Research paper

Using Allometric Models to Predict the Aboveground Biomass of Thorny Bamboo (*Bambusa stenostachya*) and Estimate Its Carbon Storage

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【Summary】

Bamboo dominates in biomass accumulation and carbon storage due to its rapid growth, which has been widely reported worldwide. Thorny bamboo (*Bambusa stenostachya*) is one of the most dominant bamboo species in Taiwan due to its multiuse functions. The aims of this research were to access the aboveground biomass (AGB) and carbon storage capability of individual culms and at the stand level of thorny bamboo using 4 different allometric models: the general (I), general (II), WBE, and Ruark. The thorny bamboo of this study was sampled in southern Taiwan; its basic biomass accumulation and carbon storage of each aboveground component (leaves, branches, and culms) were determined in a previous study (Lin et al. 2011). We further analyzed the allometric relationships between the diameter at breast height (DBH) and each aboveground component based on various allometric models. The results showed that the general (II) model was the best predictor of AGB compared to the other models. We used this model to predict the AGB and carbon storage at the stand level obtaining amounts of around 58.5 Mg ha^{-1} and 26.8 Mg ha^{-1} C, respectively. The results illustrate that thorny bamboo possesses high potential for carbon storage.

Key words: biomass, carbon storage, thorny bamboo (*Bambusa stenostachya*), allometric model.

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研究報告

刺竹(*Bambusa stenostachya*)地上部生物量模式及碳貯存量之推估

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摘 要

竹類植物由於生長快速，所以具有很高的生物量累積和碳貯存能力，這類研究已在世界各地廣為發表。刺竹是臺灣最為重要的優良竹種之一，具有多元的用途，本研究以此竹種為主要的研究材料。研究所採用之樣竹取樣自臺灣南部地區，樣竹地上部各部位(葉、枝和稈)之生物量和碳貯存量已於之前的研究分析完成(Lin et al. 2011)。本研究進一步以不同的allometric模式，包括general (I)、general (II)、WBE和Ruark模式，分析胸高直徑(diameter at breast height, DBH)和地上部各部位的關係，結果顯示general (II)模式的推估效果最佳，採用此模式推估林分層級地上部生物量及碳貯存量分別為58.5 Mg ha^{-1}和26.8 Mg ha^{-1} C，研究結果也顯示刺竹為具有高碳貯存潛力的竹種。

關鍵詞：生物量、碳貯存量、刺竹(*Bambusa stenostachya*)、allometric模式。

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INTRODUCTION

Bamboo forests worldwide are estimated to cover an area of approximately 31.5×10^6 ha, which are mostly distributed in tropical and subtropical zones (Lu 2001, FAO 2010). These zones have average higher temperatures and more-frequent rains, what are suitable for bamboo habitats with its fast-growing characteristics (Lu 2001, FAO 2010). Taiwan has abundant bamboo resources because its northern and central regions are in the subtropical zone and the southern region is in the tropical zone (Lu 2001, Yen and Wang 2013, Yen 2015). Over 150,000 ha in Taiwan are covered by bamboo forests, which contribute various benefits to local farming communities, including social, economic, and ecological values (TFB 1995, Yen et al. 2010, Yen and Lee 2011). Most of these bamboo forests are classified as plantations and mainly managed by farmers for commercial utilization, because bamboo forests provide great benefits to local village people (TFB 1995, Yen et al. 2010, Lin 2011, Yen and Lee 2011, Yen 2015).

