BIOMASS EQUATIONS FOR TROPICAL TREE PLANTATION SPECIES USING SECONDARY DATA FROM THE PHILIPPINES

Ma. Regina N. Banaticla, Renezita F. Sales and Rodel D. Lasco

Estimation of the magnitude of sinks and sources of carbon requires reliable estimates of the biomass of forests and of individual trees. Equations for predicting tree biomass have been developed using secondary data involving destructive sampling in plantations in several localities in the Philippines. These equations allow estimates of carbon sequestration to be made at much lower cost than would be incurred if detailed stand inventories were undertaken. The species included in the study reported here include *Gmelina arborea*, *Paraserianthes falcataria*, *Swietenia macrophylla* and Dipterocarp species in Mindanao; *Leucaena leucocephala* from Laguna, Antique, Cebu, Iloilo, Rizal, and Ilocos Sur, and *Acacia mangium*, *Acacia auriculiformis* and *G. arborea* in Leyte. Non-linear regression was used to derive species-specific, site-specific and generic equations between yield and diameter of the form $y = aD^b$. Equations were evaluated based on the correlation coefficient, standard error of the estimate and residual plots. Regressions resulted to high r values (>0.90). In some cases, non-homogeneous variance was encountered. The generic equation improved estimates compared with models used in previous studies.

INTRODUCTION

Climate change is of major community concern, the most recent Intergovernmental Panel on Climate Change (IPCC) assessment report concluding that there is strong evidence that anthropogenic activities have affected the world's climate (IPCC 2001). The rise in global temperatures has been attributed to emission of greenhouse gases, notably CO_2 (Schimell *et al*. 1995). Forest ecosystems can be sources and sinks of carbon (Watson *et al*. 2000). Deforestation and change in land use result in a high level of emissions of CO_2 and other greenhouse gases. Presently, it is estimated that the world's tropical forests emit about 1.6 Gt of CO_2-C per year (Watson *et al.* 2000). Land-use and forestry also have the potential to mitigate carbon emissions through the conservation of existing carbon reservoirs (i.e. by preventing deforestation and forest degradation), improvement of carbon storage in vegetation and soils and wood products, and substitution of biomass for fossil fuels for energy production (Brown *et al*. 1993). Estimation of the magnitude of these sinks and sources of carbon requires reliable estimates of the biomass of forests and of individual trees.

Direct measurement of tree biomass involves felling an appropriate number of trees and estimating their field- and oven-dry weights, a method that can be costly and impractical, especially when dealing with numerous species and large sample areas. Rather than performing destructive sampling all the time in the field, an alternative method is to use regression equations (developed from a previously felled sample of trees) that predict biomass given some easily measurable predictor variable, such as tree diameter or total height. Such equations have been developed for many species (Parde 1980), including fast-growing tropical species (Lim 1988, Fownes and Harrington 1991, Dudley and Fownes 1992, Stewart *et al*. 1992).

Biomass is typically predicted using either a linear (in the parameter to be estimated) or non-linear regression model, of the following forms:

Linear: $Y = \beta X + \varepsilon$ (Equation 1)
Nonlinear: $Y = X^{\beta} + \varepsilon$ (Equation 2)

where
Y = observed tree biomass
X = predictor variable (diameter, height)
β = model parameter
ε = error term

The nonlinear model can be subdivided into two types: 'intrinsically linear' and 'intrinsically nonlinear'. A model that is intrinsically linear can be expressed by transformation of the variables into standard linear form. If a nonlinear model cannot be expressed in this form, then it is intrinsically nonlinear. An example of an intrinsically linear model is the power function:

$$y = aD^{b}e \quad \text{(Equation 3)}$$

where
y = tree biomass (or total height)
D = diameter at 1.30 m (dbh)
a, b = model parameters
e = error term

Taking the natural logarithms of both sides of the equation yields the linear form:

$$\ln y = \ln a + b \ln D + \ln e \quad \text{(Equation 4)}$$

In this form, the regression model can be fitted to biomass (or height) data using standard linear regression and least squares estimation. In earlier attempts to develop biomass equations for trees, logarithmic transformation was traditionally employed as a means of linearising nonlinear relationships, mainly because of the difficulty of solving non-linear relationships without the aid of high-speed computers (Payandeh 1981). However, there are disadvantages in using logarithmic transformations, including the assumption of a multiplicative error term in the model (Baskerville 1972) and difficulties in evaluating usual measures of fit such as R^2 and the standard error of estimate (SEE) in terms of the original data. In the case of biomass equations, nonlinear models usually produce a better fit than both the logarithmic and multiple linear regression models (Payandeh 1981).

Many works on mathematical models for biomass show the superiority of the power function (Equation 3 above), notably for estimation of the stems and roots of trees (Parde 1980, Fownes and Harrington 1991, Ketterings *et al*. 2001). The model also expresses the long-recognised allometry between two parts of the plant (Parde 1980), i.e. proportionality in the relative increment between the two parts (e.g. stem biomass and girth of a tree).

A generic equation for predicting individual aboveground tree biomass using dbh as predictor variable was developed by Brown (1997) using data on 170 trees of many species harvested from the moist forest zone of three tropical regions. This equation has been used in previous studies to determine indirectly the biomass and C storage of forest ecosystems n the Philippines (Lasco *et al*. 2002a and b, Lasco *et al*. 2004) because of the scarcity of local species- or site-specific biomass equations. However, generic equations applied to local data tend to overestimate the actual biomass of trees (Ketterings *et al*. 2000, Van Noordwijk *et al*. 2002, Macandog and Delgado 2002), which highlights the need to develop species-specific and site-specific equations that produce estimates that more closely reflect the characteristics of species and conditions in the Philippines.

RESEARCH METHOD

For this study, no destructive sampling of trees was done; instead existing data from studies involving destructive sampling for biomass determination of trees conducted in several localities in the Philippines by Kawahara *et al.* (1981), Tandug (1986) and Buante (1997) were re-analysed. A general description of the study sites from these sources is provided in Table 1.

The data sets consisted of individual tree measurements for dbh, total height and total aboveground biomass of tropical tree species, majority of which are fast-growing plantation species (Tables 2-4). Tandug (1986) and Buante (1997) both developed biomass regression equations with dbh and height as predictor variables. Nevertheless, both data sets were still analysed in order to develop simpler equations (i.e., those with fewer parameters and would not require prior transformation of data).

