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Radial growth response of *Pinus densiflora* and *Quercus* spp. to topographic and climatic factors in South Korea

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Abstract

Aims
This study aimed to develop radial growth models and to predict the potential spatial distribution of *Pinus densiflora* (Japanese red pine) and *Quercus* spp. (Oaks) in South Korea, considering topographic and climatic factors.

Methods
We used a dataset of diameter at breast height and radial growth estimates of individual trees, topographic and climatic factors in systematic sample plots distributed over the whole of South Korea. On the basis that radial growth is attributed primarily to tree age, we developed a radial growth model employing tree age as an explanatory variable. We estimated standard growth (SG), defined as radial growth of the tree at age 30, to eliminate the influence of tree age on radial growth. In addition, SG estimates including the Topographic Wetness Index, temperature and precipitation were calculated by the Generalized Additive Model.

Important Findings
As a result of variogram analysis of SG, we found spatial autocorrelation between SG, topographic and climatic factors. Incremental temperature had negative impacts on radial growth of *P. densiflora* and positive impacts on that of *Quercus* spp. Precipitation was associated with positive effects on both tree species. Based on the model, we found that radial growth of *P. densiflora* would be more vulnerable than that of *Quercus* spp. to climatic factors. Through simulation with the radial growth model, it was predicted that *P. densiflora* stands would be gradually replaced with *Quercus* spp. stands in eastern coastal and southern regions of South Korea in the future. The models developed in this study will be helpful for understanding the impact of climatic factors on tree growth and for predicting changes in distribution of *P. densiflora* and *Quercus* spp. due to climate change in South Korea.

Keywords: standard radial growth, general additive model, climatic factors, climate change, forest-cover change

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INTRODUCTION

Forest tree growth is generally determined by environmental conditions such as precipitation, temperature, drought and soil (Schweingruber 1988; Du *et al*. 2013; Li *et al*. 2013; Muraoka *et al*. 2013; Tang *et al*. 2013). Recently, it has been well recognized that climate change also has impacts on the growth and spatial distribution of tree species (Neilson and Marks

1994; Box 1996; Kramer *et al.* 2000). Therefore, it is important to understand the relationship between forest growth and climatic factors in order to manage forest resources under changing climatic conditions (Seo and Park 2010).

Tree-ring growth has played an essential key role for identifying the growth response of trees to environmental and climatic variations (Fritts 1974, 1976). Annual tree-ring growth in climate-stressed sites has been shown to enable quantitative estimates of environmental variables such as monthly precipitation, temperature and solar radiation (Hughes *et al.* 1982; Stahle 1991). Biondi (2000) argued that studies of the relationship between climate and tree-ring growth are fundamental not only for the reconstruction of past climate but also for the estimation of future changes associated with anthropogenic greenhouse gas emissions. The sensitivity of tree-ring records to climatic factors has recently been reported as an important element for evaluating vulnerability of forests in connection to global warming phenomena (Briffa *et al.* 1998a, b).

Among factors that affect tree-ring growth, tree age can be used for modelling at the individual tree level, while competition and site quality can be used to estimate stand-level growth. It is obvious that climatic factors also influence tree growth (Fritts 1976; Graumlich and Brubaker 1986; Carrer and Urbinati 2006). However, distinct differences in climate are not apparent at small scales (e.g. the individual tree or stand level). Therefore, climatic factors should be used to explain tree-growth variation at large scales such as the regional or landscape level. If there exists differences of tree growth at the regional level due to climate change, tree growth can have spatial autocorrelation that can define the spatial unit of some growth pattern, and then the threshold of regional scale can be determined. Most studies have not addressed auto-correlation between independent variables to explain tree-ring growth (Biondi 2000) due to a lack of understanding of its impact during the process of regression analyses such as parameter estimation, residuals distribution, model selection and evaluation and spatial predictions (Lehmann *et al.* 2002). Auto-correlated factors may weaken the correspondence between plant distribution and environmental conditions (Leduc *et al.* 1992). An auto-correlated response variable is a problem primarily when testing explicit causal factors (Legendre 1993; Lennon 2000). In this study, the Generalized Additive Model (GAM) was used to overcome such errors and to identify the responses of tree-ring growth to environmental and climatic factors, because the GAM considers auto-correlation between explanatory variables (Bio *et al.* 2002; Lehmann *et al.* 2003).

When differentiating general regression models, the GAM does not force a parametric relationship (e.g. linear and parabolic) between responses and predictors, but implements non-parametric smoothers in regression models (Nelder and Wedderburn 1972; McCullagh and Nelder 1989). Smoothers allow the GAM to suggest a functional relationship between independent and dependent variables (Megrey *et al.* 2005). The GAM allows the data to determine the shape of the response curves, rather than being limited by the shapes available in a parametric class (Yee and Mitchell 1991; Vetaas 2000; Lehmann *et al.* 2003), so that features such as bimodality and pronounced asymmetry in the data can be easily detected. The GAM can also reduce sensitivity to outliers in the dependent variable. Therefore, the GAM has been shown to be particularly useful in various fields of research (Austin 2002b; Elith *et al.* 2006; Franklin 1995; Albert and Schmidt 2010; Guisan and Zimmermann 2000).