Generally, there are 2 main commercial uses of bamboo in Taiwan: using its culms for raw materials, and edible foods as bamboo shoots. Both uses are dependent on the bamboo species; for instance, long-branch bamboo (*Bambusa dolichoclada*) and thorny bamboo (*Bambusa stenostachya*) are focused on culm production; green bamboo (*Dendrocalamopsis oldhami*) and ma bamboo (*Dendrocalamus latiflorus*) on bamboo shoot production; and makino bamboo (*Phyllostachys makinoi*) and moso bamboo (*Phyllostachys pubescens*) on both culm and bamboo shoot production (Lu 2001, Lin 2011, Yen et al. 2010, Yen and Lee 2011). In addition to commercial production, these bamboo plantations also play important roles in soil and water conservation, environmental protection, and other ecological services (Lu 2001). In recent years, we found that much research has dealt with bamboo carbon sequestration worldwide because bamboo possesses a high growth rate and rapid biomass accumulation (Cheng et al. 2009, Yen et al. 2010, Yen and Lee 2011, Zhou et al. 2011, Yen and Wang 2013). Some studies indicated that bamboo is a great potential species for carbon storage if bamboo forests are well managed (Cheng et al. 2009, Yen 2015).

Thorny bamboo is one of the important economic species of the world and possesses many advantages and economic values, such as rapid growth, excellent woody properties, and short harvest periods under good management. However, in Taiwan, many studies concerning bamboo carbon storage were carried out on makino and moso bamboo, but few have addressed thorny bamboo (Wang et al. 2009, Yen et al. 2010, Yen and Lee 2011). The reason could be that thorny bamboo belongs to the sympodial type; it is more complex to assess carbon storage, and it is necessary to further consider the amount of clumps on site. This study investigated the carbon storage of thorny bamboo at the individual and stand levels. The purposes of this study were: (1) to predict allometric relationships between the aboveground biomass (AGB) and diameter at breast height (DBH), (2) to compare the prediction effects among different allometric models, and (3) to predict the AGB and carbon storage of thorny bamboo at the stand level.

MATERIALS AND Methods

Study areas

Study sampling was conducted at 2 sites in southern Taiwan, one located in Longci (22°59′01.9″N, 120°22′02.9″E), and the other one in Neimen (22°55′19.7″N, 120°25′17.3″E), which belong to low-elevation areas at elevations of 84 and 126 m, respectively (Lin et al. 2011). In these areas, there are abundant thorny bamboo forests. The 2 sites have similar temperature ranges of 24.1~24.7℃ and a rainfall range of 1672~1784 mm yr^{-1} (Lin et al. 2011). Detailed information about the location, geographic status, and climate conditions of the study sites was described in a previous study by Lin et al. (2011). Bamboo samples were collected from the Longci and Neimen regions, and the AGB components of these bamboos were also measured after they were cut in the fields. In addition, we also sampled a thorny bamboo stand, located in the Longci region, as an example to predict biomass and carbon storage at the stand level.

Methods

Individual bamboos were stratified sampled from the Longci and Neimen regions based on their age classes and sizes. In general, 1~5-yr-old bamboo was evenly distributed in a stand if the bamboo was well managed, because older bamboo (over 5 yr old) should have been harvested (Yen et al. 2010, Yen 2015). The bamboo age can be identified directly from its features; however, this work was usually assisted by experienced bamboo farmers (Lin et al. 2011). In total, 51 bamboo samples were selected and cut down in the field after their ages was identified and DBH was measured, among which 25 bamboo samples were from Longci and 26 samples were from Neimen. Among these samples, weights of 10 samples from each region were measured for biomass calculations of different components, including leaves, branches, and culms; culm weights of the other 31 bamboo samples were only measured in the field. Because a previous study mainly focused on the bulk density of culms of each bamboo age class, more culms needed to be measured (Lin et al. 2011). On the other hand, culms are the main component of each bamboo; therefore, more culm data would be helpful to accurately calculate the biomass and carbon storage.

