



Site index for Chinese fir plantations varies with climatic and soil factors in southern China

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Abstract Chinese fir [*Cunninghamia lanceolata* (Lamb.) Hook.] has a large native distribution range in southern China. Here, we tested differences in productivity of Chinese fir plantations in different climatic regions and screened the main environmental factors affecting site productivity in each region. Relationships of a Chinese fir site index with climatic factors and the soil physiochemical properties of five soil layers were examined in a long-term positioning observation trial comprising a total of 45 permanent plots in Fujian (eastern region in the middle subtropics), Guangxi (south subtropics) and Sichuan (central region in the middle subtropics) in southern China. Linear mixed effects models were developed to predict the site index for Chinese fir, which was found to vary significantly among different climatic regions. Available P, total N, bulk density and total K were dominant predictors of site index in three climatic regions. The regional linear mixed models built

using these predictors in the three climatic regions fit well ($R^2 = 0.86\text{--}0.97$). For the whole study area, the available P in the 0–20-cm soil layer and total N in the 80–100-cm soil layer were the most indicative soil factors. MAP was the most important climatic variable influencing the site index. The model evaluation results showed that the fitting performance and prediction accuracy of the global site index model using the climatic region as the dummy variable and random parameters and the most important soil factors of the three climatic regions as predictors was higher than that of global site index model using the climatic variable and the most indicative soil variables of the whole study area. Our results will help with further evaluation of site quality of Chinese fir plantations and the selection of its appropriate sites in southern China as the climatic changes.

Keywords Site productivity · Site index · Climate · Soil · Chinese fir

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Introduction

Potential forest productivity in different site conditions is one of the most important criteria for decision-making in forest management (Kayahara et al. 1998). Setting forest productivity potential as a reference criterion creates an opportunity for forest managers to select the most suitable tree species and allows foresters to accurately predict stand yield (Bergès et al. 2005). Forest site productivity may be defined as the potential of a site to produce timber or forest biomass (Sharma et al. 2012), and site index, defined as the average height of dominant trees at a given age, is widely used as a measure of forest site productivity (Seynave et al. 2005; Shen et al. 2018).

Stand growth is dependent on numerous environmental factors such as climate, topography, soil and vegetation (Grant et al. 2010; Beaulieu et al. 2011). As the global climate changes, however, the relationship between forest growth and environmental variables becomes even more complex (Bravo-Oviedo et al. 2010). Because an accurate estimate of the relationship between forest growth or productivity and these environmental factors is essential for evaluating forest site quality as the climate changes, the site index has been indirectly predicted using ecological environmental factors and applied to evaluate site quality (Curt et al. 2001; Özel et al. 2020). The most commonly used method for evaluating site productivity, based on various environmental factors, is to predict site index as a function of climatic, topography and soil factors (Wang et al. 2004; Gülsoy and Çınar 2019). Numerous studies have explored the relationship between site index and various site quality variables to select the best site factors for explaining the variation in site index, but have had varying degrees of success (Chen et al. 1998; Mitsuda et al. 2001; Fontes et al. 2003; Wang 2011). Based on the site–growth relationship, many studies have focused on predicting the site index using climatic and soil variables. The site index has been shown to be related to soil type, lithology, depth, texture and pH and level of soil nutrients (Grant et al. 2010; Farrelly et al. 2011a, b; Paulo et al. 2015; Subedi and Fox 2016). Therefore, soil variables have been considered as an important predictor of stand growth and productivity. Climatic factors are also important site factors influencing the site index (Albert and Schmidt 2010; Menéndez-Miguélez et al. 2015). Generally, hydrothermal conditions are the main climatic factors affecting forest growth (Kishchenko 2004; Tyukavina et al. 2019). At the same time, changes in temperature and precipitation patterns and increases in atmospheric CO₂ concentration could lead to major changes in forest structure and productivity (Kirilenko and Sedjo 2007; Wamelink et al. 2009). Several studies predicted the site index as a function of various climatic factors (Monserud et al. 2006; Albert and Schmidt 2010; Menéndez-Miguélez et al. 2015). Because of differences in regions and tree species investigated in different studies, the determined variables with important predictive ability for explaining the site index varied among these studies (McKenney and Pedlar 2003; Sabatia and Burkhart 2014). Because forest growth is affected by various site factors, it is absolutely critical to select suitable site factors for describing site characteristics in different regions and revealing the relationship between site and forest growth.

Chinese fir [*Cunninghamia lanceolata* (Lamb.) Hook.] is native to southern China and the most important timber tree species in this region, where it is widely distributed in areas with a subtropical climate. Because of its vast production area, its growth can vary greatly among the southern, northern and central production areas within the subtropical belt

of southern China (Tong and Liu 2019). Given the increasing changes in climatic patterns worldwide, it becomes more urgent and critical to fully understand the relationships among forest growth, yield prediction and environmental variables. Developing a site index model for Chinese fir based on various site factors is also critical and will help to quantitatively evaluate site quality of non-forest land. In previous studies, site quality for Chinese fir was evaluated by classifying site types and compiling a site index table (Huang et al. 1989; Li 2017). However, the essential relationship between site productivity and site quality variables of Chinese fir in different climatic regions is not well understood, and the influence of climatic factors and soil physiochemical properties in different soil layers, in particular, on site productivity has not been fully investigated. Therefore, in this study, we explored the importance of various climatic and soil factors in predicting the growth of Chinese fir in southern China.

The main objectives of this study were to (1) explore the relationship of site index with climatic factors and the physical and chemical properties of the top five soil layers, (2) analyze the variation in site index in different climatic regions, (3) select the dominant site factors affecting site productivity in each climatic region and examine the ability of soil factors in different soil layers to predict the Chinese fir site index in each region, and (4) develop linear mixed effects models to predict site index using these dominant site factors as predictors. The results of this study will help us better understand the response of Chinese fir site index to various site factors, which will provide guidance or a reference for evaluating site quality for Chinese fir plantations in southern China.

Materials and methods

Study area and site index data

Study sites in three provinces in southern China (Fig. 1) included Fujian (eastern region in mid-subtropics), Sichuan (central region in mid-subtropics) and Guangxi (southern subtropical climatic zone). The soil type is mainly red soil developed on granite in Fujian and Guangxi and red soil developed on shale in Sichuan.

In each of these three regions, long-term positioning observation test plantations of Chinese fir established in 1982, with even-aged trees, were selected for this study. In each study area, 15 plots were installed in a random block arrangement with five initial planting densities: A (1667 trees ha⁻¹, 2 m × 3 m), B (3333 trees ha⁻¹, 2 m × 1.5 m), C (5000 trees ha⁻¹, 2 m × 1 m), D (6667 trees ha⁻¹, 1 m × 1.5 m), E (10,000 trees ha⁻¹, 1 m × 1 m). Each treatment level was replicated three times for a total of 15 plots.

