

Article

Estimation of Biomass Dynamics and Allocation in Chinese Fir Trees Using Tree Ring Analysis in Hunan Province, China

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Abstract: Studying tree biomass dynamics and allocation is crucial to understanding the forest carbon cycle and the adaptation of trees to the environment. However, traditional biomass surveys are time-consuming and labor-intensive, so few studies have specifically examined biomass formation in terms of the increase in individual tree biomass, and the role that tree age and site conditions play in this process, especially tree roots, is unclear. We studied the tree ring characteristics of 87 sample trees (8–40 years old) from 29 Chinese fir plantations with different site conditions and measured the biomass of their stems, crowns, and roots. The biomass increment at various age stages during tree growth was determined via using tree ring analysis, and a generalized additive mixed model (GAMM) was used to analyze biomass formation and allocation, as well as the specific impact of site conditions on them. The results showed that the biomass increment of Chinese fir trees first increased and then decreased with age, and improving site conditions delayed the carbon maturation of the trees. The proportion of stem biomass increased with age, while the proportion of crown biomass decreased and the proportion of root biomass increased and then decreased. The effect of the site conditions on the tree biomass allocation showed a nonlinear trend. Tree ring analysis provides a feasible and effective method for assessing tree growth and biomass dynamics. Forest managers can use the findings of this study to scientifically optimize the management of increasing forest carbon sequestration.

Keywords: tree ring analysis; biomass; allocation; tree age; site condition



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1. Introduction

Forests provide a variety of vital ecosystem services that contribute to maintaining the global climate system, mitigating global warming, and adjusting the global carbon balance [1–3]. One such service is carbon sequestration. Growing forests can capture atmospheric carbon dioxide through assimilation and release oxygen, and these processes can be utilized to mitigate climate change [4]. Forest carbon storage accounts for 82.5% of the total carbon storage of land vegetation, and this is an important indicator of a forest's carbon sequestration capacity [5]. However, global warming has caused an increase in the occurrence of natural disasters, redistribution of global precipitation, melting of glaciers and permafrost, sea level rise, and other hazards that pose a significant threat to human society [6]. To avoid extreme environmental harm, more than 70 countries have committed to reaching net-zero carbon emissions by 2050 or even earlier [7]. In terms of carbon sequestration, forests are pollution-free, low input, and sustainable. Hence, implementing

afforestation programs has become an important means for achieving ecological carbon sequestration enhancement, and the planting area of plantations is increasing globally [8,9].

Currently, a forest's carbon storage capacity is usually calculated by multiplying the forest's biomass by a carbon coefficient. Thus, it is critical to obtain an accurate understanding of a forest's biomass to determine its carbon sequestration capacity and evaluate the regional forest carbon balance [10,11]. The most common factors which affect forest biomass are stand age, community structure, growth environment, management measures, and natural disturbances [12–14]. Previous studies have shown that the factors that directly influence biomass in the short term are water, heat, and soil nutrient conditions, whereas in terms of long-term community structure succession, the determining factors are the biota, site conditions, and development time [15]. Due to different growth environments, trees adopt different survival strategies and different resource allocation and utilization patterns [16,17], which impact the biomass allocation of various organs. However, most current forest biomass research focuses on explaining the static research on the overall biomass of trees at a certain time node, while research on the specific formation process of biomass is rare. For example, in the relative growth relationship model, the relative relationship between biomass and external morphological indicators of trees is generally considered to be a constant, whereas in the stand volume model the ratio of biomass to volume is generally considered a constant [18]. Although destructive sampling can be used to accurately estimate biomass, it is difficult, expensive, and time-consuming, and it requires cutting down a large number of trees for detailed measurements. Predicting belowground biomass is also difficult [19]. Therefore, only a limited number of studies have focused on biomass allocation changes in different growth environments, especially in tree roots, and few studies have examined biomass allocation tradeoffs related to site conditions, particularly increases in the biomass of individual trees [20–26]. Without such knowledge, it is extremely challenging to accurately assess a forest's carbon storage capacity and to develop and implement management and regulation measures that will improve the carbon sequestration capacity of forests.

Tree ring analysis is a retrogressive growth measurement method, the great advantage of which is that a single field sampling program can produce annual growth data that can be traced back almost to the time the tree was established [27]. Tree rings can be considered long-term growth records, and are thus valuable tools for understanding past growth drivers and predicting future forest change [28]. Through the analysis of tree rings, tree growth tracks can be reconstructed, and information obtained about a tree's growth dynamics, such as the tree diameter at breast height and the tree height [29]. Tree ring analysis can be performed on trees growing in a wide range of conditions, including different stand or soil conditions, and over a substantial period of time. Hence, in combination with the use of the appropriate allometric equation, tree ring analysis has become an important tool for the rapid assessment of forest productivity at different stand ages and for understanding forest species growth, biomass allocation, and climate characteristics [30]. It has been widely applied to estimate the biomass accumulation and interannual increment of individual trees and their responses to climate factors [31–34].