Pinus densiflora, a primary subject of this study, is considered one of the most important tree species in South Korea for its timber and cultural values. *P. densiflora* occupies ~23% (1,447,000 ha) of all forested area in South Korea (Korea Forest Service 2011). *Quercus* spp. such as *Q. acutissima*, *Q. mongolica*, *Q. variabilis, Q. serrata* and *Q. aliena* occupy ~27% (1,699,000 ha) of forested area and are recognized to have the potential to become more abundant in South Korea (Lim *et al.* 1995). According to the Korea Forest Service (2011), *P. densiflora* forests have naturally decreased by ~4% (296,200 ha) from 1996 to 2010, while *Quercus* and mixed-species forests have increased by 1.13% (50,716 ha) and 2.77% (154,557 ha), respectively. Kim *et al.* (2011) and Song *et al.* (2012) reported that a large decrease in coniferous forests has been observed in various regions, accompanied by a continual increase in deciduous and mixed forests. This indicates that the distribution of forest types in South Korea is changing gradually into deciduous, broad-leaved forest in conjunction with the rise in annual mean temperature. Therefore, it is necessary to model and predict changes in tree species and growth according to future climate change.

Park and Yadav (1998a, b) and Park *et al.* (2001) performed dendrochronological analyses using tree-rings of *P. densiflora*. Seo *et al.* (2000) analysed the heterogeneous tree-ring growth of *P. densiflora* in relation to topographic characteristics. Seo and Park (2010) also found a relationship between climate and tree-ring growth of *Q. mongolica* (Mongolian oak). Byun *et al.* (2010) developed a model to estimate radial growth of *P. densiflora* and *Q.* spp. However, such tree-ring analyses were not growth-based models (Park and Yadav 1998a, b; Park *et al.* 2001) and did not cover the whole of South Korean forests (Seo *et al.* 2000; Seo and Park 2010; Byun *et al.* 2010). In models developed for South Korea, tree growth has been explained primarily by age, density and site index as representatives of growth pattern, competition and soil and topographic condition, respectively, at the stand level (Woo *et al.* 2007). The influence of climatic factors such as temperature, precipitation and humidity has been little studied for South Korean forests as a whole.

In this study, we analysed the relationship between radial growth of *P. densiflora* and *Q.* spp. and topographic and climatic factors for the entire forested area of South Korea and developed radial growth models for two tree species. Based on the difference in radial growth between the present and the future, changes in potential spatial distribution of *P. densiflora* and *Q.* spp. were predicted according to the climate change scenarios described by the Intergovernmental Panel on Climate Change (IPCC 2007).

MATERIALS

Study area

The study encompassed the entirety of South Korean forest, located geographically from latitudes 33°09′–38°45′N and longitudes 124°54′–131°06′E (Fig. 1). Approximately 64% (6,368,844 ha) of South Korea is covered with forest. Evergreen needle-leaved forests (mainly *P. densiflora*), deciduous broad-leaved forests (mainly *Q.* spp.) and mixed forests occupied ~41%, 27% and 29%, respectively, of total forest area in 2010 (Korea Forest Service 2011).

National forest inventory data

The fifth National Forest Inventory (NFI) was conducted from 2006 to 2010 for all South Korean forests. The survey scheme involved systematic sampling at intervals of 4 km (latitude) × 4 km (longitude). In addition, four circular sample plots were located in one intersection of grid line by 4×4 km. Each sample plot covered 0.08 ha (16 m radius). Diameter at breast height (DBH), age, tree height and crown height were measured in all sample plots, and tree-core samples were acquired from average trees in each sample plot.

In this study, 7843 *P. densiflora* and 9971 *Q.* spp. trees were measured during 2007–2008 and were used to model radial growth of these species (Table 1). Tree-ring widths were measured in the laboratory using core samples to determine annual radial growth for 10 years (1997–2006). Using annual estimates, mean radial growth data for 1997–2006 were used to construct a standard growth (SG) model and to analyse effects of climatic and topographic factors on radial growth. The mean radial growth data for each 5-year set (1997–2001 and 2002–2006) were arranged to predict future radial growth using the SG model.