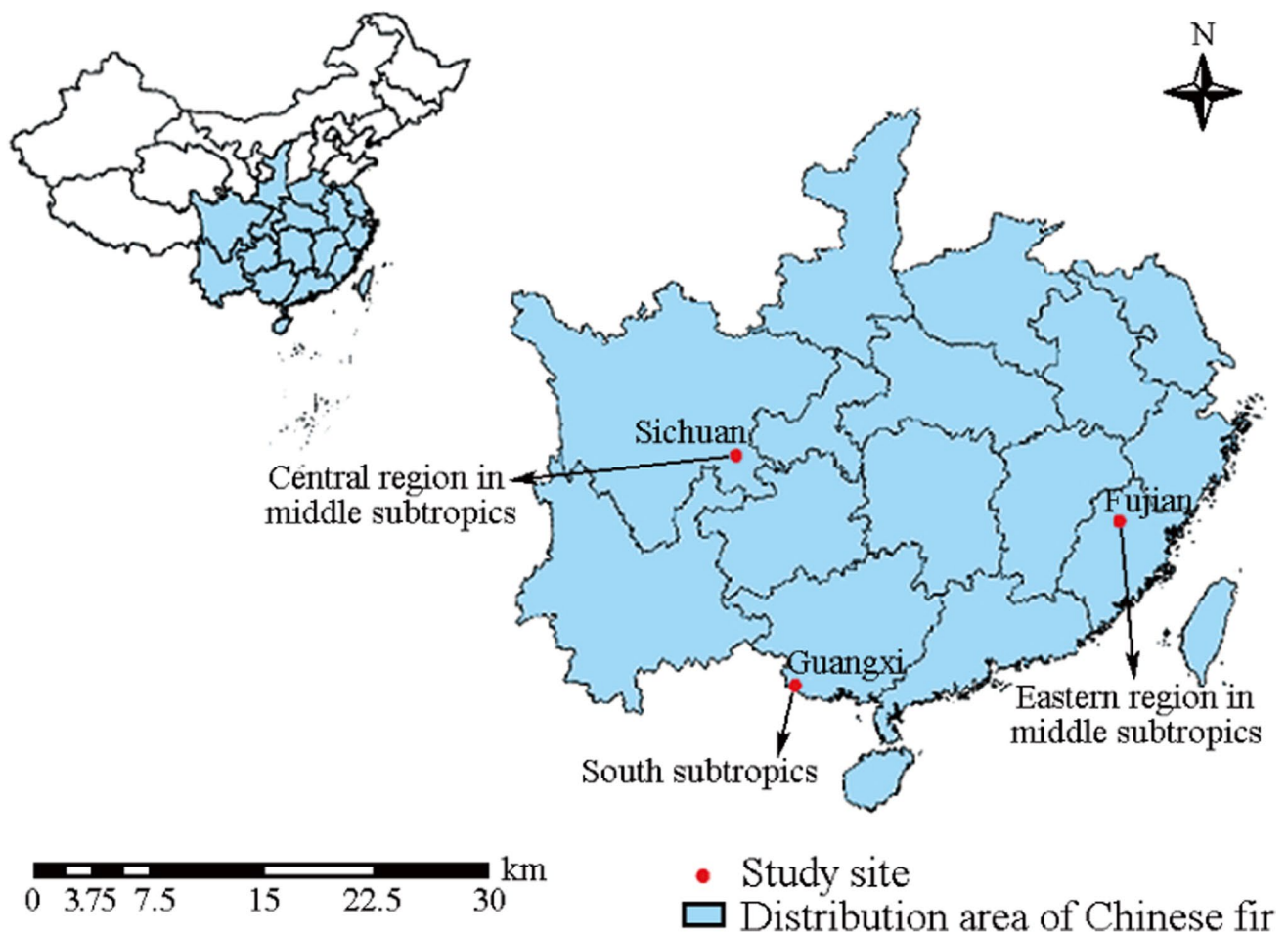


Fig. 1 Map of distribution of Chinese fir plantations and location of study sites in China

Each plot was 20 m × 30 m and surrounded by a 2-row buffer zone, comprising similarly treated trees. Three experiments were established using bare-root seedlings, and all trees were tagged. After afforestation, each plot was surveyed in the winter at 1–3-year intervals. Height data for 18–20 years were obtained from each plot. The dominant height was computed as the average height of six tallest trees in each plot. The site index was calculated for each plot at the reference age of 20 years using the dominant height data (Fujian and Guangxi) or using the Richards model with three parameters (Sichuan).

Climatic data

ClimateAP is an online platform to generate annual, seasonal and monthly climatic data for historical and future periods in the Asia Pacific region (<http://climateap.net/>; Wang et al. 2012, 2017a, b). To explore the effects of climate factors on the site index of Chinese fir plantations, climatic data of each site was obtained using ClimateAP through spatially interpolated estimations based on site longitude, latitude, and

elevation. In this study, eight climatic variables including mean annual temperature (MAT, °C), mean annual precipitation (MAP; mm), degree-days above 5 °C (DD5), degree-days below 0 °C (DD_0), July maximum mean temperature (Tmax07; °C), summer mean maximum temperature (Tmax_JJA; °C), spring precipitation (PPT_MAM; mm), annual heat–moisture index (AHM) were chosen as candidate variables for model fitting of the site index. What's more, AHM integrates MAT and MAP data into a single parameter, as shown below:

$$AHM = \frac{(MAT + 10)}{MAP} \times 1000 \quad (1)$$

where *AHM* is the annual heat–moisture index. *MAT* is the mean annual temperature. *MAP* is the mean annual precipitation. Lower *AHM* values indicate relatively wetter conditions. The climatic data for each study site are shown in Table 1.

Table 1 Summary of elevation, latitude, longitude and climatic variables at the three study areas

Regions	Elevation (m a.s.l.)	Latitude (°N)	Longitude (°E)	MAT (°C)	AHM (mm)	DD_0 (°C)	DD5 (°C)	Tmax_JJA (°C)	PPT_MAM (°C)	Tmax07 (°C)
Fujian	300	27.08	117.72	18.95	1798.27	1.50	5064.97	32.13	716.17	33.56
Guangxi	460	22.10	106.72	22.02	1488.91	0.00	6147.63	31.76	349.19	31.91
Sichuan	440	28.78	105.38	18.39	1173.5	1.75	4867.28	30.60	252.09	31.36

MAT is mean annual temperature; MAP, mean annual precipitation; AHM, annual heat-moisture index; DD_0, degree-days below 0 °C; DD5, degree-days above 5 °C; Tmax_JJA, summer mean maximum temperature; PPT_MAM, spring precipitation; Tmax07, July maximum mean temperature

Soil data

Soil samples were collected by digging a soil profile in mature Chinese fir plantations in Fujian, Guangxi and Sichuan. Three soil profiles were selected and diagonally distributed in each plot. A total of 135 soil profiles were manually dug at the three study sites. Each soil profile was 1 m deep and divided into five soil depths: 0–20, > 20–40, > 40–60, > 60–80 and > 80–100 cm. Bulk density was determined by inserting three cutting rings (5 cm height, 5 cm inner diameter and known volume) at each depth of the soil profile. At the same time, soil water content was determined from soil samples collected in three aluminum boxes placed at each depth. Approximately 1 kg of soil was sampled at each depth, stored in bags and transported to the laboratory. The soil samples were then air-dried, ground, sieved, then analyzed for pH, organic matter content (g kg^{-1}), total N (g kg^{-1}), alkali-hydrolyzable N (mg kg^{-1}), total P (g kg^{-1}), available P (mg kg^{-1}), total K (g kg^{-1}), available K (mg kg^{-1}), bulk density (g cm^{-3}), water content (%), C/N ratio, C/P ratio and N/P ratio. The soil pH was determined using the potentiometer method using a suspension of 1-part soil to 2.5 parts 1 M KCl. Soil organic matter content was measured using the $\text{K}_2\text{Cr}_2\text{O}_7\text{-H}_2\text{SO}_4$ oxidation method. Total N was determined using the Kjeldahl method and alkali-hydrolyzable N using alkaline hydrolysis method. Total P was measured using the NaOH alkali solution–molybdenum antimony colorimetric method and available P using the NaHCO_3 alkali solution–molybdenum antimony colorimetric method. Total K and available K were determined using flame photometry (Bao 2000; Venanzi et al. 2016). The soil data for the three provinces are summarized in Table 2.

