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## Aboveground biomass and vertical distribution of crown for Taiwan red cypress 20 years after thinning

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**Abstract:** The aim of this study was to analyze the influence of thinning on the different growth stages of the Taiwan red cypress (*Chamaecyparis formosensis* Matsum) on the aboveground biomass allocation patterns and vertical distribution of foliage and branch biomass at the tree level. Although numerous studies in various fields have focused on the influence of thinning effects for Taiwan red cypress, few have assessed the aboveground biomass allocation of different growth stages, or conducted a long-term thinning observation. In this study, we examined 3 even-aged plantations in central Taiwan. In 1982, 3 stands, at ages 7, 15, 21 years, simultaneously began thinning trials. A thinning study was conducted once 20 years ago, and we assessed the long-term effects. The effects of thinning in each of the stands were analyzed and compared at the tree level 20 years later. Each component of the aboveground biomass (foliage, branches, and boles) increased with the thinning intensity, regardless of the age category of the trees; however, the crown mass/ aboveground tree mass appeared the same for each tree age category, regardless of the thinning intensity. We inferred that this phenomenon might result from the same proportional increase of crown mass and aboveground tree mass as the thinning intensity was increased. An allometric function was used to quantify the vertical distribution of the foliage and branch biomass; the results showed an increase in the accumulation of the branch biomass at lower heights following thinning, and the same trend was apparent in all 3 plantations.

**Additional key words:** allometric function; crown mass; tree biomass; thinning effect; thinning intensity; thinning trial

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### Introduction

Taiwan has approximately 2.10 million ha of forestland distributed around the island, which comprises 58.53% of the total land area (Taiwan Forestry Bureau (TFB) 1995). Taiwan red cypress (*Chamaecyparis formosensis* Matsum), widely distributed across mountain regions at elevations between 1500 to 2300 m, is one of the most important indigenous and coniferous species of cypress in Taiwan, possessing both

ecological and economical value because of its aesthetic shape and excellent material properties (TFB 1995; Yen et al. 2009). The Taiwan red cypress and Taiwan hinoki cypress (*Chamaecyparis obtusa* (Sieb. & Zucc.) Endl. var. *formosana* (Hayata) Rehder) are usually regarded as a single forest type, namely, a Taiwan cypress forest, which comprises approximately 48,000 ha of natural forest and 24,800 ha of man-made forest in Taiwan, meaning that the Taiwan cypress forest occupies 3.5% of the total forest lands

in Taiwan (TFB 1995). Numerous scholars in various fields have studied Taiwan red cypress (e.g. Yen 1999; Huang et al. 2005; 2010; Lai et al. 2005; Yen et al. 2009; Li and Yen 2010; Lin et al. 2011; P. S. Huang et al. 2011). However, the long-term effects of thinning on the tree growth and crown properties of Taiwan red cypress at different growth stages have not been examined.

Because to harvest Taiwan red cypress will need long-term plantations, monitoring tree and stand development at different stages of growth is vital for determining the long-term effects of thinning, and hence, selecting an optimal thinning strategy. Various studies have indicated that thinning has a positive effect on growth rate and tree size, possibly improving current biomass accumulation for remaining trees in coniferous stands (e.g. Brix 1981; Yu et al. 2003; Varmola and Salminen 2004; Masaki et al. 2006). The characteristics of trees might change because of thinning treatment and the environment (Brix 1981; Filiapiak 2005; Jarčuška 2009). Numerous studies on thinning have indicated that crown properties (e.g. biomass, shape and structure of crown) might alter after the thinning process (Baldwin et al. 2000; Pinkard and Neilsen 2003; Yu et al. 2003). Employing vertical distribution models to quantify the biomass and shape of the crown can assist in the interpretation of crown property differences resulting from thinning (Baldwin et al. 2000).

