Research paper

Allometric Equations for Predicting the Aboveground Biomass of Tree Species in the Fushan Forest

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【Summary】

Two groups of allometric regression equations were developed. These were derived from a mature-phase stand and a building-phase stand caused by gap regeneration, respectively, and relate the aboveground tree biomass component and leaf area to tree diameter at breast height (dbh) based on harvesting 94 trees in the Fushan broadleaf forest of northeastern Taiwan. After analysis, all equations were highly significant. Two methods, the general linear model (GLM) approach and 95% confidence intervals, were used to test whether the 2 sets of equations are statistically equivalent. The results show no stand effect for the equations of biomass component and leaf area. It does appear that common equations can be applied to the 2 stands of the Fushan forest due to gap regeneration.

Key words: allometric equation, mature-phase stand, building-phase stand, gap regeneration.

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研究報告

福山闊葉林林木地上部生物量估算之異率迴歸式

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摘 要

本研究係以福山闊葉林兩孔隙更新時期的兩樣區，已伐取94株喬木之資料，用兩組異率迴歸式，以胸高直徑估算建造期與成熟期林分，樹體各部位之生物量及葉面積。經分析結果顯示，所有迴歸式皆呈現極顯著差異。利用綜合直線迴歸法和95%信賴區間兩種方法比較兩組迴歸式，顯示各部位生物量及葉面積兩組迴歸式無差異。此一結果可確定只需要一組迴歸式，即可以胸高直徑估算兩孔隙更新時期福山闊葉林的生物量和葉面積。

關鍵字：異率迴歸式、成熟期、建造期、孔隙更新。

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INTRODUCTION

In recent years, improved tree utilization and increased interest in the structure and function of forest ecosystems have stimulated a need for precise estimates of the aboveground biomass and leaf area of forest tree species. A regression approach is commonly used to predict biomass from parameters that can be easily measured (Baldwin 1986, Dudley and Fownes 1992, Halpern et al. 1996, Ola-adams 1997). Allometric equations have been used to estimate biomass and leaf area for various types of stands (Horng et al. 1985, Burton et al. 1991, Lövenstein and Berliner 1993, Lavigne et al. 1996). Forms of the allometric equations vary widely, but the most common one uses a natural logarithm function y = a + b In(dbh), where y is biomass or leaf area and dbh is the diameter at breast height (Dudley and Fownes 1992). In Taiwan, several authors have published biomass estimations using allometric equations, but all of them were focused on a single tree species, including *Leucaena leucocephala* (Lam.) de Wit (Liu and Kao 1987), *Cinnamomum camphora* (L.) Presl (Lo and Feng 1987), *Cryptomeria japonica* (L. f.) Don (Chang 1986, Lin 1989), and *Casuarina* spp. (Chen et al. 1998). There are few regression models related to aboveground biomass of natural mixed forests in Taiwan. The biomass of natural broadleaf forests at Fushan has also been studied (Lin et al. 1994), but models to estimate biomass of forest tree species are not established. Therefore, in this report, allometric regression models to predict the aboveground biomass and leaf area for tree species in the Fushan forest are developed and analyzed. Data are based on the biomass of tree species at Fushan forest collected in 1993 (Lin et al. 1994).

MATERIALS AND METHODS

Site

Situated in northeastern Taiwan, the Fushan forest is operated by the Fushan Research Branch, of the Taiwan Forestry Research Institute. Geographically, Fushan forest lies at 24°46'N and 121°43'E. The site is about 1,100 ha in size and ranges from about 400 to 1,400 m in elevation. The forest is a mixed subtropical evergreen hardwood forest and is composed predominantly of species of the Fagaceae and Lauraceae. From 1993 to 1997, the monthly mean temperature of the area was 18.2℃, and the mean annual rainfall was 3,660 mm with 221 rainy days yearly (Hsia and Hwong 1999). The forest is currently a long-term ecological research (LTER) site.