In order to determine biomass allocation, the weights of different components, such as leaves, branches, and culms, of each bamboo of these 20 samples were immediately weighed after being separated in the field. These samples of leaves, branches, and culms were brought back to the laboratory, and oven-drying at 105℃ was used to obtain an absolute dry weight of each component. The fresh culm weights of the other 31 bamboo samples were also measured. The process biomass determination was based on the ratio of the oven-dried weight to fresh weight of each component. The biomass of each component can be calculated from the fresh weight×(oven-dried weight / fresh weight). For instance, the culm biomass equals the culm fresh weight×(oven-dried weight of culms / fresh weight of culms). Likewise, the biomass of leaves, branches, and culms was obtained using the same calculation process. Extending these samples to the laboratory, biomass allocation of all of the individual bamboo samples could be predicted. The detailed processes of biomass determination are described in a study by Lin et al. (2011). On the other hand, the percent carbon contents (PCCs) of different-aged culms of thorny bamboo were measured and found to be 46.42, 46.51, 45.37, 44.77, and 46.06% for bamboo that was 1~5 yr old, respectively (Lin et al. 2011).

After the biomass of each component was measured, relationships between biomass components and DBH were built based on the allometric models. In this study, 4 allometric models from reviewed studies were tested (Table 1). The allometric relationship has a general form in the function: $Y = aX^b$ (where Y is biomass, X is DBH, and a and b are parameters) (Ruark et al. 1987). The general allometric model was further developed into various types to meet data requirements (e.g., Ruark et al. 1987, West et al. 1999, Chamber et al. 2001, Zianis 2008). These models were widely applied to various tree species and have had good results on regional or global scales (West et al. 1999, Chamber et al. 2001, Zianis 2008, Yen et al. 2009).

We used DBH or DBH and tree height (H) as independent variables to predict the biomass (leaves, branches, culms, and aboveground total), and the bias between observed data and the models was evaluated by the root mean squared error (RMSE) and mean absolute percentage error (MAPE) for all models. The RMSE and MAPE are defined in equations (1) and (2) where smaller values of these 2 indicators imply a better model fit in biomass prediction (Lewis 1982, Kutner et al. 2005):

$$\mathrm{RMSE} = [\textstyle\sum_{i=1}^{n}(y_i - \hat{y}_i)^2 / (n - p)]^{0.5} \text{ and} \quad (1)$$

Table 1. Allometric models used in this study

Model	Model type[a)]	Reference
General model (I)	$Y = a \times DBH^{b}$	Ruark et al. (1987)
General model (II)	$Y = a \times (DBH^2 \times H)^{b}$	Ruark et al. (1987)
WBE model	$Y = a \times DBH^{2.67}$	West et al. (1999)
Ruark model	$Y = a \times DBH^{b} e^{c \times DBH}$	Ruark et al. (1987)

a) Y is of leaves, branches, culms, and aboveground biomass; DBH, diameter at breast area height; H, culm height; a and b, parameters of models; e, exponential.

$$\mathrm{MAPE}(\%) = \frac{1}{n}\sum_{i=1}^{n}\frac{|y_i - \hat{y}_i|}{y_i}\times 100\%; \qquad (2)$$

where y_i is an observation, $\hat{y}_i$ is an estimator by the model, n is the sample size and p is the number of parameters in the model.

Moreover, we predicted carbon storage of different components based on biomass and the PCC as mentioned above (Lin et al. 2011). Noticeably, because the PCC only showed slight differences with culm age (44.77~46.51%), we directly used the mean PCC of culm age to predict carbon storage at the stand level. The developing pattern of thorny bamboo is sympodial, and the stand structure consists of clumps (Lu 2001). Since culms are distributed within clumps, area and clumps should be measured for thorny bamboo stands, and then the DBH of culms within each clump was measured in detail. We adopted a thorny bamboo site at Longci as an example to illustrate predictions of AGB and carbon storage for the stand level. The site was surveyed in January 2013. The process of the survey in the field consist of calculating the clump number after the stand area was obtained. Then, some samples of clumps were randomly selected from entire clumps, and the DBH of each culm was accurately measured in the sampled clumps. Since allometric relationships between DBH and AGB (carbon storage) were built at the individual bamboo level, the model can be utilized to predict carbon storage for these clumps. Then, the carbon storage of the entire stand was obtained based on the ratios of the total clump number to the sample clump number; that is, the aboveground carbon storage = aboveground carbon storage of the sample clump × (total clump number / sample clump number). Moreover, it can also be calculated as the aboveground carbon storage per ha (Mg ha^{-1} C).

