


## Article

# Development of an Integrated DBH Estimation Model Based on Stand and Climatic Conditions

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**Abstract:** Using Korean National Forest Inventory (NFI) data, our study developed a model to estimate stand mean diameter at breast height (DBH) reflecting the influence of site and climate factors on forest growth for the major tree species in South Korea. A DBH estimation model was developed using stand-level variables (stand age, site index and number of trees per hectare) as independent factors. The spatial autocorrelation of residuals of the model was identified using semi-variogram analysis for each tree species. Further, a residual model, in which residuals were estimated by climatic factors (mean temperature, sum temperature in the growing season and precipitation), was developed assuming that the spatial autocorrelation of residuals reflects the differences in regional climatic conditions. Linear regression analysis showed that residuals of all tree species were significantly correlated with temperature and precipitation. The DBH and residual models were integrated to estimate the current DBH under different climatic factors (temperature and precipitation) and stand-level variables. This model had high reliability ( $R^2 = 0.74\text{--}0.79$ ), and no obvious dependencies or patterns in residuals were noted. Our results indicated that temperature increases caused by climate change would negatively affect the DBH estimate of coniferous trees, but not of oak species.

**Keywords:** climate factor; diameter at breast height (DBH); semi-variogram; residuals; national forest inventory

## 1. Introduction

Many tree growth models that can effectively project changes in forest resources have been developed to establish forest management planning practices [1–3]. Various stand-level factors and indicators such as stand age, site quality and density are considered as integral components of tree growth models to reflect the characteristics of stands and their natural environments [4–6]. It is necessary to develop a forest growth model for the establishment of rational management [7,8]. Ji et al. [9] used observed data (such as stand age, site quality and density) from fixed sample plots to develop a stand growth model in Lishui City; then, using the model, predicted forest growth. Forest growth can also be influenced by climate factors. Efforts have been undertaken to include

climatic condition as a core component of growth models [10–12]. According to Tian et al. [13], net primary productivity (NPP) has decreased due to global warming over the past century in the Amazon rain forest.

Stand-level factors have been recognized as essential for forest growth models because growth rates can vary according to mean age, site quality and stand density [14–16]. Climatic and topographic factors can be used to localize growth models to specific regions [17,18]. Nirmal and Mahadev [19] reported that higher temperatures can increase the diameter of Jack pine (*Pinus banksiana* Lamb.) in the boreal forest in Ontario, Canada. Gao et al. [20] showed that the diameter at breast height (DBH) of Korean pine (*Pinus koraiensis* Siebold & Zucc.) in Changbai Mountains was negatively correlated with winter temperature. In addition, the changes in tree growth over time can be explained by both tree age and climate factors [12,21]. Byun et al. [12] found that temperature adversely affects red pine growth, whereas it improves the growth of oak tree species.

However, previous studies had a major limitation. Some previous studies [12,22] included climate indicators within the regression equation. Unlike stand-level environmental factors that are traditionally used to generate tree estimation models, climate factors have spatially-continuous attributes. They can exert strong spatial autocorrelation. Not using different attributes of factors or using both spatial and non-spatial factors in a single model can result in low reliability of the model and overestimation of uncertainties [23,24]. Therefore, this study aimed to analyze quantitatively the influence of climate on diameter development and identifying the characteristics of diameter development for the major tree species (*Pinus densiflora* Siebold & Zucc., *Larix kaempferi* (Lamb.) Carr., *Pinus koraiensis*, *Quercus variabilis* Blume and *Quercus mongolica* Fisch. ex Ledeb.) in South Korea by using the DBH estimation model developed based on surveyed age, site quality and stand density.

## 2. Data and Methods

### 2.1. Study Area and Materials

The study area (approximately 124°54′–131°06′ E and 33°09′–38°45′ N) covered the entire country of South Korea (100,201 km<sup>2</sup>). It has a wide variety of forest habitats, ranging from a warm temperate climate zone to a cold climate zone. The total forest area (6,450,438 ha) accounts for 64% of the total land area of South Korea. Forests of South Korea consist of coniferous forest (approximately 38%), oak forest (47%), mixed forest (12%) and other types (3%) [25].

The Korean National Forest Inventory (NFI) uses a standard design, in which sample points are placed at nodes of each a 4 × 4 km grid (Figure 1) [26]. A systematic 4-km grid was created for permanent plots in South Korea when the Korean NFI was established in 2006–2010 [27]. Four circular sample plots were located at the intersection of each 4 × 4 km grid line. Each sample plot (31.6 m radius) covered 0.16 ha. Each year, 20% of grid locations were sampled. As such, the entirety of South Korea was sampled during the inventory period. Forest characteristics (tree species, age and height), DBH, number of trees with a diameter greater than 6 cm and topographical factors (coordinates, elevation, slope and aspect) were measured at all sites. In addition, in each plot, increment cores were obtained from approximately six dominant or co-dominant trees. One core per tree was extracted from trees at breast height from a direction parallel to the slope using an increment borer. Each tree age was defined using an increment core. The stand age of a plot was defined by the mean age of six trees. Tree species in plots were identified according to basal area of the dominant species. If the basal area of red pine occupied more than 75% in a plot, the plot was considered a “red pine” stand.

In this study, NFI data were used. The data investigated approximately 4000 fixed sites nationwide. Each site consisted of four subplots and a total of 16,000 stand survey data (species, age, site index, diameter, etc.). In addition, the data included all observed management information such as thinning and harvesting and observed disturbance information such as wind damage, forest fire and landslides. This study did not consider the effect of human activities (management) and disturbances on DBH development. In order to estimate the DBH development site and climate, a total of 1647 plots

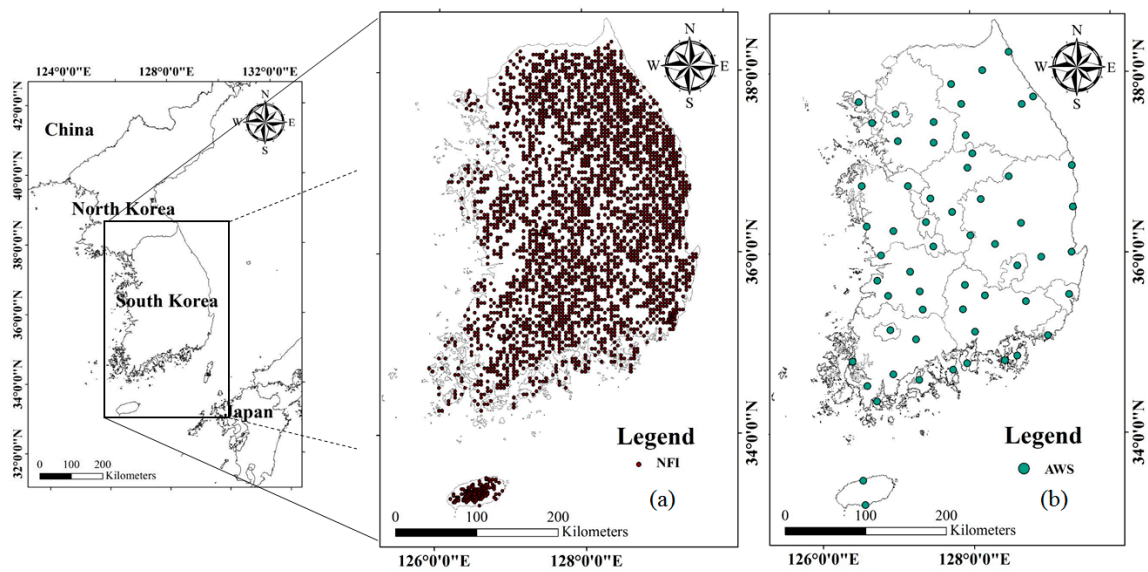
were excluded under the consideration of the management and disturbance information listed above. In addition, a total of 5292 plots (among 6939) corresponding to the major species that exist in Korea were used in our analyses (Table 1). These included *Pinus densiflora* Siebold & Zucc., *Larix kaempferi* (Lamb.) Carr., *Pinus koraiensis* Siebold & Zucc., *Quercus variabilis* Blume and *Quercus* L. total (*Quercus variabilis* Blume and *Quercus mongolica* Fisch. ex Ledeb.). This study was conducted based on detailed and comprehensive data collected at national scales; the conditions of the stands, such as age, site index and stand density, were very diverse in each space, such as for *Pinus densiflora* Siebold & Zucc. (Figure 2).

