

Growth process and model simulation of three different classes of *Schima superba* in a natural subtropical forest in China

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Abstract. *Schima superba* is an important fire-resistant, high-quality timber species in southern China. Growth in height, diameter at breast height (DBH), and volume of the three different classes (overtopped, average and dominant) of *S. superba* were examined in a natural subtropical forest. Four growth models (Richards, edited Weibull, Logistic and Gompertz) were selected to fit the growth of the three different classes of trees. The results showed that there was a fluctuation phenomenon in height and DBH current annual growth process of all three classes. Multiple intersections were found between current annual increment (CAI) and mean annual increment (MAI) curves of both height and DBH, but there was no intersection between volume CAI and MAI curves. All selected models could be used to fit the growth of the three classes of *S. superba*, with determinant coefficients above 0.9637. However, the edited Weibull model performed best with the highest R^2 and the lowest root of mean square error (RMSE). *S. superba* is a fast-growing tree with a higher growth rate during youth. The height and DBH CAIs of overtopped, average and dominant trees reached growth peaks at ages 5–10, 10–15 and 15–20 years, respectively. According to model simulation, the volume CAIs of overtopped, average and dominant trees reached growth peaks at ages 17, 55 and 76 years, respectively. The biological rotation ages of the overtopped, average and dominant trees of *S. superba* were 29, 85 and 128 years, respectively.

1. Introduction

Schima superba is a large evergreen species of the Theaceae family, also known as lotus wood or the lotus tree. It has fire-resistant qualities and produces high-grade timber, and is mainly distributed at an elevation of 400~1500 m to the south of the Yangtze River in China. With current global warming and the threat of forest fires [1], it is useful to study the growth process and characteristics of this fire-resistant tree species. Cheng examined the relationship between the height and diameter at breast height (DBH) of *S. superba* [2]; however, the growth process of *S. superba* has seldom been reported. Due to the differentiation within a forest, trees in the same forest stand have different growth characteristics [3]. Thus, being an excellent fire-resistant species, it is important to investigate the growth process and model simulations of *S. superba*, especially for the three different classes of trees (overtopped, average and dominant).



This study aimed to investigate the growth process of the different classes of *S. superba* using stem analysis data and four growth models (Richards, edited Weibull, Logistic and Gompertz) in natural subtropical forest. We suggest that our results will provide important information for the cultivation of forest fire prevention belts and will help to optimize forestry operations and management.

2. Materials and Methods

2.1. Site description

The study site was located in the Paiyashan state-owned forest farm, Jingzhou Miao and Dong autonomous county, Hunan province, China (latitude 26°24'-26°35'N; longitude 109°27'-109°38'E, elevation 400–800 m above sea level; figure 1).

