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Full Length Research Paper

Effect of pre-commercial thinning on diameter class distribution and total merchantable volume growth in Chinese fir stands in Southern China

Honggang Sun[1], Jianguo Zhang[2]*, Aiguo Duan[2] and Guobin Zhang[3]

[1]Institute of Subtropical Forestry Research of Chinese Academy of Forestry, China.
[2]Institute of Forestry Research of Chinese Academy of Forestry, China.
[3]Forestry Sequestration of Accounting and Monitoring Center of State Forestry Administration, China.

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The effect of thinning has not been investigated previously in young even-aged Chinese fir [*Cunninghamia lanceolata* (Lamb.) Hook.] stands in Southern China. In long-term experiments, the effect of thinning on growth and yield of Chinese fir trees at five spacing levels was studied (2 × 3 m, 2 × 1.5 m, 2 × 1 m, 1 × 1.5 m and 1 × 1 m) thinned or left unthinned every 2 years from age 10. Trees in 2 × 3 m spaced unthinned plots were used as controls. Tree growth at the highest planting densities was lower in thinning treatments than in the control. The highest proportions of small, intermediate- and large stems were in plots with initial planting densities of 1 × 1 m, 1 × 1.5 m and 2 × 1 m, respectively. Merchantable volume increment after thinning showed no significant difference but increased with the initial planting density. The proportion of large-diameter trees and merchantable volume were highest in the controls. The total stand volume in thinning treatments increased with increasing initial planting density, but was lower than that of the control. Thinning Chinese fir stands with a planting density greater than 2 × 1 m could increase tree diameter but not merchantable volume. A stand density of less than 2 × 3 m is most profitable for increased tree growth and merchantable volume.

Key words: Diameter class distribution, thinning, *Cunninghamia lanceolata* (Lamb.) Hook., merchantable volume.

INTRODUCTION

Thinning of a forest stand is an important approach to achieve a variety of management objectives. Traditionally, thinning has been used to harvest anticipated mortality of suppressed trees as merchantable volume and to increase the growth of residual trees as a result of the increased growing space and resource availability (Mäkinen and Isomäki, 2004; Huuskonen and Hynynen, 2006; Rytter and Werner, 2007; Bradford and Palik, 2009). Thinning from below can promote the development of large-diameter trees and increase the quality of sawlogs (Peterson et al., 1997; Zeide, 2001; Simard et al., 2004). Chinese fir is economically and ecologically one of the most important tree species in Southern China with 9.21 million ha planted in pure or mixed stands (Lei, 2005). The market value of large-sized stems (diameter at breast height [DBH] ≥ 20 cm) has increased recently compared to that of small- and intermediate-sized stems (DBH 8 to 12 cm and 14 to 18 cm, respectively). Forest managers have assumed that thinning a stand with a high initial planting density can yield a greater merchantable volume and more large-sized stems than thinning a stand with a lower initial planting density.

The objective of this study was to examine the effects of thinning on diameter-class distribution and merchantable volume yield in Chinese fir stands on the

*Corresponding author. E-mail: zhangjg@caf.ac.cn, zhangjg@mail.forestry.ac.cn. Tel: +86 10 6288 9603. Fax: +86 10 6287 2015.

basis of data obtained during a seven-year period.

MATERIALS AND METHODS

Study sites

Chinese fir stands located in Fenyi County (27°34′N and 117°29′E), Jiangxi province, Southern China, were established in the spring of 1982. The stands are located on the middle, South-facing the slope of Qingshiwan Mountain between 200 and 250 m in elevation. The soil, derived from sand-shale parent material is a red luvisol. The average annual precipitation is 1591 mm of which 85 to 90% is from rainfall. The mean temperature during the growing season varies between 15.8 and 17.7°C, the mean maximum temperature in July is 28.8°C and the mean minimum temperature in January is -5.3°C. The annual mean number of frost-free days is 265. The site index is 16 m at 20 years (Tong et al., 2000).

Experimental design and treatments

The plots were planted in a random block arrangement with the following tree spacings; 2 × 3 m (A; 1667 stems ha^{-1}), 2 × 1.5 m (B; 3333 stems ha^{-1}), 2 × 1 m (C; 5000 stems ha^{-1}), 1 × 1.5 m (D; 6667 stems ha^{-1}) and 1 × 1 m (E; 10,000 stems ha^{-1}). Each spacing density was replicated three times. Each plot was 20 × 30 m in size with a 6 m wide buffer zone that consisted of similarly treated trees surrounding each plot. Tree measurements were recorded each winter from 1983 to 1990 and then every second year until 2006. The average height of the 10% largest (in terms of DBH) trees in the stand was calculated to compute the site index with a 20-year reference age. The selective thinning criteria were: 1) dominant or codominant crown class; 2) uniform spacing relative to the other trees; and 3) single, straight, and healthy stems.

