Research paper

Aboveground Carbon Contents and Storage of Three Major Taiwanese Conifer Species

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【Summary】

This research presents estimations of the aboveground carbon storage of 3 major Taiwanese conifer species: Taiwan red cypress (*Chamaecyparis formosensis* Matsum.), Japanese cedar (*Cryptomeria japonica* D. Don), and China fir (*Cunninghamia lanceolata* (Lamb.) Hook.). The percent carbon content (PCC) of the biomass of different tree portions was determined for these species. We found that the PCC was higher in the foliage of all species, while the PCC in other portions of the trees varied with tree species, and the mean PCC of trees increased with the diameter class for both Taiwan red cypress and China fir. At the tree level, using the method based on determining the PCC of different tree portions (the PCC method) and the conventional method (using 50% as the carbon content) to estimate carbon storage of trees revealed significant differences for all species by the *t*-test for paired comparisons. The conventional method showed higher estimates of carbon storage than the PCC method by 3.96, 1.83 and 0.89% for Taiwan red cypress, Japanese cedar, and China fir, respectively. A allometric models were developed to estimate the carbon storage of the 3 species based on the diameter at breast height (DBH). Moreover, the transformation coefficients between the volume and aboveground carbon storage of trees by a linear regression model were 309.05, 274.33 and 190.34 kg m^{-3} for Taiwan red cypress, Japanese cedar, and China fir, respectively.

Key words: carbon storage, Taiwan red cypress (*Chamaecyparis formosensis* Matsum.), Japanese cedar (*Cryptomeria japonica* D. Don), China fir (*Cunninghamia lanceolata* (Lamb.) Hook.), allometric model, transformation coefficient.

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研究報告

台灣主要三種針葉樹種地上部之碳含量及碳貯存量

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摘 要

本研究旨在探討台灣三種主要針葉樹種－紅檜、柳杉及杉木之地上部碳貯存量。分別測定林木不同部位生物量之碳含量比例(PCC)，結果顯示PCC在林木部位內所有樹種皆以葉部最高，其餘在各部位的順序則隨樹種而有所不同，此外在紅檜和杉木兩樹種之PCC隨著DBH增加而呈遞增的趨勢。在林木層級上，以成對比較T檢定分析以PCC為基礎所推估之碳貯存量(各別部位之PCC×生物量)及傳統方式所推估之碳貯存量(碳含量以50%計算)，所得結果顯示三種樹種用此二種方式推估碳貯存量在統計檢定上皆呈現顯著性差異，採用傳統方式所推估之碳貯存量較以PCC為基礎所推估之碳貯存量為高，在紅檜將高估3.96%，柳杉將高估1.83%，杉木則將高估0.89%。本研究亦建構此三種樹種之碳貯存量及胸徑之相對關係式，用以推估林分之碳貯存量。此外，以線性模式所建立之材積與地上部之轉換係數，紅檜、柳杉及杉木分別為309.05、274.33及190.34 kg m^{-3}。

關鍵詞：碳貯存、紅檜、柳杉、杉木、相對關係模式、轉換係數。

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INTRODUCTION

Global warming may be a result of the atmospheric greenhouse effect, and CO_2 is a major component of greenhouse gases (Marland et al. 2001). Limiting the emissions of greenhouse gases into the atmosphere is a common goal for humans, and this was formalized in an agreement among nations known as the “Kyoto Protocol” (Marland et al. 2001). Forests play a very important role in the global carbon cycle. A large amount of carbon has accumulated and has been sequestered in these plant bodies over a long period (Kramer and Kozlowski 1979). Therefore, validly assessing the carbon storage of different tree species or forest types is an essential task in current forest management.

