

Article

Modeling Primary Branch Diameter and Length for Planted *Pinus koraiensis* by Incorporating Neighbor Competition in Northeast China

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Abstract: Korean pine (*Pinus koraiensis* Sieb. et Zucc.) is the most important forest vegetation in northeast China. The timber quality of this tree species is largely driven by branch growth and distribution within the crown. Thus, developing branch diameter and length models, especially those that include competition indices, is essential. A total of 48 Korean pine trees were selected to conduct destructive measurements of branch characteristics. This was carried out on all live branches, and a branch diameter and length model was developed. Various indices, including the absolute depth into the branch base (DINC) from tree tip, were used. The equation with the largest R_{adj}^2 and smallest root mean square error (RMSE) values was selected as the best model. Each parameter from the best model was reparameterized to the tree variables and competition indices. Finally, the branch diameter model that included diameter at the breast height (DBH), tree height (HT), and the crown length index (CLI), and the branch length model that included DBH and HT exhibited the best performance. The R_{adj}^2 and RMSE values were 0.42 and 4 mm, respectively, for the branch diameter model, and 0.77 and 63 cm, respectively, for the branch length model. Branch diameter and length increased as DBH increased and decreased as HT increased. Furthermore, branch diameter decreased as the CLI increased.

Keywords: branch diameter; branch length; crown length index; *Pinus koraiensis* plantation; mixed-effects model



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1. Introduction

Korean pine (*Pinus koraiensis* Sieb. et Zucc.) is the most important forest vegetation in the temperate moist climate zone in northeast China and is vital for regional climate and terrestrial ecosystem regulation [1]. Plantations of Korean pine have been established in many locations in northeast China since 1950 [2]. Korean pine trees are valuable due to the quality of their timber and seeds, and they account for approximately 5.2% of the total plantation area in northeast China according to the ninth forest inventory of China (2014–2018) [3,4]. High-accuracy growth and yield models are an indispensable component in practical forest management systems. Therefore, developing a growth and yield model for Korean pine plantations would improve timber quality and ecological benefits in northeast China.

The crown structure of individual trees is characterized by the number, size, and location of primary branches within the live crown, and it can be used to assess the dynamics and productivity of forest stands [5]. The tree crown directly influences several stand attributes, including fire susceptibility [6], microclimate [7], and stem area increment [8]. Branch size, including branch diameter, branch length, branch chord length, and branch angle, determines crown structure and forest stand ecology [9]. The function of branches

is to hold the leaves of a tree aloft to ensure exposure to sunlight [10]. Larger branches have the ability to carry more foliage without breaking to ensure effective photosynthesis. However, larger branches produce a knot, which is determined by branch diameter, embedded in the point of the stem from which the branch emerges. From the point of view of commercial forestry, branch diameter is useful in evaluating wood quality [11,12]. Therefore, branch diameter is an important attribute and more attention should be focused on it. Branch length is also very important because it reflects crown plasticity in forest stands [13]. Despite the close relationship between branch length and branch diameter, a direct branch length model remains to be developed. However, measuring branch diameter and branch length from individual trees is costly and time consuming [14]. Therefore, it is essential to develop an accurate branch diameter and length model based on tree- and stand-level variables.

To date, numerous studies have focused on branch diameter and length on the individual tree level. Branch diameter and the length of an individual tree were found to be dependent on the social status and the density of the forest stand [15,16]. In addition, tree variables, including distance from the apex, total tree height, diameter at breast height, and the crown ratio, were also found to have a significant effect on branch diameter [17,18]. Neighbor competition has been demonstrated to be an important influencing factor in shaping the crown of individual trees [19]. Studies of neighborhood competitive interactions showed that the subject tree experiences a greater intensity of competitive stress from larger, nearby neighbors, as compared to small and distant neighbors [20]. This competition affects the growth status of branches and thus affects the survival of the individual tree [21]. In the forest stand, competition also affects crown morphology through influencing branch growth [22]. Consequently, it is necessary to incorporate the competition index into the branch diameter and length prediction model. However, the success of a competition index in the growth and yield model depends on the tree species, the available data from the field, and the structure of the model [23,24]. It may be challenging to select an optimal competition index for the various growth and yield models conducted so far. However, to the best of our knowledge, competition, which has a significant influence on the growth and mortality of individual trees, has not been incorporated into a branch diameter and length model. Crown asymmetry determines leaf display, which drives biomass allocation between the leaves, branches, and other structural components of individual trees [25]. Moreover, it increases the chance of wind throw and stem breakage, which is closely related to branch growth [26]. However, branch diameter and length distribution are poorly understood at present. Branch inventory data are often from whorls, which are nested in the sample trees, which themselves are selected from the sample plots. Therefore, these forest inventory data are organized into a nested structure (i.e., branch–whorl–tree–plot). The mixed-effects model is powerful in analyzing this hierarchically structured data and improving model prediction accuracy [27,28].

