Responses of the Crown Shape of *Larix kaempferi* Plantations to Site Index in Subtropical Areas of China

Huolin Gao¹,†, Dongsheng Chen²,†, Xiaomei Sun²,* and Shougong Zhang²

¹ College of Forestry, Shenyang Agricultural University, Shenyang 110866, China; ghl2017@syau.edu.cn
² State Key Laboratory of Tree Genetics and Breeding, Key Laboratory of Tree Breeding and Cultivation of State Forestry and Grassland Administration, Research Institute of Forestry, Chinese Academy of Forestry, Beijing 100091, China; chends@caf.ac.cn (D.C.); larch_rif@163.com (S.Z.)
* Correspondence: xmsun@caf.ac.cn
† The authors contributed equally to this work.

Abstract: This study addresses how site index may affect crown shape by developing a crown shape regression model for the planted *L. kaempferi* at high altitudes in the subtropical climate of China. A total of 9241 branches from 78 trees, including 39 dominant trees and 39 intermediate trees, were measured in Hubei Province, southern China. The branch characteristics, including branch length, branch angle, and branch chord length of all living branches, were measured by felling trees. The models that showed good performance in crown shape modeling were used and compared in the present study. The goodness of fit statistics and stability of parameter estimation of the modified Kozak equation were better than those of the segmented polynomial equation. A nonlinear mixed-effect crown shape model was developed based on the modified Kozak equation. In addition to the tree level variables of diameter at the breast height (DBH), crown ratio (CR), and tree height-to-DBH ratio, an attempt was made to incorporate the site index into the crown shape model for the planted *L. kaempferi*. However, the site index was not a significant variable in the crown shape model. The purpose of our study was to lay the foundation for further study of the growth of the trees and the effects of crown morphology on stem growth in the future.

Keywords: crown shape model; site index; high altitude; *L. kaempferi* plantation; southern China

1. Introduction

Tree crown shape is a potentially important crown parameter that has already been in the forefront of interest for researchers and influences the interception of radiation and hence tree productivity and forest stand dynamics [1,2]. Variations in crown shape represent the sum of all past and present biotic and abiotic factor influences and, thus, impact the growth of all other organisms [3,4]. Crown shape modeling with high accuracy also has potential applications in evaluations of the effect of forest management practices on the growth of tree bole [5]. Therefore, quantifying the effect of abiotic factors on crown shape is important. However, to the best of our knowledge, this topic remains poorly understood.

Crown shape is generally divided into three basic forms (i.e., excurrent, decurrent, and shrub) depending on the growth rate of the terminal and lateral branch growth [6–9]. Crown shape is influenced by both internal (e.g., genotype) and external (e.g., biotic and abiotic control) factors, of which the hereditary property is the most important. Competition is an important biotic factor affecting the tree crown [10,11]. Given the fact that the resources needed during the growth of the individual tree in the forests are limited, competition has been an important factor in shaping the crown morphology through modifying the branch size and extension [12–15]. Trees within a stand tend to reach their crown into the upper layer when resource availability enables them to suppress their neighbors [16,17]. The lateral growth of tree branches is always needed to resist asymmetric competition.
in forests to maximize space resource utility, and this process results in morphological plasticity [18–20]. Additionally, crown asymmetry has been reported to have a significant effect on radial stem growth and wood quality assessments [21–23]. Information regarding the effect of topography [24–26], latitude [27,28], and wind [29–31] on crown variations can be found in previous studies. The slope, as an important topographic factor, has also been reported to shape the tree crown of some tree species [32]. Crown shape has shown an evident response to slope aspect because slope aspect changes the wind direction and thus affects the collision of branches, which limits branch growth [33]. Slope position will also change the local soil condition and light interception, ultimately shaping the crown [34]. Altitude is another essential factor that can change individual tree growth because it affects the temperature and precipitation in mountainous areas [35]. Acting as a comprehensive variable for topographic variables [36–38], site quality was preferable for use in growth models of the trees (e.g., basal area growth) [39,40] to avoid mutual correlations of topographic variables. Site quality is regarded as one of the important factors influencing tree growth and stand productivity during the process of stand development [16,41,42]. Despite the importance of site quality in tree growth prediction, little attention has been given to the topic of the influence of site quality on crown shape.

