J Korean Soc Appl Biol Chem (2013) 56, 173−180
DOI 10.1007/s13765-012-3255-2

ORIGINAL ARTICLE

Developing a Site Index Model Considering Soil Characteristics for *Pinus thunbergii* Stands Grown on the West Coast of Korea

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Received: 10 November 2012 / Accepted: 8 February 2013 / Published Online: 30 April 2013

Abstract Height model of the dominant tree was developed and derived site index curves of *Pinus thunbergii*, which is the main species of windbreak forests along the west coast of Korea. The site index of a tree is affected by various environmental factors. In the present study, however, the soil characteristics of *P. thunbergii* stands, which are scattered along the west coast of Korea were used. Eight sites of windbreak forest were investigated from October 2011 to October 2012. The Schumacher polymorphic equation was the most suitable equation to develop a site index model of *P. thunbergii* stands, and it was the best site index model when Ca-P and fungus were applied to the asymptotic parameter (α). The equation yielded site index curves using the developed model, which is based on trees aged 50 years, considering the soil characteristic factors of *P. thunbergii* stands in different areas. The site index model and site index curves suggest important growth information, such as windbreak forests, green spaces development, and height growth estimation, which are needed for management of the stands, with consideration of the proposed soil characteristic factors of this study.

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Keywords *Pinus thunbergii* · Saemangeum · site index curve · site index model · soil characteristics

Introduction

The Saemangeum Development Project will create 283 km^2 of reclaimed land, together with a lake as large as 118 km^2, by constructing the world's longest 33.9 km^2 sea dike on the west coast of Korea. The reclaimed land will be used for many different purposes, such as agricultural land, industry, residence, environment, and green spaces. In order to benefit from the reclaimed land, vegetation, particularly a variety of trees, should be introduced. However, it may be difficult to estimate the growth of trees for development and management, such as windbreak forests, and green spaces, because the reclaimed land has very different geographic environments, including soil environment and sea wind, among others.

On the other hand, site quality is, by definition, the potential capacity of production of tree species and forest land. A method of employing a site index, which is the estimation of site quality, is not only used to collect data, estimate growth, and harvest easily, but is also used in many countries, due to its high accuracy (Avery and Burkhart, 1994; Husch et al., 2003; Pyo et al., 2009). A site index is described with dominant trees or co-dominant trees. The site index model can be developed using height data, from which site index curves can be derived. Most studies estimate the site index using the height of trees and an algebraic difference equation (Lee, 2002; Lee, 2003; Jeon et al., 2007; Pyo et al., 2009). In addition, it is considered that site environmental factors in relation to the site index were interpreted using a linear regression model (Shin et al., 2006; Shin et al., 2007; Park et al., 2008). However, there are structural limitations if a linear regression model is applied during the development of a growth model for a tree-like site index (Kim et al., 2012). In response, Lee and Kim (2005) studied *Chamaecyparis obtusa* with altitude, which is used as an independent variable. Cho (2008) studied *Larix kaempferi* and developed a growth model using a non-linear regression model, which is applied to altitude, mean annual precipitation, and the average temperature as independent variables. Studies using a non-linear regression model that applied independent variables of the environmental factor sites were rare. Additionally, site index studies on *P. thunbergii* stands on the west coast of Korea were lacking.

Hence, the present study was carried out to develop a site index model and derive site index curves using a non-linear regression model. The model is applied to soil characteristic factors of *P. thunbergii* in windbreak forests on the west coast of Korea, in order to corroborate the growth information needed for development and management of green spaces and windbreak forests, with regard to the tree species, *P. thunbergii*.