The study area is a forest on a relatively flat ridge top at 680-700 m elevation. The Fagaceae-Lauraceae association, the dominant community on mountain ridges and slopes in this area, is considered to be a subclimax successional stage. But small gaps occasionally open up due to natural disturbance. When this occurs, growth rates of understory saplings increase, and mid-tolerant tree species invade the open space, occupy the gap, and complete gap regeneration (Canham and Marks 1985). Because a stand is at the middle or late stage of the building phase during gap regeneration, the canopy is closed, there are many small trees (dbh < 15 cm and tree height > 1.3 m), and mid-tolerant tree species such as Fagaceae account for a large proportion of the trees. The stand is defined as a building-phase stand. Over time, another undisturbed subclimax stand is formed, and this is defined as the mature phase of gap regeneration. Details about the definition of these 2 phases are given in Lin et al. (1994).

METHODS

Two sampling plots (20 × 20 m) representing stands at the building and mature phases during gap regeneration were selected. All trees in the plots were cut and weighed, and the distribution, total biomass, and leaf area of the trees and the stands were calculated. Each tree was divided into 4 components, foliage, small branches (branches with attached foliage), large branches (branches without attached foliage), and boles. Details of the methodology of cutting trees and estimating biomass and leaf area of the trees and the stands are described in a previous paper (Lin et al. 1994). A total of 94 trees (42 trees from the mature-phase

Table 1. Characteristics of sampled trees in the Fushan forest

Stand and tree species	No.	DBH (cm)	Tree height (m)
Mature phase			
Machilus thunbergii (Sieb.&Zucc.) Kostermaus	8	24.8[1] (14.5-38.7)[2]	13.2 (10.8-17.0)
Engelhardtia roxburghiana Wall.	6	18.7 (12.3-26.0)	13.7 (8.0-15.6)
Castauopsis carlesii var. *sessilis* Nakai	5	28.9 (17.5-43.7)	15.5 (13.6-17.3)
Litsea acuminata (Blume) Kurata	5	20.0 (11.5-33.4)	12.3 (9.0-15.5)
Symplocos cochinchinensis subsp. *laurina* (Retz.) Noot.	3	16.9 (13.2-19.7)	12.1 (11.3-13.5)
Prunus phaeosticta (Hance) Maxim.	2	14.1 (10.1-18.1)	9.8 (9.6-10.0)
Pyrenaria shinkoensis (Hayata) Keng	2	12.2 (10.1-14.3)	9.0 (7.4-10.5)
Meliosma squamulata Hance	2	19.6 (19.2-20.0)	12.0 (11.8-12.2)
Cyclobalanopsis gilva (Blume) Oerst.	2	23.4 (19.9-26.9)	14.3 (14.1-14.5)
Cyclobalanopsis longinux (Hayata) Schott.	2	21.8 (13.0-30.6)	11.7 (11.5-11.8)
Itea parviflora Hemsl.	1	11.6	12.2
Pasania ternaticupula (Hayata) Schott.	1	16.5	11.5
Cryptocarya chinensis (Hauce) Hemsl.	1	12.6	10.2
Diospyros morrisiana Hance	1	34.0	14.9
Daphniphyllum glaucescens subsp. *oldhamii* (Hemsl.) Huang	1	12.4	12.0
Building phase			
Myrsine sequinii Levl.	9	11.3 (10.0-13.8)	9.4 (8.8-10.6)
Castauopsis carlesii var. *sessilis* Nakai	9	19.6 (10.8-37.3)	11.8 (9.9-15.9)
Pyrenaria shinkoensis (Hayata) Keng	8	13.0 (11.4-15.7)	10.8 (9.3-12.8)
Machilus thunbergii (Sieb.&Zucc.) Kostermaus	8	17.3 (11.0-36.8)	10.6 (9.3-12.3)
Meliosma squamulata Hance	4	19.9 (13.5-29.6)	9.9 (8.2-11.3)
Elaeocarpus japonicus Sieb. & Zucc.	3	23.3 (17.7-29.3)	11.8 (11.4-12.0)
Schefflera octophylla (Lour.) Horms	2	11.6 (10.3-12.8)	9.5 (8.8-10.1)
Symplocos cochinchinensis subsp. *laurina* (Retz.) Noot.	2	25.4 (16.9-33.8)	12.8 (11.0-14.5)
Cyclobalanopsis longinux (Hayata)Schott.	2	17.8 (12.8-22.7)	11.6 (10.5-12.6)
Engelhardtia roxburghiana Wall.	2	10.7 (10.3-11.0)	10.3 (9.7-10.9)
Cinnamomum randaiense Hayata	1	11.0	12.2
Cryptocarya chinensis (Hauce) Hemsl.	1	16.8	11.3
Litsea acuminata (Blume) Kurata	1	13.0	10.6

[1]Mean.

