Research paper

Wood Carbon Content and Basic Density of Taiwan Red Cypress (*Chamaecyparis formosensis*) Trees Grown under Different Thinning Treatments in the Liouguei Area

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【Summary】

Understanding the wood carbon content and basic density is important for accurately assessing forest carbon sequestration. The effects of different thinning treatments on the wood carbon content and basic density of Taiwan red cypress (*Chamaecyparis formosensis*) trees were investigated. The results revealed that the average wood carbon contents under different thinning treatments showed no statistically significant differences. However, trees from heavily thinned plantations (basal area, 30 m^2 ha^{-1}) had lower wood basic density than those from plantations with medium, light, and no thinning. Significant differences in the wood carbon content and basic density were observed among cambium of various ages.

The effects of ring characteristics on the wood carbon content of Taiwan red cypress were examined. The wood carbon content increased with increasing ring width parameters and decreasing ring density parameters. In our analyses, the carbon content was affected by various ring characteristics; moreover, both the latewood width and latewood percentage in a ring were the best predictors. The results suggest that using a moderate ($\leq$ medium thinning) plantation density will have no effects on the wood carbon content or wood basic density; however, different tree ages should be considered for calculating carbon sequestration.

Key words: thinning, Taiwan red cypress, wood carbon content, wood basic density.

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研究報告

六龜地區不同疏伐處理紅檜造林木的木材碳含量及基本密度

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摘 要

為了正確評估森林中碳吸存量，瞭解木材碳含量及基本密度是重要的，本報告調查不同疏伐處理紅檜(*Chamaecyparis formosensis*)造林木對木材碳含量及基本密度的影響，結果顯示紅檜造林木的木材碳含量，在不同疏伐處理中並沒有顯著差異性存在，然而，強度疏伐處理(斷面積為30 m^2 ha^{-1})比中度、弱度及沒有疏伐處理的紅檜造林木有較低的基本密度，而紅檜木材碳含量及基本密度，在不同樹齡中有顯著差異性存在。

樹輪特徵值對紅檜木材碳含量的影響經過檢測分析發現，木材碳含量隨著樹輪寬度參數的增加而增大，但是，隨著樹輪密度參數的增大而降低的結果，不同的樹輪特徵值會影響木材碳含量，其中，晚材寬度及晚材率是最重要的影響因素。本報告結果得知紅檜造林木木材碳含量及基本密度在適當疏伐(中度)以下的林分密度中沒有差異，因此，對於計算碳吸存量沒有影響，但是在不同樹齡時則會有影響而需要考慮樹齡變數。

關鍵詞：疏伐、紅檜、木材碳含量、木材基本密度。

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INTRODUCTION

All assessments of forest carbon sequestration must make assumptions regarding the carbon content and density of wood. The figure of 50% carbon content of woody tissues is widely promulgated as a generic value. However, Lamlom and Savidge (2003) indicated that a 50% generic value is an over simplication of limited application in relation to global warming and the concept of carbon credits. In addition, carbon content substantially varies among species as well as among individual trees. Thomas and Malczewski (2007) identified in a review that at least 2 important correlates of variations (lignin content and the volatile carbon fraction) in the wood carbon content exist. Elias and Potvin (2003) indicated that the carbon content widely varies between sampling sites. A few scientists reported large inter-tree and within-tree (compartments, radial, and tree height direction) variations in carbon contents in a given species (Tamura et al. 2005, Bert and Danjon 2006, Lamlom and Savidge 2006, Ma et al. 2007).

Wood basic density [oven-dry weight (green volume)$^{-1}$], rather than specific gravity, is another important factor for accurately assessing forest carbon sequestration. Basic density is known to vary within and between trees, and is affected by wood species, tree age, genetic factors of the trees, environmental conditions of the site, silvicultural practices, and other reasons (Zobel and van Buijtenen 1989, Zobel and Sprague 1998).