Materials and Methods

Materials. The present study was conducted with *P. thunbergii* stands, and data were obtained from eight regions: Muchangpo, Chunjangdae, Songrim, Gosapo, Sangrok, Dongho, Gusipo, and Baekbawi (Fig. 1). In each of the eight regions, temporary sample plots of size 20 m × 20 m, were randomly set up, from where the trees were surveyed (Table 1). To create the basic data for a height growth model, 10 dominant trees were selected from each plot. The total number of dominant trees was 80, and the cores were gathered using an increment borer from 1.2 m (diameter at breast height; DBH). After estimating the approximate ages using the cores, the height of the surveyed dominant trees created basic data. In addition four spots were selected from each plot, and soil analysis was carried out after collecting the total 128 soil samples from 4 layers (of 0–20, 20–40, 40–60, and 60–80 cm depth), in order to analyze soil characteristics to be applied to the height growth model.

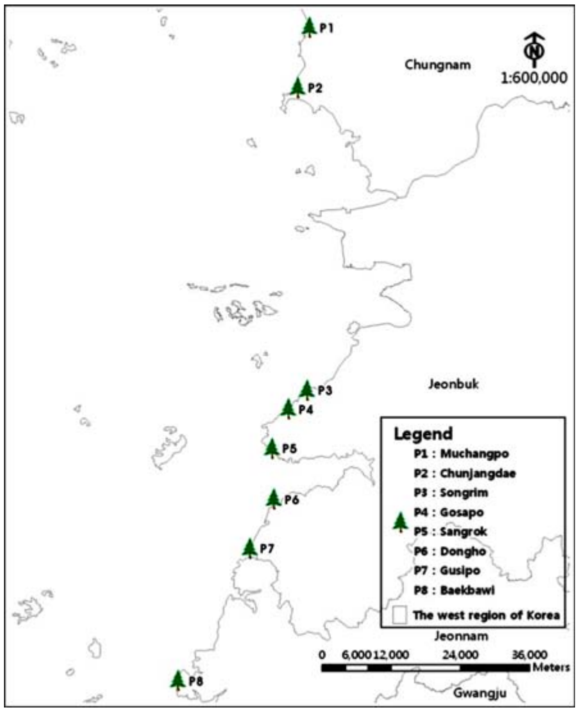

Fig. 1 Location of study area.

Methods. The prediction model to develop a height growth and site index model used an algebraic difference equation, which has been used widely for growth and yield modeling studies (Clutter

Table 1 Status of *Pinus thunbergii* stands in study area

Area	GPS coordinate	Mean height (m)	Mean DBH (cm)	Elevation (m)	Orientation bearing (°)	Slope (°)
Muchangpo	N36°15'41.72" E126°32'52.38"	10.2	15.4	16	300	5
Chunjangdae	N36°10'00.03" E126°31'35.66"	12.9	26.0	15	310	0
Songrim	N35°41'32.59" E126°32'51.74"	13.4	25.7	35	170	5
Gosapo	N35°39'47.00" E126°30'36.67"	12.0	26.9	5	320	0
Sangrok	N35°36'01.57" E126°28'55.24"	5.3	15.7	12	250	0
Dongho	N35°31'11.11" E126°29'03.31"	10.2	52.8	9	270	5
Gusipo	N35°26'30.76" E126°26'02.31"	13.3	28.9	35	170	5
Baekbawi	N35°13'58.33" E126°18'04.93"	10.4	24.0	11	280	0

Table 2 General forms of the polymorphic equation applied to data

Equation name	Equation form
Schumacher	$Y_2=\exp(\ln(Y_1)(T_1/T_2)^{\beta}+\alpha(1-(T_1/T_2)^{\beta})$
Hossfeld	$Y_2=1/((1/Y_1)(T_1/T_2)^{\gamma}+(1/\alpha)(1-(T_1/T_2)^{\gamma}))$
Chapman-Richards	$Y_2=(\alpha/\gamma)^{(1/(1-\beta))}(1-(1-(\gamma/\alpha)Y_1^{(1-\beta)}))\exp(-\gamma(1-\beta)(T_2-T_1))^{(1/(1-\beta))}$
Gompertz	$Y_2=\exp(\ln(Y_1))\exp(-\beta(T_2-T_1)+\gamma(T_2^2-T_1^2)+\alpha(1-\exp(-\beta(T_2-T_1)+\gamma(T_2^2-T_1^2))))$

