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:

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

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:

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

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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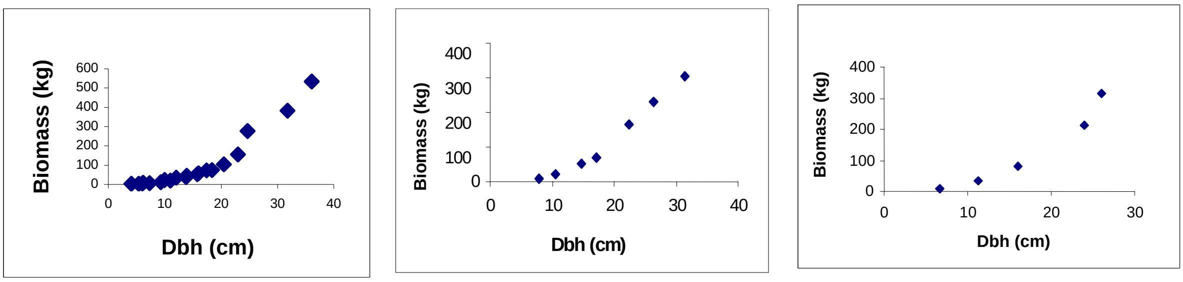
RESULTS AND DISCUSSION

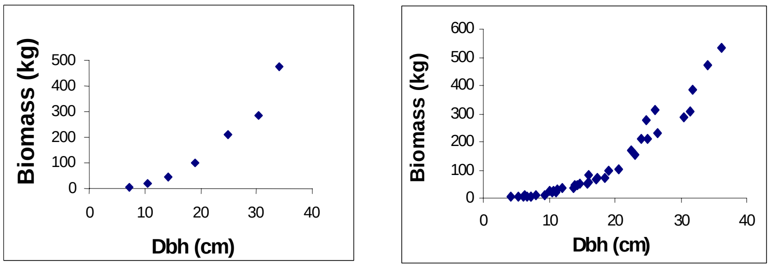
Scatter plots of Buante’s data for *Acacia mangium*, *Acacia auriculiformis* and *Gmelina arborea* (Figure 3 and Figure 6) show no apparent relationship between biomass and diameter, which was not the case with the other two data sets. Log-transformed values also failed to achieve a good linear fit. 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*

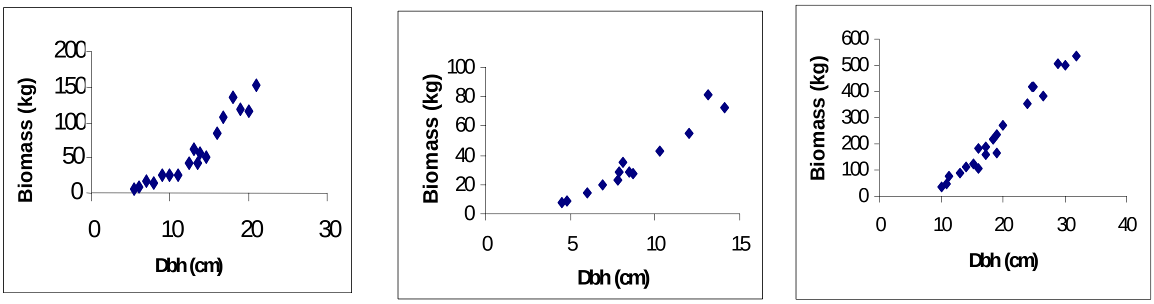
c. Biomass vs. Dbh: *S. macrophylla*



d. Biomass vs. Dbh: Dipterocarp species

e. Biomass vs. Dbh: all species

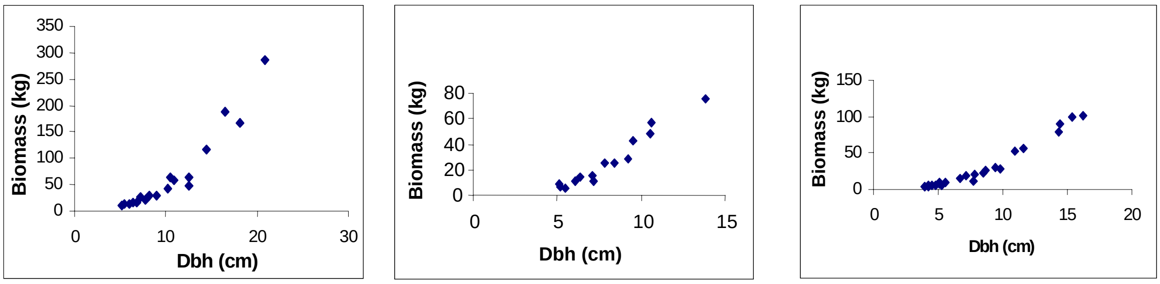
Figure 1. Scatter plots of untransformed biomass vs. dbh from Kawahara *et al*. (1981)



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

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

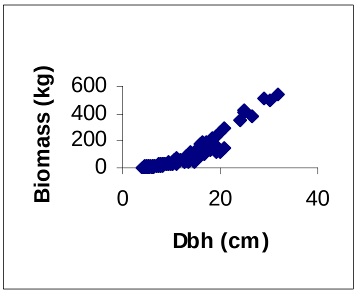
c. Biomass vs. Dbh: *L. leucocephala* - Cebu



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

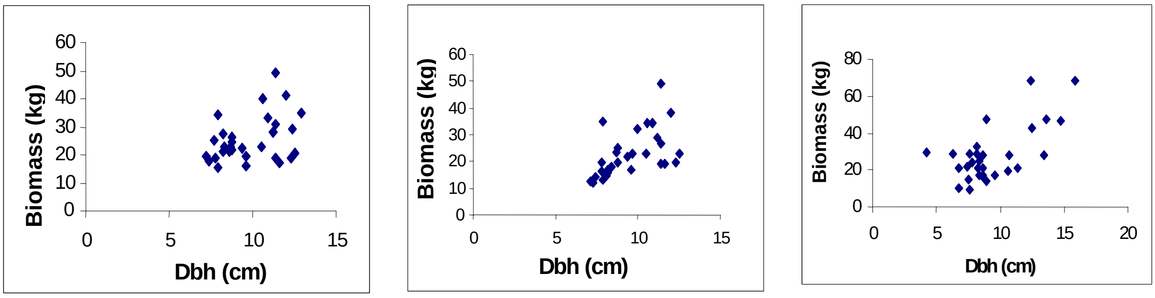
e. Biomass vs. Dbh: : *L. leucocephala* - Iloilo

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



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

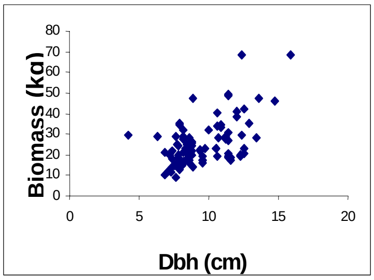
Figure 2. Scatter plots of untransformed biomass vs. dbh from Tandug (1986)



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

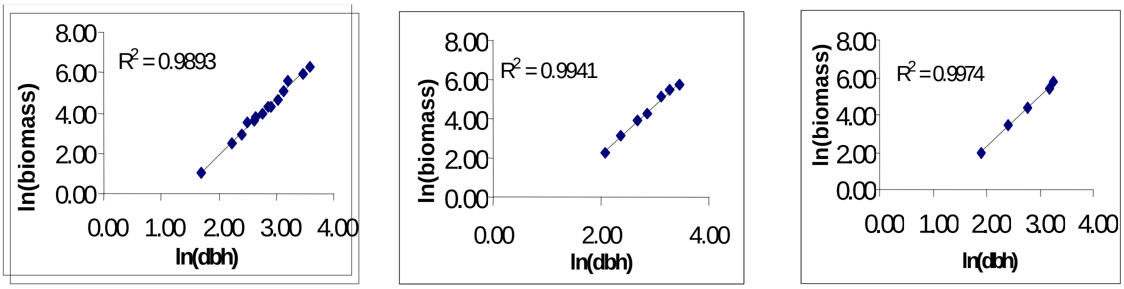
b. Biomass vs. Dbh: *A. mangium*

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



d. Biomass vs. Dbh: all species

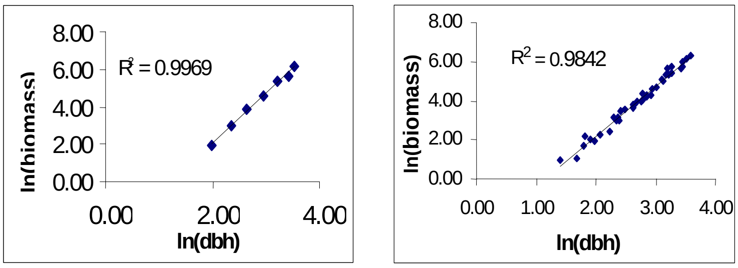
Figure 3. Scatter plots of untransformed biomass vs. dbh from Buante (1997)