Data analyses

Analysis of variance (ANOVA) and multiple comparisons test were performed to compare the differences in site index among different regions. The relationship between site index and soil factors at the different soil depths in the three provinces and that between site index and climatic variables were examined by Pearson correlation analysis. To reveal the importance of site factors across regions with different climates, while taking into account the interdependency among independent variables, stepwise regression analysis was used to limit the number of explanatory variables for the three climatic regions, and the most important site quality variables affecting the site index of Chinese fir in each climatic region were determined.

Linear mixed effects model (LMM)

The linear mixed effects model was used to predict the site index as a function of the most important soil factors and

Table 2 Soil characteristics for the three study areas in Chinese fir plantations in Fujian, Guangxi and Sichuan in China

Regions	pH	Organic matter (g kg ⁻¹)	Total N (g kg ⁻¹)	Alkali-hydrolyz- able N (mg kg ⁻¹)	Total P (g kg ⁻¹)	Available P (mg kg ⁻¹)	Total K (g kg ⁻¹)
Fujian	4.37 (3.45, 5.38)	20.23 (6.68, 45.24)	0.87 (0.38, 1.58)	71.79 (27.12, 145.31)	0.47 (0.3, 0.65)	2.53 (0.32, 4.46)	23.52 (12.69, 29.76)
Guangxi	3.83 (3.4, 4.11)	18.10 (8.97, 39.07)	0.78 (0.47, 1.39)	78.23 (48.92, 148.18)	0.23 (0.19, 0.31)	0.6 (0.15, 2.32)	1.35 (0.71, 2.72)
Sichuan	3.96 (3.62, 4.2)	11.77 (1.06, 43.04)	0.46 (0.07, 1.31)	41.55 (7.43, 123.63)	0.18 (0.08, 0.63)	0.63 (0.16, 2.74)	18.11 (8.34, 39.47)
Regions	Available K (mg kg ⁻¹)	Bulk density (g cm ⁻³)	C/N	C/P	N/P	Water content (%)	
Fujian	56.36 (26.33, 117.79)	1.33 (1.21, 1.55)	13.12 (6.08, 26.02)	25.22 (7.66, 67.03)	1.88 (0.75, 3.67)	26 (19, 34)	
Guangxi	12.52 (5.24, 35.84)	1.53 (1.29, 1.68)	12.96 (9.2, 17.54)	44.50 (18.07, 95.25)	3.32 (1.69, 5.65)	14 (11, 18)	
Sichuan	48.07 (24.62, 92.34)	1.51 (1.06, 1.73)	15.51 (1.45, 51.83)	39.16 (3.28, 139.57)	2.67 (0.37, 6.08)	26 (16, 40)	

Values in parentheses are minimum and maximum values

climatic factors. Three regional models were established based on the determined soil factors for each climatic region, a climatic model also developed using the most dominant climatic variable. The following basic model was used for modeling site index related to regional models and climatic model:

$$S_I = \alpha_0 + \alpha X + \varepsilon \quad (2)$$

where S_I is the site index, α_0 is the intercept, α is a vector of coefficients, X is a vector of independent variables, including various soil and climatic variables, and ε is the error term, $\varepsilon \sim N(0, \sigma^2)$.

Considering the differences among different climatic regions, we treated climatic region as a dummy variable. A global site index model for the whole study area was established, which used the dummy variable and the most important soil factors of the three climatic regions as predictors. The basic site index model could be given by:

$$S_I = \beta_0 + S_1(\beta_1 X_1) + S_2(\beta_2 X_2) + S_3(\beta_3 X_3) + \varepsilon \quad (3)$$

where S_I is the site index, β_0 is the intercept, $\beta_1, \beta_2, \beta_3$ are vectors of coefficients for Fujian, Guangxi and Sichuan, respectively; X_1, X_2, X_3 are vectors of independent variables for Fujian, Guangxi and Sichuan, respectively; S_1, S_2, S_3 represent dummy variables for Fujian, Guangxi and Sichuan, respectively; $S_1 = 1$ indicates the Fujian and 0 indicates the other climatic regions; $S_2 = 1$ indicates the Guangxi region and 0 indicates the other climatic regions; $S_3 = 1$ indicates the Sichuan and 0 indicates the other climatic regions.

In addition, based on the important soil factors selected in the three climatic regions, the relationship between these soil

factors and site index was explored in the whole study area. A polynomial relation between the soil factors and site index was obtained, from which the soil factors most related to site index in the whole study area were determined. Therefore, another global site index model was established by using the most important soil and climatic variables in the whole study area.

We selected 30 plots from the 45 plots as modeling data, and the remaining 15 plots were used as verification data. Since data collected from three regions and five planting densities in each region, the random effects of region and planting density were added to the intercept of the site index model. In addition, we used the independent equal variance structure for describing the variance–covariance structure of random effects. Parameters in the LMM models were estimated through restricted maximum likelihood approach implemented in ForStat2.2 software (Tang et al. 2009).

Model evaluation

The model evaluation and testing were based on the mean absolute error (MAE), mean relative error (MRE), root mean square error (RMSE) and coefficient of determination (R^2).

$$M_{AE} = \frac{1}{n} \sum_{i=1}^n |y_i - \hat{y}_i| \quad (4)$$

$$M_{RE} = \frac{1}{n} \sum_{i=1}^n \left| \frac{y_i - \hat{y}_i}{y_i} \right| \quad (5)$$

$$R_{\text{MSE}} = \sqrt{\frac{1}{n-1} \sum_{i=1}^n |y_i - \hat{y}_i|^2} \quad (6)$$

$$R^2 = 1 - \left[\frac{\sum_{i=1}^n (y_i - \hat{y}_i)^2}{\sum_{i=1}^n (y_i - \bar{y})^2} \right] \quad (7)$$

where y_i is the observed value, $\hat{y}_i$ is the predicted value, $\bar{y}$ is the mean value of the observed value, and n is the number of the sample plots.

The independent sample data not used in the modeling were used to test the model, and the prediction performance of the global site index models was evaluated. Equation 8 (Jiang and Li 2014) was used to calculate the random parameter value in the LMM models:

$$\hat{b}_k = \hat{D}\hat{Z}_k^T (\hat{Z}_k\hat{D}\hat{Z}_k^T + \hat{R}_k)^{-1} \hat{e}_k \quad (8)$$

where $\hat{b}_k$ is the random parameter, $\hat{D}$ is the variance–covariance matrix of the random effect parameters, $\hat{R}_k$ is the variance–covariance structure in the model, and $\hat{Z}_k$ is the design matrix of random effect. The actual value minus the predicted value calculated using the fixed effect parameters is $\hat{e}_k$.

Results

Variation in site index across different climatic regions

The effect of climatic region on the site index of Chinese fir was significant. The site index in Sichuan province was

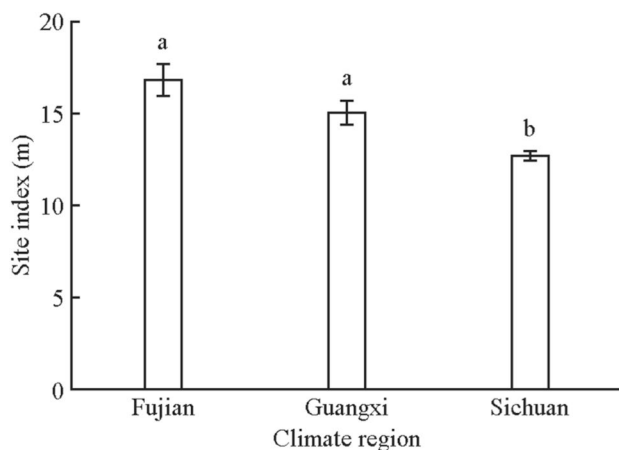


Fig. 2 Variation in Chinese fir site index among different climatic regions. Data represent mean $\pm$ standard error (SE) of the mean (SEM). Different lowercase letters indicate significant differences ($P < 0.05$)

significantly lower than that in Fujian and Guangxi provinces (Fig. 2).