In recent years, numerous researchers have made efforts to assess the carbon storage of forests, including at the tree, stand, and landscape levels (e.g., Fukuda et al. 2003, Lin et al. 2003, Lamolom and Savidge 2006, Smith et al. 2006, Yen and Huang 2006, Tan et al. 2007, Kindermann et al. 2008). The percent carbon content (PCC) is a major factor for estimating the carbon of trees and forests, and the PCC using 50% of biomass (dry mass) is widely accepted as a generic value for calculating the carbon stored within biomass (e.g., Brown et al. 1986, Hall and Uhlig 1991, Schroeder 1992, Karjalaninen 1996, Marland and Schlamadinger 1997, Nogueira et al. 2008). However, we also found many studies which attempted to determine the PCC of different tree portions (e.g., stems, branches, and leaves) or tree species for estimating the carbon storage of trees or forests in greater detail (Gifford 2000, Lin et al. 2002, 2003, Lamolom and Savidge

2003, 2006, Yen and Huang 2006, Smith et al. 2006). As to differences in estimating forest carbon storage by directly determining the PCC (the PCC method) and by using 50% as the carbon content within biomass (the conventional method), Losi et al. (2003) compared the errors in carbon storage measurements in young tropical plantations based on the PCC method, and found small differences between the 2 methods. In other words, estimates of carbon storage can use the PCC method as a basis for comparisons with other methods.

The present study was conducted on 3 major tree species of Taiwan: Taiwan red cypress (*Chamaecyparis formosensis* Matsum.), Japanese cedar (*Cryptomeria japonica* D. Don), and China fir (*Cunninghamia lanceolata* (Lamb.) Hook.). Our major purposes were to develop allometric models and transformation coefficients for translating a tree volume into aboveground carbon storage of trees for these species. To establish details of these models, we also tried to explore the PCC and carbon storage within different tree portions and for different diameter classes. At the tree portion level, we determined the PCC in the biomass of stems, branches, and leaves, and compared the PCC distributions within different tree portions. At the tree level, estimates of tree carbon storage by the PCC method and conventional method were compared. Furthermore, these models were used to estimate carbon storage at the stand level of the 3 species.

MATERIALS AND METHODS

Study areas

The study was conducted on 3 plantations managed by the Taiwan Forestry Bureau: a 29-yr-old Taiwan red cypress plantation in compartment nos. 121 and 123 of the Da-An-Shi Working Circle (24°15'N, 120°57'E), a 31-yr-old Japanese cedar plantation in compartment no. 74 of the Luan-Da Working Circle (23°42'N, 120°54'E), and an uneven-aged China fir plantation in compartment no. 111 of the Pa-Hsien-Shan Working Circle (24°13'N, 120°55'E). The Taiwan red cypress plantation was planted in 1975 and has an area of 22.53 ha with 1371 stems ha^{-1}; and the Japanese cedar plantation was planted in 1971 and has an area of 12 ha with 1640 stems ha^{-1}. The 2 plantations were investigated in 2004. In addition, the China fir plantation was planted in 1952, has an area of 3.14 ha, and was investigated in 2002. Timber stand improvement at the China fir plantation was carried out, and small trees were planted in the understory, and only 364 dominant trees ha^{-1} of China fir were found in this plantation (Yen et al. 2006).

Methods

Each tree in all 3 plantations had its diameter measured at breast height (DBH), and a stratified sampling method was used based on the DBH. In the Taiwan red cypress and Japanese cedar plantations, 5 diameter classes (x) were established (x < 15 cm, 15 cm ≦ x < 20 cm, 20 cm ≦ x < 25 cm, 25 cm ≦ x < 30 cm, and x ≧ 30 cm), and 4 sample trees were selected in each diameter class for analysis after they were cut down. In total, 20 sample trees were obtained from each plantation. In the China fir plantation, 5 diameter classes were used as well, but the diameter classes had larger ranges (x < 18 cm, 18 cm ≦ x < 26 cm, 26 cm ≦ x < 34 cm, 34 cm ≦ x < 42 cm, and x ≧ 42 cm), and 3 or 4 sample trees were selected for each diameter class for analysis after they had been cut down. Totally, 16 sample trees were obtained from this plantation.

All sample trees were divided into 1-m intervals to measure the biomass after being cut down, and stems, branches, and leaves were weighed separately. The fresh weight of all stems, branches, and leaves was determined after the branches were taken from each interval, and the leaves had been stripped off the branches in the field. Then, these 3 portions of trees were sampled for the laboratory analysis. Each portion was composed of 3 samples from a sample tree, including 3 stem discs (5 cm thick) from the upper, middle, and lower stem, 3 branches, and 3 leaves of 50 g per unit randomly taken from the upper, middle, and lower crown. There were 9 samples from each sample tree. Because the sampling for China fir was not done simultaneously with the 2 species of Taiwan red cypress and Japanese cedar, some differences between China fir and the 2 species were found in the stem portions. That is, the stem wood and bark were measured separately for Taiwan red cypress and Japanese cedar, but both of these parts were combined for the China fir. These samples were dried at 105℃ until the absolute dry weight of the biomass was obtained. Using the ratio of the absolute dry weight to the fresh weight of each sample, the biomass of stems, branches, and leaves, and total aboveground biomass were estimated. After estimating the biomass, samples were ground into a powder to determine the PCC using an elemental analyzer (ELEMENTAR, Vario-EL, Hanau, Germany).