Thinning from below was performed based on the Chinese fir stand density management diagram in which the residual stand density of the thinned stands equals the initial planting density of the unthinned stands (Liu and Tong, 1980). In the autumn of 1990, stands with an initial planting density of 10,000 stems ha^{-1} (E) were thinned to 6733 stems ha^{-1}, which was close to 6667 stems ha^{-1} (D). In the autumn of 1992, the E stands with 6733 stems ha^{-1} were thinned to 5000 stems ha^{-1} (C); stands with an initial planting density of 6667 stems ha^{-1} (D) were thinned to 4967 stems ha^{-1}, which was close to 5000 stems ha^{-1} (C); and the C stands with an initial planting density of 5000 stems ha^{-1} were thinned to 3333 stems ha^{-1} (B). In the autumn of 1994, the E stands with 5000 stems ha^{-1} were thinned to 3317 stems ha^{-1}, which was close to 3333 stems ha^{-1} (B); the D stands with 4967 stems ha^{-1} were thinned to 3333 stems ha^{-1} (B); and the C stands with 3333 stems ha^{-1} were thinned to 1675 stems ha^{-1}, which was close to 1667 stems ha^{-1} (A). In the autumn of 1996, the E stands with 3317 stems ha^{-1} were thinned to 1650 stems ha^{-1}, which was close to 1667 stems ha^{-1} (A); and the D stands with 3333 stems ha^{-1} were thinned to 1675 stems ha^{-1}, which was close to 1667 stems ha^{-1} (A).

Measurements

Total tree height (m), DBH (cm), crown width within and between rows (m), and height to the base of the lowest live branch (m) were measured for all trees in the plots in each winter from 1983 to 1990 and then every other year, until 2006. Basal area per hectare was calculated from DBH and quadratic mean diameter (QMD) was calculated from basal area. Stem volume (m^3) was estimated with the empirical formulae developed by Liu and Tong (1980) for Chinese fir stands. Total merchantable volume per hectare was determined by summing values for all trees in the plot. Live crown ratio (LCR) was obtained by dividing live crown length by total tree height. Crown volume was calculated using a cone volume equation. Trees were split into 2 cm diameter classes in order to investigate variation in diameter class distribution. The periodic gross increment was calculated from the difference between two successive measurements.

Statistical analysis

Stand variables were compared among thinning treatments every two years after thinning using a mixed-model analysis of variance (ANOVA). Thinning treatment was a fixed effect and thinning period was a random effect. The statistical results are shown in Table 1. Where a difference was significant (α = 0.05), multiple comparisons were made among treatments using the Waller-Duncan-Bays least significant difference (LSD) procedure (Duncan, 1975). Pearson's correlation coefficient was determined to evaluate the correlation between (1) QMD growth and LCR, and (2) total merchantable volume and crown volume. For comparative purposes, growths in the 2 × 3 m spaced unthinned plots in the 1988, 1990, 1992, 1994 and 1996 growing seasons were treated as controls.

RESULTS

Diameter growth development

The average diameter distribution in the 1 × 1 m, 1 × 1.5 m and 2 × 1 m thinned stands were almost bell shaped (Figure 1). The respective symmetry axes increased from the 9 to 15 cm DBH classes, 11 to 17 cm DBH classes, and 11 to 17 cm DBH classes. The average diameter distribution of the 2 × 3 m unthinned treatment was always left-skewed and its symmetry axis increased from the 11 to 21 cm DBH classes (Figure 1).

Prior to thinning, QMD cumulative growth did not significantly vary among treatments and averaged 9.53 cm over the three initial planting density plots (1 × 1 m, 1 × 1.5 m, and 2 × 1 m) (p = 0.0607). However, thinning promoted QMD cumulative growth (Table 1). Following thinning, the two highest initial planting density plots (1 × 1 m and 1 × 1.5 m) showed greater QMD cumulative growth than the lowest initial planting density plots (2 × 1 m) (p = 0.0047). The QMD cumulative growth in the 1 × 1 m, 1 × 1.5 m, and 2 × 1 m thinned treatments increased by 47.1, 39.3 and 38.7% respectively, from pre-thinning to the end of thinning. The QMD cumulative growth in the 2 × 3 m unthinned treatment increased by 57.7%. In 1996, the QMD in the 2 × 3 m unthinned treatment was 19.09 cm, which was greater than those in the 1 × 1 m, 1 × 1.5 m, and 2 × 1 m thinned treatments (15.10, 16.64, and 17.44 cm, respectively) (Table 2). In addition, differences in the QMD between the thinned plots increased with the total duration of thinning owing to the increase in diameter with increasing growing space (Table 2).

