Front. For. China 2008, 3(3): 254–263
DOI 10.1007/s11461-008-0039-2

RESEARCH ARTICLE

Shuisong ZHANG, Changfa CHEN, Shouqing HE, Kexuan WU, Yousheng ZHAN

Natural thinning and structural patterns of intermediate cutting intensity in a *Cunninghamia lanceolata* stand

Abstract In the intermediate cutting intensity experiment of a *Cunninghamia lanceolata* plantation for 20 years, the changing pattern of natural thinning in these stands, with different intermediate cutting intensities, was studied. The relationship between the number of trees removed by natural thinning and stand density and site conditions was explained. The mathematical equation $M = K_1 \cdot K_2$ of natural thinning lines of *C. lanceolata* stand density management maps was tested and the relationship of diameter, height and canopy structure of stands with different intermediate cutting intensities are proposed. Our study of natural thinning in these stands indicates that the starting and peak periods of natural thinning in the check and slightly thinned plots were both early. The amount of thinned wood was large and the course of thinning proceeded continuously. The three levels of thinning: the slight thinning period, the intensive thinning period and the continued thinning period could be divided on the basis of the amount of thinned wood. Natural thinning would be a very long process without artificial interference. The starting and peak periods of thinning in the middle and strong intermediate felling are both late and present intermittence. Their thinning stages were not clearly evident. Through our studies, we also discovered that stand density and site conditions had important effects on the number of dead and dying trees, but that density was more important than site conditions. By way of tests, the relative error of the mathematical equation of natural thinning lines of *C. lanceolata* stand density management maps was 3.91% and the precision was relatively high. The practical test results of the stands, given different intermediate cutting intensities and different site indices, show that the relative error of the check plots was 5.23%, while the relative errors of the other tested items were all $< 5\%$, well within the allowable experimental error. The mathematical equation was comparatively practical. The study demonstrated the distribution laws of diameter and height classes of the stand at different intermediate cutting intensities. From this study we also obtained the growth differences and changing dynamics of the height to the first branch, canopy length and relative canopy height of the stand at different intermediate cutting intensities and various related patterns with an increase of stand age and proposed a mathematical model relating stand age and the single-tree periodic volume increment.

Keywords *Cunninghamia lanceolata*, intermediate cutting intensity, natural thinning, stand structure

1 Introduction

Natural thinning occurs because of decay and death of understory trees and shrubs in the process of the establishment of Chinese fir (*Cunninghamia lanceolata*) plantations, in which competition and differentiation arises between trees as the result of genetic differences and the effect of its growth habitat. According to Wu (1984), there is a close relationship between the distinct starting period of natural thinning of trees, stand density and site class. Similar studies in the starting age and the amount of natural thinning of Chinese fir stands were carried out by Yang et al. (1959) and the Jiangxi Academy of Forestry (1978). Natural thinning lines of *C. lanceolata* stands were established through a mathematical equation by Liu and Tong (1980) when they compiled density management maps of Chinese fir stands. Previous research provided very important clues to the next studies on the afforestation density and density control of Chinese fir stands. But there are few papers on the process of natural thinning of Chinese fir, its magnitude, practical tests and application results of this mathematical equation on natural thinning lines. Since the 1980s, investigations of the structural law

---

Translated from *Scientia Silvae Sinicae*, 2006, 42(1): 55–62 [译自: 林业科学]

Shuisong ZHANG (✉)
Fujian Academy of Forestry, Fuzhou 350012, China
E-mail: pjcheng78@163.com

Changfa CHEN, Shouqing HE, Kexuan WU, Yousheng ZHAN
Jiangxi Academy of Forestry, Nanchang 330032, China

of diameter and height of Chinese fir stands have been gradually carried out with progressive results (Jiang and Ye, 1980; Zhang and Duan, 2003). Our aims were to achieve a systematic summary and evaluation of the pattern of natural thinning in Chinese fir plantations, to record the practical effects of the mathematical equation of natural thinning lines of *C. lanceolata* from stand density management maps, as well as to investigate the rules of variety of stand structure through the huge orientation research data available on intermediate cutting intensity of the *C. lanceolata* plantations for over 20 years.

2 Natural and stand conditions of study site

2.1 Natural conditions

The study was conducted in the low mountains and hilly region of the Zaoxia Forest Farm, Fengxin County, Jiangxi Province. The Zaoxia Forest Farm, which belongs to the eastern extension of the Mufu Mountain, lies in the northwest of Fengxin County with a mid-subtropical southeastern monsoon climate. Its average annual temperature is 17.4°C, with a growth period of 266 days and average annual precipitation of 1613 mm. The characteristic climate is of a rainy spring, a hot and dry summer, with frost and snow in the winter which are very suitable conditions for the growth of the Chinese fir. The average elevation of the site is about 200 m, the parent rock is granite, the red mountain earth is more than 1 m deep with a loose texture and good drainage. The forest vegetation type is a secondary evergreen broadleaved forest, whose main species are *Castanopsis sclerophylla*, *Cyclobalanopsis glauca* and *Schima superba*.