Table 1. Description of sampling sites from various data sources

Locality	Climate Type	Species	Forest type	Age (yr)	Stand density (stems/ha)	Source
Aras-asan, Mindanao	IV	*Paraserianthes falcataria*(L.) Nielsen	Plantation (timber)	4.9, 8.3	1085, 315	Kawahara *et al*. 1981
		Swietenia macrophylla King	Plantation (timber)	15.3	1147	
		Gmelina arborea Roxb.	Plantation (timber)	9.3	1191	
		Dipterocarpaceae	Natural forest	unknown	1144	
Laguna	I	*Leucaena leucocephala* de Wit	Plantation	9	459	Tandug 1986
Antique	III	*L. leucocephala*	Plantation	4	10742	
Cebu	III	*L. leucocephala*	Plantation	10	1500	
Ilocos Sur	I	*L. leucocephala*	Plantation	7	8140	
Iloilo	IV	*L. leucocephala*	Plantation	5	648	
Rizal	I	*L. leucocephala*	Plantation	2-4	8926	
Leyte	II	*Acacia auriculiformis* A. Cunn. ex Benth	Plantation (fuelwood)	4	2500	Buante 1997
		Acacia mangium Willd.	Plantation (fuelwood)	4	2500	
		G. arborea	Plantation (fuelwood)	4	2500	

A preliminary screening was done for each data set by producing scatter plots of raw i.e. untransformed data and log-transformed values of biomass vs dbh (Figures 1 to 6). Plots of log-transformed biomass vs dbh are expected to assume the shape of a straight line, based on the allometric relationship previously mentioned.

Table 2. Summary data of trees sampled by Kawahara *et al.* (1981)

Species	Number of trees	Dbh (cm)	Total height (m)	Total above-ground biomass (kg/tree)
Paraserianthes falcataria (5-yr old)	7	5.4 - 20.5	9.3 - 18.3	2.865 - 104.845
Paraserianthes falcataria (8-yr old)	13	4.1 - 36.1	4.3 - 33.6	2.682 - 533.299
Gmelina arborea	7	8.0 - 31.4	7.3 - 25.0	9.384 - 306.008
Swietenia macrophylla	5	6.7 - 26.0	5.6 - 18.9	7.247 - 314.610
Dipterocarpaceae	7	7.3 - 34.0	7.9 - 26.9	6.85 - 472.822

Table 3. Summary data of *L. leucocephala* trees sampled by Tandug (1986)

Locality or province	Number of trees	Dbh (cm)	Total height (m)	Total above-ground biomass (kg/tree)
Laguna	18	5.4 – 21.0	5.7 - 10.5	5.141 - 151.368
Antique	13	4.5 - 14.1	9.0 - 12.7	7.4896 - 72.8962
Cebu	21	10.0 - 31.8	12.3 - 19.0	35.995 - 534. 973
Ilocos Sur	18	5.2 - 20.8	10.1 - 21.0	11.093 - 287.349
Iloilo	14	5.1 - 13.8	8.3 - 10.3	8.7576 - 75.7346
Rizal	27	4.0 -16.2	5 .5 - 16.1	3.274 - 100.984

Table 4. Summary data of trees sampled by Buante (1997)

Species	Number of trees	Dbh (cm)	Total height (m)	Total above-ground biomass (kg/tree)
Acacia auriculiformis	30	7.2 - 12.9	6.48 - 9.50	15.708 - 49.080
Acacia mangium	30	7.1 - 12.5	6.20 - 8.90	11.775 - 48.827
Gmelina arborea	30	4.2 - 15.9	3.94 - 8.21	9.177 - 68.579

After this initial screening, nonlinear regression analysis of the data was performed with CurveExpert v.1.3 (Hyams 1997) software using the Levenberg-Marquardt algorithm. Practical experience in the field has shown the difficulty of obtaining accurate measurements of the height of standing trees, especially in natural forest stands. Bearing this in mind, priority has thus been given to a model with only diameter as predictor variable. Separate biomass equations of the form $y = aD^b$, with Y = total above-ground biomass of tree, D = diameter at breast height, and a,b = parameter estimates, were derived for each species and each site in the data sets. Pooled biomass data were also analysed to obtain generic equations with potential wider applicability. In the analysis, the effect of species and site differences on biomass was not considered. Species-specific, site-specific as well as generic equations were evaluated based on the correlation coefficient (r), standard error of the estimate (SEE) and residual plots.

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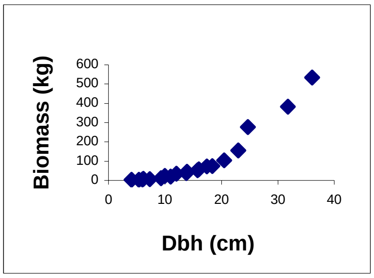
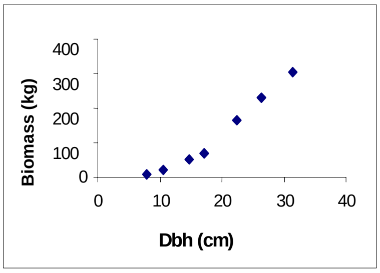
RESULTS AND DISCUSSION

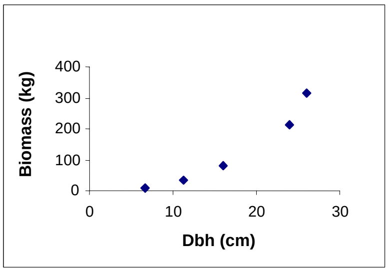
Scatter plots of Buante's data for *Acacia mangium*, *Acacia auriculiformis* and *Gmelina arborea* (Figure 3 and Figure 6) show no apparent relationship between biomass and diameter, which was not the case with the other two data sets. Log-transformed values also failed to achieve a good linear fit. Because Buante's data set appears not to exhibit the expected functional relationship between dbh and total aboveground biomass, it was decided to exclude this (secondary) data set from further analysis.