On the basis of branch diameter and length measurements from 48 Korean pine trees in 2021, in the present study, we attempted to: (1) analyze branch diameter and branch length distribution from the tree tip down to the crown base; (2) select the best equation to develop the nonlinear mixed-effects branch diameter and length model for Korean pine plantations; and (3) analyze the effect of tree variables and different competition indices on branch diameter and branch length. The purpose of this study was to provide a reference for forest management decision making for Korean pine plantations in northeast China.

2. Materials and Methods

2.1. Study Area

The field investigation was conducted on Dabiangou forest farm (124°4′–125°18′ E, 41°51′–42°00′ N) in Qingyuan county, Liaoning province, northeast China. The total area of the forest is 4736 hm² and the total area of the Korean pine plantation is 405 hm². The forest coverage percentage is 89.6% and the total forest growing stock is 830 thousand m³. The altitude of this forest farm ranges from 500 to 600 m. The typical climate type is a monsoon

climate, which is characterized by hot and rainy summers and cold and dry winters. The mean yearly temperature is 5 °C, with the highest and lowest yearly temperatures being 36.5 and −37.7 °C, respectively. Total annual precipitation varies from 700 to 800 mm and is mainly concentrated in June to September. The mean number of frost-free days is approximately 130 and brown soil is the main soil type. *Larix gmelinii*, *Pinus koraiensis*, *Quercus mongolica* Fisch, *Pinus tabulaeformis* Carr., and *Picea asperata* Mast are the main tree species distributed on this farm.

2.2. Data Collection

In the June of 2020, a total of 12 forest stands in the plantations (8–56 years), with a complete appearance and no insect disease or disturbance, were selected in Dabiangou forest farm, Qingyuan county. Six permanent sample plots sized 0.06 ha (20 m × 30 m) from each plot were established. Therefore, a total of 72 permanent plots were developed. For all the live individual trees from each sample plot, diameter over bark at breast height (DBH, cm) at 1.3 m above ground level was measured using a diameter tape. Total tree height (HT, m) and the height to crown base (HCB, m) of the individual trees were measured using a Vertex IV Ultrasonic Hypsometer (Haglöf Sweden). Crown width (CW, m) on the north, east, south, and west sides from the center of the tree bole was measured using a measuring tape. The relative position in the rectangular coordinate system for each tree in the plot was recorded by defining the first corner of the plot as the origin.

The destructive tree sampling process was conducted from July to August in 2021. A subset of 6 forest stands from the 12 forest stands were selected, in which 3 sample plots from 5 forest stands and 1 sample plot from the remaining forest stand were randomly selected to conduct destructive tree sampling. The descriptive statistics for the 16 sample plots are shown in Table 1. For each of the selected sample plots, all the trees were ranked in descending order by DBH, and then the basal area for each tree was calculated. The total basal area for the plot was divided into five groups to ensure each group had an approximately equivalent cumulative basal area. The average tree with a DBH that was closest to the quadratic mean diameter for the first, third, and fifth groups was defined as the dominant tree, the intermediate tree, and the suppressed tree, respectively. Thus, a total of 48 sample trees including 16 dominant trees, 16 intermediate trees, and 16 suppressed trees were selected. The summary for the sample trees is shown in Table 2. To keep the permanent plot intact for further remeasurements, all sample trees were selected outside the sample plot in which the growing conditions were similar to those in the sample plots. Before felling, DBH, HT, and CW were measured for all sample trees. The trees around each sample tree whose crown came into contact with the crown of the sample tree were defined as neighbor trees. The DBH, HT, and CW of the neighbor trees and the distance between the sample trees and their neighbors were measured. The directions of the neighbor trees as compared to the tree bole center of each sample tree were recorded. In addition, the vertical overlap between each neighbor tree and sample tree was calculated as the difference between the upper contacting point and lower contacting point between the sample tree crown and neighbor tree crown. In summary, a total of 204 neighbor trees were measured and the descriptive statistics of the sample tree attributes are shown in Table 2.

Before felling, a vertical line was marked on the stem on the magnetic north side from the ground level to breast height. The sample trees were felled as carefully as possible using a chainsaw to avoid damage to the branches. After felling, the line marked on the tree bole was extended from breast height to tree tip to facilitate the measurement of the azimuth angle of the branches. The total tree height of the sample tree was remeasured. The crown bases of the sample trees' live crowns were noted, after the lowest whorl that was continuous to the former whorl was defined. The crown length (CL, m) was measured as the length from tree tip to the crown base. The whole tree bole was cut to a 1 m length from tree base to tree tip as carefully as possible to avoid damage to the branches, and the section measuring less than 1 m was defined as the tree tip. From the tree tip, each section was presented upright on the ground to ensure that all the branches were in their natural

growth state. Branch attributes, including branch length (BL, cm), branch azimuth (AZ, °), branch chord length (BC, cm), branch angle (VA, °), absolute distance from tree tip to the branch base (L, cm), and branch diameter (BD, mm) at the branch base, were measured for all the live branches [8] (Figure 1). To describe the tendency of branch diameter from the tree tip down to the crown base, the absolute depth into the first-order branch tip (DINC, m) was calculated as the $DINC = L - BC \cdot \cos(VA)$.