Chinese fir (*Cunninghamia lanceolata* (Lamb.) Hook.) is the principal native tree species extensively planted for the economic purpose of timber production and for environmental purposes, such as carbon sequestration and soil erosion control, in subtropical areas of southern China [20]. According to the results of the Ninth National Forest Resources Continuous Inventory, Hunan Province is one of the main Chinese fir production areas, and its Chinese fir plantations account for 21.09% of the total area of Chinese fir plantations in China [35]. Therefore, clarifying the dynamics of the Chinese fir's biomass and its components will deepen our understanding of the carbon sequestration mechanism and potential of Chinese fir plantations, and provide empirical evidence and theoretical guidance for management measures to increase carbon storage. Here, a biomass equation has been constructed, and the dynamics of the Chinese fir biomass and its allocation have

been studied using tree ring analysis to provide a more feasible and effective method for researching Chinese fir biomass and carbon storage.

2. Materials and Methods

2.1. Study Area

The study was conducted in Chinese fir plantations in Hunan Province ($24^{\circ}38' \text{ N}$ – $30^{\circ}08' \text{ N}$, $108^{\circ}47' \text{ E}$ – $114^{\circ}15' \text{ E}$), China. Hunan Province is a key forest region in southern China, with a forest coverage rate of 49.69%, ranking ninth in the country. The Chinese fir forest area accounts for 26.14% of the arbor forest area. The zonal soil is mainly red-yellow soil and yellow soil, with scattered red soil, purple soil, and yellow-brown soil. The soil texture is mainly loam and clay, and the parent materials are mainly slate and shale. The climate is a subtropical humid monsoon climate. The annual average temperature is 16.0 – 18.5 °C, the daylight hours are 1300–1800 h, the annual precipitation is 1200–1800 mm, and the altitude of most areas is 100–800 m. Jindong Forest Farm, Paiyashan Forest Farm, Huangfengqiao Forest Farm, Shichangxi Forest Farm, and Xishan Forest Farm were selected as the sampling areas in this study (Figure 1).

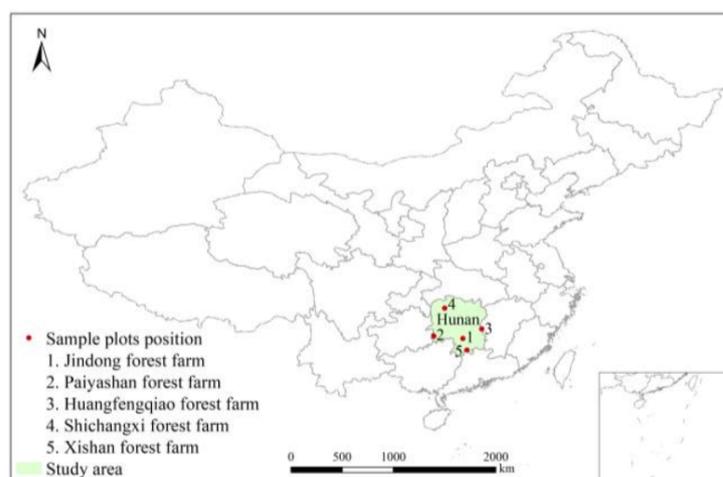


Figure 1. Distribution of the study area and the forest farms selected for sampling.

2.2. Forest Inventory and Sample Collection

The study was conducted in August 2021. We established 29 temporary sample plots ($20 \text{ m} \times 20 \text{ m}$) in Chinese fir plantations. All trees in each sample plot with a diameter at breast height greater than 5 cm were numbered. The total height and diameter at breast height were measured, and the main stand characteristics of the sample plots were recorded (Table 1). The site index was represented by stand dominant height at a given base age [36]. In each sample plot, three average trees selected as sample trees according to the average diameter at breast height, average total tree height, and average stem form were felled from the ground level, and all the roots were dug out. Before felling the sample trees, the north direction was marked on the stem. Then, for trees with tree heights greater than 10 m, the discs were cut at 0, 1.3, 3.6, 5.6 m, and so on, until the treetop was reached. For trees with heights of less than 10 m, the discs were cut at 0, 0.5, 1.3, 1.5, 2.5 m, and so on, until the treetop was reached. The discs were approximately 5 cm thick, and the north direction was marked on each disc. The obtained discs were used for tree ring analysis. In addition, the stem was divided into upper, middle, and lower sections of equal length, and a disc was cut from the middle of each section. The stem (upper, middle, and lower sections), bark, leaves, branches, and roots of each sample tree were weighed, and samples were collected for biomass estimation. A total of 87 Chinese fir trees from 29 sample plots aged 8–40 years were included in this analysis, including 9 young-stage trees, 21 middle-stage trees, 21 near-mature trees, 24 mature trees, and 12 over-mature trees.

Table 1. The main stand characteristics of the temporary Chinese fir plantation sample plots.