Recent (2000–2013) automated weather station (AWS) observed data such as temperature and precipitation obtained from the Korean Meteorological Administration (KMA) were used to analyze the relationship between the DBH development and climatic indicators. These data were converted to grid-type data with a spatial resolution of  $1 \times 1$  km by using an interpolation method described previously [28]. NFI data were split into two sets: the majority (90%) was used for model development, and the remaining data (10%) in each diameter class for each species were randomly selected and reserved for model validation. Results of basic statistics for the datasets are summarized in Table 1.

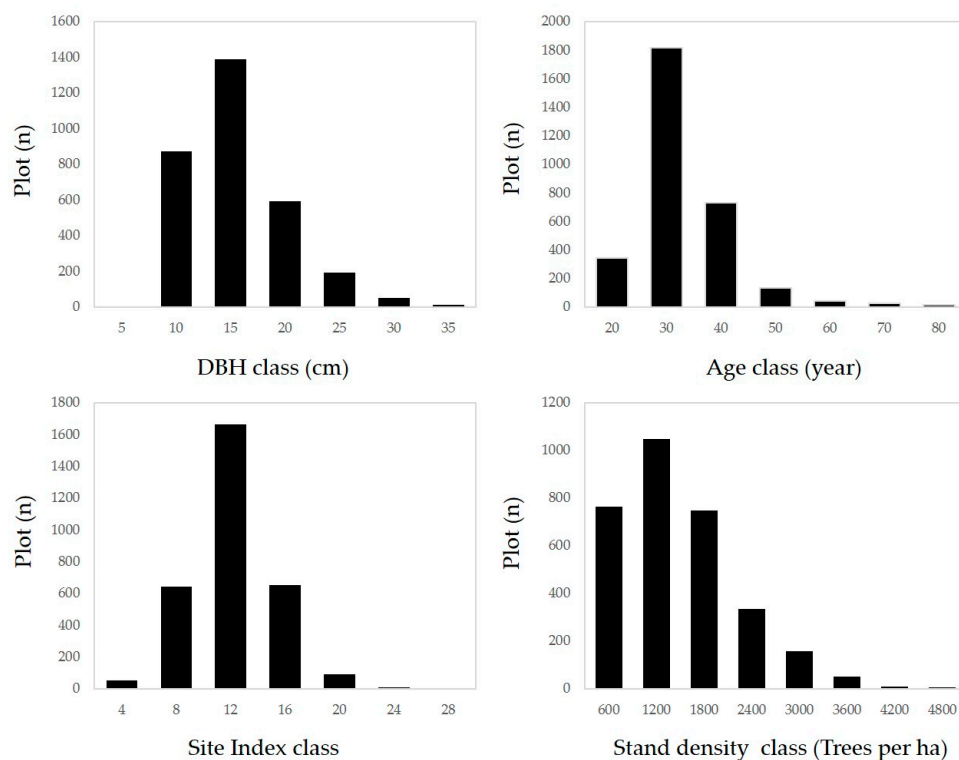
**Table 1.** General description of variables used in this study from the 5th National Forest Inventory (NFI; 2006–2010) and automated weather station (AWS).

Variables	Use	<i>Pinus densiflora</i> Siebold & Zucc.		<i>Larix kaempferi</i> (Lamb.) Carr.		<i>Pinus koraiensis</i> Siebold & Zucc.		<i>Quercus</i> Total ( <i>Quercus variabilis</i> Blume+ <i>Quercus</i> <i>mongolica</i> Fisch. ex Ledeb.)	
		Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
No. of plots	Model Verify	2796 311		301 33		185 20		1481 165	
Stand age (year)*	Model	33.6	8.4	33.9	7.9	28.8	8.5	37.1	5.7
	Verify	33.8	8.4	31.5	7.1	35.6	9.7	38.1	7.0
Stand mean DBH (cm)	Model	15.5	4.5	17.9	4.3	17.8	6.4	15.1	4.1
	Verify	15.8	4.5	18.5	4.6	24.3	7.5	15.0	4.0
Site index*	Model	12.1	2.9	17.2	3.2	14.1	2.8	12.6	1.2
	Verify	12.1	3.1	16.8	3.0	15.1	2.5	12.3	1.7
Tree height (m)	Model	10.45	2.75	15.38	3.85	11.80	3.81	11.19	11.47
	Verify	10.20	2.72	15.01	3.82	9.71	3.20	10.50	2.15
Stand density (n/ha)	Model	1467.0	729.1	875.9	383.4	952.5	562.2	1410.4	284.4
	Verify	1463.9	724.1	890.2	126.9	403.6	537.8	1359.7	223.6
Mean temperature (°C)	Model	11.0	2.1	8.8	2.0	9.5	1.9	8.9	1.1
	Verify	10.9	0.7	8.8	0.5	1.6	1.8	8.4	1.0
Temperature (sum) in the growing season* (°C)	Model	3323.3	84.3	3282.7	76.5	3243.9	80.1	3281.1	43.0
	Verify	3324.4	80.0	3299.8	77.5	3296.9	79.9	3265.4	42.5
Precipitation in growing season* (mm)	Model	980.5	184.1	921.2	59.5	918.7	50.3	941.0	84.7
	Verify	981.9	154.3	926.8	47.1	47.1	43.1	951.8	92.1

Stand age (year)\*: the stand age of a plot was defined by the mean age of 6 trees. Site index\*: Among the methods used to judge site quality, site index (SI) is one of the most used indicators and has high reliability. The SI refers to the height of a given tree species at the base ages of 25, 50 and 100, on the site of interest. In fact, the SI is defined by the Korea Forest Service as the height of the dominant tree at 30 years of age. For example, the SI is 16, if the height of tree is 16 m at a stand age of 30. The SI of each NFI plot is recorded by field survey and the Chapman-Richard model and Schumacher model [27]. Growing season\*: from March–October [29].



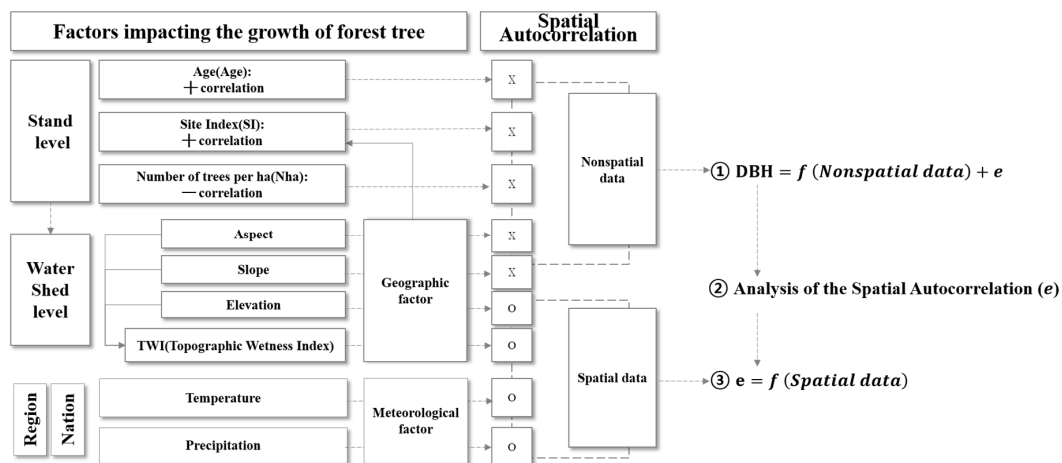
**Figure 1.** Study area with permanent plots of the Korean National Forest Inventory (NFI) (a) and automated weather station (AWS) points (b).