In summary, the framework of this study to predict carbon storage contains 2 main parts at the individual and stand levels for thorny bamboo. At the individual bamboo level, the allometric models were used to construct the relationship of DBH and biomass, and the best model was chosen to predict the AGB. We employed AGB with the PCC to predict the carbon storage for thorny bamboo. After the relationships of DBH and carbon storage were obtained, we used survey data of the stand to estimate carbon storage at the stand level. The above method has also been widely utilized to predict carbon storage of various bamboo species, such as makino bamboo (Yen et al. 2010), moso bamboo (Yen and Lee 2011, Sun et al. 2013), and ma bamboo (Sun 2012).

RESULTS AND DISCUSSION

Sample characteristics

Samples of individual bamboo biomass were measured by Lin et al. (2011), and detailed items with DBH and culm height (H) are shown in Table 2. Biomass weights of leaves, branches, culms, and aboveground total were estimated to be 0.565±0.295, 1.949±1.235, 19.290±7.293, and 22.607±8.922 kg culm^{-1} for individual samples, respectively. Biomass proportions of leaves, branches, and culms to the aboveground total were 0.44~8.92, 2.67~18.49, and 78.78~94.10%, respectively. The maximum AGB being allocated to culms is a common pattern for most bamboo species, and the ratio was > 78% for thorny bamboo.

Model predicting capabilities

Distributions of leaf and branch biomass with DBH were disperse and without a clear trend (Fig. 1). We further utilized various allometric models (Table 3) to predict these 2 components using DBH and H. However, test results were not satisfactory with these mod-

Table 2. Characteristics of samples of thorny bamboo (Lin et al. 2011)

Characteristic	*N*	Minimum	Maximum	Mean	Std. Dev.
DBH (cm)	20	5.9	10.7	8.8	1.4
Culm height (m)	20	11.7	25.0	18.8	3.1
Aboveground biomass (kg)	20	8.74	46.40	22.61	8.92
Leaves (kg)	20	0.10	1.09	0.57	0.30
Branches (kg)	20	0.68	4.25	1.95	1.24
DBH[a] (cm)	51	5.9	11.7	9.0	1.3
Culm height[a] (m)	51	10.3	25.0	18.2	3.1
Culms (kg)	51	4.12	43.27	19.29	7.29
Leaf biomass proportion (%)	20	0.44	8.92	2.95	2.00
Branch biomass proportion (%)	20	2.67	18.49	8.73	4.15
Culm biomass proportion (%)	20	78.78	94.10	88.32	4.85

[a] The dataset using the culm model. DBH, diameter at breast area height; Std. Dev., standard deviation.