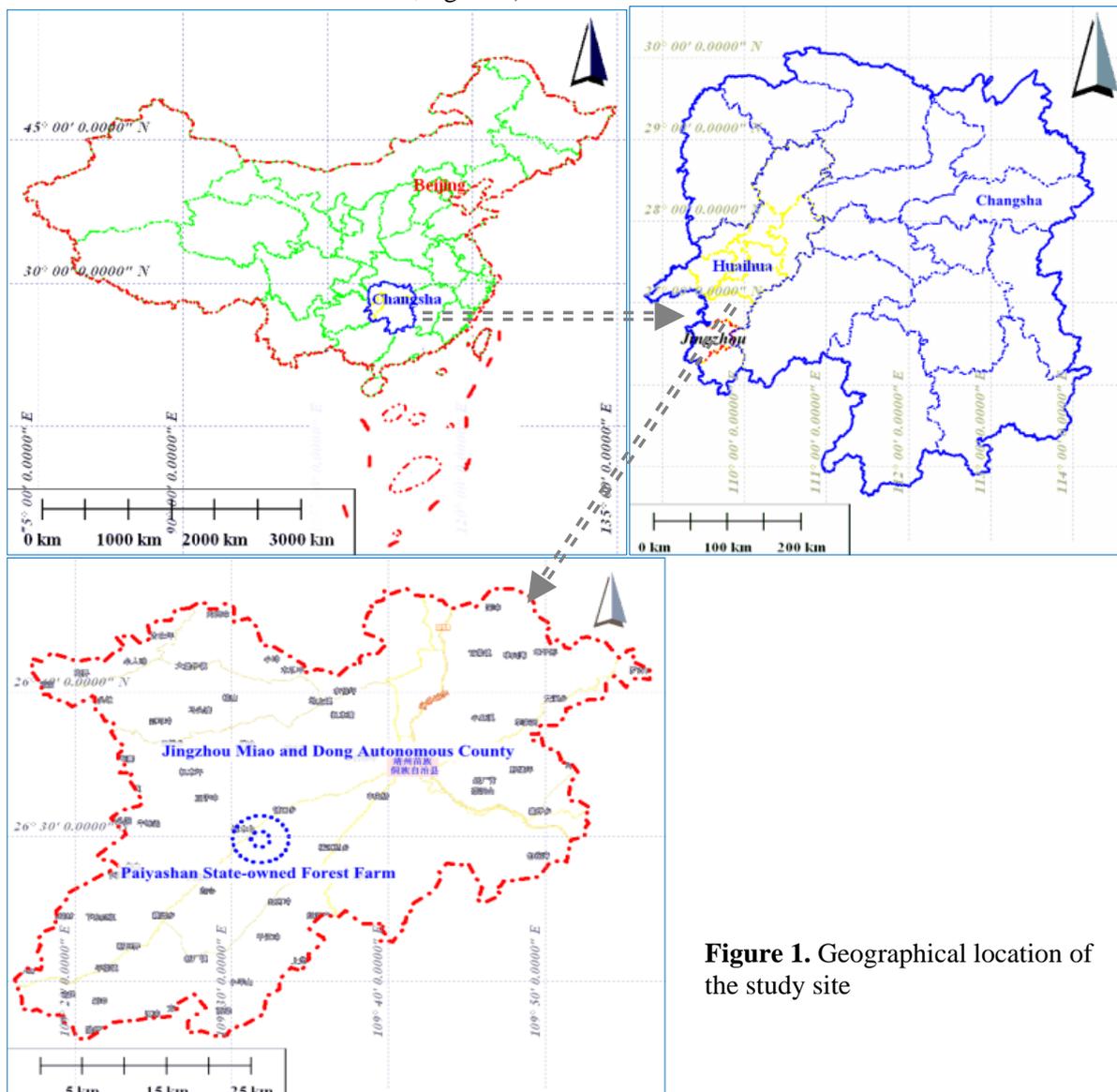


Figure 1. Geographical location of the study site

The region has a humid mid-subtropical monsoon climate with a mean annual temperature of 16.7 °C. Mean annual precipitation amounts to 1250 mm, occurring mostly between April and August (Figure 2). The soil parent material is purple sandshale and with a red soil or a mountain yellow soil. The dominant vegetation is plantations and secondary forests that are composed of many native tree species.

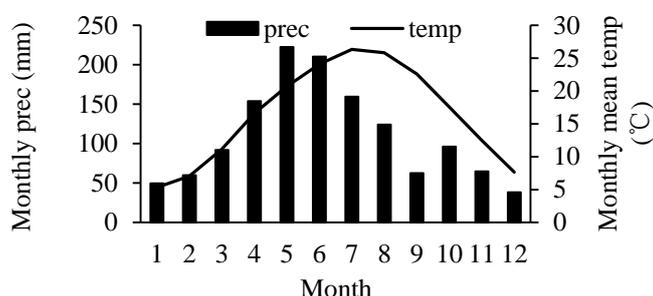


Figure 2. Monthly mean temperature and precipitation in the study area. ‘Prec’ and ‘temp’ represent precipitation and temperature, respectively.