Previous studies have indicated that thinning improves the tree growth of Taiwan red cypress (Lee 1985; Lee and Yen 1994; Yen 2002; Li and Yen 2010). We expected thinning to improve tree biomass accumulation; we also assessed the thinning effects on different growth stages and quantified the vertical distribution of foliage and branch biomass for the Taiwan red cypress at various tree levels, with paying careful attention to the long-term thinning effects. This study explores the effects of thinning that occurred 20 years ago on the tree levels of the Taiwan red cypress at 3 different growth stages. The objectives were to assess the aboveground tree biomass after thinning and to quantify the vertical distributions of foliage and branches caused by thinning.

## Materials and methods

### Study plantation

The study area was located in the Ta-An-His Working Circle ( $24^{\circ}\text{N}$ ,  $121^{\circ}\text{E}$ ), one of the national forests in central Taiwan. The area consisted of 3 plantations planted in 1975, 1967, and 1961. The experimental sites had brown humic soil with a soil depth of 40–100 cm (Lee 1985). The monthly temperature was  $14.2\text{--}23.0^{\circ}\text{C}$  (mean  $19.2^{\circ}\text{C}$ ) and the rainfall was  $2401.9 \text{ mm year}^{-1}$  based on the statistics obtained

from the Sun Moon Lake weather station (Taiwan Central Weather Bureau 2013). The history of the 3 plantations can be summarized as follows: (1) the stand planted in 1975 had an area of 22.53 ha; (2) the stand planted in 1967 had an area of 16.42 ha; and (3) the stand planted in 1961 had an area of 18.69 ha. All 3 stands were machine-planted at an initial spacing of  $1.75 \times 1.75 \text{ m}$  ( $3,265 \text{ stems ha}^{-1}$ ). According to the site index curves for this study area (Lee and Yen 2000), the dominant tree height of all 3 stands was nearly 10 m at the index age of 21 years, indicating that the 3 stands were at similar sites.

In 1982, these 3 stands, at ages 7, 15, and 21 years, simultaneously underwent thinning treatment (Lee 1985). The basal area (BA) of the stands was adopted as the criterion for the thinning operation. Each stand had 4 treatment levels expressed as a percentage of BA: 45% (heavy thinning); 30% (middle thinning); 15% (light thinning); and 0% (no thinning). Each level was replicated 3 times. The area of each plot was 0.05 ha ( $20 \times 25 \text{ m}$ ), and the experimental area of each stand was 0.6 ha, resulting in a total experimental area of 1.8 ha. The thinning process was initiated from below (thinning the suppressed trees), to improve the growth of the upper (dominant) standing trees. This thinning study was conducted once 20 years ago, and we assessed the long-term effects. The stand characteristics of the 3 plantations before and after thinning are shown in Table 1 (Lee 1985).

To understand the aboveground biomass accumulation and crown characteristics 20 years after thinning, 36 sample trees (one tree per plot according to the mean diameter at breast height (DBH) of each plot) were selected for analysis in October 2002. Tree characteristics were measured in detail for each tree after felled the 36 sample trees in the field. These sample trees were felled at a 0.3 m aboveground height. After measuring the crown parameters (e.g. crown length, crown width and crown ratio), the sample trees were cut into 1 m sections from the base (0.3 m) to the top.

For each 1 m section of sample tree, all stems, branches, and leaves were separately weighed to determine the different components of biomass, and certain fresh samples were selected to determine the dry weight by using oven drying. In addition, 5 cm thick stem discs at DBH and other portions (the upper, middle, and lower portions of trees) were taken from each sample tree. Three branches were taken from each of the upper, middle, and lower portions of the crowns; and leaves of 50 g per unit were taken from each sample branch; in total, 9 branches and 9 leaves of 50 g per unit were obtained from each sample tree. The samples were then dried at  $70^{\circ}\text{C}$  for 15–25 days until a constant weight was measured for each component. The biomass of the different components was then obtained by using the ratio of