**Figure 2.** Extensive diversity of each factor (DBH, age, site index and stand density) by plot (*Pinus densiflora* Siebold & Zucc.), based on the 5th National Forest Inventory data.

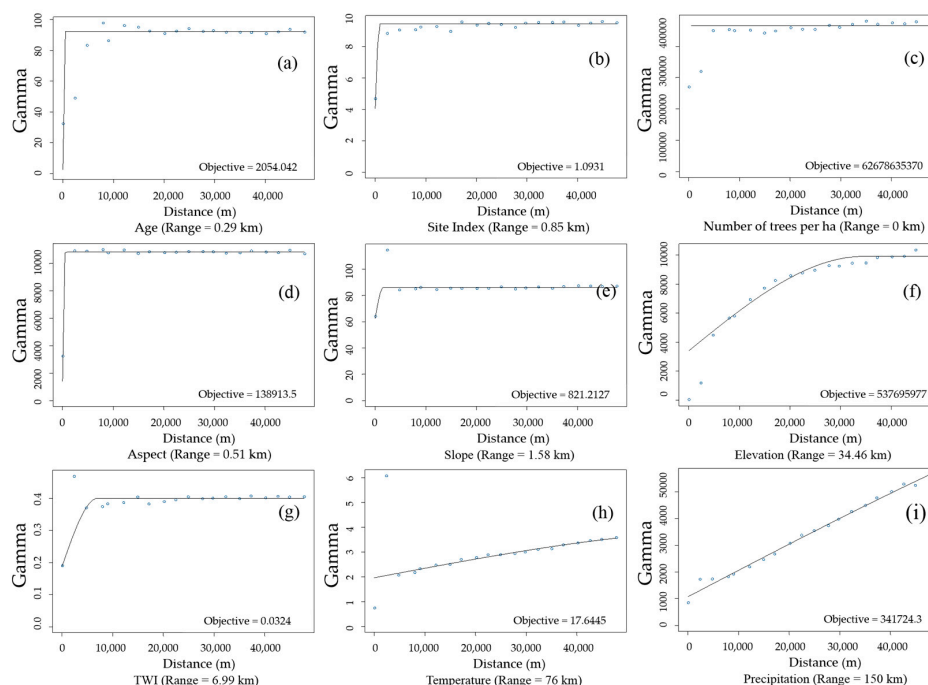
## 2.2. Method

This study was conducted to develop an integrated DBH estimation model by considering both climatic factors and stand-level variables. Factors that might influence tree growth were classified into three spatial categories, namely stand-level, watershed-level and regional-level (Figure 3).



**Figure 3.** Hypothesis for developing the diameter at breast height (DBH) model in this study. “x” and “o” represent the absence and presence of spatial autocorrelation, respectively.

Stand-level factors (age, site index and stand density) and some watershed-level factors such as aspect and slope can be called “non-spatial data” because they do not show any spatial autocorrelation. Factors such as age, site index, number of trees per ha, aspect and slope, within the range of 4 km, did not elicit spatial autocorrelations, whereas elevation, the topographic wetness index (TWI), temperature and precipitation yielded spatial autocorrelation at ranges over 4 km (Figure 4). Therefore, they are called “spatial data.” When these non-spatial data and spatial data are used together in a regression model, the fitting performance of the spatial data might lead to low significance. To address this issue, we developed an integrated DBH estimation model in the following three steps.



**Figure 4.** Analysis of spatial autocorrelation by using factors that affect DBH estimation at the stand level ((a), (b), (c), (d), (e), (f), (g), (h) and (i) represent spatial autocorrelation of age, site index, number of trees per ha, aspect, slope, elevation, TWI, temperature and precipitation, respectively).

First, a diameter model for DBH estimation was developed using stand-level factors without spatial autocorrelation. According to previous research in forestry science, forest growth is largely indicated by stand-level factors such as age, site index and stand density [16,30–32]. Therefore, stand-level factors that could affect tree growth were assumed as the main indicators of DBH estimation. They were used in the DBH estimation model to estimate DBH. The model is simple and can be applied in practical forest management and planning.

Second, a residual model was developed to predict the relationship between residuals and climate factors with spatial autocorrelation by including temperature and precipitation as sub-indicators. Climate has spatial patterns at any spatial scale. Although the estimation model might have a good statistical fit with a random pattern of residuals, residuals might exhibit spatial autocorrelation if climate influences tree growth [33]. In addition, residuals of tree estimate models might serve as indicators of altered environmental conditions [34].

Finally, the diameter model and residual model were integrated to develop an integrated DBH estimation model, in which DBH could be predicted by climate factors (mean temperature, temperature (sum) in the growing season and precipitation in the growing season) and stand-level factors (age, site index (*SI*) and number of trees per ha (*Nha*)).

### 2.2.1. DBH Estimation Model with Stand Age, *SI* and *Nha*

Among various factors, *age*, *SI* and *Nha* from NFI data were used to develop the DBH estimation model in this study. According to Moore et al. [35], the NFI data have been split into two sets: the majority (90%) was used for model development; 10% of trees in each diameter class for each species were randomly selected and reserved for model validation. In addition, three candidate curve equations were carefully designed to reflect the characteristics of each tree species (Equations (1)–(3)). This study focused on the DBH estimation model in accordance with previous studies. Elicited results showed that nonlinear regression had a better performance than linear regression of DBH development in a stand [36,37]. Therefore, we did not implement additional linear regressions. The best regression among these three equations was selected for each tree species. Therefore, in this study, nonlinear regression was adopted and performed using SAS 9.2 software (SAS Institute, Cary, NC, USA).

$$DBH = a \cdot age^b \cdot SI^c \cdot Nha^d \quad (1)$$

$$DBH = e^{(a+b \cdot age+c \cdot SI+d \cdot Nha)} \quad (2)$$

$$DBH = a \cdot e^{b \cdot (\frac{1}{age})} \cdot SI^c \cdot Nha^d \quad (3)$$

where DBH is diameter at breast height; *age* refers to stand age; *SI* is the site index; *Nha* is the stem number per hectare (stand density index); and *a*, *b*, *c* and *d* are coefficients.

### 2.2.2. Semi-Variogram Analysis for Residuals of the DBH Estimation Model

“Spatial autocorrelation” is a correlation among values of a single variable strictly attributable to their relatively close locational positions on a two-dimensional (2D) surface. It introduces deviation from the independent-observation assumption of classical statistics. Spatial autocorrelation exists because real-world phenomena are typified by orderliness, (map) patterns and systematic concentration rather than randomness. If differences in residuals exist at the regional level because of other factors such as climate and topographic factors, residuals will show spatial autocorrelation. The semi-variogram has been used to analyze spatial variability [38]. Therefore, semi-variogram analysis was performed in this study to identify spatial autocorrelation. Additional spatial parameters in residuals were estimated using the SPATIAL STATS sub-module of the S-PLUS Program [39]. In general, spatial autocorrelation is analyzed by the ratio of the nugget to the sill. The sill refers to the maximum observed variability of the data, whereas the nugget refers to the variability of the field data



that cannot be explained by the distances among the observations. If the ratio is high, the chance of spatial autocorrelation is low. If the ratio is low, there is spatial autocorrelation [40].