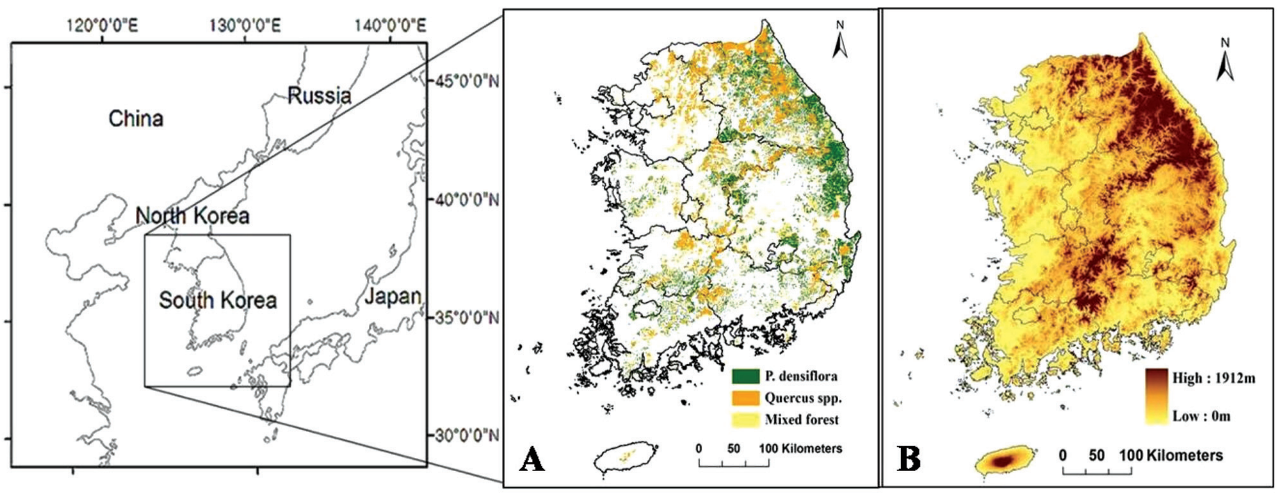


Figure 1: location of study area and distribution of (A) *P. densiflora* and *Q.* spp. and of (B) elevation in South Korea.

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

		P. densiflora				*Q.* spp.			
Factors	Variables	mean	min.	max.	Std	mean	min.	max.	Std
Age	Age (year)	37.4	12.0	132.0	11.9	37.6	10.0	150.0	14.2
Size	Radial Growth (mm)	1.8	0.2	10.5	0.9	1.8	0.2	9.9	0.9
	DBH (cm)	19.8	6.0	75.0	8.3	16.6	6.0	53.0	6.6
	Height (m)	10.8	2.2	27.3	3.4	11.2	1.5	27.6	3.2
Topography	Elevation (m)	195	8	1174	182	265	10	1632	260
	Slope (°)	25.9	4.0	68.0	8.4	27.6	4.0	65.0	9.0
	TWI	3.0	0.9	27.6	1.9	2.9	0.9	27.6	1.8
Climate	Temperature (°C)	11.4	4.2	15.4	1.7	10.4	3.3	16.0	2.0
	Precipitation (mm)	1311	981	1831	147	1296	981	1831	125
	Humidity (%)	66.9	58.8	76.5	2.7	67.1	59.1	78.1	2.4

METHODS

Data preparation for radial growth model

The growth of individual trees can be expressed by the increment of diameter (West 1980; Pukkala 1989; Wykoff 1990; Lee 1996; Lee *et al.* 1999; Sterba *et al.* 2002). In the field of forest management, stand age, site productivity and density are generally considered to be essential factors affecting forest growth (Ryan *et al.* 2008; Monserud and Sterba 1996; Noh *et al.* 2013), as statistical and biological relationships between these parameters are obvious (Woo *et al.* 2007). We considered topographic and climatic factors in addition to tree age and size to explain annual radial growth over 10 years (Equation 1)

$$\text{Radial growth} = f\ (\text{age, size, topography, climatic factors}) \quad (1)$$

Tree age is an important variable in radial growth because tree growth depends primarily on tree or stand age (Woo *et al.* 2007). Tree age can be estimated by adding five years to the number of tree-rings measured at breast height in Equation 1 (Korea Forest Research Institute 2007). Tree size can be described by DBH, tree height and crown depth (Lee *et al.* 2004). DBH is a general factor for the explanation of tree growth (Brienen *et al.* 2006; Lee *et al.* 2003; Trasobares *et al.* 2004). Therefore, we also employed DBH as a second explanatory variable for radial growth.

As a third variable, we applied the Topographic Wetness Index (TWI)—a factor that indicates the concentration of water flow for a given site according to the spatial distribution of soil moisture as determined by aspect, elevation and slope (Lee and Lee 2000). The TWI indicates where water concentrates, under the assumption of equal soil permeability regardless of environmental conditions. A high TWI value indicates that an area contains a large volume of water (Moore *et al.* 1991); a low TWI value indicates the opposite. The TWI has been frequently used in the field of topographic and spatial analysis (Hengl *et al.* 2009; Kim *et al.* 2009; Sherman *et al.* 2005). In this study, the TWI was extracted using a Digital Elevation Model with a 30-m grid size provided by the Ministry of Land, Transport and Maritime Affairs of Korea.