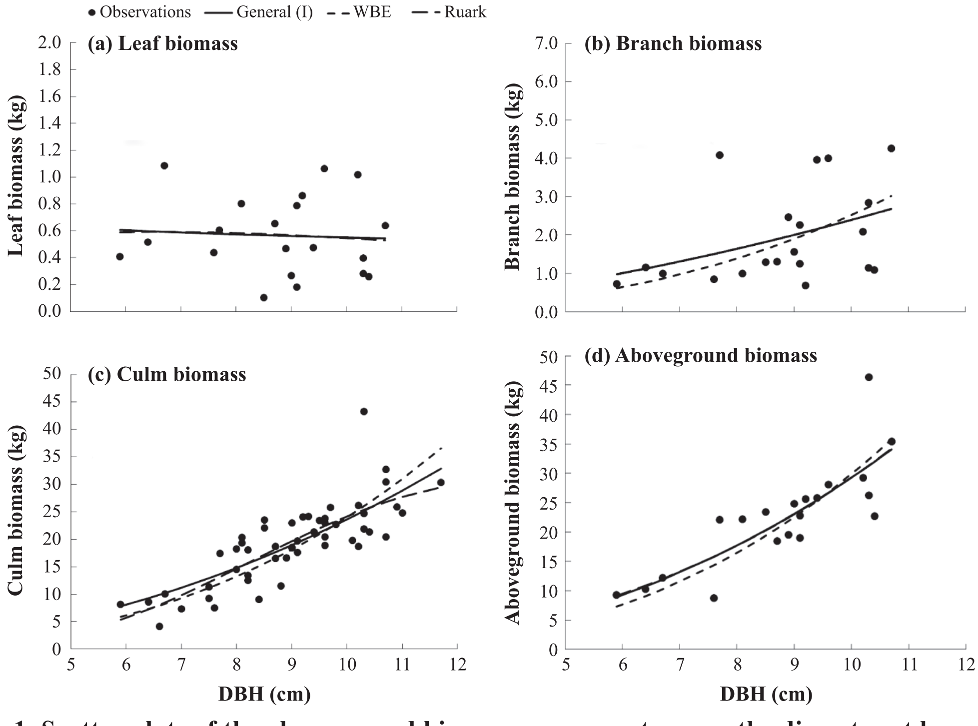

Fig. 1. Scatter plots of the aboveground biomass component versus the diameter at breast height (DBH) and the predictions of each allometric model for thorny bamboo.

els for leaf and branch biomass, and even the WBE model failed to predict leaf data (Fig. 1, Table 3). We used the MAPE value as an indicator to examine models and observations and found inaccurate forecasts by the models. Lewis (1982) pointed out that a MAPE of > 50% indicates an inaccurate forecast of model fit. Unfortunately, values of MAPE were > 50% for all models, regardless of whether for leaves or branches. This implied that DBH

Table 3. The 4 allometric models for predicting biomass components of thorny bamboo

Portion	Model	Parameters			Model fit	
		a	b	c	RMSE	MAPE
Leaves	General (I)	0.8372	-0.1820		0.3022	71.01%
(*n*=20)	General (II)	1.0488	-0.0854		0.3018	70.80%
	WBE	-[a)]	-	-	-	-
	Ruark	0.2803	0.8384	-0.1264	0.3108	71.05%
Branches	General (I)	0.0489	1.6898		1.1620	54.58%
(*n*=20)	General (II)	0.0161	0.6562		1.1418	52.00%
	WBE	0.0054	2.6700		1.1542	51.67%
	Ruark	0.0434	1.7940	-0.0122	1.1956	54.58%
Culms	General (I)	0.1098	2.3797		4.8867	17.05%
(*n*=20)	General (II)	0.0143	0.9876		3.4915	12.06%
	WBE	0.0571	2.6700		4.8047	18.24%
	Ruark	0.1195	2.3069	0.0083	5.0283	17.05%
Culms	General (I)	0.1887	2.0982		4.4762	20.79%
(*n*=51)	General (II)	0.0452	0.8265		3.3374	13.98%
	WBE	0.0514	2.6700		4.6500	20.32%
	Ruark	5.37×10^4	6.9237	-0.5227	4.4210	20.20%
Aboveground biomass	General (I)	0.1659	2.2463		5.2641	16.37%
(*n*=20)	General (II)	0.0262	0.9215		3.8575	11.54%
	WBE	0.0639	2.6700		5.2448	18.22%
	Ruark	0.2442	1.9140	0.0378	5.4160	16.30%

[a)] The dash symbol indicates that the model could not converge.

is not a valid variable for predicting biomass of these 2 components for thorny bamboo. Since leaf and branch data had a dispersed distribution (Fig. 1), larger MAPE values for the models are expected. Nevertheless, only lower biomass proportions of leaves and branches to the aboveground total (2.95% for leaves and 8.73% for branches) were exhibited by thorny bamboo.

In culm and aboveground biomass prediction, we found that the general model (II) was the best predictor of both culm and AGB, especially for culm biomass (Fig. 1, Table 3). Due to the lower correlation between DBH and H for thorny bamboo, adding the H variable into the equations as the general model (II) obviously improved the prediction ability (producing lower RMSE and MAPE values). It was also suggested to predict culms and AGB for thorny bamboo using DBH and H as allometric parameters, if possible.