Correlation of Chinese fir site index with soil and climatic variables

Soil variables

The correlations between soil factors at the five soil depths and site index in different climatic regions are shown in Fig. 3. The correlation between site index and a given soil factor varied with the climatic region and soil depth, indicating that soil factors in different regions and at different depths had different effects on the site index. Fujian site index of Chinese fir was strongly negatively correlated with the total P at all soil depths and was strongly positively correlated with available P in the top three soil layers (0–20, > 20–40, > 40–60 cm) ($P < 0.05$). The correlation between Fujian site index and available P decreased with the increase in soil depth; consequently, the Fujian site index was negatively correlated with available P in the last two soil layers (> 60–80 cm, > 80–100 cm). The strength of the correlation between Fujian site index and available K increased with the increase in soil depth, reaching statistical significance in the last three soil layers (> 40–60, > 60–80, > 80–100 cm) ($P < 0.05$). A significant positive correlation was detected between Fujian site index and soil bulk density, although the strength of the correlation decreased with the increase in soil depth. The opposite trend was observed for N/P ratio (i.e., the deeper the soil layer, the stronger the correlation), and a significant correlation was observed in the lowest soil layer (> 80–100 cm). Soil pH, total K and C/P ratio at all soil depths were positively correlated with the Fujian site index, although the correlations were not statistically significant. Additionally, the Fujian site index was negatively correlated with the soil water content at all soil depths; however, Fujian site index was not closely correlated with the soil organic matter content, total N and alkali-hydrolyzable N, and there was no obvious soil layer effect.

The Guangxi site index, however, was positively correlated with total P and water content of all soil layers and negatively correlated with available P, C/P ratio and N/P ratio of all soil layers, and its correlation with available P was statistically significant ($P < 0.05$). Moreover, the Guangxi site index was significantly positively correlated with total K at all soil depths, consistent with the Fujian site index. In addition, the organic matter content, C/N ratio and total N content in all soil layers (except the total N content of the > 80–100-cm soil layer) were negatively correlated with the Guangxi site index. However, soil pH, alkali-hydrolyzable N and bulk density of different soil layers showed weak or nonsignificant correlations with the Guangxi site index,

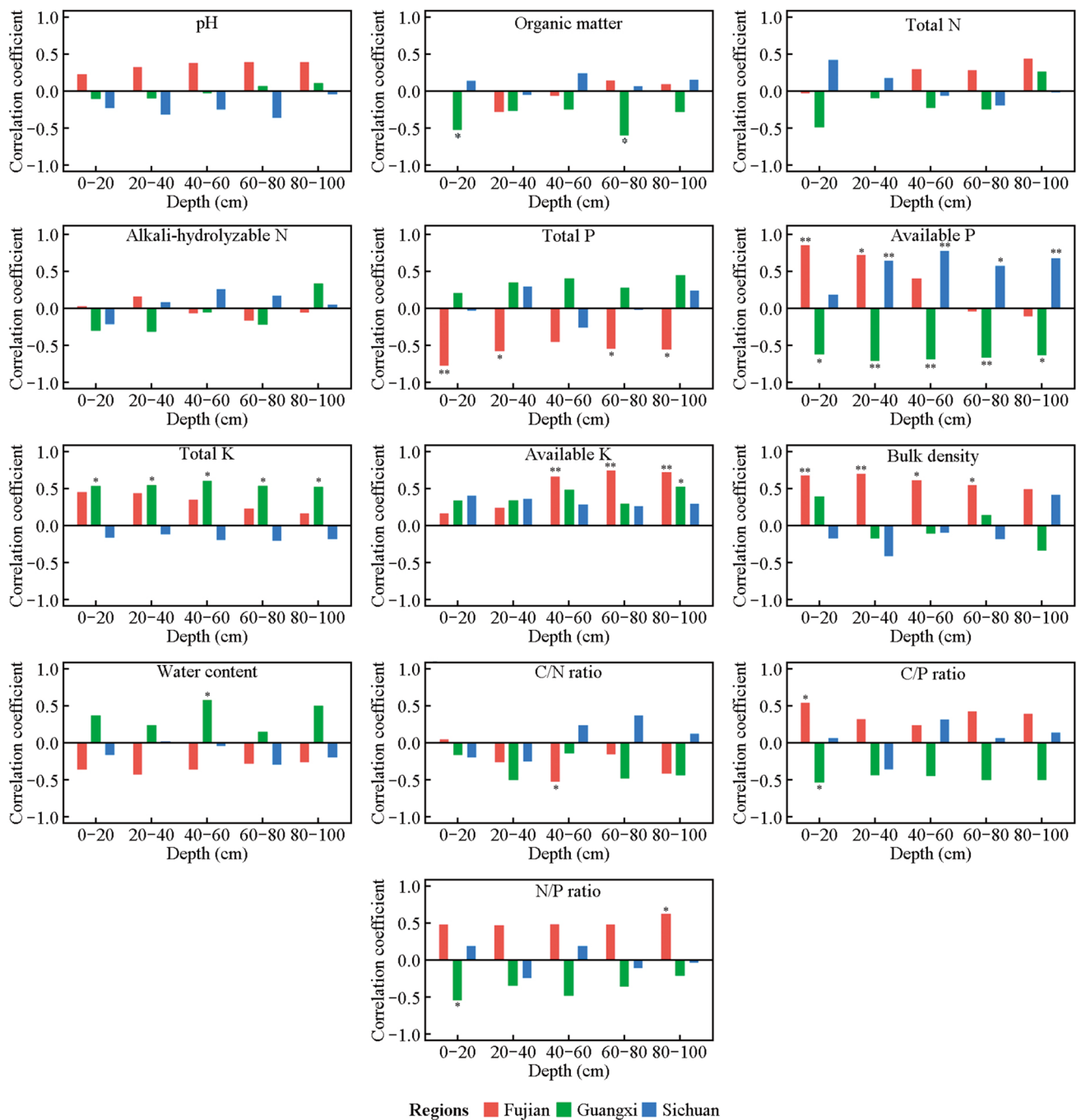


Fig. 3 Plots showing the correlation coefficient between site index and soil variables at five depths in three different climatic regions. Significant differences: * $P < 0.05$ and ** $P < 0.01$ levels

and these correlations were not verified with the increase in soil depth.

Compared with Fujian and Guangxi site indices, the Sichuan site index showed a negative correlation with total K at all soil depths. A significant positive response of the Sichuan site index to increasing available K of all soil layers, according to this result, the three climatic regions were

consistent. Furthermore, available P showed a significant positive relationship with the Sichuan site index at all soil depths, except at 0–20 cm. The correlations between Sichuan site index and other soil factors were weak or not significant, and the correlations were not verified with the increase in soil depth.