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

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

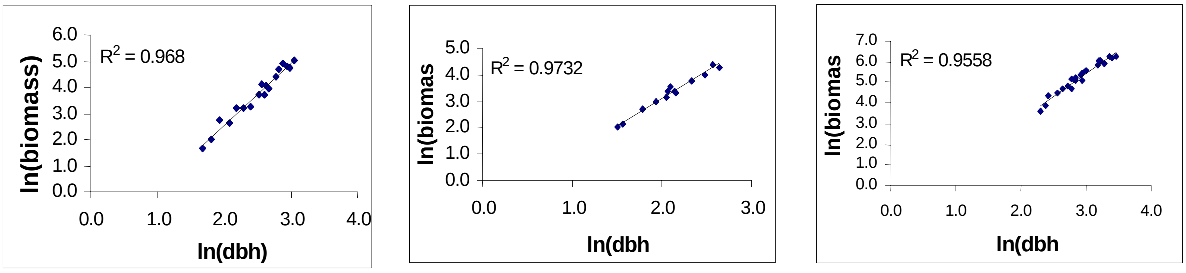
c. ln(biomass) vs. ln(dbh) : *S. macrophylla*



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

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

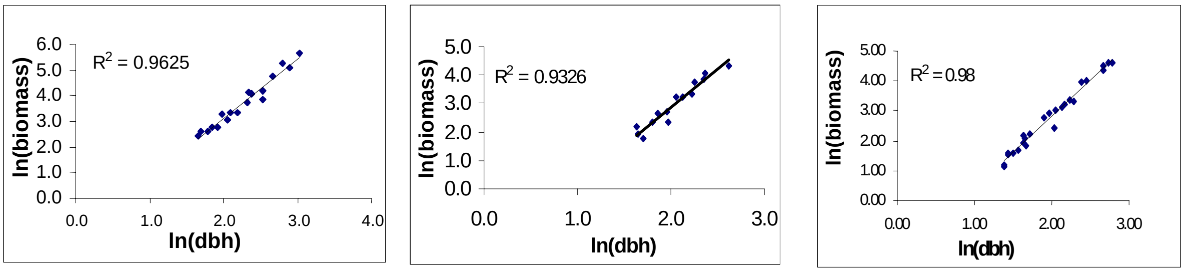
Figure 4. Scatter plots of log-transformed biomass vs. dbh from Kawahara *et al.* (1981)



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

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

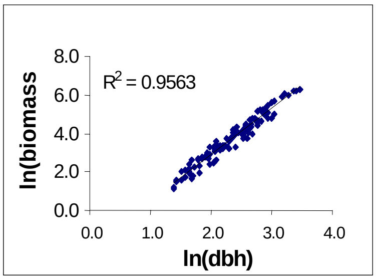
c. ln(biomass) vs. ln(dbh): *L. leucocephala* - Cebu



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

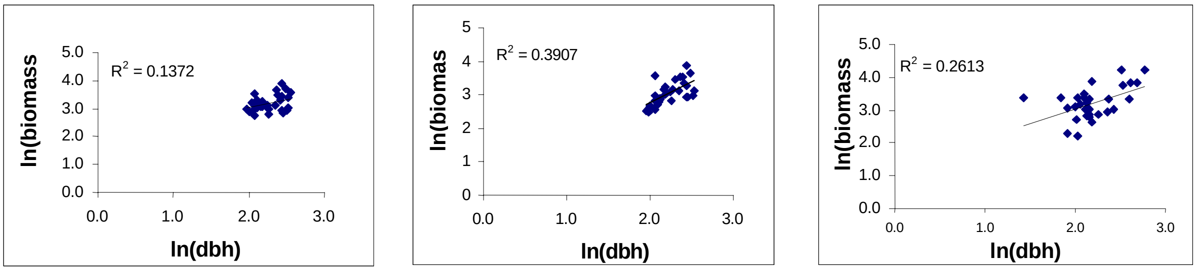
e. ln(biomass) vs. ln(dbh): *L. leucocephala* – Iloilo

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



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

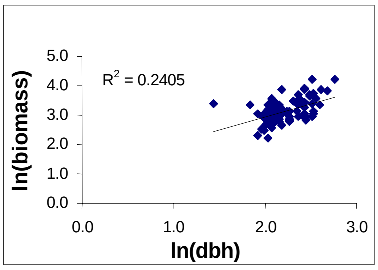
Figure 5. Scatter plots of log-transformed biomass vs. dbh from Tandug (1986)



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

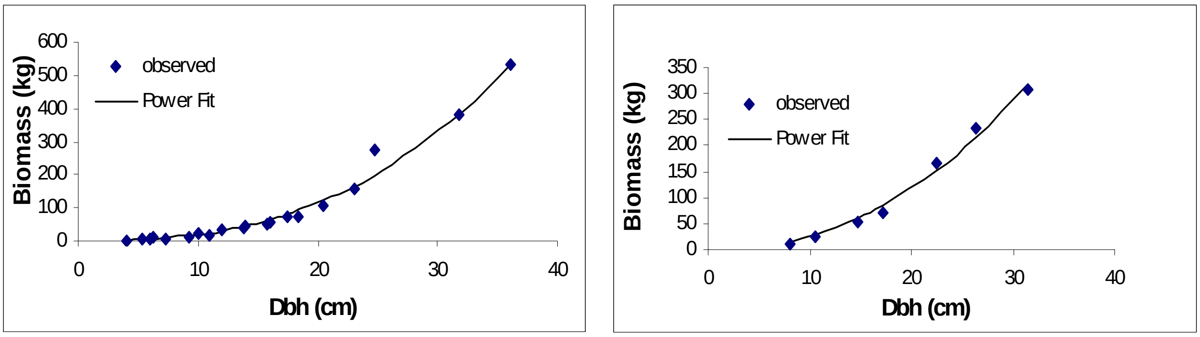
Figure 6. Scatter plots of log-transformed biomass vs. dbh from Buante (1997)

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.

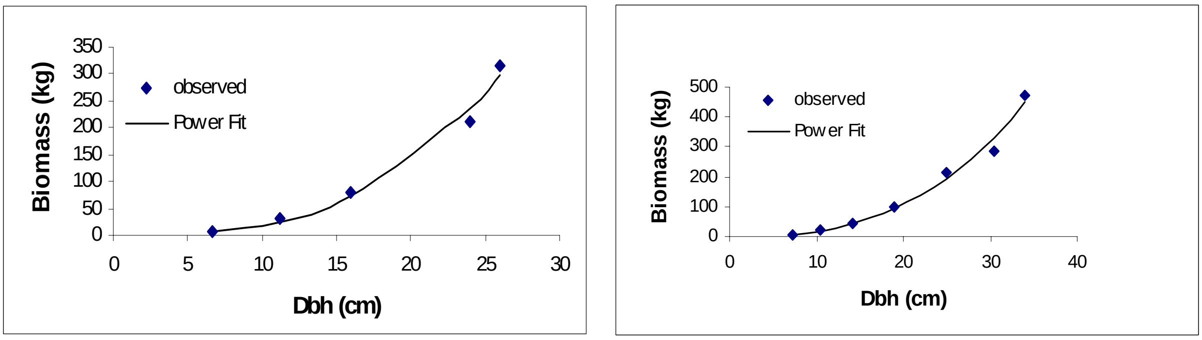
Table 5. Summary of regression parameter estimates and statistics for biomass equations for five species using model: $y = aD^b$, where y = total above-ground tree biomass (kg), D = dbh (cm) and a,b = model parameters