Regression analysis is widely used in describing crown shape. The crown radius can be calculated at any position within the crown with easily measurable tree and stand variables as independent variables [43–46]. The limitations of most previous studies that delineated crown shapes included the supposition of the symmetrical shape for all directions [44,47,48]. The symmetrical crown shape model is hardly satisfied for trees growing in the forest due to the local heterogeneous resources [49,50], microtopography [51,52], and wind sway [53]. Thus, modeling crown shape for different directions is a preferable approach to quantifying the asymmetric crown shape on a spatial scale [54]. Based on the basic crown shape model, incorporating site index into the crown shape model is practical for simulating the effect of site quality on crown shape.

Japanese larch (L. kaempferi), a tree species native to Japan, has been present in China for almost 110 years. As a main commercial tree species, L. kaempferi has been widely planted in a range of temperate to subtropical climate zones in China. The area that is suitable to plant L. kaempferi has reached approximately 35.59 × 10^4 hm^2, and the suitable planting area will increase in the future [55]. The high altitude of the subtropical climate in China is probably the most southern area in which L. kaempferi can grow well. Therefore, studying the crown shape of the L. kaempferi planted in the subtropical climate zone of China is important in evaluating the adaptability of this tree species to the environment. Based on the measurement of branches of sample trees, the main purpose of our research was to examine whether or not the site index impacts the crown shape of L. kaempferi plantations in the high-altitude subtropical climate zone in China.

2. Materials and Methods

2.1. Study Area Description

The present study was conducted in the Changlinggang forest farm with an altitude of 1200–2000 m in Jianshi County (109°32′–110°12′ E, 30°06′–30°54′ N) in Hubei Province, in the central area of China. The climate type is a subtropical monsoon. The extreme high and low temperatures are 29 °C and −17.2 °C, respectively, with a mean value of 11.7 °C. The total annual precipitation varies between 1500 and 1800 mm. The relative humidity is approximately 85%. Mountain brown soil is the main soil type. There are 208 frost-free days, and the soil thickness is approximately 80 cm. L. kaempferi was introduced and planted on the Changlinggang forest farm in 1977. To date, the total planted area of the L. kaempferi plantation is approximately 70% of the total area of this forest farm.

2.2. Data Collection

A field investigation was conducted from June to August in 2019 and from August to September in 2022 at the Changlinggang forest farm with a wide range of site
Forests 2023, 14, 2181

quality. In 2019, a total of 10 forest stands with a complete and typical appearance aged from 7 to 42 years were selected. In each forest stand, 6 permanent sample plots (0.06 ha, 20 × 30 m) were developed, and 3 plots were selected to conduct destructive measurements of the branches. The altitude, soil thickness, slope, slope aspect, and slope position of each sample plot were recorded in the field. In 2022, a total of 3 forest stands with a complete and typical appearance aged 18, 33, and 34, respectively, were developed, and 6 permanent sample plots (0.06 ha, 20 × 30 m) in each forest stand were established. Three plots were selected to conduct further investigations. Therefore, a total of 39 permanent sample plots were selected to conduct further analysis, and the age of each plot was the same. The range of the altitudes for all the plots was 1372–1932 m. The overbark diameter at breast height (DBH, 1.3 m) was measured using a diameter tape for all trees. Following the study of Gao et al. (2017) [56], tree height (HT), height to crown base (HCB), and crown width (CW) of north, east, south, and west directions were carefully measured and recorded in the field. The dominant tree height at the basal age of 20 years was used to evaluate the site index for each plot. Based on the developed site index table for the L. kaempferi plantation in the study area, the site indices of all the plots have been determined [57]. The descriptive statistics for the plot information are shown in Table 1.

Table 1. Descriptive statistics for the 39 permanent plots established in the 13 forest stands of the L. kaempferi plantation in the Changlinggang forest farm in Hubei Province, China. \( D_g \) is the quadratic mean diameter at breast height of each forest stand, \( H_{\text{dom}} \) is the dominant tree height of each forest stand, and CW is the crown width of each forest stand. Q1 is the 25% quantile, and Q3 is the 75% quantile.