After thinning, the QMD increment was greater in the two highest initial planting density plots than in the lower initial planting density plots (Table 3). The stand means QMD increment of the 1 × 1 m, 1 × 1.5 m, and 2 × 1 m

Table 1. Summary of the mixed-model ANOVA including source of variation, degrees of freedom for both numerator and denominator, *F*-values and probability values for cumulative mean height, quadratic mean diameter (QMD), crown volume and stand volume after thinning Chinese fir stands.

Source of variation	df (numerator)	df(denominator)	Cumulative mean height (m)		Cumulative QMD (cm)		Cumulative crown volume (m^3)		Cumulative stand volume (m^3)	
			F	P	F	P	F	P	F	P
Thinning treatment	3	9	35.74	<0.001	21.37	0.0073	22.71	<0.01	43.87	<0.01
Thinning period	3	32	8.26	0.003	62.94	0.0049	41.85	<0.01	45.56	<0.01
Treatment × period	9	32	0.61	0.748	7.21	<0.001	19.33	<0.01	3.20	<0.043

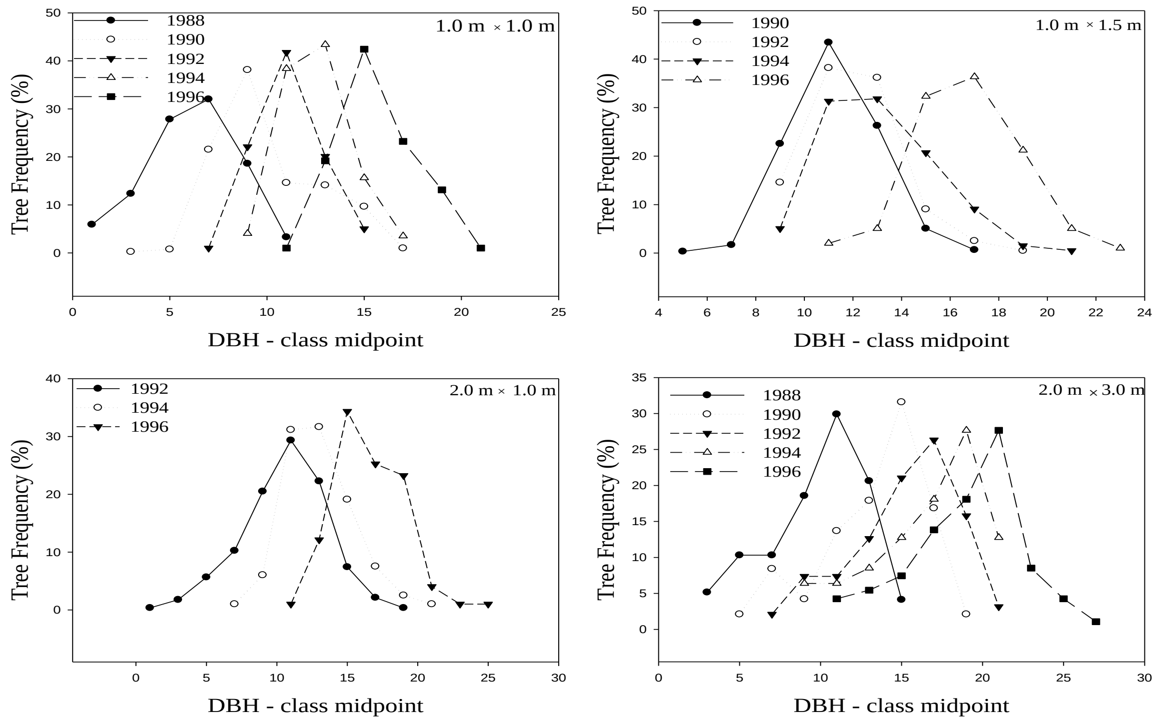

Figure 1. Frequencies (%) of trees in different DBH classes in response to four thinning applications in Chinese fir stands on Qingshiwan Mountain, Fenyi County, Jiangxi province. Thinning from below was implemented from 1990 to the end of the 1996 growing season in accordance with the Chinese fir stand density management diagram (Liu and Tong, 1980). For comparative purposes, the data for 1988 in the 1.0 × 1.0 m plots, for 1990 in the 1.0 × 1.5 m plots, and for 1992 in the 2.0 × 1.0 m plots are included for the thinned stands.