2.2 Stand condition

The Chinese fir stand was established in February 1966 with a density of 3600 trees per hectare and a middle intermediate fellings was conducted when the stand was eight years old. The density of the stand in which we carried out our research was 2250–2550 trees/hm^2, 10 years old, with a canopy density of 0.8–1.0 resulting in poor light transmission through the canopy. The number of trees growing under a natural canopy was about one-third of the total trees. The vegetation under the canopy was very sparse. The main plants were *Eurya japonica*, *Vaccinium bracteatum*, *Castanea seguinii* and *Pleioblastus amarus* and others on the upper hillsides.

3 Research objectives

Our purpose was to achieve the following aims: 1) to obtain the optimum starting period of different intermediate thinning intensities, the number of trees and their changing processes; 2) to establish the relationship between the number of natural thinned trees, forest density and site index; 3) to test the mathematical equation of natural thinning lines of *C. lanceolata* stands from density management maps; and 4) to obtain the stand diameter, height and story structure of different intermediate cutting intensities.

4 Materials and methods

4.1 Materials

We located observation data from 18 experimental plots comprised of 12 test plots of intermediate cutting intensity and another six test plots of different intermediate cutting patterns and used this information in our study of natural thinning of Chinese fir stands. The area of every test plot was 0.0667 hm^2 and site indices were 18, 16 and 14. We applied a continuum of located research data of stand growth in every plot in our study of stand structure.

4.2 Methods

4.2.1 Natural thinning of different intermediate cutting intensities

We counted the number of trees with a dry and decayed canopy or whole trunks as dead trees and calculated their volume when they were cut down. In order to avoid double counting of dead trees, every tree counted was removed from the site at every investigation. The start of the thinning period of different cutting intensities, the number of trees and its changing process were analyzed and compared through the data investigated for each site.

4.2.2 Relationships between number of trees removed by natural thinning and forest density and site conditions

In order to unravel the action of the number of trees removed by natural thinning by stand density and site condition, a multiple regression equation was established from the number of dead trees and its corresponding site index of stand density (number of trees per hm^2) during the twenty year period after cutting on each test plot. The fitted equation was of the form: $y = a + b_1x_1 + b_2x_2$, where y is the number of dead trees, x_1 stand density after cutting, x_2 site index denoted as the top height of the stand at age twenty and, a, b_1 and b_2 are undetermined parameters calculated by the method of least squares.

4.2.3 Mathematical equation of natural thinning lines of *C. lanceolata* stands and its practical testing

From the formula of natural thinning lines ($M = K_1 \cdot K_2$) of *C. lanceolata* stands, advanced by Liu and Tong (1980), we calculated the equation: $N = N_0 - \frac{M}{K_1} \cdot N_0^{1.9579}$, where M is stand volume (m^3/hm^2), $K_1 = 7034643.43$, $K_2 = \left(1 - \frac{N}{N_0}\right) N_0^{-B_1}$, $B_1 = 0.9579$, N_0 (number of trees per hm^2) is stand density after intermediate cutting and N (trees/hm^2) is the theoretical density corresponding with M. Given this equation, we calculated the values N and M for every plot separately and constructed tables for testing N values and actual stand density (trees/hm^2) calculated after the removal of decayed and dead trees. After that, we computed the standard error (S_e) and estimated the relative error (%) according to the method of error calculation. In the end, the precision and practical use of the mathematical equation was determined by testing relative errors.

4.2.4 Stand structure

Based on the measurement of diameters at breast height (DBH) of all Chinese fir trees at 12 different intermediate cutting intensity plots, the diameter structure of stands was obtained from the number of trees and percentages by 2 cm diameter classes, for which we selected the even numbered mid-class values. Then, the table of different age diameter-class distributions was constructed with thinning intensity. The stand diameter-class distribution (%) was calculated using the Weibull density function $y = 1 - e^{-\left(\frac{x}{B}\right)^c}$ or normal distribution, where x is diameter class, y the relative value of the number of trees (%) and B and C are the parameters to be fitted. In the end, the diameter-class distribution of stands with different intermediate cutting intensities at different ages was deduced after a chi-square test (χ^2).

Twenty years after cutting, every individual tree height was measured on the plots whose site indices were 18, 16, and 14. Site-index, the number of trees and the percentage of every site-index were obtained in 1 m tree-height grade steps, from which we acquired the distribution table of tree-height grade, defined as percentage of trees. The tree height grade framework distribution (%) of different site indices was calculated from computing the Weibull density function or normal distribution and tested by a chi-square test (χ^2 test).

In order to study the stand canopy structure, tree height, height to first branch, stand canopy length, relative value percentage of stand canopy length and height at different thinning intensities were calculated from observations of every individual tree and height to the first branch on every plot, where the relative value percentage of stand canopy length and height is defined as canopy length/tree height. Then, the mathematical model was fitted from the correlation between the above stand canopy structure factors and stand ages or periodic volume increment of individual trees.

5 Results and analysis

5.1 Starting period of natural thinning of different intermediate cutting intensities, number of trees and changing regulation

Starting periods of different intermediate cutting intensities, peak periods, number of trees and its changing regulation, obtained from twenty years of continual investigation, are presented in Table 1.