2.2. Data collection

All trees in the *S. superba* natural forest stand were placed into three classes (overtopped, average and dominant) according to their height and DBH. Three overtopped sample trees, four average sample trees and two dominant sample trees were selected for stem analysis (Table 1).

The standard stem analysis method was used in this study, a disc was cut out from the middle of each section, and the number of rings and annual ring width of each disc were measured using the WinDENDRO tree-ring analysis instrument (Regent Instruments Canada INC.). Visual FoxPro 9.0 was used to calculate the height (m), DBH (cm) and volume (m³). Formula (1) is the mean annual increment (MAI), which refers to the average growth per year of a tree; and formula (2) is the current annual increment (CAI), which describes the annual change in the increment of a tree. The interpolation method was used to calculate height increments, and the central basal area approximate quadrature method was used to calculate volume increments [4].

Table 1. Information on classified trees (*Schima superba*)

Classified trees	Age	Height (m)	DBH (cm)	Under-branch height (m)	Mean crown (m)
Dominant tree ^a	56	18.2	28.5	5.4	9.0
Dominant tree	65	18.5	33.8	6.7	8.0
Average tree ^b	30	14.6	13.0	4.6	3.9
Average tree	30	15.6	17.8	2.9	4.5
Average tree	52	16.4	24.3	7.6	6.8
Average tree	56	12.5	19.9	4.4	9.0
Overtopped tree ^c	31	9.0	7.4	5.6	3.5
Overtopped tree	34	10.0	11.1	3.5	4.0
Overtopped tree	55	11.9	14.1	2.0	6.1

^a: Growth best, no pests, with the largest crown, and occupy the upper canopy;

^b: Growth better, no pests, with a narrow crown, and located in the middle canopy;

^c: Growth worst, no pests, with a severely squeezed crown, and in a state of obvious suppression.

$$MAI = Y_t / t \tag{1}$$

$$CAI = Y_t - Y_{t-1} \tag{2}$$

Where *Y* is the height, DBH or volume increment, and *t* is the tree age.

2.3. Model description and selection criteria

Tree growth models express the regularity of tree growth increments that change along with age using mathematical equations [5]. In the current study, we chose the Richards, edited Weibull, Logistic and Gompertz growth models (Table 2) according to the principles of model building, design flexibility, good biological explanation and superior applicability [6]. Model parameters were fit using the

Levenberg–Marquardt optimization algorithm [7] of the 1stOpt program (7D-Soft High Technology INC.).

Table 2. Growth models selected for comparison of classified trees

Model	Formula	Variables	Parameters *
Richards	$y = a(1 - e^{-bx})^c$	x, y	a, b, c
Edited Weibull	$y = a(1 - e^{-bx^c})$	x, y	a, b, c
Logistic	$y = a/(1 + be^{-cx})$	x, y	a, b, c
Gompertz	$y = ae^{-be^{-cx}}$	x, y	a, b, c

*‘a’ is the parameter of biological extreme point; ‘b’ is a parameter indicating the speed of tree growth; ‘c’ is a parameter concerned with anabolism.

Model evaluation and comparisons were based on graphical and numerical analyses of the values of the following statistics: formula (3), root of mean square error (RMSE) [8], which is frequently used to measure the differences between the values (sample and population values) predicted by a model or an estimator and the values actually observed (the smaller the value, the smaller the value of the error); formula (4), coefficient of determination (R^2) [9], which reflects the consistency between simulated and measured values (the closer to 1 the value, the better the fit). The expressions for these statistics are as follows:

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (y_i - \hat{y}_i)^2}{n - p - 1}} \quad (3)$$

$$R^2 = 1 - \frac{\sum_{i=1}^n (y_i - \hat{y}_i)^2}{\sum_{i=1}^n (y_i - \bar{y}_i)^2} \quad (4)$$

Where, y_i , \hat{y}_i and \bar{y}_i are the observed, predicted and mean values of height, DBH or volume increment, respectively; n is the total number of data used in fitting the model; and p is the number of independent variables.

