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Equations for Predicting Biomass of Six Introduced Subtropical Tree Species, Island of Hawaii

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Regression equations to predict total and stem-only above-ground dry biomass for six species (*Acacia melanoxylon, Albizia falcataria, Eucalyptus globulus, E. grandis, E. robusta*, and *E. urophylla*) were developed by felling and measuring 2- to 6-year-old plantation trees on the island of Hawaii. Logarithmic transformations of the equations using diameter and height are recommended for estimating *Albizia falcataria* and *E. grandis* biomass, whereas logarithmic equations using diameter only are recommended for the other four species that have fewer sample trees collected from a single location.

Retrieval Terms: *Eucalyptus, Acacia, Albizia*, prediction equations, biomass, plantations, Hawaii

Interest in the use of biomass as an alternate source of renewable energy or as a feedstock for biochemical conversion to a variety of products continues unabated. A logical place to develop biomass production for energy conversion is the State of Hawaii—an isolated island chain with no natural reserves of fossil fuel, but with a subtropical climate, a year-round growing season, and surplus agricultural and forest lands. Burning of bagasse (plant fiber remaining after sugarcane processing) by island sugar factories has supplied a substantial portion of Hawaii's power since the early 1960's. But in the late 1970's high oil prices and declining sugar production created a need for an alternate source of biofuel.

In 1979, BioEnergy Development Corporation, a wholly-owned subsidiary of C. Brewer and Company, Ltd., and the USDA Forest Service, began a joint research and development energy project. Funded by the U.S. Department of Energy, the project is designed to explore the feasibility of growing short-rotation, intensively-cultured eucalypt plantations for the production of biomass energy on the island of Hawaii.

This note describes the use of regression equations to estimate the above-ground biomass of six subtropical tree species on the island of Hawaii. Equations using diameter and height as variables are recommended for estimating *Albizia falcataria* and *Eucalyptus grandis* biomass; equations using diameter only are recommended for the other four species studied: *Acacia melanoxylon, E. globulus, E. robusta* and *E. urophylla.*

METHODS

Methods for determining above-ground dry weight of standing trees by non-destructive measurements[1] are useful for estimating biomass in growing plantations. Sample trees were felled and measured to develop equations for predicting the biomass of the six introduced tree species: *Acacia melanoxylon* R. Br., *Albizia falcataria* (L.) Fosberg, *Eucalyptus globulus* Labill., *E. grandis* Hill ex Maid., *E. robusta* Sm., and *E. urophylla* S.T. Blake. Previously, biomass equations were developed elsewhere for *E. globulus*,[2,3] and *E. grandis*.[4,5] These equations, however, were derived for different soil-climate situations, age ranges, and cultural regimes than the Hawaiian energy plantations reported herein. Development of sampling, measurement, and analysis techniques were based on prior work in nearby plantations on another introduced species, *E. saligna* Sm.[6]

Three Test Sites

Sample trees were growing at three sites in BioEnergy tree farms along the Hamakua Coast northwest of Hilo (about lat. 19°50' N, long. 155°09' W) on the windward slope of Mauna Kea, on the island of Hawaii. Onomea is at 420 m elevation and Chin Chuck and Kamae are both at about 480 m elevation. The soil at all three sites is Akaka silty clay loam, a thixotropic isomesic Typic Hydrandept, strongly acid (pH 5.0 to 5.3), developed on volcanic ash. Rainfall averages about 6,000 mm annually, relatively evenly distributed but monthly totals vary greatly from year to year.

Sample Stands

Eucalyptus globulus, *E. robusta*, and *E. urophylla* were growing at Onomea in a 6-year-old species trial in small (24 to 36 trees) replicated plots planted at 1.5- by 1.5-m spacing.[7] The 6-year-old *E. grandis*, *Acacia melanoxylon*, and *Albizia falcataria* were also growing at Onomea in a *Eucalyptus*/legume admixture trial planted at 2- by 2-m spacing with alternating rows of *Eucalyptus* and *Acacia* or *Albizia* to provide a 50:50 *Eucalyptus*/legume mix.[8]

The 4-year-old *Albizia* were growing at Chin Chuck in a *Eucalyptus*/*Albizia* admixture trial planted with various mixtures at 2- by 2-m spacing. The 2-year-old *Albizia* were growing in species trials (108 trees per replication) on two sites at Kamae planted at 1.5- by 1.5-m spacing. The 3- and 5-year-old *E. grandis* trees sampled were growing in operational field plantings spaced at 1.5- by 1.5-m at Kamae.