Climatic factors such as temperature, precipitation and humidity influence radial growth of trees (Biondi 2000; Climent *et al.* 2002; Savva *et al.* 2010; Seo and Park 2010; Shin 2006, Shen *et al.* 2013); hence these factors were included as explanatory variables of radial growth, with the exception of humidity, which was excluded due to poor statistical performance in our analysis. The Korean Meteorological Administration provided climatic data obtained from 75 weather stations for 1998–2007. These data were interpolated with a 0.01° grid size (approximately 1 km) using Kriging and Inverse Distance Squared Weighting, considering absolute temperature and precipitation lapse rate by altitude (Cho and Jeong 2006; Lee *et al.* 2007a; Lull and Ellison 1950; Park and Jang 2008; Smith 2007; Yun *et al.* 2001). Climatic data were prepared as mean annual data for 10 years (1998–2007) to identify the relationship between climate and radial growth. The A1B scenario described by the IPCC (2007) was used to predict future changes in forest type due to climate change. Future climatic data were predicted using the Fifth-Generation NCAR/Penn State Mesoscale Model (MM5) coupled with ECHO-G under the A1B scenario (Special Report on Emission Scenario of IPCC) by the National Institute of Meteorological Research, with a 0.2432° grid size (approximately 27 km) (Choi *et al.* 2011). These datasets were resampled to a 0.01° spatial resolution in the WGS-84 coordination system. The descriptive statistics for growth, topographic and climatic factors are shown in Table 1.

Standard growth

Definition of SG

Assuming that annual radial growth depends primarily on tree age, we employed the power function to predict radial growth of two tree species (Equation 2). The power functions are justified by theories of plant science: many structural and functional variables scale as power functions of measures such as body mass, length, diameter, area and volume (West *et al.* 1999; Enquist 2002).

$$\Delta r = a \cdot \text{age}^b \quad (2)$$

Where Δr is annual radial growth (mm), and a and b are coefficients of regression models. Coefficients a and b were estimated by non-linear regression analysis using SAS v. 9.2 Program. To eliminate the influence of age on radial growth, we standardized radial growth with a fixed age. SG was defined as the radial growth at age 30 (Equation 3) (Byun *et al.* 2010):

$$\text{SG} = a \cdot 30^b \quad (3)$$

For converting growth across a range of tree ages into SG at 30 years, the transformation to algebraic differences form was applied by integrating Equations 2 and 3 as shown in Equation 4 (Bailey *et al.* 1974; Jordan *et al.* 2006; Bravo-Oviedo *et al.* 2008). SG eliminates the influence of age on tree growth while still incorporating impacts of competition, site quality and climate into Δr.

$$\text{SG} = \Delta r \cdot \left(\frac{30}{\text{age}}\right)^b \quad (4)$$

The use of SG makes it possible for individual trees to be compared under the same conditions. That is, the relationship between annual radial growth and climate and topography can be analysed quantitatively without considering age. When differences in tree growth due to climate change exist at the regional level, SG can have spatial autocorrelation, which defines the spatial unit of a growth pattern (Lee *et al.* 2006). The variogram is a general form for plotting the spatial autocorrelation of data (Lichstein *et al.* 2002; Dirnbock and Dullinger 2004; Bahn *et al.* 2008). Spatial autocorrelation can be parameterized as range, nugget and sill values in a variogram. We estimated such spatial parameters in SG data, in which spatial autocorrelation was included, using the SPATIAL STATS sub-module in the S-PLUS Program (Kaluzny *et al.* 1998; Kirilenko and Solomon 1998).

Estimation of SG

Both biological rules and statistical performance should be carefully considered in evaluating the relationship between tree growth and explanatory factors (Byun *et al.* 1996; Kramer 1988). Therefore, we analysed the relationship between SG and climate and topographic factors using the GAM. The GAM is a non-parametric extension of the generalized linear model (GLM) that has been increasingly used in ecological studies (Guisan *et al.* 2002; Hastie and Tibshirani 1990). While the GLM emphasizes estimation of coefficients for model parameters, the GAM focuses on exploring data non-parametrically (Hastie and Tibshirani 1990; Guisan *et al.* 2002). The strength of the GAM is its ability to deal with highly non-linear and non-monotonic relationships between independent and explanatory variables. GAMs are especially useful for modelling species distributions (Austin 2002a; Elith *et al.* 2006) because the smoothing functions, which have non-parametric characteristics, can describe complicated non-linear relationships found in ecosystems (Guisan and Zimmermann 2000). Lehmann (1998) introduced the GAM as a powerful tool for describing species response curves in relation to environmental gradients, enabling prediction of species distributions under changing environmental conditions. Based on such studies, we used the GAM to predict the relationship between estimated SG (eSG) in tree level and TWI, temperature (T) and precipitation (P) (Equation 5):

$$e\mathrm{SG} = f(\mathrm{TWI}, T, P) = \beta_0 + \beta_1 \cdot \mathrm{TWI} + \beta_2 \cdot T + \beta_3 \cdot P \qquad (5)$$

For fitting GAM, we used dataset within Warmth Index (WI) range in South Korea in order to ensure the changing tendency of growth to temperature change. WI can be used for a representative index of TEM because WI is the annual sum of positive differences between TEM and 5°C (Kira 1945).