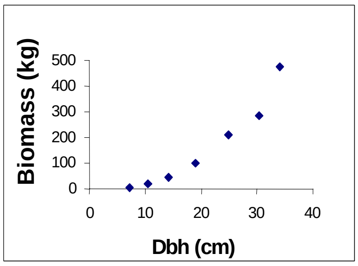
a. Biomass vs. Dbh: *P. falcataria*



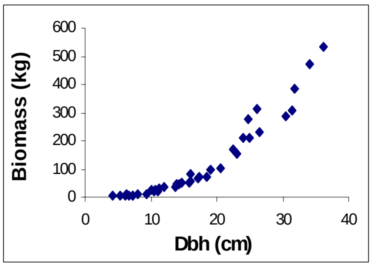
b. Biomass vs. Dbh: *G. arborea*



c. Biomass vs. Dbh: *S. macrophylla*

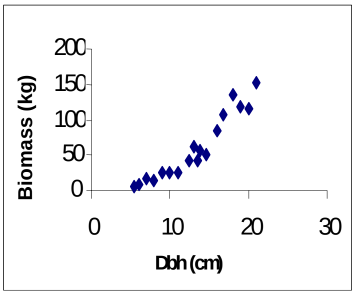


d. Biomass vs. Dbh: Dipterocarp species

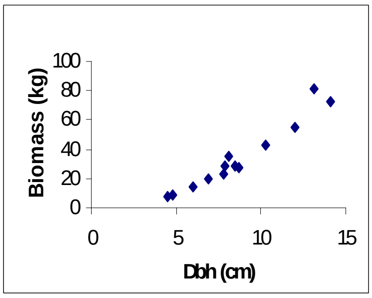


e. Biomass vs. Dbh: all species

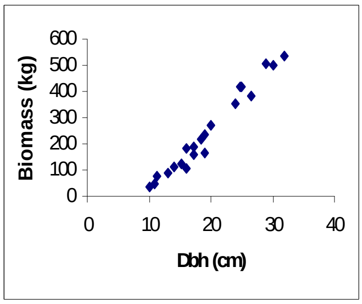
Figure 1. Scatter plots of untransformed biomass vs. dbh from Kawahara *et al*. (1981)



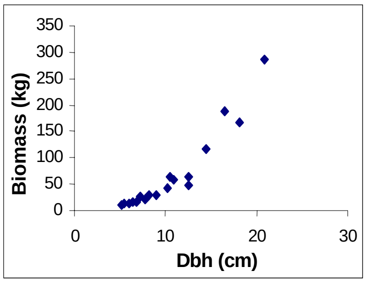
a. Biomass vs. Dbh: : *L. leucocephala* - Laguna



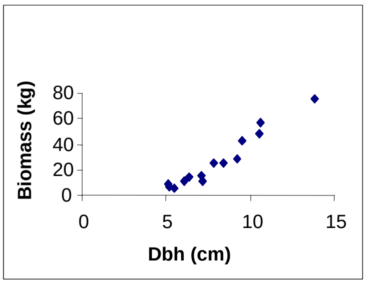
b. Biomass vs. Dbh: : *L. leucocephala* - Antique



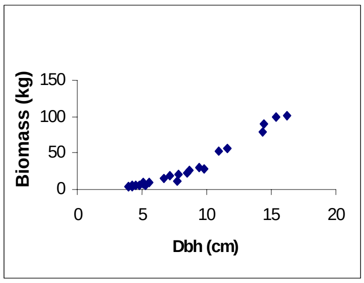
c. Biomass vs. Dbh: *L. leucocephala* - Cebu



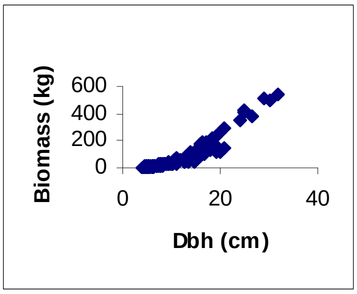
d. Biomass vs. Dbh: : *L. leucocephala* - Ilocos Sur



e. Biomass vs. Dbh: : *L. leucocephala* - Iloilo

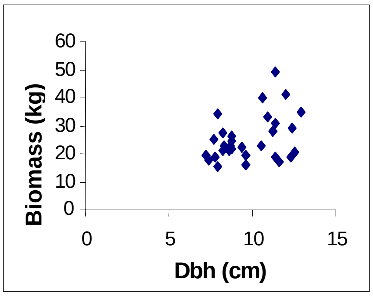


f. Biomass vs. Dbh: : *L. leucocephala* – Rizal

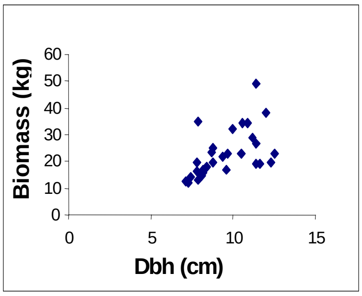


g. Biomass vs. Dbh: : *L. leucocephala* – all sites

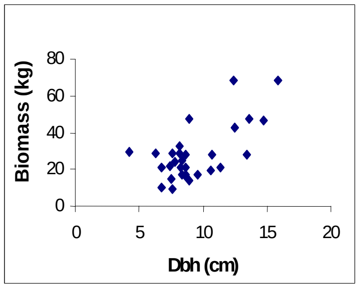
Figure 2. Scatter plots of untransformed biomass vs. dbh from Tandug (1986)



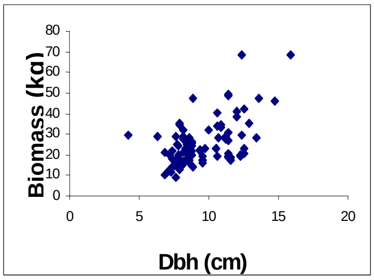
a. Biomass vs. Dbh: *A. auriculiformis*



b. Biomass vs. Dbh: *A. mangium*

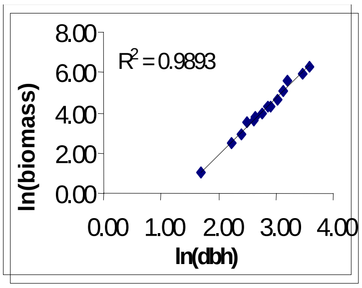


c. Biomass vs. Dbh: *G. arborea*

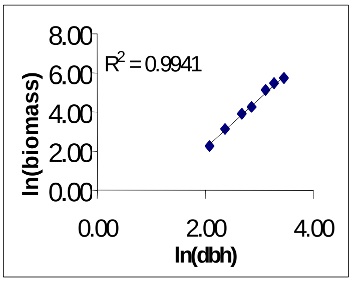


d. Biomass vs. Dbh: all species

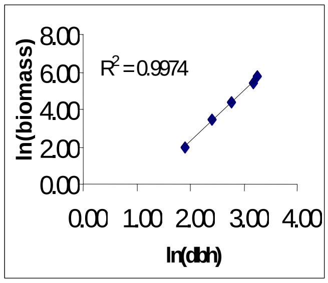
Figure 3. Scatter plots of untransformed biomass vs. dbh from Buante (1997)



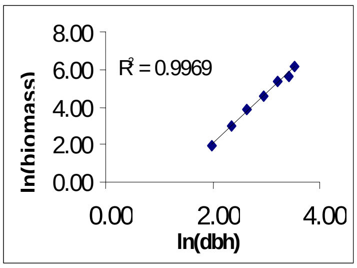
a. ln(biomass) vs. ln (dbh) : *P. falcataria*



