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Assessing the impacts of topographic and climatic factors on radial growth of major forest forming tree species of South Korea

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A R T I C L E I N F O

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A B S T R A C T

Although the annual diameter growth of trees is vital for assessing site suitability in terms of potential timber yield, the effects of climatic and topographic factors on this variable are poorly understood. The main objective of this study was to develop a tree-level radial growth model incorporating topographic and climatic factors for four major temperate tree species [red pine (*Pinus densiflora*), oak (*Quercus* spp.), Japanese larch (*Larix kaempferi*), and Korean pine (*Pinus koraiensis*)] in South Korea. The model was developed and then validated using increment cores sampled from permanent plots in the Korean National Forest Inventory country wide. The Standard Growth (SG) of each increment core, which eliminated the effect of tree age on radial growth, was derived using a SG model. Spatial autocorrelation was detected for the SGs of every species, but not for the original radial growth data. The results showed that using the SG model to standardize radial growth for age was successful for explaining the impact of topographic and climatic factors on radial growth. The influence of climatic (warmth index and precipitation effectiveness index) and topographic (topographic wetness index) factors on the SG of each species was evaluated by the estimated SG (eSG) model. Results show that for all species each variable was correlated to SG. The mean R^2 of the final radial growth model for red pine, oak, Japanese larch, and Korean pine during 2001–2009 were estimated to be 0.71, 0.73, 0.67, and 0.65, respectively. In addition, for every tree species the time sequence of estimated annual radial growth exhibited similar characteristics to that of the observed annual radial growth on an individual tree scale. Thus, this growth model can contribute to an understanding of the impacts of topographic and climatic factors on tree radial growth and predict the annual growth changes of major tree species in South Korea, given climate change.

1. Introduction

The prediction of tree growth for forest planning and management is typically achieved by considering environmental factors, such as precipitation, temperature, drought, and soil and topographic characteristics (Schweingruber, 1988). This approach has had a long tradition among foresters, particularly when the climatic parameters are considered to be major abiotic influences on the phenological, physiological, and geographical states of the forest ecosystem (Box, 1996). However, climate observations are currently exhibiting a global warming trend; global average temperatures have increased by 0.8 °C since 1900 (Hansen et al., 2006), and the 12 hottest years on record have all occurred between 1990 and 2005. Consequently, the uncertainty of future forest resource estimates has increased. Therefore, to cope with global warming and climate change, proper forest management requires understanding the relationships between forest growth and climatic factors.

Tree ring growth has played a critical role in identifying the growth response of trees to environmental and climatic variation (Fritts, 1976). For example, studies in a wide range of forest environments have shown that variations in tree ring width are correlated with variations in macroclimate (Takahashi et al., 2003). Accordingly, tree ring data have been used extensively in the development of tree growth models. Tree growth models are a fundamental component of forest growth and yield frameworks, and the development of such models is supported by large research bodies (Adame et al., 2008; Sterba et al., 2002; Trasobares et al., 2004); thus, growth models have been constructed for a wide range of forest regions and management scenarios.

Many existing tree growth models incorporate various factors that can affect tree growth, particularly the age and size of individual trees,

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topography, and climate. Some comments can be made about these factors. First, since growth rates can vary according to the age and size of trees, these factors should be incorporated into growth models (Enquist et al., 1999; Enquist, 2002). Furthermore, climatic and topographic factors localize growth models to specific regions (Moore et al., 1993; Sørensen et al., 2006; Zirlewagen et al., 2007). Finally, changes in tree growth over time can be explained by both tree age and climatic factors (Ryan et al., 2008).

Unfortunately, most models do not adequately meet the requirements of the large-scale forestry scenarios applicable to a country, or country wide analyses at the property level. Some models are based on insufficiently representative or only locally relevant data, others are adapted to certain treatments, and still others account for only one or a few specific tree species of interest. Another major limitation of previous research is that most has been quantitative rather than qualitative. Models based on a quantitative analysis of tree growth are essential for forming the sufficiently accurate predictions of forest growth and yield necessary for decision making in forestry.

The main goals of this study were to develop a model to simulate tree-level radial growth in the temperate forests of South Korea and to evaluate the effects of climatic and topographic factors on diameter growth. To achieve these objectives, the permanent sample plots recorded by the Korean National Forest Inventory (NFI), the standard growth model, semi-variogram analysis, and the generalized additive model (GAM) were used. The new model presented in this paper can be used to predict forest growth, taking into account climatic change, for entire forests across South Korea.

2. Materials

2.1. Study area

The study area included all of South Korea's forests (longitude 124°54′–131°06′ and latitude 33°09′–38 °45′; Fig. 1a). The Taebaek Mountain Range rises to over 1500 m on the eastern side of Korea and then drops steeply toward the East Sea with a narrow coastal plain (Fig. 1b). From the Taebaek Mountain Range, the Sobaek Mountain Range runs from the northeast to the southwest. In the central zone, moderately high mountains dominate the landscape. Lowlands are found primarily along the western region of the study area. Approximately 64% (6,368,844 ha) of South Korea is covered by forest.

2.2. Dataset and measurement protocols

The tree ring dataset used in this study was taken from the 5th South Korea NFI, which was conducted from 2006 to 2010 for all South Korea's forests (Fig. 1a). The survey design consisted of a systematic sampling at intervals of 4 km (longitude) × 4 km (latitude) across South Korea. The total inventory is 4200 clusters, and individual clusters consist of four circular sample plots. The Korean NFI system measured a sample representing 20% of Korea's forests every year. Fieldwork under the inventory system began in April 2006 and the enumeration was completed by 2010.

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. Cores were mounted, sanded and polished and ring width was then measured using a digital tree ring system, (DTRS)-2000, which can determine annual tree ring width at a high resolution (up to 1/100 mm), by the Korea Forest Research Institute (2013). Tree-ring widths were carefully measured, and cross-dated using several numerical methods (Aniol, 1983; van Deusen, 1990), and tree-ring characteristics were compared visually. In dendrochronological cross-dating, variations in ring widths are first examined and then synchronized with all available samples from a given region.

In this study, we used the 43,532 core samples available for the four main temperate tree species in South Korea (Table 1), which include red pine (*Pinus densiflora*), Japanese larch (*Larix kaempferi*), Korean pine (*Pinus koraiensis*) and oak (*Quercus variabilis*). These tree species form large forests in most of the mountainous areas of South Korea, and occupied approximately 37%, 5%, 4%, and 25%, respectively, of the total forested area in 2010. The available data for each species were divided into two sets: the data obtained between 2006 and 2008 were used to estimate model parameters and the remaining data (2009–2010) were reserved for subsequently validating the models (Table 1).

2.3. Climatic data preparation

Climate data were collected from recent years (1996–2009). The Korean Meteorological Administration (KMA) provided climatic data from 75 weather stations during this period. These data were interpolated with a 0.01° grid size (about 1 km) using the kriging interpolation methods and inverse distance squared weights (IDSW) based on absolute temperature and precipitation lapse rate by altitude (Choi et al., 2011; Yun et al., 2001).