Integration of radial growth with SG

Radial growth at age *i* ($\Delta\hat{r}_i$) can be estimated from radial growth at age *i-5* ($\Delta\hat{r}_{i-5}$), age *i* (age_i) and age *i–5* (age_{i-5}) by equation 6—a transformation of Equation 2 to an algebraic differences form. Using Equation 6, it is possible to estimate radial growth based on the previous growth status of the target tree:

$$\Delta\hat{r}_i = \Delta\hat{r}_{i-5} \cdot \left(\frac{\mathrm{age}_i}{\mathrm{age}_{i-5}}\right)^b \qquad (6)$$

However, radial growth is influenced by topographic and climatic factors (Biondi 2000; Climent *et al.* 2002; Savva *et al.* 2010; Seo and Park 2010; Shin 2006). Therefore, eSG was added to the radial growth model to integrate these factors. The eSG can be normalized with mean estimated SG (meSG), and this value was added to the radial growth model as Equation 7. From integrating the normalized SG with the radial growth model, we could estimate the radial growth for which variations due to topographic and climatic conditions decreased.

$$\Delta\hat{r}_{ie} = \Delta\hat{r}_{i-5} \cdot \left(\frac{\mathrm{age}_i}{\mathrm{age}_{i-5}}\right)^b \cdot \frac{\mathrm{eSG}}{\mathrm{meSG}} \qquad (7)$$

Sensitivity analysis

Sensitivity analysis was performed to compare changes in forest type according to differences in present and future growth using SG of *P. densiflora* and *Q.* spp. Sensitivity to climate change is defined as the changing frequency of vegetation types in a grid area (Choi *et al.* 2011). For instance, the vegetation type in a certain area is likely to change if it is not suited to the new climate conditions (Yu *et al.* 2006; Lee *et al.* 2007b; Choi *et al.* 2011). Therefore, a high frequency indicates a high sensitivity, and low frequency indicates low sensitivity.

Based on these definitions of sensitivity of vegetation types to change, the eSG model was used to evaluate sensitivity of SG when comparing present and future growth according to climate change. The sensitivity of each species was calculated by subtracting current eSG ($\mathrm{eSG}_{\mathrm{present}}$) from future eSG ($\mathrm{eSG}_{\mathrm{future}}$) simulated under climatic conditions of the A1B scenario (Equation 8). A negative value for the future growth decrement indicates high sensitivity, whereas a positive value for the future growth increment represents low sensitivity. In addition, inter-species sensitivity—the difference in eSG between *P. densiflora* and *Q.* spp.—was calculated using Equation 9. A negative value means that *P. densiflora* forest may change into *Q.* spp. forest because the growth of *Q.* spp. surpasses that of *P. densiflora*. However, a positive sensitivity value implies that *P. densiflora* forest cannot be changed into a *Q.* spp. forest because the growth of *P. densiflora* still predominates that of *Q.* spp.:

$$\mathrm{Sensitivity}_{\mathrm{species}} = \mathrm{eSG}_{\mathrm{Future}} - \mathrm{eSG}_{\mathrm{present}} \qquad (8)$$

$$\mathrm{Sensitivity}_{\mathrm{relative}} = \mathrm{eSG}_{P.densiflora} - \mathrm{eSG}_{Q.spp.} \qquad (9)$$

RESULTS AND DISCUSSION

Estimation of SG

The coefficients for Equation 1 were estimated as shown in Table 2. All coefficients were statistically significant. The coefficient of determination (R^2) suggested that approximately 20% of growth variability could be explained by age alone for both tree species. This attributed the fact that the radial growth model identifies growth pattern with age and does not consider other growth factors. The estimated coefficients were

Table 2: parameter estimates for Equation 2 ($\Delta r = a{\cdot}age^b$)

Species	Coefficients		Std Error	*t*-value	Prob>|*T*|	Pseudo R^2
P. densiflora	a	7.0308	0.4899	14.3515	<0.0001	0.21
	b	−0.3735	0.0198	−18.8636	<0.0001	
Q. spp.	a	9.1102	0.4485	20.3126	<0.0001	0.19
	b	−0.4497	0.0142	−31.6690	<0.0001	

Table 3: parameter estimates and statistics for GAM of SG

Tree species	Parameter	Estimate	Std Error	*t*-value	Pr > |*t*|
P. densiflora	Intercept	1.79708	0.12106	14.85	<0.0001
	TWI	0.02079	0.00614	3.39	0.0007
	TEM	−0.03761	0.01139	−3.30	0.0010
	PRE	0.00047329	0.00009496	4.98	<0.0001
Q. spp.	Intercept	1.36310	0.09965	13.68	<0.0001
	TWI	0.01529	0.00544	2.81	0.0050
	TEM	0.02314	0.00513	4.51	<0.0001
	PRE	0.00025474	0.00008395	3.03	0.0024

used to predict radial and SG of *P. densiflora* and *Q.* spp. at the individual tree level.