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*

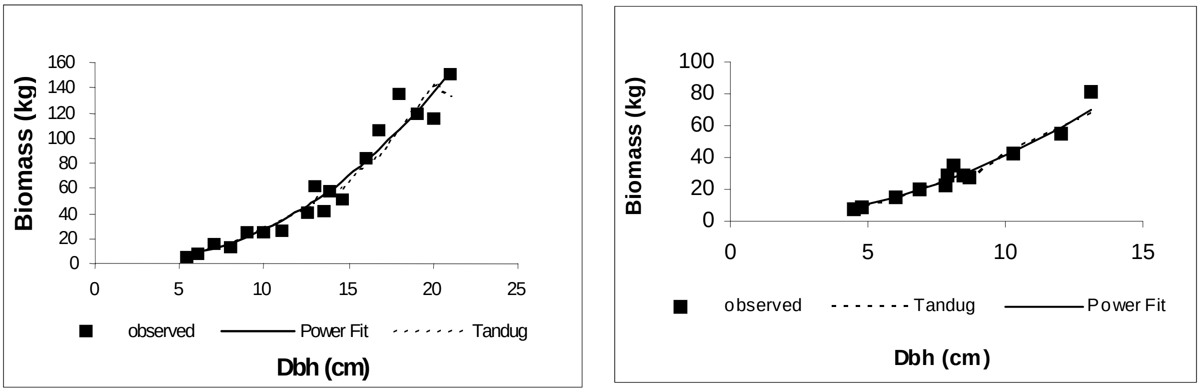


c. *S. macrophylla*

d. Dipterocarp species

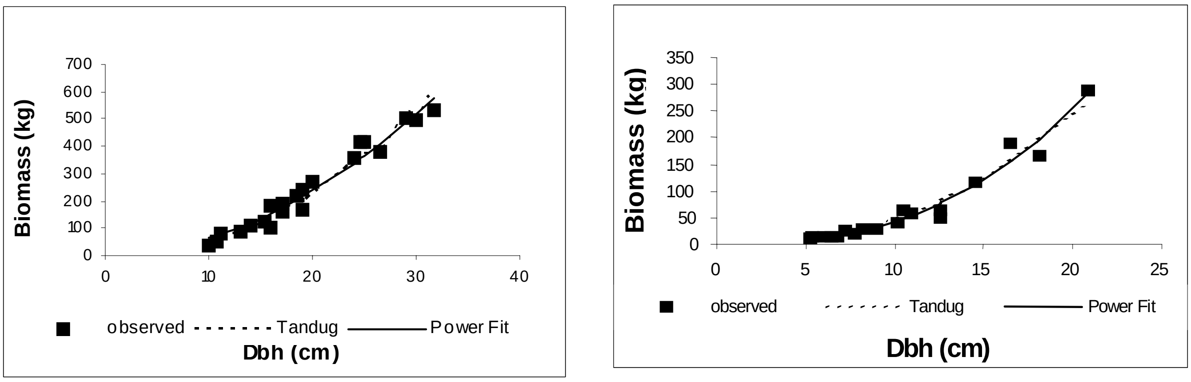
Figure 7. Observed vs. fitted biomass values for trees sampled by Kawahara *et al*. (1981)

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



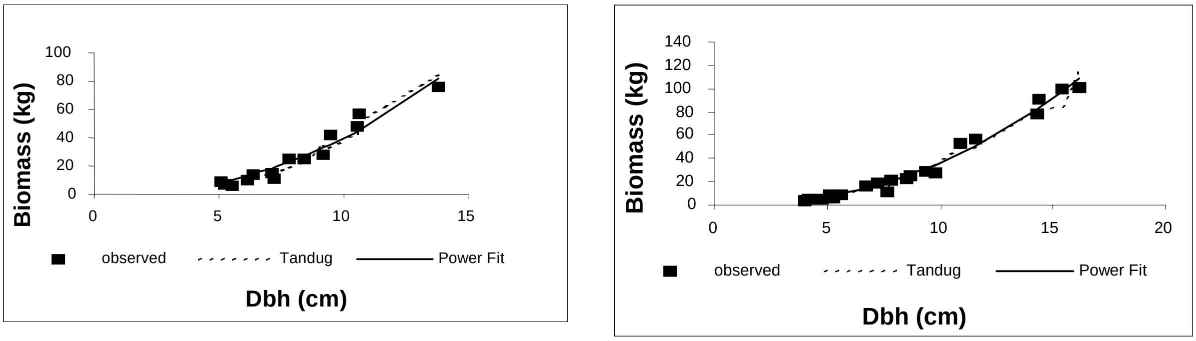
a. *L. leucocephala* -Laguna

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 ($Y= aD^{b1}H^{b2}$).

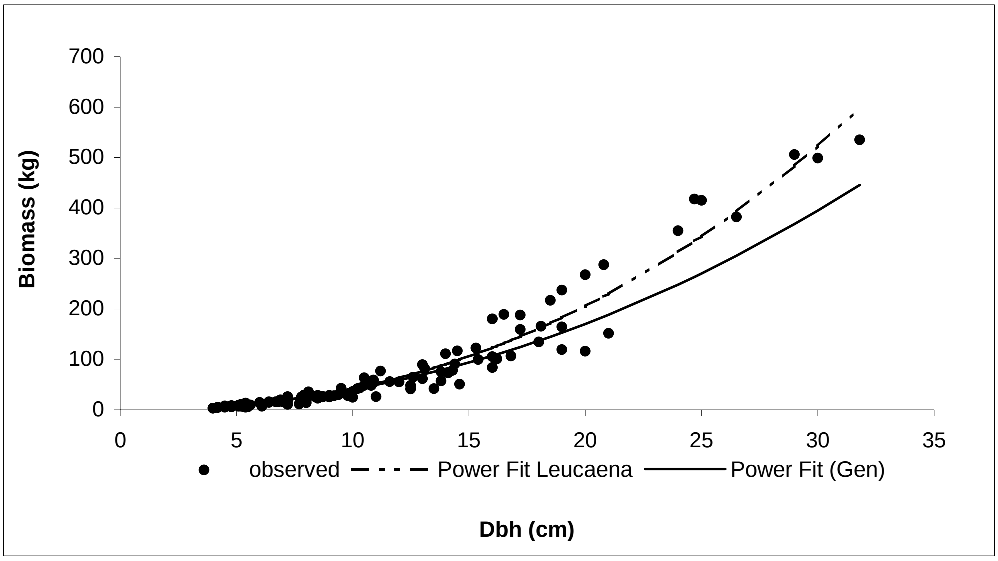


Figure 9. Observed vs. predicted biomass values of trees sampled by Tandug (1986)

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').

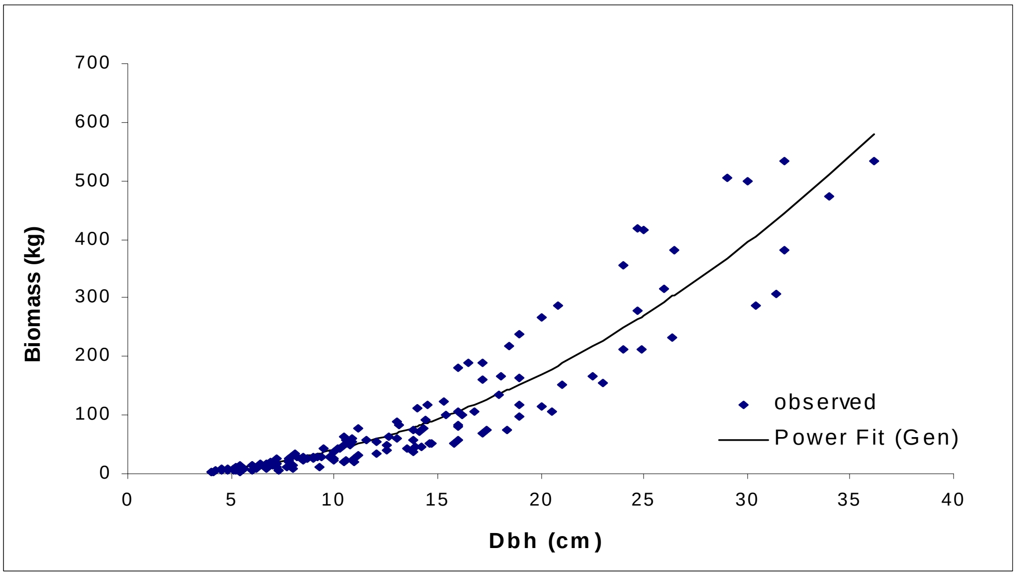


Figure 10. Observed vs. fitted biomass values of the pooled Tandug-Kawahara *et al*. data