Table 1. Stand characteristics of stem number, mean diameter at breast height (DBH), basal area (BA) and mean height (H) for 3 different age stands before and after thinned at 1982; the four thinning treatments, namely, heavy thinning, middle thinning, light thinning and no thinning (Lee 1985)

Stand	Treatment	Before treatment				After treatment		
		Number of tree per ha	DBH (cm)	H (m)	BA ( $m^2 ha^{-1}$ )	Number of tree per ha	DBH (cm)	H (m)
7-yr-old	heavy thinning	2594	5.6	4.77	6.34	1208	6.4	4.64
	middle thinning	2360	5.6	4.63	5.83	1428	6.3	4.60
	light thinning	2464	5.7	4.47	6.27	1660	6.9	4.84
	no thinning	2250	5.7	4.50	6.08	2250	—	—
15-yr-old	heavy thinning	1474	12.3	8.60	17.40	626	14.2	9.79
	middle thinning	1436	12.9	7.90	18.68	660	15.4	10.70
	light thinning	1464	13.4	8.37	20.71	998	14.1	9.67
	no thinning	1222	12.7	8.79	17.08	1222	—	—
21-yr-old	heavy thinning	1008	16.6	10.83	21.89	448	17.1	13.33
	middle thinning	1390	14.0	9.43	21.32	868	14.6	11.80
	light thinning	1548	15.2	10.67	27.97	1194	16.1	12.67
	no thinning	1352	14.7	9.09	22.89	1352	—	—

oven-dried weight to fresh weight for each component of the sample trees (details please see Lin et al. 2001; Lehtonen et al. 2004; Yen et al. 2009).

## Data Analysis

This study focused on the effects of thinning on variously aged trees. However, a general rule of tree development is that tree biomass increases with age. Before designing this study, we examined 2 factors, the age and thinning treatment, during the pretest, and learned that both factors were significant in biomass. In this study, we focused on the thinning effects, and analyzed the biomass separately for each of the age classes. After the biomass components were measured, the foliage, branch, bole, aboveground biomass, and crown mass/tree mass were examined and the different thinning treatments were compared by using analysis of variance (ANOVA) and least significant difference (LSD) methods. The LSD method has been widely used in relevant biomass studies (Yen et al. 2010; Yen and Lee 2011).

The allometric function (with a variable allometric ratio) was employed to model the vertical biomass distributions of the foliage and branches at the tree level, and the types of distribution of foliage and branch biomass were compared with trees at same the age but different thinning treatments. This allometric equation was developed by Ruark et al. (1987), and has the following form:

$$F(x) = ax^b \exp^{cx} \quad (1)$$

where  $x$  is the relative vertical height of trees calculated from the vertical height of trees/total tree height (H).  $F(x)$  is the cumulative biomass of foliage and branches in  $x$ , and  $a$ ,  $b$  and  $c$  are the parameters of the allometric model.

## Results

The results revealed that foliage biomass, branch biomass, bole biomass, and aboveground biomass differed according to the thinning treatment; the effect of thinning on biomass was clearly shown, and all previously defined components of biomass increased alongside thinning intensity (Table 2). However, the crown mass/aboveground tree mass appeared the same for each tree age category, regardless of the thinning intensity.

For an explanation of the relationship between the observed data and the simulated model, Figure 1 shows a sample of 41-year-old trees with heavy thinning. We found that the allometric models fit the observed data well for foliage and branches of trees of all ages (with high  $R^2$  and small RMSE), revealing that the vertical distribution model had a good predicted capacity (Table 3). The observed data closely matches the vertical distribution curves for foliage and branch biomass that is clearly shown in Figure 1. The distribution type shown in Figure 1 is a cumulative distribution and the foliage and branch biomass within each interval required calculation to separate the results from the cumulative distribution.

The results of the foliage and branch biomass distributions were reproduced from the parameters and calculated at 1 m intervals to present the distribution types (Fig. 2). The experiment revealed that more foliage biomass accumulates at a lower relative height after heavy thinning in 27-year-old trees, but this phenomenon was not apparent in 35- and 41-y-old trees. However, an increase in branch biomass accumulation at lower heights followed the thinning, which was especially apparent after heavy thinning, regardless of the age category (Fig. 2).

