Research paper

Building Allometric Models to Estimate Above-ground and Below-ground Biomass of Mahogany Sapling

Jeng-I Tsai,[1)] Kai-Ling Chang,[1,2)] Fong-Long Feng[1)]

【Summary】

There are large areas of big-leaf mahogany (*Swietenia macrophylla* King) afforestation and reforestation plantations for reducing carbon dioxide due to climate change in Taiwan. In Taiwan, out of the total area of mahogany plantations of approximately 2982.00 ha, 125.40 ha is in national forests and 232.00 is at the Hsin-Hua Experimental Forest Station. Biomass is a plant attribute that accumulates over time. It is an important indicator of growth and is used in analysis and management processes. Above-ground biomass is the key parameter in many allometric relationships. However, there are few studies on below-ground biomass estimations of mahogany, for it is difficult to excavate and quantify these portions. The aim of this study was to establish an allometric relationship to estimate the above-ground (stem wood, stem bark, branches, and foliage) and below-ground (roots) biomass using an easily measured value, such as the diameter at breast height (DBH), diameter at the stem base (DSB) and tree height (H). Forty-six mahogany saplings (0 cm ≤ DBH ≤ 10 cm), with different ages in the second compartment of this forest station, were used to establish the allometric functions of DBH and biomass, and functions of DSB and biomass. A significance test of the correlation was used to test the relationship between DBH and biomass in different sections, including foliage, branches, stems, above-ground, below-ground, and the entire tree. The DSB was also tested. The results showed that the power regression function was superior to other functions. The correlation between DBH and biomass was higher than the correlation between DSB and biomass. The allometric functions for the entire tree biomass, above-ground biomass, and below-ground biomass were $W = 175.67 \times DBH^{2.29}$ ($R^2 = 0.9692$), $W_{above} = 112.21 \times DBH^{2.34}$ ($R^2 = 0.9621$), and $W_{below} = 61.65 \times DBH^{2.19}$ ($R^2 = 0.9610$), respectively. The carbon content of each part of mahogany trees was as follows: stem wood (45.83±0.92%), roots (45.09±0.89%), foliage (44.95±1.21%), branches (43.74±1.09%), and stem bark (42.64±1.01%). Managers can estimate the biomass, carbon content ratio, and carbon storage of mahogany without destroying trees.

Key words: *Swietenia macrophylla* King (mahogany), allometric relationship, carbon content, above-ground biomass, below-ground biomass.

Tsai JI, Chang KL, Feng FL. 2012. Building allometric models to estimate above-ground and below-ground biomass of mahogany sapling. Taiwan J For Sci 27(3):229-38.

[1)] Department of Forestry, National Chung Hsing Univ., 250 Guoguang Rd., Taichung 40227, Taiwan. 國立中興大學森林學系，40227台中市南區國光路250號。

[2)] Corresponding author, e-mail:pig313328@yahoo.com.tw 通訊作者。

Received August 2011, Accepted May 2012. 2011年8月送審 2012年5月通過。

研究報告

建立大葉桃花心木幼林木地上部與地下部生長關係式

蔡正一[1)] 張愷玲[1,2)] 馮豐隆[1)]

摘　要

近年來台灣的平地造林、農地造林、綠海計畫及愛台十二大建設等造林計畫都大量栽植大葉桃花心木(*Swietenia macrophylla* King)，目前在台灣，大葉桃花心木人工林栽植面積將近2982.00 ha，其中125.40 ha種植於國有林班，而新化林場則種植了232.00 ha。根據京都議定書的規範，削減二氧化碳排放量，以減緩氣候變遷之衝擊，已為世界各國所共同關注的議題與努力的目標，大量栽植林木已成為目前主要的趨勢。生物量係指稱生物在生長過程中，乾物的累積重量，為了解生物資源之生產潛力及經營方向的重要指標。地上部生物量在生長關係函數中，是一個重要性態值，卻鮮少有文獻針對地下部生物量進行推估與建立生長關係函數式，主要原因為地下部生物量不易挖掘與量化。本研究係針對新化林場第二林班不同年齡的林分中，46株大葉桃花心木幼林木(DBH小於10 cm)，建立地下部(根部)、地上部(樹幹、葉及枝)及全株林木的生長關係函數，期望以較容易測定的林木性態值(DBH、地徑(DSB)及樹高)，取得不易量化的資料，如地上部、地下部及全株生物量等。建模結果顯示，DBH模式中的乘冪式，分別為$W_{全株生物量} = 175.67 \times DBH^{2.29}$，$W_{地上部生物量} = 112.21 \times DBH^{2.34}$及$W_{地下部生物量} = 61.65 \times DBH^{2.19}$較佳；迴歸判定係數$R^2$分別為0.9692、0.9621和0.9610。大葉桃花心木幼林木含碳量情形為樹幹木材(45.83±0.92%) > 根部(45.09±0.89%) > 葉子(44.95±1.21%) > 枝條(43.74±1.09%) > 樹幹樹皮(42.64±1.01%)，經營者可依據這些資訊，在不用砍伐林木情況下，推估與計算大葉桃花心木的生物量、碳含量比率及碳貯存量等。