### 2.2.3. Residual Model with Climate Variables

Residuals were differences between actual measurements and estimates of DBH. Residuals of empirical tree-prediction models accounting for tree size and between-tree competition with actual growth can also serve as indicators of changing environmental conditions [34]. According to existing studies [20,24,41], tree growth is associated with precipitation and temperature. If residuals are spatially autocorrelated, the relationship between tree growth and climate factors can be analyzed quantitatively. Therefore, the relationship between climate factors and residuals of DBH was modeled using a simple linear function (Equations (4) and (5)) in the present study.

After regression analysis was performed on residuals and climate factors (temperature and precipitation) by using Equations (4) and (5), the final DBH model (Equation (6)) was derived by combining results of the regression analysis with one of the DBH estimation models (Equations (1)–(3)).

Byun et al. [12] used linear regression model to analyze the correlation between climate factors and tree growth and obtained relatively good results. Therefore, a linear regression model was used in this study to analyze residuals.

$$e_i = a + b \cdot T_{Mean} + c \cdot P_{Season} \quad (4)$$

$$e_i = a + b \cdot T_{Season} + c \cdot P_{Season} \quad (5)$$

where  $i$  is permanent plot number;  $T_{Mean}$  is the mean temperature and  $T_{Season}$  is the temperature (sum) in the growing season during 2000–2013 at  $i$ ;  $P_{Season}$  is the precipitation in the growing season during 2000–2013 at  $i$ ;  $a$ ,  $b$  and  $c$  are coefficients; and  $e$  is the residual of  $i$ .

Equation (4) is a model that considered both mean temperature and precipitation in the growing season as parameters in residual analysis, whereas Equation (5) considered temperature (sum) in the growing season and precipitation in the growing season. Finally, the equation with the better coefficient of determination ( $R^2$ ) was chosen for estimation as an integrated model.

### 2.2.4. Integrated DBH Estimation Model with Stand-Level and Climate Variables

In previous steps, the DBH estimation model and residual model for each tree species were selected by best performance, i.e., the highest  $R^2$  among models. The final model for each tree species was developed by integrating the optimal DBH estimation model and residual model. In the present study, a simple method was used for integration (Equation (6)).

$$\begin{aligned} \text{Integrated DBH estimation model} = \\ \text{Stand-level DBH estimation model} + \text{residual model} \end{aligned} \quad (6)$$

In order to verify the accuracy of the integrated model, the  $R^2$  value of the model was calculated again. In addition, semi-variogram analysis was performed using residuals generated in the integrated model to confirm the self-spatiality of the residuals.

## 3. Results and Discussion

### 3.1. DBH Estimation with Stand Age, SI and Nha

DBH estimated from Equations (1) and (3) showed relatively good performance with relatively high correlation (ranging from 0.814–0.904) compared with that estimated from Equation (3) at the national scale (Table 2). Equation (3) was selected as the optimal model for DBH estimation of *Pinus densiflora* Siebold & Zucc., *Larix kaempferi* (Lamb.) Carr., *Pinus koraiensis* Siebold & Zucc., *Quercus variabilis* Blume and *Quercus* L. total (*Quercus variabilis* Blume and *Quercus mongolica* Fisch. ex Ledeb.) because it has better performance (higher  $R^2$  and lower AIC and RMSE) than Equations (1) and (2).

The  $R^2$  values of the optimal model for *Pinus densiflora* Siebold & Zucc., *Larix kaempferi* (Lamb.) Carr., *Pinus koraiensis* Siebold & Zucc., *Quercus variabilis* Blume and *Quercus* L. total (*Quercus variabilis* Blume and *Quercus mongolica* Fisch. ex Ledeb.) were 0.835, 0.790, 0.904 and 0.814, respectively. However, Cameron et al. [42] suggested that the coefficient of determination ( $R^2$ ) is not advisable for assessing nonlinear regression models. Therefore, this study evaluated the performance of the models by consideration of the root mean square error (RMSE) and Akaike's information criterion (AIC) [43]. As a result, among the three equations, Equation (3) shows the best performance in  $R^2$ , RMSE and AIC (the lower AIC and RMSE are the higher significance of the model) (Table 2).

**Table 2.** Comparison of coefficient of determination ( $R^2$ ), Akaike's information criterion (AIC) and root mean square error (RMSE) for the models corresponding to each tree species.

Tree Species	Equation (1)			Equation (2)			Equation (3)			Optimal Equation
	$R^2$	AIC	RMSE	$R^2$	AIC	RMSE	$R^2$	AIC	RMSE	
<i>Pinus densiflora</i> Siebold & Zucc.	0.826	1826.4	2.241	0.748	2096.0	2.798	0.835	1766.5	2.134	Equation (3)
<i>Larix kaempferi</i> (Lamb.) Carr.	0.787	238.5	2.446	0.741	244.0	2.497	0.790	236.2	2.424	Equation (3)
<i>Pinus koraiensis</i> Siebold & Zucc.	0.886	179.7	2.971	0.867	192.7	3.223	0.904	178.8	2.956	Equation (3)
<i>Quercus</i> L. total ( <i>Quercus variabilis</i> Blume+ <i>Quercus mongolica</i> Fisch. ex Ledeb.)	0.574	1119.6	2.379	0.563	1188.4	2.510	0.814	1104.1	2.351	Equation (3)

All parameter estimates for Equations (1) and (3) for each tree species were logical and significant at  $p = 0.001$  level (Tables 3 and 4). Comparing the significance of Equations (1) and (3), Equation (3) has better performance than Equation (1) for all tree species. According to Table 3, the coefficient  $b$  (indicate stand age) of *Larix kaempferi* (Lamb.) Carr. is estimated to be higher than the other tree species. These results showed that the diameter growth of Japanese larch is relatively high and slowed more sharply with age than for the other main tree species. This result was similar to that presented in previous studies [33].

These results indicated close correlation between stand-level factors and DBH. The correlation coefficients for age and SI were positive for all cases, suggesting that increasing DBH would promote the competition between trees and, then, cause slower diameter growth; which means, DBH decreased with tree density in the stand.

**Table 3.** Coefficient and significance level for the major tree species estimated from Equation (1).

Tree Species	Parameter	Estimate	Std. Error	t-Value	p-Value
<i>Pinus densiflora</i> Siebold & Zucc.	$a$	2.437	0.162	15.171	<0.001
	$b$	0.613	0.010	60.118	<0.001
	$c$	0.491	0.011	45.491	<0.001
	$d$	−0.213	0.005	−47.333	<0.001
<i>Larix kaempferi</i> (Lamb.) Carr.	$a$	1.982	0.387	5.116	<0.001
	$b$	0.670	0.036	18.862	<0.001
	$c$	0.370	0.039	9.386	<0.001
	$d$	−0.172	0.014	−12.134	<0.001
<i>Pinus koraiensis</i> Siebold & Zucc.	$a$	1.563	0.425	3.681	<0.001
	$b$	0.781	0.046	17.169	<0.001
	$c$	0.358	0.066	5.454	<0.001
	$d$	−0.172	0.019	−9.182	<0.001
<i>Quercus</i> L. total ( <i>Quercus variabilis</i> Blume+ <i>Quercus mongolica</i> Fisch. ex Ledeb.)	$a$	16.564	1.560	10.61578	<0.001
	$b$	0.488	0.014	35.36957	<0.001
	$c$	0.060	0.019	3.210811	<0.001
	$d$	−0.281	0.008	−36.4036	<0.001