Table 2. Treatment means at the stand level for mean height, quadratic mean diameter (QMD), crown volume, and stand merchantable volume between 1990 and 1996.

Spacing (m)	Year	Mean height (m)	QMD (cm)	Crown volume (m^3)	Stand merchantable volume (m^3/ha)
	1988	4.85a[a]	7.51[a]	7.50[a]	64.23[a]
	1990	6.66a[b]	10.56[ab]	12.61[a]	123.80[a]
1.0 ×1.0	1992	8.45b[c]	11.91[bc]	16.69[a]	174.40[ab]
	1994	10.12[c]	14.24[cd]	27.69[b]	235.25[ab]
	1996	10.87[c]	15.10[d]	32.49[b]	284.82[b]
Standard error		2.411	0.003	1.162	4.797
p-value		0.0037	0.0062	0.1341	0.0525
	1990	7.67[a]	9.90[a]	22.51[a]	114.04[a]
1.0 ×1.5	1992	9.30[b]	11.75[b]	26.49[a]	214.70[b]
	1994	11.12[c]	12.89[c]	27.83[a]	244.37[b]
	1996	11.86[d]	16.64[d]	31.49[a]	261.07[b]
Standard error		1.779	0.026	2.640	3.429
p-value		0.0031	0.0002	0.8489	0.0959
	1992	9.05[a]	11.19[a]	25.79[a]	88.29[a]
2.0 ×1.0	1994	10.82[b]	13.92[b]	27.59[a]	190.49[b]
	1996	11.87[b]	17.44[c]	34.38[a]	233.83[b]
Standard error		1.13	0.022	4.95	3.166
p-value		0.0213	0.2436	0.1882	0.1322
	1988	6.00[a]	13.00[a]	34.61[a]	48.58[a]
	1990	7.64[b]	14.75[b]	72.85[b]	100.59[b]
2.0 × 3.0	1992	9.70[c]	16.53[c]	76.65[b]	152.24[c]
	1994	11.06[d]	18.20[d]	87.67[bc]	223.71[d]
	1996	12.09[e]	19.09[e]	100.31[c]	316.76[e]
Standard error		2.411	0.030	23.76	5.966
p-value		0.0001	0.0001	0.0011	0.0001

[a] Values with the same letters among thinned years are not significantly different (α = 0.05).

thinned treatments increased by 24.5, 18.7, and 13.3% respectively, from pre-thinning to the end of thinning. However, the mean QMD increment of all thinned treatments was smaller than that of the 2 × 3 m unthinned treatment which showed a mean QMD increment of 35.6%. The LCR was significantly correlated with stand average QMD in the unthinned (r^2 = 0.89, p < 0.001) and thinned (r^2 = 0.92, p < 0.0001) treatments (Figure 2). The LCR decreased with increasing inter-tree competition, which caused a reduction in the rate of QMD growth. The QMD growth in the unthinned treatment was larger than that in the thinned treatments.

Stand volume growth

Stand merchantable volume increased by 26 to 59% in the thinned treatments and differences among the thinned treatments were significant (p < 0.001) (Table 1). The stand merchantable volume increased with decreasing residual stand density and was greatest in the 1 × 1 m thinned plots (304.82 m^3 ha^{-1}) and smallest in the 2 × 1 m thinned plots (233.83 m^3 ha^{-1}) (Table 2). Stand merchantable volume in the 2 × 3 m unthinned plots was 316.76 m^3 ha^{-1}, which was higher than those in the thinned plots. The difference in stand merchantable volume between the 2 × 3 m unthinned plots and the thinned treatments was significant (p < 0.0001) over the thinning period.

The stand merchantable volume increment increased over the course of the thinning period. The greatest stand merchantable volume increment was observed in the 1 × 1.5 m thinned plots (8.02 m^3 ha^{-1}), whereas, the smallest increment was observed in the 1 × 1 m thinned plots (7.33 m^3 ha^{-1}) (Table 3). Compared with the thinned treatments, the 2 × 3 m unthinned plots showed higher stand merchantable volume increments (19.46 m^3 ha^{-1}).