關鍵詞：大葉桃花心木、生長關係函數、碳含量、地上部、地下部。

蔡正一、張愷玲、馮豐隆。2012。建立大葉桃花心木幼林木地上部與地下部生長關係式。台灣林業科學27(3):229-38。

INTRODUCTION

Carbon-tradable offsets are of great importance worldwide. Recently, the Kyoto Protocol drew greater attention to carbon storage in forests, which plays a major role in climate change. Therefore, forests, including afforested and reforested areas, are considered major sinks for atmospheric carbon dioxide. Mahogany (*Swietenia macrophylla* King), locally known as Caoba or big-leaf mahogany, is a popular and valuable tropical timber from the Caribbean, and Central, North, and South America. However, the use of this species is restricted due to it being listed as an endangered species by the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) Appendix II, as it is threatened by habitat loss (CITES 2011). Native mahogany has been commercially unavailable since the late 1990s. Hence, great importance is given to mahogany when drafting policies for forest conservation and sustainable management in forestry (Feng et al. 2010). Mahogany is one of the tree species often chosen for afforestation in Taiwan. In Taiwan, out of the total mahogany plantations of approximately 2982.00 ha, 125.40 ha is in national forests. The government paid attention to the benefits of man-made plantations. There is 232.00 ha of mahogany plantations at the Hsin-Hua Experimental Forest Station, and we chose this station for our study area.

Biomass is a plant attribute that accumulates over time. It is an important indicator of growth for analysis of ecological and management processes. Above-ground biomass (often indicating stem biomass) is one of the central characteristics in functional plant ecology and growth analysis. It is also a key parameter in many allometric relationships (West et al. 1999, Niklas and Enquist 2002, Tackenberg 2007), but it only represents part of a tree. Few reports in the literature have estimated the below-ground biomass because of the difficulty in excavating and quantifying these portions (Hakkila 1975, 1979, Xiao and Ceulemans 2004). The aim of this study was to quantify the biomass and carbon content of the foliage, branches, stems, bark, and roots, and establish allometric models to estimate the above-ground, below-ground, and entire tree biomass using easily measured variables, such as diameter at breast height (DBH) and diameter at the stem base (DSB). A typical method uses theoretical carbon contents (50%) to measure carbon storage and carbon sequestration of vegetation. This method might overestimate carbon storage. Different species likely have distinct carbon contents. The carbon contents might differ in the foliage, branches, stems, bark, and roots. The carbon content of each part of mahogany was also analyzed. The allometric functions and carbon contents can help us estimate the carbon storage of this species without destroying another tree.

MATERIALS AND METHODS

The site and plantation at the Hsin-Hua Experimental Forest Station, an ancillary organization of National Chung Hsing University in Hsin-Hua District, Tainan City, is described in Fig. 1. It is a protected forest of the Hutoupei Reservoir and has 10 compartments that cover an area of 505.92 ha. The national forest is only 373.92 ha (excluding private forests), out of which 232.00 ha is mahogany plantations including 64.30 ha of pure-mahogany plantations and 167.70 ha of mixed-mahogany plantations at this experimental forest station (Chang and Feng 2008).