[2]Range.

Table 2. Characteristics of trees in study plots of Fushan forest[1)]
(mean (range))

Item	Mature-phase stand	Building-phase stand	*F* test[2)]
DBH (cm)	20.84 [3)] (10.10-43.70)[4)]	16.07 (10.0-37.30)	**
Tree height (m)	12.78 (7.40-17.30)	10.71 (8.20-15.90)	**
Leaf area (m^2/tree)	44.28 (1.42-170.99)	20.72 (2.26-121.81)	**
Foliage (kg/tree)	4.30 (0.15-16.02)	2.32 (0.20-15.02)	**
Small branches (kg/ tree)	11.79 (0.56-52.41)	5.80 (0.37-34.33)	**
Large branches (kg/tree)	47.73 (0.12-525.21)	24.78 (0.30-221.24)	ns
All branches (kg/tree)	59.52 (0.68-575.61)	30.57 (0.67-255.57)	*
Boles (kg/tree)	141.82 (14.69-640.88)	77.06 (13.92-484.45)	**
Total biomass (kg/tree)	205.64 (15.51-1232.17)	109.96 (22.63-755.03)	*

1) Lin et al. 1994.
2) * $p < 0.05$, ** $p < 0.01$, ns: not significant.
3) Mean.
4) Range.

stand and 52 trees from the building-phase stand) was included in the regression analysis. Characteristics of sampled trees and plots are given in tables 1 and 2, respectively, and the aboveground biomass per hectare of trees in the plots is given in table 3.

After preliminary analysis, biomass of tree components (foliage, small branches, large branches, all branches, and boles), tree height, and leaf area of individual trees provided the data to run the regression analysis. Allometric equations for estimating biomass, leaf area, and tree height of individual trees were generated with dbh as an independent variable. The regression model was $\ln Y = a + b \ln(X)$. Tree components in kg, tree height in m, and leaf area in m^2 were the dependent variables (Y); dbh in cm was the independent variable (X); and a and b were intercept and slope coefficients, respectively.

The allometric equation was derived from the regression $Y = cX^b$ where c is calculated from exp(a + cf). The coefficient, cf, which is needed to transform the logarithmic equation back into a power function, is a correction factor to account for the bias inherent in the model. The correction factor was calculated as $cf = S_{y.x}^2/2$ where $S_{y.x}$ is the standard error of the estimate (*SEE*) of the regression ($S_{y.x} = [\sum_{i=1}^{n} (Y_i - \hat{Y}_i)^2/(n - p)]^{1/2}$). Therefore, the actual intercept (a) of the allometric equation was calculated as a = c + cf, where c is the coefficient of the equation $Y = cX^b$.

Table 3. Biomass of tree components (kg/ha) and leaf area (m^2/ha) of trees, as well as tree number (trees/ha) in the plots of Fushan forest[1)]

Component	Mature-phase stand	Building-phase stand
Foliage	5,660	3,130
Small branches	15,520	7,820
Large branches	62,640	33,450
All branches	78,160	41,270
Boles	186,610	104,640
Total biomass	270,430	148,440
Leaf area	58,270	27,980
No. of trees	1,330	1,350

1) Lin et al. 1994.