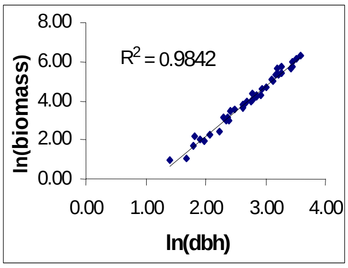
b. ln(biomass) vs. ln (dbh) : *G. arborea*



c. ln(biomass) vs. ln(dbh) : *S. macrophylla*

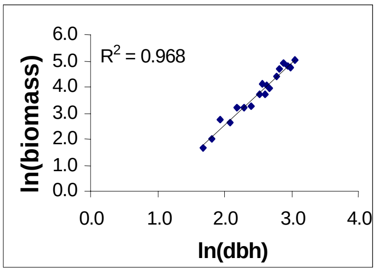


d. ln(biomass) vs. ln(dbh) : Dipterocarp species

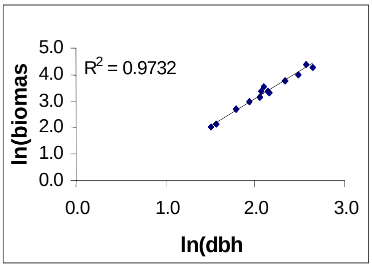


e. ln(biomass) vs. ln(dbh) : all species

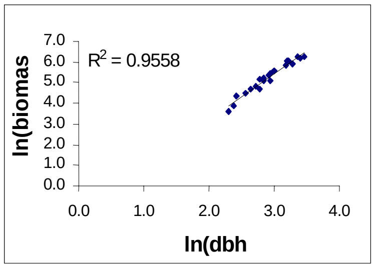
Figure 4. Scatter plots of log-transformed biomass vs. dbh from Kawahara *et al.* (1981)



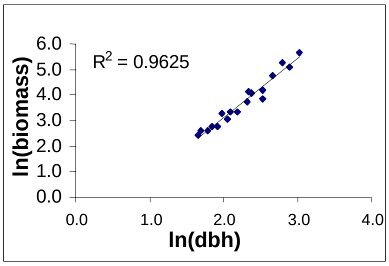
a. ln(biomass) vs. ln(dbh): *L. leucocephala* - Laguna



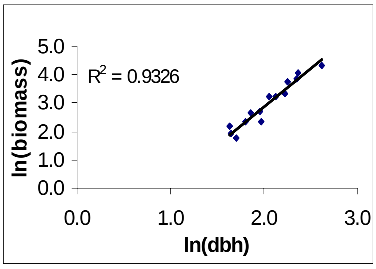
b. ln(biomass) vs. ln(dbh): *L. leucocephala* – Antique



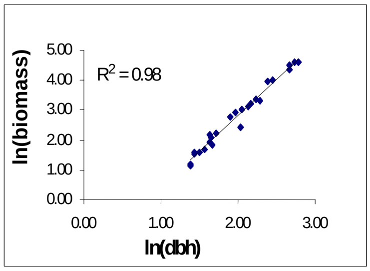
c. ln(biomass) vs. ln(dbh): *L. leucocephala* - Cebu



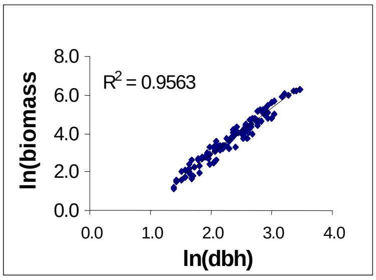
d. ln(biomass) vs. ln(dbh): *L. leucocephala* - Ilocos Sur



e. ln(biomass) vs. ln(dbh): *L. leucocephala* – Iloilo

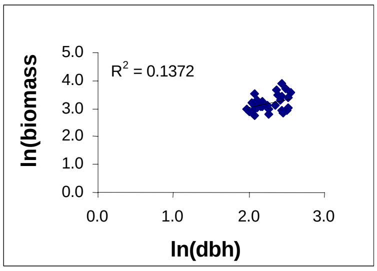


f. ln(biomass) vs. ln(dbh): *L. leucocephala* - Rizal

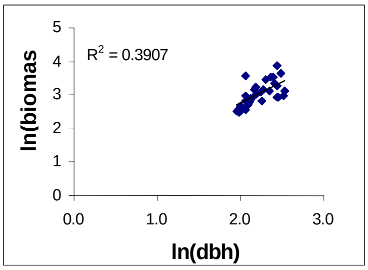


g. ln(biomass) vs. ln(dbh): all sites

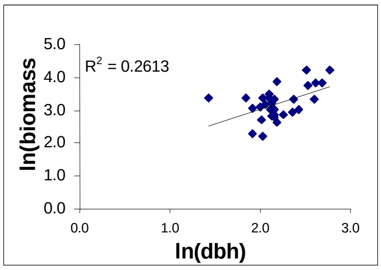
Figure 5. Scatter plots of log-transformed biomass vs. dbh from Tandug (1986)



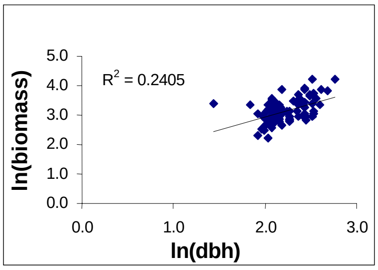
a. ln(biomass) vs. ln (dbh) : *A. auriculiformis*



b. ln(biomass) vs. ln (dbh) : *A. mangium*



c. ln(biomass) vs. ln(dbh) : *G. arborea*



d. ln(biomass) vs. ln(dbh) :all species

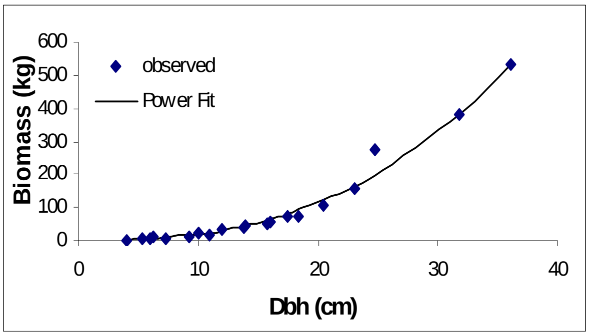
Figure 6. Scatter plots of log-transformed biomass vs. dbh from Buante (1997)

Estimates for the parameters of the power function fitted to individual species and sites and the pooled biomass data are presented in Table 5, and graphs of the observed vs. fitted values are shown in Figures 7 to 10. All analyses resulted in high r values (>0.90), although the SEE are variable. Figures 7 and 8 show the good fit of the generated power functions for each species-site combination. Figure 8 in particular indicates that in the absence of height data for *L. leucocephala*, the new equations can adequately approximate the observed biomass values with diameter at breast height as sole predictor variable. The regressions for pooled sites for *L. leucocephala* (Figure 9) and pooled species and sites – i.e. Tandug's and Kawahara *et al.'s* data combined (Figure 10) – indicate a good fit to the lower range of the data, but greater uncertainty in predicting biomass with greater diameters (> 20 cm). Despite this, as seen in Figure 11, the use of the power function $y = 0.342D^{2.073}$, improved estimates compared with applying the generic equation by Brown (1997) used in previous studies.