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

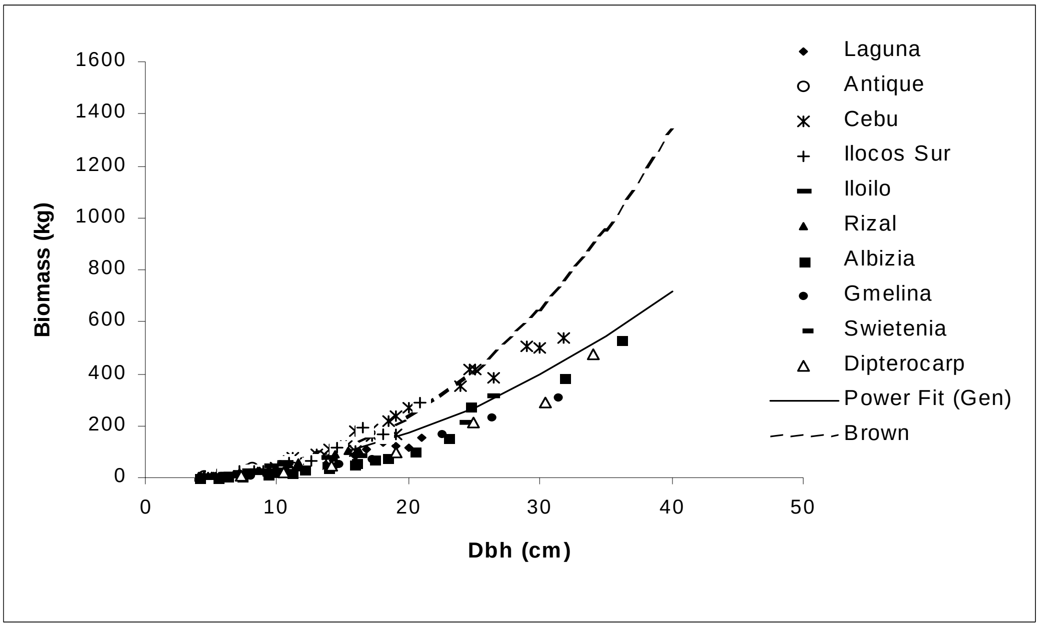
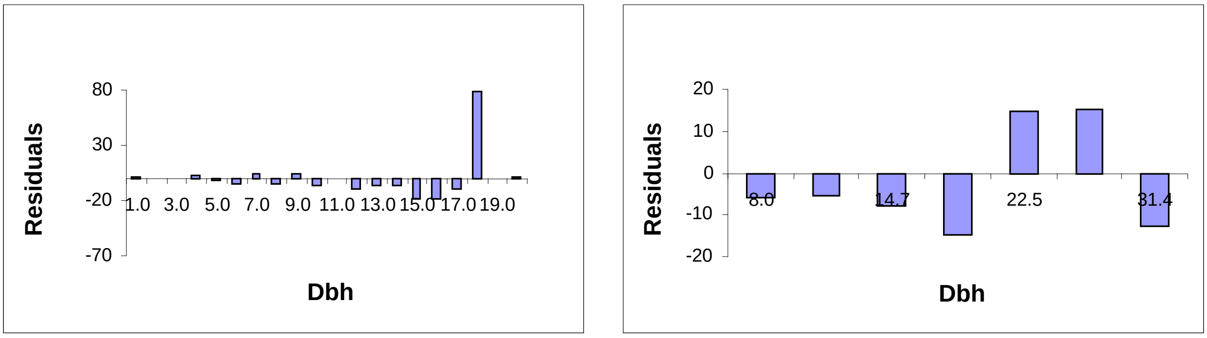
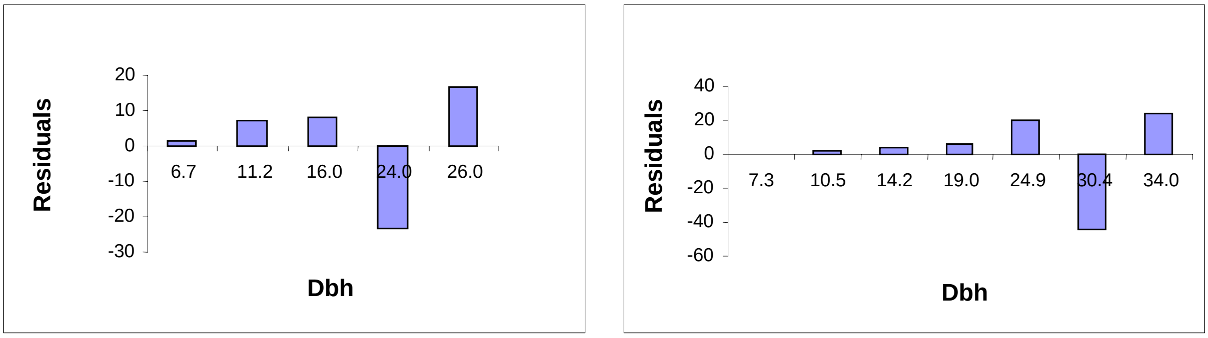


Figure 11. Observed vs. predicted biomass values using the generic equation $y = 0.342D^{2.073}$ ('Power Fit-Gen'), and Brown's (1997) equation $y = \exp(-2.134+2.530\ln(D))$