Table 2. Treatment means of tree biomass components for 27-, 35- and 41-year-old Taiwan red cypress and the treatment means (mean $\pm$ standard deviation) marked with the same letter are not significantly different at  $p=0.05$  by the LSD method (in the same line)

Tree age	Variable	ANOVA		Thinning treatment		
		F-value	P-value	Heavy thinning	Middle thinning	Light thinning
27-year-old	Foliage biomass (kg)	23.69	0.000	11.3 $\pm$ 1.1 <sup>c</sup>	9.0 $\pm$ 0.4 <sup>b</sup>	8.0 $\pm$ 0.5 <sup>ab</sup>
	Branch biomass (kg)	7.11	0.012	16.2 $\pm$ 1.3 <sup>c</sup>	14.8 $\pm$ 0.8 <sup>bc</sup>	13.3 $\pm$ 1.5 <sup>ab</sup>
	Bole biomass (kg)	12.28	0.002	48.3 $\pm$ 5.8 <sup>b</sup>	33.6 $\pm$ 6.2 <sup>a</sup>	28.5 $\pm$ 4.5 <sup>a</sup>
	Aboveground biomass (kg)	18.01	0.001	75.7 $\pm$ 4.4 <sup>c</sup>	57.3 $\pm$ 6.7 <sup>b</sup>	49.8 $\pm$ 6.3 <sup>ab</sup>
	Crown mass/ tree mass	2.73	0.114	0.36 $\pm$ 0.04	0.42 $\pm$ 0.04	0.43 $\pm$ 0.02
35-year-old	Foliage biomass (kg)	8.62	0.007	11.8 $\pm$ 1.4 <sup>b</sup>	11.3 $\pm$ 1.1 <sup>b</sup>	10.4 $\pm$ 0.9 <sup>b</sup>
	Branch biomass (kg)	16.18	0.001	27.7 $\pm$ 1.4 <sup>c</sup>	19.8 $\pm$ 4.0 <sup>b</sup>	19.0 $\pm$ 1.2 <sup>ab</sup>
	Bole biomass (kg)	87.26	0.000	93.4 $\pm$ 1.9 <sup>d</sup>	78.3 $\pm$ 4.3 <sup>c</sup>	61.5 $\pm$ 3.0 <sup>b</sup>
	Aboveground biomass (kg)	140.10	0.000	132.9 $\pm$ 3.8 <sup>d</sup>	109.4 $\pm$ 2.1 <sup>c</sup>	90.9 $\pm$ 1.7 <sup>b</sup>
	Crown mass/tree mass	2.60	0.125	0.30 $\pm$ 0.01	0.28 $\pm$ 0.03	0.32 $\pm$ 0.02 <sup>a</sup>
41-year-old	Foliage biomass (kg)	14.95	0.001	19.2 $\pm$ 1.6 <sup>b</sup>	14.4 $\pm$ 0.9 <sup>a</sup>	14.2 $\pm$ 1.2 <sup>a</sup>
	Branch biomass (kg)	18.94	0.001	39.6 $\pm$ 2.8 <sup>b</sup>	27.8 $\pm$ 2.0 <sup>a</sup>	28.8 $\pm$ 3.3 <sup>a</sup>
	Bole biomass (kg)	23.61	0.000	126.3 $\pm$ 9.5 <sup>b</sup>	95.3 $\pm$ 6.3 <sup>a</sup>	92.6 $\pm$ 4.8 <sup>a</sup>
	Aboveground biomass (kg)	34.83	0.000	185.0 $\pm$ 13.5 <sup>c</sup>	137.4 $\pm$ 6.7 <sup>b</sup>	135.5 $\pm$ 4.1 <sup>b</sup>
	Crown mass/tree mass	0.32	0.811	0.32 $\pm$ 0.01	0.31 $\pm$ 0.01	0.32 $\pm$ 0.02 <sup>a</sup>