A total stand volume in thinned plots increased with increasing initial planting density (Figure 3). Total stand volume in the 2 × 1 m, 1 × 1.5 m and 1 × 1 m thinned

Table 3. Treatment means at the stand level for mean height, quadratic mean diameter (QMD), crown volume, and stand merchantable volume increment between 1990 and 1996 (the sample size for 2.0 × 1.0 m plots did not satisfy with multiple comparisons test assumption and thus no results are shown).

Spacing (m)	Year	Mean height (m)	QMD (cm)	Crown volume (m^3)	Stand merchantable volume (m^3/ha)
1.0 ×1.0	1990	0.75a[a]	0.10[a]	4.10[a]	1.25[a]
	1992	1.67a	0.20[a]	4.79[a]	5.09[a]
	1994	1.79[a]	0.25[b]	5.11[a]	6.38[b]
	1996	1.81[b]	0.25[b]	10.99[a]	7.33[b]
Standard error		0.487	0.012	3.786	3.542
p-value		0.0099	0.0099	0.2437	0.0427
1.0 ×1.5	1992	0.75[a]	0.04[a]	4.99[a]	3.15[a]
	1994	1.63[a]	0.10[b]	5.32[a]	5.38[ab]
	1996	1.82[b]	0.15b	8.98[a]	8.02[b]
Standard error		0.534	0.010	4.617	5.000
p-value		0.0228	0.0491	0.4991	0.0475
2.0 × 3.0	1990	1.08[a]	0.20[a]	12.36[a]	9.09[a]
	1992	1.39[b]	0.20[b]	19.36[a]	12.68[a]
	1994	1.69[c]	0.20[b]	23.66[b]	16.46[a]
	1996	2.09 [d]	0.30[b]	28.23[b]	19.46[a]
Standard error		0.413	3.118	2.756	1.319
p-value		0.0004	0.0001	0.0057	0.1656

[a] Values with the same letters among thinned years are not significantly different (α = 0.05).

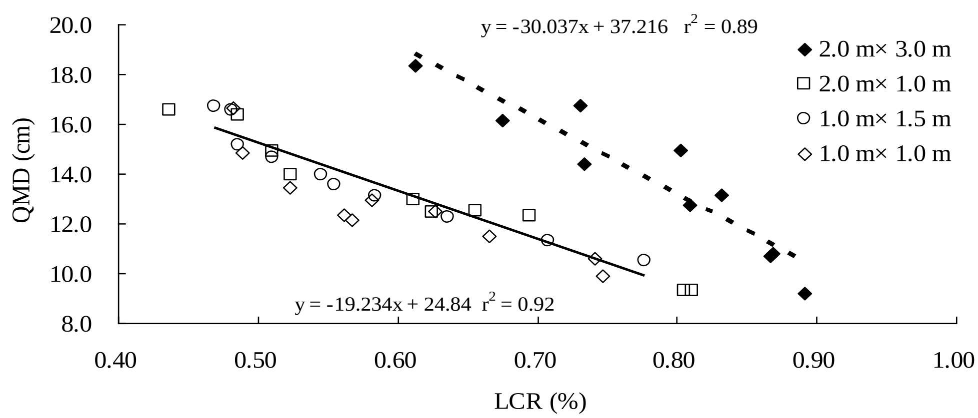

Figure 2. Relationship between the live crown ratio (LCR) and quadratic mean diameter (QMD) of Chinese fir stands in the thinned and unthinned treatments between the beginning and end of the thinning period.

plots were 296.87 m^3 ha^{-1}, 297.83 m^3 ha^{-1}, and 299.99 m^3 ha^{-1}, respectively. However, total stand volume was highest (316.83 m^3 ha^{-1}) in the 2 × 3 m unthinned plots. In the thinned treatments, the removed stand volume increased as tree age increased. For example, the removed stem volume in the 1 × 1 m plots in 1990, 1992 and 1994 were 4.50, 9.44, and 16.22 m^3 ha^{-1}, respectively.

Crown volume was significantly correlated with total merchantable volume in the unthinned (r^2 = 0.92, p = 0.0041) and thinned (r^2 = 0.94, p < 0.0001) treatments (Figure 4). Total merchantable volume increased with increasing crown volume.

