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Height Growth Models for *Pinus thunbergii* in Jeju Island

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Abstract

Height growth models for *Pinus thunbergii* in Jeju Island were developed in this study using four widely used nonlinear growth models; Exponential, Modified Logistic, Chapman-Richards, and Weibull. All functions were found to be significant at the 1% level. Chapman-Richards model for height-DBH allometry and Weibull model for height-age allometry was chosen as the best model on the all validation. All the model curves showed the similar pattern. Additionally, there was no abnormal pattern when the previous studies were compared. Therefore, these models are highly expected to be used to estimate the tree height using DBH or age for *Pinus thunbergii* especially in Jeju Island.

Key Words: Nonlinear growth models, Height, DBH, Age, *Pinus thunbergii*

Introduction

Pinus thunbergii, which is a well-known rapid growing species in early growth stage, is highly resistant to damage from salt water and grows in groups near the coast areas and in the southern areas of Korea including Jeju Island. It has been planted about 421 ha per year from 2009 to 2013 and is a representative species in Gyeongsang and Jeolla provinces (Korea Forest Service 2014). However, it is reported that *Pinus thunbergii* has been severely damaged by *Bursaphelenchus xylophilus* in Jeju Island (Jeju Special Self-Governing Province 2015). It encouraged to protect forest resources.

DBH, height, and age are an essential part of variables in understanding forest resources, and thus these measurements must be entailed. However, measuring height takes much more time and efforts. It is common that tree height is estimated by developing height-DBH or height-age growth model (Avery and Burkhart 2002).

A number of height growth equations have already been developed all over the world, and the practical functions being utilized for regional main species in many developed countries (Huang et al. 1992; Soares and Tomé 2002; Sánchez-González et al. 2007). In Korea, the height growth functions have also been studied for the major species (Lee 1996; Kwak et al. 2004; Lee et al. 2009; Lumbres et al. 2011; Seo et al. 2011; Lee et al. 2014).

However, it is still insufficient in the height growth models for *Pinus thunbergii*, especially for the regional growth estimation. Therefore, the objectives of this research are to estimate the best-fit nonlinear height growth models for *Pinus thunbergii* and to compare our models with the previous studies for verification process.

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Materials and Methods

Data collection

In this study, the models were developed targeting *Pinus thunbergii* in Jeju Island. The data was basically used the 5th National Forest Inventory dataset. In the dataset, only *Pinus thunbergii* sample trees located in Jeju Island were analyzed to develop the height growth model. The total number of *Pinus thunbergii* trees was 493. DBH in the dataset ranged from 6.0 cm to 58.0 cm, height ranged from 2.9 m to 21.9 m, and age ranged from 11 year to 67 year. The statistics of the dataset were shown in Table 1.

Model selection and validation

In this study, four nonlinear growth models were used for *Pinus thunbergii*; Exponential, Modified Logistic, Chapman-Richards, and Weibull (Richards 1959; Chapman 1961; Yang et al. 1978; Ratkowsky and Reedy 1986; Ratkowsky 1990; Huang et al. 1992). These models were modified depending on the independent variable, and thus models have an intercept in the case of height-DBH allometric models (Table 2). To find the parameters of models, PROC NLIN procedure on SAS 9.4 software was performed (SAS Institute Inc. 2013). After finding the parameters of each models, the curve shape and coefficients of best-fit model in this study were compared with the previous studies (Lumbres et al. 2011; Son et al. 2013).

For model validation, four fit statistics were evaluated to determine the best model. Coefficient of determination (R^2) was typically used to provide all the functions with power of explanation about regression lines. Additionally, root mean square error (RMSE), mean deviation (MD), and mean absolute deviation (MAD) were used. The equations were summarized as follows:

$$R^2 = 1 - [\sum_{i=1}^{n}(H_i - \widehat{H}_i)^2 / \sum_{i=1}^{n}(H_i - \overline{H})^2]$$

$$\text{RMSE} = \sqrt{\sum_{i=1}^{n}(H_i - \widehat{H}_i)^2 / n}$$

$$\text{MD} = \sum_{i=1}^{n}(H_i - \widehat{H}_i)/n$$

$$\text{MAD} = \sum_{i=1}^{n}|H_i - \widehat{H}_i|/n$$

Where H_i = measured height for the ith tree, $\widehat{H}_i$ = predicted height for the ith tree, $\overline{H}$ = measured mean tree height, n = the total number of observations used to fit the model.