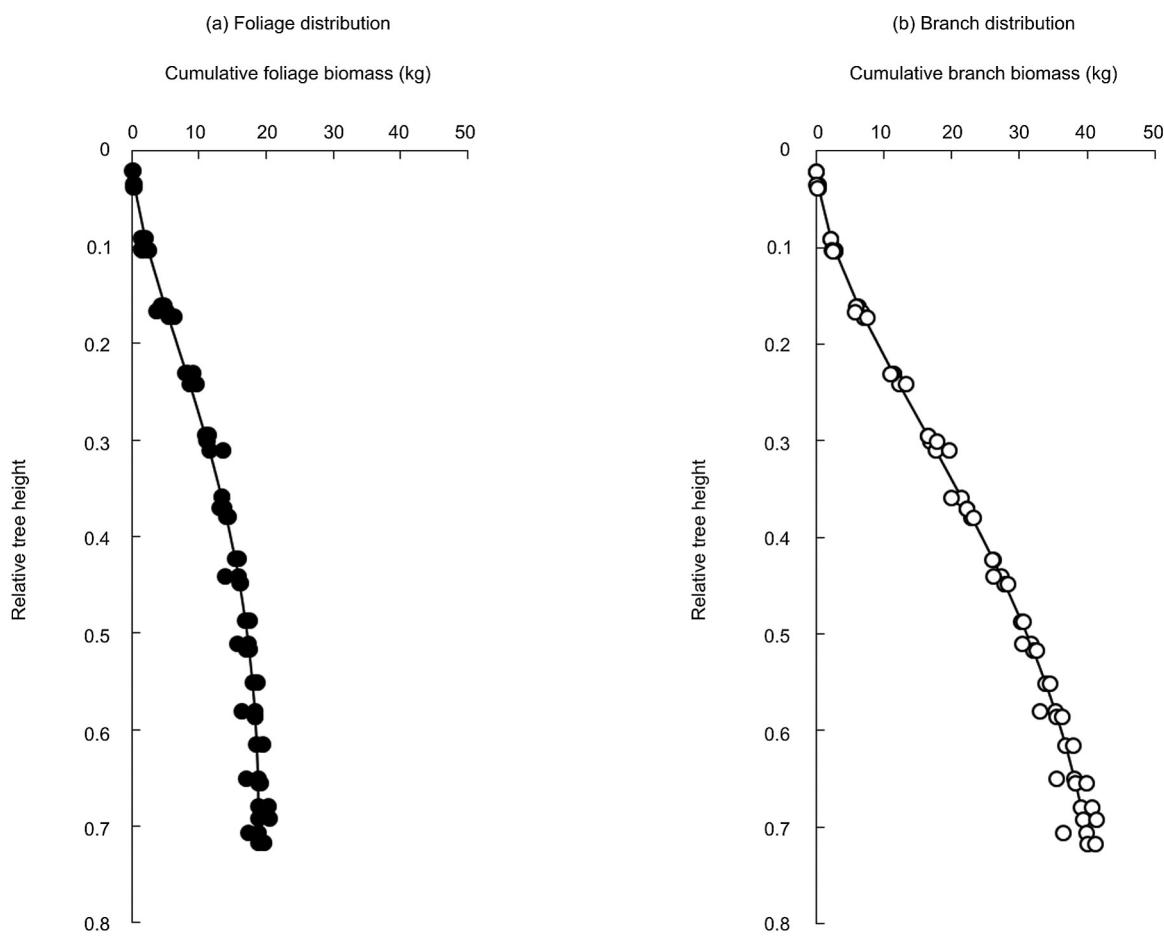


Fig. 1. Cumulative distributions of foliage and branch biomass from the crown apex to the base expressing by relative tree height scale and an example of 41-year-old trees with heavy thinning treatment

