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CASE REPORT

Analysis of biomass compatibility model of Chinese fir in Jiangle, Fujian Province

Mingjing Wu*

Jiangle National Forest Farm, Jiangle 353300, Fujian Province, China. E-mail: wmj0598@163.com

ABSTRACT

Aiming at the problem of incompatibility of biomass models of forest organs, taking Chinese fir in Fujian Jiangle State-owned Forest Farm as the research object, based on selecting the optimal independent model of each organ, the biomass compatibility model of Chinese fir was established with a three-level joint control scheme. The results show that the compatibility equation system based on the whole plant biomass can effectively solve the problem of incompatibility in the whole plant biomass, each sub-biomass and between sub-biomass. Besides, except for the leaf biomass model, all other biomass models have good fitting effect, which is of great significance to the guidance of the analysis of local Chinese fir biomass.

Keywords: Chinese Fir; Biomass; Compatibility Model

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1. Introduction

Forest biomass is one of the most basic quantitative characteristics of forest ecosystem[1]. Measuring forest biomass is time-consuming and laborious, and establishing biomass model to reduce field work is currently recognized by people[2]. However, in terms of research methods, researchers at home and abroad generally select the model according to each organ (stem, branch, leaf and root) of forest tree respectively and fitting the parameters in their respective equations, that is, the estimation of each organ is carried out independently[3], which leads to the incompatibility between the fitted models. In order to solve the problem of incompatibility between models, Luo *et al.*[4] proposed to use linear simultaneous model and nonlinear joint estimation model to solve the problem of incompatibility between the total and the components. Tang *et al.*[3] used the nonlinear joint estimation scheme to fit the model, and compared the results with the proportional adjustment method, and considered that the two-level algebra and fitting distribution scheme was the best scheme; Dong *et al.*[5] established a compatibility model based on total biomass by using the ratio function hierarchical joint control equations to fit the biomass compatibility model of main tree species in Heilongjiang Province, and the model accuracy was high. In this paper, the Chinese fir in Jiangle State-owned Forest Farm in Fujian Province was taken as the research object, and the biomass compatibility model was established by using the three-level joint control scheme.

2. Overview of study area

The analysis data of this study were collected from Fujian Jiangle

State-owned Forest Farm, which is located in the southeast of Wuyi Mountain Range. It is a subtropical seasonal climate zone with marine and continental climate characteristics, with an average annual temperature of 18.7 ℃, an average annual precipitation of 1,676 mm, an average annual evaporation of 1,204 mm and an annual frost-free period of 298 d, and a warm and humid climate. The landform is mainly low hills, with an altitude of 140–1,403 m, and the forest coverage rate of the forest farm is 93.5%. The main conifer species for afforestation are *Cunninghamia lanceolata* (Lamb.) Hook., *Pinus massoniana* Lamb., *Pinus elliottii* Engelmann, etc.

3. Materials and methods

3.1 Standard wood selection and biomass determination

In this study, there are 14 standard Chinese fir trees in different age groups, including 3 young forests, 2 middle-aged forests, 3 near-mature forests, 3 mature forests and 3 over-mature forests. See **Table 1** for information of the standard land. On the basis of each wood gauge, two trees with no broken tip, no bifurcation, normal growth and typical crown width and length are selected as standard trees. The biomass is measured in the aboveground part and underground part respectively. The aboveground part is divided into the biomass of trunk and crown (branches and leaves), and the underground part refers to the biomass of roots. Dong *et al.*[6] provided the determination methods of biomass of each component (organ).

Table 1. Standard information table

Age group	Area/(m × m)	Average breast diameter/cm	Average tree height/m	Density/(a tree/hm^{-2})
Young and semi-mature forest	20 × 30	8.9	6.5	4,400
	20 × 30	10.3	7.3	4,000
	20 × 30	11.5	9.5	4,000
Middle-aged forest	20 × 30	11.4	9.8	3,667
	20 × 30	12.5	10.2	3,667
Near-mature forest	20 × 30	12.8	10.5	3,500
	20 × 30	13.2	10.8	3,500
	20 × 30	15.0	12.0	3,070
Mature forest	20 × 30	17.2	13.2	2,500
	20 × 30	18.2	13.7	2,500
	20 × 30	21.2	16.8	1,767
Overmature forest	30 × 30	22.0	18.3	1,250
	30 × 30	23.6	18.9	850
	30 × 30	26.0	18.8	800

3.2 biomass independent model fitting

The biomass of the whole plant and each component (organ) is fitted by using the unitary and binary models of biomass, which are: $W = aD^b$ (formula 1), $W = aD^bH^c$ (formula 2), where: W is biomass; D is the standard DBH of wood; H is the standard tree height; a, b and c are the parameters of the equation[7].