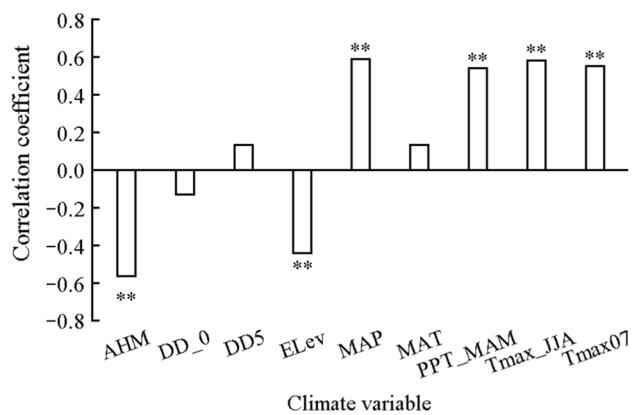


Fig. 4 Correlation coefficient between site index and climatic variables. Significance: ** $P < 0.01$ level

The results showed that soil variables closely related to the site index were not consistent due to the differences in climatic conditions among different geographical locations and the uneven distribution of nutrients in different soil profiles. Additionally, the correlation between a given soil variable and site index varied across the three climatic regions.

Climatic variables

The correlation between the site index of all plots and climatic and elevation factors is shown in Fig. 4. The site index showed a significant correlation with elevation (Elev), MAP, AHM, Tmax_JJA, PPT_MAM and Tmax07. Additionally, the site index was significantly positively correlated with MAP, Tmax_JJA, PPT_MAM and Tmax07 and significantly negatively correlated with Elev and AHM. However, there was no significant correlation between site index and various thermal variables, such as MAT, DD_0 and DD5.

Linear mixed effects model

Regional model based on soil factors

Based on the stepwise regression analysis, the dominant soil variables influencing site index varied among the different climatic regions and soil depths. All these selected variables were significant ($P < 0.05$) in the site index models of these three climatic regions. The final base models for each climatic region are:

$$S_{IF} = \alpha_{01} + \alpha_{11}(AP_1) + \alpha_{21}(TN_5) + \alpha_{31}(BD_4) + \varepsilon \quad (9)$$

Table 3 Regional models based on soil factors and climatic model using MAP

Item	Parameters	Linear mixed models			
		Fujian	Guangxi	Sichuan	Climatic model
Fixed-effects parameters	α_{01}	-19.913			
	α_{11}	2.881			
	α_{21}	8.119			
	α_{31}	17.204			
	α_{02}		25.539		
	α_{12}		-7.919		
	α_{22}		-8.258		
	α_{32}		2.034		
	α_{03}			11.547	
	α_{13}			1.254	
	α_{23}			0.983	
	α_{04}				5.041
	α_{04}				0.007
Variance components	α_1^2	0.458			
	α_2^2		0.308		
	α_3^2			0.116	
	α_C^2				7.782E-11
	α^2	0.471	1.026	0.180	5.347
Fitting performance	MAE	0.455	0.675	0.271	1.792
	MRE	0.028	0.047	0.022	0.123
	RMSE	0.526	0.686	0.351	2.286
	R^2	0.973	0.864	0.863	0.358

MAE is mean absolute error; MRE, mean relative error; RMSE, root mean square error

$$S_{IG} = \alpha_{02} + \alpha_{12}(AP_3) + \alpha_{22}(TN_1) + \alpha_{32}(BK_3) + \varepsilon \quad (10)$$

$$S_{IS} = \alpha_{03} + \alpha_{13}(AP_3) + \alpha_{23}(AP_2) + \varepsilon \quad (11)$$

Accounting for the random effects of planting density on site index, we added the random parameters to the intercept, and the one-level LMM model is given by Table 3 as:

$$S_{IF} = \alpha_{01} + \mu_{01} + \alpha_{11}(AP_1) + \alpha_{21}(TN_5) + \alpha_{31}(BD_4) + \varepsilon \quad (12)$$

$$S_{IG} = \alpha_{02} + \mu_{02} + \alpha_{12}(AP_3) + \alpha_{22}(TN_1) + \alpha_{32}(TK_3) + \varepsilon \quad (13)$$

$$S_{IS} = \alpha_{03} + \mu_{03} + \alpha_{13}(AP_3) + \alpha_{23}(AP_2) + \varepsilon \quad (14)$$

where S_{IF} , S_{IG} , and S_{IS} represent the site index of Fujian, Guangxi and Sichuan, respectively; μ_{01} , μ_{02} , μ_{03} are the random-effect parameters of the planting density; $\mu_{01} \sim N(0, \sigma_1^2)$, $\mu_{02} \sim N(0, \sigma_2^2)$, and $\mu_{03} \sim N(0, \sigma_3^2)$, and σ_1^2 , σ_2^2 , σ_3^2 are the covariance matrices of the random effect in Fujian, Guangxi and Sichuan, respectively; A_p is available P; T_N is total N; B_D is bulk density; and T_K is total K. Numbers 1–5 represent the five soil layers: 1, 0–20 cm; 2, > 20–40 cm; 3, > 40–60 cm; 4, > 60–80 cm; 5, > 80–100 cm. The same definitions are used throughout.

In Fujian, three variables were selected in the final model, including available P in the 0–20-cm soil layer, total N in the > 80–100-cm soil layer and bulk density in the > 60–80-cm soil layer, as these were the most important soil factors that significantly affected the site index; the site index values increased with the increase in available P, total N and bulk density in the specified soil layers. In Guangxi, available P in > 40–60-cm soil layer, total N in 0–20-cm soil layer and total K in > 40–60-cm soil layer were the most important factors controlling the growth of Chinese fir. The Guangxi site index decreased with the increase in available P in (> 40–60 cm) and total N (0–20 cm), and increased linearly with the increase in total K (> 40–60 cm). In Sichuan, available P in > 40–60-cm and > 20–40-cm soil layers had significant effects on site index.

The fitting results of the linear mixed models for the three climatic regions showed that MAE was below 0.7, MRE was less than 0.05, RMSE was less than 0.7, and R^2 ranged from 0.86 to 0.97. These values from the planting density-level random effects model indicated that the models of the three climatic regions fit the data well and better simulated the variation in site index in the local area.

Effect of climatic factors on site index

Stepwise regression analysis showed that MAP was the main climatic factor that significantly influenced the site index. The final base model is:

$$S_{IC} = \alpha_{04} + \alpha_{14}(MAP) + \varepsilon \quad (15)$$

Accounting for the random effects of region on site index, the region-level random-effect parameter was incorporated into the intercept, and the LMM model is given in Table 3 as:

$$S_{IC} = \alpha_{04} + \mu_{04} + \alpha_{14}(MAP) + \varepsilon \quad (16)$$

where S_{IC} represents the site index estimated by the climatic variable; μ_{04} is the random-effect parameter of the region, and $\mu_{04} \sim N(0, \sigma_C^2)$.

Although the correlation analysis showed that six climatic factors had significant correlations with the site index, MAP was the only climatic variable output at $P < 0.05$ when considering the multicollinearity of various climatic variables and the significance test of regression coefficient.

