139. Jahrgang (2022), Heft 1, S. 51–72

Austrian Journal of Forest Science
Centralblatt für das gesamte Forstwesen

Impacts of stand origin, species composition, and stand density on height-diameter relationships of dominant trees in Sichuan Province, China

Einfluss von Bestandesursprung, Mischungsgrad und Bestandesdichte auf Höhe-Durchmesser-Beziehungen in der Provinz Sichuan, China

Heng Wu[1,2], Hui Xu[1], Fanglin Tang[2], Guang-long Ou[1*], Zi-yan Liao[3]

Keywords: site quality, dominant height, origin, species composition, stand density, *Abies fabri*, *Picea asperata*, *Pinus yunnanensis*, *Pinus massoniana*, *Cupressus funebris*, *Cunninghamia lanceolata*, *Quercus glauca*, *Betula platyphylla*

Schlüsselbegriffe: Bonität, Bestandesqualität, *Abies fabri*, *Picea asperata*, *Pinus yunnanensis*, *Pinus massoniana*, *Cupressus funebris*, *Cunninghamia lanceolata*, *Quercus glauca*, *Betula platyphylla*

Abstract

Analysis of height growth of dominant trees is crucial for accurate evaluation of site quality and how this influences stand characteristics. This study explores, whether stand origin, tree species composition and stand density influence the growth process of stand dominant height. We used forest resource inventory data from 1283 permanent plots in Sichuan Province, China. Three dominant trees were selected from each permanent plot to calculate the average dominant height and diameter at breast height (*DBH*). The Chapman-Richards equation was used to construct a dominant height prediction model of each tree species based on *DBH*. The effects of the stand origin, species composition, and stand density on the upper asymptote

[1] College of Forestry, Southwest Forestry University, Kunming, 650224, China
[2] Kunming Survey & Design Institute of State Forestry and Grassland Administration, Kunming, 650216, China
[3] CAS Key Laboratory of Mountain Ecological Restoration and Bioresource Utilization & Ecological Restoration Biodiversity Conservation Key Laboratory of Sichuan Province, Chengdu Institute of Biology, Chinese Academy of Sciences, Chengdu 610041, China
*Corresponding author: Guang-long Ou, olg2007621@126.com

parameter *a*, shape parameter *b*, and growth rate parameter *c* were analyzed using a dummy variable method. The results show that there was no statistically significant difference in parameters *a*, *b*, and *c* among different stand origins, species composition, and stand density. The upper asymptote parameters of the stand with a natural origin were greater than stands with an artificial origin. Species composition influenced the parameters among different coniferous species but was associated with large coefficients of variation, especially for broadleaf species. Stand density moderatly influenced the model parameters for all species. With an increase in stand density, the influence of stand density on the model parameters decreased gradually. Our results confirm that the relationship between *DBH* and height of dominant trees is useful to evaluate site productivity. However, this method has to consider stand origin and differences in stand density and species composition, especially for species with *DBH*-height relations sensitive to stand conditions.

Zusammenfassung

Die Analyse des Höhenwachstums dominanter Bäume ist wichtig für die präzise Beurteilung der Bonität und wie diese die Bestandesstruktur beeinflusst. Hier verwenden wir Waldinventurdaten von 1283 permanenten Plots aus der Provinz Sichuan, China. Drei dominante Bäume wurden ausgewählt, um mittlere Oberhöhe und Brusthöhendurchmesser (*DBH*) zu berechnen. Die Chapman-Richards-Gleichung wurde verwendet, um ein Oberhöhenschätzmodell für jede Baumart zu erstellen. Wir untersuchten dann den Einfluss von Bestandesursprung, des Mischungsgrads und der Bestandesdichte auf die Parameter *a*, *b* und *c* mittels Dummy-Variablen. Unsere Ergebnisse zeigten keine signifikanten Unterschiede von *a*, *b* und *c* nach Bestandesursprung, Mischungsgrad und Bestandesdichte. Der Parameter *a* war höher in Beständen mit natürlichen Ursprung im Vergleich zu künstlich begründeten Beständen. Der Mischungsgrad beeinflusste die Modellparameter, aber hatte eine sehr hohe Variabilität, insbesondere für Laubholzbestände. Bestandesdichte hat einen nennenswerten Einfluss auf die Parameter für alle Baumarten. Mit steigender Bestandesdichte nahm der Einfluss von Bestandesdichte auf die Modellparameter ab. Unsere Ergebnisse bestätigen, dass die Durchmesser-Höhenbeziehung hilfreich bei der Beurteilung der Bonität ist. Allerdings müssen bei dieser Methode der Bestandesursprung und Unterschiede in Bestandesdichte und Mischungsgrad berücksichtigt werden, insbesondere für Baumarten, die sensitiv gegenüber Bestandesbedingungen sind.

1 Introduction

The problem of an uneven age structure in mixed forests can be solved by using *DBH* instead of stand age (Trorey 1932) and the mean height of dominant trees to establish regression models to evaluate site productivity (Meyer 1940; Stout & Shumway 1982; Reinhardt 1982). The height of dominant trees corresponding to a reference *DBH* is referred to as the site condition (Vanclay & Henry 1988; Weiskittel *et al.* 2011), similar to the site index, which is the expected height at a certain reference age. As an effective method to evaluate mixed forests and uneven-aged forests (Huang & Titus 1993, 1994; Adeyemi & Adesoji 2016; Kourosh *et al.* 2017; Moreno-Fernández *et al.* 2018), the selection of the reference *DBH* affects the accurate assessment of the site form (Vanclay & Henry 1988). However, the method is quite sensitive to the selection of an index diameter (Goelz & Burk 1992), and Wang (1998a) found it to be an inadequate measure of site quality because it was not related to site index or ecological measures of site quality. This is likely because diameter growth is much more sensitive to stand density than height growth. Site form appears superior for natural secondary forests, whereas site index is superior for plantations, when assessing site quality in Qinling Mountains (Wu *et al.* 2015). Site index and site form are more accurate than site class in evaluating site quality (Buda & Wang 2006; Beltran *et al.* 2016; Duan *et al.* 2018; Fu *et al.* 2018). Forest formation was taken as the basic unit of site quality evaluation of tropical natural mountain rainforest in Hainan Island, and the vertical topographic guidance curve model was established by applying the average height of the dominant trees as the dependent variable and the average *DBH* as the independent variable. There was no statistically significant difference between the theoretical and measured values of the compiled site form model (Chen *et al.* 2000). The reference *DBH* obtained when the second derivative of the height – *DBH* equation is zero is the *DBH* with the maximum continuous growth of tree height.

It is particularly important to analyze the influence of stand origin, species composition and stand density on the relationship between *DBH* and the height of the dominant tree, when using the relationship to evaluate site quality. There are many studies on the impact of the origin, species composition, and stand density on stand factors (Weiskittel *et al.* 2011; Fu *et al.* 2018). Artificial stands, that is, stands originated from planting or sowing, have been reported to have a higher growth limit than natural stands (Weiskittel *et al.* 2011). Studies on mixed stands of *Cunninghamia lanceolata* show that different species composition had significant effects on the growth of *DBH* and the height of individual trees (Fu *et al.* 2018). The influence of stand density on the height of taller trees is not significant, and the influence of stand density on the average height of stands is also small with certain level of stand density (Stout & Shumway 1982; Huang & Titus 1993). There are further studies that show a significant effect of stand density on the allometric relations between diameter at breast height over bark and tree height (Wang 1998b; Bhandari *et al.* 2021). Stand density also has a significant effect on average *DBH* (Weiskittel *et al.* 2011). Existing studies lack analysis of the influence of stand origin, species composition and stand density on the relationship between *DBH* and the height of dominant trees by species, which also limits the application of the relationship between *DBH* and height to evaluate site quality.