3.3 Biomass model test

The commonly used Bias, root mean square error (RMSE) and adjusted determination coefficient ($adj - R^2$) are used to test the accuracy of the above model.

$$Bias = \frac{\sum_{i=1}^{n}\left(\hat{y}_i - y_i\right)}{n},\ RMSE = \sqrt{\frac{\sum_{i=1}^{n}\left(\hat{y}_i - y_i\right)^2}{n-r}},$$

$$adj - R^2 = 1 - \frac{(n-1)\sum_{i=1}^{n}\left(\hat{y}_i - y_i\right)^2}{(n-r)\sum_{i=1}^{n}\left(\bar{y}_i - y_i\right)^2}$$

Where: y_i, $\hat{y}_i$ and $\bar{y}_i$ are the measured value, predicted value and average value of biomass respectively; n is the number of samples; r is the number of parameters.

3.4 Biomass compatibility model fitting

A three-level joint control scheme is adopted to establish the biomass compatibility model: the first-level control variable is the whole plant biomass, and the independent optimal model of the whole plant biomass is regressed, and the sum of the aboveground biomass and the root biomass is equal to the whole plant biomass through proportional distribution of the first-level control; the second-level control variable is the aboveground biomass, and the aboveground biomass is equal to the sum of trunk biomass and crown biomass through the proportional distribution of the second-level control. Level 3 control variable is canopy biomass, which makes canopy biomass equal to the sum of branch biomass and leaf biomass.

Level 1 control: $\tilde{w}_2 = \frac{f_2(x)}{f_2(x)+f_3(x)} \times \hat{w}_1$ (formula 3), $\tilde{w}_3 = \frac{f_3(x)}{f_2(x)+f_3(x)} \times \hat{w}_1$ (formula 4); Level 2 control: $\tilde{w}_4 = \frac{f_4(x)}{f_4(x)+f_7(x)} \times \tilde{w}_2$ (formula 5), $\tilde{w}_7 = \frac{f_7(x)}{f_4(x)+f_7(x)} \times \tilde{w}_2$ (formula 6); Level 3 control: $\tilde{w}_5 = \frac{f_5(x)}{f_5(x)+f_6(x)} \times \tilde{w}_7$ (formula 7), $\tilde{w}_6 = \frac{f_6(x)}{f_5(x)+f_6(x)} \times \tilde{w}_7$ (formula 8); where, $f_2(x)$, $f_3(x)$, $f_4(x)$, $f_5(x)$, $f_6(x)$ and $f_7(x)$ are the optimal biomass models of above-ground part, root, trunk, branches, leaves and crown respectively; $\hat{w}_1$ is the fitting value of total biomass; $\tilde{w}_i$ is the fitting value of compatibility model; i is 2–7, representing biomass of aboveground parts, roots, trunks, branches, leaves and crowns respectively[5].

4. Results and analysis

4.1 The optimal model of biomass of each organ

According to the measured biomass data of 28 Chinese fir standard trees, the biomass of each organ of Chinese fir was fitted with univariate and binary biomass models, and the optimal independent model of each organ was selected through the model inspection indexes, which are shown in **Table 2**.

Table 2. Evaluation indexes of unitary and binary models of various organs

Organ	Unitary model			Binary model		
	E	*RMSE*	R^2	*E*	*RMSE*	R^2
Whole plant	-1.0103	16.5508	0.9494	-0.0601	15.7621	0.9541
Aboveground	-0.7637	16.4009	0.9328	0.0155	15.9069	0.9368
Trunk	-1.3152	15.0502	0.9351	-0.2553	14.0613	0.9434
Root	-0.2336	6.5855	0.7192	-0.0650	6.4965	0.7267
Crown	0.0944	5.2154	0.3212	0.0217	5.0820	0.3555
Branch	0.0586	3.3507	0.4341	0.0271	3.3421	0.4370
Leaf	0.0105	2.2756	0.542	0.0015	2.1389	0.1645

As can be seen from **Table 2**, the error and root mean square error of binary model of each organ are smaller than that of unitary model, and the determination coefficient is higher than that of unitary model, so the binary model with DBH (*D*) and tree height (*H*) as independent variables is selected as the optimal model of biomass of each organ.