Finally, 2 methods were used to test whether the 2 sets of equations had the same slope and intercept. First, the general linear model (GLM) approach was used to run the following SAS codes:

Proc glm; Class stand; Model Y = stand Indbh stand*Indbh; where stand represents

Table 4. Regression coefficients and statistics of allometric equations (InY = a + bIn(dbh)) predicting aboveground biomass, height, and leaf area of trees

Y	Stand[1)]	a	b	Adjusted R^2	*SEE*[2)]
Foliage	M	-4.9819	2.0893	0.582	0.670
	B	-4.4464	1.8658	0.497	0.673
Small branches	M	-4.2336	2.1589	0.689	0.551
	B	-3.3412	1.8173	0.487	0.669
Large branches	M	-6.1040	3.1490	0.713	0.758
	B	-4.7829	2.7792	0.638	0.754
All branches	M	-4.8621	2.8223	0.761	0.602
	B	-3.7896	2.5141	0.635	0.687
Boles	M	-2.1623	2.2753	0.929	0.239
	B	-1.0546	1.8901	0.845	0.292
Total biomass	M	-2.1670	2.3828	0.918	0.271
	B	-1.0958	2.0207	0.837	0.323
Tree height	M	1.4067	0.3819	0.529	0.136
	B	1.7865	0.2149	0.346	0.105
Leaf area	M	-1.9214	1.8669	0.498	0.706
	B	-2.0082	1.7782	0.474	0.672

[1)] M: mature-phase stand, B: building-phase stand.

[2)] Standard error of estimates.

the 2 types of stands, Y is the dependent variables mentioned above, Indbh is In(dbh), and stand*Indbh is the interaction between stand and In(dbh). The last term indicates whether the 2 stands have the same slope or not; the first term indicates whether the 2 stands have the same intercept; and Indbh is the slopes of the models. Then, 95% confidence intervals were determined for the slope and intercept coefficients of the models of the 2 stands to compare if they overlap. All statistical analyses were performed using SAS software.

RESULTS AND DISCUSSION

Table 2 shows that the means of dbh, tree height, leaf area, and all-component biomass of the mature-phase stand were larger than those of the building-phase stand . Most differences were statistically significant, except for large branches (Table 2). The component biomass and leaf area accumulation of individual trees at both stands showed a wide range, with the largest mass from 33 to 4,377 times larger than the smallest mass. The dbh of sampled trees in the mature-phase and building-phase stands also varied widely, from 10.1 to 43.7 cm and from 10.0 to 37.3 cm, respectively. Tree height ranged from 7.4 to 17.3 m for the mature-phase stand, and from 8.2 to 15.9 m for the building-phase stand. The aboveground biomass and leaf area per unit area showed similar results, and all components of trees in the mature-phase stand had accumulated higher biomass than those in the building-phase stand, but there were similar tree numbers per hectare in both stands (Table 3).

Based on the allometric models for estimating biomass, leaf area, and tree height of individual trees by dbh; the coefficients, adjusted R^2, and standard error of the estimate (*SEE*) of the regression equations were calculated, and are listed in table 4. The adjusted R^2 for component biomass was from 0.49 for small branches in the building-phase stand to 0.93 for boles in the mature-phase stand. The *SEE* was from 0.24 for boles in the building-phase stand to 0.76 for large branches in the mature-phase stand. All regressions were highly significant ($p < 0.001$).

Two methods were used to test whether the 2 sets of equations had the same slope and intercept. The results of the GLM approach are given in table 5. From this table, *p* values of both the stand and stand*Indbh terms for the biomass of foliage, small branches, large branches, and all branches as well as leaf area were larger than 0.05, indicating that these terms are statistically non-significant. This shows that the regression models of the 2 stands had the same slope and intercept. For bole biomass, total biomass, and tree height, *p* values were smaller than 0.05, but still larger than 0.01. If a *p* value of 0.01 was selected as the level of significance, both slope and intercept of these 3 components would be treated as the

Table 5. Results (*p* values) from the GLM procedure for intercepts and slopes of regressions for component biomass, leaf area, and height of trees

Y	Stand (intercept)	Stand*Indbn(slope)
Foliage	0.620 ns[1)]	0.553 ns
Small branches	0.411 ns	0.326 ns
Large branches	0.277 ns	0.383 ns
All branches	0.332 ns	0.399 ns
Boles	0.013*	0.012*
Total biomass	0.031*	0.034*
Tree height	0.048*	0.014*
Leaf area	0.956 ns	0.818 ns

[1)] *0.01 < p < 0.05, ns: not significant.