Table 3. The parameters of allometric model ( $F(x) = ax^b \exp^{cx}$ ) for different thinning treatments of 27-, 35- and 41-year-old Taiwan red cypress

Biomass component	Tree age	Treatment	Parameter			RMSE	$R^2$
			a	b	c		
Foliage	27-year-old	Heavy thinning	782.99	3.08	-4.51	1.26	0.94
		Middle thinning	1341.92	3.19	-5.65	0.18	0.99
		Light thinning	406.69	2.65	-4.32	0.24	0.98
		No thinning	1653.97	3.29	-6.35	0.13	0.93
	35-year-old	Heavy thinning	313.24	2.30	-3.53	0.88	0.96
		Middle thinning	1255.94	3.15	-5.18	0.71	0.97
		Light thinning	306.87	2.30	-3.72	0.42	0.97
		No thinning	145.80	1.93	-3.26	0.49	0.94
	41-year-old	Heavy thinning	263.91	1.94	-2.78	1.14	0.98
		Middle thinning	244.13	2.06	-3.02	0.41	0.99
		Light thinning	272.65	2.02	-3.23	0.69	0.98
		No thinning	268.83	2.10	-3.43	1.06	0.95
Branch	27-year-old	Heavy thinning	2236.15	3.82	-5.13	1.14	0.97
		Middle thinning	1977.73	3.43	-5.26	0.22	0.99
		Light thinning	939.53	3.04	-4.53	1.29	0.95
		No thinning	2830.20	3.53	-6.26	1.30	0.94
	35-year-old	Heavy thinning	732.22	2.68	-3.32	1.19	0.99
		Middle thinning	2090.72	3.34	-5.02	5.84	0.91
		Light thinning	1041.32	2.87	-4.27	0.62	0.99
		No thinning	609.51	2.50	-4.03	0.47	0.99
	41-year-old	Heavy thinning	413.74	2.09	-2.29	1.59	0.99
		Middle thinning	938.75	2.61	-3.72	2.48	0.98
		Light thinning	1776.47	2.84	-4.54	4.23	0.96
		No thinning	570.01	2.33	-3.26	2.13	0.98

## Discussions

The purpose of this study was to interpret the thinning effects on the biomass and vertical distributions of foliage and branch biomass of 3 different Taiwan red cypress even-aged plantations 20 years after thinning. Previous studies on the thinning effects of Taiwan red cypress plantations have chiefly focused on growth and yield, with little emphasis on long-term thinning effects (e.g. Hwang 1977; Yen 2002; Li and Yen 2010). This study extends the field knowledge, to include multiple thinning effects occurring from thinning trials initiated 20 years before, especially in relation to tree levels. The relationship between stand biomass accumulation and thinning is helpful for assessing forest productivity, and we will extend our results to the stand levels for Taiwan red cypress in the future.

Lee and Yen (1994) indicated that the mean growth rate of Taiwan red cypress shows an increase in the first 2 to 6 years after thinning, clearly demonstrating that thinning affected the stocking growth in this period. Because mean-growth space is created by thinning and the growth rate is closely related to the

thinning intensity, a heavier thinning intensity is expected to yield a higher growth rate at the tree level. Numerous conifer-thinning trials have demonstrated this phenomenon (Lee and Yen 1994; Baldwin et al. 2000; Yu et al. 2003; Varmola and Salminen 2004).

Because man-made forests in Taiwan were planted with small spacings, the initial planting density of man-made Taiwan red cypress forests was more than 3,000 stems  $\text{ha}^{-1}$ ; consequently, competition within stands occurred earlier than expected (Yen 2002). Lee and Yen (1994) suggested that Taiwan red cypress plantations should receive their first thinning in juvenile periods (at approximately 7 to 10 years) to improve stand development. By extending previous studies, our study provides precise results concerning the aboveground biomass accumulation at the tree level for Taiwan red cypress plantations 20 years after thinning. By comparing biomass accumulation and thinning, a clear trend emerged in the biomass components for the 3 different ages of trees; thinning intensity positively correlated with biomass accumulation for each component (foliage, branches, boles and aboveground biomass) (Table 2).