Sampling Forest Farm	Plot No.	Stand Age	Age Group	Site Index	Mean Diameter at Breast Height (cm)	Average Total Tree Height (m)	Stand Density (Trees ha ⁻¹)
Jindong	JD-1	17	II	14	12.1	10.8	2550
	JD-2	31	IV	12	14.9	12.2	1675
	JD-3	25	III	16	19	15	1200
	JD-4	40	V	14	19.9	16.5	950
	JD-5	27	IV	18	20.4	17.4	1175
	JD-6	8	I	14	8.3	6.4	3250
Paiyashan	PYS-1	18	II	20	18.4	17.2	1875
	PYS-2	39	V	20	25.2	23	975
	PYS-3	28	IV	14	15.8	12.9	1475
	PYS-4	21	III	12	11.9	9.9	2025
	PYS-5	36	V	16	24	19	1150
	PYS-6	29	IV	20	27.7	20.4	800
	PYS-7	24	III	12	17	11.8	1350
Huangfengqiao	HFQ-1	33	IV	16	22.3	18.7	900
	HFQ-2	24	III	18	22.5	17.9	1325
	HFQ-3	18	II	16	16.2	12.5	2125
	HFQ-4	14	II	14	11.4	9	2650
	HFQ-5	24	III	18	22.2	16	1200
Shichangxi	SCX-1	13	II	16	14.8	10.3	2700
	SCX-2	31	IV	18	27.2	17.9	1075
	SCX-3	27	IV	18	25	16.7	925
	SCX-4	8	I	12	7.9	6.1	3350
	SCX-5	17	II	16	17.2	11.8	2175
	SCX-6	23	III	16	19.8	13.3	1325
Xishan	XS-1	9	I	12	8.5	6.4	2850
	XS-2	39	V	14	22	14.7	825
	XS-3	13	II	12	11	8	2750
	XS-4	31	IV	14	21.8	14.6	950
	XS-5	21	III	18	22	14.7	1150

I represents young stage (≤ 10 years); II, middle stage (11–20 years); III, near mature (21–25 years); IV, mature (26–35 years); V, over mature (≥ 36 years).

2.3. Biomass Estimation and Tree Ring Analysis

The discs to be used in the tree ring analysis were polished, and two diameter lines were drawn on each through the pith: one from east to west and one from north to south (Figure 2). The rings on each disc were then counted, and according to an age gradation of every three or five years, the diameter of each age gradation on the east–west and north–south diameter lines of each disc was measured with a ruler, and the average diameter of the same age gradation in two directions was recorded as the diameter of the age gradation. The number of years required for a tree to grow to the height of the section was calculated as the difference between the age of the tree and the number of annual rings on each disc. The tree height at each age gradation was calculated via an interpolation method using the height of the section and the number of years required to grow to the height of the section [37]. The stem, bark, branch, leaf, and root samples collected in the field were transferred to the laboratory within three days of collection. After the deactivation of enzymes in an oven at 105 °C, the samples were dried to constant weight in an incubator at 85 °C, and the dry weight was measured. The following formula was used to calculate the biomass of each whole tree and each organ:

$$W_i = (M_{sf} - M_{sd}) / M_{sf} \quad (1)$$

$$B_i = M_{tf} \times (1 - W_i) \quad (2)$$

where W_i is the moisture content of each organ sample, M_{sf} is the fresh weight of each organ sample, M_{sd} is the dry weight of each organ sample, M_{tf} is the total fresh weight of each organ sample, and B_i is the biomass of each organ sample.



Figure 2. A representative polished disc showing the east–west and north–south diameter lines.

Stem biomass is equal to wood biomass plus bark biomass, crown biomass is equal to branch biomass plus leaf biomass, root biomass only includes the root biomass, and total biomass is equal to stem biomass plus crown biomass plus root biomass. The basic information of the sample trees is presented in Table 2.

Table 2. Basic information of the sample trees.

Age Group	Num.	Site Index Range	Mean Diameter at Breast Height	Mean Height	Total Biomass	Stem Biomass	Crown Biomass	Root Biomass
I	9	12–14	8.1	6.1	11.88	6.37	3.75	1.77
II	21	12–20	14.4	11.6	55.45	35.06	9.68	10.71
III	21	12–18	19.2	14.2	107.27	69.68	15.61	21.97
IV	24	12–20	21.9	16.8	180.9	120.99	23.04	36.87
V	12	14–20	22.7	17.6	171.29	120.48	16.35	34.46

I represents young stage (≤ 10 years); II, middle stage (11–20 years); III, near mature (21–25 years); IV, mature (26–35 years); V, over mature (≥ 36 years).

