Analysis

Green weights were converted to dry weights by using moisture content values developed from stem disk, leaf and branch samples. Initial prediction of tree biomass from regression analysis with tree diameter and height resulted in increasing variances with increasing tree size. Logarithmic transformation was used to equalize variances over the range of tree size, an assumption essential to regression analysis.

Equations were developed from three data bases: 1) Younger, 190 sample trees, 2- and 3.5-year-old; 2) Older, 96 sample trees, 4- to 6-year-old; and 3) Combined, 286 sample trees, 2- to 6-year-old. Predicted values included both stem-only and total above-ground biomass, to simulate two different levels of harvesting and utilization. Tree d.b.h. was used as an independent variable in combination with tree height. Two equation forms were tested in regression analysis of tree biomass:

Model 1: $\ln Y = a + 2b*\ln(D)$ (diameter-only)

Model 2: $\ln Y = a + 2b*\ln(D) + c*\ln(H)$ (diameter plus height)

in which ln = natural logarithm, Y = dry biomass in kg/tree, D = diameter at breast height (1.3 m) in centimeters, and H = total height in meters. Model 1 was used to consider the effect of removing the height component, thereby simplifying field operations by not measuring heights. Model 2 was used to assess the contributions the height parameters and corresponding "t" values made to the prediction equation (*tables 2, 3*).

To correct for bias in the estimate due to the logarithmic transformation, a correction factor (cf) for each derived equation was calculated utilizing the formula $cf = e^{\frac{variance}{2}}$. The variance is the square of the root mean square error ($RMSE^2$) in logarithmic form. This correction is necessary due to the fact that regression fitting in logarithms estimates the geometric mean rather than the arithmetic mean.[9]

Table 2—*Regression characteristics for two total above-ground biomass equation forms for* Eucalyptus saligna, *three data bases, island of Hawaii, 1988*

Data base	Model[1]	Parameter[1] estimates	P[2]	CF[3]
Younger	1	a= -2.0095		1.013
		b= 1.1168	<0.0001	
	2	a= -2.1313		1.013
		b= 1.0724	<0.0001	
		c= 0.1352	0.0566	
Older	1	a= -2.7329		1.014
		b= 1.2886	<0.0001	
	2	a= -3.9200		1.006
		b= 0.9572	<0.0001	
		c= 0.9976	<0.0001	
Combined	1	a= -2.2909		1.016
		b= 1.1907	<0.0001	
	2	a= -2.4966		1.015
		b= 1.0777	<0.0001	
		c= 0.2864	<0.0001	

[1] 1: $Y_t = (e^{(a + 2b*\ln(D))}) * cf$
2: $Y_t = (e^{(a + 2b*\ln(D) + c*\ln(H))}) * cf$
in which:
Y_t = total above-ground biomass kg/tree
e = natural anti-logarithm
ln = natural logarithm
a = intercept (transformed)
c = height coefficient (transformed)
cf = correction factor (de-transformed)
[2] Observed significance level of regression model
[3] Correction factor (de-transformed)

RESULTS AND DISCUSSION

Of the two models tested, Model 2 had the best overall coefficients of variation (c.v.) and adjusted coefficients of determination (R^2) (*table 4*). Values for c.v. range from 9.7- to 17.5-percent, with adjusted R^2 values ranging from 0.968 to 0.993 for Model 2. Equations derived from Model 1 tend to have higher coefficients of variation (16.3- to 24.8-percent) and lower adjusted R^2 values (0.958 to 0.978) than Model 2 (*table 5*).

Equations that use d.b.h. but do not require height measurement can provide more rapid and less costly estimates of biomass. The equations for the younger age group had similar c.v.'s and adjusted R^2's for both models. However, for the older age group and combined equations, Model 1 was clearly less suitable for biomass prediction than Model 2.

Table 3—*Regression characteristics for two stem-only biomass equation forms for* Eucalyptus saligna, *three data bases, island of Hawaii, 1988*

Data base	Model[1]	Parameter[1] estimates	P[2]	CF[3]
Younger	1	a= -2.4279		1.019
		b= 1.1247	<0.0001	
	2	a= -2.9152		1.015
		b= 0.9471	<0.0001	
		c= 0.5408	<0.0001	
Older	1	a= -2.7733		1.017
		b= 1.2706	<0.0001	
	2	a= -4.2426		1.005
		b= 0.8605	<0.0001	
		c= 1.2347	<0.0001	
Combined	1	a= -2.8232		1.030
		b= 1.2442	<0.0001	
	2	a= -3.4383		1.015
		b= 0.9065	<0.0001	
		c= 0.8565	<0.0001	

[1] 1: $Y_s = (e^{[a + 2b*\ln(D)]}) * cf$
2: $Y_s = (e^{[a + 2b*\ln(D) + c*\ln(H)]}) * cf$
in which:
Y_s = stem-only biomass kg/tree
e = natural anti-logarithm
ln = natural logarithm
a = intercept (transformed)
b = diameter coefficient (transformed)
c = height coefficient (transformed)
cf = correction factor (de-transformed)
[2] Observed significance level of regression model
[3] Correction factor (de-transformed)