3. Results

3.1. Growth in height

The height CAI and MAI curves for the three classes (dominant, average and overtopped) of *S. superba* are presented in figure 3. The height MAI curves of dominant and average trees remained constant with time. However, the height MAI curve of overtopped trees gradually decreased with time and levelled off from the second year. The height CAI curves for the three tree classes showed a multiple-peak phenomenon. Height CAI curve peaks for dominant trees appeared at age 16 years, 23 years and 51 years; for average trees at age 6 years and 23 years; and for overtopped trees in years 1, 3 and 9. There were multiple intersections between height CAI and MAI curves, which indicated there were multiple distorted relationships between height CAI and MAI curves for the three classes of trees. It was therefore necessary to investigate the distortion, and regression methods and model simulations were used to reduce it.

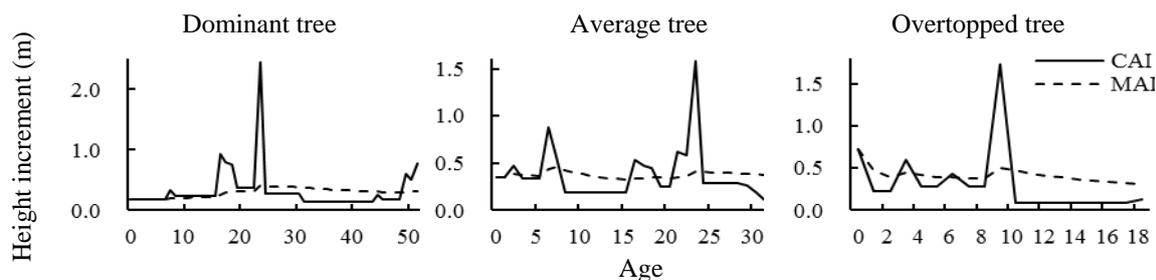


Figure 3. Height growth process of three classes of *Schima superba*

3.2. DBH growth process

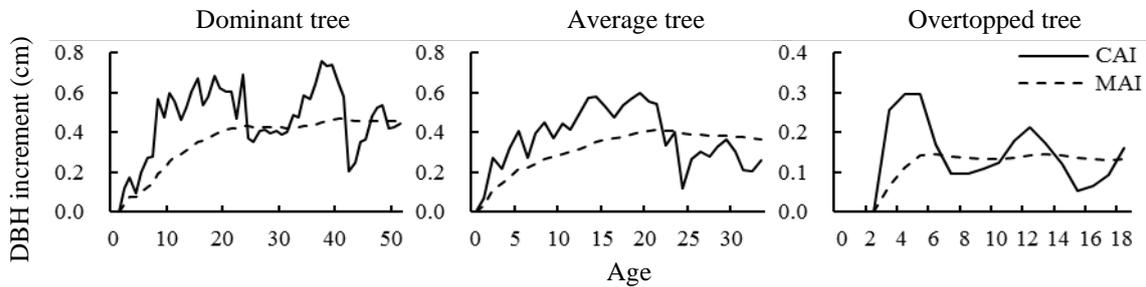


Figure 4. DBH growth process of three classes of *Schima superba*

Figure 4 shows the DBH CAI and MAI curves for the three classes of *S. superba*. The DBH MAIs increased with time during early life. Subsequently, the MAI curves of the dominant, average and overtopped trees started to stabilize in the 25th year, 22nd year and 6th year, respectively. The DBH CAI curves of dominant and average trees took on a fluctuant increasing process during their early life. Later on, the DBH CAI curve for dominant trees had two troughs at 24–31 years and 42 years; but there were 2 troughs for average trees at 24 years and 32 years. The DBH CAI for overtopped trees increased to a maximum during the first two years when the height of overtopped trees reached breast height; the trough values of the DBH CAI curve for overtopped trees appeared at age 7–10 years and 15 years, meanwhile, a peak appeared at 12 years. There were multiple intersections between DBH CAI and MAI curves, but less than that of the tree height curves, especially in the average class. In other words, the DBH was less influenced than tree height by random factors such as environment, tending and thinning.