Sampling of mahogany saplings

Swietenia macrophylla, commonly known as big-leaf mahogany, is in the Meliaceae family. This species is an upright growing tree with a broad, rounded, and symmetrical crown. The leaves are even-pinnately compound and ovate-lanceolate, and the length of leaf is around 6~21 cm. The flowers are inconspicuous, but the fruit is a large (around 16 cm long and 8 cm wide) greenish-brown woody capsule, that splits into 5 sections. Each fruit has 50~60 seeds. Seeds are flat, long, winged, and light-brown. The wood is famous for its hard, beautiful texture, is reddish-brown, and is used for furniture, musical instruments, boats, caskets, and fixtures (Liu et al. 1994).

All materials were collected in the second compartment of this forest station, which has the largest pure mahogany forest, and those samples grew in different stands. According to the stand description, sampled trees were planted from 1978 to 1987. Liu et al. (1994) defined a sapling as having a diameter of 10 cm. We measured the diameters of mahogany saplings in the second compartment of the Hsin-Hua Experimental Forest Station. Saplings were divided into 6 diameter classes: class 0, tree height < 1.3 m; class 1, diameters of 0.00~2.00 cm; class 2, diameters of 2.01~4.00 cm; class 3, diameters of

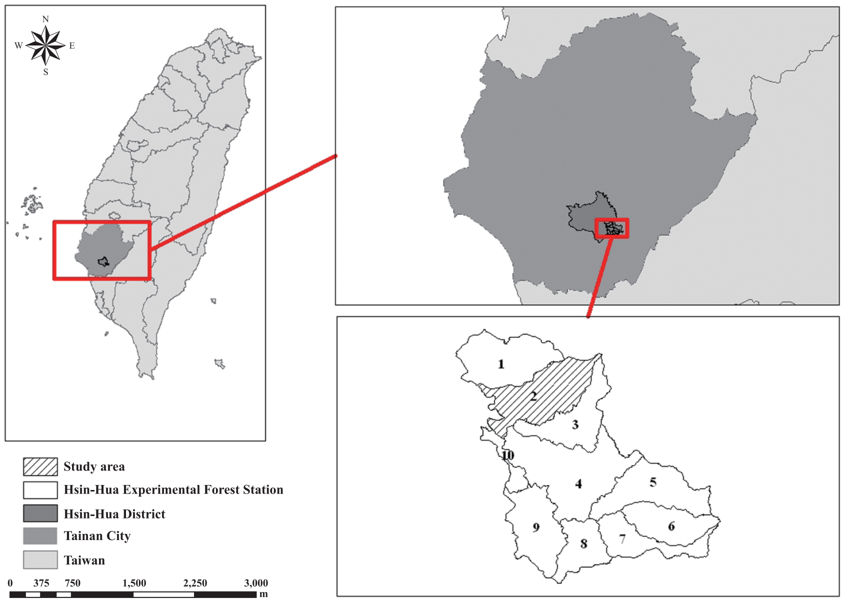

Fig. 1. Location of the Hsin-Hua Experimental Forest Station.

4.01~6.00 cm; class 4, diameters of 6.01~8.00 cm; and class 5, diameters of 8.01~10.0 cm. Ten sampled trees were excavated from each of classes 0~3. For other classes in which the roots were hard to excavate, only 3 samples were collected (Table 1).

Biomass measurement

Biomass is a plant attribute that accumulates over time and is difficult to measure or estimate. Biomass is also an essential indicator of growth for analysis of ecological and management processes. The stratified clip technique was used to measure the biomass of an entire tree, including the above-ground (foliage, branches, stems, and bark) and below-ground portions (roots). We measured the biomass according to a project which constructed models for transforming forest stocks into biomass values (Wang et al. 2006).

The directly measured above-ground and below-ground variables were the fresh weights of stems, branches, foliage, and roots in the field. Stem measurements were the DSB; moreover, stem sections were collected at 0.5 m intervals to estimate the fresh weight. Root measurements included the diameters of the primary, lateral, and fibrous roots. The moisture content (MC, %) was determined using a 3~5 cm stem section, 100~300 g of branches and foliage, and a 3~5 cm root section according to protocols previously described by Peichl and Arain (2007).