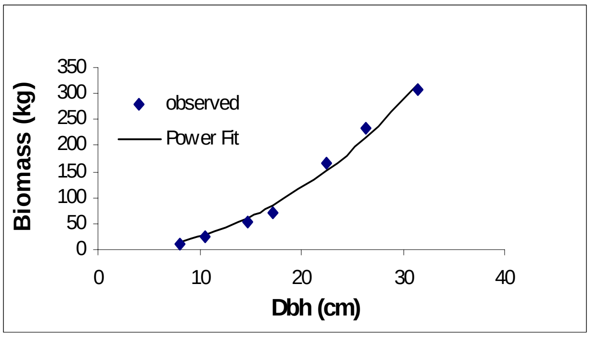
Examination of residual plots (Figure 12-14) revealed that in some cases (*L. leucocephala* in Laguna and Ilocos Sur, and the generic equations), non-homogeneous error variance was encountered, i.e. increases as dbh increases. Future work should address this problem to improve the predictive ability of the equations. One remedy discussed in Ballard *et al*. (1998) is the application of a weighting scheme for the non-linear fitting.

Table 5. Summary of regression parameter estimates and statistics for biomass equations for five species using model: $y = aD^b$, where y = total above-ground tree biomass (kg), D = dbh (cm) and a,b = model parameters

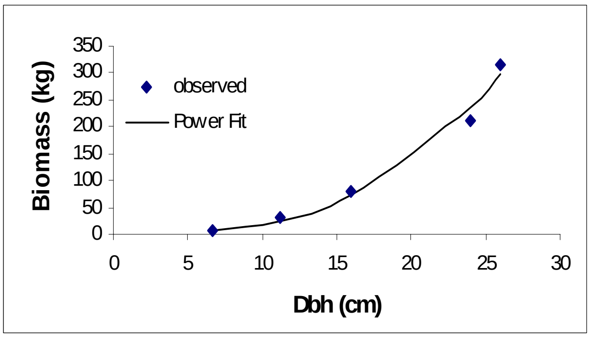
Species	n	Min D	Max D	A	b	SEE	r
Paraserianthes falcataria	20	4.1	36.1	0.049	2.591	19.766	0.991
Gmelina arborea	7	8.0	31.4	0.153	2.217	13.831	0.994
Swietenia macrophylla	5	6.7	26.0	0.022	2.920	17.616	0.993
Dipterocarpaceae	7	7.3	34.0	0.031	2.717	24.374	0.992
Leucaena leucocephala							
Laguna	18	5.4	21.0	0.132	2.316	11.424	0.972
Antique	13	4.5	14.0	0.477	1.937	5.412	0.975
Cebu	21	10	31.8	0.753	1.921	32.151	0.981
Ilocos Sur	18	5.2	20.8	0.112	2.580	14.860	0.982
Iloilo	14	5.1	13.8	0.225	2.247	5.710	0.967
Rizal	25	4.0	16.2	0.182	2.296	4.149	0.992
All sites combined	111	4.0	31.8	0.206	2.305	26.468	0.973
All species/sites	148	4.0	36.1	0.342	2.073	41.964	0.938



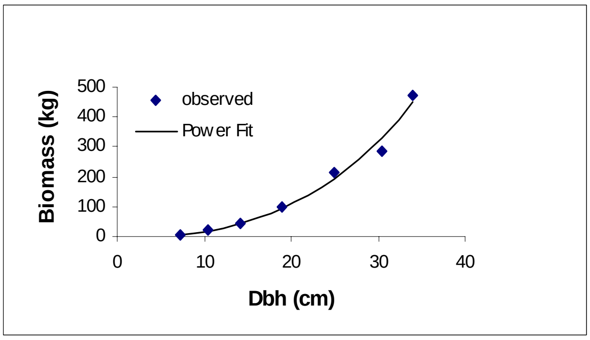
a. *P. falcataria*



b. *G. arborea*



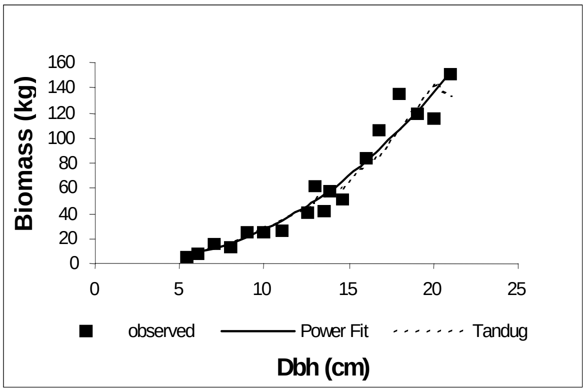
c. *S. macrophylla*



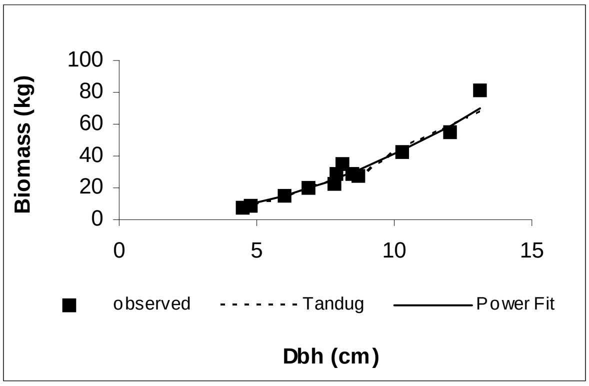
d. Dipterocarp species

Figure 7. Observed vs. fitted biomass values for trees sampled by Kawahara *et al*. (1981)

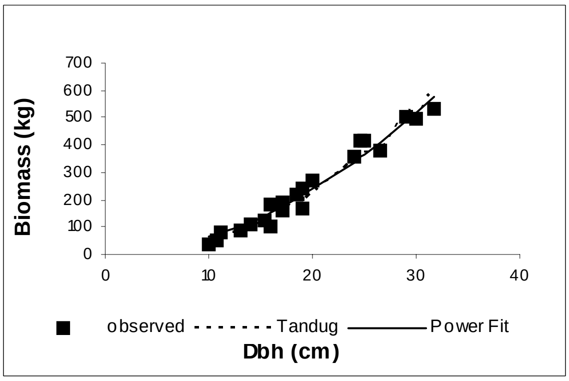
'Power Fit' refers to allometric equation specific for each species.