Spatial autocorrelation

Fig. 2 shows the variograms of SG for *P. densiflora* and *Q.* spp. In ranges of ~40 km, *P. densiflora* and *Q.* spp. showed spatial autocorrelation. This meant that each species could exhibit variation in radial growth due to climatic factors within a 40-km range. Therefore, SG could be explained by regional variables such as topography and climate.

SG with GAM

Table 3 explains the statistical performance of the GAM analysis for the relationship between SG and TWI, temperature and precipitation. The GAM model showed relatively good statistical performance in terms of the significance level of the coefficients. The coefficient of temperature for *P. densiflora* is negative and that for *Q.* spp. is positive. The negative and positive coefficients for TEM at *P. densiflora* and *Q.* spp., respectively, can be explained by the distribution of SG for them in terms of WI in South Korea (Fig. 3). In Fig. 3a, SG according to WI increment begins to decreases in the range >85°C of WI for *P. densiflora* when all dataset used to develop GAM. Moreover, the area >85°C of WI is approximately 78% when seeing the distribution area of WI in the whole of South Korea. Therefore, the coefficient of TEM for *P. densiflora* must be negative, since most of *P. densiflora* are distributed in the area where their SG decreases from 85°C of WI in both the present and future. Therefore, we used temperature data only >85°C of WI for fitting GAM, so that the coefficient for TEM could be estimated significantly for *P. densiflora*. In the case of *Q.* spp, SG increases in the total WI range of both the present and future (Fig. 3a) when compared with *P. densiflora*. Therefore, the coefficient for TEM of *Q.* spp. must be always positive.

Results of GAM analysis implied that growth of both tree species was positively affected by precipitation. This result is similar to findings of previous studies (Lee *et al.* 2009; Shin 2006; Tessier *et al.* 1995). On the other hand, the temperature increment had a negative effect on growth of *P. densiflora* and a positive effect on growth of *Q.* spp. This is attributed to the fact that high temperatures with low precipitation would induce water stress that would limit radial growth in *P. densiflora* (Lee *et al.* 2009).

According to the distribution of eSG (Fig. 4), TWI, temperature and precipitation could not fully explain SG. In general, the radial growth of individual trees is affected by age, DBH and height, tree density and site quality (Fritts 1976; Tappeiner *et al.* 1997). In this study, radial growth was also affected by age, density and site quality. This is attributed to the fact that Δr in Equation 4 already included the influence of tree density and site quality when estimated with the previous year's growth. On the other hand, climatic

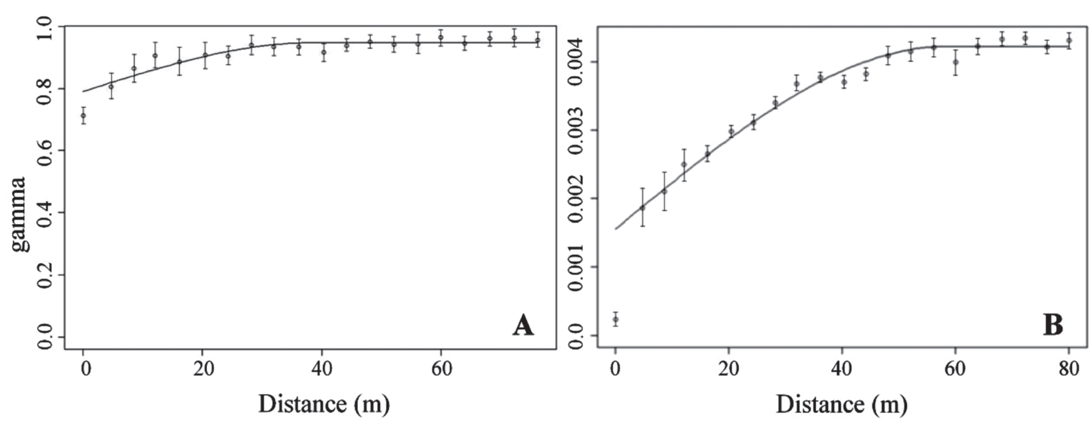
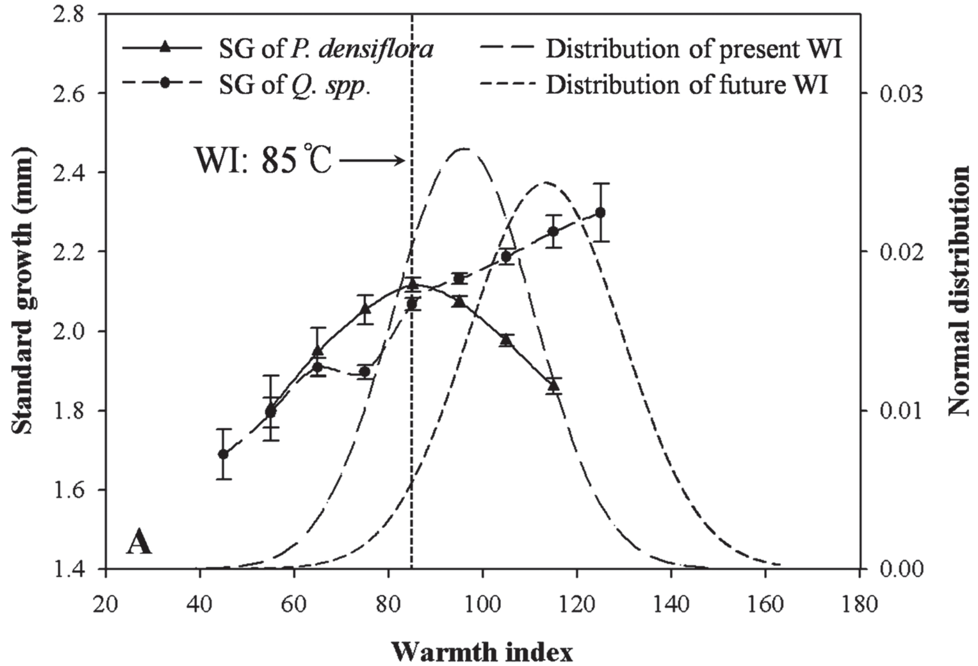