Two-way analysis of variance (ANOVA) was used to analyze the PCC of each species, consisting of tree diameter classes (5 classes) and portions of trees. The portions of trees consisted of stems, bark, branches, and leaves for Taiwan red cypress and Japanese cedar; whereas, only stems, branches, and leaves were used for China fir. When the PCC of the factors of tree diameter classes or portions of trees showed a significant difference (at p = 0.05), we then used the least significant difference (LSD) method to compare differences in the PCC. After measuring the PCC, we calculated the carbon storage of sample trees from each portion of the biomass × PCC as the observed data, and total aboveground biomass × 0.5 as the theoretical data. Due to the source of carbon storage for stems including stems and bark for Taiwan red cypress and Japanese cedar, these 2 portions had to be calculated from the individual biomass × PCC, and then integrated as the carbon storage of stems. Using the t-test for paired comparisons to examine the observed and theoretical data of carbon storage of trees, we calculated the error ratio (ER) as:

$$\text{ER}\ (\%) = \frac{\text{MTCS - MOCS}}{\text{MOCS}} \times 100\%; \qquad (1)$$

where MTCS is the means of theoretical carbon storage of sampled trees and MOCS is the mean of observed carbon storage of sample trees.

A general allometric equation was used to estimate the carbon storage of leaves, branches, stems, and total aboveground portions with the DBH. The model is:

$$Y = aX^b; \qquad (2)$$

where Y is the carbon storage of leaves, branches, stems and total aboveground portions, calculated from the PCC of each portion × biomass; X is the DBH; and a and b are parameters of the allometric model which vary with tree species and stand conditions (e.g., stand age, site quality, and stand density). The 3 stands were investigated by complete enumeration methods before sampling, and the DBH of each standing tree in the 3 stands was measured. After combining the PCC values of stems, branches, and leaves and establishing the allometric models to estimate the biomass by the DBH, the data were used to predict the carbon storage at the stand level. A general linear equation was used to predict the carbon storage by volume:

$Y = aX$; (3)
where Y is the aboveground carbon storage of trees, X volume of trees, and a is the parameter of the linear model. Tree volume was divided into 1-m intervals for the stem analysis after cutting the sample trees of the 3 species (Yen et al. 2004, 2008). The dataset contained the aboveground carbon storage of trees with volume in pairs for the 3 species.

RESULT AND DISCUSSION

Biomass component and PCC of sample trees

The aboveground biomass of trees varied with the diameter class, i.e., the larger the diameter of a tree, the higher biomass it contained for all 3 species (Table 1). On the other hand, all 3 conifers had a main bole structure. Reasonably, the stem biomass occupied the major component of the aboveground biomass, where the ratios of stem biomass to aboveground biomass were 66.44, 82.31, and 81.58% for Taiwan red cypress, Japanese cedar, and China fir, respectively (Table 2). Besides stem biomass, other portions of biomass varied with the tree species. However, our study was not focused on biomass differences within either diameter classes or different portions of trees. Therefore, comparisons of biomass among these items were not further tested for the 3 species.

Using a two-way ANOVA, the PCC was analyzed for different diameter classes and portions for each tree species. The results showed that the PCC in both diameter classes ($p < 0.01$, $F = 5.43$) and portions of trees ($p < 0.01$, $F = 64.49$) were significant for Taiwan red cypress. Only portions of the trees ($p < 0.01$, $F = 83.03$) were significant for Japanese

Table 1. Mean percent carbon content (PCC) of different diameter classes of sample trees of Taiwan red cypress, Japanese cedar, and China fir. The standard deviation of the mean is given in parentheses