This study emphasized the thinning effects on trees of the same age, but did not perform a further

analysis of the interactions between tree age and thinning intensity. We assumed that the biomass component increases with age. After thinning, the spacing of the remaining trees increased according to the thinning intensity; therefore, assuming that all biomass components (foliage, branches, and boles) increased with the thinning intensity is reasonable. In addition, crown biomass (foliage and branches) increased with

thinning, accompanied by an increase in bole biomass, which might cause the ratio of crown mass to tree mass to remain constant for trees of the same age. This ratio changes for different tree ages, and the changes in the ratio are 0.36–0.43, 0.28–0.32, and 0.31–0.32 for 27-, 35-, and 41-year-old trees, respectively. Baldwin et al. (2000) indicated that the ratio of crown mass to tree mass increases for stands with

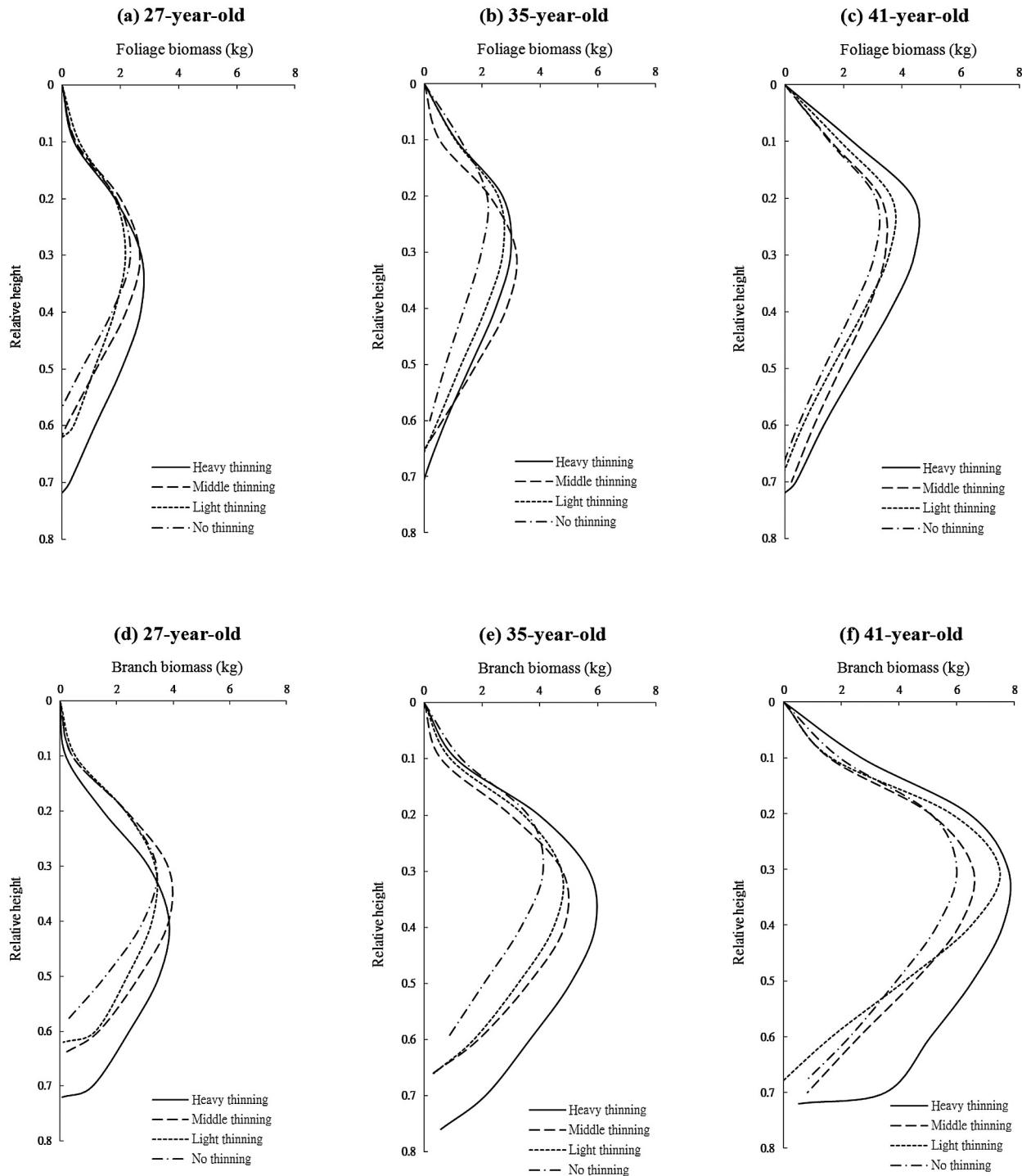


Fig. 2. Foliage and branch biomass distributions within four treatments of the different age categories of the trees, which recovered from the parameters of Table 3 and calculating by 1 m per interval

heavier thinning and wider spacing; the ratio ranged from 0.11 to 0.15 in loblolly pine. We inferred that heavier thinning and wider spacing will lead to crown mass developing more rapidly in loblolly pine; consequently, the ratio of crown mass to tree mass would increase.

Furthermore, the foliage and branch biomass was measured, along 1 m intervals of tree height, and were simulated using the allometric equation. The results demonstrated that this model had a good fit for the vertical distributions of both foliage and branch biomass of Taiwan red cypress; regardless of the age category of the trees and thinning intensity (Table 3 and Fig. 1). The example using 41-year-old trees (Fig. 1) showed that the vertical distributions of foliage and branch biomass of the observed data approximated symmetrical curves. The allometric model employed in this study, termed a “variable allometric ratio (VAR) model”, was developed by Ruark et al. (1987). Hashimoto (1991) adopted the VAR model to simulate the vertical distribution of foliage biomass for sugi (*Cryptomeria japonica*) conifers and obtained a good predicted