It is still controversial to use the height – *DBH* relationship of dominant trees to evaluate site quality (Molina-Valero *et al.* 2019); the main reasons are the lack of systematic analysis of stand origin, species composition and stand density and other factors on the height – *DBH* growth process (Skovsgaard & Vanclay 2008; Peng 2000), which is the aim of this work. Combining a large number of plots with modeling, we use here dummy variables to analyze the different model parameters according to the factor classification, to explore the effect of stand factors on the growth process of dominant trees. This study is relevant for the scientific evaluation of site quality using systematic analysis.

2 Materials and methods

2.1 Research area and data source

Sichuan Province is located in the hinterland of southwestern China, straddling five geomorphic units: Sichuan Basin, Qinghai-Tibet Plateau, Hengduan Mountains, Yunnan-Guizhou Plateau, and Qinba mountains. The soil types are diverse. Yellow soil is the base soil in the eastern basin, while red soil is the base soil in the western basin. Sichuan Province is a transition zone between the eastern monsoon region and the Qinghai-Tibet Plateau in southwestern China. Extensive evergreen broad-leaved forests are distributed in the east and southwest of China. The alpine canyons and subalpine coniferous forests in the west of China are luxuriant. The northwestern plateau is covered with shrubs and meadows adapted to the alpine habitat. The distribution of tree species is shown in Figure 1.

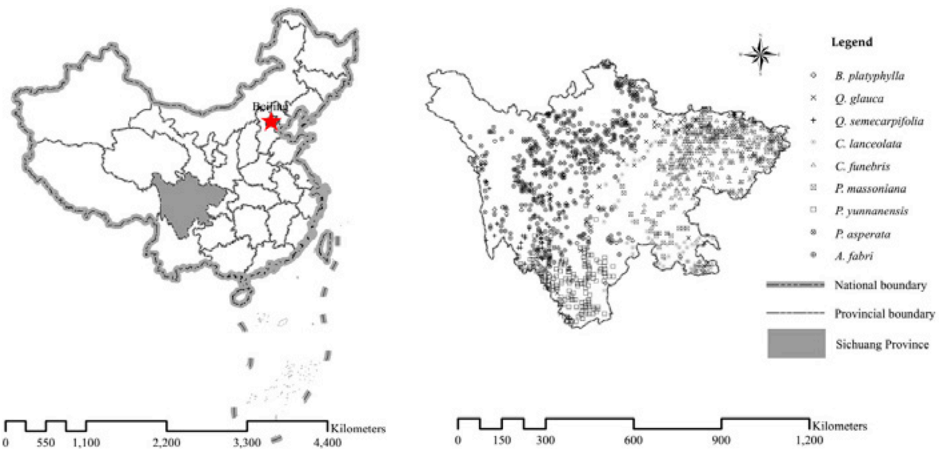

Figure 1: Geographical location and distribution of the used forest inventory plots in Sichuan Province, China.

Abbildung 1: Lage des Untersuchungsgebiets und Positionen der verwendeten Waldinventurplots in der Provinz Sichuan, China.

The data used in this paper were obtained from the ninth continuous forest resource inventory data of Sichuan Province, which was established in 1979. Taking the whole province as a whole, the systematic sampling theory was adopted to arrange the plots in alternating intervals of 4 km × 8 km and 8 km × 8 km crossing each other successively. A total of 10,098 permanent plots were set up. The side length of a square plot was 25.82 m, and the area was 0.0667 hectare (ha). Species, size, relative location and other characteristics of each tree were measured in the plots. The diameter of the smallest tree measured was 5 cm. According to the dominant tree species whose stock accounted for the main part of the plot stock, 241 sample plots of *Abies fabri*, 173 sample plots of *Picea asperata*, 158 sample plots of *Pinus yunnanensis*, 127 sample plots of *Pinus massoniana*, 293 sample plots of *Cupressus funebris*, 89 sample plots of *Cunninghamia lanceolata*, 78 sample plots of *Quercus semecarpifolia*, 46 sample plots of *Quercus glauca* (also known as *Cyclobalanopsis glauca*), and 78 sample plots of *Betula platyphylla* were selected. The average height and *DBH* of dominant trees were calculated by selecting three dominant trees, which were the two tallest trees and the thickest tree, from each sample plot. In total, 1283 permanent plots were analyzed (Table 1).

Table 1: Means and standard deviations (S.D.) of stand attributes for each species.

Tabelle 1: Mittelwert und Standardabweichung (S.D.) der Bestandeskennwerte für alle analysierten Baumarten.

Tree species	Number of plots	Stem number (ha^{-1})		*DBH* (cm)		Dominant height (m)		Basal area (m^2/ha)	
		Mean	S.D	Mean	S.D	Mean	S.D	Mean	S.D
All species	1283	1265	50.5	17.6	7.18	12.2	4.33	27.75	23.39
Abies fabri	241	631	27.16	30.3	13.50	17.2	6.77	48.00	54.92
Picea asperata	173	838	36.98	24.2	13.86	15.6	8.11	39.64	47.25
Pinus yunnanensis	158	1133	49.92	16.7	6.97	11.1	4.12	23.41	22.13
Pinus massoniana	127	1504	47.38	16.0	5.09	13.5	3.96	30.89	21.22
Cupressus funebris	293	1398	51.40	13.0	3.44	11.0	2.70	16.68	7.89
Cunninghamia lanceolata	89	1606	55.94	13.0	4.08	10.2	2.92	21.97	14.43
Quercus semecarpifolia	78	1668	67.58	16.3	6.22	9.1	3.34	30.72	15.96
Quercus glauca	46	1284	62.07	13.2	5.46	10.5	3.21	14.52	11.11
Betula platyphylla	78	1323	56.39	15.9	6.05	11.7	3.83	23.88	15.59

2.2 Methods

The Chapman-Richards function (Lee *et al.* 2021; Nigh 2015) (equation 1), Schumacher function (equation (2) and Hossfeld function (equation 3) were used to fit the relationship between average *DBH* and average tree height of dominant tree species, and appropriate model fitting results were determined according to the goodness of model fitting (equation 4) and root mean square error (equation 5). Mean error (equation 6) was used for residuals analysis. A dummy variable analysis model was established based on the average *DBH* and average tree height of dominant trees. Dummy variable analysis has an advantage over other models in parameter comparison. Compared with other models, the Chapman-Richards model had a better fit and each parameter had biological meaning. Thus the Chapman-Richards model was used in the following analysis.

$$H_D = 1.3 + a(1 - e^{-bDBH})^c \quad (1)$$

$$H_D = 1.3 + a \cdot e^{-\left(\frac{b}{DBH}\right)} \quad (2)$$

$$H_D = 1.3 + \frac{a}{\left(1 + b \cdot DBH^{-c}\right)} \quad (3)$$

H_D is the mean dominant height; *DBH* is the mean diameter at breast height of dominant trees; and *a*, *b*, *c* are parameters.