Table 1. The number of mahogany saplings in different classes

Class	Diameter at breast height range (cm)	No.
[0]	Tree height < 1.3 m	10
[1]	0.00~2.00	10
[2]	2.01~4.00	10
[3]	4.01~6.00	10
[4]	6.01~8.00	3
[5]	8.01~10.00	3

Total 46

Development of allometric functions

A one-way analysis of variance (ANO-

VA) is used to determine whether there are any significant differences between the means of 3 or more independent (unrelated) groups. The ANOVA approach provides a battery of highly useful tests for regression models. The coefficient of determination, R^2, is a statistic that provides information about the goodness of fit of a model. The R^2 is a statistical measure of how well the regression line approximates the observations.

Power and linear equations were used to examine relationships between the biomass (dependent value) and DBH and DSB (independent values) using data from the 46 saplings. Models with a better goodness of fit were selected based on the R^2 and beta coefficient.

Carbon content

The typical method is to use theoretical carbon contents (50%) to estimate carbon storage and carbon sequestration by vegetation. This method is convenient, but it might overestimate the carbon storage and carbon sequestration of mahogany. Different species likely have distinct carbon contents. Carbon contents may differ among sapling sections, so foliage, branches, stems, bark, and roots were separately analyzed. Samples were ground into a powder, filtered using a no. 100 mesh, and analyzed using the dry combustion method with an elemental analyzer (EA). Subsequently, the carbon content ratio was determined. Before we analyzed the carbon contents at different sections with ANOVA, Levene's test was used to analyze the homogeneity of the variances. The result showed that all variances ($p = 0.55 > 0.05$) were the same, and so the ANOVA was applied. We then used the Fisher's least significant difference (LSD) test ($p = 0.05$) to determine whether carbon contents differed between sections.

RESULTS AND DISCUSSION

Allometric functions based on DBH data

Thirty-six mahogany saplings taller than 1.3 m were used to develop the allometric functions of DBH and biomass. The parameters of power regression functions [$W = aD^b$ and $W = a(D^2H)^b$] and linear function ($W = a + bD$) were estimated using SPSS 10.0 (SPSS, Chicago, IL, USA). W, D, and H were the biomass, DBH, and tree height, respectively. We used the significance test of the correlation to study the relationship between the DBH and biomass. Moreover, the *t*-test was used to test whether these equations could estimate the biomass or not. The results showed that the DBH could estimate the biomass of different sections, including foliage, branches, stems, above-ground portion, below-ground portion, and the entire tree, because the *F*-value was higher than the theoretical *F*-value.

Results in Table 2 show that the R^2 and beta coefficient of the power regression function were higher than those of other functions. Satoo (1955) used DBH and tree height to develop the tree biomass relationship function. However, we found that inclusion of tree height (H) as an explanatory variable only slightly increased the R^2 and beta coefficient. Several authors who studied the relationship between the biomass and DBH or other characteristics pointed out that the biomass can be accurately estimated using the DBH (Lü and Chen 1992, Xiao and Ceulemans 2004, Wang and Guo 2005). The regression curves showed relationships between biomass and DBH of mahogany saplings as illustrated in Fig. 2. As shown in the figure, the DBH was highly correlated to the above-ground and below-ground biomass values of the entire tree. The above-ground biomass allometric function was $W_{above} = 112.21 \times DBH^{2.34}$, whereas

Table 2. Diameter at breast height (DBH)-biomass relationship curves of mahogany saplings

Parameter	$W = aD^b$				$W = a + bD$				$W = a(D^2H)^b$			
	a	b	R^2	Beta	a	b	R^2	Beta	a	b	R^2	Beta
Foliage	13.53	2.51	0.9196*	0.9589a	-1463.46	635.65	0.7362*	0.8565a	9.47	0.87	0.9157*	0.9569a
Branches	0.30	3.97	0.9369*	0.9654a	-498.07	203.75	0.6491*	0.8421a	0.15	1.39	0.9123*	0.9453a
Stems	98.56	2.27	0.9590*	0.9793a	-3744.61	1888.51	0.8266*	0.9092a	69.12	0.79	0.9765*	0.9882a
Above-ground	112.21	2.34	0.9621*	0.9809a	-5706.13	2727.91	0.7994*	0.8938a	78.30	0.81	0.9755*	0.9877a
Below-ground	61.65	2.19	0.9610*	0.9803a	-1790.91	952.49	0.8199*	0.9055a	44.59	0.76	0.9629*	0.9825a
Total	175.67	2.29	0.9692*	0.9845a	-7497.05	3680.39	0.8099*	0.9000a	124.12	0.79	0.9796*	0.9897a

n = 36; W, biomass (g); D, DBH; a, b: parameters; R^2, coefficient of determination; RMSE, root mean square error.