Table 1. Statistics of the stand age, diameter at breast height (DBH), quadratic mean diameter (D_g), dominant tree height (H_{dom}), density and crown width of the six forest stands used to conduct destructive tree sampling in Dabianguo forest farm. N is the number of the sample plot selected in each forest stand to conduct destructive tree sampling.

Age (Year)	N	D_g (cm)	H_{dom} (m)	Density (Trees ha ⁻¹)	Crown Width (m)		
					Mean	Minimum	Maximum
8	3	1.8	2.2	1917	0.55	0.10	1.45
21	3	13.8	11.4	1806	1.71	0.43	4.93
23	3	12.9	11.5	1256	1.62	0.58	3.15
40	3	23.6	16.8	700	2.21	1.50	3.05
52	3	31.7	20.7	322	3.11	1.03	5.15
56	1	35.1	21.0	233	3.68	2.80	4.65

Table 2. The descriptive statistics of the tree attribute variables for the sample trees, nearest neighbor trees, and the branches. HT is total tree height, HD is the ratio of HT and DBH, CR is the crown ratio, and Q1 and Q3 are the 25% and 75% quantiles, respectively.

	Variable	Mean	Minimum	Maximum	Std	Q1	Q3
Sample tree (N = 48)	DBH (cm)	22.2	1.1	43.1	10.7	15.8	28.7
	HT (m)	13.0	1.8	20.2	5.2	9.5	17.3
	HD	0.7	0.5	1.8	0.2	0.5	0.7
	CR	0.7	0.4	1.0	0.1	0.6	0.7
Neighbor tree (N = 204)	DBH (cm)	22.7	5.0	49.0	9.6	14.9	30.6
	HT (m)	13.3	6.2	23.7	4.5	9.2	17.5
	HD	0.62	0.41	1.30	0.14	0.54	0.69
	CR	0.63	0.39	0.82	0.09	0.56	0.69
	Dist (m)	3.54	1.47	8.90	1.67	2.10	4.70
	Angle (°)	173	0	356	106	80	265
Branches (N = 3412)	BD (mm)	23.04	1.36	96.95	16.50	10.64	30.85
	BL (cm)	179	1	760	145	57	263
	BC (cm)	165	1	692	132	54	241
	VA (°)	40	3	150	18	27	50

2.3. Competition Indices Selection

A total of five competition indices, which exhibited excellent performance in the individual tree growth and yield model, were used in the branch diameter and length model in the present study. The relationship between a tree and its neighbors cannot always be determined directly if its location within the stand is not identified [24]. Therefore, a comparison of the size of the subject tree with the sizes of all the other trees is essential in calculating the competition indices. The competition indices tested in our study were as follows: (i) the ratio of the diameter of the subject tree to the quadratic mean diameter (CI_1); (ii) the ratio of the basal area of the subject tree to the mean basal area of the stand (CI_2); (iii) the sum of the basal area of the trees with a DBH larger than the subject tree (CI_3); (iv) the crown length index of the subject tree, which was well documented in the study of Ledermann (2011) (CLI_i) [29]; and (v) the CLO_i , which is the newly developed competition index in which the vertical overlap length between the subject trees and their neighbors

was replaced by the heights between the upper and lower contact points. The calculations for the five competition indices are shown in Equations (1)–(5).

$$CI_1 = \frac{d_i}{d_g} \quad (1)$$

$$CI_2 = \frac{g_i}{\bar{g}} \quad (2)$$

$$CI_3 = BAL = \frac{\sum_{d_i < d_j} g_i}{S} \quad (3)$$

$$CLI_i = \frac{1}{CL_i} \left(CL_i \cdot Nha_i + \sum_{\substack{j=1 \\ i \neq j}}^n TCL_j \cdot Nha_j \right) \quad (4)$$

$$CLO_i = \frac{1}{CL_i} \left(CL_i \cdot Nha_i + \sum_{\substack{j=1 \\ i \neq j}}^n LCO_j \cdot Nha_j \right) \quad (5)$$

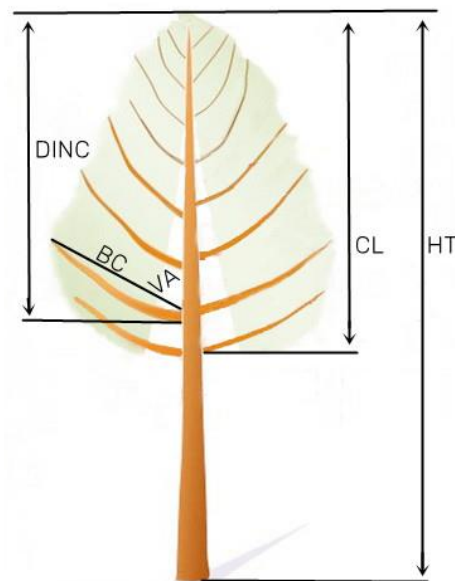


Figure 1. A graphical description for the characteristics of the individual tree and branch variables, which are similar to those in the study of Gao et al. (2021) [8]. HT is total tree height, CL is crown length, DINC is the depth into the crown base from tree tip, BC is branch chord length, and VA is branch angle.