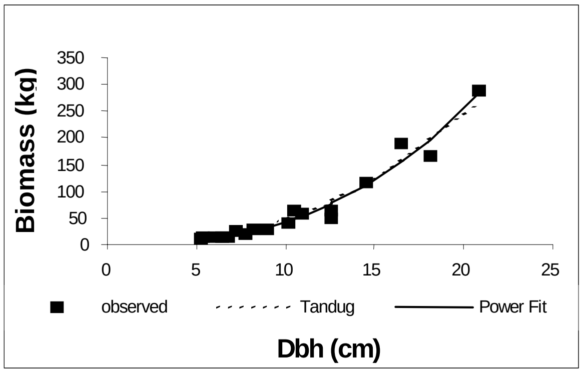
a. *L. leucocephala* -Laguna



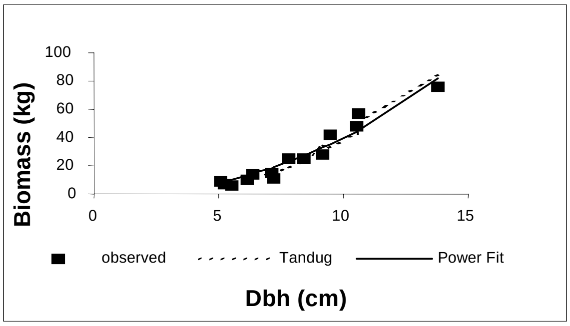
b. *L. leucocephala* -Antique



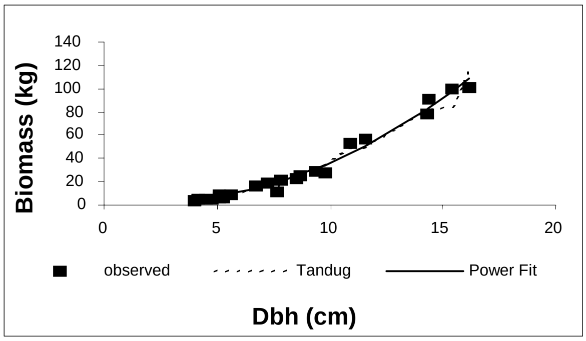
c. *L. leucocephala* - Cebu



d. *L. leucocephala* - Ilocos Sur



e. *L. leucocephala* - Iloilo



f. *L. leucocephala* - Rizal

Figure 8. Observed vs. predicted biomass values of trees sampled by Tandug (1986)

'Power Fit' refers to allometric equation specific to a site and 'Tandug' = biomass equations by Tandug with dbh and height as predictors ($Y = aD^{b1}H^{b2}$).

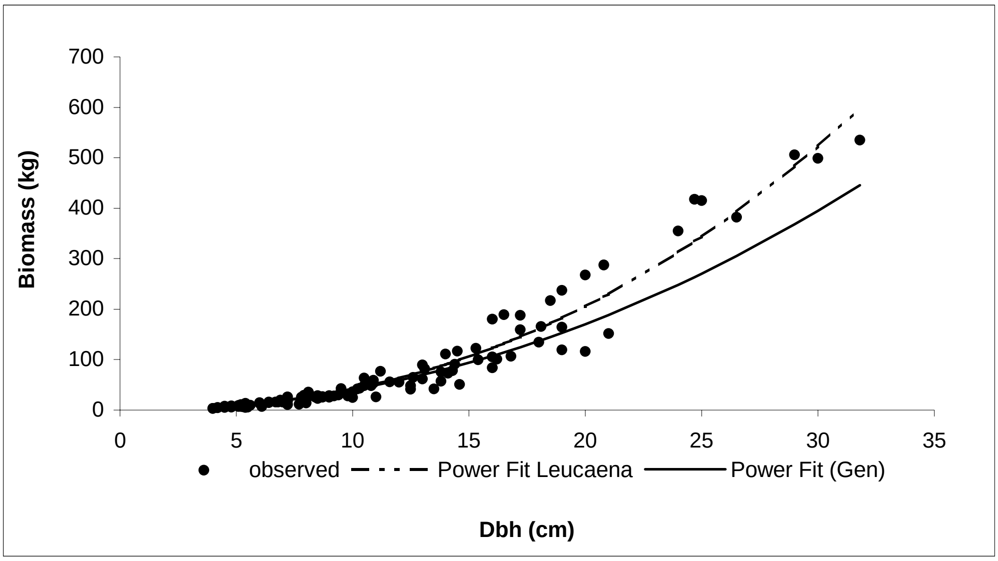


Figure 9. Observed vs. predicted biomass values of trees sampled by Tandug (1986)

These are estimated using the power function y = $0.206D^{2.305}$ fitted to the pooled *L .leucocephala* data ('Power Fit *Leucaena*'), and the generic equation y = $0.342D^{2.073}$ fitted to the pooled Tandug-Kawahara *et al*. data ('Power Fit-Gen').

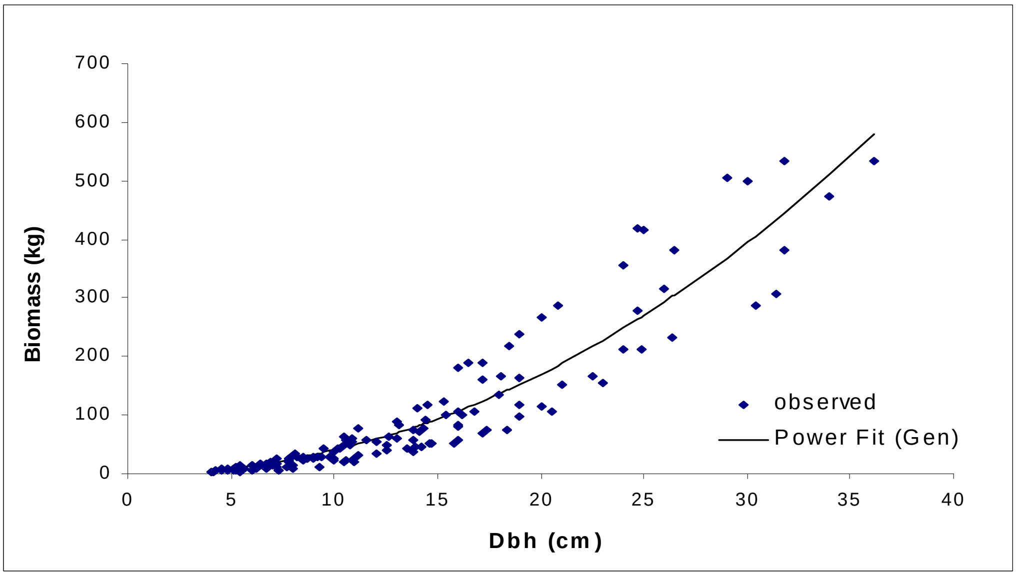


Figure 10. Observed vs. fitted biomass values of the pooled Tandug-Kawahara *et al*. data

Fitted using the generic equation y = $0.342D^{2.073}$ ('Power Fit-Gen').