**Table 4.** Coefficient and significance level for the major tree species estimated from Equation (3).

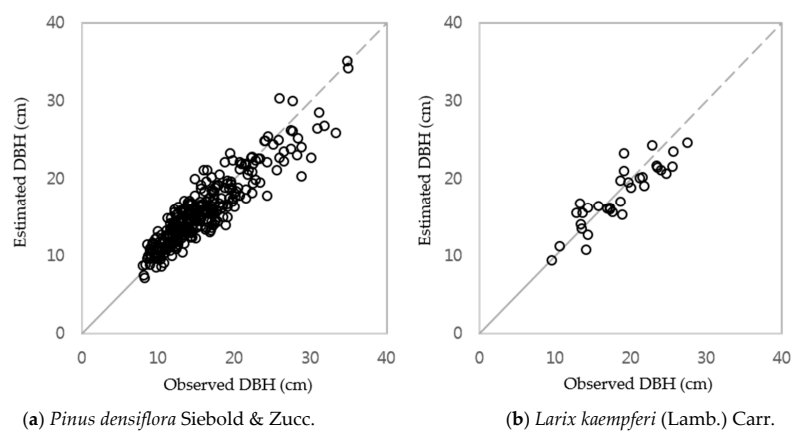
Tree Species	Parameter	Estimate	Std. Error	t-Value	p-Value
<i>Pinus densiflora</i> Siebold & Zucc.	<i>a</i>	43.896	1.906	23.033	<0.001
	<i>b</i>	−22.959	0.381	−60.259	<0.001
	<i>c</i>	0.485	0.011	45.745	<0.001
	<i>d</i>	−0.216	0.004	−49.269	<0.001
<i>Larix kaempferi</i> Carr.	<i>a</i>	37.753	5.423	6.962	<0.001
	<i>b</i>	−18.456	1.059	−17.434	<0.001
	<i>c</i>	0.369	0.040	9.295	<0.001
	<i>d</i>	−0.177	0.014	−12.385	<0.001
<i>Pinus koraiensis</i>	<i>a</i>	56.486	11.450	4.933	<0.001
	<i>b</i>	−24.406	1.513	−16.130	<0.001
	<i>c</i>	0.314	0.066	4.793	<0.001
	<i>d</i>	−0.167	0.019	−8.941	<0.001
<i>Quercus</i> L. total ( <i>Quercus variabilis</i> Blume+ <i>Quercus mongolica</i> Fisch. ex Ledeb.)	<i>a</i>	177.200	12.552	14.117	<0.001
	<i>b</i>	−18.896	0.545	−34.672	<0.001
	<i>c</i>	0.053	0.014	3.804	<0.001
	<i>d</i>	−0.290	0.008	−38.145	<0.001

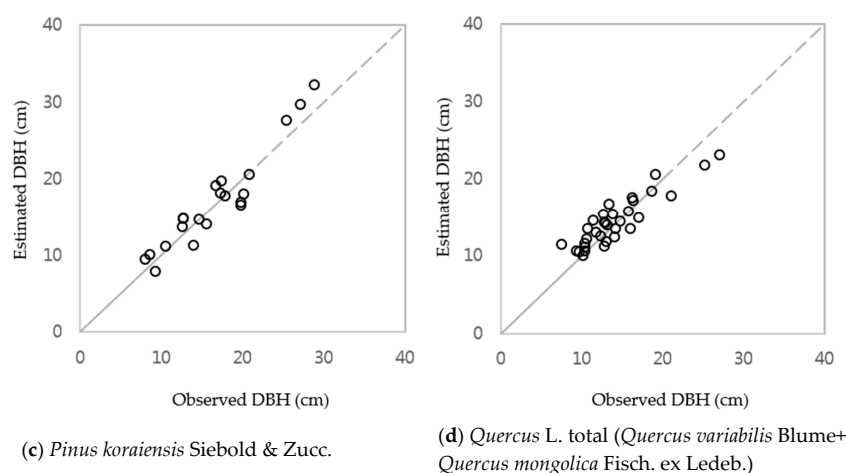
The DBH for each species was then calculated based on these results. Coefficients *b*, *c* and *d* reflected the effects of *age*, *SI* and *Nha*, respectively, on DBH. The effect of *SI* on DBH for *Pinus densiflora* Siebold & Zucc. was higher than that for the other species. Unlike the other species, *Quercus* L. total was more affected by *Nha*. These findings might contribute to forest management based on tree species.

The measured and estimated DBH for 10% of NFI data by tree species are shown in Figure 5. The models exhibited good performance in explaining variation in DBH by stand age.

Statistical fit is very important for determining whether a prediction model is adequate. It is even more important when evaluating the ecological performance of a model over a wide range of stand conditions.

According to the Korea Forest Service [27], a close correlation exists between stand-level factors and DBH estimation. In addition, among the watershed-level factors, elevation has a slight effect on DBH estimation; however, aspect, slope and TWI had almost no influence on forest growth [44]. No autocorrelation with either aspect or slopes was noted (Figure 3). In fact, elevation is one of the factors influencing DBH estimation. Conversely, factors such as elevation and temperature that have a close connection should not be used for the development of a model. In addition, we analyzed climatic factors in residuals; therefore, considering them in addition to watershed-level variables is not necessary.

**Figure 5.** Cont.



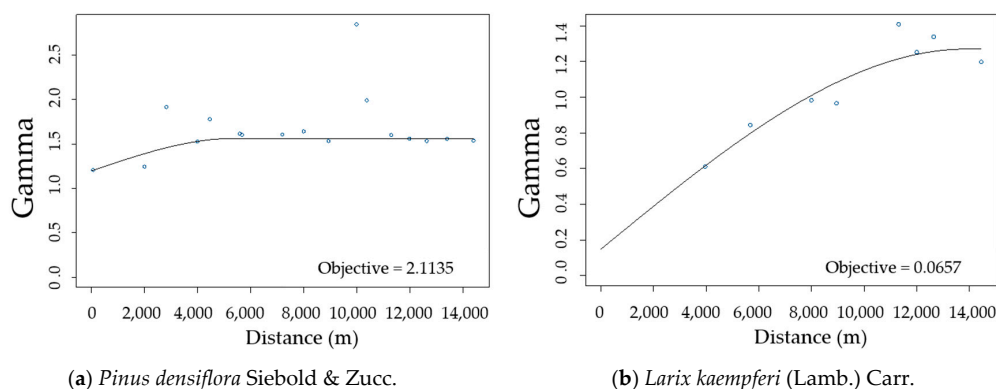
**Figure 5.** Observed vs. predicted diameter at breast height (DBH) for the major tree species in South Korea.

### 3.2. Spatial Autocorrelation of Residuals

Semi-variogram results of spatial autocorrelation of residuals by using the DBH estimation model with stand-level factors such as *age*, *SI* and *Nha* for each tree species are shown in Figure 6. The semi-variogram values for *Pinus densiflora* Siebold & Zucc., *Larix kaempferi* (Lamb.) Carr., *Pinus koraiensis*, *Quercus variabilis* Blume and *Quercus* L. total (*Quercus variabilis* Blume and *Quercus mongolica* Fisch. ex Ledeb.) from the DBH estimation model residuals were estimated to be 5.40, 11.73, 2.50 and 14.49 km, respectively, similar to the results shown in previous studies for South Korean forests [12,33].

Partial sill values of these species were estimated to be 0.365, 0.764, 2.68 and 0.22, respectively. These results suggest that coniferous species might vary in growth level because other factors have spatial autocorrelation in the range of 2.50–11.73 km. Conversely, the sill value was very low for *Quercus* L. total (*Quercus variabilis* Blume and *Quercus mongolica* Fisch. ex Ledeb.), indicating that a relatively low degree of spatial autocorrelation might be present in the DBH estimation model residuals of *Quercus* L. total (*Quercus variabilis* Blume and *Quercus mongolica* Fisch. ex Ledeb.).