Table 6. Confidence intervals (95%) for intercepts and slopes of regressions for component biomass, leaf area, and height of trees

Y	Stand[1)]	95% Confidence intervals for a (intercept)	95% Confidence intervals for b (slope)
Foliage	M	-3.3753~-6.5885	2.6271~1.5515
	B	-3.0806~-5.8122	2.3664~1.3652
Small branches	M	-2.9129~-5.5543	2.6010~1.7168
	B	-1.9846~-4.6978	2.3145~1.3201
Large branches	M	-4.2857~-7.9223	3.7576~2.5404
	B	-3.2528~-6.3130	3.3399~2.2185
All branches	M	-3.4192~-6.3050	3.3052~2.3394
	B	-2.3964~-5.1828	3.0247~2.0035
Boles	M	-1.5884~-2.7362	2.4674~2.0832
	B	-0.4619~-1.6473	2.1073~1.6729
Total biomass	M	-1.5173~-2.8167	2.6003~2.1653
	B	-0.4410~-1.7506	2.2607~1.7807
Tree height	M	1.7330~1.0804	0.4911~0.2727
	B	1.9997~1.5733	0.2930~0.1368
Leaf area	M	-0.2272~-3.6156	2.4340~1.2998
	B	-0.6455~-3.3709	2.2776~1.2788

[1)] M: mature-phase stand, B: building-phase stand.

same. Therefore, for the 2 selected stands, the 2 sets of regression models had the same slope and intercept.

The confidence intervals for the equations are given in table 6. The confidence intervals of the equations for biomass of various components were rather wide, especially for foliage and large branches at both stands. The intercepts and their confidence intervals of the equations from the building-phase stand were larger than those from the mature-phase stand, while the slopes and their confidence intervals from the mature-phase stand were larger than those from the building-phase stand (Tables 4 and 6). The only exception was the intercept of the model for leaf area, for which the mature-phase stand showed a higher value and wider range than the building-phase stand (Tables 4 and 6). However, between both stands, the confidence intervals of each component overlapped. For foliage, small branches, large branches, all branches, and leaf area, the confidence intervals were nearly the same, while for boles, total biomass, and tree height, the overlap was much less (Table 6). The overlap of the confidence intervals confirms the conclusion obtained from the GLM approach, that is, the slopes and intercepts are the same for component biomass, leaf area, and tree height of the 2 stands. Overall, 1 set of equations can be selected for estimating tree biomass, leaf area, and tree height for these 2 stands of the Fushan forest (Table 7). It does appear that common equations can be applied to both phases of the Fagaceae-Lauraceae association in this area for estimating component biomass, leaf area, and tree height (Table 7). The intercepts of the allometric equations for component biomass ranged from -5.0342 to -1.5340 for the 2 stands, while the slopes ranged from 2.0112 to 2.8350. The positive slopes of the equations show the expected result that biomass component, leaf area, and tree height increase with increasing dbh.

The effective predictive set of equations for estimating tree biomass is limited by many factors, such as site characteristics, age, species, and density. For casuarina stands the slopes of allometric equations from 2 age classes at the same location significantly differed, and 2 groups of equations were built for different age classes (Chen et al. 1998). Also for *Leucaena leucocephala* plantations, the intercepts and slopes of allometric equations from 2 sites significantly differed, indicating the effects of site specificity (Liu and Kao 1987). But common equations for predicting biomass were obtained for 5 sites in hardwood forests located in Michigan and Minnesota in the USA (Burton et al. 1991) and for 6 stands of red maple in the same area (Crow 1983). For the study site, a broadleaf forest in Fushan, the allometric equations to estimate tree biomass can be represented by 1 group of equations on mountain ridges and slopes regardless of the various characteristics of stands.