Relationship between diameter class distribution and merchantable volume

Diameter class distribution in 1996 was significantly different between the thinned and unthinned plots

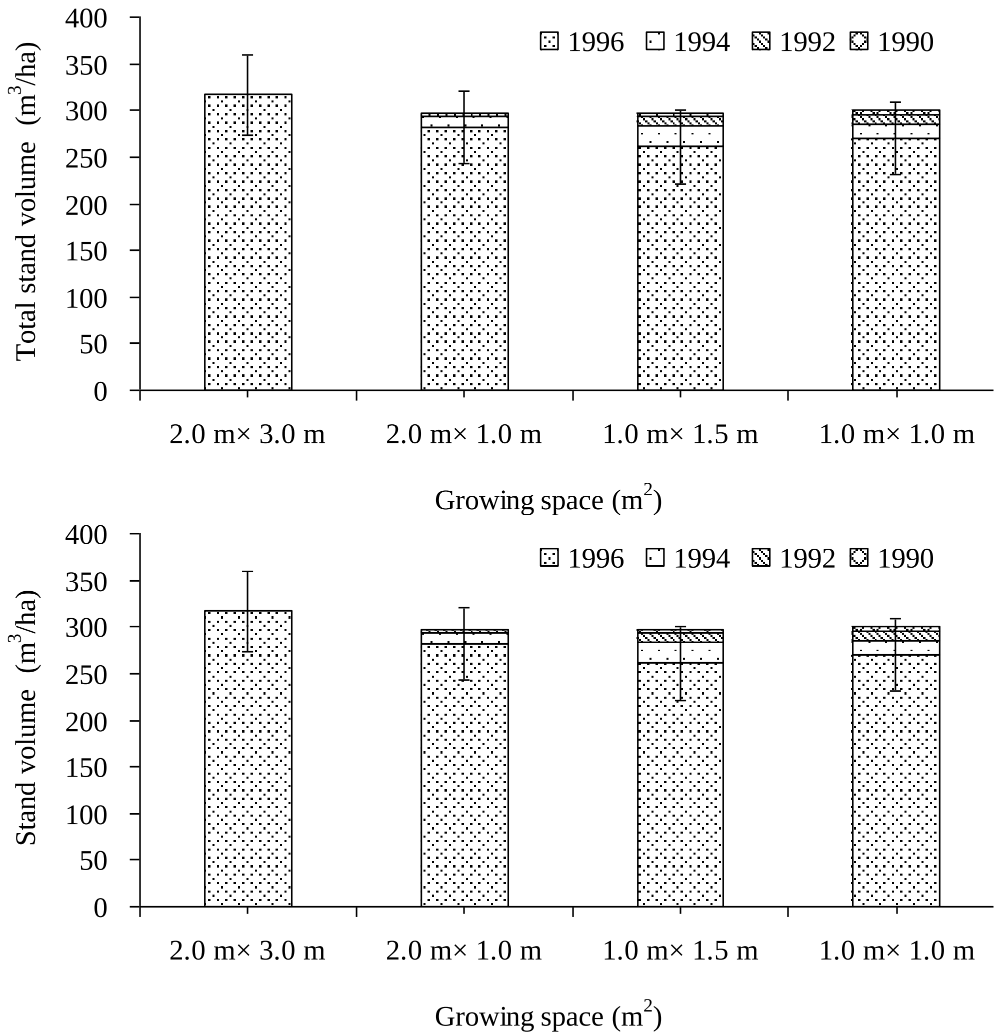

Figure 3. Total stand volume in the 1.0 × 1.0 m, 1.0 × 1.5 m, 2.0 × 1.0 m thinning treatments and the unthinned 2.0 × 3.0 m plots.

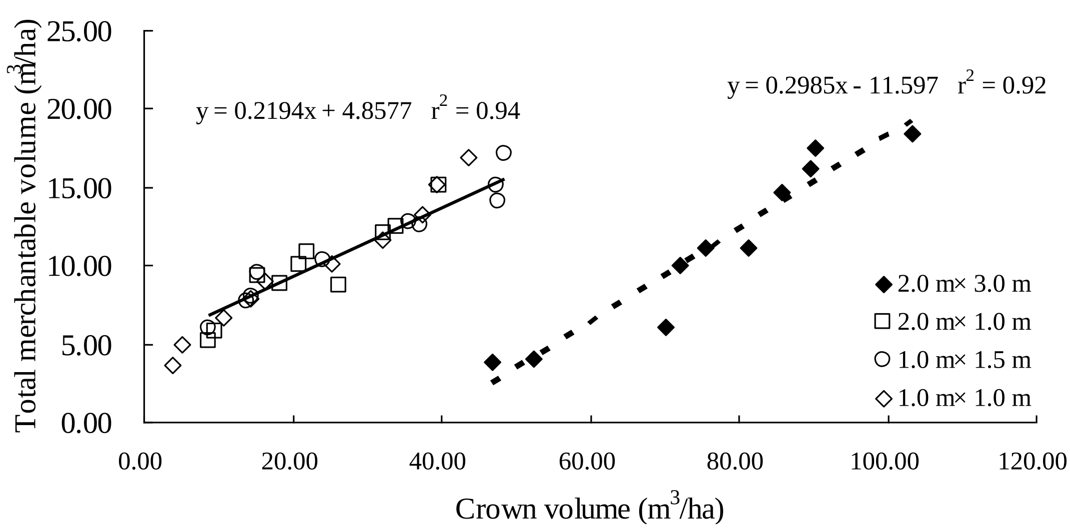

Figure 4. Relationship between crown volume and total merchantable volume of Chinese fir stands in the thinned and unthinned treatments between the beginning and end of the thinning period.