3.3. Volume growth process

Figure 5 presents the volume CAI and MAI curves for the three classes of *S. superba*. Growths in volume for all types were similar; CAIs and MAIs increased year by year, but the CAI curve of dominant trees showed some fluctuation. Furthermore, volume CAI was always greater than volume MAI in the three classes. The volume of dominant and average trees increased slowly during the early growth stage; later on, dominant trees at 5 years and average trees at 7 years began to enter a period of fast-growth. Moreover, both volume CAI and MAI curves showed no downward trend and did not intersect. In other words, the age of all sample trees did not achieve maximum volume MAI, as confirmed by the models below.

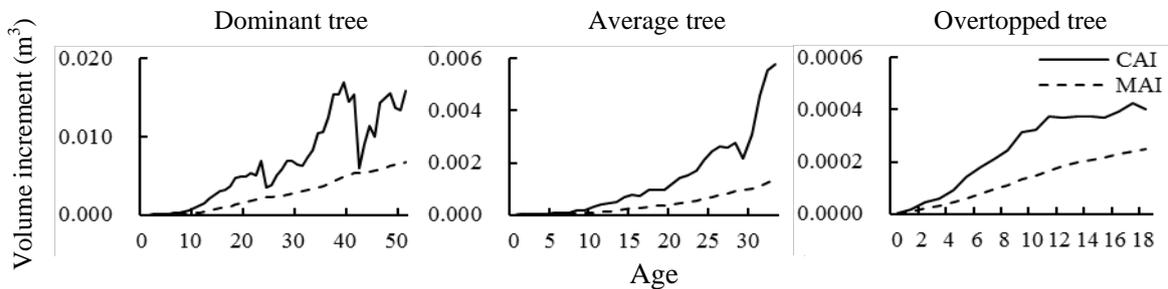


Figure 5. Volume growth process of three classes of *Schima superba*

3.4. Model fit and selection

In current study, tree age was used as an independent variable, and annual height, DBH and volume were used as dependent variables in the four models that were selected to simulate tree growth. The R² values of the four models were higher and similar among the four models (Table 3). The minimum

value of R^2 was 0.9637 when using the Richards model to simulate growth in height of overtopped *S. superba*. The RMSE values ranged from 0.0001 to 0.8496, and the edited Weibull model showed the best fit to the growth of all three tree classes (with the highest R^2 and the lowest RMSE).

3.5. Model simulation of height

The most suitable model to simulate the height increment was the edited Weibull model. The height CAI and MAI fitted curves of the three classes of *S. superba* are presented in figure 6. As can be seen from the graph, the relationship between the height CAI and MAI is very clear. During the youthful stage, the height CAI and MAI increased with age, but the CAI curves increased faster and reached maximum values earlier than that of the MAI curves. The CAI and MAI curves crossed when the MAI reached its maximum; from then on, the CAI always remained less than the MAI.

The height CAI of dominant trees reached its maximum value of $0.54 \text{ m}\cdot\text{a}^{-1}$ in the 17th year, and the MAI reached its maximum value of $0.37 \text{ m}\cdot\text{a}^{-1}$ in the 29th year. The height CAI and MAI of average trees reached their maximum values earlier than the dominant trees, which were $0.43 \text{ m}\cdot\text{a}^{-1}$ in the 10th year and $0.39 \text{ m}\cdot\text{a}^{-1}$ in the 17th year, respectively. The height CAI and MAI of overtopped trees reached their maximum values at the earliest age, which were $0.53 \text{ m}\cdot\text{a}^{-1}$ in the 4th year and $0.45 \text{ m}\cdot\text{a}^{-1}$ in the 8th year, respectively.