a. *P. falcataria*

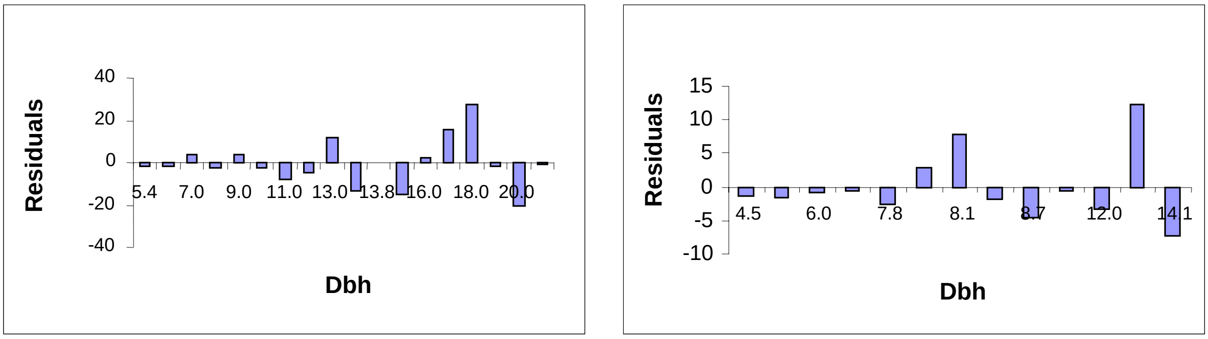
b. *G. arborea*



c. *S. macrophylla*

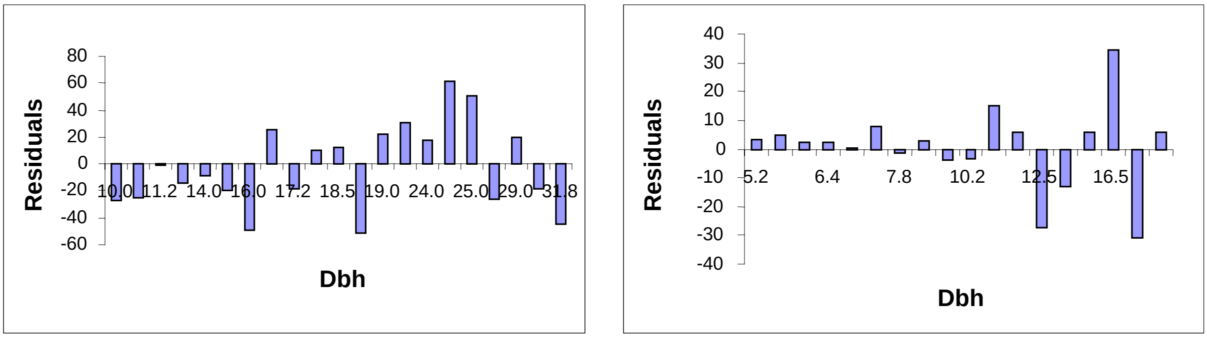
d. Dipterocarps

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



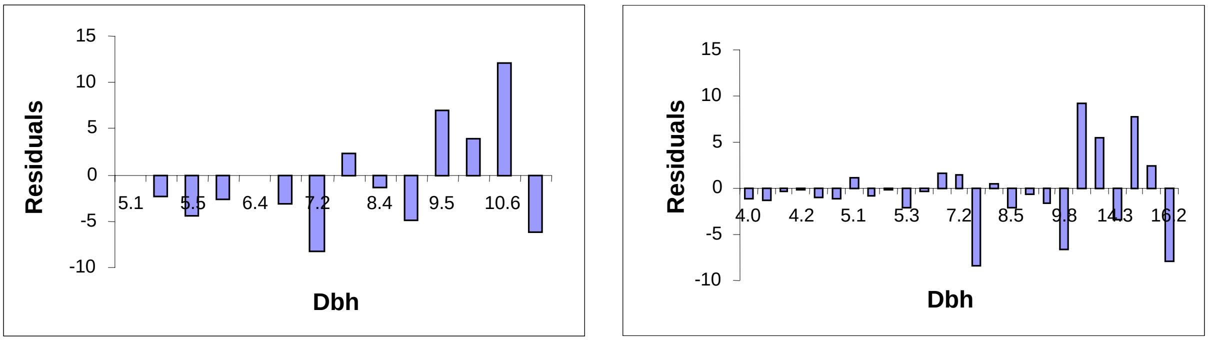
a. L. leucocephala –Laguna

b. L. leucocephala -Antique



c. L. leucocephala –Cebu

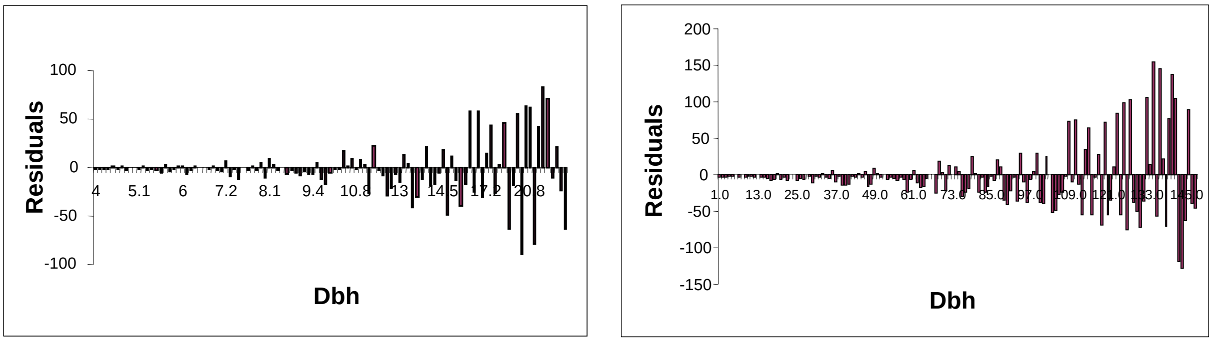
d. L. leucocephala -Ilocos Sur



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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CARBON STORAGE AND SEQUESTRATION POTENTIAL OF SMALLHOLDER TREE FARMS ON LEYTE ISLAND, THE PHILIPPINES

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

The role of terrestrial ecosystem in mitigating the effects of climate change entails the assessment of carbon stocks in various pools. This study predicts the carbon storage and sequestration potential of common tree farm species in Leyte Island, the Philippines. Data gathered from field measurements has been used to fit the Chapman-Richards growth function to predict the volume and biomass increment of *Gmelina arborea* and *Swietenia macrophylla* tree farms until they reached their respective rotation ages. Biomass and carbon density values are found to vary with age, type of species, site conditions and silvicultural treatments applied in the stand. Although differences in year when the trees were planted had no relation with its soil carbon storage, this pool had greater storage capacity than the above-ground biomass and roots. The average maximum growth was attained after 10 years for *G. arborea* and 13 years for *S. macrophylla*. Volume growth started to slow down when the tree species reached almost half its rotation age. The same trend was observed for the biomass and carbon density of each farm. The maximum mean annual increment of both species was attained before the expected maximum growth year. Growth increment decreased as the species reached their rotation age. The total C storage capacity of a 15-year-old *G. arborea* tree farm was estimated at 64 MgC/ha while that of a 25–year-old *S. macrophylla* was estimated at 159 MgC/ha. The average carbon sequestration rate of both species was 5 MgC/ha/yr which is lower than the average rate of most tree plantation species in the Philippines. With almost 2 M ha of grasslands in the country, establishing tree farms is a strategy to attain the national goal on sustainable development and at the same time reduce the greenhouse gases (GHGs) emissions.

INTRODUCTION

The IPCC Third Assessment Report (2001) presented new and stronger evidence that most of the warming observed in the last 50 years is due to human activities and warming is expected to continue this century and alter atmospheric composition. It was also predicted that by the year 2100, the average surface temperature will increase by between 1.4 to 5.8°C while sea level is expected to rise by 0.09 to 0.88 cm, resulting in flooding of low-lying areas. CO_2 is the most abundant greenhouse gas and is responsible for more than half of the radiative forcing associated with the greenhouse effect (Dixon *et al.* 1993, Moura-Costa 1996).

Forest ecosystems play an important role in climate change because they can be both sources and sinks of CO_2 (Trexler and Haugen 1994). At present, the world's tropical forests are found to be a net source of C due to anthropologic activities including deforestation with an emission of 1.6 Gt (1 Gt = 10^9 tons), in the year 1990 alone. In fact, Philippine forests, through massive deforestation, were found to have contributed about 3.7 Pg (1 Pg = 10^{15} tons) of C to the atmosphere from year 1500 to the modern era (Lasco and Pulhin 1998). Other causes could be mainly human-induced activities including fossil fuel burning and changes in land use and land cover (IPCC 1995).

The rehabilitation of degraded lands through the establishment of tree plantations and agroforestry may play an important role in sequestering CO_2. These strategies have become popular in many places due to a combination of economic return and the environmental benefits they provide (Aggangan 2000); however, there is little information on the carbon budgets of tropical tree plantations and tree farms. This information is needed for a more accurate picture of their role in mitigating climate change.

The study reported here aimed to predict the carbon stocks and sequestration of smallholder tree farms by using field data and fitting to Chapman-Richards growth functions throughout the species' rotation age. In addition carbon stocks in the above-ground biomass, roots and soil were quantified. The capability of smallholder tree farms to store and sequester CO_2 especially when trees are planted in grassland areas is examined. The next section discusses the field measurements done in the sample tree farms. This is followed by volume, biomass and carbon storage and sequestration prediction, for the farms' respective rotation ages.

LOCATION AND DESCRIPTION OF THE STUDY AREA

The study was conducted on Leyte Island, which is the eighth largest island in the Philippines. It is located in the Eastern Visayas region (Region 8), at about 9°45' N latitude and 123°50'- 126°00' E longitude. The island consists of two provinces, Leyte and Southern Leyte, and covers a total land area of about 750,000 ha. The capital cities of Leyte and Southern Leyte are Tacloban City and Maasin City, respectively. The smallholder tree farms for the study are located in the municipalities of Albuera, Matalom, Panan-awan and Badiang, Maasin City and Macrohon, Southern Leyte (Figure 1). The location and elevation of the farms were determined using a GPS receiver.

According to the Corona System of classification (PAGASA 2005), two types of climate exist in Leyte Province. In the east, climate is characterised by high pronounced rainfall from November to January while the climate of the west is characterised by rainfall that is relatively uniformly distributed throughout the year. Most of the sample farm belongs to the latter climate type. Sample smallholder tree farms were selected by purposive sampling

RESEARCH METHOD

A survey of all the existing smallholder tree farms in Leyte Island was conducted, then smallholder tree farms planted with common species with varying ages were selected by purposive sampling, taking into consideration the year of establishment and the area coverage for each species. Initial selection was made from the data of the ACIAR Smallholder Forestry Program based at the College of Forestry, Leyte State University, Baybay, Leyte. The data were compiled from the various studies conducted on smallholder tree farms in the province. Initial selection was made from the data of the ACIAR Smallholder Forestry Program based at the College of Forestry, Leyte State University, Baybay, Leyte. The data were compiled from the various studies conducted on smallholder tree farms in the province. The data provided a detailed description of the farms which included the operators' name, location, species planted, approximated area planted per species, and the year of planting.