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

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(\hat{y}_i - y_i)^2}{n}} \quad (5)$$

$$ME = \sum_{i=1}^{n}\frac{(\hat{y}_i - y_i)}{n} \quad (6)$$

$\hat{y}_i$ is the predicted value; y_i is the observed value; and *n* is the number of samples.

Based on the dummy variable method, mixed the differences in the upper limit asymptote parameter *a*, growth curve shape parameter *b* and growth rate parameter *c* among different factors were analyzed.

$$H_D = 1.3 + a_\delta(1 - e^{-bDBH})^c \quad (7)$$

$$H_D = 1.3 + a(1 - e^{-b_\delta DBH})^c \quad (8)$$

$$H_D = 1.3 + a(1 - e^{-bDBH})^{c_\delta} \quad (9)$$

$$\delta = (x, \quad i, j \text{ or } k) = \begin{cases} 1, & \text{when } n \text{ is the } i \text{ stand origin or } j \text{ species composition or } k \text{ density} \\ 0, & \text{or else} \end{cases}$$

H_D is the mean dominant height; *DBH* is the mean diameter at breast height of dominant trees; a_δ in equation (7), b_δ in equation (8), and c_δ in equation (9) are parameters to be solved.

Three factors, *i.e.*, stand origin, species composition, and stand density were selected to analyze the impact on stand dominant height growth. Then, stand origin includes natural forests and artificial forests, and species composition includes the following: *Pcs* is a pure conifer stand (individual conifer species volume accumulation exceeds the threshold of 90%), *Pbs* is a pure broadleaf stand (individual broadleaf species volume accumulation exceeds the threshold of 90%), *Rpcs* is a relatively pure conifer stand (individual conifer species volume accumulation is between the range from 65% to 90%), *Rpbs* is a relatively pure broadleaf stand (individual broadleaf species volume accumulation is between the range from 65% to 90%), *Mcs* is a mixed conifer stand (conifer species volume accumulation exceeds the threshold of 65%), *Mcbs* is a mixed conifer and broadleaf stand (conifer species or broadleaf species volume accumulation is between the range from 35% to 65%), *Mbf* is a mixed broadleaf stand (broadleaf species volume accumulation exceeds the threshold of 65%), and volume accumulation is the ratio of the dominant species stock to the stock of the whole plot. We used eight stand density classes, including 1–300 ha^{-1}, 301–600 ha^{-1}, 601–900 ha^{-1}, 901–1200 ha^{-1}, 1201–1500 ha^{-1}, 1501–1800 ha^{-1}, 1801–2100 ha^{-1}, and more than 2101 ha^{-1}. In total, there were eight stand density levels of dummy variables based on the distribution of stand density of plots in Sichuan Province.

3 Results

3.1 Dominant height growth models

The fitting models for mean *DBH* and mean tree height of dominant trees are shown in Table 2. Compared with Schumacher and Hossfeld equation, the Chapman-Richards equation has better fitting efficiency. The best fit was found for *Picea asperata*, whereas *Betula platyphylla* had the lowest goodness of fit. The fit for coniferous species was better than that for broadleaf species. The root mean square error for *Cupressus funebris* model fitting was the smallest, compared with the largest for *Abies fabri*. The dominant height growth of a stand can effectively reflect the tree differentiation caused by site quality differences.

Table 2: Fitting results of stand dominant height growth using three function types, for each of the studied species.

Tabelle 2: Modellparameter für Oberhöhenmodelle mittels drei Funktionstypen für jede der untersuchten Baumarten.

Tree species	Model	Parameters			Regression statistics	
		a	*b*	*c*	R^2	*RMSE*
	(1)	25.0300	0.0631	2.2750	0.7518	3.3749
Abies fabri	(2)	34.7397	21.2093	-	0.7441	3.4417
	(3)	27.4007	559.7549	2.0174	0.7497	3.4506
	(1)	33.0992	0.0437	1.7692	0.8479	3.1635
Picea asperata	(2)	40.9540	22.5251	-	0.8419	3.2442
	(3)	38.4334	289.7942	1.6603	0.8476	3.1945
	(1)	19.7234	0.0739	1.8452	0.7024	2.2483
Pinus yunnanensis	(2)	26.3933	15.2145	-	0.6969	2.2570
	(3)	26.8994	115.2416	1.5209	0.6977	2.2615
	(1)	17.0420	0.1800	4.4933	0.5364	2.6970
Pinus massoniana	(2)	26.2388	13.3416	-	0.5237	2.7556
	(3)	17.7435	461.3275	2.4614	0.5312	2.7447
	(1)	17.1501	0.1101	1.9640	0.6562	1.5841
Cupressus funebris	(2)	23.5226	12.8920	-	0.6555	1.5912
	(3)	17.2332	197.2903	2.0711	0.6561	1.5854
	(1)	14.3428	0.1573	3.0475	0.6890	1.6278
Cunninghamia lanceolata	(2)	22.1996	13.3787	-	0.6858	1.6549
	(3)	13.5339	696.3769	2.7101	0.6886	1.6369
	(1)	20.8002	0.0342	1.1165	0.5549	2.2295
Quercus semecarpifolia	(2)	18.5656	15.9697		0.5481	2.2760
	(3)	19.9133	142.7166	1.5380	0.5517	2.2691
	(1)	22.7142	0.0351	0.8802	0.6044	2.0183
Quercus glauca	(2)	18.8857	10.5896	-	0.5971	2.0824
	(3)	25.4277	45.6382	1.1922	0.6041	2.0381
	(1)	17.4499	0.0714	1.2068	0.5164	2.6606
Betula platyphylla	(2)	19.3968	10.9283	-	0.5148	2.7000
	(3)	18.6346	63.0043	1.5220	0.5161	2.6742

According to the residual diagram of model fitting results (Figure 2), the residual sum of squares for *Abies fabri*, *Picea asperata*, *Pinus yunnanensis*, *Pinus massoniana*, *Cupressus funebris*, *Cunninghamia lanceolata*, *Quercus semecarpifolia*, *Quercus glauca*, and *Betula platyphylla* were 2745, 1731, 798.7, 923.7, 735.3, 235.8, 387.7, 187.4, and 552.1, respectively. The residuals were evenly distributed, so the mean errors were small, which were –0.0279, –0.0025, 0.0063, –0.0006, –0.0034, 0.0046, –0.0153, 0.0096, and 0.0032, respectively.