Species	Diameter class	Range (cm)	Mean biomass (kg $tree^{-1}$)[1)]	Mean PCC (%)[2)]
Taiwan red cypress	I	10 ≦ x < 15	45.86 (11.66)	48.26 (1.14)[a]
	II	15 ≦ x < 20	76.35 (12.53)	47.83 (0.98)[b]
	III	20 ≦ x < 25	137.64 (13.12)	47.70 (0.97)[b,c]
	IV	25 ≦ x < 30	200.56 (29.54)	47.34 (1.13)[c]
	V	30 ≦ x < 35	330.50 (29.49)	47.73 (1.14)[b,c]
Japanese cedar	I	10 ≦ x < 15	50.24 (18.76)	48.50 (1.27)
	II	15 ≦ x < 20	83.65 (4.63)	48.60 (1.46)
	III	20 ≦ x < 25	126.37 (17.26)	48.87 (1.74)
	IV	25 ≦ x < 30	165.90 (64.04)	48.38 (1.59)
	V	30 ≦ x < 35	270.06 (43.23)	48.69 (1.41)
China fir[3)]	I	x < 18	37.97 (16.13)	49.27 (0.28)[a]
	II	18 ≦ x < 26	118.76 (31.74)	49.74 (0.30)[a,b]
	III	26 ≦ x < 34	161.36 (39.07)	50.52 (0.33)[b,c]
	IV	34 ≦ x < 42	555.55 (106.21)	50.29 (0.25)[b,c]
	V	x ≧ 42	754.48 (23.55)	50.97 (0.31)[c]

1) Tree size differences with different biomass values is a general phenomenon. Means among diameter classes were not compared by statistical analysis.
2) Means marked with the same letter do not significantly differ at $p = 0.05$ by the LSD method.
3) Yen and Huang (2006).

Table 2. Mean percent carbon content (PCC) in different portions of trees of Taiwan red cypress, Japanese cedar, and China fir. The standard deviation of the mean is given in parentheses

Species	Portion of trees	Mean biomass (kg $tree^{-1}$)[1)]	Mean PCC (%)[2)]
Taiwan red cypress	Foliage	13.93 (11.78)	48.66 (0.44)[a]
	Branches	32.02 (30.59)	46.71 (0.35)[b]
	Stems	105.09 (63.38)	48.62 (0.92)[a]
	Bark	7.13 (3.68)	47.08 (0.69)[b]
Japanese cedar	Foliage	8.09 (5.89)	50.38 (0.74)[a]
	Branches	8.40 (5.01)	47.41 (0.70)[c]
	Stems	114.61 (70.24)	49.24 (0.68)[b]
	Bark	8.15 (6.14)	47.39 (0.84)[c]
China fir[3)]	Foliage	13.97 (8.06)	51.74 (0.20)[a]
	Branches	45.60 (45.65)	50.02 (0.19)[b]
	Stems	263.87 (237.79)	48.78 (0.12)[c]

[1)] Different portions of trees having different biomass values is a general phenomenon. Means among portions of trees were not compared by statistical analysis.

[2)] Means marked with the same letter do not significantly differ at $p = 0.05$ by the LSD method.

[3)] Yen and Huang (2006).

cedar. On the other hand, the PCC of all factors, i.e., diameter class ($p < 0.01$, $F = 11.93$), portions of trees ($p < 0.01$, $F = 95.81$), and diameter class × portions of trees ($p = 0.02$, $F = 2.46$), were significant for China fir (Yen and Huang 2006). The LSD method was used to compare the PCC among diameter classes and portions of trees, and 2 or more groups were classified (Tables 1, 2).

The PCC within diameter classes did not show a certain pattern among the 3 species (Table 1), and the PCC within tree portions varied with species (Table 2). In general, the PCC was higher in the foliage of each species; whereas, other tree portions differed among species, for example, foliage (48.66%) and stems (48.62%) > bark (47.08%) and branches (46.71%) for Taiwan red cypress; foliage (50. 38%) > stems (49.24%) > branches (47.41%) and bark (47.39%) for Japanese cedar; and foliage (51.74%) > branches (50.02%) > stems (48.78%) for China fir.

The PCC within portions of trees of diameter classes of Taiwan red cypress and the Japanese cedar are shown in Fig. 1. The PCC of foliage of diameter classes II~V was > 50% for Japanese cedar (Fig. 1). The PCC of portions of trees of different diameter classes of China fir was previously published (Yen and Huang 2006), and results showed that the PCC of foliage of all diameter classes and of branches of diameter classes III~V was > 50%, but the detailed data were not illustrated in Fig. 1.