Table 7. Regression coefficients and statistics of allometric equations (lnY = a + bln(dbh)) predicting aboveground biomass, height, and leaf area of trees for the 2 plots

Y	a	b	Adjusted R^2	*SEE*[1)]
Foliage	-4.8019	2.0112	0.579	0.667
Small branches	-3.9122	2.0387	0.620	0.621
Large branches	-5.0342	2.8350	0.678	0.762
All banches	-4.0929	2.5968	0.708	0.650
Boles	-1.5415	2.0688	0.895	0.277
Total biomass	-1.5340	2.1770	0.885	0.306
Tree height	1.5120	0.3306	0.495	0.130
Leaf area	-2.3358	1.9513	0.543	0.696

[1)] Standard error of estimates.

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LITERATURE CITED

Baldwin VC Jr. 1986. A summary of equations for predicting biomass of planted southern pines. In: Estimating tree biomass regressions and their error. Proceedings of the Workshop on Tree Biomass Regression Functions and Their Estimates; 1986 May 26-30; Syracuse, NY. Gen Tech Rep NE-117, USDA, For Service, Northeastern For Exp Station. p 157-71.

Burton AJ, Pregitzer KS, Reed DD. 1991. Leaf area and foliar biomass relationships in northern hardwood forests located along an 800 km acid deposition gradient. For Sci 37 (4):1041-59.

Canham CD, Marks PL. 1985. The response of woody plants to disturbance: patterns of establishment and growth. In: Pickett STA, White PS, editors. The ecology of natural disturbance and patch dynamics. Orlando, FL: Academic Press. p 197-216.

Chang CT. 1986. Biomass productivity of *Cryptomeria japonica* stand in central and northern Taiwan. Q J Chin For 19(4):45-85. [in Chinese with English summary].

Chen TH, Sheu BH, Chang CT. 1998. Accumulation of stand biomass and nutrient content of casuarina plantations in the Suhu coastal area. Taiwan J For Sci 13(4):335-49. [in Chinese with English summary].

Crow TR. 1983. Comparing biomass regressions by site and stand age for red maple. Can J For Res 13:283-8.

Dudley NS, Fownes JH. 1992. Preliminary biomass equations for eight species of fast-growing tropical trees. J Trop For Sci 5(1):68-73.

Halpern CB, Miller EA, Geyer MA. 1996. Equations for predicting above-ground biomass of plant species in early successional forests of the western Cascade Range, Oregon. NW Sci 70(4):306-20.

Horng FW, Sun JC, Hwang SG. 1985. Aboveground biomass distribution of China-fir plantations with respect to age at Lin-Hua-Chi. Bull TFRI No. 444. 12 p. [in Chinese with English summary].

Hsia YJ, Hwong JL. 1999. Hydrological characteristics of Fushan experimental forest. Q J Chin For 32(1):39-51. [in Chinese with English summary].

Lavigne MB, Luther JE, Franklin SE, Hunt ER Jr. 1996. Comparing branch biomass prediction equations for *Abies balsamea*. Can J For Res 26:611-6.

Lin KC, Horng FW, Yu HM, Ma FC. 1994. Biomass and leaf area index estimates of broadleaf forests in Fu-shan forest. Bull Taiwan For Res Inst New Series 9(4):299-315. [in Chinese with English summary].

Lin ST. 1989. Studies on the growth and nutrient dynamics of Japanese cedar (*Cryptomeria japonica*) plantation under different spacing [dissertation]. Taipei, Taiwan: National Taiwan University. 120 p. [in Chinese with English summary].

Liu SC, Kao YP. 1987. The comparison of different methods for estimating the biomass of *Leucaena leucophala* plantations. Bull Taiwan For Res Inst New Series 2(1):43-64. [in Chinese with English summary].

Lo SL, Feng FL. 1987. The biomass survey and analysis method used in inventory of camphor stand. Bull Exp For NCHU No 8: 67-87.

Lövenstein HM, Berliner PR. 1993. Biometric relationships for non-destructive above-ground biomass estimations in young plantations of *Acacia salicina* Lindl. and

Eucalyptus occidentalis Endl. New For 7: 255-73.
Ola-Adams BA. 1997. Assessment of three allometric regression techniques of biomass determination in two hardwood species. J Trop For Sci 9(3):321-8.