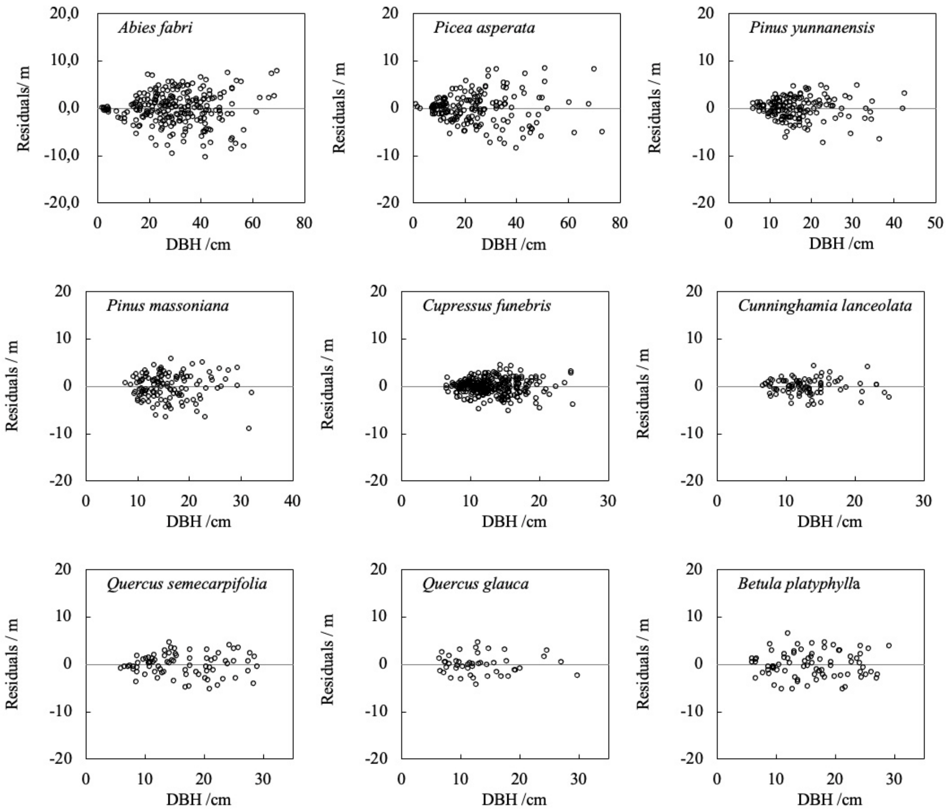

Figure 2: Residuals analysis of stand dominant height model using Chapman-Richards equations.

Abbildung 2: Residuenplots der Oberhöhenmodelle mittels Chapman-Richards-Gleichung.

According to the scatter diagram of the height growth of dominant trees (Figure 3), *Abies fabri*, *Picea asperata*, *Pinus yunnanensis*, *Pinus massoniana*, *Cupressus funebris*, and *Cunninghamia lanceolata* height increased rapidly as the *DBH* increased, and the rapid height growth continued until the *DBH* reached 30 cm, 35 cm, 20 cm, 15 cm, 15 cm, and 15 cm, respectively. Then the height growth rate started to slow down. For *Quercus semecarpifolia*, *Quercus glauca* and *Betula platyphylla*, the rapid height growth continued, which is different from coniferous species. The height growth process of dominant trees of different species can reflect the difference in site productivity. All species are still growing in height with an increase of *DBH* except for *Pinus massoniana* based on the selected models.

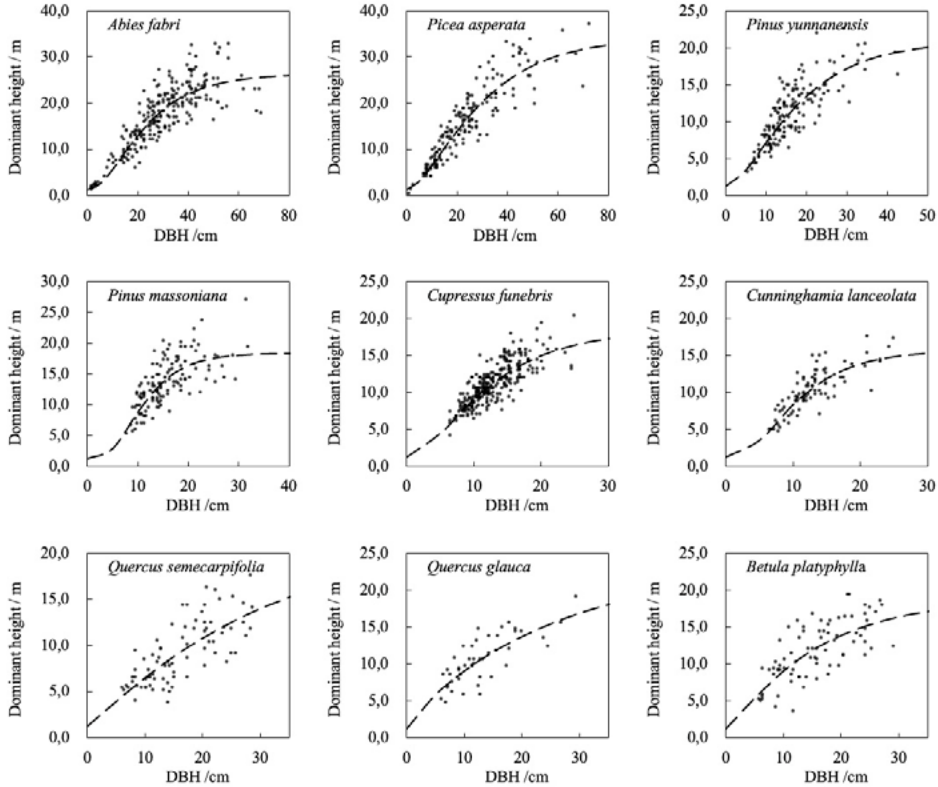

Figure 3: Curves and observations of stand dominant height growth.

Abbildung 3: Modelle und Beobachtungen der Bestandesoberhöhen.

3.2 Influence of stand conditions on dominant tree height growth

3.2.1 Stand origin

According to the results of parameter fitting by tree species in Table 3, the average value of the upper asymptote parameter *a* for the natural origin of different tree species was 28.8225, and the average value of parameter *a* for artificial origin was 20.5043. The mean value of the shape parameter *b* for the natural origin of different tree species was 0.0916, and the mean value of parameter *b* for artificial origin was 0.0935. The mean value of the growth rate parameter *c* for the natural origin of different tree species was 2.1883, and the mean value of parameter *c* for artificial origin was 2.1818.

Table 3: Modell parameters a, b, and c, fitted separatedly by stand origin.

Tabelle 3: Modellparameter *a*, *b*, and *c*, unterteilt nach Bestandesursprung.

Tree species	Stand origin					
	Natural	Artificial	Natural	Artificial	Natural	Artificial
	a		*b*		*c*	
Abies fabri	25.0572	22.3018	0.0632	0.0590	2.2726	2.3051
Picea asperata	33.1198	32.2741	0.0438	0.0429	1.7645	1.7951
Pinus yunnanensis	20.1159	18.2070	0.0759	0.0671	1.7781	2.0855
Pinus massoniana	17.1611	16.8493	0.1808	0.1787	4.4595	4.5584
Cupressus funebris	17.6689	16.5814	0.1135	0.1054	1.8866	2.1066
Cunninghamia lanceolata	14.3010	14.3486	0.1577	0.1572	3.0189	3.0558
Quercus glauca	22.8974	20.2978	0.0355	0.0305	0.8730	0.9377
Betula platyphylla	22.0867	17.3461	0.0991	0.0705	0.8298	1.2328

The results of Analysis of Variance in Table 4 showed that there was no statistical difference in parameters *a*, *b*, and *c* ($p > 0.10$) of the *DBH* – height growth model of dominant trees with different origins. Except for *Cunninghamia lanceolata*, the upper asymptote parameters of stands with a natural origin were greater than those of artificial origin, which means the origin had an impact on the assessment of the growth potential of the stand. All *Quercus semecarpifolia* stands were natural.