Selection of Sample Trees

From 6-year-old stands, 15 to 21 trees of each species were sampled across the range of stem diameters, as were the 19 *Albizia* trees from the 4-year-old stand. One-third of the trees felled had diameters smaller than the average diameter at breast height (1.3 m) for the stand, including one at or near the minimum. Among the other trees, one was selected with a diameter close to the average for the stand and the rest had larger diameters, including one at or near the maximum. For the 3- and 5-year-old *E. grandis* trees taken from field plantings, a range of sizes were sampled. In the case of the 2-year-old *Albizia*, complete isolation rows were cut (56 trees) with no attempt to select representative diameter sizes. The number of trees sampled, average diameter at breast height and average total height of each stand, and the range of diameters and heights covered by the sample trees were tabulated (*tables 1, 2*).

Table 1—*Parameters of stands sampled for biomass equation development for six species grown on the island of Hawaii, 1988*

Parameters	Acacia melanoxylon	Albizia falcataria	Eucalyptus			
			globulus	grandis	robusta	urophylla
	6-year-old stands					
Spacing (m)	2.0x2.0	2.0x2.0	1.5x1.5	2.0x2.0	1.5x1.5	1.5x1.5
Average d.b.h. (cm)	8.4	13.6	6.9	13.2	9.5	9.4
Average height (m)	9.1	15.6	10.6	16.8	13.4	13.1
Sample trees (no.)	16	20	15	21	16	15
		4-year-old stands		*5-year-old stands*		
Spacing (m)		2.0x2.0		1.5x1.5		
Average d.b.h. (cm)		10.4		(1)		
Average height (m)		11.5		(1)		
Sample trees (no.)		19		8		
		2-year-old stands		*3-year-old stands*		
Spacing (m)		1.5x1.5		1.5x1.5		
Average d.b.h. (cm)		8.3		(1)		
Average height (m)		7.3		(1)		
Sample trees (no.)		56		10		

[1]Trees sampled were in field plantings for which average d.b.h. and height were not obtained.

Table 2—*Size ranges of sample trees used in biomass equation development for six species in plantations grown on the island of Hawaii, 1988*

Parameters	Acacia melanoxylon	Albizia falcataria	Eucalyptus			
			globulus	grandis	robusta	urophylla
	Range in size of sample trees					
D.b.h. (cm)	2.7-17.9	3.2-26.0	1.6-15.5	1.5-38.2	1.4-26.0	1.8-23.3
Height (m)	4.4-15.1	4.5-25.6	4.5-17.2	4.2-29.4	3.6-22.0	3.6-23.8
	Number of sample trees					
Total[1]	16	95	15	39	16	15
D.b.h. <10 cm	7	66	9	17	7	6
D.b.h. ≥10 cm	9	29	6	22	9	9
D.b.h. ≥20 cm	0	9	0	10	3	3

[1]Total does not add since trees in the ≥20 cm class are also included in the ≥10 cm class.

Field Measurements

All trees were felled with a chain saw, leaving a 15 cm stump. Dead branches were removed and discarded on the assumption that in an operational harvest they would be broken off during felling and skidding and therefore would not reach the landing to be chipped.

Total height was measured to the nearest 0.1 m and number of stems (if more than one) originating below mid-height was recorded for *Albizia*, which tends to fork low on the stem. Diameters (outside bark) were measured to the nearest 0.1 cm at the butt, d.b.h., and at one-half and three-fourths of total height.

All live branches and leaves were removed, including the green top of the main stem at the point where the bark changed from brown to green at a diameter of about 2.5 cm. Total green weight of all leaves and branches was determined for each tree. For each tree, a representative subsample of the leaves and branches was weighed, then all leaves were stripped off and the bare branches were reweighed (scale precision ± 0.23 kg) to determine the green weight of leaves and branches. A subsample of the leaves and ten 5-cm long sections of branches including the green top were collected to determine the dry weight percentage. The stem was cut into manageable pieces, weighed separately and totaled to obtain green stem weight for each tree. Stem disks about 2.5 cm thick were cut at d.b.h., at one-half height, and at three-fourths height, and bagged for determining dry-weight percentage.

Green weights of leaf, branch section,

and stem disk samples were determined in the laboratory (scale precision ±0.1g). Leaf and branch samples were then dried at 105 °C in a forced-draft oven for at least 48 hours. Stem disk samples were dried at 105 °C to a constant weight. Dry matter content as a percent of green weight was then calculated for the leaves, branches and stems of each tree. Dry matter percentages were used to calculate dry weight for each tree component from field measurements of green weight.