2.4. Correction of Diameter at Breast Height of Each Age Gradation

The diameter at breast height calculated using the cumulative tree ring data was not equal to that measured in the field using a diameter tape, and the diameter at breast height of other age gradations measured by tree ring analysis did not include bark thickness. Thus, Formula (3) from Zhang et al. [38] and Wang et al. [39] was applied to eliminate the error by calibrating tree ring width at different age gradations:

$$\theta_k = (D_{mk} - D_{tk}) / N_k \quad (3)$$

where θ_k is the corrected value (cm) for each tree ring width of the k th tree, D_{mk} is the diameter of the k th tree measured at breast height using a diameter tape (cm), D_{tk} is the diameter at breast height (with bark thickness) calculated from the cumulative tree diameter (m) of the k th tree, and N_k is the tree age (year) of the k th tree.

Formula (4) from Tang et al. [40] was applied to estimate bark thickness at each age gradation:

$$BR_k = D_{bk}/D_{mk} \quad (4)$$

where BR_k is the bark ratio of the k th tree, and D_{bk} is the bark thickness of the k th tree.

Assuming that the θ_k and BR_k of each sample tree are constant, then the corrected diameter at breast height value can be obtained according to Formulas (3) and (4):

$$D_{cik} = (D_{nik} + N_{ik} \times \theta_k)/(1 - BR_k) \quad (5)$$

where D_{cik} is the corrected diameter at breast height value of the i th age gradation of the k th tree, and D_{nik} is the diameter at breast height (without bark thickness) calculated from the cumulative tree diameter (m) of the i th age gradation of the k th tree.

2.5. Construction of the Biomass Model

Using the methods described above, biomass data were obtained for each component of the sample trees, and the diameter at breast height and tree height at each age gradation were determined. Next, we needed a model to estimate the biomass of each component at each age gradation. For this, a biomass model of tree height (h) and diameter at breast height (dbh) was constructed based on the allometric growth equation. The basic model form is as follows:

$$B = a \times dbh^b \times h^c \quad (6)$$

where a , b , and c are the fitted coefficients.

Considering that the prediction of the model should be additive (compatible), that is, the sum of the biomass of the stem, crown, and root should equal the total biomass, an aggregation method was introduced to build an additive biomass model. The resultant model form is as follows:

$$B_s = a_1 \times dbh^{b_1} \times h^{c_1} \quad (7)$$

$$B_c = a_2 \times dbh^{b_2} \times h^{c_2} \quad (8)$$

$$B_r = a_3 \times dbh^{b_3} \times h^{c_3} \quad (9)$$

$$B_t = B_s + B_c + B_r \quad (10)$$

where B_s , B_c , B_r , and B_t is the biomass of the stem, crown, root, and total tree, respectively. The estimated values of each parameter are shown in Table 3.

Table 3. The estimated values of each parameter in the biomass model.

	a	b	c	R^2
B_s	0.02730	2.21501	0.48488	0.9522
B_c	0.02181	2.54169	−0.38784	0.7601
B_r	0.00911	2.24540	0.41587	0.9545
B_t	-	-	-	0.9484

2.6. Statistical Analysis

Two-way analysis of variance (ANOVA) and Tukey's multiple comparisons were used to separate the significant differences ($p < 0.05$) among tree age and site index if the homogeneity of variance and normal distribution tests were passed. If not, the data were treated with inverse sine transformation, logarithmic transformation, etc.

The generalized additive mixed model (GAMM) in the "mgcv" package of the R 4.2.1 software was used to analyze the effects of age and site condition on the biomass of the individual trees and each biomass component, annual increment, and allocation [41]. GAMM is a semi-parametric model with linear predictors that involves the sum of smooth

functions of covariates, which allows flexible functional dependence of outcome variables on covariates through nonparametric regression, and uses random effects to explain the correlation between observations [42,43]. The model is expressed as follows:

$$E_{ijk} = K_0 + S_i(\text{Age}_{ijk}) + S_i(\text{Site index}_{ijk}) + R_{ijk} + \varepsilon_{ijk} \quad (11)$$

where E_{ijk} is the dependent variable (total and each component biomass, annual biomass increment, proportion of each component biomass), K_0 is the overall intercept, $S_i(\text{Age}_{ijk})$ is a smooth function of tree age, $S_i(\text{Site index}_{ijk})$ is a smooth function of site index, R_{ijk} is a random effect assumed to be distributed as $N(0, \sigma^2)$ with a variance component σ^2 , and ε_{ijk} is an error vector.

3. Results

3.1. Growth and Change in Total Biomass

The results of the variance analysis showed that age, site index, and their interaction all had a significant effect on the total biomass and its annual increment of each individual tree ($p < 0.001$). The total biomass of the individual trees increased with age and site index, while the annual biomass increment first increased and then decreased with tree age. Improvement in the site conditions was found to significantly enhance biomass accumulation (Figure 3). Under different site conditions, differences were observed in both the total biomass and its annual increment. When the site conditions were poor, the biomass increased at a low rate after the age of 20 years. On the contrary, when the site conditions were good, the annual biomass increment rapidly declined after reaching the maximum. However, the annual increment was still positive at the age of 40 years, and higher than that recorded when the site conditions were poor.