Note. Y_1 = height of trees at age T_1, Y_2 = height of trees at age T_2, *exp* = exponential function, *ln* = natural logarithm, α, β, and γ = coefficients

et al., 1983; Borders et al., 1984; Jeon et al., 2007). To obtain an exact estimate of the height growth form of *Pinus thunbergii*, the model was developed by using the polymorphic equation of Schumacher (Schumacher, 1939; Clutter and Jones, 1980; Woollons, 1988), Hossfeld (Woollons et al., 1990), Chapman-Richards (Pienaar and Turnbull, 1973; Goulding, 1979), and Gompertz (Whyte and Woollons, 1990) (Table 2).

In order to develop the best height growth model, SAS Ver. 9.3 (SAS Institute Inc., USA) was used. The main method for statistics used non-linear least squares regression of PROC NLIN. With the method for the development of a reliable model, main values were the mean square error (MSE) of estimation values for

Table 3 Analysis results of soil characteristics

Classification	pH	EC (μS/cm)	Organic matter (%)	Tot-P (mg/kg)	Tot-N (mg/kg)	Heavy metals (mg/kg)			
						Cd	Cu	Pb	Zn
Muchangpo	5.6±0.2	114.4±40.5	1.1±0.5	114.1±11.3	324.3±97.9	0.2±0.1	2.4±0.6	4.5±1.3	13.9±7.3
Chunjangdae	6.7±0.2	141.7±37.8	0.7±0.3	129.8±14.1	465.6±220.9	0.3±0.1	2.2±0.5	6.1±2.2	21.2±7.6
Songrim	5.9±0.1	385.3±40.8	4.6±1.3	115.5±11.6	672.5±116.2	0.3±0.1	9.3±0.6	7.7±2.0	18.3±7.9
Gosapo	5.7±0.3	152.8±39.6	1.2±0.4	143.3±21.3	220.5±62.0	0.2±0.0	2.6±0.6	4.7±2.2	19.2±10.3
Sangrok	8.4±0.2	153.5±23.8	0.7±0.2	126.4±21.3	193.6±40.4	0.3±0.0	2.1±0.4	5.8±2.4	16.2±8.1
Dongho	6.4±0.2	98.8±23.5	1.3±0.3	116.4±10.9	230.2±75.6	0.3±0.1	2.6±0.7	5.2±1.4	35.7±15.5
Gusipo	5.9±0.2	94.2±16.0	1.2±0.3	121.4±17.2	272.7±60.6	0.2±0.0	2.4±0.8	5.1±1.1	18.3±5.6
Baekbawi	6.4±0.2	127.1±34.3	1.1±0.2	136.0±18.5	216.5±37.3	0.3±0.0	2.3±0.5	8.8±3.9	14.8±5.5
Mean	6.4±0.9	158.5±94.4	1.5±1.3	125.4±18.7	324.5±186.1	0.3±0.1	3.2±2.4	6.0±2.6	19.7±10.9