Table 3—*Regression characteristics for two models for estimating stem-only dry biomass of six species from 2- to 6-year-old plantations grown on the island of Hawaii, 1988*

Species	Model[1]	Parameter[1] estimates	P[2]	C.V.[3] (pct)	Adj. R^2
Acacia melanoxylon	1	a= -2.4476		14.39	0.990
		b= 1.1889	<0.0001		
		cf= 1.010			
Acacia melanoxylon	2	a= -2.6127		14.82	0.989
		b= 1.1265	<0.0001		
		c= 0.1894	0.6553([4])		
		cf= 1.011			
Albizia falcataria	1	a= -3.6395		36.00	0.936
		b= 1.3587	<0.0001		
		cf= 1.063			
Albizia falcataria	2	a= -4.0770		34.47	0.941
		b= 1.1018	<0.0001		
		c= 0.6652	0.0035		
		cf= 1.058			
Eucalyptus globulus	1	a= -2.5818		16.28	0.991
		b= 1.2502	<0.0001		
		cf= 1.013			
Eucalyptus globulus	2	a= -3.1932		16.50	0.991
		b= 1.0851	0.0002		
		c= 0.5177	0.4295([4])		
		cf= 1.014			
Eucalyptus grandis	1	a= -2.6168		21.09	0.983
		b= 1.1953	<0.0001		
		cf= 1.022			
Eucalyptus grandis	2	a= -3.6544		12.95	0.993
		b= 0.8589	<0.0001		
		c= 0.9824	<0.0001		
		cf= 1.008			
Eucalyptus robusta	1	a= -2.2407		30.50	0.976
		b= 1.1335	<0.0001		
		cf= 1.045			
Eucalyptus robusta	2	a= -1.1670		30.85	0.976
		b= 1.4122	0.0010		
		c= -0.9025	0.4176([4])		
		cf= 1.047			
Eucalyptus urophylla	1	a= -2.5984		16.26	0.993
		b= 1.2475	<0.0001		
		cf= 1.013			
Eucalyptus urophylla	2	a= -2.6068		16.93	0.993
		b= 1.2443	<0.0001		
		c= 0.0086	0.9824([4])		
		cf= 1.014			

[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 dry 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 parameter
[3]Coefficient of variation (de-transformed)
[4]Statistically not significant at 0.05 confidence level

Data Analysis

Regression analyses of tree biomass on tree diameter and height demonstrated that variance increased as tree size increased for the six species. As was the case for *E. saligna*,[6] logarithmic transformation of the equations was used to equalize variances to satisfy an underlying assumption of regression analysis. Equations were developed for both stem-only and total above-ground dry biomass to simulate different levels of crop removal and utilization. Tree diameter was used as an independent variable singly and in combination with tree height.

RESULTS AND DISCUSSION

Two models were tested in regression analyses of tree biomass data for the six introduced tree species:

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 tree height in meters. To correct for bias in the estimate due to the logarithmic transformation, a correction factor (cf) for each derived equation, was calculated utilizing the following formula: $cf = e^{variance/2}$, in which e = the natural anti-logarithm, and 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]

Differences in de-transformed coefficient of variation (c.v.) and coefficient of determination (adjusted R^2) were relatively small (*tables 3, 4*). The largest differences were seen between species, comparing the same model and type of biomass. For Model 1 (stem-only biomass) the largest differences in the coefficient of variation were between *A. falcataria* vs. *A. melanoxylon*, 14.4- vs. 36.0-percent. The largest differences for adjusted R^2 were found between the species *E. urophylla* and *A. falcataria*, 0.993 vs. 0.936 respectively. Somewhat smaller differences occurred between stem-only and total above-ground biomass for the same species and model; e.g., for *A. melanoxylon*, 25.5- vs. 14.4-percent in c.v. and 0.990 vs. 0.968 in adjusted R^2 for Model 1. The smallest differences were found by comparing models of

Table 4—*Regression characteristics for two models for estimating total above-ground dry biomass of six species from 2- to 6-year-old plantations grown on the island of Hawaii, 1988*