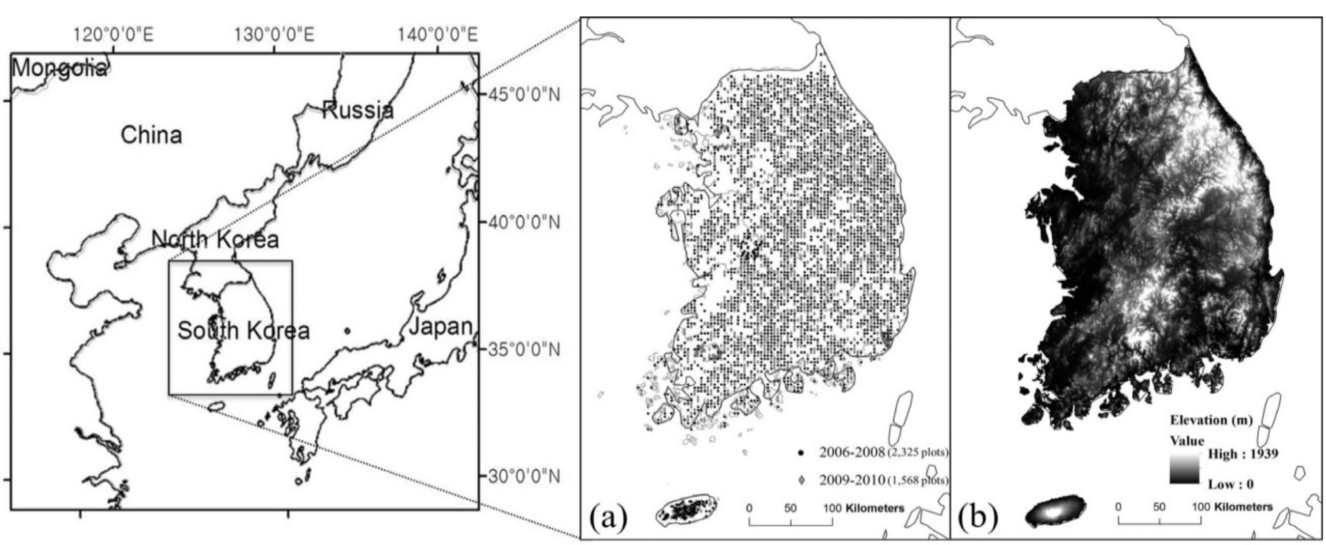

Fig. 1. (a) Locations of National Forest Inventory plots from which data were obtained and (b) a map of the digital elevation model of South Korea.

Table 1
Descriptive statistics of size, and topographic and climatic factors of tree species in sample plots by tree species.

Factors	variables	Use	Pinus densiflora				Quercus spp.				Larix kaempferi				Pinus koraiensis			
			mean	min	max	[d]SD	mean	min	max	[d]SD	mean	min	max	[d]SD	mean	min	max	[d]SD
Age	Age (year)	Model	29.7	8.0	117.0	10.9	30.2	6.0	145.0	13.4	28.6	6.0	73.0	9.0	29.4	7.0	159.0	11.5
		Verify	32.5	11.0	127.0	11.4	31.4	12	237.0	12.7	31.2	14.0	74.0	8.5	30.8	19	92	9.3
Size	DBH (cm)	Model	19.0	6.0	75.0	7.8	16.7	6.0	53.0	6.7	22.0	6.0	61.0	6.6	17.9	6.0	59.0	8.2
		Verify	20.5	6.0	70.0	8.7	16.7	6.0	52.0	7.0	23.3	6.0	60.0	8.6	17.1	6.0	56.0	8.3
Topography	[a]TWI	Model	5.8	3.8	10.9	1.0	5.4	3.7	9.5	0.6	5.3	4.2	9.4	0.7	5.6	3.9	8.6	0.6
		Verify	5.8	3.9	10.5	1.0	5.7	3.7	10.5	0.9	5.9	4.5	10.3	1.1	5.6	4.1	10.3	0.9
Climate	[b]WI	Model	86.8	51.0	120.7	11.2	92.4	40.7	125.9	12.0	85.6	48.9	116.6	11.6	85.9	43.3	116.4	12.6
		Verify	94.9	53.2	123.1	12.2	89.1	47.1	130.5	13.9	84.9	51.8	111.0	11.0	86.5	47.2	116.4	11.1
	[c]PEI	Model	159.4	73.7	225.3	21.6	150.6	69.4	226.3	25.1	149.5	77.3	215.9	25.9	158.6	73.7	213.8	26.8
		Verify	144.6	74.9	209.1	22.4	141.8	63.7	209.9	26.4	139.8	77.5	206.1	26.9	155.9	86.1	200.4	28.2

[a] TWI: Topographic wetness index.
[b] WI: Warmth index.
[c] PEI: Precipitation effectiveness index.
[d] SD: Standard deviation.

3. Methods

3.1. Factors and variables

One of the goals of this study was to identify the climatic and topographic factors that could be used to develop a growth model. The influence of climatic and topographic factors on tree growth was evaluated by multiple regression analysis and climatic and topographic indices, which were closely related to tree physiology. Temperature, precipitation, and topographic conditions have been recognized as major factors affecting tree growth and physiology. Therefore, the warmth index (WI) (Kira, 1945; Yim, 1977), precipitation effectiveness index (PEI) (Thornthwaite, 1948), and topographic wetness index (TWI) (Moore et al., 1993) were selected to assess the influence of environmental conditions.

WI is the summation of monthly mean temperatures (t, in °C) with 5 °C as the threshold [i.e., $WI = \Sigma(t - 5)$] and where the summation is only made for the months in which $t > 5$ °C (Kira, 1991). This index has been shown to be appropriate for the distribution of vegetation types and tree growth in East Asia, including South Korea (Choi et al., 2011; Umeki, 2001). The PEI is equal to the sum of the monthly precipitation-evaporation ratios (PE ratio: ratio of monthly precipitation to monthly evaporation). The PEI has been used to classify climatic zones corresponding to forest ecosystem types (Thornthwaite, 1948) and to demonstrate the relationship between a hydrological index and vegetation regimes (McCabe and Wolock, 1992). We used the summer (June to August) PEI instead of the annual PEI because, according to previous research, summer precipitation (June to August) is positively correlated with the annual radial growth of red pine (Lee et al., 2008), oak species (cork oak and Mongolian oak) (Shin, 2006; Shin et al., 2008), and Korean pine (Lee et al., 2009).

Topographic and soil moisture conditions are also very important determinants of tree growth and vegetation composition. Several topographic-based indices of soil moisture have been proposed in previous years (Iverson et al., 1997; Murphy et al., 2009); however, the most popular indicator is the Topographic Wetness Index (TWI). This index is defined as $TWI = \ln(\alpha/\tan \beta)$, where $\tan \beta$ is the local slope of the ground surface and α is the upslope area per unit contour length; α is also known as the specific upslope area and computed as $\alpha = A/L$, where A is the upslope area and L is the contour length (Beven and Kirkby, 1979). TWI has been shown to be correlated with soil attributes, including horizon depth, silt percentage, and organic matter (Moore et al., 1993). It has also been used as a predictor variable for forest health conditions (Zirlewagen et al., 2007). In this study, a high-resolution digital elevation model (DEM) with a 30 m grid size was used to compute TWI values to reflect the real spatial patterns more similarly (Sørensen and Seibert, 2007).