Classification	Ex.- cation (mg/kg)				NH_4-N (mg/kg)	P-fractionation (mg/kg)		
	Ca	K	Na	Mg		Al-P	Ca-P	Fe-P
Muchangpo	1,176.8±213.9	281.1±54.7	199.9±34.4	714.9±65.8	35.5±9.4	29.1±8.1	68.2±11.9	5.7±3.7
Chunjangdae	1,169.6±164.4	316.6±57.0	211.4±60.6	542.5±71.0	31.5±8.4	15.1±5.1	65.6±14.4	5.4±1.6
Songrim	1,207.9±173.9	513.8±168.9	549.1±39.7	687.5±55.2	30.6±4.6	28.1±8.4	65.0±8.6	5.0±2.8
Gosapo	1,295.5±186.0	590.4±261.6	325.5±74.8	332.3±59.1	34.7±6.5	25.3±7.6	95.9±18.3	4.2±2.3
Sangrok	1,668.0±342.4	367.6±69.2	254.6±59.2	520.2±62.8	24.4±2.9	13.1±4.2	107.2±20.2	1.8±1.4
Dongho	1,112.6±224.0	324.0±65.9	299.2±78.8	751.6±134.1	34.1±11.2	25.5±8.1	72.3±11.5	3.7±1.5
Gusipo	993.6±350.9	278.1±57.3	222.7±45.1	829.2±129.1	29.4±8.8	25.4±5.6	79.0±14.7	5.0±2.8
Baekbawi	1,297.4±146.6	309.9±125.0	317.0±69.8	739.3±52.3	42.7±9.4	22.3±5.8	89.4±22.6	5.8±2.1
Mean	1,240.2±296.5	372.7±165.4	297.4±120.7	639.7±173.2	32.9±9.3	23.0±8.6	80.3±21.3	4.6±2.6

Classification	NO_3-N (mg/kg)	CEC ($cmol^+$/kg)	Particle density	Bulk density	Microbe (CFU/Soil gram)		Soil texture
					Aerobic bacterium	Fungus	
Muchangpo	23.9±6.4	4.4±0.8	2.5±0.1	1.1±0.1	12,500.0±2,973.2	1,968.8±692.5	Loamy sand
Chunjangdae	28.5±7.7	4.5±0.6	2.5±0.1	1.1±0.1	23,100.0±14,140.6	1,787.5±1,197.1	Loamy sand
Songrim	18.0±6.8	12.5±1.1	2.3±0.1	1.2±0.1	1,400.0±634.6	881.3±600.2	Silty clay
Gosapo	21.6±6.2	5.2±0.7	2.5±0.1	1.1±0.1	6,293.8±1,479.4	1,937.5±1,004.6	Loamy sand
Sangrok	20.6±3.0	3.1±0.6	2.5±0.1	1.1±0.0	13,362.5±6,099.9	662.5±391.4	Loamy sand
Dongho	29.7±7.7	3.9±1.2	2.5±0.1	1.1±0.1	24,925.0±7,452.9	5,100.0±2,697.2	Loamy sand
Gusipo	21.7±5.7	2.6±0.5	2.5±0.1	1.0±0.0	3,487.5±1,737.4	2,887.5±1,630.9	Loamy sand
Baekbawi	29.1±6.3	5.1±0.8	2.4±0.1	1.1±0.0	5,881.3±2,719.1	1,456.3±991.9	Loamy sand
Mean	24.2±7.5	5.2±3.0	2.5±0.1	1.1±0.1	11,368.8±10,280.5	2,085.2±1,850.6	-

Table 4 Correlation analysis between height and soil characteristics

	pH	EC	OM	Tot-P	Tot-N	Cd
Height PC	-0.439	-0.190	0.093	-0.527	0.129	0.018
Sig. (2-tailed)	0.276	0.653	0.827	0.180	0.760	0.967
N	8	8	8	8	8	8
	Cu	Pb	Zn	Ca	K	Na
Height PC	0.042	-0.063	0.724*	-0.763*	-0.415	-0.018
Sig. (2-tailed)	0.921	0.883	0.042	0.028	0.306	0.966
N	8	8	8	8	8	8
	Mg	NH_4-N	NO_3-N	Al-P	Ca-P	Fe-P
Height PC	0.639	0.335	0.579	0.454	-0.716*	0.386
Sig. (2-tailed)	0.088	0.418	0.133	0.259	0.046	0.345
N	8	8	8	8	8	8
	CEC	PD	BD	AB	Fungus	
Height PC	-0.011	0.098	-0.090	0.449	0.836**	
Sig. (2-tailed)	0.980	0.818	0.832	0.265	0.010	
N	8	8	8	8	8	