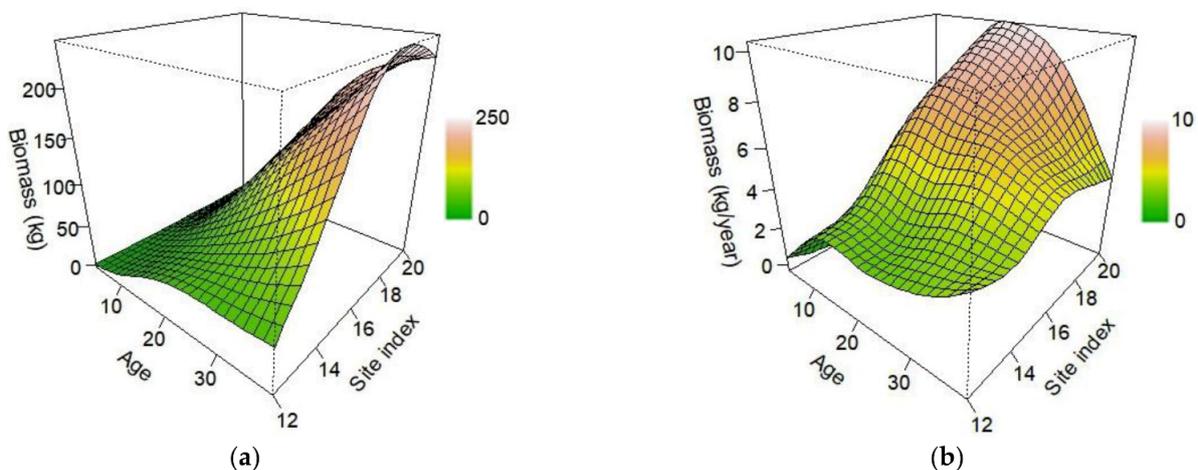


Figure 3. Tree-level biomass dynamics: (a) total biomass, and (b) annual biomass increment.

3.2. Growth and Change in the Biomass of the Tree Components

The results of the variance analysis showed that age, site index, and their interaction had a significant effect on the biomass of tree components as well as on the annual biomass increment of each component ($p < 0.001$). Significant and strong nonlinearity was observed between the biomass/annual biomass increment of each component and age/site index (Figure 4). The influence of age and site condition on the biomass and annual biomass increment of each component was found to follow the order of stem > root > branch. As age increased, the biomass of each component increased, while the annual biomass increment of each component first increased and then decreased. The annual biomass increments of the stem and root began to decline after 15 years, and that of the crown after 10 years (Figure 4a,c). The site index was found to have the same effect on the biomass and its

increment of each component (Figure 4b,d). When the site index rose from 14 to 20, an improvement in the site conditions was found to significantly enhance the biomass and its increment; however, when the site index increased from 12 to 14, the positive effect was not so obvious.