* The mean difference was significant at the 5% level by Fisher's test.

[a)] The mean difference was significant at the 5% level by *t*-test.

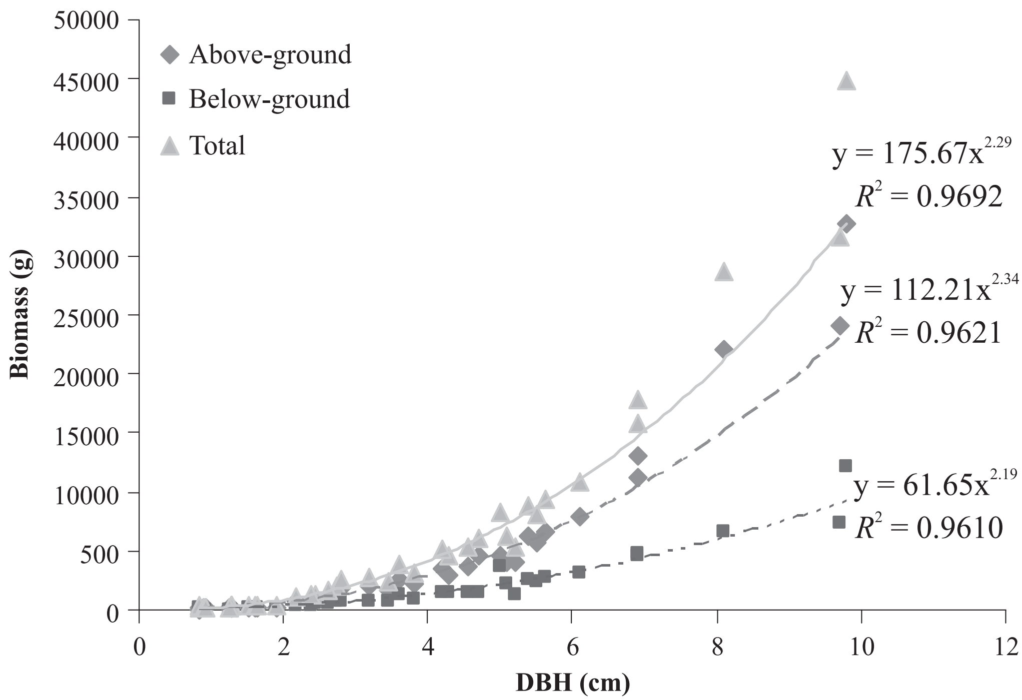

Fig. 2. Relationship between biomass and the diameter at breast height (DBH) of mahogany saplings.

the below-ground biomass allometric function was $W_{below} = 61.65 \times DBH^{2.19}$.

Allometric functions based on DSB data

Forty-six mahogany saplings were used to establish the allometric functions of DSB and biomass. The power regression functions [$W = aZ^b$ and $W = a(Z^2H)^b$] and the linear function ($W = a + bZ$) were estimated. We used the significance test of correlation and one-way ANOVA to study the relationship between the DSB and biomass and determine whether the DSB could estimate the biomass or not.

The results showed that the DSB could estimate the biomass of different sections, including foliage, branches, stems, above-ground portion, below-ground portion, and the entire tree, because the *F*-value was higher than the theoretical *F*-value .

The results given in Table 3 and Fig. 3 show that the R^2 and beta coefficient of the power regression function were higher than those of the other functions. The model was similar to the one developed using DBH. Values of a, b, and R^2 were 63.49, 2.29, and 0.8820, respectively. The results also showed that the DBH is the best characteristic for estimating the biomass of the entire tree.