Table 3. Parameters and related statistics for the four growth models

Model	Tree class	Growth factor	Parameters			R^2	RMSE
			a	b	c		
Richards	Dominant	Height	15.746	0.081	3.927	0.9879	0.5852
		DBH	41.293	0.026	1.904	0.9977	0.3677
		Volume	2.390	0.017	3.682	0.9984	0.0043
	Average	Height	17.973	0.041	1.448	0.9849	0.5573
		DBH	15.614	0.074	2.636	0.9988	0.1479
		Volume	0.618	0.037	7.608	0.9975	0.0030
	Overtopped	Height	6.812	0.147	1.756	0.9637	0.3586
		DBH	3.039	0.130	2.410	0.9893	0.0871
		Volume	0.012	0.077	3.553	0.9999	0.0001
Edited Weibull	Dominant	Height	14.734	0.001	2.136	0.9870	0.5926
		DBH	34.292	0.002	1.623	0.9974	0.3952
		Volume	0.704	0.000	3.031	0.9985	0.0041
	Average	Height	16.609	0.011	1.334	0.9856	0.5452
		DBH	13.540	0.003	1.922	0.9992	0.1204
		Volume	0.618	0.037	7.608	0.9975	0.0030
	Overtopped	Height	6.252	0.034	1.551	0.9680	0.3418
		DBH	2.779	0.012	1.746	0.9881	0.0933
		Volume	0.007	0.001	2.606	0.9998	0.0000
Logistic	Dominant	Height	14.341	32.207	0.161	0.9876	0.5774
		DBH	24.872	20.708	0.104	0.9885	0.8496
		Volume	0.457	164.536	0.118	0.9980	0.0051
	Average	Height	14.503	10.871	0.121	0.9867	0.5220
		DBH	12.449	25.208	0.190	0.9965	0.2595
		Volume	0.244	523.444	0.143	0.9972	0.0032
	Overtopped	Height	6.007	11.704	0.347	0.9790	0.2686
		DBH	2.481	20.172	0.322	0.9755	0.1343
		Volume	0.006	80.377	0.313	0.9977	0.0001
Gompertz	Dominant	Height	15.366	5.646	0.095	0.9887	0.5549
		DBH	29.599	4.197	0.055	0.9949	0.5531
		Volume	0.991	7.906	0.039	0.9985	0.0042
	Average	height	15.720	3.085	0.072	0.9874	0.5059
		DBH	14.058	4.707	0.105	0.9991	0.1242
		volume	0.485	12.085	0.049	0.9976	0.0029
	Overtopped	Height	6.412	3.206	0.210	0.9717	0.3123
		DBH	2.712	4.485	0.192	0.9851	0.1030
		Volume	0.008	6.816	0.130	0.9998	0.0001

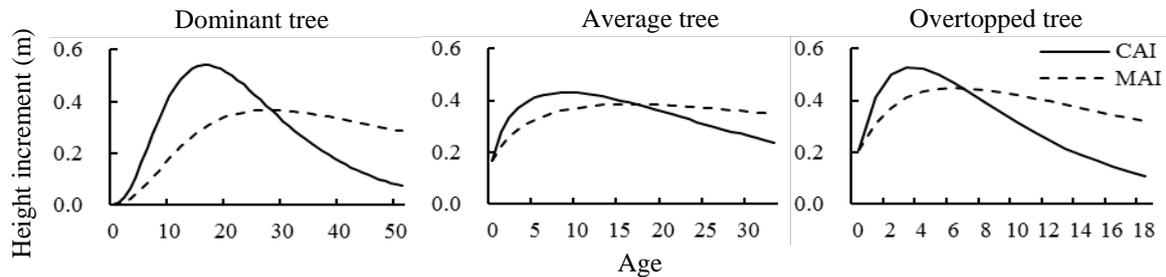


Figure 6. Height CAI and MAI fitted curves of the three classes of *S. superba* using edited Weibull model