Notably, certain nonlinear models might be unstable for predictions with different diameter classes; particularly for small trees, test results usually showed smaller RMSE but greater MAPE values (Ruark et al. 1987, Cole and Ewel 2006). This phenomenon was also found in our study; for instance, although RMSE values were similar among the general (I), WBE, and Ruark models in AGB predictions (Table 3), a greater MAPE value was exhibited by the WBE model. This implies that the WBE model obviously underestimated values of the small-diameter class of AGB as illustrated in Fig. 1d.

AGB and carbon storage at the stand level

Stand characteristics were estimated to

be 22±10 culms clump^{-1}, 86 clumps ha^{-1} and 1892 culms ha^{-1}. The detailed diameter distributions of culms are shown in Fig. 2, and culms were mostly distributed in the 8~12-cm class. Because the general (II) model was the best predictor (with smaller RMSE and MAPE values), we used this model to predict the AGB at stand level for the Longci area. Then, we predicted the aboveground carbon storage using biomass×PCC, where PCC was determined by Lin et al. (2011). The AGB and carbon storage were predicted to be 58.5 Mg ha^{-1} and 26.8 Mg ha^{-1} C, respectively. The detailed distributions of each aboveground component within diameter classes for biomass and carbon storage are illustrated in Fig. 3, and the AGB and carbon storage were mostly distributed in the 9-13-cm class. Comparing the ABG and carbon storage of this study to other important bamboo species in Taiwan (Table 4), we found higher ABG and carbon storage for thorny bamboo at the individual bamboo level. However, the ABG of stand level varied with management strategies for bamboo forests, including bamboo type (sympodial or monopodial), management target (for bamboo shoots or culms), and the intensity of selective cutting (Yen 2015). Because thorny bamboo belongs to the sympodial type, the ABG was strongly influenced by clumps ha^{-1}. Therefore, increasing the number of clumps planted in an area is an important way to improve the ABG. Overall, thorny bamboo has good potential for carbon storage compared to other important bamboo species.

CONCLUSIONS

In order to predict carbon storage for thorny bamboo forests, various allometric models were utilized to predict each AGB component. However, leaf and branch biomass values were difficult to predict by allometric models because their distributions were dispersed. On the contrary, culm and AGB could be quantified by allometric models, especially using the general (II) model in this study. In general, the general (II) model showed the best prediction for each biomass component, followed by the general (I) model, Ruark model, and WBE model, even though the WBE model failed to predict leaf data. Our study results also indicated that

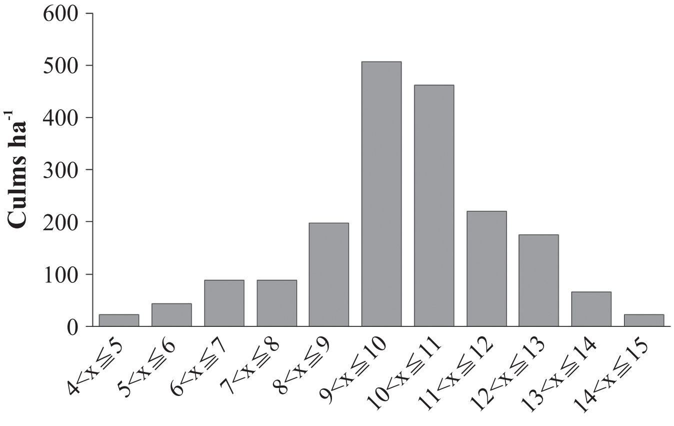

Fig. 2. Stand diameter at breast height (DBH) distributions of a thorny bamboo plantation in the Longci study area.