Table 4: Results of Analysis of Variance for the effects of stand origin on dummy variable model parameters.

Tabelle 4: Ergebnisse der Varianzanalyse für die Auswirkungen des Bestandesursprungs auf Dummy-Variablenmodellparameter.

Parameters	Stand origin	Mean±S.D.	Sum squared residual	*F*-value	*p*-value
a	Natural	20.8225 ± 6.0941	469.25	0.01	0.91
	Artificial	20.5043 ± 5.4625			
b	Natural	0.0916 ± 0.0527	0.04	0.01	0.94
	Artificial	0.0935 ± 0.0537			
c	Natural	2.1883 ± 1.1246	18.90	0.00	0.99
	Artificial	2.1818 ± 1.1982			

3.2.2 Species composition

According to the results of parameter fitting with dummy variables, the average values of the upper asymptote parameter *a* for *Pcs*, *Rpcs*, *Mcs*, *Mcbs*, *Pbs*, *Rpbs*, and *Mbf* for different tree species were 21.1838, 21.0037, 21.7931, 20.5539, 19.7455, 20.0284, and 21.7698, respectively. the average values of the shape parameter *b* for pure conifer stands, relatively pure conifer stands, mixed conifer stands, mixed conifer and broadleaf stands, pure broadleaf stands, relatively pure broadleaf stands, and mixed broadleaf stands were 0.1044, 0.1042, 0.1492, 0.0835, 0.0443, 0.0467, and 0.0521, respectively. the average values of the growth rate parameter *c* for the pure conifer stand, relatively pure conifer stand, mixed conifer stand, mixed conifer and broadleaf stand, pure broadleaf stand, relatively pure broadleaf stand, and mixed broadleaf stand were 2.5895, 2.5873, 2.3965, 2.1507, 1.1439, 1.0764, and 0.9657, respectively.

It was obvious that species composition had an impact on the upper asymptote parameters among different coniferous species accompanied by a large coefficient of variation, while the impact was not statistically significant for broadleaf species (Figure 4A). Species composition had an influence on the upper asymptote parameters for *Pinus yunnanensis*, *Pinus massoniana*, *Quercus semecarpifolia*, and *Quercus glauca* stands (Figure 4B). Species composition exerted an impact on growth curve shape parameters among different coniferous species accompanied by a large coefficient of variation, while broadleaf species had a slight influence (Figure 4C). Species composition had an influence on the upper asymptote parameters in the *Abies fabri* stand (Figure 4D). Species composition exerted an impact on the growth rate parameters among different coniferous species accompanied by a large coefficient of variation, while broadleaf species had no influence (Figure 4E). Species composition had an influence on the growth rate parameters of the *Pinus yunnanensis*, *Pinus massoniana*, and *Cunninghamia lanceolata* stands (Figure 4F), which might be related to the artificial management of the main timber species in Sichuan Province.

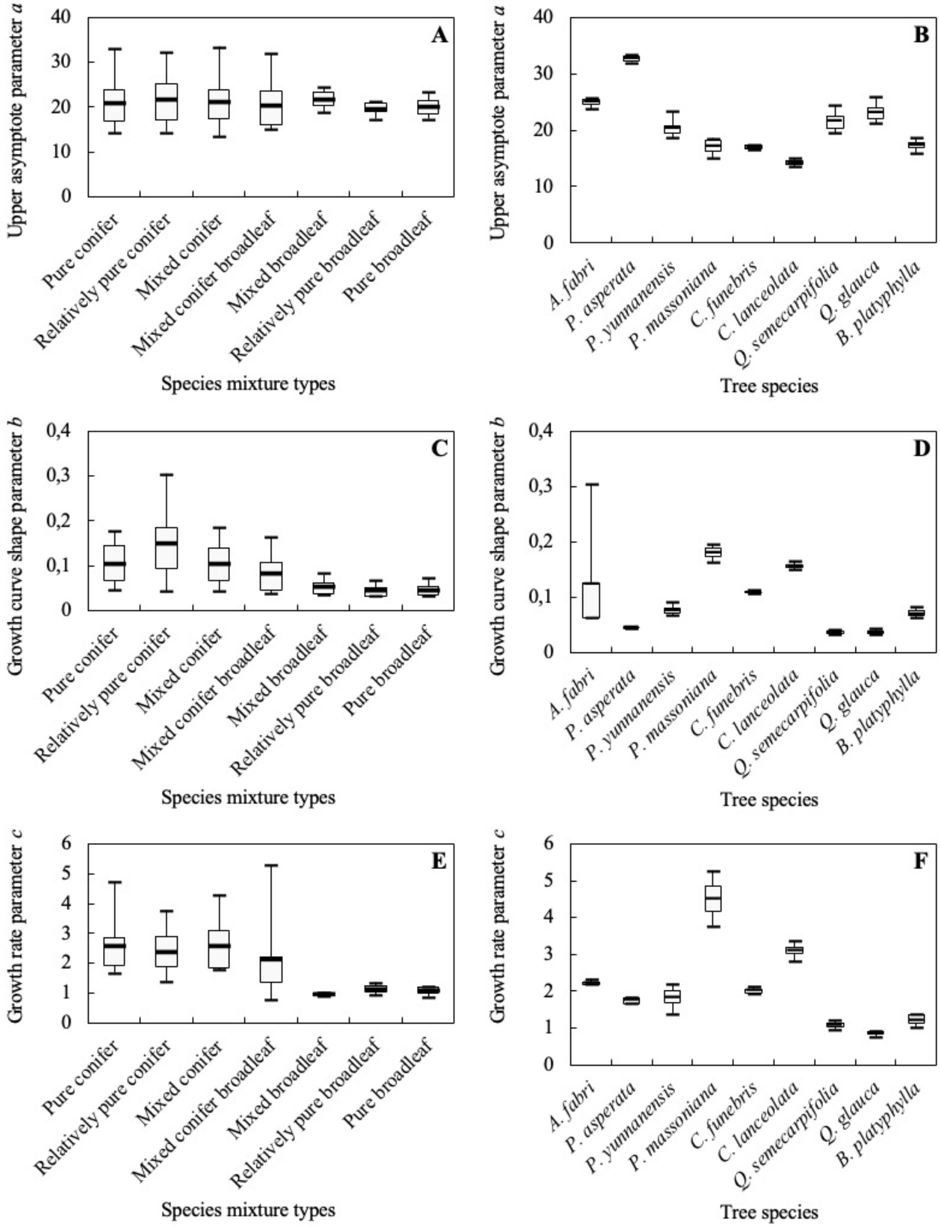

Figure 4: Impact of species composition and dominant tree species on the parameters a, b and c.

Abbildung 4: Einfluss von Bestandestyp und Hauptbaumart auf Parameter *a*, *b* und *c*.