CI_1 – CI_3 are the three competition indices that reflect the crowding degree from the horizontal level; i and j denote the subject tree and competitor tree, respectively; d_i is the DBH of the subject tree; d_g is the quadratic mean diameter of the sample plot; g_i and $\bar{g}$ are the basal area of the subject tree and mean basal area of the sample plot, respectively; and S is the plot area. The CLI_i and the CLO_i are comprehensive competition indices relating the stand density to the crown base of the subject tree, combining the horizontal and vertical competition effects. As regards the CLI_i , the CL_i is the crown length of the subject tree i , the CL_j is the length of vertical crown overlap between the subject tree and its competitor j (Figure 2), Nha_i is the per hectare expansion factor of the subject tree i , Nha_j is the per hectare expansion factor of competitor j , and n is the total number of competitors for the specific subject tree. As regards the calculation of the CLO_i , the vertical

contact length between the subject trees and their neighbors was carefully quantified. The heights between the upper and lower contact points (TCL_j) were measured using a Vertex IV ultrasonic hypsometer made by Hagl f Sweden (Figure 2). The difference in the heights was calculated as the vertical contacting overlap between the subject trees and their neighbors. LCO_j is the heights between the upper and lower contact points for competitor j . All the listed competition indices were incorporated into the branch diameter and length prediction model and the specific competition index that made the largest contribution was selected.

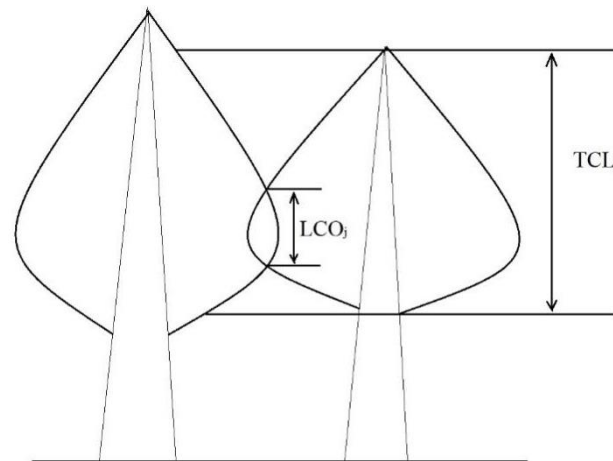


Figure 2. A graphical description for the calculation of the two competition indices (the CLI and the CLO) reflecting both horizontal and vertical competition. TCL_j is the heights between the upper and lower contact points and LCO_i is the vertical overlap length between the upper and lower contacting points between the sample and neighbor tree crowns.

2.4. Branch Diameter Modeling

Graphical analysis of primary branch diameter and length showed that branch diameter and length were mainly related to the DINC (Figure 3). We used and compared five standard functions, which performed excellently in previous research (Table 3). Cross validation has been a popular strategy for model selection and the main idea of cross validation is to split the data into once or several times [30]. The leave-one-out approach is the most classical exhaustive cross-validation procedure in which each data point is successively “left out” from the sample and used for validation [30]. In our study, we used the leave-one-out approach to evaluate the basic models. In each round, 47 trees were used to fit model and the one “left out” tree was used for validation. R_{adj}^2 and the prediction for each left out independent tree were calculated for each round of fitting. Ordinary least square estimation (OLS) was used to fit the models and the specific model with the largest R_{adj}^2 and lowest root mean square error (RMSE) values was selected as the best [24]. Equations (6) and (7) were used to calculate R_{adj}^2 and RMSE:

$$R_{adj}^2 = 1 - \left(1 - R^2\right) \cdot \left(\frac{n-1}{n-p-1}\right) \quad (6)$$

$$\text{where } R^2 = 1 - \frac{\sum_{i=1}^n (y_i - \hat{y}_{i,-i})^2}{\sum_{i=1}^n (y_i - \bar{y})^2}$$

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^n (y_i - \hat{y}_{i,-i})^2}{n-p}} \quad (7)$$

where n is the number of observations, p is the number of parameters, and y_i is the i th observed value, and $\hat{y}_{i,-i}$ is the predicted value for the predicted value without inclusion of the i th observation.