At the start of the research period (i.e., the first year of investigation) a few dead trees were present in the slight intermediate intensity and control sites, but dead trees appeared only at the fifth year in the severe and medium thinning intensities which shows that the start of the thinning period was earlier in slight intermediate intensity and control plots than that in severe and medium intensity plots. The number of trees and their changing state varied with each thinning intensity. Before the stand age of the slight intermediate intensity and control plots reaching fifteen, the proportion of dead wood in terms of the total number of trees was 16.7% and 28.6%, respectively. During the period from sixteen to twenty-four years, the peak period of natural thinning, abundant dead wood appeared. The proportion of dead trees in terms of the

Table 1 Natural thinning status of stands with different intermediate cutting intensities (unit: tree·hm^{-2})

stand age/year	severe intermediate cutting				medium intermediate cutting				slight intermediate cutting				CK			
	NOT	TA	%	AC/%	NOT	TA	%	AC/%	NOT	TA	%	AC/%	NOT	TA	%	AC/%
11									20	20	1.00	1.00	20	20	0.81	0.81
12									20	40	1.00	2.00	10	30	0.42	1.23
15	25	25	1.78	1.78	20	20	1.17	1.17	10	50	0.50	2.50	20	50	0.81	2.04
18					10	30	0.59	1.76	10	60	0.50	3.00	25	75	1.01	3.05
20									10	70	0.50	3.50	20	95	0.81	3.86
24	10	35	0.71	2.49	15	45	0.88	2.64	50	120	2.50	6.00	90	185	3.70	7.56
30	25	60	1.78	4.27	45	90	2.64	5.28	55	175	2.75	8.75	115	300	4.73	12.29

Note: NOT, number of trees; TA, tree accumulation; AC%, accumulative percentage.

total number of trees accounted for 45.0% and 40.0%, respectively. During the period of twenty-five to thirty years, the proportion of dead wood accounted for 38.3% and 31.4% of the total number of trees, respectively. This period is called the continuous peak period of natural thinning. But with the severe and medium thinning intensities, the stages of natural thinning processes were indistinct and the number of dead trees was less than that in the slight intermediate intensity and control plots. There was no natural thinning at all in some stands investigated. The most obvious characteristic of natural thinning in the severe and medium thinning intensity plots was the intermittent changing of natural thinning and the postponement of the peak period. Between the ages of twenty-four to thirty years, the proportion of dead trees accounted for 66.7% and 58.3% of the total number of trees. The conclusion of the difference of the starting period and the thinning stages of natural thinning between different intermediate cutting intensities differed little with the conclusions from previous studies (Wu, 1984).

During the entire process, the amount of wood decreased with the increase of the cutting intensity. If we consider the amount of dead wood in the control plot as 100%, then the amount of dead wood from severe, medium and slight thinning intensities accounted for 20.0%, 30.0% and 58.3% respectively. Analysis of variance shows that the differences in the amount of dead wood from the various thinning intensities was quite remarkable ($F = 10.94 > F_{0.01(3,6)} = 9.78$). According to a least significant difference (LSD) test, the amount of dead wood on the control plot was significantly greater than that in slightly thinned plots and was significantly greater than that in medium and severe plots. The amount of dead wood in the slightly thinned plots was significantly greater than that in the severely thinned plots. There were no significant differences between other plots with different thinning intensities. In general, we speculated that the amount of dead wood from severe and medium thinning plots would dramatically decrease and that it was suitable to practice intermediate cutting with slight to medium intensity thinning with an interval of about ten years.

In order to study further the natural thinning law with different intermediate cutting intensities, we regressed the amount of thinned wood from different intermediate cutting intensities as dead and dry wood accumulated in terms of percentage on stand age, using the exponential equation: $y = a \cdot e^{\frac{b}{x}}$, where y is the accumulated value of dead and dry wood amount calculated as a percentage, x is stand age and a and b are parameters to be estimated. The regression equations are listed in Table 2.

From Table 2, we can see that during the twenty year period after slight thinning and for the control plots, the exponential curves show a close correlation between the amount of accumulated dead and dry wood calculated as a percentage and stand ages. This correlation agrees with the fact that the natural thinning process was continuous and the accumulated dead wood increased over stand age. The regression equations can be used to estimate the accumulated dead and dry wood defined in terms of percentage with changes in stand age after intermediate thinnings. In contrast, we must come to the conclusion that the regression equations of the medium and severely thinned plots are not of much value in practice because of the small correlation between the accumulated dead wood and stand age after thinning in the medium and severely thinned plots. The natural thinning law in the medium and severely thinned plots was clearly different from that at the slightly thinned and the control plots.

5.2 Relationship between number of trees removed by natural thinning and forest density and site conditions

In order to discuss the relationship between the number of trees removed by natural thinning and the site conditions, a regression equation with two independent variables was established using amount of dead wood as dependent variable and its corresponding stand density (trees/hm^2) and site index over the twenty year period after thinning as independent variables: $y = a + b_1x_1 + b_2x_2$, where y is the amount of dead and dry wood, x_1 stand density (trees/hm^2) after intermediate cutting and x_2 site index; a, b_1 and b_2 are parameters to be estimated. Using the method of least square, we computed their values as follows: $a = -1464.0252$, $b_1 = 0.26166$, $b_2 = 70.9771$, we obtained the polynomial regression equation: $\hat{y} = -1464.0252 + 0.26166x_1 + 70.9771x_2$ where $R = 0.8975$, the standard error was 59.7804 and the relative error 35.4%. The results show that there is close correlation between the amount of dead wood, stand density and site index. Although, the independent variables, stand density and site index were important in explaining the amount of dead wood, their importance differed. To distinguish their importance, we used standardized regression coefficients b for comparison. The result shows that the standardized regression