* $p < 0.05$, ** $p < 0.01$
Note. PC: pearson correlation, PD: particle density, BD: bulk density, AB: aerobic bacterium

Table 5 Coefficient, MSE, and residual statistics for the polymorphic equations fitted to height data

Model	Parameter			MSE	Mean of residuals	Skewness	Kurtosis	W:Normal
	α	β	γ					
Schumacher	4.4145	0.3599		5.6205	0.2634	-0.2093	-0.1145	0.9853
Hossfeld	28.4873		1.2877	5.7558	0.2665	-0.2343	-0.1207	0.9837
Gompertz	-	-	-	-	-	-	-	-
Chapman-Richards	-	-	-	-	-	-	-	-

Table 6 MSE and residual statistics of the Schumacher polymorphic equation based on soil characteristic factors

Soil factor group	MSE	Mean of residuals	Skewness	Kurtosis	W:Normal
A (Zn)	4.8071	0.2420	-0.1145	-0.6209	0.9531
B (Ca)	4.3259	0.2300	-0.0290	-0.7774	0.9740
C (Ca-P)	3.9980	0.2207	0.0414	-0.4315	0.9876
D (F)	3.7385	0.2134	-0.6440	-0.7561	0.9160
E (Zn, Ca)	-	-	-	-	-
F (Zn, Ca-P)	2.6620	0.1789	0.2456	-1.2386	0.9248
G (Zn, F)	3.7416	0.2121	-0.6045	-0.8211	0.9201
H (Ca, Ca-P)	3.5835	0.2075	0.2775	-0.7285	0.9638
I (Ca, F)	2.8343	0.1846	-0.5636	-1.1457	0.8876
J (Ca-P, F)	1.1313	0.1166	1.2724	1.6811	0.8822
K (Zn, Ca, Ca-P)	-	-	-	-	-
L (Zn, Ca, F)	-	-	-	-	-
M (Zn, Ca-P, F)	1.1179	1.1152	1.2860	1.6307	0.8829
N (Ca, Ca-P, F)	1.1350	1.1161	1.2892	1.6386	0.8800
O (Zn, Ca, Ca-P, F)	1.1283	0.1149	1.2783	1.6603	0.8861

Note. F: fungus

actual measurement values, and the estimation bias of the model and its precision were examined. In addition, residual statistics were examined through PROC UNIVARIATE. Furthermore, to understand the soil characteristic factors, a correlation analysis between the height and the result of soil analysis was conducted. Herein, the best site index model was developed by applying the soil characteristic factors.

Soil analysis. All soil samples were air-dried for seven days at ambient temperature, and sieved to 1 mm. Soil analyses were conducted by conventional standard procedures (Sumner and

Table 7 Coefficient and associated statistics for the Schumacher polymorphic equation based on selected soil characteristic factors

Soil factor group	Coefficient		Standard error	Lower 95% confidence level	Upper 95% confidence level
J (Ca-P, F)	α	3.1640	0.0720	3.0206	3.3075
	β	2.3304	0.8693	0.5990	4.0618
	ε(Ca-P)	-0.0114	0.000857	-0.0131	-0.00966
	θ(F)	0.000126	7.634E-6	0.000111	0.000141
M (Zn, Ca-P, F)	α	3.2336	0.0962	3.0420	3.4252
	β	1.9433	0.5110	0.9254	2.9613
	γ(Zn)	-0.00399	0.00297	-0.00990	0.00192
	ε(Ca-P)	-0.0114	0.000861	-0.0132	-0.00973
	θ(F)	0.000142	0.000014	0.000114	0.000170
N (Ca, Ca-P, F)	α	3.2316	0.1072	3.0181	3.4451
	β	2.5951	1.4215	-0.2366	5.4269
	δ(Ca)	-0.00009	0.000104	-0.00030	0.000118
	ε(Ca-P)	-0.0109	0.00104	-0.0129	-0.00879
	θ(F)	0.000124	7.969E-6	0.000108	0.000140
O (Zn, Ca, Ca-P, F)	α	3.2066	0.1143	2.9787	3.4344
	β	1.7004	0.4766	0.7507	2.6500
	γ(Zn)	-0.00659	0.00543	-0.0174	0.00424
	δ(Ca)	0.000105	0.000184	-0.00026	0.000471
	ε(Ca-P)	-0.0121	0.00150	-0.0151	-0.00913
	θ(F)	0.000155	0.000027	0.000102	0.000208