<table>
<thead>
<tr>
<th>Variables</th>
<th>Mean</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Standard Deviation</th>
<th>Q1</th>
<th>Q3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (year)</td>
<td>26</td>
<td>7</td>
<td>44</td>
<td>9.2</td>
<td>18</td>
<td>34</td>
</tr>
<tr>
<td>( D_g ) (cm)</td>
<td>16.7</td>
<td>4.2</td>
<td>28.0</td>
<td>7.4</td>
<td>8.9</td>
<td>23.2</td>
</tr>
<tr>
<td>( H_{\text{dom}} ) (m)</td>
<td>20.7</td>
<td>6.5</td>
<td>32.5</td>
<td>4.5</td>
<td>20.2</td>
<td>22.2</td>
</tr>
<tr>
<td>CW (m)</td>
<td>1.7</td>
<td>1.1</td>
<td>2.3</td>
<td>0.3</td>
<td>1.6</td>
<td>1.9</td>
</tr>
<tr>
<td>Density (trees·ha(^{-1}))</td>
<td>927</td>
<td>283</td>
<td>1444</td>
<td>417</td>
<td>492</td>
<td>1392</td>
</tr>
<tr>
<td>Site index</td>
<td>18.6</td>
<td>12</td>
<td>24</td>
<td>3.0</td>
<td>16</td>
<td>22</td>
</tr>
</tbody>
</table>

The sample trees were selected using a method similar to the study of Gao et al. (2021) [46]. In our study, we only selected 1 dominant tree and 1 intermediate tree from each plot to conduct further investigation in the field. To maintain the plot for further measurement, the sample trees were selected from a nearby stand rather than from the permanent sample plots. As a result, a total of 78 sample trees, including 39 dominant trees and 39 intermediate trees, were selected. The descriptive statistics for the sample tree attributes are shown in Table 2.

Table 2. Descriptive statistics for the attributes of the sample trees and all living branches from the 78 sample trees. \( n \) is the total number of sample trees or branches.

<table>
<thead>
<tr>
<th>Components</th>
<th>Variables</th>
<th>Mean</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Standard Deviation</th>
<th>Q1</th>
<th>Q3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tree ( (n = 78) )</td>
<td>DBH (cm)</td>
<td>19.0</td>
<td>3.8</td>
<td>35.7</td>
<td>8.7</td>
<td>11.2</td>
<td>26.8</td>
</tr>
<tr>
<td></td>
<td>HT (m)</td>
<td>18.2</td>
<td>4.7</td>
<td>33.2</td>
<td>8.3</td>
<td>10.5</td>
<td>23.9</td>
</tr>
<tr>
<td></td>
<td>HD</td>
<td>0.96</td>
<td>0.73</td>
<td>1.27</td>
<td>0.11</td>
<td>0.89</td>
<td>1.04</td>
</tr>
<tr>
<td></td>
<td>CR</td>
<td>0.58</td>
<td>0.24</td>
<td>1.74</td>
<td>0.27</td>
<td>0.36</td>
<td>0.79</td>
</tr>
<tr>
<td>Largest branch ( (n = 1147) )</td>
<td>BD (mm)</td>
<td>17.41</td>
<td>1.35</td>
<td>73.74</td>
<td>12.34</td>
<td>7.14</td>
<td>25.01</td>
</tr>
<tr>
<td></td>
<td>BL (cm)</td>
<td>174.7</td>
<td>1.0</td>
<td>690.0</td>
<td>128.0</td>
<td>60.0</td>
<td>255.6</td>
</tr>
<tr>
<td></td>
<td>BC (cm)</td>
<td>162.3</td>
<td>1.0</td>
<td>635.0</td>
<td>118.1</td>
<td>60.0</td>
<td>239.5</td>
</tr>
<tr>
<td></td>
<td>VA (°)</td>
<td>58.4</td>
<td>10.0</td>
<td>101.0</td>
<td>13.2</td>
<td>50.0</td>
<td>68.0</td>
</tr>
</tbody>
</table>
For all the sample trees, the DBH, HT, CW, and HCB were measured first, and then the magnetic north side of the trunk was marked on the breast height before felling. The sample trees were then carefully felled. After the tree was felled, the HT was remeasured, and the marked line was extended to the tree top along the trunk. From the stem base to the tree top, the stem was divided into equal lengths of 1 m, and the last section less than 1 m was recognized as the tree tip. From the tree tip to the crown base, each section was erected and held upright at ground level. The branch attributes, including branch diameter (BD) measured at the location 1 cm from the branch base on a branch, branch length (BL), branch chord length (BC), branch angle (VA) to the vertical direction, branch azimuth (AZ), and the depth into the branch base from the tree tip (L), were measured for all live branches. Crown length (CL) was calculated as CL = HT - HCB. The crown ratio (CR) was calculated as the ratio between CL and HT. Thus, the vertical distance from the branch tip to the tree tip (DINC) was calculated by using the trigonometric relationship DINC = L - BC cos(VA), and the relative DINC was defined as RDINC = DINC/CL. After eliminating the branches with damage to the branch tips during tree felling, a total of 9241 branches were measured (Table 2). The live crown was divided into equal sections that were 0.5 m in length from the tree tip down to the crown base, and the branch with the largest radius from each section was selected to develop the crown shape model. A total of 1147 largest branches were used to fit the crown profile model.