3.2. Evaluation of diameter growth

In dendroclimatological studies of various stand age forests, climate-growth relationships can be biased because at any given time different trees are responding differently to the climate depending on their age (Szeicz and Macdonald, 1994). Moreover, the Korean NFI data reflected the full range of variability with respect to its sites, forest structure, and tree species. To overcome these limitations, two methodological approaches were adopted. In the first approach, the radial growth data from the individual increment core samples were rebuilt. The core samples from the Korean NFI featured high variation in radial growth. In this study, to reduce uncertainties present in the raw data, the mean radial growth data for the most recent 10 years (1996–2005) were used to construct a growth model to analyze the effects of climatic and topographic factors on radial growth.

$$MR_{ij} = \sum_{k=1996}^{2005} AR_{ijk}\ (\text{mm}) \div 10 \tag{1}$$

where i is the identification number of the NFI plot, j is the unique number of each tree in one NFI plot, AR is the annual radial growth at k year, k is the year, and MR is the mean radial growth of each tree from 1996 to 2005.

In the second approach, the SG model was adopted to remove age-related growth trends from the raw ring-width series. The SG model is a standardization technique that uses the detrending method and algebraic differences form (Byun et al., 2010). The SG model is created in a three-step process. First, the following power function (Eq. (2)) is used to extract the general age-related growth patterns of each species. Second, SG was defined as the radial growth at a specific age. In this study, the mean age of Korean trees (30 years) was used. Third, to convert the MR from various tree ages to the SG at age 30, the transformation to algebraic differences form was applied by integrating Eqs. (2) and (3), as shown in Eq. (4).

$$MR_{ij} = a \cdot age_{ij}^{b} \tag{2}$$

$$SG_{ij} = a \cdot 30_{ij}^{b} \tag{3}$$

$$SG_{ij} = MR_{ij} \cdot \left(\frac{30}{age_{ij}}\right)^{b} \tag{4}$$

where SG is the estimated radial growth at age 30, and a and b are

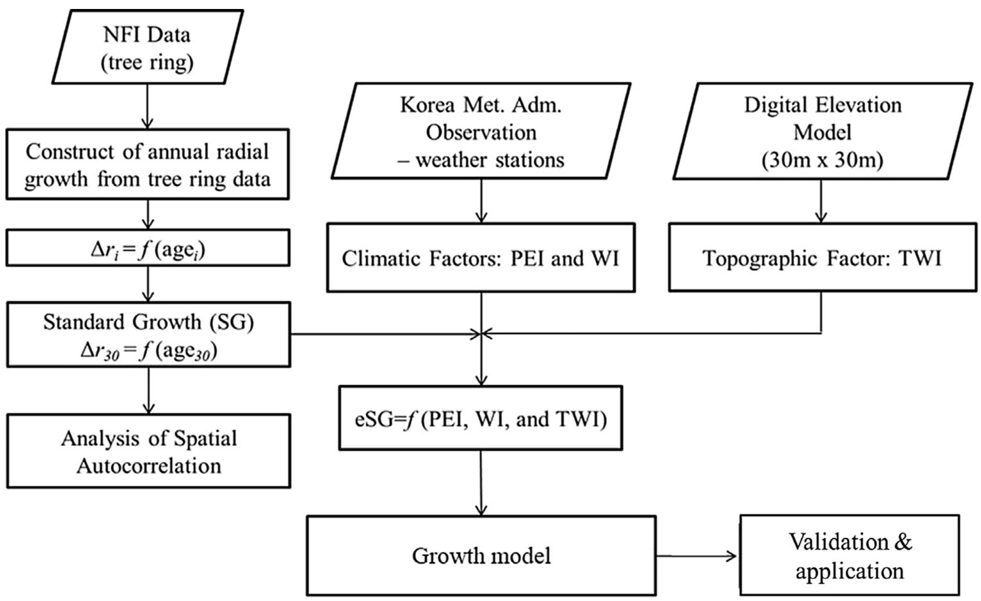

Fig. 2. Schematic diagram showing the development of the radial growth model and the analysis of the growth response of the four major tree species to climatic and topographic factors.

coefficients.

The use of SG makes it possible for individual trees of different ages to be compared under equivalent conditions by eliminating the effect of tree age on tree growth. This allows the relationship between SG and climate and topography to be analyzed quantitatively, without age-dependent responses of tree-ring growth to environmental conditions.

3.3. Spatial autocorrelation

Climatic and topographic variables often fluctuate synchronously over wide geographical areas, a phenomenon known as spatial autocorrelation. Therefore, although the SG model had a good statistical fit, the SGs can exhibit spatial autocorrelation if climate influences tree growth. Therefore, we evaluated and compared the spatial autocorrelation of MRs and SGs.

If differences in SGs exist at the regional level as a result of other factors, such as climatic or topographic factors, the SGs will exhibit spatial autocorrelation. We used a semi-variogram analysis to identify spatial autocorrelation (Bahn et al., 2008). In this paper, the semi-variograms were applied all fitted to the spherical model using the SPATIAL STATS sub-module of the S-PLUS program (Kirilenko and Solomon, 1998).

3.4. Model structure development

Growth data were sorted according to species and the following model was applied to each species to extract their growth patterns associated with climatic and topographic factors (Eq. (5)). The models were analyzed using a generalized additive model (GAM) with a spline function (SAS Institute, 2008). The GAM is a nonparametric extension of the generalized linear model (GLM) and has been increasingly used in ecological studies (Austin, 2002; Guisan and Zimmermann, 2000).

$$SG_{ij} = \beta_1\cdot WI_i^2 + \beta_2\cdot WI_i + \beta_3\cdot PEI_i^2 + \beta_4\cdot PEI_i + \beta_5\cdot TWI_i + Int \quad (5)$$

where *WI* is the warmth index, *PEI* is the precipitation effectiveness index, *TWI* is the topographic wetness index, *Int* is an intercept, and β_1, β_2, β_3, β_4, and β_5 are the parameters estimated by the GAM.

Each tree species had optimal ranges of climatic conditions for growth (Kozlowski and Pallardy, 1997; Lambers et al., 1998; Andalo et al., 2005). Accordingly, the relationships between climatic factors and tree growth were modeled using a non-linear quadratic function, except for the relationship with TWI, which was modeled as a linear function based on previous research (Dean et al., 2004; Zirlewagen et al., 2007).

The estimated SG (eSG) of each tree was computed using Eq. (5). SG is defined as the expected radial growth at 30 years of age given the environmental conditions at the tree's location. Thus, eSGs can indicate the relative spatial suitability of the different species. Alternatively, the eSGs of one species can indicate the relative suitabilities of the environmental conditions at different sites. In conclusion, eSG can be used as an independent variable in the growth model. The result of the eSG for each tree species was indirectly validated using standardized indices of tree-ring width. The indices were produced using the C-method (Biondi and Qeadan, 2008). The C-method is a tree-ring standardization method based on the assumption that the annual growth rate of mature trees fluctuates around a specific level, expressed by a constant ring width. Of the standardization methods based on the biological age of tree rings, the C-method has the advantage of calculating an expected growth curve for each measurement series, whereas the regional curve standardization applies the same growth curve to all samples.