Table 1. Summary statistics of *Pinus thunbergiitree* inventory data (n=493)

Statistic	Age	DBH (cm)	Height (m)
Mean	29.5	21.6	10.8
Maximum	67.0	58.0	21.9
Minimum	11.0	6.0	2.9
SD	10.6	10.1	4.0

Results and Discussion

Model development

To develop the model of height growth, age and DBH

Table 2. Selected nonlinear height growth models for *Pinus thunbergii*

Model name	Equations	
	Height-DBH	Height-AGE
[1] Exponential (EP)	$HT = 1.2 + a \times e^{\frac{b}{(DBH+c)}}$	$HT = a \times e^{\frac{b}{(AGE+c)}}$
[2] Modified Logistic (ML)	$HT = 1.2 + \frac{a}{1 + b^{-1} \times DBH^{-c}}$	$HT = \frac{a}{1 + b^{-1} \times AGE^{-c}}$
[3] Chapman-Richards (CR)	$HT = 1.2 + a(1 - e^{-bDBH})^c$	$HT = 1.2 + a(1 - e^{-bAGE})^c$
[4] Weibull (WE)	$HT = 1.2 + a(1 - e^{-bDBH^c})$	$HT = 1.2 + a(1 - e^{-bAGE^c})$

Note: HT is the tree total height (m); DBH is the tree diameter at breast height (cm); 1.2 (m) is the distance from the ground to the point where DBH was measured; AGE is the tree age calculated from tree core (year); a, b, c are the parameters to be estimated in this study; e is the base of natural logarithm.

were used as independent variables. The parameters of all functions by independent variables were shown in Table 3. The estimates of all parameters in each models were within 95% confidence limits, and all the models were found to be significant at the 1% level ($p < 0.0001$). The form of all equations was an asymptotic curve, which converges an asymptote.

The four height-DBH growth curves were similar to one another, and a subtle difference was found when DBH was bigger than 40 cm (Fig. 1). Also, the four height-age model curves were almost the same with one another, a subtle difference was found when age was bigger than 50 year (Fig. 2). To check the suitability, the parameters of this study were compared with the parameters of the previous studies: Lumbres et al. (2011) for four height-DBH models and Son et al. (2013) for Chapman-Richards and Weibull height-age models. As a result, all the parameters were similar, no abnormal parameters were found.

Table 3. Coefficients and fit statistics of four selected models for *Pinus thunbergii*

Dependent-independent variable	Equations	Coefficients			Fit statistics				
		a	b	c	R^2	RMSE	MD	MAD	Pr > F
Height-DBH	$HT=1.2+a\times e^{\frac{b}{(DBH+c)}}$	17.9216	-11.0253	-0.7482	0.9436	2.7366	0.0021	2.1541	< 0.0001
	$HT=1.2+\frac{a}{1+b^{-1}\times DBH^{-c}}$	15.0069	0.0062	1.9498	0.9438	2.7317	0.0036	2.1500	< 0.0001
	$HT=1.2+a(1-e^{-bDBH})^c$	13.8731	0.0980	2.0329	0.9438	2.7321	0.0015	2.1502	< 0.0001
	$HT=1.2+a(1-e^{-bDBH^c})$	13.5741	0.0171	1.4661	0.9438	2.7335	0.0060	2.1496	< 0.0001
Height-AGE	$HT=a\times e^{\frac{b}{(AGE+c)}}$	21.8124	-16.6324	-3.1889	0.9494	2.5927	0.0027	2.0400	< 0.0001
	$HT=\frac{a}{1+b^{-1}\times AGE^{-c}}$	17.0935	0.0008	2.3476	0.9500	2.5779	0.0075	2.0275	< 0.0001
	$HT=1.2+a(1-e^{-bAGE})^c$	15.9546	0.0788	3.0097	0.9501	2.5736	0.0057	2.0236	< 0.0001
	$HT=1.2+a(1-e^{-bAGE^c})$	15.2844	0.0037	1.8030	0.9504	2.5678	0.0068	2.0178	< 0.0001

Note: HT is the tree total height (m); DBH is the tree diameter at breast height (cm); 1.2 (m) is the distance from the ground to the point where DBH was measured; AGE is the tree age calculated from tree core (year); a, b, c are the parameters to be estimated in this study; e is the base of natural logarithm. R^2 is coefficient of determination; RMSE is root mean square error; MD is mean deviation; MAD is mean absolute deviation.