Analysis of carbon content

Samples were analyzed using the dry

Table 3. Diameter at the stem base (DSB)-biomass relationship curves of mahogany saplings

Parameter	$W = aZ^b$				$W = a + bZ$				$W = a(Z^2H)^b$			
	a	b	R^2	Beta	a	b	R^2	Beta	a	b	R^2	Beta
Foliage	6.86	2.23	0.8168*	0.9038a	-1002.64	388.06	0.6609*	0.8129 a	6.67	0.79	0.8807*	0.9385a
Branches	0.03	4.36	0.8974*	0.9133 a	-348.32	125.22	0.7762*	0.7762a	0.03	1.50	0.8950*	0.9412a
Stems	33.89	2.30	0.8817*	0.9390 a	-2763.45	1208.99	0.7873*	0.8873a	32.97	0.81	0.9500*	0.9747a
Above-ground	42.25	2.30	0.8750*	0.9354 a	-4114.41	1722.27	0.7507*	0.8664a	41.07	0.81	0.9434*	0.9713a
Below-ground	19.93	2.28	0.8821*	0.9392 a	-1364.29	620.31	0.8005*	0.8947a	19.72	0.80	0.9388*	0.9689a
Total	63.49	2.29	0.8820*	0.9392a	-5478.70	2342.58	0.7685*	0.8766a	62.08	0.80	0.9469*	0.9731a

n = 46; W, biomass (g); Z, DSB; a, b: parameters; R^2, coefficient of determination; RMSE, root mean square error.

* The mean difference was significant at the 5% level by Fisher's test.

a) The mean difference was significant at the 5% level by *t*-test.

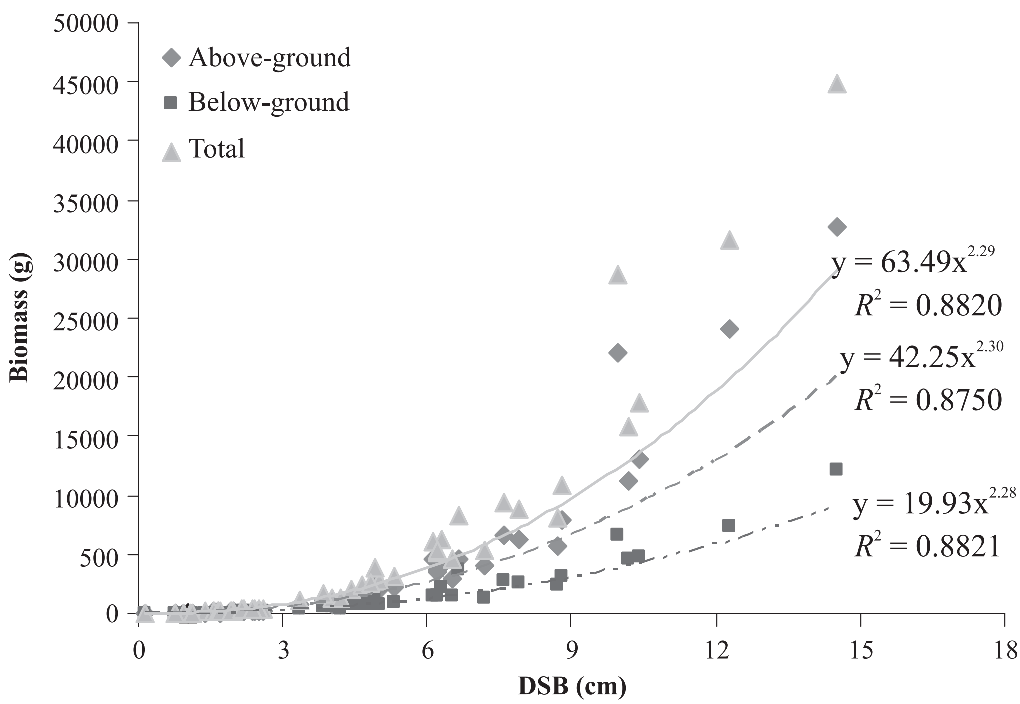

Fig. 3. Relationship between biomass and the diameter at stem base (DSB) of mahogany saplings.

combustion method with the EA, and the carbon content ratio was determined. Moreover, the multiple-comparison of Fisher's LSD test was used to analyze variances of carbon contents for different sections. We found that the carbon content was significantly distinct for different sections (Table 4). Results showed that the carbon content of the stem was the highest, while that of the bark was the lowest. Carbon contents of the stems, roots, foliage, branches, and bark was 45.83, 45.09, 44.95, 43.74, and 42.64%, respectively (listed in Table 5).