2.3. Basic Crown Shape Model for L. kaempferi

The segmented polynomial equation (Equation (1)) and modified Kozak equation (Equation (2)), which have been successfully used in crown shape modeling, were compared in the present study (Gao et al., 2017) [56]. The two basic models are given in Equations (1) and (2), respectively.

\[
OCR = b_1 \cdot RDINC + b_2 \cdot RDINC^2 + b_3 \cdot (RDINC - b_4)^2 \cdot I_+ \tag{1}
\]

\[
OCR = c_1 \cdot \left[ \frac{1 - (1 - RDINC)^{0.5}}{1 - p^{0.5}} \right] \tag{2}
\]

where OCR is the outer crown radius for any position within the crown, and \(b_1\)–\(b_4\) and \(c_1\)–\(c_2\) are parameters to be estimated; \(I_+\) is the indicator that equals 0 when RDINC < \(b_4\), and 1 otherwise; and \(p\) is the inflection point.

In comparison, the segmented polynomial equation was very rigid because the estimate of parameter \(b_4\) was restricted to the range of (0, 1). Following the study of Gao et al. (2017) [56], the two basic models, including the tree-level variables, are shown in Equations (3) and (4), respectively.

\[
OCR = (a_{11} + a_{12} \cdot DBH) \cdot RDINC + (a_{21} + a_{22} \cdot CR) \cdot RDINC^2 + (a_{31} + a_{32} \cdot CL) \cdot (RDINC - (a_{01} + a_{02} \cdot HD))^2 \cdot I_+ \tag{3}
\]

\[
OCR = \left( b_{11} \cdot DBH^{b_2} \right) \cdot \left[ \frac{1 - (1 - RDINC)^{0.5}}{1 - \left( b_{31} \cdot CR^{b_4} \right)^{0.5}} \right] \tag{4}
\]

where \(a_{01}\)–\(a_{32}\) and \(b_{1}–b_{5}\) are model parameters to be estimated. The other variables were defined as above. Equations (3) and (4) were fitted using the branches with the largest radius selected from each 0.5 m section. The R²_adj, RMSE, AIC, and BIC were used to compare models. The site index was incorporated into the best basic model to evaluate the effect on the crown shape.
2.4. Inclusion of Site Index

Site quality was considered an abiotic factor. Each parameter of the basic crown shape model was defined as a linear function of the site quality. The specific model with the largest $R^2_{adj}$ and the smallest RMSE, AIC, and BIC was defined as the best crown shape model for *L. kaempferi*. Mean square error reduction (MSER) was used to evaluate the contribution of site quality to the crown shape models and is shown as Equation (5). In addition, the correlation between the estimates of the parameters and the biological reasoning for the sign of the parameter estimates was considered. The MSER was calculated as follows:

$$\text{MSER} = \left(1 - \frac{\text{MSE}_i}{\text{MSE}_j}\right) \times 100 \tag{5}$$

where MSE$_i$ is the mean square error for the selected model incorporating site quality, and MSE$_j$ is the mean square error for the model without site quality.

The measured crown radius data within each individual tree can be correlated, as can the tree data within each sample plot. The nonlinear mixed-effects model (NLME), including fixed and random parameters, provides an efficient means of describing the heterogeneities and correlations in data. We first introduced the random effect for each parameter and the parameter combinations at the sample plot level, with AIC and BIC as the main criteria to evaluate the performance of the model. The exponential function and power function were used to account for the heteroscedasticity. The model fitting process was conducted using the “nlme” package through R software (Version 4.2.1, R Foundation for Statistical Computing, Vienna, Austria).