Forests in South Korea cover a total area of 6.3 million ha with complicated topography, such as mountainous areas. The average size of stands was 13.2 ha based on the Fifth Korean NFI map. Thus, having the same topographic and forest characteristics in a forest with a spatial size of 6.25 km<sup>2</sup> (i.e., a linear distance of 2.49 km for each side of a square plot) is practically impossible. Therefore, such spatial autocorrelation might be associated with climatic factors rather than topographic factors.



**Figure 6.** Cont.

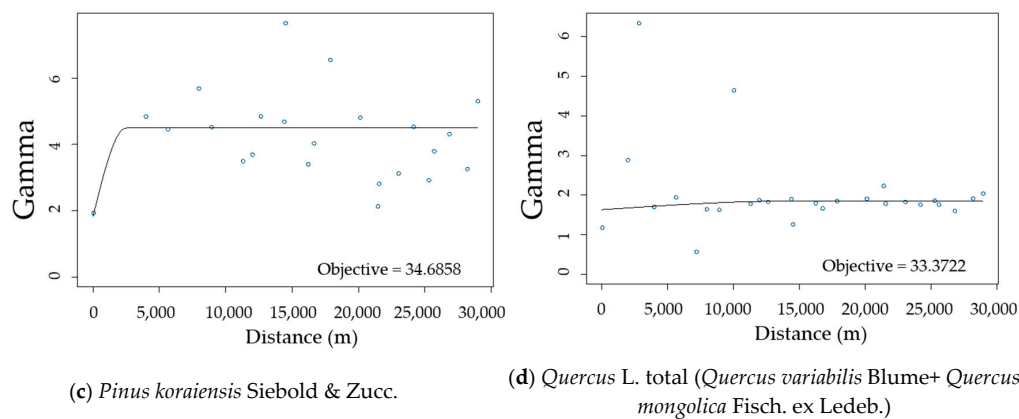


Figure 6. Semi-variogram analysis for each species (non-spatial model).

### 3.3. Residual Model with Climate Factors

Analysis of residuals was implemented based on the consideration of climatic factors for DBH development of each tree species. The effect of mean temperature on DBH development can be more clearly noted in Tables 5 and 6. All coefficients were statistically significant. The coefficient of the mean temperature for coniferous species (*Pinus densiflora* Siebold & Zucc., *Larix kaempferi* (Lamb.) Carr., *Pinus koraiensis*, *Quercus variabilis* Blume) was negative, whereas that for *Quercus* L. total (*Quercus variabilis* Blume and *Quercus mongolica* Fisch. ex Ledeb.) was positive.

Table 5. Estimated parameters and associated standard errors for Equation (4) by using residuals and climate factors for each tree species.

Tree Species	Parameter	Estimate	Std. Error	t-Value	p-Value
<i>Pinus densiflora</i> Siebold & Zucc.	a	0.69769	0.25136	2.78	0.0055
	b	−0.03962	0.01804	−2.2	0.0282
	c	−0.00038	0.000204	−1.88	0.0608
<i>Larix kaempferi</i> (Lamb.) Carr.	a	−1.36713	1.90875	−0.72	0.4746
	b	−0.26735	0.06112	−4.37	<0.0001
	c	0.00516	0.00196	2.64	0.0089
<i>Pinus koraiensis</i> Siebold & Zucc.	a	13.39043	3.47305	3.86	0.002
	b	−0.25759	0.09842	−2.62	0.01
	c	−0.0072	0.0035	−2.08	0.0386
<i>Quercus</i> L. total ( <i>Quercus variabilis</i> Blume+ <i>Quercus mongolica</i> Fisch. ex Ledeb.)	a	−0.48854	0.38888	−1.26	0.2092
	b	0.09703	0.02479	3.91	<0.0001
	c	−0.00065	0.00035	−1.85	0.0652

Table 6. Estimated parameters and associated standard errors for Equation (5) by using residuals and temperature for each tree species.

Tree Species	Parameter	Estimate	Std. Error	t-Value	p-Value
<i>Pinus densiflora</i> Siebold & Zucc.	a	−0.67988	1.46426	−0.46	0.6425
	b	0.000323	0.000451	0.72	0.4738
	c	−0.00052	0.000205	−2.52	0.0119
<i>Larix kaempferi</i> (Lamb.) Carr.	a	0.63004	6.04169	0.1	0.917
	b	−0.00146	0.00168	−0.87	0.3878
	c	0.00568	0.00205	2.78	0.006
<i>Pinus koraiensis</i> Siebold & Zucc.	a	21.27081	8.31303	2.56	0.0117
	b	−0.00296	0.00241	−1.23	0.2204
	c	−0.01268	0.00383	−3.31	0.0012
<i>Quercus</i> L. total ( <i>Quercus variabilis</i> Blume+ <i>Quercus mongolica</i> Fisch. ex Ledeb.)	a	−7.16166	2.62723	−2.73	0.0065
	b	0.00232	0.000814	2.85	0.0044
	c	−0.00076	0.000358	−2.13	0.0334

Coefficient  $b$  reflecting the effect of mean temperature on DBH for red pine, Japanese larch, Korean pine and oaks was estimated to be  $-0.03962$ ,  $-0.26735$ ,  $-0.25759$  and  $0.09703$ , respectively (Table 5). Coefficient  $b$  of coniferous species (red pine, Japanese larch and Korean pine) was estimated to be lower than that of oak species (Chinese cork oak and Mongolian oak). The mean temperature significantly affected DBH estimation of coniferous species, whereas accumulated temperature in the growing season was important for DBH estimation of oak species (Tables 5 and 6).

*Larix kaempferi* (Lamb.) Carr. is one of the main tree species in South Korea. It occupies approximately 9% (509,000 ha) of the entire forest area [45]. Japanese larch is one of the most economically-important tree species in South Korea because of its rapid growth. Approximately two billion Japanese larches have been planted during the last 40 years. Therefore, the Korean government needs to develop short- and long-term plans to address the issue of declining tree growth or size, particularly in Japanese larches because of the rising temperatures caused by climate change.

The present findings are consistent with those from previous studies. According to Byun et al. [12], temperature increment has a negative effect on the growth of red pine (*Pinus densiflora* Siebold & Zucc.). *Pinus densiflora* Siebold & Zucc. was found to yield a negative correlation between temperature and radial growth in the region where the warmth index (WI) was higher than 85. In addition, the area for which WI became higher than 85 occupied 78% of the *Pinus densiflora* Siebold & Zucc. forest in South Korea [12]. Therefore, the diameter growth could be negatively affected by increases in temperature for most of the *Pinus densiflora* Siebold & Zucc. forests [12]. Furthermore, many other studies have shown that incremental temperatures had negative effects on forest growth and on the distribution of red pine and Japanese larch, in South Korean forests [22,46]. However, the cases of oak forest, temperature and radial growth showed positive (+) correlations, even in areas where the WI was higher than 120. Therefore, the results of this study were reasonable compared to those of previous studies.

The annual diameter development rates of red pine have been reported to be declining in approximately 78% of forests in South Korea. Kim et al. [28] also showed that the mortality of red pine tends to increase with rising seasonal temperature. Thus, the increase in temperature can enhance the vulnerability of forests by reducing the growth of coniferous forests [47]. The Korean Forest Service [48] has also reported that coniferous forest area is gradually shrinking due to climate change.