In this study, the radial growth model was developed to account for the effects of climatic and topographical factors on diameter growth using eSG (Eq. (6)).

$$\Delta\hat{r}_{fij} = \Delta r_{pij}\cdot\left(\frac{age_{ij}}{age_{pij}}\right)^{b}\cdot\left(\frac{eSG_{fi}}{meSG_p}\right), \quad (6)$$

where *f* is each year from 2001 to 2009, *p* is the base periods (1996–2000), $\Delta\hat{r}$ is the predicted annual radial increment at the breast height of a tree, Δr is the mean observed radial increment from tree core data during the base periods, *eSG* is the estimated standard growth, *meSG* is the mean estimated standard growth of each species during the base period, and *b* is a constant for each species from Eq. (3). In this study, the base period was the five years from 1996 to 2000 and the model was applied to estimate the annual radial growth of trees from 2001 to 2009.

In this model, Δr_{pij} was considered to reflect the individual and tree-stand level growth conditions, which would include competition among trees, site index, and size. Growth conditions are major factors influencing both the growth of individual trees and community dynamics. The eSG_{fi} can be normalized using $meSG_p$. Because the normalized eSG_{fi} is integrated into the radial growth model, radial growth increments can be estimated from topographic and annual climatic conditions. The overall scheme of the radial growth model is described in Fig. 2.

Table 2
Parameter estimates for Eq. (1) ($\Delta r = a.\ age^{b}$).

Tree species	Coefficients	Estimate	Std. Error	*t* value	Pr > |t|	R^2
[a]PD	a	5.39	0.20	26.77	< 0.001	0.09
	b	−0.30	0.01	−25.88	< 0.001	
[b]QU	a	7.33	0.20	36.30	< 0.001	0.14
	b	−0.39	0.01	−44.78	< 0.001	
[c]LK	a	11.56	1.04	11.07	< 0.001	0.20
	b	−0.48	0.03	−16.98	< 0.001	
[d]PK	a	8.83	0.78	11.33	< 0.001	0.18
	b	−0.39	0.03	−13.14	< 0.001	

[a] PD: *P. densiflora*.
[b] QU: *Quercus* spp.
[c] LK: *L. kaempferi*.
[d] PK: *P. koraiensis*.

4. Results and discussion

4.1. Estimation of standard growth

The coefficients for Eq. (2) are shown in Table 2. All coefficients were statistically significant. Coefficients *a* and *b* in Eq. (2) indicated the average radial growth (mm) in 1 year and the effect of aging on diameter growth. According to the regression analysis, both coefficients of Japanese larch were estimated to be higher than other 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 (Kim et al., 2017). Japanese larch is one of the most economically important tree species in Korea because it is fast growing, so these results reflect the reality of the Korean forest.

The coefficient of determination (R^2) suggested that approximately 9.3–20.4% of radial growth variability could be explained by age. The regression model for each species had a low R^2 value, which indicated relatively good statistical performance in terms of the significance level of the coefficients (Table 2). It can be inferred from the results that, although uncertainties remained for individual stand environments, at the national scale age successfully explained much of the trends of radial growth change observed in the major forests of Korea.

4.2. Spatial autocorrelation

The spatial autocorrelation of the tree ring dataset and SG from Eq. (4) for each tree species is shown in the semi-variograms (Fig. 3). The range of the semi-variograms of red pine, oak, Japanese larch, and Korean pine from the tree ring datasets was estimated to be 116.9, 98.3, 99.0, and 99.2 km, respectively. The related partial sill values of these species were estimated to be 0.0, 0.08, 0.0, and 0.0, respectively. This indicated a very low degree of spatial autocorrelation in the tree ring dataset. Conversely, with SG all species had partial sill values, estimated to be 0.30, 0.19, 0.23, and 0.21, respectively. These results suggested that every species varied in diameter growth because of other factors, with spatial autocorrelation in the range of 30–50 km. Forests in South Korea cover a total area of 63,100 km^2 and have a complicated topography (Korea Forest Service, 2016). Therefore, this spatial autocorrelation may be associated with climatic rather than topographic factors.

These results showed that the general trend of tree growth with age in the SG of each species had been effectively eliminated. Therefore, the differences between their SGs shown by the tree ring data could be explained by regional climatic and topographic variables.

4.3. The distribution of WI, PEI, and TWI in South Korea

The WI distribution for South Korea from 1996–2009 ranged from 34.8 to 148.0 °C per month (mean 95.8 °C; std. dev. 15.0) (Fig. 4a). These values corresponded to the criteria of Yim (1977): subalpine species zone (30–70 °C per month), cool-temperate species zone (50–90 °C per month), warm-temperate deciduous zone (80–100 °C per month), and evergreen species zone (100–120 °C per month). The WI distribution was likely related to latitudinal and altitudinal patterns, which correlated with the dominant tree species of the forest ecosystems.

The summer PEI distribution ranged from 57.1 to 234.0 in/°F (mean 156.6 in/°F; std. dev. 25.6) (Fig. 4b) and the TWI distribution ranged from 3.4 to 25.7 (mean 6.4; std. dev. 1.5) (Fig. 4c).

4.4. Estimated standard growth with GAM

Table 3 shows the statistical performance of the GAM analysis for examining the relationships between SG and WI, PEI, and TWI. All the parameter estimates of the GAM analysis are logical and significant at the 0.05 level. These results suggested that these indices had a significant relationship with diameter growth at the individual tree level. In each species, the *SG* tended to decrease when the WI and PEI increased past a certain threshold (WI: [*P. densiflora*: 93.6, *Q.* spp.: 121.9,

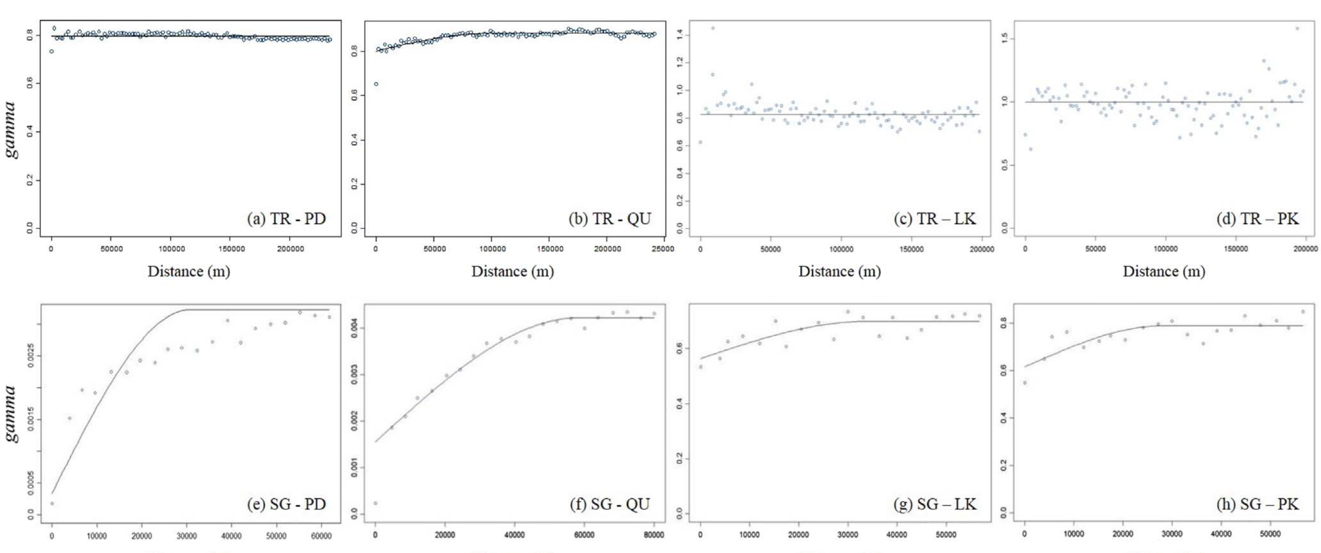

Fig. 3. Semi-variograms of tree ring (TR) dataset and standard growth (SG) for each tree species. PD: *P. densiflora*, QU: *Quercus* spp., LK: *L. kaempferi*, PK: *P. koraiensis.*