The general PCC of the biomass of trees uses 50%. The results of the present study of the PCC of the 3 species in different tree portions and diameter classes were close to 50%, but significant differences appeared among different tree portions and different diameter classes. We also found many studies which focused on the PCC of various tree portions or species differences. These studies are summarized as follows. Li et al. (1998) analyzed the PCC of more than 150 tree species in the Hainan area of China, and the average PCC

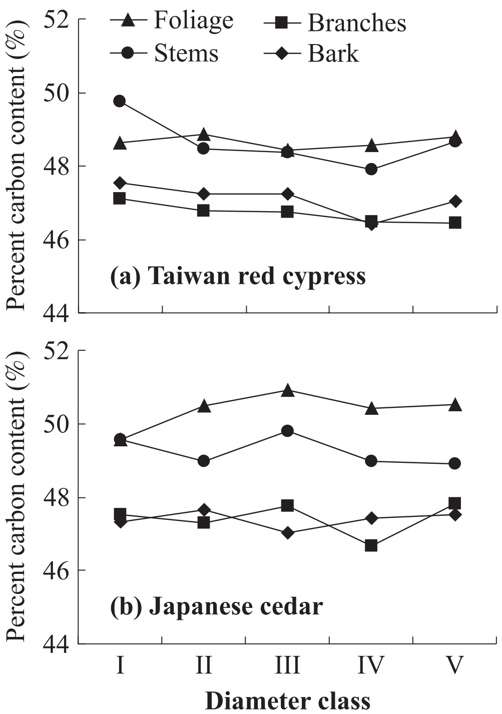

Fig. 1. Percent carbon contents (%) of foliage, branches, stems, and bark of trees of different diameter classes of Taiwan red cypress and Japanese cedar. (I, < 15 cm; II, 15 cm ≦ x < 20 cm; III, 20 cm ≦ x < 25 cm; IV, 25 cm ≦ x < 30 cm; V, ≧ 30 cm).

values of stems, branches, foliage, and roots were 55.49, 46.53, 45.84, and 53.90%, respectively. Gifford (2000) surveyed 19 eastern native Australian tree species, and analyzed the PCC of these tree species. The mean PCC values of green leaves, branches, sap wood, deep wood, and bark were 52.8, 47, 48.7, 50.7, and 49%, respectively. Lin et al. (2004) measured the PCC of 20- and 27-yr-old Taiwania (*Taiwania cryptomerioides*) plantations in southern Taiwan. PCC values of leaves and twigs, living branches, dead branches, and stems were 50.28, 50.80, 49.94, and 51.90% for the 20-yr-old plantation, and were 49.88, 50.83, 50.88, and 52.33% for the 27-yr-old plantation, respectively. However, the trends of PCC among portions of trees may vary with the tree species.

Therefore, to accurately estimate the carbon storage of trees or forests, detailed PCC measurements of tree species should be adopted when possible, if the information has been established. On the other hand, we also found that some of the above-described studies only expressed values of the PCC in tree portions or tree species, since they may consider that the PCC varying with tree portions or tree species is a general phenomenon. For this reason, they did not perform comparisons by statistical analysis in any detail. In fact, values of the PCC of tree portions or tree species were close to 50%; therefore, we do not emphasize whether the deviation is negligible or not, if researchers accept this, or if PCC values of some tree species are not yet established.

Comparison of observed and theoretical values of carbon storage of trees

Using the PCC measuring method as the observed data and biomass×0.5 as the theoretical data, we used the *t*-test for paired comparisons to compare the carbon storage values of sample trees (Table 3). The results showed the observed and theoretical carbon storage values of trees were similar, but all significantly differed at $p = 0.05$ by the *t*-test for paired comparisons for all 3 species. The error ratios (%) of carbon storage from sample trees of Taiwan red cypress, Japanese cedar, and China fir were 3.96, 1.83, and 0.89%, respectively; that is, using the theoretical method would give higher estimations of carbon storage of 3.96, 1.83, and 0.89% for Taiwan red cypress, Japanese cedar, and China fir.