Figure 2: variogram with standard deviation of standard growth for (A) *P. densiflora* and (B) *Q.* spp.



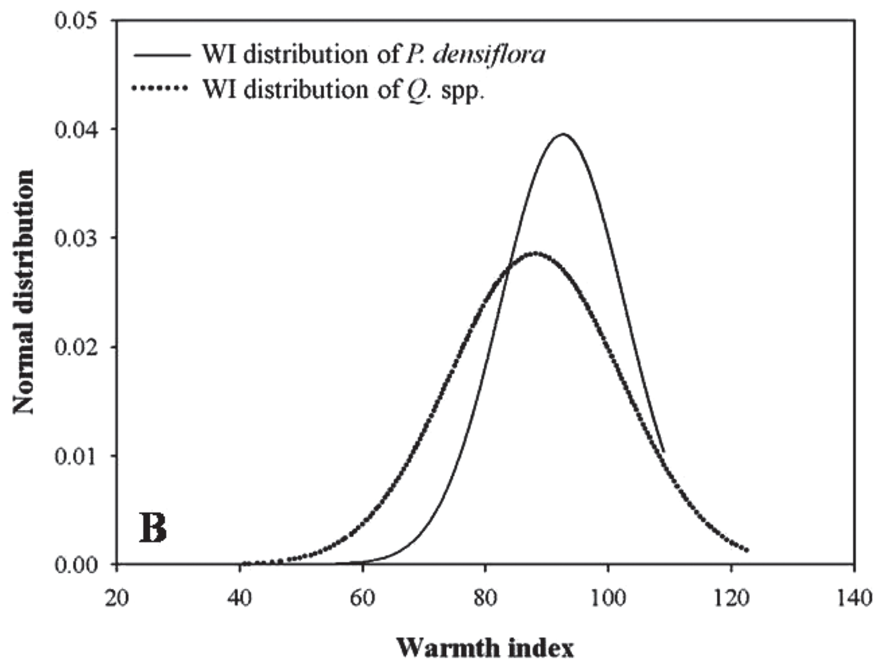


Figure 3: (A) distribution of SG according to WI and of WI range in the present (1997–2006) and future (2047–2056) for *P. densiflora* and *Q.* spp. and (B) the WI range for *P. densiflora* and *Q.* spp. in the present.

factors used in this study explained annual variation in estimated standard radial growth under the same conditions of tree age, size, density and site quality. This approach is considered efficacious for analysing the impact of climatic and topographic factors on tree growth under a given set of conditions. However, this study is limited in that the number of independent variables to explain tree growth is too small. Therefore, future studies that incorporate more variables are required to improve model accuracy in explaining tree growth.

Integration of radial growth with SG

By using the eSG, the meSG and radial growth during the past five years could be estimated with good statistical performance