Conversely, the growth of oak forest species was positively affected by increases in temperature, although their estimated coefficient values were smaller than those of coniferous forest species. In other words, oak forest species are relatively less affected by temperature than coniferous forest species.

Therefore, Equations (4) and (5) were used to predict DBH in coniferous and oak forests, respectively, under the consideration of accuracy.

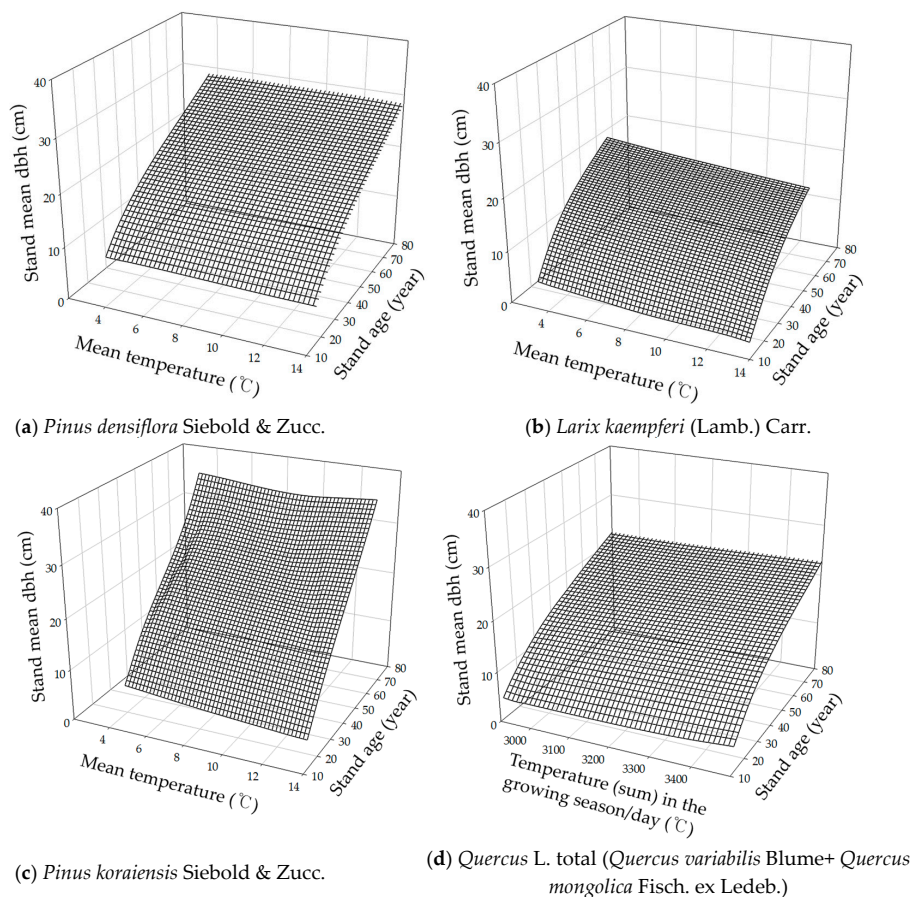
### 3.4. Integrated DBH Estimation Model with Stand and Climate Variables

An integrated DBH estimation model for each tree species was developed based on the results of the DBH estimation model and the residual model (Table 7). The effects of temperature on DBH for each plot of forest types were visualized using SigmaPlot (SPSS Inc., Chicago, IL, USA) (Figure 7). Three-dimensional graphs utilized fixed values of  $SI$  (such as the mean  $SI$  of each tree species) and  $Nha$  by age from the Korean yield table [49] (see Appendix A Table A1).

**Table 7.** Integrated model to estimate diameter at breast height (DBH), including climate factors, for each tree species.

Tree Species	Integrated DBH Estimation Model	
	Non-Spatial Variable	Spatial Variable
<i>Pinus densiflora</i> Siebold & Zucc.	$DBH = 43.896 \cdot e^{-22.959(\frac{1}{age})} \cdot SI^{0.485} \cdot Nha^{-0.216}$	$+0.698 - 0.040 \cdot T_{Mean} - 0.0004 \cdot P_{Season}$
<i>Larix kaempferi</i> (Lamb.) Carr.	$DBH = 37.753 \cdot e^{-18.456(\frac{1}{age})} \cdot SI^{0.369} \cdot Nha^{-0.177}$	$-1.367 - 0.267 \cdot T_{Mean} + 0.005 \cdot P_{Season}$
<i>Pinus koraiensis</i> Siebold & Zucc.	$DBH = 56.486 \cdot e^{-24.406(\frac{1}{age})} \cdot SI^{0.314} \cdot Nha^{-0.167}$	$+9.390 - 0.258 \cdot T_{Mean} - 0.007 \cdot P_{Season}$
<i>Quercus</i> L. total ( <i>Quercus variabilis</i> Blume+ <i>Quercus mongolica</i> Fisch. ex Ledeb.)	$DBH = 177.200 \cdot e^{-18.896(\frac{1}{age})} \cdot SI^{0.053} \cdot Nha^{-0.290}$	$-7.162 + 0.002 \cdot T_{Season} - 0.001 \cdot P_{Season}$

The values of DBH for coniferous forest species decreased as temperature increased. The DBH of *Pinus koraiensis* Siebold & Zucc. was found to be the most sensitive to temperature, whereas *Quercus* was the least sensitive. Habitat temperature ranges of *Pinus densiflora* Siebold & Zucc. (range: 3.53–4.76 °C), *Larix kaempferi* (Lamb.) Carr. (3.3–13.85 °C), *Pinus koraiensis* Siebold & Zucc. (4.76–13.95 °C) and *Quercus* L. total (*Quercus variabilis* Blume and *Quercus mongolica* Fisch. ex Ledeb.) (1.85–14.55 °C) are shown in Figure 7. If the age of tree was fixed at 60 years, differences between estimated DBH at maximum and minimum temperatures for each tree species were −1.2 (−6.0%), −2.8 (−13.7%), −2.4 (−5.6%) and 1.0 (5.4%) cm, respectively.

**Figure 7.** Three-dimensional analyses of stand age, temperature (mean temperature estimated over a 13-year period for coniferous forests and in growing seasons for oak forests) and diameter at breast height (DBH).

These results are consistent with those of previous studies, indicating that coniferous forest trees are more sensitive to climate change (warming) than oak forest species. Their area is declining with increasing temperature caused by climate change [32,40,48].

The result of validation by using 10% NFI data is shown in Table 8. Semi-variogram analysis was performed again with residuals generated from the integrated model to confirm the self-spatiality of residuals. The results showed that none of the tree species showed any spatial correlation (Figure 8). Therefore, temperature and precipitation were found to influence DBH estimation.

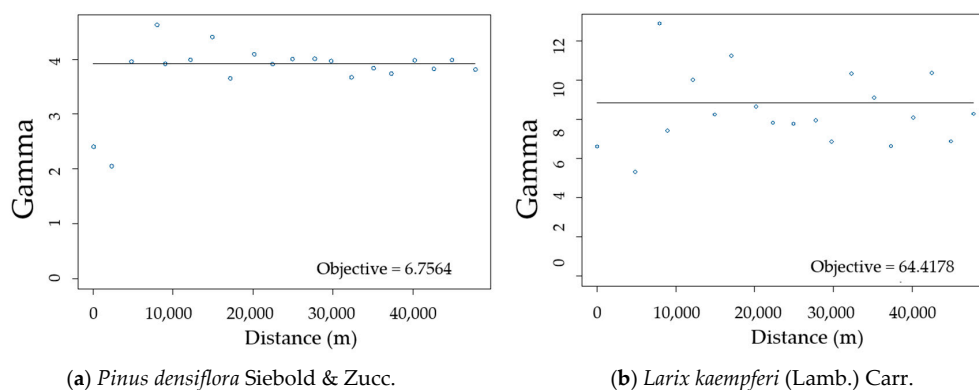
**Table 8.** Correlation between observed and estimated DBH for each model (DBH estimation model  $R^2$ , integrated DBH estimation model  $R^2$ ).