The observed and theoretical carbon storage values of trees were discussed in 2 dimensions. From the viewpoint of statistics, we found significant differences between the observed and theoretical carbon storage

Table 3. Results of *t*-test for paired comparisons of observed and theoretical carbon storage values of trees of Taiwan red cypress, Japanese cedar, and China fir. The standard deviation of the mean is given in parentheses

Species	Carbon storage of trees (kg tree^{-1})		Mean difference between the pair	*t* value	*p* value	ER (%)[1)]
	Observed data	Theoretical data				
Taiwan red cypress	76.08 (50.53)	79.09 (52.75)	3.01 (2.45)	5.48	0.00	3.96
Japanese cedar	68.37 (41.21)	69.62 (42.29)	1.25 (1.70)	3.29	0.00	1.83
China fir	160.29 (141.15)	161.72 (141.32)	1.43 (1.70)	3.34	0.00	0.89

[1)] Error ratio (%).

values of trees; that is, the carbon storage by the 2 methods showed significant differences, since it may look closely at the pair of values. This phenomenon was found for all 3 species. The results may be regarded as unimportant, but it did prove that differences in estimates of carbon storage exist between the 2 methods. On the other hand, in practice, a maximum error ratio of 3.96% was found for Taiwan red cypress, and many forest ecologists or researchers might think this small deviation can be allowed. We also agree that the differences between the 2 methods for estimating carbon storage of trees are small, and it seemed the results are not so important in terms of the carbon storage of trees. However, whether researchers accept the deviation depends on the purpose of the study; we only provide information about the deviation between the 2 methods. On the other hand, reducing errors is very important for model building, and error measures should be based on some criteria. Direct PCC measurements are regarded as a criterion for comparing with other methods for determining the carbon storage of forests (Losi et al. 2003). Since direct PCC measurements were obtained in our research, it is rational to establish carbon storage models based on the PCC data.

Allometric model for estimating carbon storage

An allometric model estimating carbon storage for the 3 species is shown in Table 4. Allometric models are powerful instruments for estimating tree biomass by DBH. Zianis and Mencuccini (2004) collected 278 studies as a meta-dataset, and tried to conduct a test using allometric coefficients of different species spanning the globe scale. The present study used allometric models to estimate the carbon storage of different portions of trees, and we found a good fit between the observed data and models, except for foliage of China fir (Table 4).

Using the allometric models established from sample trees to estimate the component carbon storage of the 2 plantations, the results showed that stems = 60.98 Mg ha^{-1} (74.24%), branches = 14.57 Mg ha^{-1} (17.74%), foliage = 6.59 Mg ha^{-1} (8.02%), and total = 82.14 Mg ha^{-1} (100%) for aboveground Taiwan red cypress; and stems = 129.14 Mg ha^{-1} (88.23%), branches = 8.40 Mg ha^{-1} (5.74%), foliage = 8.82 Mg ha^{-1} (6.03%), and total = 146.36 Mg ha^{-1} (100%) for aboveground Japanese cedar; whereas, for aboveground China fir, the results showed that stems = 30.53 Mg ha^{-1} (81.05%), branches = 4.85 Mg ha^{-1} (12.87%), foliage = 2.29 Mg ha^{-1} (6.08%), and total = 37.67 Mg ha^{-1} (100%).

Volume and carbon storage translation

The carbon storage of the aboveground portions and tree volume showed a linear relationship for the 3 species. The coeffi-

Table 4. Allometric models of $Y = aX^b$ for Taiwan red cypress, Japanese cedar, and China fir

Species	Portion	Parameter a	Parameter b	RMS[1)]	R^2
Taiwan red cypress	Stems	0.1429	1.8988	98.05	0.91
	Branches	0.0016	2.8806	53.11	0.75
	Foliage	0.0013	2.7111	4.19	0.88
	Aboveground	0.0848	2.1654	200.95	0.93
Japanese cedar	Stems	0.1290	1.9631	171.25	0.88
	Branches	0.0129	1.8331	13.33	0.78
	Foliage	0.0154	1.7949	3.27	0.65
	Aboveground	0.1565	1.9427	201.14	0.89
China-fir[2)]	Stems	0.0521	2.2700	999.34	0.93
	Branches	0.0020	2.6865	93.89	0.84
	Foliage	0.7273	0.6888	13.21	0.29
	Aboveground	0.0681	2.2521	1091.97	0.95

[1)] Residual mean square.
[2)] Yen and Huang (2006).

cients were 309.05, 274.33, and 190.35 kg m^{-3} for Taiwan red cypress, Japanese cedar, and China fir, respectively (Fig. 2), where the coefficient of China fir was based on Yen and Huang (2006). The results can be used to directly estimate the aboveground biomass by the transformation coefficients, when volume stocks are obtained.