The results of one-way ANOVA in Table 5 showed that there were no statistical differences in parameter *a* ($p > 0.10$), b ($p > 0.10$), and *c* ($p > 0.10$) of the *DBH* – height growth model of dominant trees with different tree structures. Similar results were obtained in coniferous or broadleaf stands in Table5.

Table 5: Results of one-way ANOVA for the effects of species composition on model parameters.

Tabelle 5: Ergebnisse der einfachen Varianzanalyse (ANOVA) zum Effekt des Bestandestyps auf Modellparameter.

Parameters	Species composition	Mean±S.D.	Sum squared residual	*F*-value	*p*-value
a	*Pcs*	21.1838 ± 7.0812			
	Rpcs	21.0036 ± 6.9885			
	Mcs	21.7931 ± 6.6533	1041.75 (All species)	0.07 (All species)	0.99 (All species)
	Mcbs	20.5539 ± 5.7915	941.88 (coniferous)	0.05 (coniferous)	0.98 (coniferous)
	Pbs	19.7455 ± 2.0255	99.87 (broadleaf)	0.24 (broadleaf)	0.87 (broadleaf)
	Rpbs	20.0284 ± 2.9755			
	Mbf	21.7698 ± 2.8580			
b	*Pcs*	0.1044 ± 0.0544			
	Rpcs	0.1042 ± 0.0530			
	Mcs	0.1492 ± 0.0928	0.14 (All species)	2.03 (All species)	0.18 (All species)
	Mcbs	0.0835 ± 0.0500	0.095 (coniferous)	0.74 (coniferous)	0.54 (coniferous)
	Pbs	0.0443 ± 0.0199	0.045 (broadleaf)	0.08 (broadleaf)	0.97 (broadleaf)
	Rpbs	0.0467 ± 0.0222			
	Mbf	0.0521 ± 0.0254			
c	*Pcs*	2.5895 ± 1.0278			
	Rpcs	2.5873 ±1.1493			
	Mcs	2.3965 ± 0.8796	43.22 (All species)	2.11 (All species)	0.11 (All species)
	Mcbs	2.1507 ± 1.3313	24.63 (coniferous)	0.08 (coniferous)	0.97 (coniferous)
	Pbs	1.1439 ± 0.2143	18.59 (broadleaf)	0.39 (broadleaf)	0.76 (broadleaf)
	Rpbs	1.0764 ± 0.1832			
	Mbf	0.9657 ± 0.0664			

3.2.3 Stand density

According to the results of parameter fitting with dummy variables, the average values of the upper asymptote parameters for various stand densities, *i.e.*, 1–300 trees/hectare, 301–600 trees/hectare, 601–900 trees/hectare, 901–1200 trees/hectare, 1201–1500 trees/hectare, 1501–1800 trees/hectare, 1801–2100 trees/hectare, and more than 2101 trees/hectare, were 20.3781, 20.1081, 20.3864, 20.6253, 20.8844, 22.7359, 20.7427, and 21.8094, respectively. The average values of the shape parameter *b* for various stand densities were 0.1705, 0.0789, 0.1691, 0.1653, 0.3091, 0.1784, 0.0992, and 0.0949, respectively. The average values of the growth rate parameter *c* for various stand densities, were 2.7036, 2.4741, 2.2802, 2.1868, 2.0614, 1.9092, 2.1189, and 1.8070, respectively.

It was obvious that stand density exerted an impact on the upper asymptote parameters among all species accompanied by a large coefficient of variation, although there was no difference in the mean of parameter *a* between different stand densities (Figure 5A). Stand density had a greater influence on the upper asymptote parameters in the *Picea asperata*, *Pinus massoniana*, and *Quercus semecarpifolia* stands, compared with the other stands (Figure 5B). Stand density exerted an impact on the growth curve shape parameters between 601 and 1800 trees/hectare accompanied by a large coefficient of variation, except for the initial stand density (Figure 5C). Stand density had a greater influence on the upper asymptote parameters in the *Abies fabri*, *Picea asperata*, *Quercus semecarpifolia*, and *Quercus glauca* stands compared with other stands (Figure 5D). With the increase in stand density, the influence of stand density on growth rate parameters decreased gradually accompanied by the coefficient of variation (Figure 5E). Stand density had a greater influence on the growth rate parameters in the *Pinus massoniana* and *Cunninghamia lanceolata* stands compared with other stands (Figure 5F), which might be related to the artificial management of the main timber species in Sichuan Province.

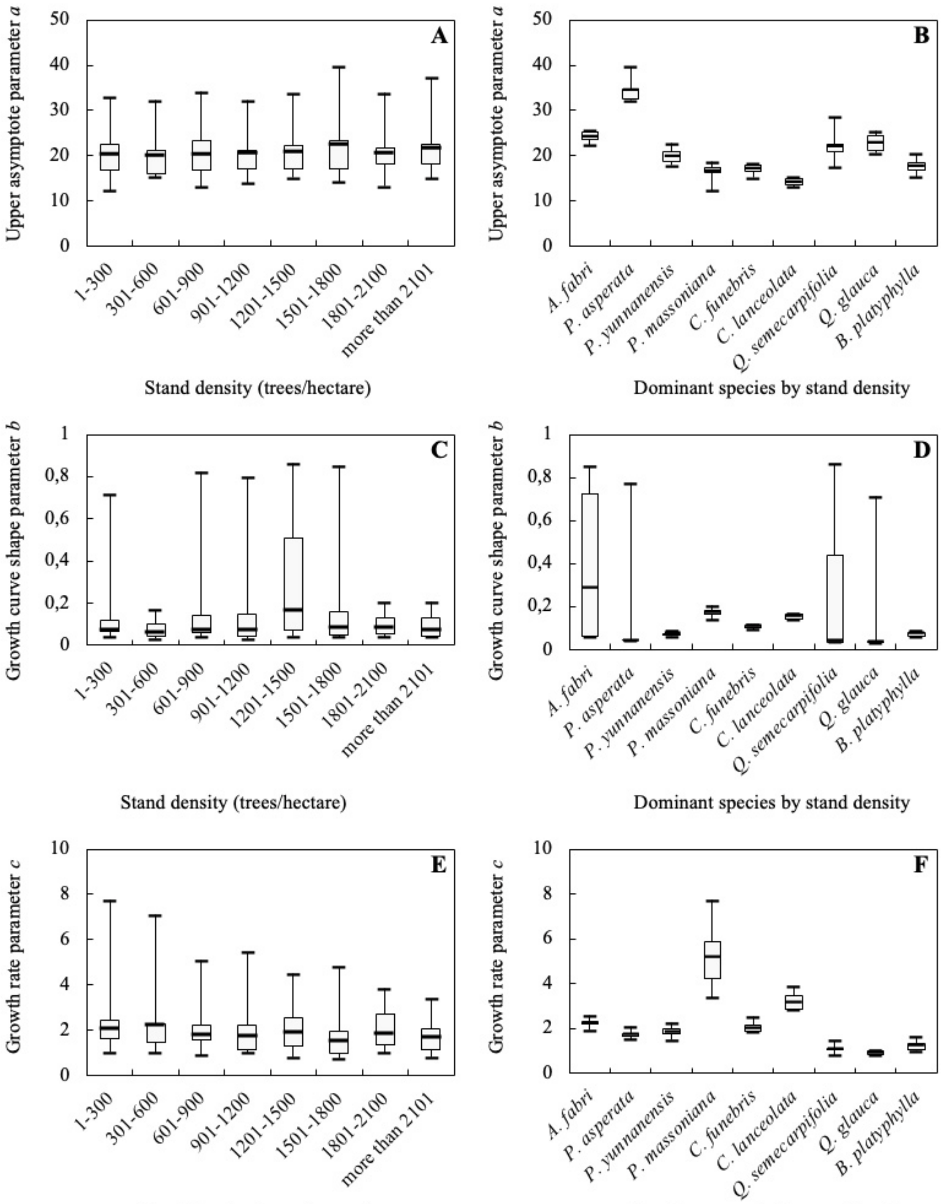

Figure 5: Impact of stand density and tree species on the modell parameters.