Table 2 Regression equations of accumulated (%) amounts of dead and dying wood and stand ages of different intermediate cutting intensities

intermediate cutting intensity	regression equation	residual standard deviation	correlation coefficient
severe intermediate cutting	$\hat{y} = 6.5032\ e^{-17.6417\ x^{-1}}$	0.9312	0.4170
medium intermediate cutting	$\hat{y} = 6.8090\ e^{-22.4333\ x^{-1}}$	0.9212	0.4251
slight intermediate cutting	$\hat{y} = 21.6499\ e^{-32.2804\ x^{-1}}$	0.6893	0.8457
CK	$\hat{y} = 44.3862\ e^{-44.7171\ x^{-1}}$	0.9973	0.8401

coefficient b_1 of stand density was 0.7669 and b_2 of site index was 0.5497, i.e., $b_1 > b_2$, indicating that stand density was more important in explaining the amount of dead wood than site condition. But the higher relative error indicated that variables other than stand density and site condition, such as stand canopy structure, snow injury and pests and diseases could affect the amount of dead and dry wood.

5.3 Testing the mathematical equation of natural thinning lines of *C. lanceolata* stand density management maps

It is very important for the determination of stand density control measures to determine stand density management maps and natural thinning lines of *C. lanceolata*. In the 1960s, Tadaki calculated the natural thinning lines of *Cryptomeria japonica* to simulate stand thinning, but his results were not approved for practical use (Research Institute of Forestry Information, Chinese Academic of Forestry, 1981). We used the twenty years real data set during natural thinning of the stands after intermediate thinnings to calculate the theoretical stand density (N) from the equation $N = N_0 - \frac{M}{K_1} \cdot N_0^{1.9579}$ where $M = K_1 \cdot K_2$ and compared the N value with the corresponding actual stand density after removal of dry and dead wood in order to estimate the natural thinning line defined by $M = K_1 \cdot K_2$. Methodology and material used in our test are as follows: 1) testing the mathematical equation of natural thinning lines of *C. lanceolata* stands, including 123 groups of stand samples; 2) testing the practical effects used in different intermediate cutting intensities, including 84 groups of stand samples; 3) testing the practical effects used for different site indices, including 123 groups of stand samples. Table 3 shows the estimated relative errors in the calculation of the theoretical stand density N, the objective of our test.

Except for the control plots, the relative errors of other thinning regimes between the actual stand density and N value were less than 5%, within the range of allowable experimental errors, indicating high precision, practicability and smaller errors in the calculation of N from the mathematical equation of natural thinning lines of *C. lanceolata* stand density management maps. It should be pointed out that the summation of actual stand density of every sample of the test item was greater than the N value calculated by the fitted equation. This difference increased with the increase of stand density, showing that the maximum stand density after natural thinning of Chinese fir was greater than the theoretical amount calculated by the equation $M = K_1 \cdot K_2$. This might be due to biological characteristics of Chinese fir, such as its shade tolerance, maintenance of the survival of tree growth under a natural canopy and other factors, according to Wu (1984).

5.4 Stand structure

5.4.1 Diameter-class structure

The diameter-class distribution (%) of Chinese fir stands with different intermediate thinning intensities at ages twenty, twenty-four and thirty are shown in Table 4.

There was a peak of diameter-class percentage distribution at each of the three stand ages after the intermediate thinning which was tested for the Weibull and partial normal distributions by a chi-square test (χ^2 test). Peak values migrated to the larger diameter-classes as the stand age increased and as well the range of the distribution expanded clearly to the larger diameter-classes. Given the four intermediate thinning intensities, the diameter-class of the peak position was the largest with severe thinning, 1–2 diameter-classes greater than that of the control plots and the diameter-class of the peak position with medium and slight thinning was between that of severe thinning and the control plots. For the ten year period between the ages of twenty to thirty years, the range of diameter-class distribution for the different thinning intensities, after the intermediate thinnings, the severe thinning had its maximum diameter-class distribution 2–3 classes higher than that of the control plots, indicating that the stand diameter increment increased sharply with a decrease in the number of trees in the small diameter-classes and an

Table 3 Test results of the natural opening line equation of *C. lanceolata* stand density management maps

tested items	plots	samples	SAD Σy_i/tree·hm^{-2}	STD $\Sigma \hat{y}$/tree·hm^{-2}	SSSDV $\Sigma(y_i - \hat{y})^2$	standard error S_e	estimated relative error/%
natural thinning line equation	18	123	220575	214366	594977	70.1225	3.91
IC intensity stand							
severe	3	21	28980	28407	17615	30.4482	2.21
medium	3	21	35160	34056	66180	59.0183	3.52
slight	3	21	40410	39639	69615	60.5305	3.12
CK	3	21	49560	48291	289857	123.5137	5.23
site index stand							
18	6	41	72495	69564	285727	85.5940	4.84
16	7	47	84000	82894	104835	48.2666	2.70
14	5	35	64110	61908	204415	78.7045	4.30

Note: SAD, sum of actual density; STD, sum of theoretical density; SSSDV, sum of squares of sample difference value.