Relationship of the site index with dominant soil factors in the whole study area

The site index changed gradually with the increase in available P content within the 0–2 mg kg⁻¹ range but increased rapidly within the 2–4 mg kg⁻¹ range (Fig. 5), probably because the available P content in Guangxi and Sichuan was low (mostly within the 0–2 mg kg⁻¹ range), and the range of the site index was also small; therefore, the change in site index within this range was relatively smooth. However, the content of available P in Fujian generally ranged from 2–4 mg kg⁻¹, and the range of site index in Fujian was large. Therefore, the site index increased rapidly with the increase in available P content within the range of 2–4 mg kg⁻¹ range. The total N content of the 0–20-cm soil layer was higher than that of the soil layer of > 80–100-cm soil layer. The content of total N in the 0–20-cm soil layer mainly ranged from 0.7 to 1.5 g kg⁻¹; however, the site index increased with the increase in total N content within the 0.7–1.3 g kg⁻¹ range, and decreased slightly within the 1.3–1.5 g kg⁻¹ range (Fig. 5), which may be due to the fact that the total N content of the 0–20-cm soil layer in Sichuan was relatively low (0.7–1.3 g kg⁻¹) and was positively correlated with the site index. However, the total N content of the 0–20-cm soil layer in Fujian and Guangxi was relatively high and was negatively correlated with the site index within the 1.3–1.5 g kg⁻¹ range. Additionally, the site index changed gradually with the increase in the total N content of the soil layer of > 80–100 cm within the 0–0.4 g kg⁻¹ range but increased rapidly within the 0.5–1.0 g kg⁻¹ range (Fig. 5). The site index increased slightly with the increase in soil bulk density in the > 60–80-cm soil layer within the 1.2–1.4 g cm⁻³ range but decreased significantly with further increase in soil bulk density from 1.4–1.7 g cm⁻³. However, the data range of

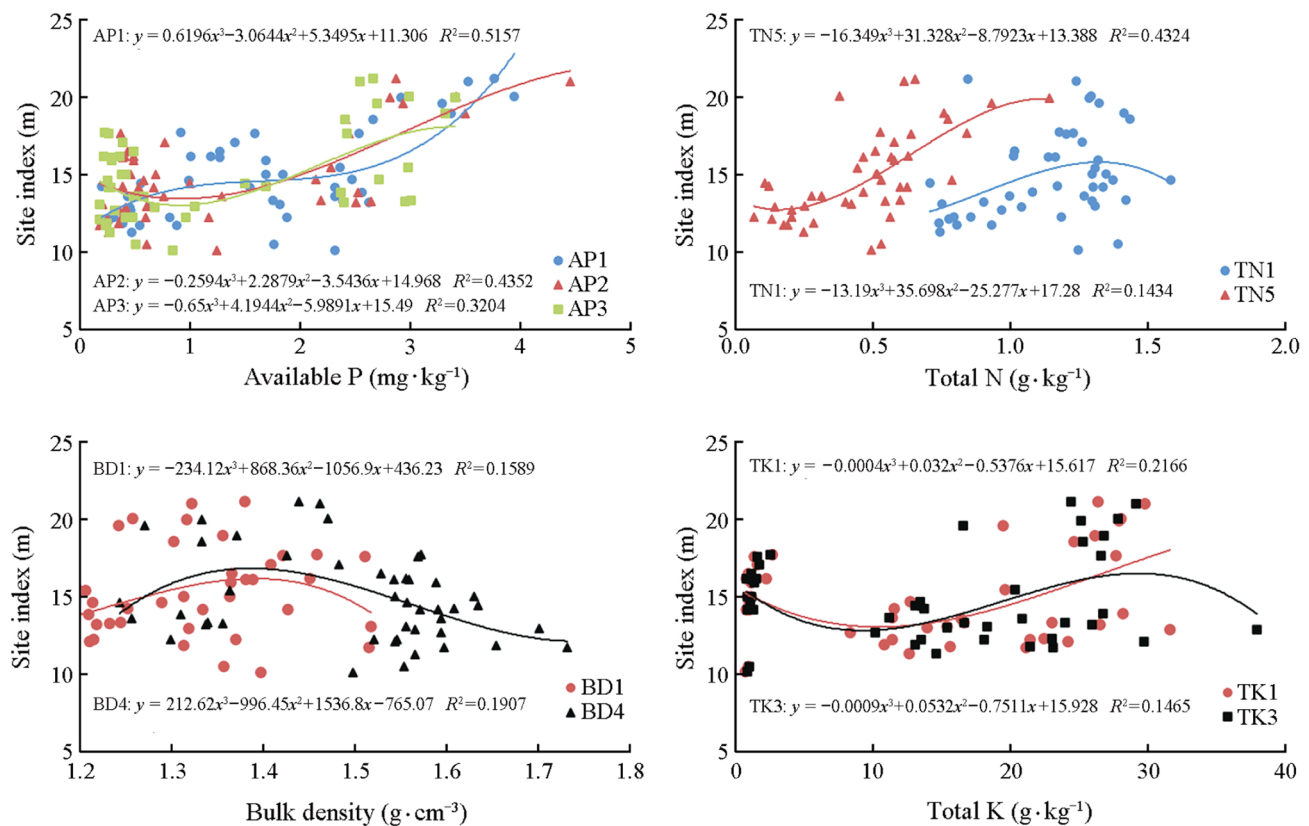


Fig. 5 Correlation of site index with available P (AP), total N (TN), bulk density (BD) and total K (TK) in the whole study area. Numbers 1–5 in variable names represent the five soil layers: 1, 0–20 cm;

2, >20–40 cm; 3, >40–60 cm; 4, >60–80 cm; 5, >80–100 cm. y is the dependent variable (site index), x is the independent variable (AP, TN, BD, TK)

bulk density in the 0–20-cm soil layer was relatively small, and changes in bulk density in the 0–20-cm soil layer had less effect on changes in the site index (Fig. 5). Total K in the >40–60-cm and 0–20-cm soil layers within the 0–3 $\text{g} \cdot \text{kg}^{-1}$ range showed no clear correlation with site index in the whole region. And site index increased with the increase in total K content within the 10–30 $\text{g} \cdot \text{kg}^{-1}$ range (Fig. 5). However, both had less effect on changes in the site index across the whole study area, mainly because of the different ranges of total K content and different correlation between site index and total K in the three climatic regions.

From Sichuan, to Guangxi, to Fujian, the available P and total N content increased gradually, consistent with the actual stand productivity. For the whole study area, the strength of the correlation between site index and total N increased with the increase in soil depth, while the

correlation between site index and available P decreased with soil depth. Meanwhile, the fitting results in Fig. 5 also showed that the available P in the 0–20-cm soil layer and total N in the >80–100-cm soil layer were the most indicative soil factor.

Development and evaluation of global site index models

The global site index model 1 for the whole study area was established using climatic region as a dummy variable and the most important soil variables of the three study sites as predictors. In addition, the global site index model 2 using climatic variable and the most indicative soil variables of the whole study area also developed. The final base model of the global site index model 1 and the global site index model 2 were listed as follows:

$$S_{I1} = \beta_0 + S_1 [\beta_{11}(AP_1) + \beta_{12}(BD_4) + \beta_{13}(TN_5)] + S_2 [\beta_{21}(AP_3) + \beta_{22}(TN_1) + \beta_{23}(TK_3)] + S_3 [\beta_{31}(AP_3) + \beta_{32}(AP_2)] + \varepsilon \quad (17)$$

$$S_{I2} = \alpha_{05} + \alpha_{15}(AP_1)^3 + \alpha_{25}(AP_1)^2 + \alpha_{35}(AN_5)^3 + \alpha_{45}(AN_5)^2 + \alpha_{55}(BD_4)^3 + \alpha_{65}(BD_4)^2 + \alpha_{75}(MAP) + \varepsilon \quad (18)$$

Table 4 Global site index model 1 based on soil variables

Item	Parameters	Global site index model 1
Fixed-effects parameters	β_0	5.986
	β_{11}	2.765
	β_{12}	17.235
	β_{13}	7.574
	β_{21}	-7.600
	β_{22}	-9.175
	β_{23}	2.536
	β_{31}	0.861
	β_{32}	1.379
	$\sigma_{\text{model 1}}^2$	574.720
Variance components	σ^2	0.926
Fitting performance	MAE	0.599
	MRE	0.042
	RMSE	0.782
	R^2	0.920

MAE is mean absolute error; MRE, mean relative error; RMSE, root mean square error