Species	Model[1]	Parameter[1] estimates	P[2]	C.V.[3] (pct)	Adj. R^2
Acacia melanoxylon	1	a= -1.9254		25.52	0.968
		b= 1.1605	<0.0001		
		cf= 1.032			
Acacia melanoxylon	2	a= -1.4709		25.97	0.967
		b= 1.3323	<0.0001		
		c= -0.5213	0.4810(4)		
		cf= 1.033			
Albizia falcataria	1	a= -3.1353		33.61	0.938
		b= 1.2965	<0.0001		
		cf= 1.055			
Albizia falcataria	2	a= -3.3724		33.27	0.940
		b= 1.1573	<0.0001		
		c= 0.3604	0.0968(4)		
		cf= 1.054			
Eucalyptus globulus	1	a= -2.5049		14.98	0.993
		b= 1.2560	<0.0001		
		cf= 1.011			
Eucalyptus globulus	2	a= -3.0699		15.18	0.992
		b= 1.1034	<0.0001		
		c= 0.4784	0.4279(4)		
		cf= 1.012			
Eucalyptus grandis	1	a= -2.3501		17.01	0.988
		b= 1.1807	<0.0001		
		cf= 1.014			
Eucalyptus grandis	2	a= -2.6806		16.37	0.989
		b= 1.0736	<0.0001		
		c= 0.3129	0.0567(4)		
		cf= 1.013			
Eucalyptus robusta	1	a= -2.1698		30.26	0.978
		b= 1.1600	<0.0001		
		cf= 1.045			
Eucalyptus robusta	2	a= -0.8914		30.22	0.978
		b= 1.4918	0.0006		
		c= -1.0745	0.3278(4)		
		cf= 1.045			
Eucalyptus urophylla	1	a= -2.1426		21.01	0.988
		b= 1.1805	<0.0001		
		cf= 1.022			
Eucalyptus urophylla	2	a= -1.5212		20.29	0.989
		b= 1.4195	<0.0001		
		c= -0.6332	0.1909(4)		
		cf= 1.020			

[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 dry biomass kg/tree
e = natural anti-logarithm
ln = natural logarithm
a = intercept (transformed)
b = diameter coefficient (transformed)
c = height coefficient (transfomed)
cf = correction factor (de-transformed)
[2]Observed significance level of regression parameter
[3]Coefficient of variation (de-transformed)
[4]Statistically not significant at 0.05 confidence level

the same species and type of biomass; e.g., for *E. grandis*, 21.1- vs. 13.0-percent in c.v. and 0.983 vs. 0.993 in adjusted R^2 for stem-only biomass. Other species showed considerably less variability.

Equation Models

The small differences in c.v. and adjusted R^2 between Models 1 and 2, indicate that in these equations d.b.h. accounts for most of the variation in biomass. Estimating biomass from one easily-measured variable such as d.b.h. is simple to apply, but over large areas, heights and thus biomass often vary for the same tree d.b.h. due to site or stocking differences. Therefore, predictions using both d.b.h. and height are preferred in most situations except in those special cases where stand conditions are similar to those where the biomass sample was derived. Only two species have significant or nearly significant height coefficients: *A. falcataria* and *E. grandis* (*tables 3, 4*). For these two species, Model 2 (diameter + height) has the lowest c.v. and the highest adjusted R^2, although the differences are small. Three of the four other species have negative as well as non-significant height coefficients. Model 2 is therefore recommended for *Albizia* and *E. grandis* while for the other four species—*A. melanoxylon*, *E. globulus*, *E. robusta*, and *E. urophylla*—Model 1 (diameter-only) is recommended.

To simplify calculation of total tree and stem-only biomass, the regression equations have been de-transformed (*table 5*). The correction factor has been built into these equations.

Sample Characteristics

Greater sample sizes resulted in greater ranges of height and diameter, and explain some of the better performances of the equation using d.b.h. and height for *A. falcataria* and *E. grandis* compared to the other species. Sample tree numbers were 95 and 39 for *Albizia* and *E. grandis* respectively, in three age classes from several locations for both species, compared to only 15 or 16 trees in one age class from one location for each of the other species (*table 1*). In addition, the number of trees larger than 10- and 20-cm d.b.h. in the samples of *Albizia* and *E. grandis* was three or more times greater than for any of the other four species (*table 2*). The larger diameters in the samples, and the site differences introduced by stands from different locations, provided better discrimination of the height contribution. For *Albizia*, which had enough trees in each age class/location sample to derive separate equations, the height coefficient was significant or nearly so for the combined equation, but not significant for any of the separate equations.