Table 4 Diameter-class distribution of the stand with different intermediate thinning intensities

stand age/ year	thinning intensity	diameter-class distribution/%														fitted parameters and χ^2 test			
		6	8	10	12	14	16	18	20	22	24	26	28	30	32	*B*	*C*	χ^2 statistics	$\chi^2_{(0.05)}$
20	severe				2.79	13.86	22.71	24.34	18.76	10.66	4.48	1.38	1.01			7.8998	2.4416	2.0647	12.5916
	medium			0.83	6.89	17.15	25.49	25.03	16.16	6.60	1.96					8.9559	3.1070	2.0788	11.0705
	slight		0.45	4.01	10.98	18.90	23.25	20.86	13.41	5.97	1.76	0.42				10.4881	3.1912	1.9182	14.0672
	CK	0.31	3.06	9.04	16.74	22.31	21.92	15.61	7.78	2.59	6.65					11.0250	3.3172	1.2910	14.0672
24	severe				2.25	11.05	18.71	21.83	19.04	13.63	7.59	3.37	1.18	0.95		8.8510	2.3978	3.1525	14.0672
	medium				3.51	15.22	22.56	22.87	17.43	10.31	4.78	3.32	0.38			8.6011	2.2089	2.9457	14.0672
	slight		0.38	3.27	8.81	15.45	20.25	20.50	16.02	9.48	4.15	1.30				11.4354	3.1191	3.0380	15.5073
	CK		1.18	7.21	14.77	20.35	21.08	16.94	10.59	5.12	2.76					9.8384	2.6752	2.4224	12.5916
30	severe				2.02	9.31	15.48	18.70	18.19	14.76	10.15	5.95	2.98	1.27	1.19	9.8804	2.2283	2.9078	15.5073
	medium				3.05	12.92	19.49	21.03	17.87	12.37	7.09	3.38	1.34	1.46		8.6011	2.2089	2.9457	14.0672
	slight			1.62	8.27	14.88	18.98	19.10	15.70	10.68	6.03	2.82	1.09	0.84		9.9984	2.4266	2.9343	15.5073
	CK		1.02	6.06	12.41	17.63	19.50	17.41	12.68	7.52	3.61	2.15				10.6882	2.6293	1.9453	14.0672

obvious increase in the number of trees in the greater diameter-classes. The characteristic diameters were more representative and the stand quality had improved greatly after the intermediate thinnings.

Other characteristics of stand diameters such as a natural diameter class, diameter range, diameter dispersion and the coefficient of variation (*CV%*) in the twenty and thirty years old stands after different intermediate thinning intensities are shown in Table 5.

The maximum of the natural diameter class and diameter dispersion of different intermediate thinning intensities were enhanced to some extent when the stand age was twenty and thirty years, when the added values were greater in the medium and severely thinned intensity plots than in the other thinning regimes. Stand diameter ranges and coefficients of variation increased over stand age and the value added was greater in the medium and severe thinning intensity plots as well where the range increased by four diameter classes. But, these characteristic indices of stand diameter in the slight intensity and control plots were clearly not changing, remaining ultimately in balance. Our results show that, after medium and severe intermediate thinning, stand density decreased, growth condition improved, the diameter increments of remaining trees accelerated and the number of large diameter-class trees was enhanced. These increases in stand diameter indices such as stand diameter range, diameter dispersion and coefficients of variation indicate the long-term effect on stand diameter growth from intermediate thinning and the optimization of stand diameter characteristics.

5.4.2 Tree height structure

The rule of stand height distribution percentages of different diameter classes was advanced by Yu (1997) from the correlation between diameter distribution and tree height of Chinese fir. We studied the stand tree height distribution rule of the 18, 16 and 14 site indices only for the severe and medium intermediate thinning intensities because the stand tree heights were not measured in the other plots. The number of trees was counted and percentages calculated for every site-index in 1 m tree-height grade steps, computed with the Weibull density function and normal distribution and tested by a chi-square test (χ^2 test). The results are shown in Table 6.

The distribution of stand height class percentages of the three site indices at age thirty was calculated with the Weibull and normal distributions and tested by a chi-square test (χ^2 test). This distribution had one peak lying in the middle of the tree height class distribution and shows a large difference with the partial normal

Table 5 Natural diameter classes, ranges and coefficients of variation of the stand for different intermediate thinning intensities

stand age/year	thinning intensity	density/trees·hm^{-2}	DBH/cm	natural diameter class		range	diameter dispersion	*CV*/%
				minimum	maximum			
20	CK	2385	15.3	0.3922	1.5658	18	1.1764	22.73
	slight	1930	16.7	0.4780	1.5569	18	1.0777	19.43
	medium	1675	17.3	0.5780	1.3873	14	0.8093	16.21
	severe	1380	18.3	0.6557	1.5301	16	0.8744	16.90
30	CK	2130	17.0	0.4701	1.5294	18	1.0588	23.58
	slight	1825	18.0	0.5465	1.6393	20	1.0928	21.29
	medium	1615	19.0	0.6316	1.5789	18	0.9473	19.66
	severe	1345	20.2	0.5941	1.5842	20	0.9901	20.65