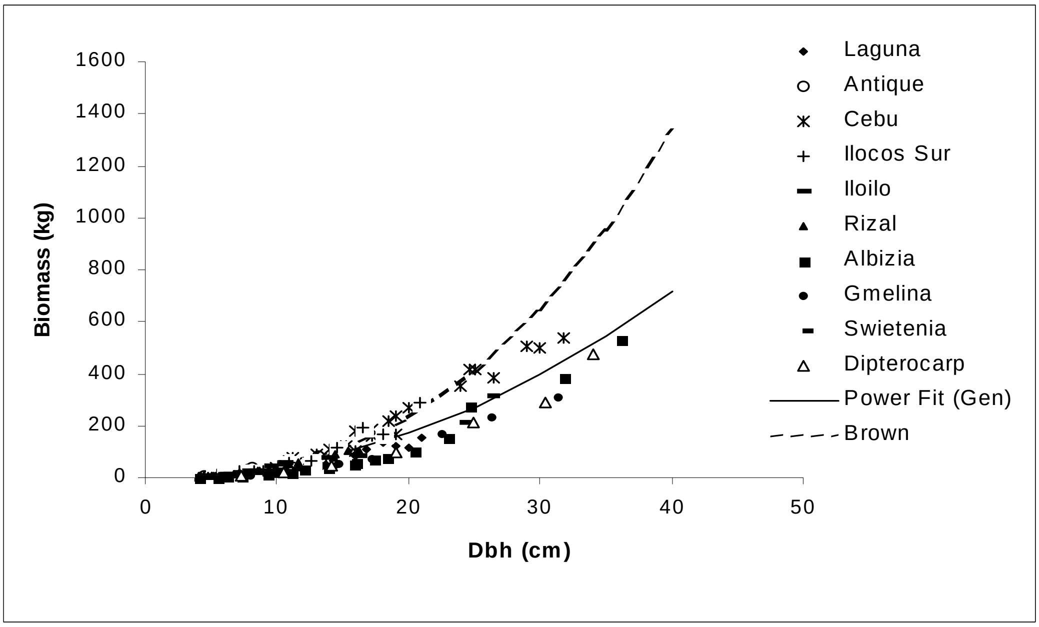
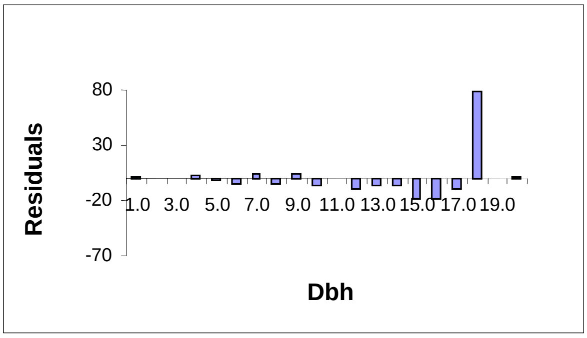
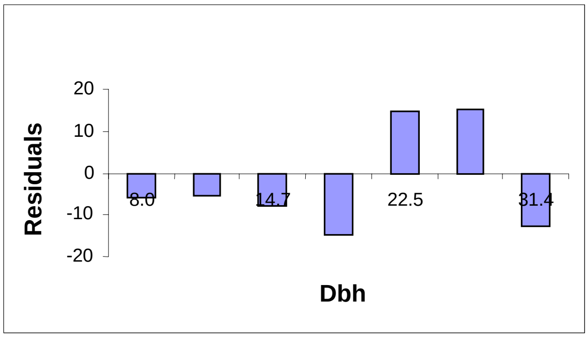


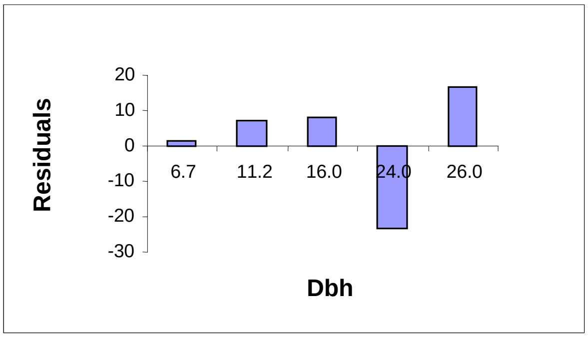
Figure 11. Observed vs. predicted biomass values using the generic equation $y = 0.342D^{2.073}$ ('Power Fit-Gen'), and Brown's (1997) equation $y = \exp(-2.134+2.530\ln(D)$



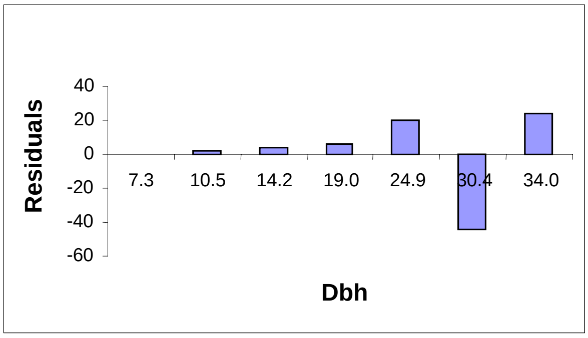
a. *P. falcataria*



b. *G. arborea*

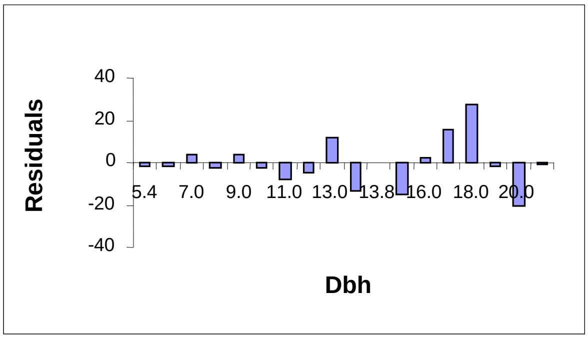


c. *S. macrophylla*

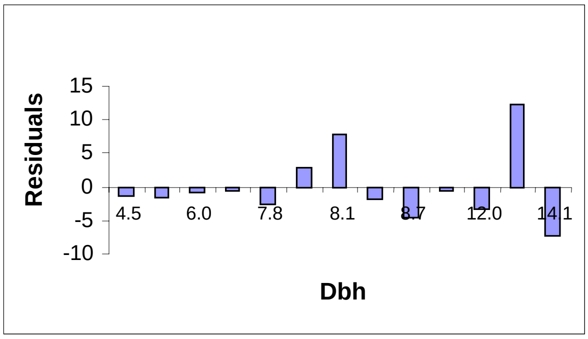


d. Dipterocarps

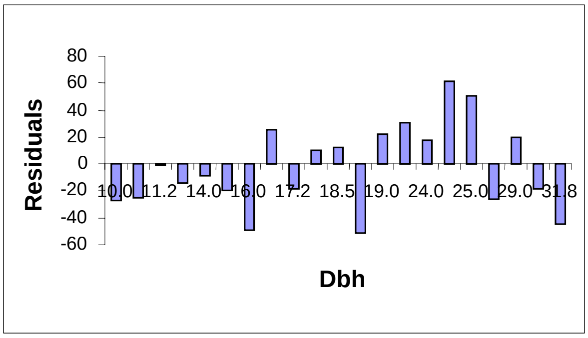
Figure 12. Residuals from the regressions for species-specific equations from Kawahara *et al*. (1981)'s data