Tree Species	DBH Estimation Model $R^2$	Integrated DBH Estimation Model $R^2$
<i>Pinus densiflora</i> Siebold & Zucc.	0.835	0.836
<i>Larix kaempferi</i> (Lamb.) Carr.	0.790	0.821
<i>Pinus koraiensis</i> Siebold & Zucc.	0.904	0.906
<i>Quercus</i> L. total ( <i>Quercus variabilis</i> Blume+ <i>Quercus mongolica</i> Fisch. ex Ledeb.)	0.6395	0.6927

The purpose of the DBH model was to estimate the current DBH for specific spatial conditions, that is stand (*age*, *SI* and *Nha*) and climatic conditions (temperature and precipitation). This model simply explains the fact that spatial differences in stand and climatic conditions can elicit differences in DBH size.

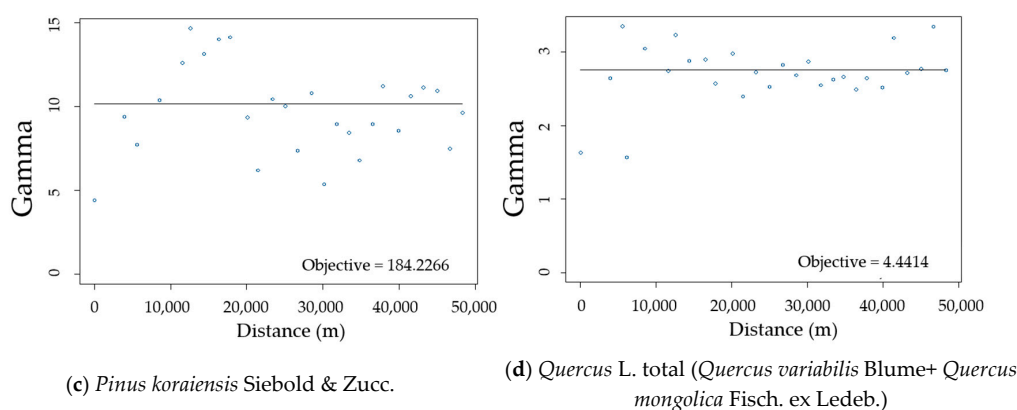
Vitality of trees is one of the most important indicators of forest condition [50]. Several findings on tree vitality have been reported in the literature [51,52]. One study stated that tree growth has various reactions to environmental stress. Tree growth has been suggested to serve as a vitality indicator if reference growth and growth trends are available [53]. These findings might contribute to the estimation of the vitality of forests.

There are major scientific uncertainties about climate-induced diameter development, such as DBH size, particularly on the mechanisms that drive diameter development, including physiological thresholds of tree growth and interactions with biotic agents [16,33]. Recent advances in the understanding of tree growth mechanisms suggest that forests could be particularly sensitive to increases in temperature in addition to drought, especially in the cases where carbon starvation rather than hydraulic failure is the primary mechanism of tree growth. However, at present, no model is available for the prediction of DBH of tree species and forest types based on specific combinations of climatic events and their interactions with biotic stressors at place-specific sites.



**Figure 8.** Cont.





**Figure 8.** Semi-variogram analysis for each species by using an integrated model (non-spatial model + spatial model).

This study developed the DBH estimation model based on current *SI*, *Nha* and climate data; we did not consider the effects of the ongoing and short-term extreme climates on the estimate of diameters. However, this study has a remarkable advantage compared to previous studies, in that analyses were conducted based on detailed data at a national scale. In other words, although the survey was performed at one time-point, there was no significant problem in quantitatively analyzing the effect of climate on the development of each species. This is because the conditions of the stands, such as *age*, *SI* and *Nha*, are very diverse in each space. Santiago-García et al. [54] developed a stand-level model by using 66 plots of data from a permanent plot within the period of 2015 and 2016 and identified the forest productivity status in Juárez, Oaxaca, and in Mexico, based on the changes in DBH. Ji et al. [9] used surveyed data from 405 plots within the period of 2014 and 2015 to develop a stand forest growth model that did not consider climatic factors and the *SI* and identified forest carbon stocks in the city of Lishui in China. Therefore, in view of the above considerations, this study was meaningful as 5292 plots of data were used, and the possibility for further improvement of the model via continually supplementing and verifying the data by re-examining each plot every five years was provided.

#### 4. Conclusions

In this study, an integrated model was developed to predict the DBH of the major tree species in South Korea considering climate factors and stand-level factors. For the development of this model, variables that could influence DBH estimation were classified into three categories (stand-, watershed- and regional-level factors) based on spatial autocorrelation. The stand-level DBH estimation model could successfully reflect the trend in the DBH of major forests according to stand-level factors. However, uncertainties remained for individual stand environments. The integrated DBH estimation model accurately described the DBH of each tree species with different stand- and regional-level factors.

Our results showed that the decreased DBH in the major coniferous forests of South Korea was associated with warmer conditions. However, the response of diameter development differed among species. In the case of oak species, rising temperature tended to have a positive effect on DBH, although this effect was relatively small. This, in part, implies that coniferous species might be more sensitive to climate change than oak species in South Korea. This result suggests that the major coniferous tree species in South Korea are more vulnerable to climate change than oak tree species. This might cause substantial changes in the structure and distribution of forests in South Korea in the long term. Therefore, decreasing vulnerability of forests to climate change and increasing their adaptability are necessary for forest management planning in South Korea.

Despite these findings, the complexity and scientific uncertainties of climate-induced DBH size challenge our understanding, particularly regarding the mechanisms that drive diameter development,

including physiological thresholds of tree death and interactions with biotic agents. Furthermore, the watershed level was not considered in the model, although three spatial levels were considered for estimating the model. Although we did not consider climate change and stand density changes in this study, a current diameter prediction model was developed based on NFI data (DBH, age, site index, stand density) and the consideration of climatic factors (average temperature and cumulative precipitation of the growing season). This can serve as an important reference point to estimate current forest production for forest conservation and management. However, developing a dynamic growth model is necessary, by generating a density model based on the annual DBH data estimated from the model provided in this study and considering climate change, for more accurate forest management.

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**Author Contributions:** Woo-Kyun Lee and Dongfan Piao conceived to research design; Go-Mee Choi and Yeong-Mo Son provided NFI data; Dongfan Piao and Moonil Kim analyzed the NFI data; Hangnan Yu and Jooyeon Moon contributed to English correction; Woo-Kyun Lee, Sonam Wangyel Wang, Seong Woo Jeon, Yowhan Son and Guishan Cui gave constructive comments to this paper.

**Conflicts of Interest:** The authors declare no conflict of interest.

## Appendix A

**Table A1.** The change of stand density by tree species and stand age (ref).

Stand Age (Year)	Number of Trees per ha (Nha)			
	<i>Pinus densiflora</i> (Site Index: 12)	<i>Larix kaempferi</i> (Site Index: 18)	<i>Pinus koraiensis</i> (Site Index: 14)	<i>Quercus Total</i> (Site Index: 12)
20	1827	1316	1362	2024
25	1681	993	994	1657
30	1418	779	868	1373
35	1186	658	733	1153
40	1006	584	644	981
45	961	538	583	936
50	859	508	541	828
55	781	490	511	741
60	720	478	489	669
65	673	471	473	609
70	636	468	462	560
75	607	467	454	518
80	583	467	448	481

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