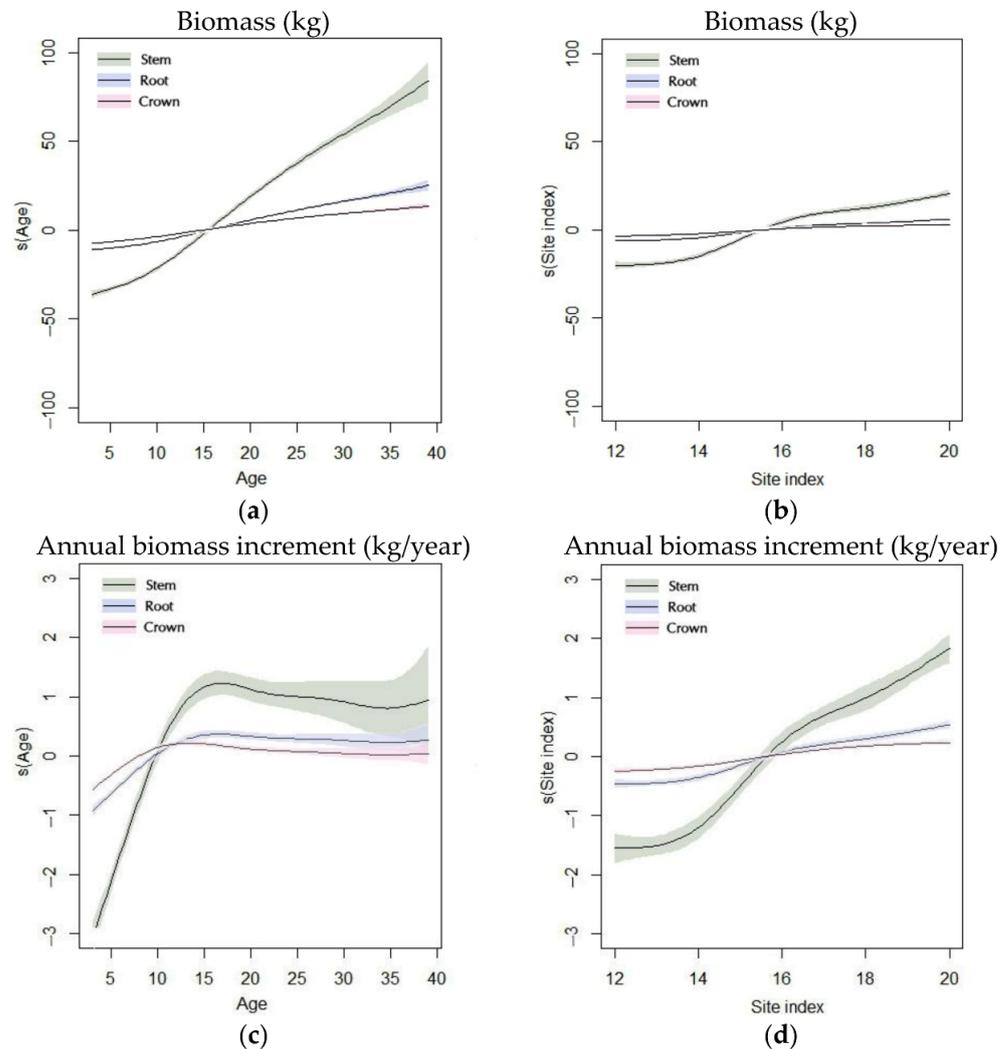


Figure 4. Estimated degrees of freedom with smooth spline functions on observed organ biomass ((a) Age and (b) Site index) and their annual increments ((c) Age and (d) Site index). The different color shades indicate the 95% confidence intervals.

3.3. Biomass Allocation within the Tree Components

As shown in Figure 5, the stem made up the largest proportion of the total biomass (49–70%), and the proportion increased with age. The root made up about 16–20% of the total biomass, and this proportion kept an obvious increasing trend only at a young age. The proportion of the crown decreased from 35% at age 8 years to 9% at age 40 years. After nine years, the root biomass made up a greater proportion of the total biomass than that of the crown, which was second only to that of the stem. The GAMM results generated by fitting the age, site condition, and biomass proportion data showed that the proportions of the stem, root, and crown biomasses increased or decreased relatively quickly before the tree reached 10 years of age (Figure 6). Tree age and site index positively contributed to the proportion of root biomass before the trees matured. After the trees matured, the proportion of root biomass decreased with age, and site index still positively contributed to it. The effect of site index on biomass allocation was nonlinear. When the site index

rose from 14 to 16 or from 18 to 20, it significantly impacted the increase or decrease in the proportion of the stem, root, and crown biomass.

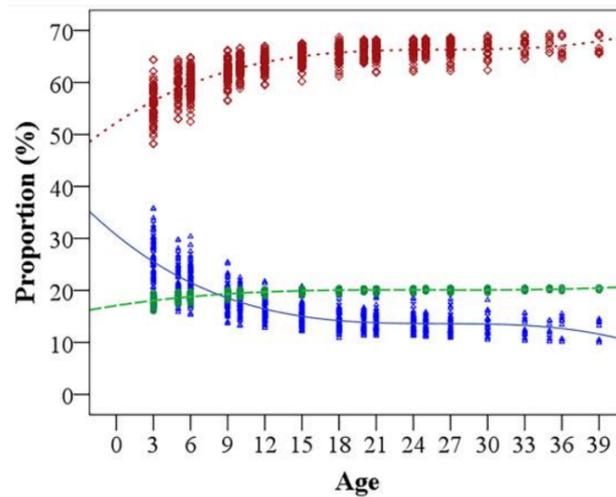


Figure 5. Tree-level dynamics of the biomass proportion of each component. The red squares and short dotted line represent the stem and its fitted line, the green triangles and long dotted line represent the root and its fitted line, and the blue circles and line represent the crown and its fitted line.