3. Results

3.1. Crown Shape Model Development by Incorporating Site Index

The segmented polynomial equation and modified Kozak equation were fitted separately and then compared. The modified Kozak equation had a relatively higher $R^2_{adj}$ and a lower RMSE, AIC, and BIC. The standard error of the model parameters for the Kozak equation was relatively lower, indicating more stable parameter estimation than that of the segmented polynomial equation. $R^2_{adj}$ of the model was improved when site index was incorporated into the model. The final crown shape model, including the site index, is shown in Equation (6):

$$\text{OCR} = b_1 \cdot \text{DBH}^{b_2} \cdot \left[\frac{1 - (1 - \text{RDINC})^{0.5}}{1 - ((b_{30} + b_{31} \cdot \text{SI}) \cdot \text{CR}^{b_{34}})^{0.5}}\right] \cdot \text{exp}\left(\frac{1}{\text{HD}}\right) \cdot (1 - \text{RDINC}) \tag{6}$$

where SI is the site index of each forest stand indicating the dominant tree height basal age of 20 years, HD is the ratio of HT to DBH, $b_1$–$b_5$ and $b_{30}$–$b_{31}$ were parameters to be estimated, and the other parameters are defined the same as above.

All the parameter estimates and goodness-of-fit for model (6) are shown in Table 3. On the whole, the performance of model (6), including site index, only slightly improved compared to the basic model regarding the goodness-of-fit statistic (Table 3). The magnitude of the MSER for the final model was 0.93% compared to the basic model (Equation (4)).

3.2. Nonlinear Mixed-Effect Crown Shape Model

Different combinations of the random effects for the model (6) were fitted and compared. The converged NLME models were compared, and the specific model with $b_2$ as the random effect showed the smallest AIC and BIC with meaningful parameter estimates. The powerful function accounted for the variance heteroscedasticity effectively. Parameter $b_{31}$ was not significant (Table 4).
Table 3. Parameter estimates and goodness-of-fit for the best basic crown shape model (model (4)) and the final crown shape model incorporating site index (model (6)). DF is the number of degrees of freedom.

<table>
<thead>
<tr>
<th>Model (4)</th>
<th>Estimate</th>
<th>SD</th>
<th>t Value</th>
<th>p Value</th>
<th>Model (6)</th>
<th>Estimate</th>
<th>SD</th>
<th>t Value</th>
<th>p Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>b_1</td>
<td>0.3193</td>
<td>0.0316</td>
<td>10.10</td>
<td>&lt;0.001</td>
<td>b_1</td>
<td>0.3350</td>
<td>0.0330</td>
<td>10.15</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>b_2</td>
<td>0.5989</td>
<td>0.0330</td>
<td>18.14</td>
<td>&lt;0.001</td>
<td>b_2</td>
<td>0.5803</td>
<td>0.0332</td>
<td>17.49</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>b_3</td>
<td>0.6824</td>
<td>0.0260</td>
<td>26.28</td>
<td>&lt;0.001</td>
<td>b_30</td>
<td>0.4950</td>
<td>0.0686</td>
<td>7.21</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>b_4</td>
<td>0.1845</td>
<td>0.0541</td>
<td>3.41</td>
<td>&lt;0.001</td>
<td>b_31</td>
<td>0.0135</td>
<td>0.0044</td>
<td>3.07</td>
<td>0.002</td>
</tr>
<tr>
<td>b_5</td>
<td>0.3115</td>
<td>0.0152</td>
<td>20.54</td>
<td>&lt;0.001</td>
<td>b_4</td>
<td>0.2798</td>
<td>0.0629</td>
<td>4.45</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>

| R^2_adj   | 0.67     | R^2_adj | 0.68     |
| MSE       | 0.2704   | MSE     | 0.2682   |
| AIC       | 1762     | AIC     | 1754     |
| BIC       | 1792     | BIC     | 1789     |
| MSER      | -        | MSER    | 0.93%    |
| DF        | 1142     | DF      | 1141     |

Table 4. Parameter estimates and goodness-of-fit for the nonlinear mixed-effect crown shape model.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Estimate</th>
<th>SD</th>
<th>t Value</th>
<th>p Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>b_1</td>
<td>0.3332</td>
<td>0.0415</td>
<td>8.30</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>b_2</td>
<td>0.5704</td>
<td>0.0406</td>
<td>14.06</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>b_30</td>
<td>0.5170</td>
<td>0.0922</td>
<td>5.61</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>b_31</td>
<td>0.0077</td>
<td>0.0059</td>
<td>1.30</td>
<td>0.1951</td>
</tr>
<tr>
<td>b_4</td>
<td>0.1652</td>
<td>0.0742</td>
<td>2.23</td>
<td>0.0261</td>
</tr>
<tr>
<td>b_5</td>
<td>0.3095</td>
<td>0.0147</td>
<td>20.99</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>

Branches of trees at higher altitudes tended to spread at the horizontal level and expressed a large crown shape, as shown in Figure 1. The trees at lower altitudes of some tree species, such as Pinus sylvestris, may be highly vulnerable to water storage, indicating differences in water conditions at different altitudes.