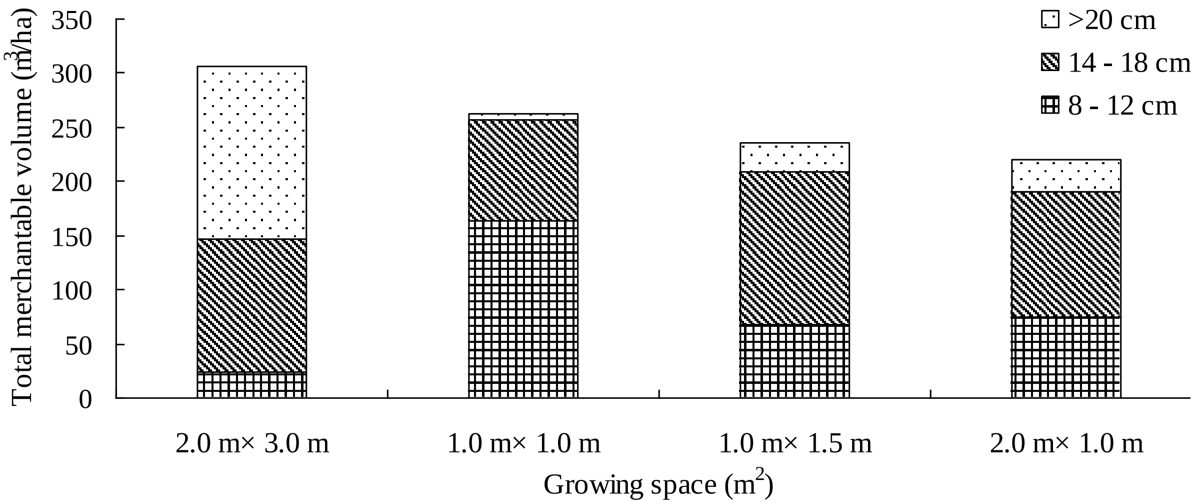

Figure 5. Relationship between diameter class and total merchantable volume in 2.0 × 3.0 m unthinned plots and 1.0 × 1.0 m, 1.0 × 1.5 m and 2.0 × 1.0 m thinning treatments in 1996.

(p < 0.0001). The higher the initial planting density, the higher the proportion of small-diameter trees; in contrast, the lower the initial planting density, the higher the proportion of large-diameter trees (Figure 5). Accordingly, the proportions of merchantable volume differed significantly between the thinned and unthinned plots (p = 0.0013). The proportions of small-diameter trees (DBH, 8 to 12 cm) in the 1 × 1 m, 1 × 1.5 m, 2 × 1 m and 2 × 3 m plots were 46.72, 21.76, 23.72, and 7.80% respectively, and the corresponding proportions of merchantable volume were 62.00, 28.87, 33.85, and 7.97% respectively. The proportions of intermediate-diameter trees (DBH, 14 to 18 cm) in the 1 × 1 m, 1 × 1.5 m, 2 × 1 m and 2 × 3 m plots were 17.01, 30.87, 25.36, and 26.76% respectively, and the corresponding proportions of merchantable volume were 35.86, 59.68, 52.71, and 39.84% respectively. The proportions of large-diameter trees (DBH ≥ 20 cm) in the 1 × 1 m, 1 × 1.5 m, 2 × 1 m and 2 × 3 m plots were 2.53, 12.17, 13.29, and 72.02% respectively, and the corresponding proportions of merchantable volume were 2.14, 11.45, 13.45, and 52.20% respectively.

The increases in diameter and corresponding merchantable volumes were higher with decreasing initial planting density. The highest proportion of small-diameter trees (46.72%) was observed in the 1 × 1 m thinned treatment and the corresponding proportion of merchantable volume (62.00%) was the highest among the treatments.