Abbildung 5: Einfluss von Bestandesdichte und dominanter Baumart auf Modellparameter.

The results of one-way ANOVA in Table 6 showed that there was no statistical difference in parameter *a* ($p > 0.10$), *b* ($p > 0.10$), and *c* ($p > 0.10$) of the *DBH* – height growth model of dominant trees with different stand densities. Similar results were obtained in coniferous or broadleaf stands in Table 6.

Table 6: Results of one-way ANOVA for the effects of stand density on the model parameters.

Tabelle 6: Ergebnisse der einfachen Varianzanalyse (ANOVA) zum Einfluss der Bestandesdichte auf die Modellparameter.

Parameters	Stand density	Mean±S.D.	Sum squared residual	*F*-value	*p*-value
a	1-300	20.3781 ± 6.7289	2458.63 (All species) 2234.75 (coniferous) 223.88 (broadleaf)	0.17 (All species) 0.04 (coniferous) 0.59 (broadleaf)	0.99 (All species) 1.00 (coniferous) 0.76 (broadleaf)
	301-600	20.1081 ± 5.7126			
	601-900	20.3864 ± 6.3861			
	901-1200	20.6253 ± 5.4536			
	1201-1500	20.8844 ± 5.6710			
	1501-1800	22.7359 ± 7.6474			
	1801-2100	20.7427 ± 6.5268			
	more than 2101	21.8094 ± 6.9030			
b	1-300	0.1705 ± 0.2416	3.06 (All species) 1.59 (coniferous) 1.47 (broadleaf)	1.00 (All species) 1.12 (coniferous) 0.81 (broadleaf)	0.44 (All species) 0.37 (coniferous) 0.60 (broadleaf)
	301-600	0.0789 ± 0.0492			
	601-900	0.1691 ± 0.2492			
	901-1200	0.1653 ± 0.2417			
	1201-1500	0.3091 ± 0.3211			
	1501-1800	0.1784 ± 0.2565			
	1801-2100	0.0992 ± 0.0574			
	more than 2101	0.0949 ± 0.0615			
c	1-300	2.7036 ± 2.2902	128.49 (All species) 88.74 (coniferous) 39.75 (broadleaf)	0.32 (All species) 0.29 (coniferous) 1.02 (broadleaf)	0.94 (All species) 0.95 (coniferous) 0.46 (broadleaf)
	301-600	2.4741 ± 1.8378			
	601-900	2.2802 ± 1.2970			
	901-1200	2.1868 ± 1.4154			
	1201-1500	2.0614 ± 1.1180			
	1501-1800	1.9092 ± 1.2665			
	1801-2100	2.1189 ± 1.1136			
	more than 2101	1.8070 ± 0.8887			

4 Discussion

A wide variety of approaches, such as phytocentric and geocentric, have been used for assessing forest site productivity, each with advantages and disadvantages (Weiskittel *et al.* 2011). Increasing site productivity produced increasing tree height for a given diameter (Larson 1963). Application of the relationship between *DBH* and height of dominant trees to evaluate site quality could solve the difficulties in using site index in mixed and uneven aged stands when assessing site quality (Huang & Titus 1993).

Site form for quality evaluation of natural secondary forest is better than the use of site index, and the site quality evaluation of artificial forests is better with the use of site index, which indicates that there are differences in site quality evaluation for stands with different origins (Wu *et al.* 2015; Buda & Wang 2006; Beltran *et al.* 2016; Duan *et al.* 2018). In this paper, there was no statistical difference in the upper asymptote parameters, shape parameters and growth rate parameters between different stand origins, which indicates that there is no statistical difference in stand origin evaluation of site quality when using the site form method (Wang 1998a). The relationship between *DBH* and height is affected by stand density (Deng *et al.* 2019; Bhandari *et al.* 2021). Increasing stand density has been found to reduce both diameter growth and height growth for mixed conifers in the northern Rocky Mountains (Wykoff *et al.* 1982), implying that the stand density impact on the height and diameter relationship will probably be minimized (Huang & Titus 1993), especially if for dominant trees in the stands (Vanclay & Henry 1988). In this paper, there was no statistical influence on *DBH* and height of dominant trees with certain different stand densities and tree structure, which might be related to the use of dominance, because dominant trees in the upper canopy are less affected in conifer stands by factors such as tree structure and stand density (Weiskittel *et al.* 2011; Huang & Titus 1993, 1994). The relationship between *DBH* and height is sensitive to the selection of reference *DBH*, but this could not deny the feasibility of the stand quality evaluation by site form. Adoption of *DBH* of the growth model with the second derivative of zero as the reference *DBH* is also unreasonable (Chen *et al.* 2000), because the selection of the reference *DBH* is the same as the reference age, which needs to be sensitive and can reflect the difference in stand quality (Fu *et al.* 2018; Chen *et al.* 2000; Molina-Valero *et al.* 2019; Skovsgaard & Vanclay 2008).

The accuracy of factor analysis is greatly affected by the sample size and data, that is, the larger the number of plots and the more uniform the plot distribution at different classification levels (Adeyemi & Adesoji 2016; Kourosh *et al.* 2017; Moreno-Fernández *et al.* 2018), the more reliable the research conclusion. In this paper, 1283 permanent plots, six coniferous species and three broadleaf species were used to reflect the growth process of *DBH* and dominant height in real stands. All phytocentric measures of forest site productivity assume that trees are effective representatives of site productivity. However, site and tree genotype interactions are complex and suggest that a variety of factors can influence a tree's productivity. Despite these drawbacks, these measures are the most commonly used in forestry (Vanclay & Henry 1988; Weiskittel *et al.* 2011). The relationships between *DBH* and height of different species (Wang & Hann 1988) have different sensitivity to stand origin, species composition and density, which was highest in pure spruce stand but decreased with increasing

Abies fraseri or *Betula lutea* component (Nicholas & Zedaker, 1992). The mixed effects model seems to be an alternative approach for studying the focus of this paper (Fu *et al.* 2012), and the stand density index is superior to the number of trees for analysis, However, mixed model with random parameters and dummy variable model approaches are almost same effective (Zeng *et al.* 2011). The methods used in this paper have to be compared and improved in followup studies.