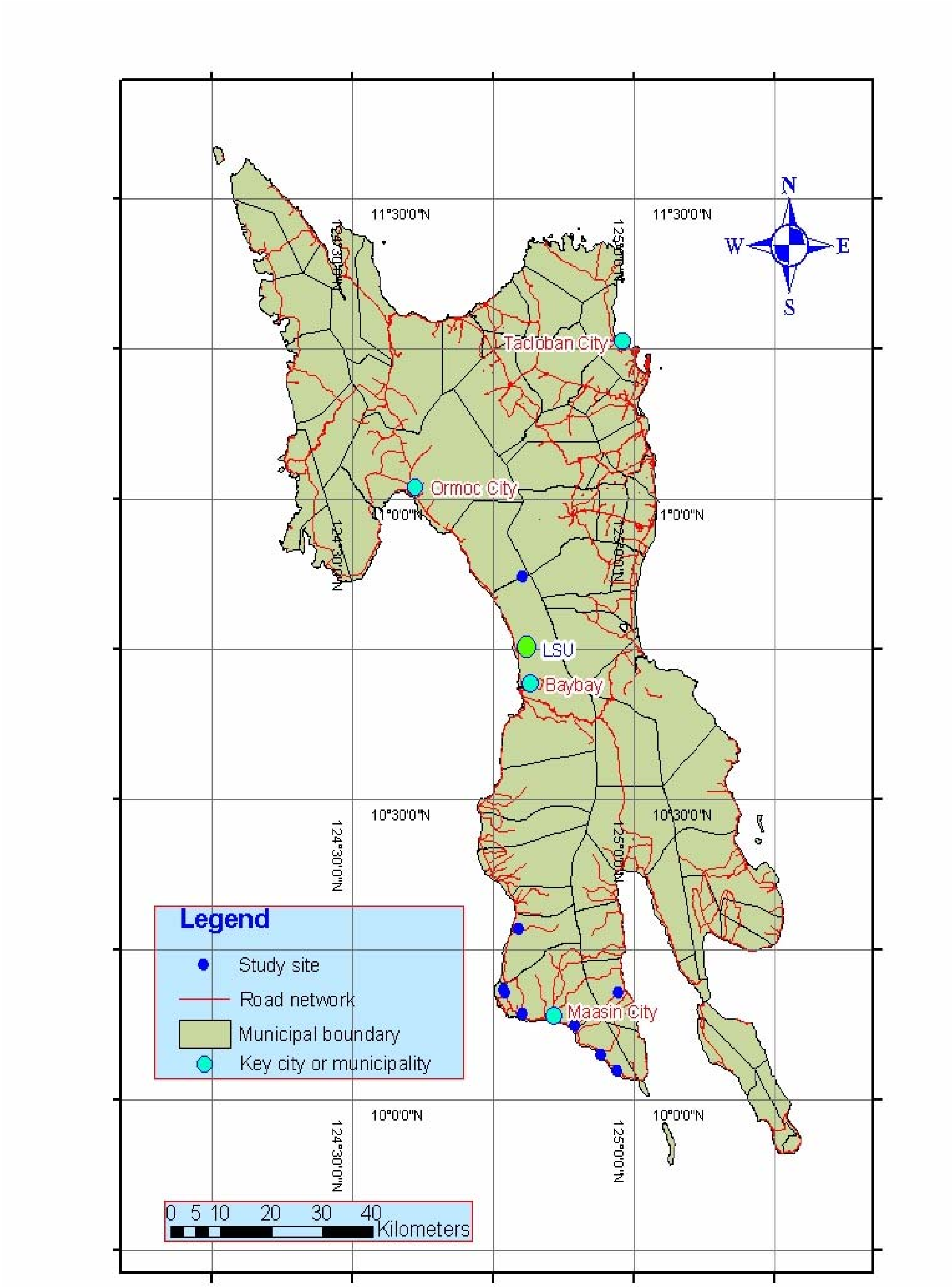

Figure 1. Location of the study sites in Leyte Island

A criterion was set on the minimum area coverage of the sample farm to be selected. Data showed that most of the tree farms on Leyte Island cover a minimum of 0.5 ha. This served as the basis for the set criterion. Species with various representative age levels from the time of establishment to those ready for harvest were preferred. Selected farms were also verified in the field.

Based on the results of the survey, *Gmelina arborea* and *Swietenia macrophylla* tree farms are the most commonly planted species in smallholder tree farms in Leyte. Sample farms are privately owned with a minimum area per species of 0.75 ha, except for one field trial site included for *Swietenia macrophylla* species with 0.25 ha (Table 1).

For above-ground measurement, the field sampling protocol was adapted from Hairiah *et al*. (2001). For live tree biomass measurements, four 5m x 40m (200 m^2) transects were randomly established per site with various species and age. Trees of more than 5 cm diameter at breast height (dbh) within 2.5m of each side of the 40m centreline were measured. For trees branching below breast height, the dbh of all branches was measured separately and added. Diameters of trees were measured with standard diameter tape. Heights were systematically taken from the first two corner trees of every plot using an Abney hand-level. The average height of the eight sample trees was obtained per farm. However, for a mature *S. macrophylla* field trial site, average height of large diameter trees was used.

Samples for soil bulk density were taken by driving an improvised metal canister (6 cm diameter and 10 cm height) into the 10-20 cm. Samples for organic carbon content were collected at the same spot were bulk density samples were taken. Composite samples of 1 kg were taken to the LSU Department of Agronomy and Soil Science for chemical analysis using the Walkley-Black method. Soil organic carbon storage was computed using the formula:

$$\text{Bulk density}\left({}^{g}\!/_{cc}\right)=\frac{\text{Oven}-\text{dried weight of soil}}{\text{Volume of canister}} \qquad \text{(Equation 1)}$$

Soil Organic Carbon (SOC) per ha

$$\text{Volume of one ha}=100\times100\times0.30\,\text{m}$$
$$\text{Weight of soil}(\text{Mg})=\text{bulk density x volume}$$
$$\text{Carbon density}\left({}^{Mg}\!/_{ha}\right)=\text{weight of soil}\times\%\,\text{SOC}$$

Determining root biomass is both expensive and laborious, thus conservative estimates are used based on literature (following the method outlined by Lasco and Sales, 2003), as a more practical approach of claiming carbon credits for this type of pool. Root biomass also varies considerably among the tropical forests, and procedural difficulties exist in recovering it from soil depths (Brown 1997). For this study, an allometric equation from Cairns *et al*. (1997), based on the above-ground biomass for tropical forests, was adapted to estimate the root biomass. The equation is illustrated as follows:

$$Root\ biomass\left({}^{Mg}\!/_{ha}\right)=e\left[-1.0587+0.8836*\ln(AGB)\right] \qquad \text{(Equation 2)}$$

where e represents the exponential function, In refers to natural logarithms, and AGB is aboveground biomass (in Mg). The growth of trees in most tree farms and plantations is affected by the initial spacing, silvicultural treatment such as fertiliser application, artificial pruning, thinning operations and site conditions (Brack and Wood, 1996). Thus, the entire management regime applied for each farm from the time of planting up to the present farm condition was noted. The information obtained was used to relate the silvicultural treatments applied and its effect on the growth of individual trees in the stand.

STAND LEVEL MEASUREMENTS OF VOLUME, BIOMASS AND CARBON DENSITY

From the direct measurement of the various parameters including dbh, merchantable height (mh) and total height (th) of individual trees contained inside the sample plots laid out for each tree farm, stand level parameters including the volume of standing trees, biomass and carbon density (Mg/ha) were derived. These values from the representative ages of the sample species served as the observed data to fit the Chapman-Richards functions.

Estimation of stand volume

Volume (m^3/ha) was estimated using small sampling units by directly measuring the volume of each tree with a given dbh at 1.3 m, total height (th) and merchantable height (mh) measurements. The volume per tree was computed using the general formula: $0.7854 * dbh^{2} *$ mh/th*form factor (following Philip, 1994). Computation was done using this formula:

$$\text{Form factor} = {}^{V_m}\!/_{g_{bh}}\,(th) \qquad \text{(Equation 3)}$$

where V_m is merchantable volume over bark, defined by specific top diameter (m), g_{bh} is basal area at breast height (1.4 m), and th is total height (m).