Biomass Equation Checks

We compared the models we developed with those found in the literature for predicting biomass. We found those other equations less suitable for predicting biomass of Hawaiian-grown *E. grandis*. An equation developed in South Africa from 2-year-old

E. grandis trees[5] underestimates stem-only biomass of *E. grandis* data base trees by an average 16.2 percent compared to a 2.8 percent overestimate by our *E. grandis* equation (*table 6*). An equation developed in Hawaii for *E. saligna*[6] was also compared with the *E. grandis* equation using *E. grandis* data base trees. The two species appear very similar in Hawaiian plantations, and the *E. saligna* equation was based on a much greater sample size (286 vs. 39 trees). However, the average biomass estimated by the *E. grandis* equation was closer to actual biomass (2.8 percent overestimate) than by the *E. saligna* equation (16.6 percent overestimate [*table 6*]). Differences in average wood specific gravity between *E. grandis* and *E. saligna* (0.358 vs. 0.386 at 2 years, + 7.5 percent; and 0.367 vs. 0.413 at 5 years, + 12.5 percent[10]) probably account for much of the difference between *E. saligna* predicted and *E. grandis* actual biomass per tree.

A South African equation[3] was used to check the *E. globulus* biomass equation. Predicted stem-only biomass averaged for the 15-tree *E. globulus* data base was underestimated 22.7 percent by the South African equation and 2.1 percent by our *E. globulus* equation (*table 6*).

A preliminary check of biomass production of *E. urophylla* in French Guiana[11] did not provide an equation check but showed similar growth rates for 2-year-old stands in French Guiana at 2- by 2-m spacing: 7.1 cm average d.b.h. and 8.4 m height; in Hawaii at 1.5- by 2.0-m spacing: 7.2 cm average d.b.h. and 8.4 m height.[12]

Table 5—*De-transformed equations for 6 species developed from 2- to 6-year-old plantations grown on the island of Hawaii and recommended for prediction of stem-only and total above-ground per tree dry biomass, 1988*

Species	Equations[1]
Acacia melanoxylon	$Y_s = 0.087366 * (D^{2.3778})$
	$Y_t = 0.150484 * (D^{2.3210})$
Albizia falcataria	$Y_s = 0.017945 * (D^{2.2026}) * (H^{0.6660})$
	$Y_t = 0.036207 * (D^{2.3146}) * (H^{0.3600})$
Eucalyptus globulus	$Y_s = 0.076621 * (D^{2.5000})$
	$Y_t = 0.082582 * (D^{2.5120})$
Eucalyptus grandis	$Y_s = 0.026084 * (D^{1.7178}) * (H^{0.9824})$
	$Y_t = 0.069413 * (D^{2.1472}) * (H^{0.3129})$
Eucalyptus robusta	$Y_s = 0.111171 * (D^{2.2670})$
	$Y_t = 0.119339 * (D^{2.3200})$
Eucalyptus urophylla	$Y_s = 0.075360 * (D^{2.4950})$
	$Y_t = 0.119931 * (D^{2.3610})$

[1] Y_s = stem-only dry biomass in kilograms
Y_t = total above-ground dry biomass in kilograms
D = diameter at breast height in centimeters (1.3 m height)
H = total tree height in meters

Table 6—*Actual and predicted mean stem-only dry weight of* Eucalyptus grandis *and* Eucalyptus globulus, *using different equations and sample tree data bases, 1988*

Species in Hawaii	Actual weight	Predicted by equation	
		Hawaii	Other
		kg/tree	
Eucalyptus grandis	74.2	76.3	[1]62.2
Eucalyptus grandis	74.2	76.3	[2]86.5
Eucalyptus globulus	23.3	22.8	[3]18.0

[1] South Africa (Darrow 1984): 2-year-old trees, 2 sq. m of growing space per tree (Ln Y = -2.082 + 2.157 Ln[DBH]).
[2] Hawaii (*Eucalyptus saligna*) (Whitesell and others 1988): 2- to 6-year-old trees, 2.25 sq. m of growing space per tree ($Y = 0.03260 * [D^{1.8130}] * [H^{0.8565}]$).
[3] South Africa (Schönau and Boden 1982): 5-year-old trees, unspecified growing space (Y = 0.2839 + 0.0202 [DBH²] - 1.1054 + 0.1924 [DBH²]).

RECOMMENDATIONS

It is often tempting to extrapolate by using biomass equations from other areas, or for other species, when estimates of biomass are needed and no local equations exist for the species of interest. However, our tests suggest that sampling as few as 15 trees to derive a local biomass equation will produce more accurate results.

The equations using diameter and height (Model 2) for *Albizia falcataria* and *Eucalyptus grandis*, and diameter-only (Model 1) for the other four species are recommended for estimating biomass on Hamakua Coast sites on the island of Hawaii. The *Albizia* and *E. grandis* equations, which are derived from a larger data base that includes several locations and age classes, are probably more suitable for extrapolation to other soil-climate situations in Hawaii. Further measurements to validate and expand data bases are advised, especially for the four species now represented by only 15 or 16 sample trees each.

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