Table 6 Tree height structure of 30-year-old stands with different thinning intensities and site indices

site index	tree height class distribution/%																fitted parameters and χ^2 test			
	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	B	C	χ^2 statistics	$\chi^{2\ (0.05)}$
18			0.23	1.82	4.84	8.80	12.80	15.64	16.33	14.61	11.16	7.21	3.90	1.75	0.64	0.27	7.1742	3.0228	8.5229	19.6752
16	0.58	0.32	2.43	6.17	10.76	14.87	17.09	16.55	13.52	9.25	5.26	2.45	1.33				6.6828	2.9528	3.1497	16.9190
14		4.18	9.92	15.88	19.49	19.02	14.85	9.22	6.85								5.6705	2.8794	4.7955	12.5916
severe		0.77	4.16	8.18	11.90	14.37	15.05	13.91	11.44	8.40	5.50	3.22	1.67	0.78	0.32	0.33	6.6020	2.4699	6.0556	21.0261
medium	0.28	2.08	5.19	9.04	12.71	15.18	15.67	14.05	10.92	7.33	4.21	2.06	1.28				7.2008	2.8984	3.9411	18.3070

distribution of the stand diameter percentages. Statistics show that stand height class dispersion for the three site indices increased exponentially. Stand height class dispersion of the 14, 16 and 18 site indices was 0.5334, 0.6020 and 0.6842, respectively and the maximum of the height class of site indices 18 and 16 were seven and four height classes higher than that of site index 14, indicating that the higher the site index, the better the site quality and the higher the potential of stand height growth. The results show it was more scientific and practical to study the rule of tree height characteristics for different site indices. The stand tree height class distribution of medium and severe thinning intensity plots exhibited a Weibull and normal distribution, also tested by a chi-square test (χ^2 test). This distribution has only one peak. The peak position varied with different intermediate thinning intensities. The peak position of severe thinning density declined towards the small tree height classes and that of medium intensity was situated in the middle of the height class distribution. The tree height class distribution of severely thinned density plots was three height classes higher than that of medium thinned plots. Furthermore, the number of trees in the height class of the peak value in the distribution of severely thinned density plots was six per cent greater than in the medium thinned plots. Differences in distribution of stand tree height class between medium and severe thinning intensities indicated that, during the twenty years of severe thinning intensity, stand height growth was larger than for the other two thinning intensities and the proportion of taller trees was larger in these stands.

5.4.3 Canopy structure

Studies by Jiang and Ye (1980) indicated that canopy morphology and structure of Chinese fir changes with stand age, density, site conditions and other factors. When the canopy growth was inhibited and natural thinning appeared to be obvious, the diameter of the canopy was reduced, the needle biomass and diameter growth decreased sharply. In order to study the changing status of the canopy structure of the stand at different intermediate thinning intensities after the thinning (shown in Table 7), we compared and analyzed the changes of canopy factors such a branch height, canopy length and relative canopy height (canopy length/height) during the twenty-year period after thinning. This analysis reveals the relationship between canopy structure and the periodic volume increment of single trees.

In general, the first branch height of stands enhances over stand age as shown in Table 7. This branch height increment is relatively small during the first five years after thinning, but should speed up gradually. The order of increment was: value of control plots > value of slightly thinned density plots > medium thinned plots > severely thinned plots. The period of the height to the first branch of the stand increased rapidly and corresponded with the period where the amount of dry and dead wood increased rapidly. The correlation between height to the first branch of the stand and stand age fitted a quadratic parabola: $y = a + bA + cA^2$, where y is height to the first branch of the stand, A is stand age and a, b and c are parameters to be estimated. Canopy length decreased over stand age, the decrease in canopy length was relatively small five years after cutting and then gradually accelerated. The order of canopy length was as follows: severely thinned density plots > medium thinned plots > slightly thinned plots > control plots. But the change law of canopy length among different intermediate cutting densities showed greater differences. In the period of twenty years after cutting, the canopy length of medium and severely cut densities plots maintained a relatively stable state, their values ranged from 4.9–6.0 m and 6.2–6.8 m, respectively. The canopy length of slightly thinned density plots and control plots diminished dramatically over stand age. We fitted canopy length and stand age with a semi-logarithmic function: $y = a + b\lg A$, where y is stand canopy length, A stand age and a and b are parameters to be estimated.

In the twenty-year period after cutting, the correlation between the single-tree periodic volume increment and canopy length was fairly close, the regression equation was $\hat{y} = -0.0491 + 0.0403x$ ($R = 0.7497 > 1\%$), where $\hat{y}$ is the single-tree periodic volume increment and x canopy length. The single-tree periodic volume increments of medium and severely thinned plots were clearly enhanced because of the longer canopy length, indicating that the stand diameter growth and single-tree periodic volume increment increased notably as the result of improvement in the growing space of the canopy by regulating stand density with medium and severe intermediate thinning, consistent with previous conclusions (Jiang et al., 1982; Zhang et al., 2005). Relative stand canopy height diminished sharply over stand age. Relative canopy height of slightly thinned plots and control plots diminished earlier and less than that of medium and severely thinned plots. The age at which relative stand canopy height began to decline was twelve years in control plots, fifteen years old in slightly and medium thinned plots and eighteen years in severely thinned plots. When the stand age was thirty years old, the order of relative stand canopy height was: severely thinned plots > medium thinned plots > slightly thinned plots > control plots. If we define the value of the relative canopy length of severely thinned plots as 100%, then the values of medium and slightly thinned plots and control plots were 80.17%, 71.39% and 42.21%, respectively. The higher the relative canopy height, the higher the living canopy of the stand and the larger the effective photosynthetic area, indicating a more suitable stand canopy structure, profitable for diameter and single-tree volume growth. The law of relative canopy height varies with stand age and can be expressed by a semi-logarithmic equation: $y = a + b\lg A$, where y is stand canopy length, A stand age and a and b are parameters to be estimated.