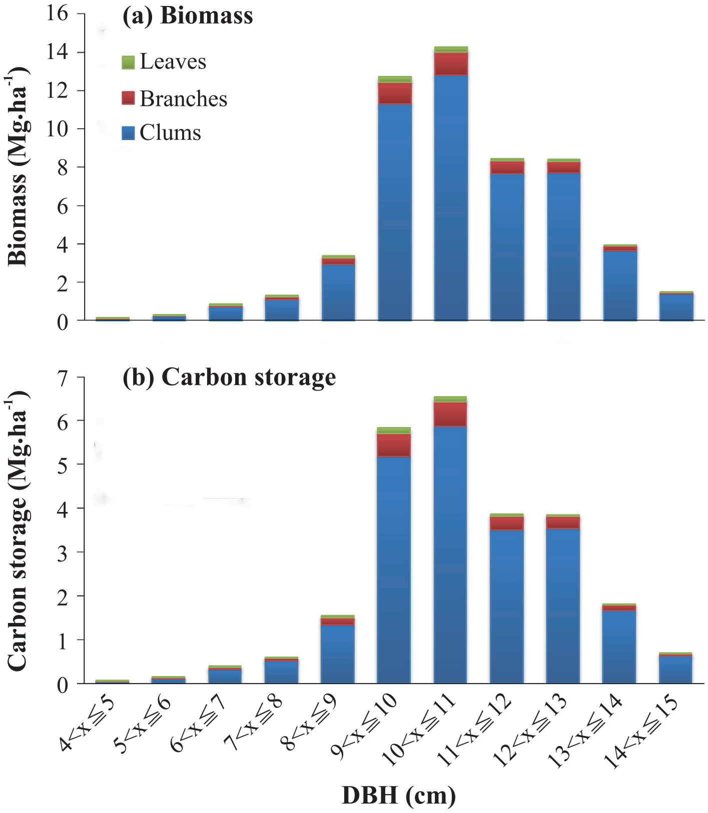

Fig. 3. Distributions of biomass and carbon storage of a thorny bamboo stand at the Longci study site. DBH, diameter at breast height.

Table 4. Comparisons of aboveground biomass and carbon storage of this study with other important bamboo species in Taiwan

Species[a)]	Stand density (culms ha^{-1})	Individual aboveground biomass (kg culm^{-1})	Aboveground biomass (Mg ha^{-1})	Aboveground carbon storage (Mg ha^{-1} C)	Reference
Pp	3967~11,467[b)]	5.5~20.5	38.6~171.3	19.0~82.9	Wang et al. (2009); Wang (2009); Wang et al. (2010); Sun et al. (2013)
Pm	18,000~ 21,191	1.9~3.5	33.6~105.3	16.3~49.8	Wang (2009); Yen et al. (2010)
Dl	300~9085	8.6~14.5	12.4~77.9	3.6~37.7	Wang (2004); Sun (2012)
Bs	1892	22.6	58.5	26.8	this study

[a)] Pp, *Phyllostachys pubescens*; Dl, *Dendrocalamus latiflorus*; Pm, *Phyllostachys makinoi*; Bs, *Bambusa stenostachya*.

[b)] Range obtained by means of each stand in each reference.

thorny bamboo possesses great potential for carbon storage at the individual bamboo level compared to other important bamboo species in Taiwan. The AGB and carbon storage were strongly influenced by stand density at the stand level. We suggest that increasing the number of clumps in an area is a possible way to improve its AGB and carbon storage.

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LITERATURE CITED

Chambers JQ, Santos JD, Ribeiro RJ, Higuchi N. 2001. Tree damage, allometric relationships, and above-ground net primary production in central Amazon forest. For Ecol Manage 152:73-84.

Chen X, Zhang X, Zhang Y, Booth T, He X. 2009. Changes of carbon stocks in bamboo stands in China during 100 years. For Ecol Manage 258:1489-96.

Cole TG, Ewel JJ. 2006. Allometric equations for four valuable tropical tree species. For Ecol Manage 229:351-60.

FAO 2010. Global forest resources assessment 2010—Main report, FAO Forestry Paper no. 163. Rome, Italy: Food and Agriculture Organization (FAO) of the United Nations.