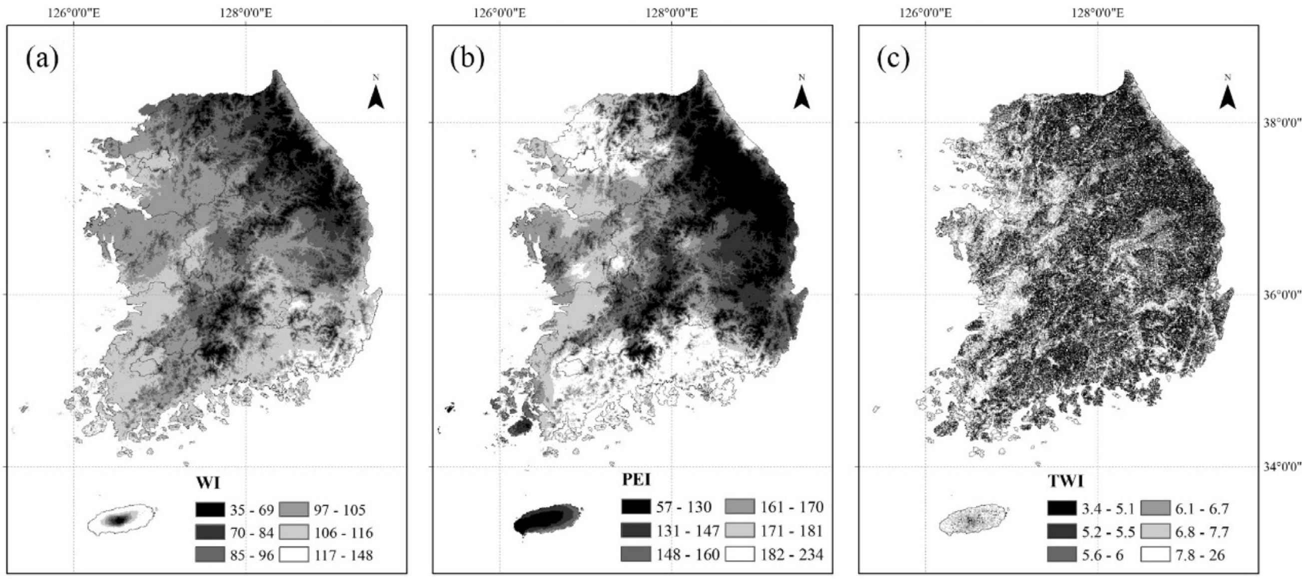

Fig. 4. (a) Warmth index (WI), (b) precipitation effectiveness index (PEI), and (c) topographic wetness index (TWI) distribution in South Korea in recent years (1996–2005).

Table 3
Parameter estimates and statistics for the GAM of *eSG*.

Tree species	Parameter	Estimate	Std. Error	*t* value	Pr > |t|
[a]PD	β_1	−0.0215	0.0057	−3.7915	0.0002
	β_2	3.8494	1.0969	3.5092	0.0005
	β_3	−0.0045	0.0016	−2.7826	0.0054
	β_4	1.6528	0.5394	3.0644	0.0022
	β_5	1.5165	0.7925	1.9136	0.0557
	Int	−110.5457	43.2428	−2.5564	0.0106
[b]QU	β_1	−0.0066	0.0032	−2.0723	0.0382
	β_2	1.9144	0.5699	3.3595	0.0008
	β_3	−0.0016	0.0010	−1.6342	0.1027
	β_4	0.6768	0.3093	2.1884	0.0287
	β_5	3.5160	0.7710	4.5605	0.0001
	Int	17.0048	17.0086	0.9998	0.3057
[c]LK	β_1	−0.0438	0.0089	−4.9246	0.0001
	β_2	6.5585	2.0585	3.1861	0.0001
	β_3	−0.0026	0.0016	−1.6111	0.1076
	β_4	0.7832	0.5353	1.4631	0.1439
	β_5	3.3452	1.3169	2.5402	0.0113
	Int	−93.1549	56.0178	−1.6629	0.0967
[d]PK	β_1	−0.0390	0.0102	−3.8066	0.0002
	β_2	5.5500	1.7755	3.1259	0.0018
	β_3	−0.0095	0.0027	−3.5296	0.0004
	β_4	3.1691	0.8738	3.6267	0.0003
	β_5	4.8319	1.9741	2.4476	0.0146
	Int	−231.5290	68.8332	−3.3636	0.0008

[a] PD: *P. densiflora*.
[b] QU: *Quercus* spp.
[c] LK: *L. kaempferi*.
[d] PK: *P. koraiensis*.

L. kaempferi: 74.8 and *P. koraiensis*: 72.4], PEI: [*P. densiflora*: 175.1, *Q.* spp.: 197.6, *L. kaempferi*: 130.6 and *P. koraiensis*: 153.2]) (Fig. 5). Consequently, the assumption that our eSG model matched the model results was confirmed. Different WI and PEI thresholds between the tree species suggested that the impact of temperature and precipitation on tree growth varies by species; it also implied that climate change could alter the growth patterns and distributions of each species. In Table 3, coniferous species had relatively larger absolute coefficient values than did oak. This suggests that major coniferous species in South Korea may be more sensitive to changes in climatic conditions than oaks.

Fig. 5 more clearly illustrates the relationships between the SGs of the 4 tree species and each factor. In spite of the large variations in the SGs of each species due to the diverse environmental conditions of the NFI plots, the trends of the change in SG with each index is shown distinctly, particularly in relation to WI. The coniferous species (*P. densiflora*, *L. kaempferi*, and *P. koraiensis*) have a similar relationship between WI and *SG*, but oak has a distinctly different one (Fig. 5). More than half of the current distribution of each coniferous species was in forest areas where potential radial growth decreases as the WI value increases. This reveals that temperature is a potent driver of coniferous forest tree growth and is retarding tree growth in most coniferous forests in South Korea. This result is similar to the findings of previous studies of South Korean forests (Byun et al., 2013; Kim et al., 2017). However, for 90 % of the oak forests the diameter growth tended to increase gradually with the WI. This means that the expected future climate conditions of South Korea will favor the growth of oak more than that of the conifers. These results are supported by previous studies showing that forest growth, cover, and mortality will change in South Korea because of climate change (Byun et al., 2010; Choi et al., 2011; Kim et al., 2017). Kim et al. (2017) showed that increased tree mortality in Korean coniferous forests was associated with warmer conditions. However, the response of tree mortality did differ between species as evident with oak species, which tend to be positively affected by rising temperatures, although the level of the significance of this observation has not been determined.

For every species, SG exhibited a positive correlation with TWI. A high TWI value is assigned to relatively flat locations with large upsloping areas; these areas are expected to have relatively higher water availability than sloping locations with only a small upslope area (Beven and Kirkby, 1979; O'Loughlin, 1981). Sitter et al. (2012) reported that TWI values and vegetation index values were positively correlated, and Wang et al. (2004) demonstrated a strong relationship between the normalized difference vegetation index (NDVI) and annual tree ring width. Therefore, the relationship between TWI and SG in our model reflects previous research.