Plantation trees of Taiwan red cypress (*Chamaecyparis formosensis*) are an important resource for lumber production in Taiwan. In general, tree growth can be directly controlled by thinning treatments, which is an important practice for commercial plantation wood. Thus, different intensive silvicultural treatments are carried out before rotation. In other words, plantation trees are subjected to different stand densities during standing tree growth. Research is lacking on both the wood carbon content and basic density resulting from various thinning treatments in Taiwan red cypress. Accurately assessing forest carbon sequestration requires an understanding of the effects of thinning treatments on these 2 factors.

Therefore, the main objective of this study was to investigate the effects of thinning treatments on the wood carbon content and basic density of Taiwan red cypress trees. Secondary objectives were to explore and understand relationships between the wood carbon content and ring characteristics.

MATERIALS AND METHODS

The study site was located at an elevation of 1500 m in the No. 4 forest compartment, Liouguei Experimental Forest of the Taiwan Forestry Research Institute (TFRI), Kaohsiung County, southwestern Taiwan. The mean annual temperature is 17.06℃, relative humidity is 86%, and precipitation is 3706 mm. Most of the annual rainfall occurs from May to September.

All sampled trees of Taiwan red cypress came from seeds obtained from a single provenance (population). The area of the study site, about 12 ha, was planted with Taiwan red cypress at a stocking rate (initial spacing) of 2500 trees ha^{-1} in 1957. Different thinning treatments were implemented in 1982. The 4 thinning treatments, cut from below, were heavy thinning (basal area, 30 m^2 ha^{-1}) at the breast height position, medium thinning (35 m^2 ha^{-1}), light thinning (40 m^2 ha^{-1}), and no thinning (52 m^2 ha^{-1}). Four 0.06-ha (20×30-m) plots were established for each thinning treatment, so 16 sample plots were used. A mean diameter of trees was selected from each plot, and 16 sample trees were cut. These trees were harvested in 2003, when they were about 46 yr old. The characteristics of the studied Taiwan red cypress plots from different stand densities are given in Table 1.

One cross-sectional disc (10 cm thick) was cut from each sampled tree at the diameter at breast height (DBH) position. A diametrical strip (passing through the pith) was sawn from each eastern aspect of each sample disc, and then 2 small, clear pith-to-bark specimens (20×20×10 and 20×20×2 mm, radial× tangential×longitudinal) were cut from the strip for wood carbon content measurements and x-ray scanning.

To estimate the wood carbon content, 6 radial sections of the thicker specimen were separated by cambium ages of 1~10, 11~20, 21~25, 26~30, 31~35, and 35~46 yr old. Samples from different thinning treatments and age stages were finely ground (< 0.5 mm). Following the dry combustion method (Sollins et al. 1999), 2~4 mg of the ground sample (< 65℃) was used for carbon concentration analysis in a CN elemental analyzer (EA, Thermo Finnigan NA 1500, North Chelmsford, MA, USA).

For x-ray scanning, the ring characteristics of extracted (using distilled water and alcohol-benzene) and conditioned thin specimens were analyzed by a QTRS-01X Tree Ring Analyzer (Quintek Measurement Systems (QMS), Knoxville, TN, USA). All thin

Table 1. Structure of different thinning treatments of Taiwan red cypress stands

Treatment	Age (yr)	Density (trees ha^{-1})	DBH[1)] (cm)	Tree height (m)	Basal area (m^2 ha^{-1})	Volume (m^3 ha^{-1})
Heavy thinning (30 m^2 ha^{-1})						
Before thinning	25	1619	20.20	13.9	53.4	339.9
After thinning	25	731	22.46	14.3	29.3	190.2
After 20 yr	45	550	27.64	17.9	37.5	300.7
Medium thinning (35 m^2 ha^{-1})						
Before thinning	25	1750	19.29	13.8	54.9	346.0
After thinning	25	981	20.95	14.1	35.5	227.0
After 20 yr	45	669	25.63	17.5	42.6	330.6
Light thinning (40 m^2 ha^{-1})						
Before thinning	25	1794	18.88	13.7	52.1	327.1
After thinning	25	1244	20.09	13.9	40.0	253.3
After 20 yr	45	725	24.13	17.1	42.9	324.1
No thinning (52 m^2 ha^{-1})						
	25	1650	19.83	13.9	52.1	330.1
	45	731	24.77	17.4	44.0	337.6