Kunter MH, Nachtsheim CJ, Neter J, Li W. 2005. Applied linear statistical models 5th ed. New York: McGraw-Hill. p 115-9.

Lewis CD. 1982. Industrial and business forecasting methods. London: Butterworth. 143 p.

Lin YJ. 2011. Review, current status, and prospects of the bamboo industry in Taiwan. Taiwan J For Sci 26(1):99-111.

Lin YJ, Wang CH, Wu S. 2011. Analyzing carbon conversion factors of four species of Taiwanese bamboo. Taiwan J For Sci 26(4):341-55.

Lu CM. 2001. Cultivation and management of bamboo forests. Taipei, Taiwan: Taiwan Forestry Research Institute Extension Series 135. [in Chinese].

Ruark GA, Martin GL, Bockheim JG. 1987. Comparison of constant and variable allometric ratios for estimating *Populous tremuloides* biomass. For Sci 33:294-300.

Sun BK. 2012. Estimation of stand structure and carbon storage on ma bamboo and moso bamboo [master's thesis]. Taichung, Taiwan: National Chung Hsing Univ. 72 p. [in Chinese with English summary].

Sun BK, Chen YT, Yen TM, Li LE. 2013. Stand characteristics, aboveground biomass and carbon storage of moso bamboo (*Phyllostachys pubescens*) stands under different management levels in central Taiwan. Q J For Res 35(1):23-32. [in Chinese with English summary].

TFB. 1995. The third national forest resources and land use in Taiwan. Taipei, Taiwan: Taiwan Forestry Bureau (TFB). 258 p. [in Chinese with English summary].

Wang J, Chen TH, Chang HC, Chung HY, Li TI, Liu CP. 2009. The structures, aboveground biomass, carbon storage of *Phyllostachys pubescens* stands in Huisun Experimental Forest Station and Shi-Zhuo. Q J For Res 31(4):17-26. [in Chinese with English summary].

Wang J, Chen TH, Chen SY, Chung HY, Liu EU, Li TI, Liu CP. 2010. Estimating aboveground biomass and carbon sequestration of moso bamboo grown under selection cutting after two years. Q J For Res 32(3):35-44. [in Chinese with English summary].

Wang YC. 2004. Estimates of biomass and carbon sequestration in *Dendrocalamus latiflorus* culms. For Prod Ind 23(1):13-22. [in Chinese with English summary].

Wang YC. 2009. Aboveground biomass and carbon sequestration of moso bamboo and makino bamboos. Hwa Kang J Agr 24:49-68.

West GB, Brown JH, Enquist BJ. 1999. A general model for the structure and allometry of plant vascular system. Nature 400:664-7.

Yen TM. 2015. Comparing aboveground structure and aboveground carbon storage of an age series of moso bamboo forests subjected to different management strategies. J For Res 20:1-8.

Yen TM, Ai LM, Li CL, Lee JS, Huang KL. 2009. Aboveground carbon contents and storage of three major Taiwanese conifer species. Taiwan J For Sci 24(2):91-102.

Yen TM, Ji YJ, Lee JS. 2010. Estimating biomass production and carbon storage for a fast-growing makino bamboo (*Phyllostachys makinoi*) plant based on the diameter distribution model. For Ecol Manage 260:339-44.

Yen TM, Lee JS. 2011. Comparing aboveground carbon sequestration between moso bamboo (*Phyllostachys heterocycla*) and China fir (*Cunninghamia lanceolata*) forests based on the allometric model. For Ecol Manage 261:995-1002.

Yen YM, Wang CT. 2013. Assessing carbon storage and carbon sequestration for natural forests, man-made forests, and bamboo forests in Taiwan. Int J Sust Develop World 20:455-60.

Zhou G, Meng C, Jiang P, Xu Q. 2011. Review of carbon fixation in bamboo forests in China. Bot Rev 77:262-70.

Zianis D. 2008. Predicting mean aboveground forest biomass and its associated variance. For Ecol Manage 256:1400-7.