5 Conclusion

There was no statistical difference in the asymptote parameters, shape parameters, and growth rate parameters between various stand origins, tree structures, and stand densities according to the results. The origin had an impact on the assessment of the growth potential of the stand. Species composition had an influence on parameters among different coniferous species accompanied by a large coefficient of variation, whereas no influence was found in broadleaf species stands. Stand density exerted an impact on parameters among all species. With the increase in stand density, the influence of stand density on the growth rate parameters decreased gradually. Reasonably, the relationship between *DBH* and the height of dominant trees could be applied in site quality evaluation because the impacts of stand origin, tree structure, and stand density on dominant height growth are limited. The method is feasible for forestry management and practice, and can be applied easily, especially in coniferous stands.

Acknowledgement

This research was funded by the National Natural Science Foundation of China (grant numbers 31560209 and 31760206), the Academician Workstation of Yunnan Province of China (grant number 2018IC066), and the Ten-Thousand Talents Program of Yunnan Province, China (YNWR-QNBJ-2018-184).

References

Adeyemi, Adesoji A, 2016. Site quality assessment and allometric models for tree species in the Oban Forest, Nigeria. Journal of Sustainable Forestry 35(4):280–298.

Beltran H A, Chauchard L, Velásquez A, Sbrancia R, Pastur G M, 2006. diametric site index: an alternative method to estimate site quality in Nothofagus obliqua and N-alpina forests. CERNE 22:345–354.

Bhandari S K, Veneklaas E J, McCaw L, Mazanec R, Whitford K, Renton M, 2021. Effect of thinning and fertilizer on growth and allometry of Eucalyptus marginata. Forest Ecology and Management. 479, 118594.

Buda N J , Wang J R, 2006. Suitability of two methods of evaluating site quality for sugar maple in central Ontario. The Forestry Chronicle 82(5):733–744.

Chen Y, Yang Y, Zhang H, Yang X, Li D, 2000. A study on site quality evaluation of natural tropical mountainous rain forest in Hainan Island. Forest Research (02):134–140.

Deng, C., Zhang, S., Lu, Y., Froese, R.E., Ming, A., Li, Q., 2019. Thinning effects on tree height diameter allometry of masson pine (*Pinus massoniana* Lamb.). Forests. 10, 1129.

Duan G, Gao Z, Wang Q, Fu L, 2018.Comparison of Different Height-Diameter Modeling Techniques for Prediction of Site Productivity in Natural Uneven-Aged Pure Stands. Forests 9–63.

Fu L, Lei X, Sharma R P, Li H, Zhu G, Hong L, You L, Duan G, Guo H, Lei Y, Li Y, Tang S, 2018. Comparing height–age and height–diameter modeling approaches for estimating site productivity of natural uneven-aged forests. Forestry 91:419–433.

Fu L, Zeng W, Tang S, Sharma E, Li H, 2012. Using linear mixed model and dummy variable model approaches to construct compatible single-tree biomass equations at different scales – a case study for masson pine in southern china. Journal of Forest Science (58):101–115.

Goelz J C G, Burk T E, 1992. Development of a well-behaved site index equation: jack pine in north central Ontario. Canadian Journal of Forest Research 22(6): 776–784.

Huang S, Titus S J, 1994. An age-independent individual tree height prediction model for boreal spruce-aspen stands in Alberta. Canadian Journal of Forest Research 24(7): 1295–1301.

Huang S, Titus S J, 1993. An index of site productivity for uneven-aged or mixed-species stands. Canadian Journal of Forest Research. 23(3): 558–562.

Kourosh, Ahmadi, Seyed, Jalil, Alavi, Masoud, 2017. Constructing site quality curves and productivity assessment for uneven-aged and mixed stands of oriental beech (*fagus oriental lipsky*) in hyrcanian forest, Iran. Forest Science and Technology 13:41–46. Meyer H A, 1940. A mathematical expression for height curves. Journal of Forestry 38:415–420.

Larson P R, 1963. Stem form development of forest trees. Forest Science, 1963, 9(suppl_2):a0001–42.

Lee, D, Beuker, E, Viher-Aarnio, A, Hynynen, J, 2021. Site index models with density effect for hybrid aspen (*Populus tremula* L. × P. *tremuloides* Michx.) plantations in southern finland. Forest Ecology and Management 480:118669.

Molina-Valero J A, Diéguez-Aranda U, Álvarez-González J G, Castedo-Dorado F, Pérez-Cruzado C, 2019. Assessing site form as an indicator of site quality in even-aged Pinus radiata D. Don stands in north-western Spain. Annals of Forest Science 76:113.

Moreno-Fernández D, Álvarez-González J G, Rodríguez-Soalleiro R, Pasalodos-Tato M, Pérez-Cruzado C, 2018. National-scale assessment of forest site productivity in Spain. Forest Ecology and Management 197–207.

Nicholas N S, Zedaker S M, 1992. Expected stand behavior: site quality estimation for southern Appalachian red spruce, Forest Ecology and Management, 47: 39–50.

Nigh, G, Aravanopoulos, F A, 2015. Engelmann spruce site index models: a comparison of model functions and parameterizations. Plos One 10(4):e0124079.

Peng C, 2000. Growth and yield models for uneven-aged stands: past, present and future. Forest Ecology & Management 132(2):259–279.

Reinhardt E D, 1982. Influence of site quality on the height-diameter relationship of western larch. University of Montana, Dissertation 13–20.

Skovsgaard J P, Vanclay J K, 2008. Forest site productivity: a review of the evolution of dendrometric concepts for even-aged stands. Forestry 81:13–31.

Wang B B, Shumway D L, 1982. Site quality estimation using height and diameter. Forest Science 28(3):639–645.

Trorey L G, 1932. A mathematical method for the construction of diameter height curves based on site. The Forestry Chronicle 8:121–132.

Vanclay J K, Henry N B, 1988. Assessing site productivity of indigenous cypress pine forest in southern Queensland. Commonwealth Forestry Review 67(1): 53.

Wang C H, Hann D W, 1988. Height-Diameter Equations for Sixteen Tree Species in the Central Western Willamette Valley of Oregon. Research Paper 51, Forest Research Laboratory, Oregon State University, Corvallis.

Wang, G.G., 1998a. An ecologically based model for site index conversion among species. Canadian Journal of Forest Research 28(2): 234–238.

Wang, G.G., 1998b. Is height of dominant trees at a reference diameter an adequate measure of site quality? Forest Ecology and Management 112, 49–54.

Weiskittel A R, Hann D W, Kershaw J A, Vanclay J K, 2011. Forest growth and yield modeling. John Wiley & Sons: New York, USA, pp. 45–52.

Wu H, Dang K, Tian X L, Sun S, Chen S, Zhao P, Cao T, 2015. Evaluating site quality for secondary forests and plantation in Qinling Mountains. Scientia Silvae Sinicae 51(04):78–88.

Wykoff W R, Crookston N L, Stage A R, 1982. User's guide to the stand prognosis model. USDA For Serv Gen Tech Rep INT–133.

Zeng W S, Tang S Z, Xia Z S, Zhu S, Luo H Z, 2011.Using linear mixed model and dummy variable model approaches to construct generalized single tree biomass equation in Guizhou. Forest Research, 24(3):285–291.