Figure 1. Pearson correlation coefficient (r) between the mean branch length (BLmean), maximum branch length (BLmax), mean branch angle (VAmean), maximum branch angle (VAmax), and altitude (AL) for planted L. kaempferi trees.
4. Discussion

The active responses of crown shape to abiotic factors reflect a fundamental strategy of tree adaptation to the environment [58]. Thus, it motivates our interest in exploring the responses of crown morphology to variations in abiotic factors. The aims of this work were to develop a statistical crown shape model including site quality with fewer parameters to achieve stable parameter estimation and to examine how abiotic factors affect crown shape. Antos et al. (2010) demonstrated that neighboring trees that are substantially shorter than the subject tree may not have an effect [59]. Neighbor competition is an important factor that shapes individual tree crowns [20]. The effect of asymmetric competition reflected the competition for light resources because our study area was located in the same area, and the light solar incident angle did not vary greatly [60]. Davies and Pommerening (2008) also found that individual trees under more competition tended to have smaller and shorter crowns [61]. Overall, competition explained approximately 0.7% of the variation, which may be smaller than the contribution of competition to the other forest growth and yield models [62,63].

Local topography is an important factor that affects environmental conditions, resource availability, soil nutrient availability, and organic matter [64]. Getzin and Wiegand (2007) even suggested that the response of individual tree growth to light heterogeneity was determined only by local topography and not by incoming solar radiation [52]. In addition, even small changes in altitude can lead to significant variations in temperature and precipitation [34], thus affecting the growth of the crown. The site index was a comprehensive variable to reflect the local topography conditions. Thus, we examined the effect of site quality, which is a comprehensive index reflecting the local topography and soil condition, on crown shape [65]. In our study, we found that the higher site quality increased the crown radius of an individual tree, which met our expectations. Therefore, we mainly focused on the effect of site index on the crown profile of the planted L. kaempferi in the present study. In fact, remarkable variability in the crown shape from different local site conditions results from a mixture of effects with topographic variables, and the factors of local topography may have mutual effects on each other. The local topography impacts crown shape and tree growth differently and is determined by whether water or light is more limiting. As a result, the crown shape varies in different directions [24]. Therefore, it is quite difficult to quantify the effect of each local topographic variable on the crown shape because a large number of samples are needed.

The increase in site quality increased the competition among the trees and reduced the rate of increase in crown shape [33,66]. The positive effect of site quality on the basal area increment of the stem has also been reported, indicating that a tree grows faster on more fertile sites than on less fertile sites [67]. In our study, we found that site quality was not a significant variable in the crown shape model in the high altitude of the subtropical climate in our study area. It encourages the focus on the crown development along the different site qualities. The crown development is not only determined by the branch growth, but also by the morphology of the branch and deserves further research.

5. Conclusions

A total of 39 dominant and 39 intermediate trees of L. kaempferi planted in Hubei Province, China, were destructively harvested to measure branch attributes and develop the crown shape model. Site index was considered an abiotic factor and was incorporated into the basic crown shape model using a reparameterization approach. We further developed the crown shape model by modifying and reducing the number of parameters in the Kozak equation for more convenient application in forest management. Site quality was not a significant variable in the crown shape model.

Author Contributions: H.G. and D.C. performed the field study and data analysis and led the writing. X.S. and S.Z. conceived and designed the experiments. All the authors supported the writing of the manuscript. All authors have read and agreed to the published version of the manuscript.
**Funding:** This study was financed by the Research project and technological innovation and development from National Forestry and Grassland Administration (No: 2023132015), and the National Natural Science Foundation of China (Grant Nos. 31971652 and 31901307).

**Data Availability Statement:** Data in this study are available from the corresponding author upon reasonable request.

**Acknowledgments:** We are deeply indebted to the other researchers who contributed to this project. The authors also thank the students who have worked hard in the field for data collection.

**Conflicts of Interest:** The authors declare that they have no known competing financial interest or personal relationships that could have appeared to influence the work reported in this paper.

**References**


**Disclaimer/Publisher’s Note:** The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.