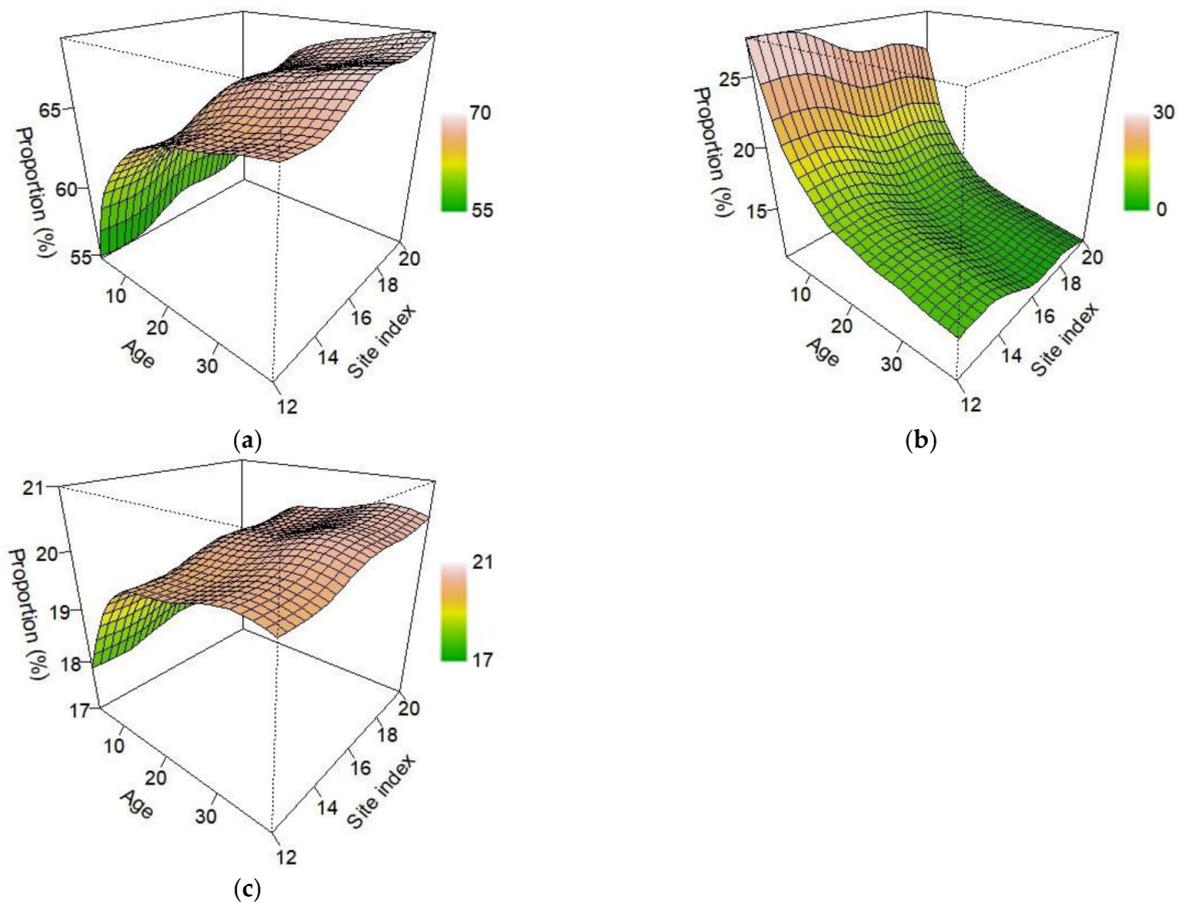


Figure 6. Observed biomass proportion of each component with age and site index interactions: (a) proportion of stem biomass, (b) proportion of crown biomass, and (c) proportion of root biomass.

4. Discussion

4.1. Dynamics of Total Biomass and Its Increment

It is widely recognized that the biomass of a single tree increases with tree age and good site conditions and that the tree biomass increment may reach its maximum at the early stage of succession due to tree recruitment and size increase. When a certain age is reached, biomass increases at a low rate for a period and then decreases. Similarly, the annual increment shows a trend of first increasing and then decreasing [40]. Others have shown that the increase in above-ground biomass of trees in plots with better site conditions is significantly higher than that of trees in plots with poorer site conditions [44,45]. This pattern was also observed in our study, in which the continuous age variable and site index variable were used. However, there were some differences due to the additive or interactive effects of age and the site conditions on tree growth and biomass accumulation. Such effects have been recognized by others, but have not been well explained [22]. If nutrient requirements are not met during rapid tree growth, tree biomass will be negatively affected [46]. Our findings show that the total biomass may stop increasing or increase only slightly after 20 years in plots with poor site conditions. In contrast, the total biomass still has growth potential after 40 years in plots with better site conditions. This indicates that site conditions affect the time at which maximum total biomass is reached; that is, improving site conditions delays the age at which the tree reaches carbon sequestration maturation. This is similar to the consensus that trees growing at sites with good site conditions have a longer natural maturation period than trees subjected to poor site conditions [47]. Nowadays, timber production is no longer the main aim of forest management. Instead, the focus is on modern forestry development with ecological considerations, such as increased carbon sequestration and the maintenance of biodiversity [48,49]. Our findings show that when considering only carbon sequestration gains, management measures should be taken to promote stand growth after 20 years in plots with poor site conditions. It is also clear from our findings that in plots with good site conditions where trees have a long natural maturity age, the carbon storage capacity of the whole ecosystem can be increased by implementing measures such as interplanting broadleaved species to improve carbon sequestration [50,51]. Unfortunately, the maximum age of the sample trees in our study was 40 years; thus, no conclusions can be drawn or recommendations made based on our results about the growth of trees after 40 years. Older sample trees should be included in future studies to improve our understanding of the full tree growth cycle.