Volume per hectare was estimated using the formula:

$$V = \frac{\sum^{n}\left(\sum^{mi} V_{ij}\right)}{na} \qquad \text{(Equation 4)}$$

where V=average volume, estimated from n samples (m^3/ha), V_{ij} is the volume of individual trees measured on the i^{th} plot after measured standing (m^3/ha), m_i is the total number of trees in the ith plot (i= 1 to n), and n is the number of plots.

Table 1. Profile of the study sites

Species	Municipality	Age of Species (year)	GPS location	Elevation (masl)	Climatic type	Area coverage (ha)
Gmelina arborea	Matalom	5	N 10° 17.042' E 124° 47.738'	36	IV	1.0
Gmelina arborea	Maasin	7	N 10° 07.388' E 124° 53.729'	38	IV	0.75
Gmelina arborea	Maasin	8	N 10° 10.699' E 124° 46.392'	53	IV	1.70
Gmelina arborea	Macrohon	9	N 10° 0.2624' E 124° 58.483'	16	IV	1.0
Gmelina arborea	Macrohon	10	N 10° 0.2846' E 124° 58.258'	16	IV	0.75
Swietenia macrophylla	Albuera	5	N 10° 52.224' E 124° 44.334'	16	IV	1.0
Swietenia macrophylla	Maasin	6	N 10° 08.537' E 124° 48.158'	34	IV	1.0
Swietenia macrophylla	Macrohon	8	N 10° 4.462' E 124° 56.630'	18	IV	0.75
Swietenia macrophylla	Maasin	38	N 10° 10.893' E 124° 46.16'	37	IV	0.25

Note: All sample farms are privately owned except for a field trial site planted with 38 years old S. macrophylla.

Measurement of stand biomass and carbon density

In the Philippines, generic biomass regression equations developed by Brown (1997) from a large data pool of species sampled throughout the tropics have been used in local studies to determine indirectly the biomass and carbon storage of forest ecosystems. However, the use of these generic equations was found to overestimate the actual biomass of trees (Ketterings *et al.* 2000, Macandog and Delgado 2002, Hairiah *et al.* 2002), which shows the need to develop species-specific and site-specific equations that yield more reliable estimates of the characteristics of species and conditions of specific locations in the Philippines.

Species-specific allometric equations, which only require diameter as predictor variable for above-ground biomass, were used in this study. The equations were developed from previous studies involving destructive sampling of trees in various locations in the Philippines (Banaticla *et al.* 2004). These secondary data were subjected to regression analysis to derive specific biomass equations per species, as reported in Banaticla *et al.* (2004) The details on how these equations were derived were further discussed in the first draft report of the ACIAR Carbon Sequestration Study funded by the Australian Centre for International Agricultural Research (Banaticla *et al.* 2004) The carbon density (MgC/ha) of each farm was derived by multiplying the stand biomass density (Mg/ha) by 45% IPCC default value for C content.

Fitting the Chapman-Richards functions

The growth of a forest stand can be represented by the Chapman-Richards function (Venn *et al*. 2001). This function was used to predict the merchantable and total growth of each species in terms of volume (m^3/ha). Biomass and carbon density of trees were predicted, using the function

$$dY/dt = \alpha . Y^{\beta} - \gamma Y, \qquad \text{(Equation 5)}$$

where $\alpha > 0$, $\gamma > 0$, $0 < \beta < 1$, Y is stand volume (m^3/ha), t is time in years, and α, γ and β are parameters of the relationship.

Carbon Storage and Carbon Sequestration Prediction up to the Species' Rotation Ages

Carbon density (MgC/ha) values were derived by multiplying the predicted biomass values (Mg/ha) from Chapman-Richards function with the carbon content default value of 0.45 based on the overall estimate of carbon content of biomass of trees as proposed by IPCC (1996).The amount of carbon stored over the species' rotation age determined the carbon sequestration rate in MgC/ha/yr of a given farm.

RESULTS AND DISCUSSION

Biomass and Carbon Density

Using the Chapman-Richards function, the measured biomass from the field of five yemane (*Gmelina arborea)* smallholder tree farms, including the below-ground biomass, was fitted to predict the biomass of the stand up to its given rotation age, which was 15 years. From the results, the farm could reach between 2.18 Mg/ha and 142.10 Mg/ha (Table 2).

The carbon density value of the farm ranged from 0.98 to 63.94 MgC/ha. The predicted above-ground biomass of a six-year-old farm was 98.54 Mg C/ha which was higher than the biomass obtained from a plantation of the same species and age in Indonesia that was classified as having favourable site conditions at C density of 65 Mg/ha (Agus 2003). Thus, the yemane farm was classified as having favourable site conditions as well.

The predicted biomass density of mahogany *(Swietenia macrophylla.)* tree farms reached 352.8 Mg/ha for a rotation of 25 years. The value obtained was comparable with a 16-year-old mahogany plantation in Mindanao with biomass density of 261 Mg/ha, and lower than a 44-year-old stand in Mt. Makiling, Laguna with biomass density of 590.40 Mg/ha. There was an insignificant increase in biomass from the early stage of establishment (Year 1) with the predicted values almost equal to zero. A 25-year-old mahogany reached a carbon density value of 158.76 MgC/ha which was higher than that of a 15-year-old yemane farm.

Table 2. Predicted biomass and carbon density for yemane and mahogany smallholder tree farms (MgC/ha)

Age (years)	Biomass density (Mg/ha)	Carbon density (MgC/ha)	Age (years)	Biomass density (Mg/ha)	Carbon density (MgC/ha)
Gmelina arborea					
1	2.18	0.98	9	128.26	57.72
2	14.78	6.65	10	133.08	59.89
3	36.17	16.28	11	136.42	61.39
4	59.81	26.91	12	138.72	62.42
5	81.19	36.54	13	140.29	63.13
6	98.54	44.34	14	141.37	63.61
7	111.74	50.28	15	142.10	63.94
8	121.39	54.62			
Swietenia macrophylla					
1	0.00	0.00	14	282.66	127.20
2	0.02	0.01	15	299.20	134.64
3	0.58	0.26	16	312.30	140.53
4	4.00	1.80	17	322.57	145.16
5	14.16	6.37	18	330.55	148.75
6	33.86	15.24	19	336.71	151.52
7	62.82	28.27	20	341.45	153.65
8	98.18	44.18	21	345.08	155.29
9	136.13	61.26	22	347.85	156.53
10	173.28	77.98	23	349.97	157.49
11	207.33	93.30	24	351.58	158.21
12	237.06	106.68	25	352.80	158.76
13	262.11	117.95			

Below-Ground Measurements of Soil Carbon

Bulk density values of yemane ranged from 0.79 to 1.13 g/cc while mahogany farms had 0.83 to 1.04 g/cc. Lower bulk density measurement indicated a higher organic matter content in the soil of the sample farms (Brady 1974). Based on the results, the seven-year-old yemane farm had the highest C density in the soil with 121.52 MgC/ha.

The results indicated that the age of the farm is not related to its soil C density. Similar findings were obtained in an afforested area, where carbon change of the soil sampled below a depth of 10 cm, had no significant relationship with stand age age (Polglase *et al.* 2000). Hence, the differences in values were due to the extent of disturbances in the soil (Sales 1998) and decrease with depth (Banaticla 2003).

Measurement of Carbon in Root Biomass

The root biomass obtained, based on the AGB (Equation 2) of yemane smallholder tree farms, ranged from 13.52 to 24.86 Mg/ha with the oldest sample stand having the highest root biomass value while an eight-year-old stand had the lowest value. The mahogany stand obtained 2.43 to 53.98 Mg/ha root biomass. Total carbon stock of above- and below-ground, of the yemane smallholder tree farms on Leyte Island, ranged from 74.17 to 171.96 MgC/ha. These values were relatively lower than the total C storage of a 15-year-old yemane plantation as reported by Philippine National Oil Company (PNOC) Geothermal Reserve in Ormoc City with 294.16 MgC/ha (Lasco *et al.* 2001).