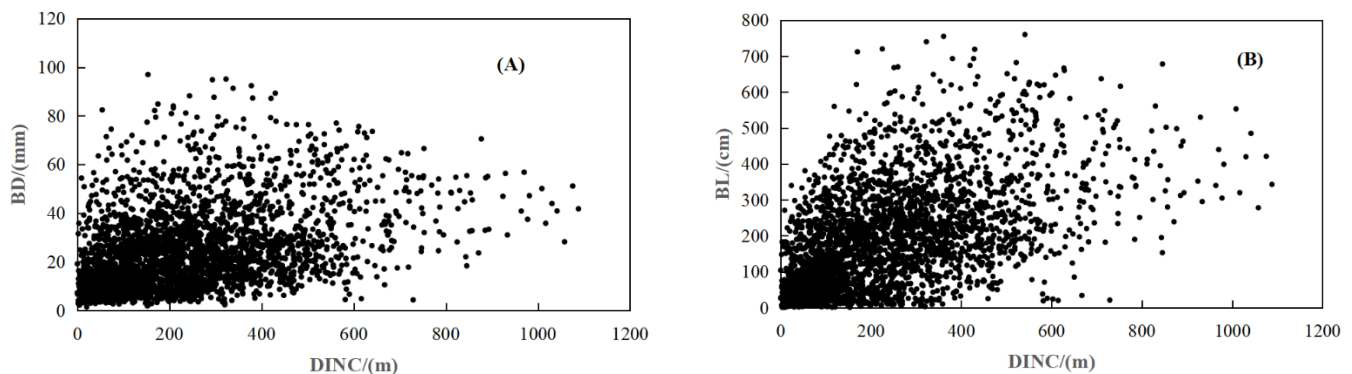


Figure 3. Distribution of branch diameter (BD, (A)) and branch length (BL, (B)) against the DINC from tree tip downwards the crown base within the entire crown.

Each parameter from the best model was reparameterized as the linear form of the tree variables and competition indices. To avoid overparameterization and collinearity in the models, only variables making a significant contribution to branch diameter and length variations were incorporated into the basic model. The nonlinear mixed-effects model, including fixed and random parameters, is an efficient approach for analyzing hierarchical measurement data and making high-accuracy predictions [31]. The branch data in our study are typical hierarchical data for branches nested in the individual tree and the trees nested in the plot. Therefore, we used the nonlinear mixed-effects regression approach by including random parameters acting at the tree level to estimate the final branch diameter and length model parameters. The variance–covariance matrices for the random vector were used to account for the random effects vector for the variability between trees. The exponential function and the powerful function were used to remove variance heterogeneity [31]. Appropriate random parameter, variance–covariance matrices and the variance function for the best model were determined by Akaike Information Criterion (AIC), Bayesian Information Criterion (BIC), and logarithm likelihood values (LogLik) [31]. All the analyses were performed on the R software platform [32].

Table 3. A list of equations used for modeling branch diameter and branch length of the Korean pine plantation.

Function NO.	Function (BD or BL)	Function Form	References
M1	$BD = b_0(1 - \exp(-b_1DINC))^{b_2}$	Richards	Payandeh and Wang, 1995 [33]
M2	$BD = b_0(1 - \exp(-b_1DINC^{b_2}))$	Weibull	Bailey and Dell TR, 1973 [34]
M3	$BD = b_0 \exp(-b_1 \exp(-b_2DINC))$	Gompertz	Rupsys and Petruskas, 2010 [35]
M4	$BD = b_0 / (1 + b_1 \exp(-b_2DINC))$	Logistic	Radim et al., 2012 [36]
M5	$BD = b_0 / (1 + b_1DINC^{-b_2})$	Hosfled	Dong et al., 2016 [18]

Notes: BD is branch diameter, BL is branch length, DINC is the depth into the crown from tree tip downwards the branch base, and b_0 , b_1 , and b_2 are model parameters from the basic model.

3. Results

3.1. Branch Diameter and Branch Length Model Development

All the candidate functions in Table 3 were fitted using ordinary least square estimation (OLS) to branch diameter and branch length, respectively, using the leave-one-out approach. The mean values of R_{adj}^2 and RMSE for the five candidate models were listed as Table 4. The equations with the largest R_{adj}^2 and smallest RMSE values were selected as the best

model. In addition, the stability of the parameter was taken into consideration in the model selection process. Therefore, the Hosfled function (M5) was selected as the best candidate equation for branch diameter and branch length predictions, which is shown in Equations (8) and (9), respectively.

$$BD = b_0 / (1 + b_1 \text{DINC}^{-b_2}) \quad (8)$$

$$BL = b_0 / (1 + b_1 \text{DINC}^{-b_2}) \quad (9)$$

where BD is branch diameter, BL is branch length, DINC is the depth into the crown of interest, and b_0 , b_1 , and b_2 are the model parameters to be estimated.

Table 4. The mean values of R_{adj}^2 and RMSE for the five equations used for modeling branch diameter and branch length of the Korean pine plantation using the leave-one-out approach.

Model	M1		M2		M3		M4		M5	
	R_{adj}^2	RMSE	R_{adj}^2	RMSE	R_{adj}^2	RMSE	R_{adj}^2	RMSE	R_{adj}^2	RMSE
BD	0.30	5	0.32	6	0.32	6	0.31	6	0.36	5
BL	0.48	80	0.51	78	0.50	79	0.46	81	0.56	76

Notes: BD is branch diameter, BL is branch length, and M1–M5 were function NO in Table 3.