3.6. Model simulation of DBH

Figure 7 shows the DBH CAI and MAI fitted curves according to the best fit model (edited Weibull model) for the three classes of *S. superba*. The process of growth in DBH is similar to that of height. A higher CAI rate than MAI rate appeared during the youthful stage. Since the two curves crossed at the time when the MAI reached its maximum, the CAI remained less than the MAI. From dominant trees to average trees to overtopped trees, the age of these intersections appeared earlier and earlier. The DBH CAI of dominant trees reached its maximum value of $0.55 \text{ cm}\cdot\text{a}^{-1}$ in the 34th year, and the MAI reached its maximum value of $0.46 \text{ cm}\cdot\text{a}^{-1}$ in the 45th year. The DBH CAI of average trees reached a maximum of $0.53 \text{ cm}\cdot\text{a}^{-1}$ in the 14th year, with a maximum MAI of $0.40 \text{ cm}\cdot\text{a}^{-1}$ in the 24th year. The DBH CAI of overtopped trees reached its maximum value of $0.18 \text{ cm}\cdot\text{a}^{-1}$ in the 9th year, with a maximum MAI of $0.14 \text{ cm}\cdot\text{a}^{-1}$ in the 13th year.

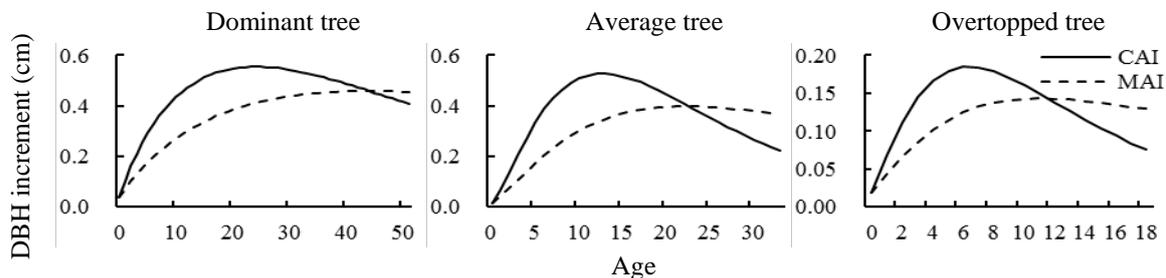


Figure 7. DBH CAI and MAI fitted curves of the three classes of *S. superba* using edited Weibull model

3.7. Model simulation of volume

Figure 8 presents the volume CAI and MAI fitted curves according to the edited Weibull model for the three *S. superba* classes. The relationship between volume CAI and MAI curves was similar to that of the height and DBH. The volume CAI of dominant trees reached a maximum value of $0.0177 \text{ m}^3\cdot\text{a}^{-1}$ in the 76th year, and the two curves crossed when the MAI of volume reached a maximum value of $0.0123 \text{ m}^3\cdot\text{a}^{-1}$ in the 128th year, which indicated that the biological rotation age of the average trees was 128 years. The biological rotation age is the age at which a tree or stand is harvested if the management objective is to maximize long-term yield [10]. The volume CAI of average trees reached a maximum value of $0.0091 \text{ m}^3\cdot\text{a}^{-1}$ in the 55th year, and the two curves crossed when the MAI reached a maximum value of $0.0053 \text{ m}^3\cdot\text{a}^{-1}$ in the 85th year, the biological rotation age of the average trees was therefore 85 years. The volume CAI of overtopped trees reached its maximum value of $0.0004 \text{ m}^3\cdot\text{a}^{-1}$ in the 17th year, the MAI reached its maximum value of $0.0003 \text{ m}^3\cdot\text{a}^{-1}$ in the 29th year, and the biological rotation age of overtopped trees was therefore 29 years.