The biomass of each organ was fitted with the selected optimal independent model, and the differences (Δ_1) between the fitted values of the whole plant biomass and the sum of the fitted values of the biomass of trunk, branches, leaves and roots were calculated respectively: $\Delta_1 = total - (\text{trunk} + \text{branches} + \text{roots} + \text{leaves})$, $\Delta_1(\%) = \Delta_1/total \times 100$ (%); Difference (Δ_2) between aboveground biomass fitting value and sum of trunk biomass fitting value and canopy biomass fitting value: $\Delta_2 = \text{aboveground part} - (\text{trunk} + \text{crown})$, $\Delta_2(\%) = \Delta_2/\text{aboveground part} \times 100$; Difference ($\Delta_3$) between fitting value of canopy biomass and sum of fitting value of branch biomass and leaf biomass: $\Delta_3 = crown - (\text{branches} + \text{leaves})$, $\Delta_3(\%) = \Delta_3/\text{crown} \times 100(\%)$. The results are shown in **Table 3**.

Table 3. Incompatibility analysis of biomass of various organs

D	H	Δ_1/kg	$\Delta_1/\%$	Δ_2/kg	$\Delta_2/\%$	Δ_3/kg	$\Delta_3/\%$
8.0	6.6	-1.1618	-10.9457	-1.1690	-13.2817	-0.0780	-2.1812
10.1	6.9	-1.5735	-8.7681	-1.6018	-10.6507	-0.0320	-0.5559
10.3	7.6	-1.1565	-5.9031	-1.1816	-7.2098	0.0146	0.2655
10.7	7.8	-1.1109	-5.1585	-1.1393	-6.3166	0.0367	0.6294
11.1	9.4	-0.4441	-1.7455	-0.4626	-2.1778	0.0645	1.2145
11.3	10.2	-0.2298	-0.8364	-0.2421	-1.0570	0.0575	1.1242
11.4	9.4	-0.4476	-1.6605	-0.4702	-2.0867	0.0793	1.4066
11.4	11.2	-0.0571	-0.1951	-0.0585	-0.2402	0.0313	0.6549
11.7	8.2	-1.0176	-3.8046	-1.0553	-4.6959	0.0946	1.3918
12.8	10.4	-0.1003	-0.2761	-0.1319	-0.4331	0.1335	2.0129
12.9	12.8	0.2180	0.5356	0.2156	0.6351	0.0284	0.5113
13.1	8.0	-1.3592	-4.0255	-1.4145	-4.9545	0.1741	1.9452
13.4	10.2	-0.1177	-0.2961	-0.1598	-0.4782	0.1815	2.4251
13.6	10.5	-0.0063	-0.0152	-0.0482	-0.1377	0.1837	2.4413
14.7	13.6	0.5119	0.9214	0.4921	1.0572	0.0720	1.0278
15.8	15.0	0.5923	0.8712	0.5760	1.0101	0.0289	0.3856
16.9	15.8	0.6741	0.8364	0.6530	0.9642	0.0210	0.2525
18.0	19.4	-0.5098	-0.5013	-0.4830	-0.5667	-0.2482	-3.1545
18.5	17.0	0.6741	0.6646	0.6488	0.7592	-0.0061	-0.0648
19.1	16.5	1.0236	0.9551	0.9829	1.0860	0.0845	0.8069
20.7	19.9	-0.4553	-0.3269	-0.4582	-0.3901	-0.2163	-2.0618
21.8	21.3	-1.4207	-0.8835	-1.4087	-1.0378	-0.3397	-3.0767
22.0	20.1	-0.4015	-0.2515	-1.4135	-0.3062	-0.1862	-1.5642
22.4	19.3	0.3086	0.1895	0.2813	0.2038	-0.0581	-0.4515
23.2	20.5	-0.5477	-0.3031	-0.5597	-0.3653	-0.1823	-1.3859
24.1	20.0	0.0955	0.0492	0.0754	0.0458	-0.0554	-0.3779
26.5	19.8	0.9401	0.3965	0.9397	0.4640	0.1690	0.9248
27.7	20.3	0.6942	0.2630	0.7211	0.3193	0.1778	0.9025

From **Table 3**, it can be seen that there are different degrees of errors between the sum of the total amount of the whole plant, aboveground biomass, crown biomass and their corresponding components, which is consistent with the research results of Tang *et al.*[3] and Dong *et al.*[5], which is mainly because the model fitting of each organ is carried out independently, leading to the incompatibility between the biomass models of each organ.