Equations (8) and (9) were fitted to all the individual trees, respectively. The relationship between the model parameters, the tree variables, and competition indices were analyzed. For Equations (8) and (9), parameter b_0 was reparameterized to DBH, and b_1 was reparameterized to HT. In the branch diameter model (Equation (8)), the CLI and the CLO made similar contributions to the basic model. As a result of the simpler measurement process for the CLI, we finally incorporated the CLI into the branch diameter model. As for the branch length model, the CLI and CLO parameters were not statistically significant. The final models for branch diameter and length are shown in Equations (10) and (11), respectively.

$$BD = (b_0 + b_1 \cdot \text{DBH} + b_2 \cdot \text{CLI}) / (1 + b_3 \cdot \text{HT} \cdot \text{DINC}^{-b_4}) \quad (10)$$

$$BL = (b_0 + b_1 \cdot \text{DBH}) / (1 + b_2 \cdot \text{HT} \cdot \text{DINC}^{-b_3}) \quad (11)$$

where BD and BL are branch diameter and branch length, respectively, DBH is diameter at breast height, HT is total tree height, the CLI is the crown length index of the subject tree, as in Equation (4), and b_0 – b_4 are the model parameters to be estimated.

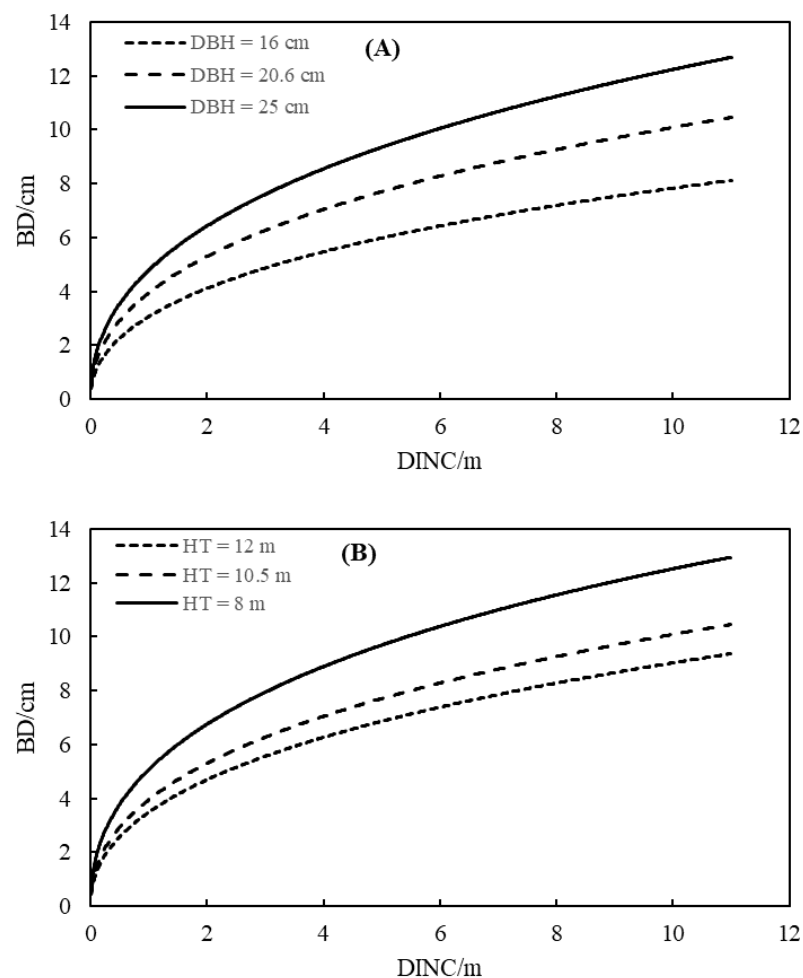
Parameter b_4 and b_3 acting as the random effect parameter for the branch diameter and branch length model, respectively, yielded the smallest AIC and BIC, and the largest Loglik. Both the exponential function and the powerful function did not improve the performance of branch diameter and length model according to AIC, BIC, and Loglik. The parameter estimates and goodness-of-fit statistics for the branch diameter and length model from the nonlinear mixed-effects approach are shown in Table 5. All the parameter estimates were stable and exhibited a small standard error of the mean. Therefore, this indicated that DBH, HT, and the CLI exerted a significant effect on branch diameter, and only DBH and HT exerted a significant effect on branch length. We also incorporated the crown length, CR, and HD into the branch diameter and length model, but none of these variables were significant for either of the two models. Finally, we retained DBH, HT, and the CLI in the final branch diameter model, and we only retained DBH and HT in the final branch length model. The R_{adj}^2 and RMSE values were 0.77 and 63 cm, respectively, for the branch length model, and 0.42 and 4 mm, respectively, for the branch diameter model.

Table 5. Parameter estimates and goodness-of-fit statistics for the branch diameter and branch length model for the planted Korean pine.