4.5. Validation and application

4.5.1. Validation of the radial growth model

The estimated annual radial growth of each tree simulated by the developed growth model (Eq. (5)) was compared with the observed annual radial growth of each tree core from the 5th NFI (Korea Forestry Promotion Institute, 2013). The growth model explained a significant amount of variance (R^2 = 0.59–0.77) in radial growth from 2001 to

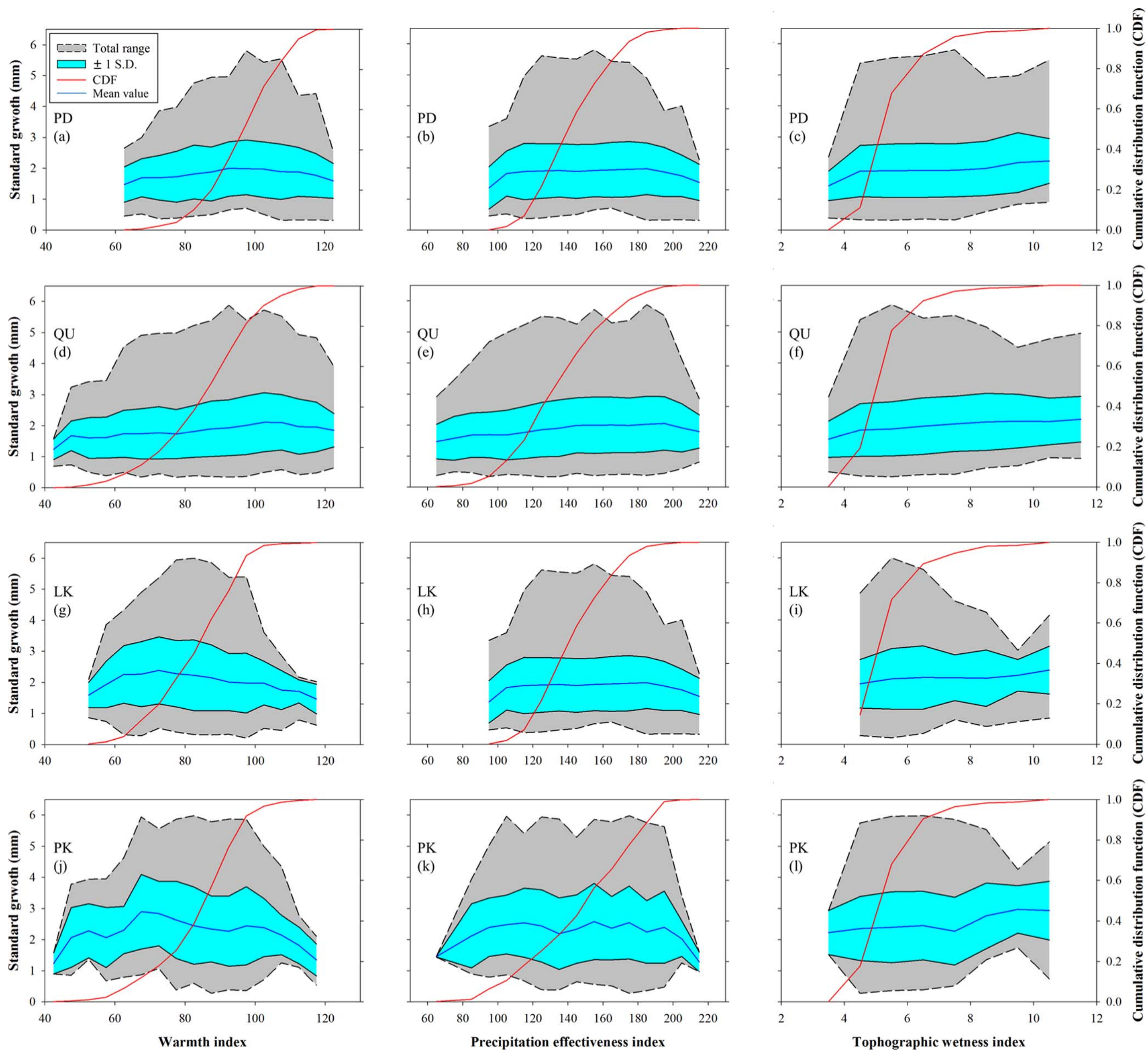

Fig. 5. The correlation between standard growth (SG) and warmth index (a, d, f, j), precipitation effectiveness index (b, e, h, k), and topographic wetness index (c, f, i, l) for each tree species. The cyan and gray areas represented the ± 1 standard deviation and total range of each index. The red and blue lines indicate the cumulative distribution of samples and the mean values of SG, respectively, for each climatic and topographic index. PD: *P. densiflora*, QU: *Quercus* spp., LK: *L. kaempferi*, PK: *P. koraiensis*.

Table 4
Statistical evaluation of the radial growth model from 2001 to 2009.

Tree species	Mean RMSE	Mean R^2
[a]PD	0.5318	0.7132
[b]QU	0.4351	0.7297
[c]LK	0.5596	0.6742
[d]PK	0.6286	0.6536

[a] PD: *P. densiflora*.
[b] QU: *Quercus* spp.
[c] LK: *L. kaempferi*.
[d] PK: *P. koraiensis*.

2009 (Table 4). The mean R^2 of red pine, oak, Japanese larch, and Korean pine was estimated as 0.71, 0.73, 0.67, and 0.65, respectively. In addition, for every tree species the estimated annual radial growth exhibited a similar trend throughout the study period to that of the observed annual radial growth at the individual tree scale (Fig. 6). However, the ranges of radial growth differed. During most of the period, the ranges of the observed radial growth values were wider than the estimated values. One major reason for this result is that the annual growth of a tree is a result of complex interactions between multiple factors. Another cause is that this study used nationwide forest inventory data that included forests in atypical locations such as urban areas and islands. Therefore, this range discrepancy does not represent an important issue for the reliability of the growth model developed in this study.

According to the observed annual radial growth from the 5th NFI, the mean radial growth of red pine, Japanese larch, and Korean pine increased from 1.90, 1.97, and 2.29 mm in 2001 to 2.03, 2.04, and 2.41 mm in 2002, respectively. The overall increment of annual radial growth in these tree species could be explained by climatic conditions. The year 2001 was a historical drought period in South Korea (KMA, 2001), in which the mean annual precipitation was 997.3 mm, much less than the average mean annual precipitation for 1981–2010 (1366.7 mm). The drought had a critical impact on South Korea that led