Two variables, classes and sections, were statistically analyzed using coefficients and one-way ANOVA to respectively determine their effects on the carbon content. The analysis showed significant differences in carbon contents between different sapling sections (p = 0.000), but no significant effect of diameter class. In previous studies, however, species variations were not considered, and a hypothetical value (50%) was applied when estimating carbon storage (Kinerson et al. 1977). This method may result in overestimation of carbon storage. Lin et al. (2002) measured the specific gravity and carbon content of important timber species in Taiwan and estimated that the carbon content of mahogany was approximately 47.26%. Differences between their findings and our study might be because they only sampled the heartwood, whereas we sampled both the heartwood and sapwood.

CONCLUSIONS

Mahogany, a popular and valuable tropical timber species, is often chosen to reduce carbon dioxide under climate change in Taiwan. The sustainable management of this species has become an important issue. Biomass is an important indicator of growth for the analysis of ecological and management processes. However, there are few stud-

Table 4. Multiple comparisons using Fisher's least significant difference

	Foliage	Branches	Stems	Bark	Roots
Foliage	-	-1.2171±0.3264*	0.8726±0.2877*	-2.3134±0.2849*	-0.7327±0.2877*
Branches	1.2171±0.3264*	-	2.0897±0.3289*	-1.0963±0.3264*	1.3498±0.3264*
Stems	-0.8726±0.2877*	-2.0897±0.3289*	-	-3.186±0.2877*	-0.7399±0.2877*
Bark	2.3134±0.2849*	1.0963±0.3264*	3.186±0.2877*	-	2.4461±0.2849*
Roots	-0.7327±0.2877*	-1.3498±0.3264*	0.7399±0.2877*	-2.4461±0.2849*	-

Mean±standard error (n = 26).* The mean difference was significant at the 5% level by Fisher's protected LSD test.

Table 5. Carbon contents of mahogany saplings in different sections and classes

Class	DBH range (cm)	Foliage	Branches	Stems	Bark	Roots
[0]	< 0.00	44.46±0.88	-	45.36±1.40	42.94±1.01	45.83±0.83
[1]	0.00~2.00	45.39±2.23	-	45.12±1.48	43.35±1.18	45.57±0.32
[2]	2.10~4.00	45.47±0.51	43.02±0.81	45.78±0.26	42.07±0.60	44.53±0.69
[3]	4.10~6.00	44.51±0.28	43.38±0.70	46.25±0.46	41.77±0.77	44.86±0.84
[4]	6.10~8.00	45.56±0.55	44.64±0.66	46.34±0.27	42.89±0.56	45.24±0.63
[5]	8.10~10.00	44.31±1.52	44.61±1.49	46.26±0.43	43.20±0.88	44.19±1.23
All		44.95±1.21	43.74±1.09	45.83±0.92	42.64±1.01	45.09±0.89

DBH, diameter at breast height.

ies on below-ground biomass estimations for mahogany, for it is difficult to excavate and quantify those portions. We quantified biomass and established allometric models to estimate the entire tree (above-ground and below-ground) biomass using DBH and DSB. A one-way ANOVA (*F*-test) was used to demonstrate that those functions could estimate the biomass of different sections. Results showed that the DBH and H measurements were suitable for developing power regression allometric functions of mahogany saplings. The R^2 and beta coefficient between DBH-H and biomass were > 0.9. Results of the one-way ANOVA showed that the carbon contents in each part of mahogany significantly differed, but there were no significant effect of the diameter class. The carbon contents of each part of mahogany were as follows: stem wood (45.83±0.92%), roots (45.09±0.89%), foliage (44.95±1.21%), branches (43.74±1.09%), and stem bark (42.64±1.01%). Samples were collected from different stands in the second compartment of the Hsin-Hua Experimental Forest Station. The different stands had distinct ages and environmental factors, so the samples were not homogenous. Those functions and results can be used to estimate the biomass of mahogany saplings at this forest station. This model still has to be tested at other locations. Further research could lead to the development of a model for estimating carbon storage and the carbon content ratio without the need for cutting another tree.

ACKNOWLEDGEMENTS

This research was supported by the Taiwan Forestry Bureau (project no. 98-00-5-40). We also thank the Hsin-Hua Experimental Forest Station for providing the study area.

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