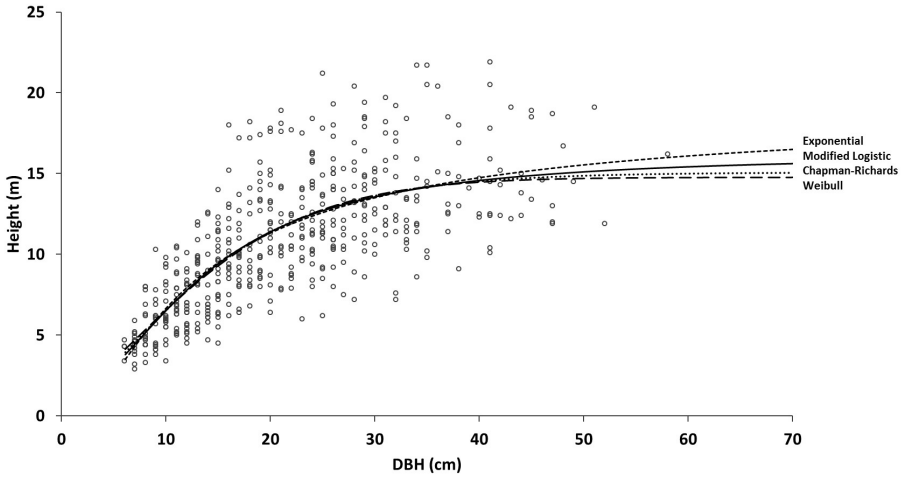

Fig. 1. Four different nonlinear model curves on scatter plot of height over DBH for *Pinus thunbergii*.

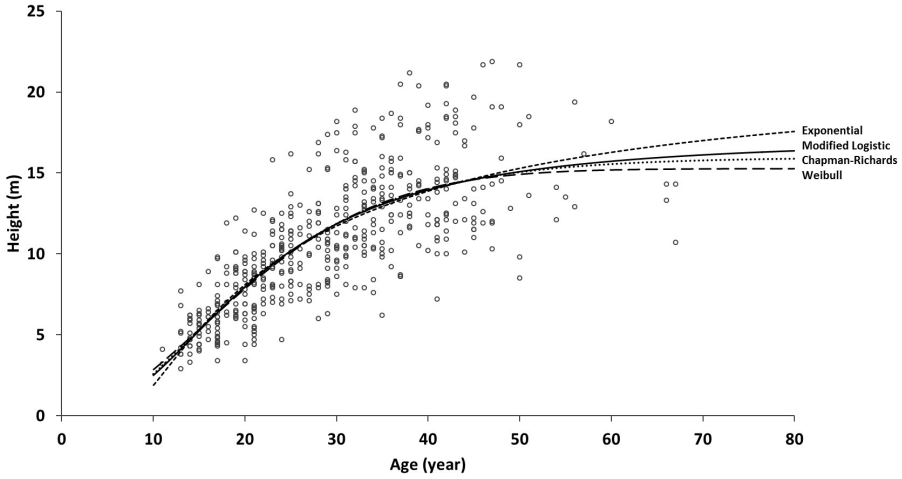

Fig. 2. Four different nonlinear model curves on scatter plot of height over age for *Pinus thunbergii*.

Model validation

For the height-DBH growth models, each fit statistics of the models had similar values; R^2 ranged in 0.9436-0.9438, RMSE in 2.7317-2.7366, MD in 0.0015-0.0060, and MAD in 2.1496-2.1541. Chapman-Richards function was verified as the best model, all things considered. The model evaluation of Chapman-Richards was as follows: R^2= 0.9438, RMSE=2.7321, MD=0.0015, MAD=2.1502 (Table 3).

In addition, for the height-age growth models, fit statistics of all models had also similar values; R^2 ranged in 0.9494-0.9504, RMSE in 2.5678-2.5927, MD in 0.0027-0.0075, and MAD in 2.0178-2.0400. As a result, Weibull equation was verified as the best model. R^2 and RMSE were 0.9504 and 2.5678, respectively, which were better fit statistics than those of Chapman-Richards height-DBH growth model. Also, MD and MAD of Weibull height-age growth model were 0.0068 and 2.0178, respectively.

Model comparison

The best-fit model of this study were compared with the same model of previous studies. That is, Chapman-Richards model of height-DBH equation was compared to that of Lumbres et al. (2011), and Weibull model of height-age equation was compared to that of Son et al. (2013). First of all, the shape of the model curves were shown in Fig. 3 and Fig. 4.

In comparison of height-DBH model, the curve line in the study of Lumbres et al. (2011) was located below the curve line of this study, but the difference was negligible (Fig. 3). In the study of Lumbres et al. (2011), the data was derived from full dataset of National Forest Inventory in 2007 and 2008. However, in comparison of height-age model, the curve line in the study of Son et al. (2013) was located above the curve line of this study, and the difference was noticeable when age was bigger than 50 year (Fig. 4). The analyzed dataset in the study of Son et al. (2013) was collected from Gyeongsang and Jeolla provinces, and the number of sample trees was 24 trees. Overall, the models of this study presented the similar curve patterns to the curves of the previous studies.