Table 4—*De-transformed regression equations based on three sample tree data bases used to predict stem-only and total above-ground biomass per tree for* Eucalyptus saligna, *island of Hawaii (Model 2), 1988*

Data base (age)	Regression equation[1]	CV[2] (pct)	Adjusted R^2
Younger (2-3.5 years)	$Y_s = 0.05501 * (D^{1.8942}) * (H^{0.5408})$	17.56	0.968
	$Y_t = 0.12022 * (D^{2.1448}) * (H^{0.1352})$	16.16	0.972
Older (4-6 years)	$Y_s = 0.01444 * (D^{1.7210}) * (H^{1.2347})$	9.72	0.993
	$Y_t = 0.01996 * (D^{1.9144}) * (H^{0.9976})$	11.08	0.990
Combined (2-6 years)	$Y_s = 0.03260 * (D^{1.8130}) * (H^{0.8565})$	17.43	0.979
	$Y_t = 0.08360 * (D^{2.1554}) * (H^{0.2864})$	17.17	0.977

[1] Y_s = predicted stem-only dry weight (kg)
Y_t = predicted total dry weight (kg)
D = diameter at breast height (cm)
H = total height (m)
[2] De-transformed coefficient of variation

To check the accuracy of the regressions, the average predicted biomass per tree for each equation was compared to the average actual biomass per tree for each data base and each equation (*table 6*). Not unexpectedly, all equations tested well against average actual biomass per tree for their own equation data base. The combined, Model 2 equation overestimates average tree biomass for the younger data base (Combined: +4.0 percent stem-only and +1.7 percent total biomass) and underestimates biomass for the older data base (Combined: -7.3 percent stem-only and -4.5 percent total biomass). The older tree data base's equations predicted biomass quite accurately when compared to the actual average biomass for the 96 older trees (Older: 0.0 percent stem-only and + 0.7 percent total biomass). As expected, performance of the combined equation on the overall data base was best for the total above-ground biomass (Combined: -2.2 percent vs. Older: -8.0 percent vs. Younger: -9.9 percent). For stem-only biomass however, the older tree equation was closer to the actual biomass than was the combined equation (Older: -2.0 percent vs. Combined: -3.6 percent).

Model 1 tested well against the actual biomass per tree for the younger data base, in fact it performed identically to Model 2 (Younger: -1.6 percent stem-only and -0.6 percent total biomass). For the older and combined data bases Model 1 did not perform as well as Model 2.

Twelve 5- to 6-year-old trees, from Hamakua Coast plantations, were felled and weighed to provide a check of the accuracy of the older tree stem-only and total biomass equations (Model 2: diameter + height). The mean predicted stem-only and total biomass for the 12 trees was compared to the actual measured mean biomass. The prediction equations performed quite well, with the stem-only form underestimating the actual stem-only biomass by 3.5 percent and the total biomass equation underestimating the actual total biomass of the twelve trees by 2.1 percent (*tables 7, 8*).

The predicted biomass for each individual tree also tested quite well against its actual measured biomass. The 95 percent prediction limits for the older tree biomass equations were used to assess the accuracy of the prediction. Utilizing the total biomass equation, 11 of the 12 trees (92 percent) were within the prediction limits (*table 7*). The one tree which did not meet the prediction limits, had d.b.h. and height measurements which were outside the range of data used to derive the older biomass equation (maximum sized sample tree: d.b.h. = 24.7 cm and height = 27.9 m vs. tree number 2: d.b.h. = 25.0 cm and height = 29.1 m).

For the stem-only biomass equation, 9 of the 12 trees (75 percent), fell within the prediction limits for the equation (*table 8*). Again the biomass for tree number 2 is interpolated outside of the data, while tree numbers 1 and 3 exceed their prediction limits by 15 and 17 percent, respectively.

Table 5—*De-transformed regression equations based on three sample tree data bases used to predict stem-only and total above-ground biomass per tree for* Eucalyptus saligna, *island of Hawaii (Model 1), 1988*

Data base (age)	Regression equation[1]	CV[2] (pct)	Adjusted R^2
Younger (2-3.5 years)	$Y_s = 0.089898 * (D^{2.2494})$	19.75	0.959
	$Y_t = 0.135798 * (D^{2.2336})$	16.27	0.972
Older (4-6 years)	$Y_s = 0.063517 * (D^{2.5412})$	18.57	0.973
	$Y_t = 0.065941 * (D^{2.5772})$	16.90	0.978
Combined (2-6 years)	$Y_s = 0.061198 * (D^{2.4884})$	24.83	0.958
	$Y_t = 0.102794 * (D^{2.3814})$	18.13	0.975

[1] Y_s = predicted stem-only dry weight (kg)
Y_t = predicted total dry weight (kg)
D = diameter at breast height (cm)
[2] De-transformed coefficient of variation