[1)] DBH, diameter at breast height.

specimens were conditioned in a controlled environment (20℃ and 65% relative humidity). Measurements were made on the treated core (after 12% moisture conditioning for 2 mo). Specimens were scanned in the radial direction. Dimensions of the standard collimator were 0.038 mm wide and 1.59 mm high at the detector. The increment of the sample step size was 0.02 mm. The density was determined by the relationship of x-ray attenuation and density (QMS, 1999).

The absorption of x-rays was determined in a controlled energy range. This was related to the actual sample density (at 12% moisture). The equipment was calibrated to the actual sample basic density [oven-dry weight (green volume)$^{-1}$]. The boundary of the earlywood (EW) and latewood (LW) was determined by a comparator, and the location was then converted into a density threshold in the density profile. The ring density boundary (its location and density value) was identified by a floating density threshold. Based on the density profiles, the EW and LW boundary was defined in each ring by an average density for the maximum and minimum densities in a ring. These data were input into a tree-ring analysis program (as a part of the QMS). The following characteristics were derived: the average ring width, EW width, LW width, ring density, EW density, LW density, maximum density, minimum density, and latewood percentage (LWP) in a ring across the sample.

Analysis of variance (ANOVA) was used to determine if the thinning and cambium age factors significantly affected the wood carbon content and basic density. *F* values were computed to test for significance. When the effects of the 2 factors were significant, means were compared using Tukey's test.

RESULTS AND DISCUSSION

Wood carbon content

The wood carbon contents of specimens

cut from Taiwan red cypress plantation trees subjected to different thinning densities were analyzed using ANOVA and Tukey's test, and results are shown in Table 2. The average wood carbon content (46.42~46.85%) among the 4 thinning densities did not significantly differ. The effects of the interaction of thinning by cambium age on the wood carbon content and basic density were not significant, and were not further analyzed.

Differences in the wood carbon content of Taiwan red cypress plantation trees for different cambium ages were analyzed, and results are shown in Table 3. Respective mean values of the wood carbon contents obtained from cambium ages of 26~46, 21~25, and 1~20 yr were 45.99~46.22, 46.68, and 47.61~47.69% which statistically significantly differed ($p < 0.05$). Therefore, this study indicated that variations in wood carbon contents of different cambium ages showed the following trend: 1~20 > 21~25 > 26~46 yr old. Thus, the wood carbon content in the transverse direction decreased from the pith outward to the bark side.

The results suggest that using these thinning treatments had no effects on the wood carbon content; however, different tree ages (radial within-tree variations) should be considered for accurately estimating carbon sequestration.

Table 2. Wood carbon content of Taiwan red cypress plantation trees treated with various thinning treatments

Thinning treatment	Carbon content (%)
Heavy	46.85±0.70[1)]
Medium	46.42±0.82
Light	46.75±0.69
None	46.82±0.93

[1)] ±standard deviation.

Table 3. Wood carbon content of Taiwan red cypress plantation trees at different cambium ages

Cambium age stages (yr old)	Carbon content (%)
1~10	47.61±0.25a[1)]
11~20	47.69±0.21a
21~25	46.68±0.26b
26~30	46.03±0.20c
31~35	46.22±0.25c
35~46	45.99±0.21c

[1)] Different letters (a, b, and c) in the column indicate a significant difference at the 0.05 level by ANOVA and Tukey's test.