4.2 Biomass compatibility model of various organs

Based on the obtained independent optimal model of biomass of each organ, the biomass compatibility model was established by using the three-level joint control scheme. The simultaneous equations based on the total biomass are used for joint estimation step by step, and the specific steps are as follows.

Level 1 control: Firstly, independent model regression is performed on formula 2 to obtain the total biomass model parameters and estimated values $(\hat{w}_1)$, and $\hat{w}_1$ is directly substituted into the formula 3 and formula 4, at the same time, substitute the optimal model of aboveground biomass and root biomass to simplify the equation, which can form the following equations: $\widetilde{w}_2 = \frac{1}{1+r_1 D^{r_2} H^{r_3}} \times \hat{w}_1$ (formula 9), $\widetilde{w}_3 = \frac{1}{1+\left(\frac{1}{r_1}\right) D^{-r_2} H^{-r_3}} \times \hat{w}_1$ (formula 10); level 2 control: taken $\widetilde{w}_2$ as the basis, the optimal model of biomass of the trunk and the crown is substituted into formula 5 and formula 6 respectively to simplify the equation, which can form the following equations: $\widetilde{w}_4 = \frac{1}{1+r_4 D^{r_5} H^{r_6}} \times \widetilde{w}_2$ (formula 11), $\widetilde{w}_7 = \frac{1}{1+\left(\frac{1}{r_4}\right)D^{-r_5}H^{-r_6}} \times \widetilde{w}_2$ (formula 12); level 3 control: taken $\widetilde{w}_7$ as the basis, the optimal biomass models of branches and leaves were substituted into formula 7 and formula 8 to be simplified, and the following equations can be formed: $\widetilde{w}_5 = \frac{1}{1+r_7 D^{r_8} H^{r_9}} \times \widetilde{w}_7$ (formula 13), $\widetilde{w}_6 = \frac{1}{1+\left(\frac{1}{r_7}\right)D^{-r_8}H^{-r_9}} \times \widetilde{w}_7$ (formula 14). R software is used to fit the parameter values of the constructed biomass compatibility model, and the results are shown in **Table 4**.

Table 4. Parameter estimation of compatible simultaneous model

Total biomass			**Aboveground biomass, root biomass**			**Trunk biomass, crown biomass**			**Branch biomass, leave biomass**		
a	b	c	r_1	r_2	r_3	r_4	r_5	r_6	r_7	r_8	r_9
0.049	2.164	0.468	0.253	-0.532	0.442	6.101	-0.084	-1.285	8.521	0.393	-1.370

Through the test of the compatible biomass model (**Table 5**), we can see that the biomass compatibility model is based on solving the incompatibility between the whole plant biomass and sub-biomass and in the sub-biomass, and all the evaluation indexes of the model are ideal (except leaves), and the model fitting ability is good. On the one hand, it may be related to the fact that the biomass of branches and leaves is influenced by crown shape, size, saturation and tree growth, and these factors change with different climate and habitats. On the other hand, it may be the loss of biomass in the process of investigation and sampling of branches and leaves in the field; so the evaluation index of crown biomass is low.

Table 5. Evaluation index of compatibility simultaneous model

Organ	***E***	***RMSE***	**R^2**
Whole plant	-0.060	15.762	0.954
trunk	-0.500	14.328	0.941
root	0.075	6.631	0.714
branch	0.215	3.438	0.403
leave	0.128	2.194	0.118

5. Conclusion

In this study, the unilateral model including DBH and binary model including DBH and tree height were used to fit the biomass of Chinese fir. The results showed that the binary model including DBH and tree height had better fitting effect. On the basis of selecting the optimal independent model of each organ, a three-level joint control scheme was adopted to establish the compatibility model among the biomass of each organ. The results show that the compatibility equation system based on the whole plant biomass can effectively solve the problem of incompatibility between the whole plant biomass and sub-biomass and in the sub-biomass, and the fitting effect of other biomass models is good except the tree leaf biomass model.

The evaluation index of the biomass model of branches and leaves in this study is low. On the one hand, it may be related to the influence of the biomass of branches and leaves on the shape, size and fullness of crown and the growth of trees, and these factors are related to the change of climate and habitat; on the other hand, it may be related to the loss of some biomass of branches and leaves in the field investigation and sampling process, which should be paid attention to in the later related work.

Conflict of interest

The author declares no conflict of interest.

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