Note. F: fungus

Miller, 1996). The soil properties that were determined were as follows: pH, saturation paste extract EC (EC_e), organic matter (OM), total nitrogen (Tot-N), total phosphorus (Tot-P), heavy metals (Pb, Cd, Cu, and Zn), exchangeable cations (Ca^{2+}, Mg^{2+}, K^+, and Na^+), ammonia-N, nitrate-N, phosphorus-fractionation, cation exchange capacity (CEC), bulk density, particle density, soil texture, aerobic bacterium, and fungus. The pH was potentiometrically measured in distilled water and in 1 M KCl, at a soil dry weight/solution ratio of 1:2.5). The electrical conductivity was measured in a water-saturated soil extract. Organic matter (OM) and total nitrogen (Tot-N) concentrations were analyzed by dry combustion, using a C–N analyzer (Elementar, GmbH, Germany). The total phosphorus (Tot-P) was measured photometrically, after adjusting the digests to pH 3 by the perchloric acid digestion method. Heavy metals were digested by the perchloric acid digestion method, and concentrations were determined by inductively coupled plasma (ICP, Shimadzu-7000S, Japan). Exchangeable cations were leached first with neutral 1 M ammonium acetate, and concentrations were determined by atomic absorption spectrophotometry (Perkin Elmer 2380, USA). Concentrations of NH_4^+ and NO_3^- in the KCl extracts were determined by Lachat Autoanalyzer (Lachat Instruments, USA). Selective sequential fractionation of P in the soils was performed using the following stepwise extraction scheme: Al bound P (Al-P), Fe bound P (Fe-P), and Ca bound P (Ca-P) were selectively extracted using 0.5 M NH_4F, 0.1 M NaOH, and 0.25 M H_2SO_4, respectively. CEC was determined as the sum of Ca^{2+}+Mg^{2+}+K^++Na^++Fe^{3+}+Al^{3+}+Mn^{2+} that could be extracted with 1 M ammonium acetate. Soil bulk density and particle density were measured by the core method. Particle size distribution of air-dried soil (<2 mm) was determined by the hydrometer method. Levels of aerobic bacteria and fungus were determined by counting the number of CFUs.

Results and Discussion

Soil characteristics. The soil characteristics of windbreak forests on the west coast of Korea are as follows. The soil pH was found to be low, which is believed to be due to base leaching of the forest soil. The low pH accelerates the elution of heavy metals, and causes an imbalance in the essential trace elements in soil. The EC, particle density, bulk density, and P-fractionation were similar to that of general forest soil. The SOM, Tot-N, Tot-P, nitrate-N, ammonia-N, CEC, and heavy metal levels were slightly lower than those of other general forest soil. The low value is deemed to be due to the mostly loamy sand in windbreak forests. It is believed that the contents of nutrients in windbreak forests were found to be low, because most of these windbreak forests are located on or near the seaside, where the soil is immature. The heavy metal content of most windbreak forest soils was found to be within the background level. Moreover, the exchangeable cations were found to be at a high level, due to salt wedge. The soil texture was found to be mostly loamy sand. The microbial diversity in windbreak forests was very poor. The population of