The variation of stand canopy structural factors changing with stand age are shown in Table 8 for different intermediate thinning intensities from fitting regression equations and testing.

In the twenty year period after the intermediate cuttings, the correlations between the variation of height to the first branch of the stand, canopy length, relative canopy height with different cutting intensities and changing stand age were close, given our estimated and tested regression equations. The regression equations could be used to estimate the variation of stand canopy structure after thinning with different cutting intensities. An exception should be mentioned here: canopy length of medium and severely thinned plots and stand age were not clearly related, showing that the canopy is growing well after medium and severe thinning and that the canopy length maintained a stable growth status and clearly did not diminish over stand age.

6 Conclusions

Through twenty years of continuous monitoring after intermediate cutting, there are clear differences in the starting period of natural thinning, the thinning processes and the amounts of dry and dead wood of Chinese fir (*Cunninghamia lanceolata*) removed from stands, given the different intermediate cutting intensities. There were small amounts of dry and dead wood in the slightly thinned and control plots one year after thinning, but these did not appear in the medium and severely thinned plots until five years later. The former thinning process possessed continuity, but the latter two presented discontinuity with three to five years intervals. According to stand age, natural thinning in the control and slightly thinned plots was divided into three stages: 1) a small amount of dead and dry wood, at stand age fifteen, which is called the slight thinning period; 2) the intensive thinning stage, from sixteen to twenty-four years where, the amount of dead and dry wood was large during this stage, accounting for nearly half of the total dry and dead wood; and 3) the continuous thinning period, occurring during the twenty-five to thirty year period and continuity of the peak period of natural thinning, where the amount of dead and dry wood was approximately one third of the total dry and dead wood. Natural thinning would be a very long process without artificial interference. There were small amounts of dead and dry wood in medium and severely thinned plots before age twenty-four, but a large amount appeared from twenty-four to thirty years. It was difficult to distinguish the different thinning stages. The total amount of dead and dry wood in the slightly thinned and control plots were statistically significant or very significantly different than the total amount from the medium and severely thinned plots during the twenty year period. With the change of stand age, the accumulated amount of dead and dry wood, calculated as percentage, could be represented by a closely fitted exponential equation in the slightly thinned and control plots, but the amount accumulated and stand age in the medium and severely thinned plots was not correlated.

Our study revealed that stand density and site conditions had important effects on the number of dead and dying trees, but density was more important than site conditions.

The theoretical density, which was obtained from the mathematical equation of the natural thinning lines of *C. lanceolata* stand density management maps, was tested for various items using actual stand densities of different stand ages. The result shows that the relative error of the tested items was less than 5%. Except for the control, all of them were within the allowable experimental errors. This suggested that the error of the mathematical model of natural thinning lines was low, the precision relatively high and well suited for practical use. It should be noted that in the course of testing, the actual stand density was generally larger than the theoretical density.

The stand diameter framework expressed by diameter-class percentages for the different intermediate cutting intensities were fitted by a Weibull and partial normal distribution function and tested by chi-square tests (χ^2 test), with one peak value each which migrated to the small diameter-classes. Stand diameter dispersion values increased over age, but declined with the increase in intermediate cutting intensity. The maximum stand diameter

Table 7 Changes in status of canopy structure of stands with different thinning intensities after thinning

IC intensity	stand age (after cutting)/year																						
	10			11			12			15			18			20			24			30		
	HFB/m	CL/m	CL/H/%	HFB/m	CL/m	CL/H/%	HFB/m	CL/m	CL/H/%	HFB/m	CL/m	CL/H/%	HFB/m	CL/m	CL/H/%	HFB/m	CL/m	CL/H/%	HFB/m	CL/m	CL/H/%	HFB/m	CL/m	CL/H/%
severe	4.07	6.87	62.7	4.95	6.22	55.7	5.18	6.52	55.7	6.62	6.61	50.0	8.05	6.18	43.4	9.05	6.08	40.2	10.31	6.16	37.4	11.53	6.30	35.3
medium	4.71	5.55	52.4	5.61	5.52	49.6	5.74	5.99	51.1	7.34	5.69	43.7	8.83	5.34	37.7	9.60	5.60	36.8	10.65	5.48	34.0	12.31	4.86	28.3
slight	3.88	6.59	62.9	5.14	5.76	52.8	5.67	5.37	50.3	7.06	5.67	44.5	8.57	5.16	37.6	9.78	4.68	32.3	10.80	4.80	30.8	12.76	4.37	25.2
CK	4.40	5.54	55.7	5.50	4.97	47.5	6.13	4.73	43.6	7.78	4.29	35.5	9.10	4.10	31.1	10.35	3.65	26.1	11.90	3.00	20.1	14.04	2.46	14.9

Note: HFB, height to first branch; CL, canopy length; H, height.