Parameter	Branch Diameter Model			Branch Length Model		
	Estimate	Std	p Value	Estimate	Std	p Value
b_0	6.5356	1.1662	<0.001	43.9236	9.5103	<0.001
b_1	2.6743	0.5375	<0.001	16.3817	1.3339	<0.001
b_2	−0.0715	0.0297	0.0161	8.6665	1.7127	<0.001
b_3	1.2335	0.1302	<0.001	0.8864	0.0597	<0.001
b_4	0.4626	0.0483	<0.001			
R_{adj}^2	0.42			0.77		
RMSE	4			63		

3.2. Responses of Branch Attributes to Competition

On the basis of the developed branch diameter model (Equation (8)) and branch length model (Equation (9)), the effect of the tree variables (DBH, HT) and the competition index (CLI) on branch diameter and length was simulated, as shown in Figures 4 and 5, respectively. As shown in Figure 4, branch diameter exhibited an increasing tendency from tree tip downwards the crown base. Branch diameter increased with increasing DBH (Figure 4A), and decreased with the increasing HT of the individual trees (Figure 4B), while the other variables remained unchanged. As for the crown length index (CLI), branch diameter rapidly decreased with the increasing CLI (Figure 4C), while DBH and HT remained constant. As shown in Figure 5, branch length also increased with increasing DBH (Figure 5A), and decreased with increasing HT (Figure 5B).

**Figure 4.** Cont.

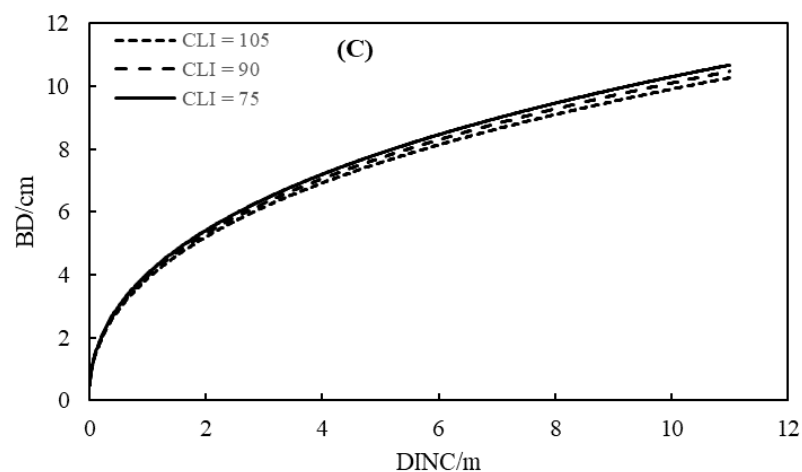


Figure 4. Effect of DBH (A), HT (B), and the CLI (C) on branch diameter with an increasing DINC within the entire crown for the planted Korean pine.

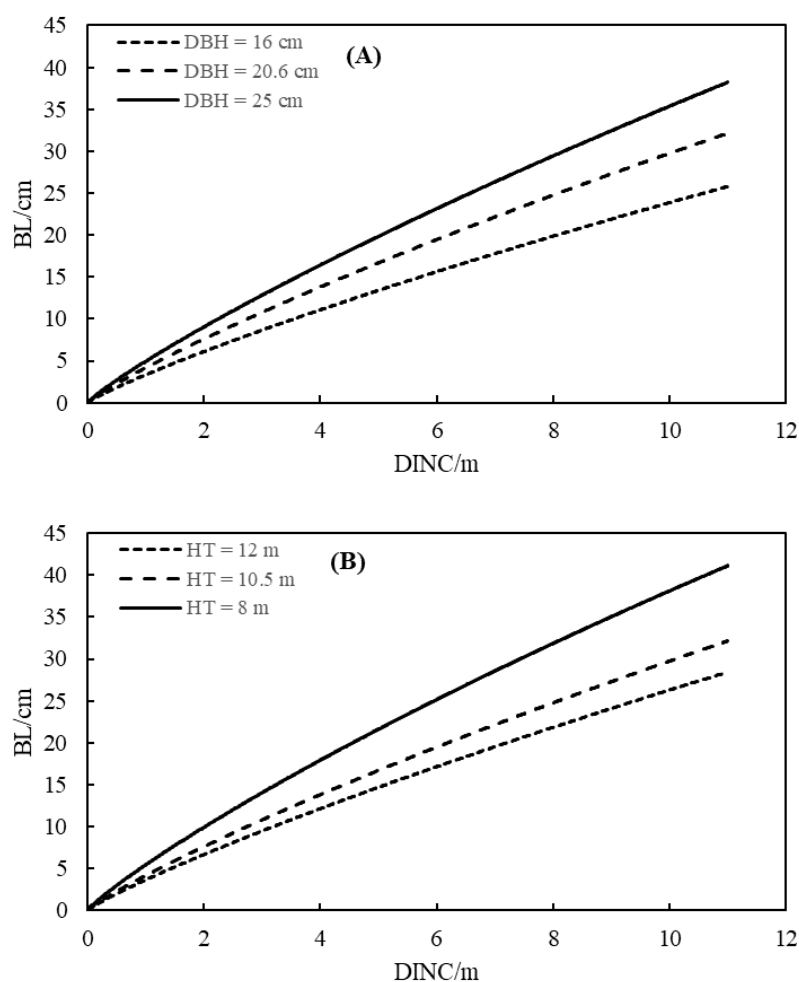


Figure 5. Effect of DBH (A) and HT (B) on branch length with an increasing DINC within the entire crown for the planted Korean pine.