Assessing forest volume stocks and biomass is very important for forest productivity and management goals, and the carbon storage in forests can also be assessed by the biomass of plants or indirectly through timber volume (Parresol 1999, Fukuda et al. 2003). There are 2.10×10^6 ha of forested land in Taiwan. Man-made forests occupy 20% of the total forestland area, and play a very important role in forest management since natural forest cutting was prohibited in 1991 (TFB 1995, 2008). Japanese cedar, Taiwan red cypress, and China fir are the most commonly imported species in Taiwan. These occupy the second, third, and fourth largest reforestation areas in national forest land, respectively (TFB 1995). In past studies, many researchers made efforts to estimate stand volume

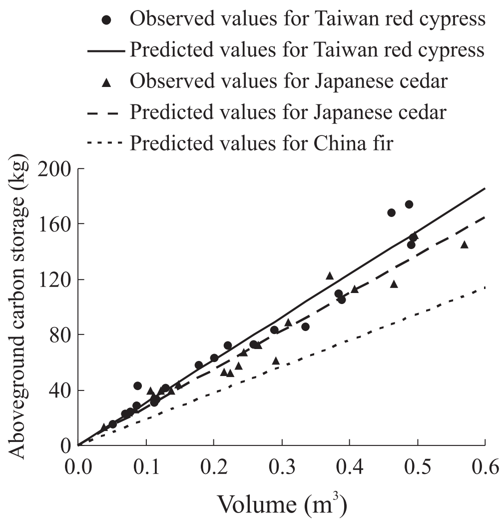

Fig. 2. Relationships between aboveground carbon storage of trees and tree volume by a linear regression for the 3 species. Data for China fir were based on Yen and Huang (2006), and tree volume was measured from stem analysis after cutting sample trees of the 3 species (Yen et al. 2004, 2008). The transformation coefficients of the linear regression models ($Y = aX$) were 309.05, 274.33, and 190.34 kg m^{-3} for Taiwan red cypress, Japanese cedar, and China fir, respectively.

stocks and biomass for the 3 species (e.g., Yang 1975, Hwang 1977, Lo and Feng 1985, Lee and Chan 1988, Chiu and Lo-Cho 2002, Yen et al. 2004). We compared PCC values of different portions of the tree biomass, and used these data to develop allometric models for estimating carbon storage by DBH as well as determining the coefficients between the volume and carbon storage for the 3 species. These models can be helpful tools for estimating carbon storage using either DBH or tree volume. Moreover, these models can be applied to earlier published data or forest inventory data to estimate carbon storage.

The above-mentioned properties of the PCC will help estimate the carbon storage of forests. However, the results may still be restricted to stands with certain conditions, such as stand age, site quality, and stand density. Furthermore, data of other stands in different regions should be collected and analyzed to revise the results of our study.

CONCLUSIONS

After the Kyoto Protocol, carbon storage of trees and forests became 1 of the most important issues for environmental management. However, PCC differences in tree portions and tree species are a general phenomenon. Our study focused on PCC values of different tree portions and assessed carbon storage based on the PCC of these tree portions. We found the trends of PCC between DBH and tree portions differed among tree species. Therefore, we suggest that PCC values based on different tree portions and tree species should be adopted to estimate the carbon storage of forests if this information has been established. On the other hand, although the *t*-test for paired comparisons showed significant differences, only small differences were found between the observed and theoretical carbon storage values of trees. However, the PCC of these tree species was close to 50%, therefore, we did not emphasize this deviation, since many studies still use 50% carbon content for estimating carbon storage. After calculating the error ratio of sample trees between the 2 methods, it was found that 3.96, 1.83, and 0.89% can be used to adjust for Taiwan red cypress, Japanese cedar, and China fir, respectively. Finally, determining the coefficients between tree volume carbon and the aboveground storage of trees can help estimate carbon storage from the publications of past volume stock data of the 3 species.

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