Table 8 Regression equations between the under- branch height, canopy length, canopy relative height and the stand age

intermediate cutting intensity	height to the first branch			canopy length			canopy relative height		
	regression equation	*RSD*	*CC*	regression equation	*RSD*	*CC*	regression equation	*RSD*	*CC*
severe	$\hat{y}=-2.7826+0.7982A-0.01066A^2$	0.1264	0.9983				$\hat{y}=117.4682-57.63033\lg A$	1.8934	0.9824
medium	$\hat{y}=-1.8019+0.7578A-0.00964A^2$	0.1386	0.9986				$\hat{y}=104.3373-51.6043\lg A$	1.1974	0.9896
slight	$\hat{y}=-3.5471+0.8766A-0.01125A^2$	0.1589	0.9989	$\hat{y}=10.7940-4.5407\lg A$	0.2066	0.9340	$\hat{y}=131.5915-73.7696\lg A$	2.5884	0.9761
CK	$\hat{y}=-2.6797+0.7966A-0.00792A^2$	0.2318	0.9973	$\hat{y}=11.3576-5.9836\lg A$	0.1367	0.9908	$\hat{y}=133.5548-81.7617\lg A$	1.9034	0.9791

Note: *RSD*, residual standard deviation; *CC*, correlation coefficient.

class for medium and severe thinning intensity was 2–3 classes larger than that of control. The distribution of stand height-class percentages of different site indices at thirty years was fitted with a Weibull and normal distribution function and tested by a chi-square test (χ^2 test) with one peak in the middle of the tree height class distribution. The stand height class dispersion for the three site indices increased exponentially and the height class of site indices 18 and 16 were 7 and 4 height classes higher than site index 14.

The height to the first branch increased over stand age. The order of increment was as follows: value of control plots > value of slightly thinned density plots > medium thinned plots > severely thinned plots. The relation between height to first branch and stand age was fitted with a quadratic equation. Canopy length decreased over stand age, but the decrease in canopy length was relatively smaller in the medium and severely thinned plots. The order of canopy length was as follows: value of severely thinned plots > medium thinned plots > slightly thinned plots > value of control plots. The canopy length of slightly thinned and control plots diminished over stand age, a relationship fitted with a semi-logarithmic function. However, the correlation between canopy length and stand age of medium and severely thinned plots was not close.

The correlation between the single-tree periodic volume increment and canopy length was close. The stand canopy length in medium and severely thinned plots was clearly longer than that in slightly thinned and control plots. The single-tree periodic volume increment was markedly larger than that in the slightly thinned and control plots. The relative stand canopy height diminished sharply over age. The relative canopy height varied with stand age. This relation could be expressed closely by a semi-logarithmic function for the different intermediate cutting intensities. It is very useful to study systematically the variety of stand structures of Chinese fir in the twenty year period after different intermediate cutting intensities to provide a theoretical basis for the fast growing, high yielding and high efficiency of direct cultivation of Chinese fir.

Acknowledgements This work was supported by an important project in 1976 of the Scientific and Technological Commission, Jiangxi Province. We thank Jianlin JIE, Wenchao HUANG, Zhanbo CAO of the Jiangxi Academy of Forestry, and Jingwen CAI of the Zaoxia Forest Farm, Fengxin County. We are grateful to Fanglin TAN for partial computations.

References

Jiang Z L, Ye J Z (1980). A preliminary study on the canopy structure of Chinese fir (*Cunninghamia lanceolata*). J Nanjing For Prod Ind Coll, (4): 46–51 (in Chinese)

Jiang Z L, Ye J Z, Zhou B L (1982). Intermediate Cutting of Chinese Fir (*Cunninghamia lanceolata*) Forestry. Beijing: China Forestry Publishing House, 12–19 (in Chinese)

Jiangxi Academy of Forestry (1978). Research on planting density and intermediate cutting on hilly region, Jiangxi Province. Sci Silv Sin, 14(1): 28–35 (in Chinese)

Liu J F, Tong S Z (1980). Research report on the construction of the density control diagrams of Chinese fir. Sci Silv Sin, 16(4): 241–251 (in Chinese)

Research Institute of Forestry Information, Chinese Academy of Forestry (1981). Intermediate Cutting of Forest: Collection of Forestry. Beijing: Chinese Forestry Publishing House, 18–19 (in Chinese)

Wu Z L (1984). Chinese Fir (*Cunninghamia lanceolata*). Beijing: China Forestry Publishing House, 171–188 (in Chinese)

Yang H X, Fang Q, Ye G Y (1959). Study on Ecological Characteristics of Chinese Fir (*Cunninghamia lanceolata*) II: Daping City, Xinyi County in Guangdong Province. Beijing: China Forestry Publishing House (in Chinese)

Yu X T (1997). Cultivation Science of Chinese Fir. Fuzhou: Fujian Science and Technology Publishing House, 164–167 (in Chinese)

Zhang J G, Duan A G (2003). Approach to theoretical growth equations for modeling stands diameter structure of Chinese fir plantations. Sci Silv Sin, 39(6): 55–61 (in Chinese)

Zhang S S, Chen C F, Wu K X, Zhan Y S, He S Q (2005). Growth effect of intermediate cuttings intensity experiment for twenty years in *Cunninghamia lanceolata*. Sci Silv Sin, 41(5): 56–65 (in Chinese)