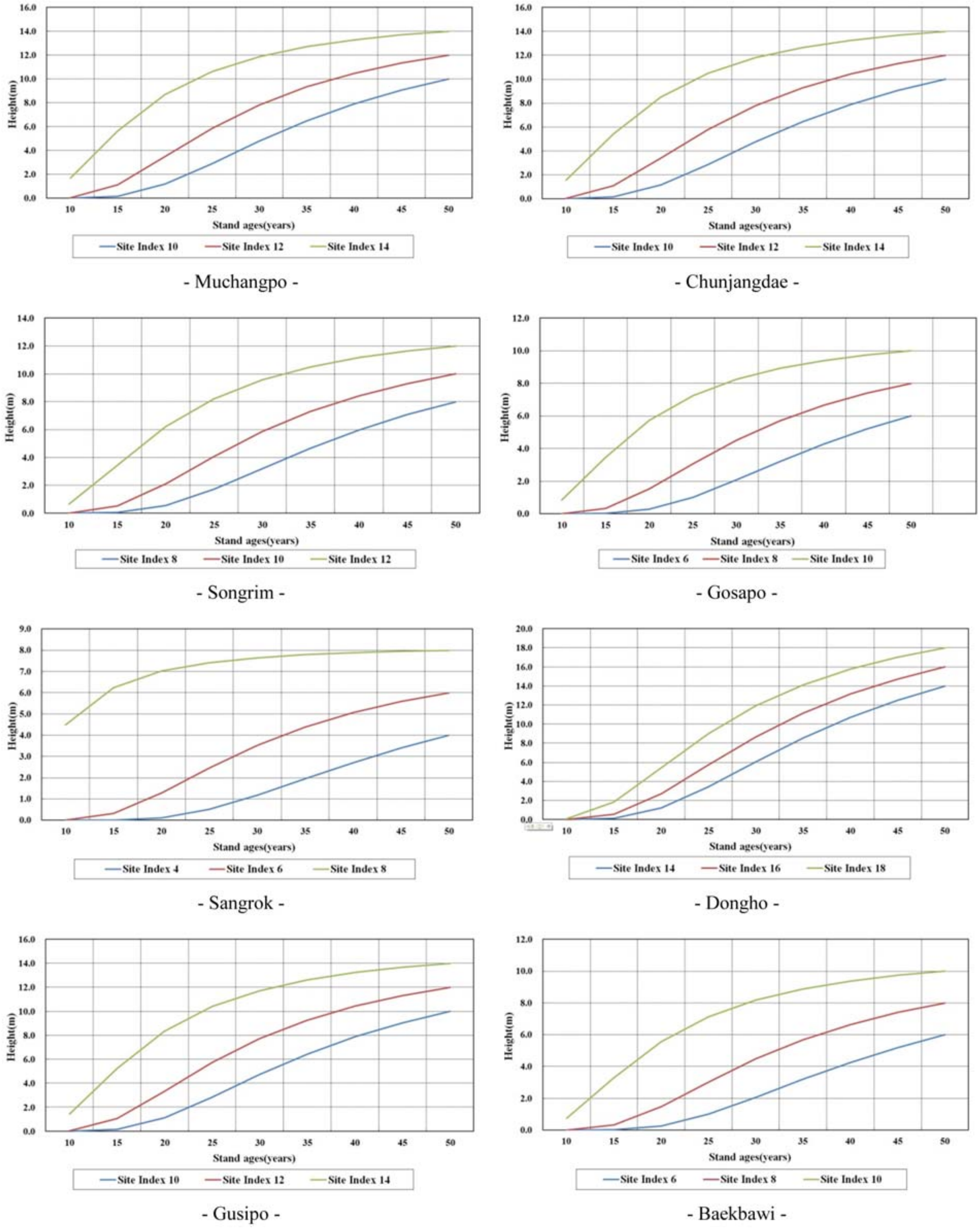

Fig. 2 Site index curves for *Pinus thunbergii* classified by each region.

aerobic bacterium was richer than that of fungus.