Considering the random effects of region on site index, we added the random parameters of region to the intercept of global site index model 1 and global site index model 2. Planting density was used as the group variable for the random effect in global site index model 2. The LMM models are given in Tables 4 and 5 as:

$$S_{11} = \beta_0 + \mu_{05} + S_1 [\beta_{11}(\text{AP}_1) + \beta_{12}(\text{BD}_4) + \beta_{13}(\text{TN}_5)] + S_2 [\beta_{21}(\text{AP}_3) + \beta_{22}(\text{TN}_1) + \beta_{23}(\text{TK}_3)] + S_3 [(\text{AP}_3) + \beta_{32}(\text{AP}_2)] + \epsilon \quad (19)$$

$$S_{12} = \alpha_{05} + \mu_{06} + \alpha_{15}(\text{AP}_1)^3 + \alpha_{25}(\text{AP}_1)^2 + \alpha_{35}(\text{TN}_5)^3 + \alpha_{45}(\text{TN}_5)^2 + \alpha_{55}(\text{BD}_4)^3 + \alpha_{65}(\text{BD}_4)^2 + \alpha_{75}(\text{MAP}) + \epsilon \quad (20)$$

where S_{11} and S_{12} represent the site index estimated by global site index model 1 and global site index model 2, respectively; μ_{05} and μ_{06} are the random-effect parameters of the region; and $\mu_{05} \sim N(0, \sigma_{\text{model 1}}^2)$, $\mu_{06} \sim N(0, \sigma_{\text{model 2}}^2)$. According to the group variable planting density, the covariance of random effect generated by region was divided into five matrices: (1) when the planting density is A, the parameter of the covariance matrix of random effect caused by region is $\sigma_{\text{model 21}}^2$; (2) when the planting density is B, the parameter of the covariance matrix of random effect caused by region is $\sigma_{\text{model 22}}^2$; (3) when the planting density is C, the parameter of the covariance matrix of random effect caused by region is $\sigma_{\text{model 23}}^2$; (4) when the planting density is D, the parameter of the covariance matrix of random effect caused by region is $\sigma_{\text{model 24}}^2$; and (5) when the planting density is

Table 5 Global site index model 2 based on soil and climatic variables

Item	Parameters	Global site index model 2
Fixed-effects parameters	α_{05}	2.042
	α_{15}	0.647
	α_{25}	-2.251
	α_{35}	-7.945
	α_{45}	16.082
	α_{55}	-2.883
	α_{65}	7.427
	α_{75}	0.003
	$\sigma_{\text{model 21}}^2$	0.828
	$\sigma_{\text{model 22}}^2$	0.294
Variance components	$\sigma_{\text{model 23}}^2$	2.012
	$\sigma_{\text{model 24}}^2$	2.136E-11
	$\sigma_{\text{model 25}}^2$	4.974E-13
	σ^2	2.388
Fitting performance	MAE	0.994
	MRE	0.074
	RMSE	1.251
	R^2	0.796

MAE is mean absolute error; MRE, mean relative error; RMSE, root mean square error

E, the parameter of the covariance matrix of random effect caused by region is $\sigma_{\text{model 25}}^2$.

The fitting performance of the global site index model 1 showed that MAE, MRE, and RMSE were all smaller than that of global site index model 2 and R^2 was greater than that of global site index model 2, which indicated that the fitting

Table 6 Predictive test of global site index models using independent validation data

Global site index model	Model	Prediction performance			
		MAE	MRE	RMSE	R^2
1	Equation 19	0.027	0.002	0.032	0.998
2	Equation 20	1.200	0.077	1.612	0.693

MAE is mean absolute error; MRE, mean relative error; RMSE, root mean square error

accuracy of global site index model 1 was higher than that of global site index model 2 (Tables 4 and 5). The predictive ability of the model was also tested using 15 groups of independent validation data, and the results showed that the R^2 for global site index model 1 was higher than that for global site index model 2, and the MAE, MRE, and RMSE were all smaller than for global site index model 2, indicating that the prediction accuracy of global site index model 1 was also higher than that of global site index model 2 (Table 6).

Discussion

Effects of soil factors at different depths on site index

Effects of total P, total K, available K, bulk density and water content on site index

The relationship between site index and soil factors has been widely discussed. Because of differences in ecosystem types and tree species in the study area, the response of site index to environmental factors varied with the climatic region. Farrelly et al. (2011a, b) explored the relationship between site index of Sitka spruce in Ireland and various soil physical and chemical properties, and developed a site index model, and showed a significant negative correlation between site index vs. soil water content, organic carbon, available K and P. Here, we found that the soil variables that significantly affected the site index varied among climatic regions, and those that affected the site index within a certain climatic region showed different trends at different depths.

A significant negative correlation was detected between Fujian site index and total P in all soil layers. However, in Guangxi and Sichuan provinces, the correlation between site index and total P was small or not significant. With the increase in soil depth, the positive correlation between Fujian site index and available K became stronger, whereas the positive correlation between site index and soil bulk density weakened. By contrast, site index showed no significant correlation with available K and bulk density in both Guangxi and Sichuan, and the soil layer effect was not obvious. In addition, a significant positive correlation was detected between Guangxi site index and total K in all soil layers. However, the positive correlation between the Fujian site index and total K decreased with increasing soil depth, indicating that the response of site index to total K in deeper soil layers was poor in Fujian Province. Moreover, a small negative correlation was evident between the site index and total K in all soil layers in Sichuan.

The site index in all three climatic regions showed a small correlation with pH and alkali-hydrolyzable N in each soil layer, indicating that these variables did not have a major impact on the site index. Furthermore, we found that the soil

water contents were relatively high in Fujian (19%–34%) and Sichuan (16%–40%), and were negatively correlated with the site index. However, the soil water content in Guangxi was relatively low (11%–18%), and the water content of each soil layer had a strong positive correlation with the Guangxi site index. These results suggest that excess soil water content could hinder the improvement of forest productivity. The water-holding capacity and water availability of the soil play a key role in the productivity of forest plantations (Besson et al. 2014). A reduction in soil water accessibility decreases forest productivity (Paulo et al. 2015). Because neither excess nor deficient soil water content are conducive to the growth of the stand, it is necessary to regulate the relationship between soil water content and soil physical properties reasonably (Farrelly et al. 2011a, b).

Effects of available P on site index

P and K are highly valued elements for plant growth (Zeng et al. 2019; Bai et al. 2020). In this study, available P and total K were the limiting factors affecting the growth of Chinese fir. The results of site index LMM models in three climatic regions showed that available P was an important predictor of site index. However, the effect of available P in different soil layers on site index varied among the three climatic regions. For example, the available P in 0–20 and 40–60-cm soil layers affected the site index in Fujian and Guangxi, respectively, while the site index in Sichuan was mainly affected by the available P in 20–40 and 40–60-cm soil layers. Additionally, the correlation between site index and available P was different in different climatic regions. For example, a significant positive correlation was observed between site index and available P in Fujian and Sichuan, but a significant negative correlation was detected between site index and available P in Guangxi. Previously, several studies have shown that P is the main limiting factor for tree growth and that increasing the application of P fertilizer can effectively promote stand growth and improve site productivity (Ma et al. 2015; Shang et al. 2020). However, in this study, the site index of Chinese fir did not show a linear positive correlation with the increase in available P in Guangxi; instead, the Guangxi site index decreased with the increase in available P. A similar result was also obtained by Kayahara et al. (1995) and Chen et al. (1998). Kayahara et al. (1995) explored the relationship between site index and various soil nutrient factors and pointed out that there was no linear positive correlation between site index and soil nutrient availability. In other words, the highly productive sites were not always nutrient-rich; as the author explained, once a tree species reaches the early nutritional sufficiency point, it is not nutrient-limited as measured by the tests, but it may be limited by one or more of the several other soil physical, chemical and biological factors. Therefore, P accumulates

because of excessive consumption in poor site conditions. However, site productivity decreases due to limitations in other nutrient elements, which increases the P content in regions with a low site index (Kayahara et al. 1995). While some factors cause P deficiency in soil, plants can alleviate P deficiency by stimulating a series of other pathways of P acquisition, such as increasing P mineralization by changing microbial communities (Deng 2016). In addition, the subtropical region of southern China is severely affected by N deposition. The intensification of N deposition can affect the soil nutrient cycle and increase P deficiency in the subtropical region (Xie et al. 2020). Moreover, the increase in N deposition can also reduce the fine root biomass of plants, thus reducing the uptake of available P by plants and increasing the accumulation of available P in the soil (Mao et al. 2018; Xie et al. 2020). However, this finding needs further verification.