The highest proportion of intermediate-diameter trees (30.87%) was in the 1 × 1.5 m thinned treatment and the corresponding proportion of merchantable volume (59.68%) was the highest among the treatments. The highest proportion of large-diameter trees (13.29%) was in the 2 × 1 m thinned treatment and the corresponding merchantable volume (13.45%) was the highest among the treatments.

DISCUSSION

Interaction between thinning from below and the initial planting density affected the stand diameter growth trends. Our results agree with previous studies on the pre-commercial thinning promoting diameter growth (Leak and Solomon, 1997; Strong and Erdemann, 2000; Zhang et al., 2006; Crecente-Campo et al., 2009). Similar trends are reported in studies on Norway spruce (*Picea abies* (L.) Karst.) in Southern Finland (Mäkinen et al., 2002), red fir (*Abies magnifica* A. Murr) in California, USA (Zhang and Oliver, 2006), and trembling aspen (*Populus tremuloides* Michx.) in Ontario, Canada (Rice et al., 2001). The average QMD cumulative growth increased significantly by 41.7% after thinning from 1988 to 1996. The QMD cumulative growth was greater in the 2 × 3 m unthinned plots compared to those of the thinned treatments (57.7%). The QMD increment between 1990 and 1996 showed the same pattern as QMD cumulative growth and was greatest in the 2 × 3 m unthinned plots. The increase in QMD cumulative growth over time was greater in the unthinned plots than in the thinned plots.

The increase in average stands of QMD after thinning decreased with increasing the initial planting density. The highest proportions of small, intermediate- and large-diameter trees were in plots with initial planting densities of 1 × 1 m, 1 × 1.5 m, and 2 × 1 m respectively, in 1996. The 2 × 3 m unthinned plots contained the highest proportion of large-diameter trees. These results indicate that large-diameter trees are more likely to develop after thinning with a low initial planting density than with a higher initial planting density. During the thinning period, the LCR decreased whereas, QMD cumulative growth increased. Thinning from below does not fully remove inter-tree competition and causes the live crown area to decline with increasing tree age. In the 2 × 3 m unthinned plots, inter-tree competition also led to a decrease in the LCR; however, the QMD cumulative growth in the 2 × 3 m unthinned plots was greater than that in the corresponding thinned plots. This finding suggests that a low initial planting density promotes live crown growth vertically because of the higher incident photosynthetically active radiation, which also accelerates stem growth horizontally (Long, 1985).

The merchantable volume and total stand volume produced per unit area were highest in the 2 × 3 m unthinned plots. Thinning resulted in the greatest increase in merchantable volume and total stand volume in the 1 × 1 m thinned plots, followed by the 1 × 1.5 m plots and 2 × 1 m plots, but no significant difference in the merchantable volume and total stand volume was observed. These results indicate that the merchantable volume and total stand volume are more affected by stand density than by thinning and a low initial planting density can help to generate a higher merchantable volume and total stand volume by increasing stem diameter.

Crown volume was increased by 42 to 55% in the thinning treatments during the thinning period and the differences among the thinning treatments were not significant (p = 0.6789). The greatest crown volume was recorded in the 2 × 3 m unthinned plots in 1996. Crown volume was positively correlated with total merchantable volume. Crown volume in the 2 × 3 m unthinned plots was larger than that in the thinned plots, and the merchantable volume in the 2 × 3 m unthinned plots was also larger than that in the thinned plots. These results suggest that a larger crown volume increases the total merchantable volume.

The present study is the first to provide information on the growth and yield responses of Chinese fir to pre-commercial thinning in young even-aged Chinese fir stands in Southern China. Our findings will be useful for the density management of young Chinese fir stands to ensure rapid diameter growth and high total merchantable volume. Our results suggest that thinning stands with a high initial planting density can promote tree growth and increase total merchantable volume; the diameter class distribution shifts rapidly from small- to intermediate- to large-sized stems. In the thinned plots, the highest proportions of small-, intermediate- and large-sized stems were in plots with initial planting densities of 1 × 1 m, 1 × 1.5 m, and 2 × 1 m, respectively. Compared with the thinned plots, the 2 × 3 m unthinned plots contained a higher proportion of large-diameter trees and a higher total merchantable volume. The results of our study suggest that thinning from below promotes an increase in average tree diameter but not an increase in total merchantable volume growth when the planting density is greater than 2 × 1 m. In the studied Chinese fir stands, an initial planting density or a pre-commercial-thinning residual stand density of less than 2 × 3 m (1667 stems ha^{-1}) is most profitable with which to obtain large-diameter stems and a high total merchantable volume.

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