Wood basic density

Differences in the wood basic density among specimens cut from trees subjected to different thinning levels were analyzed, and results are shown in Table 4. The results showed that the wood basic density of trees grown under heavy thinning (0.370 g cm^{-3}) had a lower wood basic density than those of trees grown under medium, light, and no thinning (0.386~0.391 g cm^{-3}) treatments. This indicates that heavy thinning (30 m^2 ha^{-1}) produced a lower basic density than did the other thinning treatments. The results suggest that using these appropriate thinning treatments (≥ 35 m^2 ha^{-1}, medium, light, and no regimens) with a longer rotation age should have no detrimental effects on the wood basic density.

Table 4. Average wood basic density of Taiwan red cypress plantation trees treated with various thinning treatments

Thinning treatment	Basic density (g cm^{-3})
Heavy	0.370±0.016a[1)]
Medium	0.386±0.023b
Light	0.391±0.029b
None	0.389±0.021b

[1)] Different letters (a and b) in the column indicate a significant difference at the 0.05 level by ANOVA and Tukey's test.

In reviews by Zobel and van Buijtenen (1989) and Zobel and Sprague (1998), they stated that thinning treatments had different (decreased, no, or only minor) effects on wood density, due to tree species, tree ages, tree genes, environment conditions of the site, the intensity of silvicultural practices, and other factors.

Differences in the wood basic density of Taiwan red cypress plantation trees for different cambium ages were analyzed, and results are shown in Table 5. Mean values of the wood basic density obtained from cambium ages of 1~25, 26~30, and 31~46 yr were 0.370~0.375, 0.385, and 0.392~0.394 g cm^{-3} which significantly differed ($p < 0.05$). Therefore, this study indicated that variations in wood basic density of different cambium ages showed the following trend: 31~46 > 26~30 > 1~25 yr old. Thus, the wood basic density in the transverse direction increased from the pith outward to the bark side.

In this experiment, significant differences in basic density were observed between the radial positions. These results are similar to those reported by Tsoumis (1991), Haygreen and Bowyer (1982), and Koga and Zhang (2004), all of whom indicated that variations in basic density exist within trees.

Table 5. Average wood basic density of Taiwan red cypress plantation trees at different cambium ages

Cambium ages (yr old)	Basic density (g cm^{-3})
1~10	0.370±0.023a[1)]
11~20	0.370±0.019a
21~25	0.375±0.019a
26~30	0.385±0.020b
31~35	0.392±0.015c
35~46	0.394±0.017c

[1)] Different letters (a, b, and c) in the column indicate a significant difference at the 0.05 level by ANOVA and Tukey's test.

Panshin and de Zeeuw (1980) indicated that radial distribution patterns in wood density variations within cross-sections of mature tree trunks can be classified into 3 general types on the basis of the shapes of the curves for mean wood density from the pith outward to the bark. Type I increases from the pith to the bark, type II decreases outward from the pith, then increases to the bark, and type III decreases from the pith to the bark (e.g., *Chamaecyparis lawsoniana*, *C. obtsua*, and *Calocedrus formosana*; Yang and Chiu 2006). Chiu and Lin (2007) reported that Taiwan red cypress displays several types of variations in the radial direction.

The results suggest that using a reasonable density (≥ 35 m^2 ha^{-1}, medium regimen) should have no effects on the wood carbon content or basic density; however, different tree ages should be considered in radial variations for accurate estimates of carbon sequestration.

Relationships between the wood carbon content and ring characteristics

Because wood ring characteristics (e.g., wood ring density) are easier and cheaper to measure than the trunk carbon content, we were interested in the relationships between these 2 traits. Table 6 shows the correlation coefficients between the wood carbon content and ring characteristics. Fitted using linear models, the wood carbon content was positively correlated to the ring width, EW width, and LW width (r = 0.81~0.82), but negatively related to the ring density, LW density, maximum density, and LWP (r = 0.64~0.83). Overall, the wood carbon content increased with increasing ring width parameters and decreasing ring density parameters. Particularly, a strong relationship between the wood carbon content and basic density was observed, and the following linear regression equation

was obtained:
Basic density = -0.03 × carbon content + 1.77, $r = 0.64$, $F = 13.0^{**}$ ($p < 0.01$).