Furthermore, the results of height data and correlation analysis that was conducted to determine the soil characteristic factors to apply an independent variable to the height growth model showed Zn, Ca, and Ca-P at the 95% confidence level, and fungus at the 99% confidence level. These results were related to height growth, and thus determined them as the soil characteristic factors for application to the height growth model (Table 4).

Estimation of the height growth model. In order to estimate the height growth model of P. thunbergii, polymorphic equations were applied to the collected height data. As a result, the polymorphic equations of Schumacher and Hossfeld (Schumacher, 1939; Clutter and Jones, 1980; Woollons, 1988; Woollons et al., 1990) were fitted to the height data; in contrast, the polymorphic equations of Gompertz and Chapman-Richards (Pienaar and Turnbull, 1973; Goulding, 1979; Whyte and Woollons, 1990) were not fitted. The model applying the soil characteristic factors was determined, and compared with the result of the MSE of two fitted equations and residual statistics. The MSE value (5.6205) of the Schumacher polymorphic equation was low, and showed relatively superior statistical values (Eq. 1 and Table 5).

$$H_2=\exp(\ln(H_1)(T_1/T_2)^{\beta}+\alpha(1-(T_1/T_2)^{\beta}) \qquad (1)$$

Estimation of the height growth model considering the soil characteristic factors. The result from applying an asymptotic parameter (α) of the height growth model (Eq. 1), after grouping it into the selected soil characteristic factors in all possible combinations, greatly improved the accuracy of the model. However, the E, K, and L groups were not fitted. The accuracy of the models combining the soil characteristic factors of J, M, N, and O groups were relatively improved (Table 6).

Additionally, (with the exception of the coefficient estimated by using the soil characteristic factors of J group), coefficient γ (Zn) of M group, coefficient β and δ (Ca) of N group, and coefficient γ (Zn) of O group at the 95% confidence level included '0', thus the coefficient was not statistically significant. Therefore, the Schumacher polymorphic equation, combining Ca-P and fungus of the soil characteristic factors was determined, through analysis, to be the best height growth model (Eq. 2 and Table 7). Therefore, the soil factors affecting the site index for the research site of this study appeared as Ca-P and fungus. The ingredients of these characteristics were confirmed as bearing a positive relation to the impact of the height of the trees.

$$H_2=\exp(\ln(H_1)(T_1/T_2)^{\beta}+(\alpha+(CaP\times\varepsilon)+(\text{Fungus}\times\theta))(1-(T_1/T_2)^{\beta})) \qquad (2)$$

Developing the site index model and deriving the site index curves. The site index model (Eq. 3) was derived from the best height growth model (Eq. 2) by setting H_2=site index (SI) when T_2=50 years. This is used for the standard final age of maturity of *P. thunbergii* in public and private forests of Korea (MFAFF, 2012).

$$SI=\exp(\ln(H_1)(T_1/50)^{\beta}+(\alpha+(CaP\times\varepsilon)+(\text{Fungus}\times\theta))(1-(T_1/50)^{\beta})) \qquad (3)$$

where, α=3.164,
β=2.3304,
ε=–0.0114, and
θ=0.000126.

Furthermore, site index curves can be made by rearranging H_1 of the site index model (Eq. 3) to the dependent variable (Eq. 4). Furthermore, by using equation 4, various site index curves considering soil characteristic factors for each region were determined (Fig. 2).

$$H_1=\left[\frac{SI}{\exp((\alpha+(CaP\times\varepsilon)+(Fungus\times\theta))(1-(T_1/50)^{\beta}))}\right]^{1/(T_1/50)^{\beta}} \qquad (4)$$

Fig. 2 shows the site index curves are transformed to the form of polymorphic curves according to the site index class, considering the soil characteristic factors. This presented the height of the site index by each region, based on the standard age of 50 years,and can also be used to provide information about the productive capacity on the forests of the west coast of *P. thunbergii.*

Acknowledgment This research was supported by Forest Science & Technology Development Project (S111111L050130), through the Korea Forest Service.

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