Conclusion

This study was carried out to develop the height-DBH and height-age growth model for *Pinus thunbergii* in Jeju Island. Four widely used nonlinear models, Exponential, Modified Logistic, Chapman-Richards, and Weibull, were fitted to the dataset. According to the result of this research, all functions were significant at the 1% level. In the process of all model validation for height-DBH model, R^2 were all above 0.9436. RMSE ranged from 2.7317 to 2.7366, MD from 0.0015 to 0.0060, and MAD from 2.1496 to 2.1541. Chapman-Richards model was chosen as the best model based on the all validation. Also, in the model validation for height-age model, R^2 were all above 0.9494. RMSE ranged from 2.5678 to 2.5927, MD from 0.0027 to 0.0075,

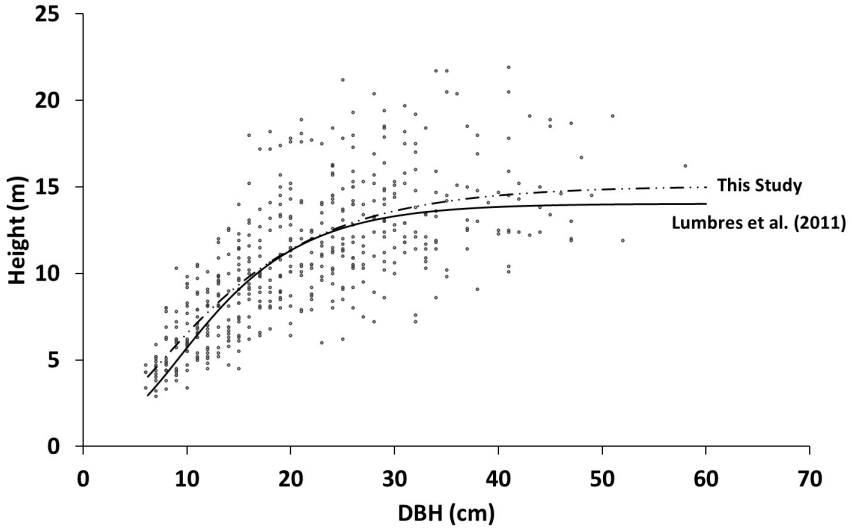

Fig. 3. The comparison of Chapman-Richards model curve between this study and Lumbres et al. (2011) on scatter plot of height over DBH.

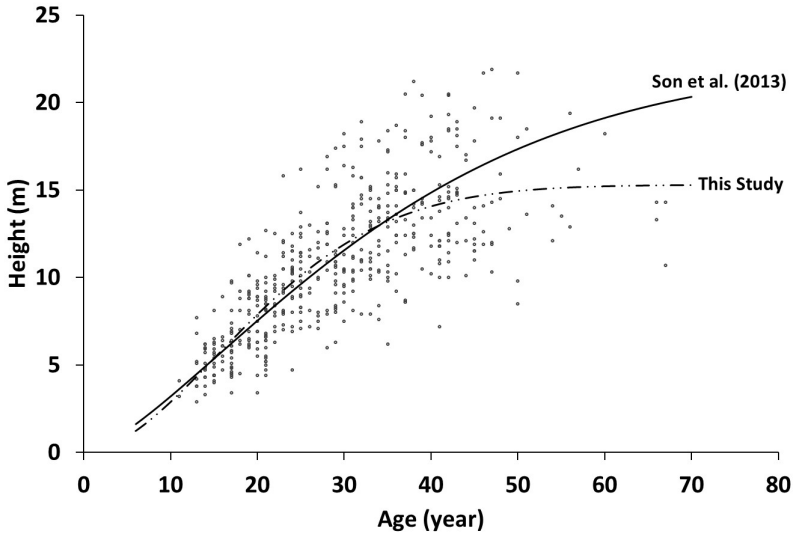

Fig. 4. The comparison of Weibull model curve between this study and Son et al. (2013) on scatter plot of height over age.

and MAD from 2.0178 to 2.0400. Weibull model was selected as the best model based on the all validation.

All the model curves presented the similar pattern. Additionally, there was no abnormal pattern when the previous studies were compared. Therefore, these models are highly expected to be used to estimate the tree height using DBH or age for *Pinus thunbergii* especially in Jeju Island.

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