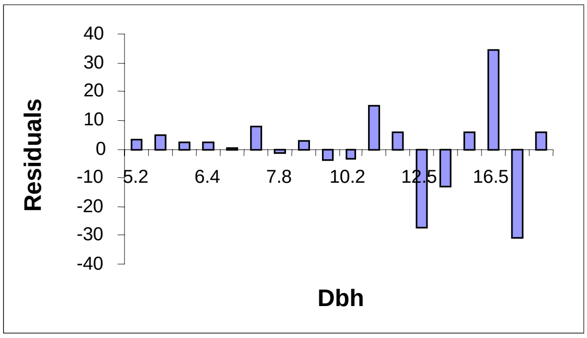
a. L. leucocephala –Laguna



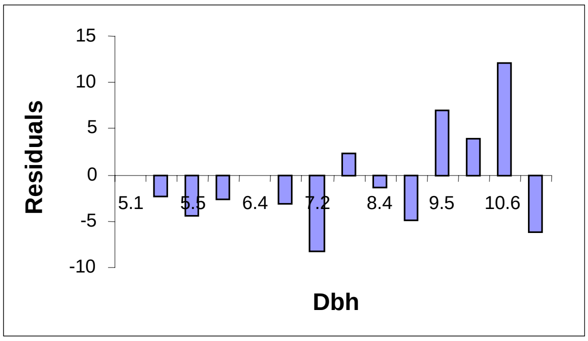
b. L. leucocephala -Antique



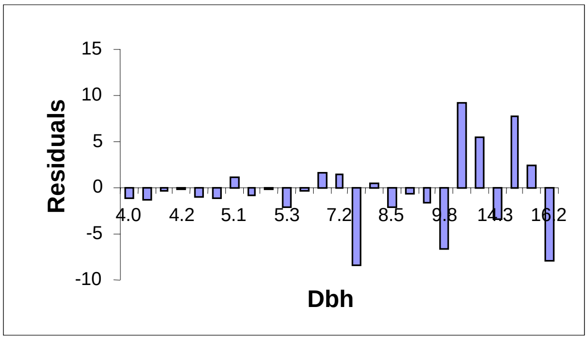
c. L. leucocephala –Cebu



d. L. leucocephala -Ilocos Sur

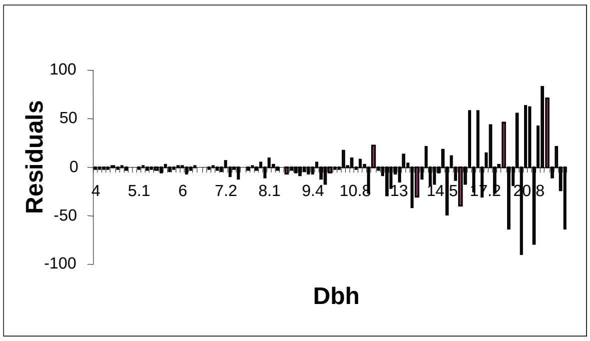


e. L. leucocephala –Iloilo

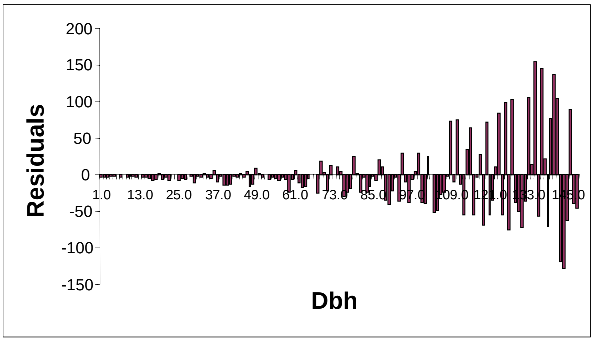


f. L. leucocephala –Rizal

Figure 13. Residuals from the regressions for site-specific equations for *L. leucocephala* from Tandug's (1986) data



a. Pooled sites- Tandug (1986) data set



b. Pooled Kawahara *et al.* (1981) and Tandug (1986) data sets

Figure 14. Residuals from the regressions for generic equations from the pooled Kawahara *et al*. (1981) and Tandug (1986) data

SUMMARY AND CONCLUSIONS

Allometric equations for predicting tree biomass were developed using secondary data from studies involving destructive sampling and conducted in the Philippines. Biomass data were taken from studies conducted independently by Kawahara *et al.* (1981) for timber plantations of *Gmelina arborea*, *Paraserianthes falcataria*, *Swietenia macrophylla* and Dipterocarp species in Mindanao; Tandug (1986) for *Leucaena leucocephala* plantations (mainly for dendrothermal power plants) from Laguna, Antique, Cebu, Iloilo, Rizal, and Ilocos Sur, and Buante (1997) for *Acacia mangium*, *Acacia auriculiformis* and *G. arborea* in Leyte. Non-linear estimation was used to fit the data to the power function $Y = aD^b$, with Y = total above-ground biomass of tree, D = diameter at breast height, and a,b = parameter estimates.

Regression equations based solely on diameter appear to estimate adequately tree biomass, with a correlation coefficient of more than 0.90, although the inclusion of height as predictor variable was not explored. A problem encountered with the regressions is that in some cases tested, errors in prediction tend to increase with increasing diameter (non-homogeneous variance).

It is emphasised that the biomass regression equations presented in this report are deterministic in nature, i.e. parameter estimates are single fixed numbers at any given time and applying them on trees under different growing conditions and to diameters outside the range of the measurements of the sampled trees is not advised.

Future efforts in equation development should consider including large trees whenever possible, because the analysis reported here shows greater variability in tree biomass among groups at larger diameters (≥ 30 cm dbh). The variability in biomass of the different species-sites in the pooled data precludes the development of a generalised biomass equation of potential wider applicability. It is still recommended that species- and site-specific equations be used whenever possible.

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