Table 6—*Average biomass predicted for* Eucalyptus saligna *by three equations and two models, and actual above-ground biomass per tree for three data bases, island of Hawaii, 1988*

Model[1] and data base	Type	Actual avg.	Predictive equation, by stand age: Younger		Older		Combined	
		kg/tree	*kg/tree*	*pct*	*kg/tree*	*pct*	*kg/tree*	*pct*
Model 1								
Younger	Stem	12.5	12.3	-1.6	—	—	14.6	+16.8
	Total	18.1	18.0	-0.6	—	—	19.2	+6.1
Older	Stem	50.4	—	—	51.1	+2.2	42.5	-15.7
	Total	57.6	—	—	58.6	+1.7	53.1	-7.8
Combined	Stem	25.2	19.0	-24.6	28.5	+13.1	24.0	-4.8
	Total	31.4	27.6	-12.1	32.5	+3.5	30.6	-2.5
Model 2								
Younger	Stem	12.5	12.3	-1.6	—	—	13.0	+4.0
	Total	18.1	18.0	-0.6	—	—	18.4	+1.7
Older	Stem	50.4	—	—	50.4	0.0	46.7	-7.3
	Total	57.6	—	—	58.0	+0.7	55.0	-4.5
Combined	Stem	25.2	20.9	-17.1	24.7	-2.0	24.3	-3.6
	Total	31.4	28.3	-9.9	28.9	-8.0	30.7	-2.2

[1]Model: 1 = $\ln Y = (a + 2b*\ln[D])$
2 = $\ln Y = (a + 2b*\ln[D] + c*\ln[H])$

Table 7—*Performance of the 4- to 6-year-old* Eucalyptus saligna *biomass equation[1] in predicting total dry biomass for 12 trees 5- to 6-years-old, island of Hawaii, 1988*

Tree No.	Total height	D.b.h.	Actual biomass	Predicted biomass	Difference	Prediction limits
	m	*cm*	*kg/tree*			
1	27.5	18.6	170.3	146.7	23.6	±32.1
2	29.1	25.0	336.8	273.4	63.4[2]	±59.7
3	26.1	17.3	143.4	121.2	22.2	±26.5
4	22.9	16.3	87.5	94.9	-7.5	±20.8
5	23.7	21.0	177.3	159.6	17.8	±34.9
6	21.1	14.1	66.7	66.6	0.1	±14.7
7	24.3	19.3	116.6	139.2	-22.6	±30.4
8	28.6	22.1	182.6	212.2	-29.7	±46.4
9	25.8	22.8	176.2	203.3	-27.1	±44.4
10	11.3	5.7	6.8	6.3	0.5	±2.4
11	22.5	13.7	62.0	66.9	-4.9	±14.7
12	18.8	10.0	27.1	30.6	-3.5	±7.0
Mean	23.5	17.2	129.4	126.7	2.7	

[1] $Y_t = 0.01996 * (D^{1.9144}) * (H^{0.9976})$
[2] Statistically non-significant at p>0.05

RECOMMENDATIONS

The recommended method of estimating stem-only and total above-ground biomass for *E. saligna* trees in Hawaiian energy plantations is to use the younger tree equations for 2- and 3.5-year-old trees and the older tree equations for 4- to 6-year-old trees. Equations using Model 1, developed from the younger data base, are recommended as alternative biomass equations for young *E. saligna* stands (<4-year-old trees). Combined equations for *E. saligna* are not recommended across the entire energy plantation age range.

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Table 8—*Performance of the 4- to 6-year-old* Eucalyptus saligna *biomass equation*[1] *in predicting stem-only dry biomass for 12 trees 5- to 6-years-old, island of Hawaii, 1988*

Tree No.	Total height	D.b.h.	Actual biomass	Predicted biomass	Difference	Prediction limits
	m	*cm*		*kg/tree*		
1	27.5	18.6	161.0	132.3	28.7[2]	±25.0
2	29.1	25.0	300.2	235.9	64.3[2]	±44.5
3	26.1	17.3	133.7	109.5	24.2[2]	±20.7
4	22.9	16.3	80.9	84.1	-3.2	±16.0
5	23.7	21.0	136.2	135.7	0.5	±25.7
6	21.1	14.1	60.7	59.6	1.1	±11.4
7	24.3	19.3	102.5	121.0	-18.5	±22.9
8	28.6	22.1	165.3	186.8	-21.5	±35.3
9	25.8	22.8	153.7	173.6	-19.9	±32.8
10	11.3	5.7	6.4	5.8	0.6	±2.2
11	22.5	13.7	56.4	61.0	-4.6	±11.7
12	18.8	10.0	24.9	28.4	-3.5	±5.7
Mean	23.5	17.2	115.1	111.1	4.0	

[1] $Y_s = 0.01444 * (D^{1.7210}) * (H^{0.9976})$
[2] Statistically non-significant at $p>0.05$

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