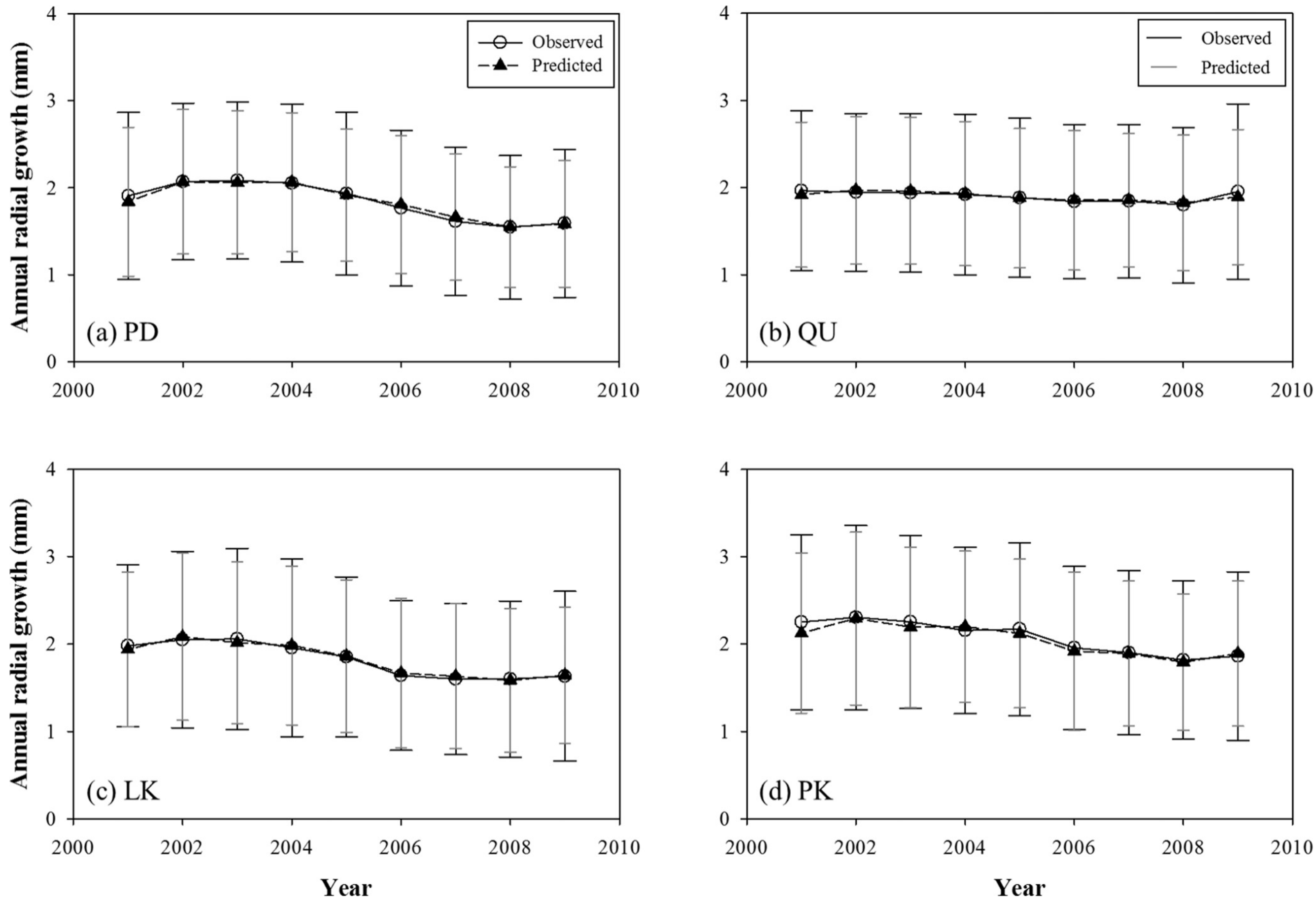

Fig. 6. Comparison between the distributions of predicted and observed annual radial growth during 2001–2009. Each error bar is ± 1 standard deviation. PD: *P. densiflora*, QU: *Quercus* spp., LK: *L. kaempferi*, PK: *P. koraiensis*.

to regional water shortages and influenced the use of water, including for agricultural and household activities (KMA, 2001). In addition, natural ecosystems were damaged by the drought and vegetation indices on the national scale were low (Park et al., 2008). Because of these factors, the annual radial growth of trees in 2001 was less than that in other years. However, the precipitation during 2002 was comparable to the annual average (KMA, 2002). The estimated results had the annual radial growth increasing from 1.83, 1.97, and 2.08 to 2.02, 2.14, and 2.43 mm, respectively, during that period. Because the observations and estimations were similar, it could be inferred that the growth model appropriately reflected the annual radial growth according to climatic and topographic variables on regional and national scales.

To indirectly validate the eSGs of each species, they were compared with the tree-ring chronologies which had been obtained using the C-method. The eSG time sequences of all four tree species showed similar trends as the tree-ring chronologies (Fig. 7). Thus, while uncertainties remain at the individual NFI plot scale, it could be inferred that the eSG model successfully reflected the impacts of topographic and climatic factors on the annual diameter growth trends of major Korean forests.

For the coniferous species (red pine, Japanese larch and Korean pine) during 2001–2009, most annual median index values were estimated to be less than 1 (Fig. 7). This indicated that the diameter growth of coniferous species was poorer than their expected values. In addition, Japanese larch and Korean pine have shown a gradually declining median index value trend since the 1990s. Conversely, in same period the median index value for oak was steadily increasing and estimated to be more than 1. These results reveal that under South Korea's recent weather the oak species is more suited to growth than the coniferous species. This is attributed to recent high temperatures inducing a water stress that limits the radial growth of red pine. Many other studies have found that rising temperatures had negative impacts on forest growth and the distribution of red pine, Japanese larch, and Korean pine in South Korean forests (Byun et al., 2013; Nam et al., 2015).

The goal of this research was to develop a forest growth model to estimate temporal and spatial pattern of growth based on future climate change scenarios. Hence, we quantified how climatic and geographical conditions affected the growth of each tree species based on tree core samples from NFI and developed a radial growth model. Although the model developed in this study was specific to one study region, South Korea, and the forest type of that region, mixed temperate, we believe that the same approach could be readily applied to other regions for which meteorological and geological data are available.

4.5.2. Application of eSG

The eSG of each species shows that potential radial growth reflected climatic and topographic conditions and was estimated spatially. Therefore, it could be used to assess site potential in terms of wood productivity, one of the most important metrics for forestry land management. To address this, the eSG of each species was estimated using Eq. (5) over not only their actual forest areas according to a vegetation map of Korea produced by the Ministry of Korea in 2008, but also over the entire land area of South Korea. This allowed the two results to be compared.

Fig. 8 shows the range of eSGs for each species in the actual distribution area and the entirety of South Korea. For every species, the 95th percentile value of eSG in the actual forest area of each species was higher than the eSG for the entirety of South Korea. This result showed