4. Discussion

The nonlinear mixed-effects model, a flexible and powerful tool for the analysis of hierarchical measurement data, can be used to study the branch variables at different hierarchical levels. In our study, the branch measurement was taken from the individual

tree, and the trees were selected from the sample plot, which conformed to a typical hierarchical data structure. Therefore, the branch diameter and branch length of the planted Korean pine in northeast China are defined as a stochastic process in which the mean value for the model development was explained by the fixed effect, and the unexplained residual variability was modeled by the random effect at the tree level [18]. Therefore, we used the nonlinear mixed-effects model to develop the branch diameter and length prediction model.

A graphical analysis of primary branch diameter and length indicated that the location of the branch within the crown (DINC) was the primary explanatory variable with which to explain branch diameter and length variability of the Korean pine plantation (Figure 3) [14]. Therefore, we employed a list of functions, using the DINC as the sole variable, to fit the branch diameter and length model. Considering the goodness-of-fit statistics, we finally selected the Hosfled function (Table 3) as the best model to fit the diameter and branch length. Dong et al. (2016) also found that the Hosfled function exhibited the best performance in modeling branch diameter and length for *Larix gmelina* [18]. In addition, we also checked the residual distribution for the mixed-effects branch diameter and branch length model, the residual plot has been improved compared to the basic model.

Through reparameterization, DBH, HT, and the CLI were successfully introduced into the branch diameter model. In comparison, only DBH and HT exhibited a good performance in the branch length model. We attempted to incorporate the crown ratio, crown length, and the ratio of total tree height to DBH into the two models, but none of these variables were significant. Colin et al. (1993) [37] found that branch diameter also depended on the social status and stand density. Because we focused on the effect of neighbor competition on branch diameter, and competition is also a reflection of stand density, the stand density was not considered in our study in order to avoid overparameterization. In addition, as a result of the limited number of sample trees in our study, the social status was assessed. The crown ratio was found to be a useful variable in the branch diameter model in many studies [17,38]. However, the crown ratio was not observed to be a significant variable in the branch diameter and length model in our study. The reason for this may be related to differences amongst tree species.

Maguire et al. (1999) [39] and Beaulieu et al. (2011) [14] reported that the growth of a branch in the higher crown mainly depends on site fertility, while the branches in the lower crown are mainly affected by competition. However, Mäkinen and Colin [16] and Umeki and Kikuzawa [40] demonstrated that competition indices do improve the branch characteristics model. As shown in Figure 4C, our study demonstrated that competition exerted a larger effect on branch diameter in the location near the crown base. Competition index selection is an important factor. The basal area of larger trees (BAL), and the size of the subject tree as compared with the sizes of all the other trees, have been widely used in the individual tree growth and yield model [41,42]. However, the majority of competition indices only characterize inter-tree competition on the horizontal level. We assumed that measuring competition on the vertical level is likely more important, because crown recession is the result of branch dieback within the crown, and the dieback itself is most likely driven by competition among the branches that are located at the same height [29]. Therefore, we took the crown length (CLI) and vertical overlapping length between the subject tree and its neighbors (CLO) into consideration. The two competition indices combines both horizontal and vertical competition effects by relating the stand density to the crown space of a subject tree. This is another reason why the stand density was not considered in our study. However, we only observed a significant effect of the CLI in the branch diameter model, and none of the competition indices were significant in the branch length model. Branch diameter was negatively related to neighbor competition strength. Therefore, we demonstrated that vertical competition from neighbor trees exerted a significant effect on branch diameter, especially for branches in the lower crown [39]. In addition, the branch diameter and length model developed in the present study may only be applicable in our study area, because all sample trees were collected from one location.

5. Conclusions

Korean pine plantations are valuable due to their high-quality timber and widely traded nuts. Branch diameter and length have a large effect on crown structure, and thus affect timber quality and nut production. Branch diameter and length models are important components in the individual tree growth and yield model system. We developed a branch diameter and length model by considering tree attributes and competition variables. We also compared the competition indices on the horizontal level and both the horizontal and vertical levels. The crown length index (CLI), which reflects both horizontal and vertical competition, exhibited the best performance in the branch diameter model. Finally, the DINC, DBH, HT, and the CLI were included in the branch diameter model, and the DINC, DBH, and HT were included in the branch length model. Branch diameter and branch length were mostly related to the position of the branch within the crown (DINC). Branch diameter increased with increasing DBH, and decreased with increasing HT and CLI. Moreover, branch length increased with increasing DBH and decreased with increasing HT.

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