capacity for the crown mass. However, the foliage and branch distributions are a cumulative distribution from the crown apex to the base (Fig. 1), which cannot directly show foliage and branch biomass at each interval, although another expression of this curve could. After reproducing foliage and branch biomass at 1 m intervals, the vertical distributions of foliage or branch biomass within each interval were obtained (Fig. 2).

A comparison of the vertical distribution of foliage biomass after thinning showed more foliage biomass accumulation at a lower height after thinning in 27-y-old trees, but this pattern did not emerge in trees of other ages. We inferred that thinning promoted foliage biomass accumulation, but the type of distribution might vary with tree age; therefore, this phenomenon does not apply to all trees after thinning. Previous studies have revealed that thinning creates more space and a lighter environment for branch development, especially within lower crowns (Ginn et al. 1991; Yu et al. 2003; Simard et al. 2004). Our findings indicate that the VAR model is a useful tool for quantifying the vertical distribution of crown mass, which can help interpret the differences in the distribution of the crown mass resulting from thinning. We found that more branch biomass accumulates at lower relative heights, especially after heavy thinning treatment, for the Taiwan red cypress after 20 years of thinning and the same trend appeared in all 3 plantations.

## Conclusions

In this study, we examined the long-term thinning effects on Taiwan red cypress, mainly focusing on

aboveground biomass at the tree level. We expected thinning to improve each component of biomass accumulation; we learned that the ratio of crown mass to aboveground tree mass was not significantly influenced by the thinning intensity, regardless of tree age category. The vertical distribution of foliage and branch biomass after quantification readily shows the changes in crown mass after examining the thinning effects on Taiwan red cypress. Understanding the relationship between stand biomass accumulation and thinning is useful for assessing forest productivity, and we will extend the knowledge of this study to the stand level in the future.

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