4.2. Biomass Dynamics and Increment Tree Components

By dividing trees into stems, crowns, and roots, we analyzed the tree-level biomass dynamics of Chinese fir plantations, which contained trees of different ages and in different plots, thus providing a higher resolution of biomass dynamics [40]. Other studies usually consider only age variables and tend to ignore root biomass and the effect of site conditions on biomass dynamics [52,53]. A recent study conducted by Tang et al. in Chinese fir forests used a method similar to that used in this study [40]. However, that study focused on Chinese fir trees of the same age, growing at the same site condition, and with different dominant grades. In addition, root biomass was not taken into account, and the trees were not separated into components for analysis. In our study, the dynamic changes in the biomass and the increment of each component caused by age and site conditions were found to be very similar to those observed in the total biomass. On the whole, increases in site index positively contributed to increases in biomass; however, the relationship was not linear. In contrast to the site conditions, which were found to contribute to the continuous increase in total biomass, the effect of the site index rising from 12 to 14 on the biomass and its increment was not as obvious as when the site index rose from 14 to 20. These findings indicate that when the site index rose from 12 to 14, the site index may not have been the main contributing factor to biomass change and that biomass dynamics may be influenced by other factors.

4.3. Dynamic of Proportion of Tree Components Biomass

Since carbon allocation is an important factor in predicting forest growth, it is critical to study biomass allocation patterns [54]. Our findings showed that tree age and site condition significantly influenced the allocation of a tree's biomass. The aboveground allocation pattern observed in this study, in which the proportion of biomass found in the stem increased and that found in the crown decreased with tree age, is consistent with that reported in previous studies [20,55,56]. However, some investigators found that the proportion of root biomass decreases with stand age [38], and others have reported that the proportion of root biomass increased slightly but remained relatively stable after the tree matured [57,58]. However, our study found that the proportion of root biomass increased with age and then gradually decreased after the trees matured, which is consistent with the results of our other study [59]. The reason for the increase in the proportion of root biomass with age may be that the part below the ground from the cutting place was treated as roots in our study, which resulted in roots usually containing part of the stem. One of the most recognized concepts used to explain this allocation pattern is "optimal allocation theory", in which plants preferentially allocate biomass to the organ that can maximize the use of the most limited resource [60]. According to this theory, more organic matter will be allocated to organs with storage and reproductive functions than to organs with growth functions [61,62]. Our findings support this theory: we observed a rapid accumulation of root biomass before the age of 10 years, and the allocation of biomass changed from stem > crown > root to stem > root > crown. This was mainly due to the rapid expansion of leaves and branches in the early growth period of the trees, the transportation of large quantities of organic substances produced by photosynthesis to other organs for growth in the crown, and the rapid increase in diameter at breast height and the total height of the trees. The proportion of root biomass gradually increases, as part of a general strategy to help trees become fixed in the soil to resist lodging and improve the nutrient absorption capacity to support sustainable growth [23].

Site conditions comprise the terrain, landform, climate, soil, and other environmental factors at the tree location, and they are closely related to the growth and development of trees [63]. In our study, biomass accumulation varied with tree age and site quality. The stem, crown, and root components represented 49–70%, 9–35%, and 16–20% of the total biomass, respectively, depending on tree age and site condition. The stem was found to be the main contributor to the total biomass throughout the tree life cycle. The proportion of crown biomass was higher than that of the root before the age of 10 years, but thereafter the root biomass was the second largest contributor to the total biomass [64,65]. Most studies have shown that tree biomass allocation is significantly different among trees at high-quality sites and low-quality sites [66]. Our results showed that the effects of tree age and site conditions on tree biomass allocation were nonlinear. When the site index rose from 12 to 14 or from 16 to 18, the site conditions may not have been the main factor affecting biomass allocation, and other environmental or non-environmental factors should be considered when attempting to improve biomass allocation. Similar conclusions were obtained using measured biomass data from sample trees [59], implying that tree ring analysis can be used to simulate growth trends in tree biomass.

5. Conclusions

Improving the understanding of tree growth processes is important for developing a comprehensive knowledge of carbon storage formation processes. We retrospectively studied the total and incremental biomass dynamics and allocation of whole trees and their components (i.e., the stem, crown, and root) using tree ring analysis. It is effective and feasible to analyze the dynamics and allocation patterns of forest biomass using tree ring analysis. Compared to traditional destructive sampling that can only obtain biomass at a given age, tree ring analysis can obtain biomass growth and changes at various ages during tree growth, which is conducive to a better understanding of the formation and change processes of forest biomass and carbon stocks. The results showed that the annual

biomass increment of Chinese fir trees tended to first increase and then decrease with age and that the biomass of the tree and each component increased nonlinearly with age. However, improving the site conditions delayed the age at which the tree reached carbon sequestration maturation. The effect of the site conditions on the tree biomass allocation was also nonlinear. These findings can be used by forest managers to help them fully understand the specific processes of biomass formation and provide guidelines for optimizing management measures to increase forest carbon storage.

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