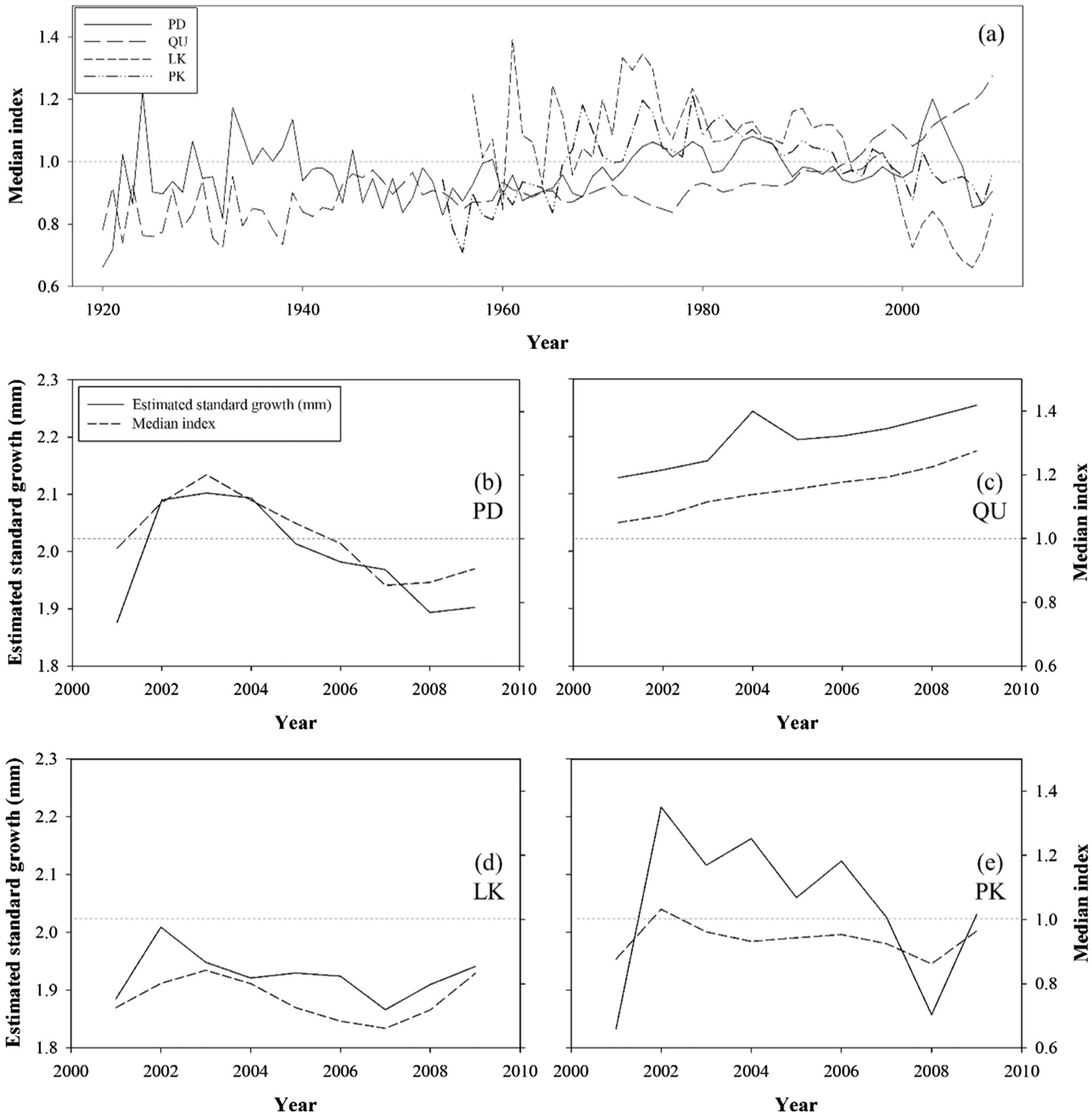

Fig. 7. (a) The tree-ring chronologies obtained using the C-method for each tree species at the Korean national inventory plots. (b–e) Comparisons between tree-ring chronologies and estimated standard growth for each tree species during 2001–2009. PD: *P. densiflora*, QU: *Quercus* spp., LK: *L. kaempferi*, PK: *P. koraiensis.*

that most of the actual forest areas of each species were distributed as if the eSG had been thoroughly considered. These results indicated that the eSG model could be used to evaluate site suitability for the cultivation of selected species and potential timber yield information, which is vital for the assessment of afforestation projects.

The eSG ranges and median values of Japanese larch and Korean pine differed significantly depending on whether their current forested areas or the entire country was considered. This difference did not exist for red pine and oak, showing that the site suitability for Japanese larch and Korean pine in their current forested areas was very high. This result is similar to findings of previous studies of South Korean forests. Kim et al. (2017) found that the mortality of Japanese larch and Korean pine have been more strongly affected by temperature than red pine and oaks in South Korea.

These results lead to the conclusion that potential changes in forest community types in South Korea would be significant given climate change. Potential changes in species composition and forest structure will have major effects on the quality and quantity of valuable plant and wildlife habitats (Iverson and Prasad, 2001; Lindner et al., 2010; Schumacher and Bugmann, 2006). Therefore, forest management plans and silviculture practices need to adapt to changing climate patterns.

5. Conclusion

The objective of this study was to develop radial growth models for *P. densiflora*, *Quercus* spp., *L. kaempferi*, and *P. koraiensis* with the goal of predicting radial growth in relation to climatic and topographic factors. We used tree ring data, from the 5th NFI, and climatic and topographic

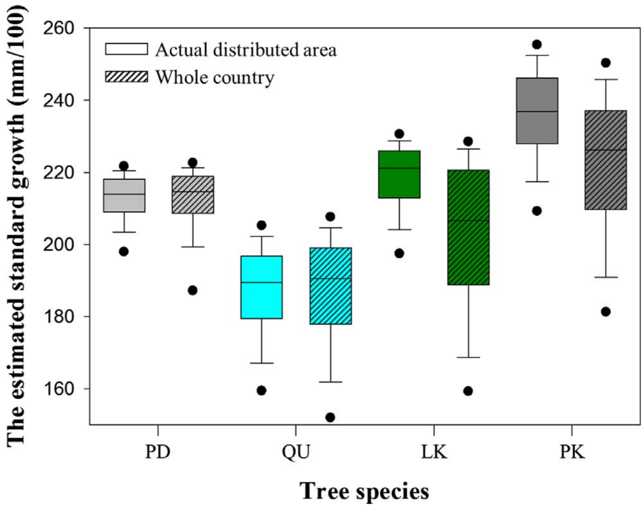

Fig. 8. Comparison between the distributions of estimated standard growth for each species in its actual distribution area and across the entirety of South Korea. For each box plot, top circle is 95th percentile, lower circle is 5th percentile, top bar is 90th percentile, lower bar is 10th percentile, top of box is upper or third quartile, bottom of box is lower or first quartile, middle bar is median value. PD: *P. densiflora*, QU: *Quercus* spp., LK: *L. kaempferi*, PK: *P. koraiensis.*

data to develop the models. We developed a Standard Growth (SG) model and analyzed the relationships between SG and the Warmth Index (WI), Precipitation Effectiveness Index (PEI), and Topographic Wetness Index (TWI) using the generalized additive model (GAM).

Based on the calculated SG semi-variograms of each tree species, all species showed clear spatial autocorrelation. This implied that climate and topography had an influence on the growth of trees, and that SG effectively standardized the growth of trees of various ages. SG appeared to have a nonlinear relationship with the climatic factors, and a linear relationship with TWI. However, TWI in this study had a weak influence on the growth of forest trees, which leads to a further supplementary study. The coefficient of determination (R^2) of the growth model for each tree species derived in this study was 0.54–0.77, relatively high. In addition for the four tree species, the time sequence of the estimated annual radial growth showed a trend similar to that observed.

Quantifying the relationship between tree growth and climate has been achieved by various research groups; however, the results of these studies have varied according to tree species, topography, climate, and the methods used, such that the relationship has only been explained by a few studies, including this one. Therefore, future research related to such topics should proceed by examining various tree species and environmental factors in other regions. Our findings and predictions will be helpful for understanding the impact of climate factors on tree growth, and for predicting the distributional changes of major tree species because of climate change.

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