A stepwise regression procedure was used to determine the most suitable multiple linear regression equation to predict the wood carbon content. These linear regression results are shown in Table 7 ($r = 0.82 \sim 0.88$). The results show that the LW width and LWP values best predicted the wood carbon content by multiple regressions, and the following linear regression equation was obtained by the F-test:
Carbon content = 6.69 × LW width - 0.05 × LWP + 47.6, $r = 0.87$, $F = 31.9^{**}$ ($p < 0.01$).

Table 6. Correlation coefficients between the wood carbon content (C) and ring characteristics by a simple linear regression

Variable	Correlation coefficient
C vs. Ring width	0.82**[1)]
C vs. EW width	0.81**
C vs. LW width	0.81**
C vs. Ring density	-0.64**
C vs. EW density	-0.10[ns]
C vs. LW density	-0.66**
C vs. Minimum density	-0.01[ns]
C vs. Maximum density	-0.71**
C vs. LWP	-0.83**

EW, earlywood; LW, latewood; LWP, latewood percentage in a ring.
[1)] Significant difference at ** $p < 0.01$, and not significant (ns), $p \geq 0.05$.

Thomas and Malczewski (2007) reported that although neither relationship was statistically significant, conifers showed a trend toward a lower carbon content among species with high wood density, while angiosperms exhibited the reverse pattern. Lamlom and Savidge (2003) indicated that wood-meal carbon contents of early woods were invariably higher than those in corresponding late woods, again in agreement with early wood having higher lignin contents. Sandstrom et al. (2007) indicated that the carbon content in dead wood biomass increased with an increase in the decay class, and the density significantly decreased with the decay class. Elias and Potvin (2003) in a review, mentioned that variations in carbon contents reflect differences in a species' chemical

Table 7. Correlation coefficients between the wood carbon content (C) and ring characteristics by a multiple linear regression

Variable	Correlation coefficient
C vs. Ring width, EW width, LW width, and LWP	0.88**[1)]
C vs. Ring width, LW width, and LWP	0.87**
C vs. Ring width, EW width, and LW width	0.83**
C vs. Ring width, EW width, and LWP	0.87**
C vs. EW width, LW width, and LWP	0.87**
C vs. EW width and LW width	0.82**
C vs. Ring width and LW width	0.82**
C vs. Ring width and EW width	0.82**
C vs. EW width and LWP	0.85**
C vs. Ring width and LWP	0.86**
C vs. LW width and LWP	0.87**

EW, earlywood; LW, latewood; LWP, latewood percentage in a ring.
[1)] Significant difference at ** $p < 0.01$.

makeup and cell wall thickness; for example, lipids, lignin, and proteins have elevated carbon contents, while organic acids and minerals respectively contain little and no carbon.

CONCLUSIONS

Information on the wood carbon content and basic density is essential for accurately assessing forest carbon sequestration. The effects of different thinning treatments on the wood carbon content and basic density of Taiwan red cypress (*Chamaecyparis formosensis*) trees and relationships between wood ring characteristics and the carbon content of Taiwan red cypress were examined. The results revealed that the average wood carbon content (46.42~46.85%) with different thinning treatments showed no statistically significant differences. However, trees from heavily thinned plantations had a lower wood basic density than those from plantations with medium, light, and no thinning treatments. Significant differences in the wood carbon content and basic density were observed among different cambium ages.

In addition, the wood carbon content increased with increasing ring width parameters and decreasing ring density parameters. A strong relationship between the wood carbon content and basic density was observed. From our analyses, carbon contents were affected by various ring characteristics; moreover, the latewood width and latewood percentage in a ring were the most important variables for evaluating the wood carbon content. The results suggest that using a reasonable stand density should have no effects on the wood carbon content or wood basic density; however, different tree ages in the radial direction should be considered when calculating carbon sequestration.

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