In Guangxi, which is located in the southern subtropical region, Chinese fir plantation grows on marginal land, with low available P content. Forest growth in Guangxi may be limited by a simultaneous deficiency in several other soil nutrient. However, because of the combination of N, K and various biophysical factors, the stand growth is restricted, which results in low site productivity and showing a negative correlation between site index and available P. Some studies showed that P addition might increase biological N fixation in subtropical forest ecosystems (Zheng et al. 2015; Wang et al. 2017a, b). Therefore, more P fertilizer should be applied to Chinese fir plantations in Guangxi, and measures should be taken to promote the absorption of available P by Chinese fir.

Effects of organic matter, total N and C/N ratio on site index

Organic matter and total N are the basis of soil fertility and also have a major impact on stand growth (Li et al. 2014). However, in this study, we found that the organic matter content in each soil layer in the three climatic regions had little effect on site index, except the organic matter content of the 0–20 and > 60–80-cm soil layers in Guangxi, which showed a significant correlation with site index. Farrelly et al. (2011a, b) pointed out that soil total N had no significant effect on the site index of Sitka spruce. In the current study, we found no significant correlation between site index of Chinese fir and total N content in any soil layer in Fujian or Guangxi, although total N significantly affected site index as a result of other significant soil physical and chemical properties. Thus, with other soil nutrients, total N plays a significant role in the growth of Chinese fir.

Studies have shown that N deposition and forest litter input have the greatest impact on surface soil nutrients, especially on the increase of soil surface N content, which may

lead to the instability of the N content on the topsoil (Fan et al. 2008; Guo et al. 2014). However, N elements are transported downward into deeper soil layers by leaching and other means. In deeper soil layers, N levels are less affected by climatic and biological factors than in the topsoil and thus more stable (Yuan et al. 2007). In this study, the strength of the correlation between the Fujian site index and total N increased with the increase in soil depth, which indicated that the Fujian site index had a better response to the total N content in the deeper soil layer. On the contrary, the strength of the correlation between Guangxi site index and total N decreased with the increase in soil depth, indicating that the Guangxi site index had a better response to the total N content in topsoil. Due to the different climatic and soil characteristics, the N deposition and the degree of forest litter decomposition differ in different regions. These factors will affect the N cycling in soil, resulting in different responses of soil N components in different regions and different soil layers to the changes in soil N input (Ma et al. 2013; Lin et al. 2016). However, the relationship between forest growth and N components in different soil layers needs to be further studied.

Many studies show that soil C/N ratio is reportedly an important index of N-use efficiency and a significant predictor of site index. For example, Seynave et al. (2005) showed that the growth of Norway spruce was affected by soil pH and N availability; low productivity was found in sites with high pH and high C/N ratio, and pH and C/N ratio were significant predictors of site index only when they present together. However, Bergès et al. (2005) suggested that C/N ratio had no effect on the site index and concluded that C/N ratio was not an accurate indicator of N supply. In the current study, we found that the C/N ratio of each soil layer in the three climatic regions had no obvious effect on site index, and the correlation was neither close nor significant.

The site index of Chinese fir showed different responses to soil physical and chemical properties in different climatic regions, and the effect of a given soil variable on site index varied with the soil depth, probably because climatic factors such as elevation and slope position and aspect differ among different climatic regions, resulting in some variation in hydrothermal conditions in each plot. These differences affect the spatial distribution and transformation process of various soil factors, resulting in an uneven distribution of soil nutrients in different soil profiles, affecting the absorption of available soil nutrients by plant roots, and thus affecting tree growth (Zhang et al. 2015).

Effects of climatic variables on site index

Our results showed that the site index of Chinese fir varied significantly among different climatic regions. MAP was the most important climatic factor responsible for the variation

in site index among different regions. In the whole study area, MAP showed a significant positive linear correlation with site index, consistent with the findings of Menéndez-Miguélez et al. (2015) and Gülsoy and Çınar (2019), who showed that precipitation was strongly correlated with tree height. However, Monserud et al. (2006) established a site index model with various climatic variables as predictors and showed that growing degree days $> 5^{\circ}\text{C}$ (GDD5), the Julian date when GDD5 reaches 100 (D100), and July mean temperature (MTWM) had the strongest predictive ability, while precipitation was not strongly correlated with site index. Nevertheless, our result showed that the site index was not closely correlated with various thermal conditions (DD_0, DD5, MAT), indicating that the response of Chinese fir plantations to these heat-related factors was low in this study area, and it was difficult to improve the prediction ability of the site index model after including these temperature variables in the model.

Global site index models

The results showed that the LMM model had some advantages after considering the random effects of region or planting density on site index. And the global site index models for the whole study area showed a good fit. R^2 of the global site index model for the whole study area using climatic region as a dummy variable and random parameter was larger than that of the single climatic region, indicating that the fitting performance of the LMM model will not decrease with the expansion of the spatial scale. In addition, the evaluation indices of R^2 , MAE, MRE, and RMSE, showed that the prediction accuracy of global site index model using the climatic region as dummy variable (Table 6, Eq. (19)) was higher than that of global site index model using the climatic variable and the most indicative soil variables of the whole study area (Table 6, Eq. 20). The main reason may be that Eq. 19 took into account the differences among different climatic regions, and it is more efficient in predicting site index among these three climatic regions. Unfortunately, Eq. 19 may only be applicable to these three climatic regions, which limits the applicability of this model in other regions. However, Eq. 20 is more likely to be universal and applicable. Our study showed that the global site index model is applicable across diverse regions and that the site index prediction quality will not decrease with the increase in spatial scale. This result is consistent with the findings of Bergès et al. (2005), who showed that increasing the spatial scale did not decrease the prediction quality of site index. However, a few studies had verified a reduction in the prediction quality of site index with the expansion of study area (Chen et al. 2002; Aertsen et al. 2012).

Conclusions

In this study of the relationship of Chinese fir site index with climatic and soil factors at three climatic regions in southern China, the site index was modeled in relation to the dominant soil and climatic factors in each local area or in the whole study area. Results showed that the dominant soil factors with the strongest predictive ability to the variation of site index varied with the climatic region and soil depth. Available P, total N, bulk density and total K were good predictors of site index in three climatic regions. Total N significantly affected site index in conjunction with other significant soil factors. Linear mixed effects SI models built using these dominant soil factors in the three climatic regions fit well, and R^2 was in the range of 0.86 to 0.97. In addition, MAP was the climatic factor responsible for the variation in site index among different regions. The global site index model for the whole study area using climatic region as a dummy variable and random parameters and the most important soil factors of the three climatic regions as predictors improved the fit and prediction accuracy of the site index model. This model effectively resolved the impact of different site types on the prediction of site index of Chinese fir plantations, thus improving its applicability to different regions. These results will aid in evaluating site quality of Chinese fir plantations and selecting appropriate sites for plantations in southern China as the climatic changes.

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