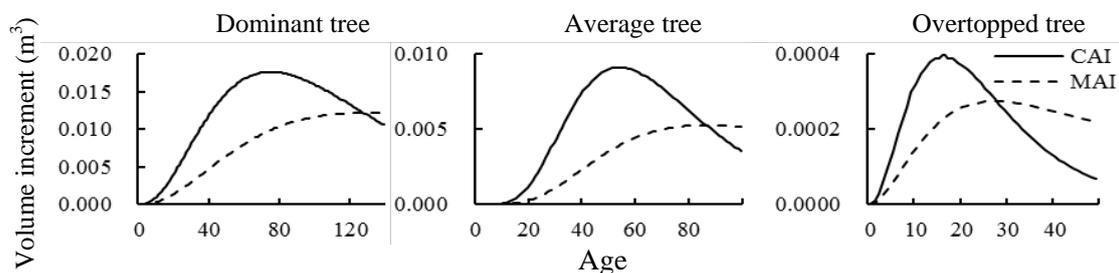


Figure 8. Volume CAI and MAI fitted curves of the three classes of *S. superba* using edited Weibull model

4. Discussion

The current study discussed the growth of three classes (overtopped, average and dominant) of *S. superba* in a natural forest based on stem analysis data. The results revealed that there were many fluctuations during the current annual growth process of the three tree classes. Previous studies show that the height CAI of *Fokienia hodginsii* (Dunn) has four peak values and the DBH CAI has two peak values [11]; multiple intersections have been found between the height or DBH CAI and MAI curves of *Quercus acutissima* [12]. These conclusions are corroborated by the current study on *S. superba*, indicating that the fluctuation phenomenon during the growth process is not species-typical, and may be due to climatic factors or human disturbance, such as tending and cutting. There have been many studies on the relationships between tree growth and climatic factors. For example, Zhang *et al.* found that the productivity of *Pinus massoniana* is significantly affected by relative humidity, moisture, air temperature, sunshine duration and so on [13].

The effectiveness of using *S. superba* as a biological fire prevention belt relate to the height under branch, the size of the crown, leaf water content and the volume of the trunk [14]. To understand the fire prevention features of *S. superba*, this study simulated its growth process using four growth models: Richards, edited Weibull, Logistic and Gompertz. The results showed that all four growth models could fit the height, DBH and volume increments of the three classes of *S. superba*. Wang *et al.* studied the growth process and models of *Quercus variabilis*; also, found that the Weibull, Logistic, and Gompertz models closely fit the DBH growth in natural forests [15]. The edited Weibull model produced the best fit in the current study, and these results suggest that it is a good predictor of tree growth too.

Tree growth varies due to the impact of genetics and environment (climate factors, site condition, competition, management and so on) [16]. Ma *et al.* found that growth differs among individual *Pinus elliotii* trees, but the overall growth trends are consistent [17]. In the current study, differences between the growth process of the three classes of *S. superba* were found; however, all the CAI and MAI curves of height and DBH intersected early (Figure 6, 7), indicating that *S. superba* is a fast-growing tree with a high growth rate during youth and that this rate decreases with time. Previous studies have shown that, for *S. superba*, maximum growth rate in height and DBH take place during the first 20 years [18]; similar results were found in the average and overtopped trees in the current study. Therefore, to produce good timber of large diameter, it is important to apply fertilizer and practice thinning during this fast-growing period.

5. Conclusions

In this study, growth in height, DBH and volume of dominant, average and overtopped trees of *S. superba* were investigated. Four growth models (Richards, edited Weibull, Logistic, and Gompertz) were selected to fit the growth process. The results revealed a fluctuation phenomenon during the current annual height and DBH growth processes for the three tree classes. All models could be used to fit the growth of the three classified trees of *S. superba*, with determinant coefficients above 0.9637. However, the edited Weibull model performed best with the highest R^2 and the lowest RMSE. *S. superba* is an early fast-growing tree with a higher growth rate during youth. CAIs in tree height and

DBH of overtopped, average and dominant trees reached growth peaks at ages of 5–10, 10–15 and 15–20 years [18], respectively. However, the CAIs of the volume of overtopped, average and dominant trees reached growth peaks at 17, 55 and 76 years, respectively. The mature ages of the overtopped, average and dominant trees of *S. superba* were 29, 85 and more than 100 years, respectively.

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