Mahogany farms had total C stocks of 30.19 MgC/ha from a five-year-old stand to 222.84 MgC/ha from the oldest stand The values obtained were comparable with the total C density above-ground, below-ground and in the soil of a nine-year-old mahogany plantation inside the PNOC with 192 MgC/ha.

Table 3 presents the amount of C stock in terms of percentage of above- and below-ground (root and soil) biomass and carbon density based on the total computed values from the sample farms. More than 80% of biomass was contained above-ground for yemane and mahogany smallholder tree farms, while root biomass comprised less than 20% of the total biomass. It was found that about 60% of carbon was contained in the soil, 34% was tied up in the AGB of the smallholder tree farms, and 6% was in the roots.

Table 3. Percent biomass carbon density values of various pools of yemane and mahogany tree farms

Species	Age (years)	AGB (%)	Root biomass (%)	AGB carbon (%)	Root carbon (%)	Soil Carbon (%)
G. arborea	5	82.46	17.54	40.57	8.63	50.8
	7	83.01	16.99	24.35	4.98	70.67
	8	82.36	17.64	31.78	6.80	61.41
	9	83.23	16.77	33.5	6.75	59.75
	10	83.50	16.50	40.53	8.01	51.46
Mean		82.91	17.09	34.15	7.03	58.82
S. macrophylla	5	78.84	21.16	13.53	3.63	82.84
	6	80.96	19.04	13.29	3.12	83.59
	8	82.79	17.21	25.76	5.35	68.89
	38	84.86	15.14	61.09	10.9	28.01
Mean		81.86	18.14	28.42	5.75	65.83

In a natural forest in Leyte, about 51% of carbon was stored in the biomass and 49% was found in the soil (Lasco *et al.* 2001). The findings agreed with the data reported in the literature where the soil was found to store at least 30% of total forest carbon or as much as the biomass (Lugo and Brown, 1992, Moura-Costa 1996). These values indicated the important role of soils in storing carbon and the need to conserve soil organic matter as one possible strategy in enhancing carbon storage. Soil organic matter can conserved by applying soil management practices such as minimum tillage and adoption of soil erosion control measures (Lasco *et al.* 2001c).

The average grasslands in Leyte had a total biomass and carbon density of 28.5 and 12.1 Mg/ha, respectively (Lasco et al., 2001). The results of the study were almost equivalent with a three-year-old yemane stand and a six-year-old mahogany stand. This meant an increase of more than 80% in biomass and carbon density if grasslands would be planted with yemane, and more than 90% increase in biomass and C density if mahogany stands would be established (Table 5). These would result to a net carbon storage of 51.84 and 146.66 MgC/ha from yemane and mahogany stands, respectively. However, computation was based on the species' rotation age of 15 years and 25 years for yemane and mahogany, respectively, and the study assumed that grasslands would have a constant C storage.

Lasco *et al*. (2001) found that on average grasslands in Leyte have a total biomass and carbon density of 28.5 and 12.1 Mg/ha, respectively These levels are similar to those of a three-year-old yemane stand and a six-year-old mahogany stand. There would be an increase of more than 80% in biomass and carbon density if grasslands were planted with yemane, and more than 90% increase if mahogany stands were established (Table 5). The net carbon storage would be 51.84 and 146.66 MgC/ha from yemane and mahogany stands, respectively. However, this computation is based on rotation ages of 15 years and 25 years for yemane and mahogany, respectively, and assumes that grasslands would have a constant C storage.

Carbon Storage and Carbon Sequestration of Mahogany and Yemane Tree Farms

Table 4 reports the farm level carbon storage or density and sequestration of yemane and mahogany. The C density data predicted by the Chapman-Richards function includes the above-ground biomass, roots and soil. The average storage estimates are 44.58 and 93.64 MgC/ha for yemane and mahogany stands, respectively. Short rotation species including yemane does not achieve a high C storage (Dewar and Cannell 1991) as compared to mahogany. In addition, agroforestry and plantation farms have C storage ranging from 4% to 27% lower than that of an undisturbed forest (Hairiah 2001).

Table 4. Tree farm level C storage and sequestration of smallholder tree farms

Age (years)	C storage (Mg/ha)	C sequestration (MgC/ha)	Age (years)	C storage (Mg/ha)	C sequestration (MgC/ha)
Gmelina arborea					
1	0.98	0.98	9	57.72	6.41
2	6.65	3.33	10	59.89	5.99
3	16.28	5.43	11	61.39	5.58
4	26.91	6.73	12	62.42	5.20
5	36.54	7.31	13	63.13	4.86
6	44.34	7.39	14	63.61	4.54
7	50.28	7.18	15	63.94	4.26
8	54.62	6.83			
Mean	44.58	5.47			
Swietenia macrophylla	0.00	0.00	14	127.20	9.09
1	0.01	0.01	15	134.64	8.98
2	0.26	0.09	16	140.53	8.78
3	1.80	0.45	17	145.16	8.54
4	6.37	1.27	18	148.75	8.26
5	15.24	2.54	19	151.52	7.97
6	28.27	4.04	20	153.65	7.68
7	44.18	5.52	21	155.29	7.39
8	61.26	6.81	22	156.53	7.12
9	77.98	7.80	23	157.49	6.85
10	93.30	8.48	24	158.21	6.59
11	106.68	8.89	25	158.76	6.35
12	117.95	9.07			
13	93.64	5.94			
Mean					

With the assumption that all silvicultural treatments and site conditions are the same, C sequestration or average annual carbon accumulation of yemane and mahogany smallholder tree farms, based on the biomass change, is 5.47 and 5.94 MgC/ha/yr, respectively. The values obtained are lower than the average C sequestration rate of tree plantations in the Philippines, averaging about 8.0 MgC/ha/yr, but varying with site conditions (Lasco 2004).

Table 5. Biomass and carbon density estimates of grassland and smallholder tree farms in Leyte Island

Forestland use	Biomass density (Mg/ha)	Carbon density (MgC/ha)
Grassland	28.5	12.1
Gmelina arborea	142.1	63.9
Swietenia macrophylla	352.8	158.8

CONCLUSIONS AND IMPLICATIONS

Applying the Chapman Richards growth function to selected yemane and mahogany smallholder tree farms on Leyte Island yields estimates of a carbon sequestration rate of more than 5 MgC/ha/yr. The carbon storage and sequestration potential obtained varied with species and age. It was expected that fast-growing species, including yemane, can store less carbon than the slow-growing mahogany due to their differences in wood density and rotation age, and this study affirmed the expectation.

About 30% of carbon was tied up in the AGB of the smallholder tree farms investigated, 6% was tied up in the roots, and more than 60% was contained in the soil. This finding has implications for soil conservation and management; minimum or zero tillage will protect this important carbon pool. However, many studies reveal that in tropical soils, carbon storage in the soil decreases as the stand matures because C is tied up in the biomass.

If grassland areas, which have the capacity to store 12 MgC/ha, are planted with these tree species, then the stands can increase storage capacity up to 80% and 90% for yemane and mahogany, respectively, depending on the maximum age when the trees are harvested and the type of products derived from them. Huge areas of barren or unproductive land in the Philippines that have been converted into smallholder tree farms could definitely help attain sustainable development and mitigate greenhouse gases. The establishment of tree farms could also answer the short-term needs of the farmers especially when trees are integrated with cash crops or livestock as immediate sources of income. Tree planting could help alleviate the warming of the environment at the micro climatic and global levels.

Further studies on the carbon storage and sequestration of other smallholder tree farms with emphasis on the indigenous species would be desirable because of their advantages over introduced species including acclimatisation in the area. Moreover, species with potentially high C sequestration capacity should be screened for each land use so that species that can absorb C fastest can be prioritised in tree planting. These studies would help prepare all sectors in case the Kyoto Protocol materializes. Under the Clean Development Mechanism, only reforestation (plantations established in 1990 and above) and afforestation (areas barren for 50 years) are qualified. Smallholder tree farms and agroforestry could be included, although many issues and debates continue regarding this international agreement.

Carbon density of the yemane and mahogany stands was found to be dependent on the biomass that they would produce. Researchers should therefore find ways to improve dry matter content by employing biological technologies, e.g. mycorhizzal application to attain high growth rates in the stand.

ACKNOWLEDGMENT

The authors would like to thank the Australian Centre for International Research on Agriculture (ACIAR) for funding this study.

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