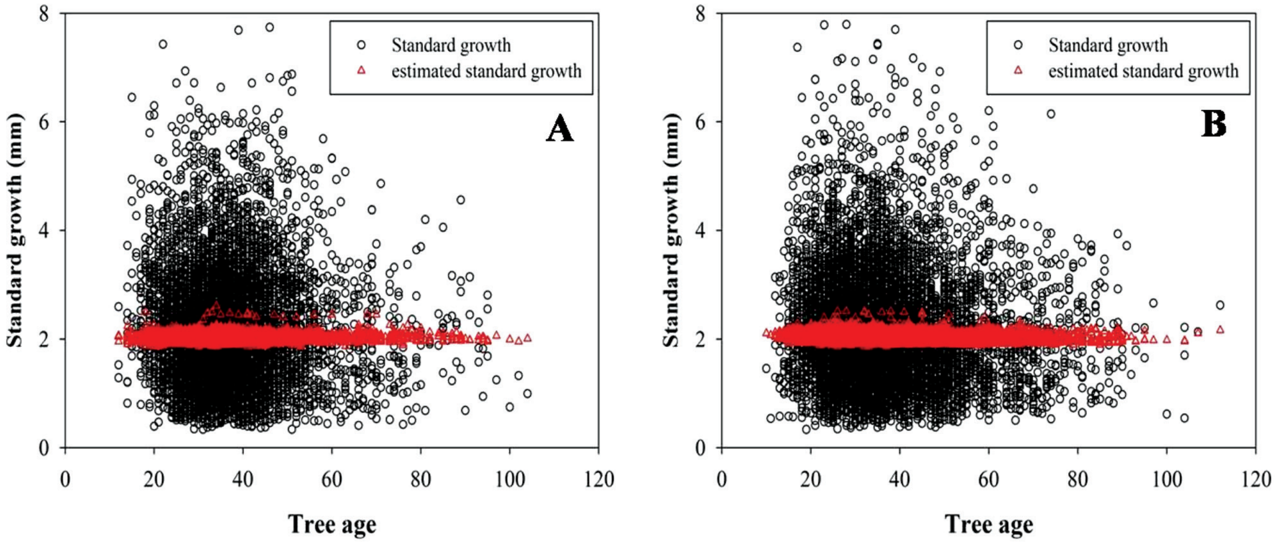


Figure 4: SG and eSG using GAM of (A) *P. densiflora* and (B) *Q.* spp.

(Table 4). When the accuracies were compared, the model that included climatic factors showed better performance than the growth model that excluded climatic factors. Therefore, the radial growth model developed with climatic parameters can be used to explain growth under a given climate. When the accuracy assessment was performed, there was no significant difference between the growth models. However, the lack of significant differences according to precipitation, temperature and TWI indicates that non-climatic parameters such as size, density, competition and site quality influence forest growth.

Furthermore, it was demonstrated that the radial growth model using the independent variable of age and normalized SG including TWI, temperature and precipitation can be used to estimate radial growth with annual variation in climatic conditions (Fig. 5).

Sensitivity

Temperature and precipitation are predicted to increase in the future (2047–2056) under the IPCC A1B scenario. The mean temperature is predicted to change from 11.36 ± 2.13 ºC in the present to 12.30 ± 2.10 ºC in the future; mean annual precipitation is predicted to increase from 1164±167.73 mm to 1253±135.48 mm in the future. The results of the GAM analysis with eSG (Table 2) imply that radial growth of

Table 4: statistics on assessment of radial growth model

	$\Delta \hat{r}_i = \Delta \hat{r}_{i-5} \cdot \left(\frac{\mathrm{age}_i}{\mathrm{age}_{i-5}}\right)^b$		$\Delta \hat{r}_{ie} = \Delta \hat{r}_{i-5} \cdot \left(\frac{\mathrm{age}_i}{\mathrm{age}_{i-5}}\right)^b \cdot \frac{\mathrm{eSG}}{\mathrm{meSG}}$	
Species	RMSE	R^2	RMSE	R^2
P. densiflora	0.9782	0.61	0.9317	0.69
Q. spp	1.0623	0.54	1.0442	0.57

P. densiflora would be more vulnerable to rising temperature than would that of *Q.* spp. Different impacts of temperature on tree growth between the two species may lead to significantly different radial growth patterns in the present and future. Therefore, we predicted change in annual radial growth of the two species with the eSG model under the A1B scenario (IPCC 2007). The model results predicted that increased precipitation would have a positive effect on radial growth whereas rising temperature would have a negative effect on growth.

According to the climate change scenario, *Q.* spp. is expected to have greater abundance than its present status in South Korea (Fig. 6b). *Q.* spp. are climax species in South Korea (Lee *et al.* 2007b) and are expected occupy the largest proportion of forest area in the future under a scenario of rising temperature (Choi *et al.* 2011). As shown in Fig. 6a, the radial growth of *P. densiflora* in most of South Korea, except for northern and high mountainous areas, was expected to decrease compared to its current status. Significant declines in radial growth were predicted in western coastal area and south-eastern inland areas in particular. This is attributed to a high sensitivity to reduced precipitation and increased temperature. It is therefore predicted that, due to climate change, *P. densiflora* will gradually lose its current habitat and diminish to northern mountainous regions in the future.

Fig. 7 shows the differences of eSG between *P. densiflora* and *Q.* spp. When the eSG model was simulated using current data, the growth of *P. densiflora* in high mountainous areas was higher than that of *Q.* spp. whereas the growth of *Q.* spp. was higher than growth of *P. densiflora* in low elevation areas. In Fig. 3a, SG of *P. densiflora* had the negative relationship to temperature, and SG of *Q.* spp. positive to temperature. Additionally, WI range of *Q.* spp. habitats is wider than that of *P. densiflora* in Fig. 3b. Such results support that the growth

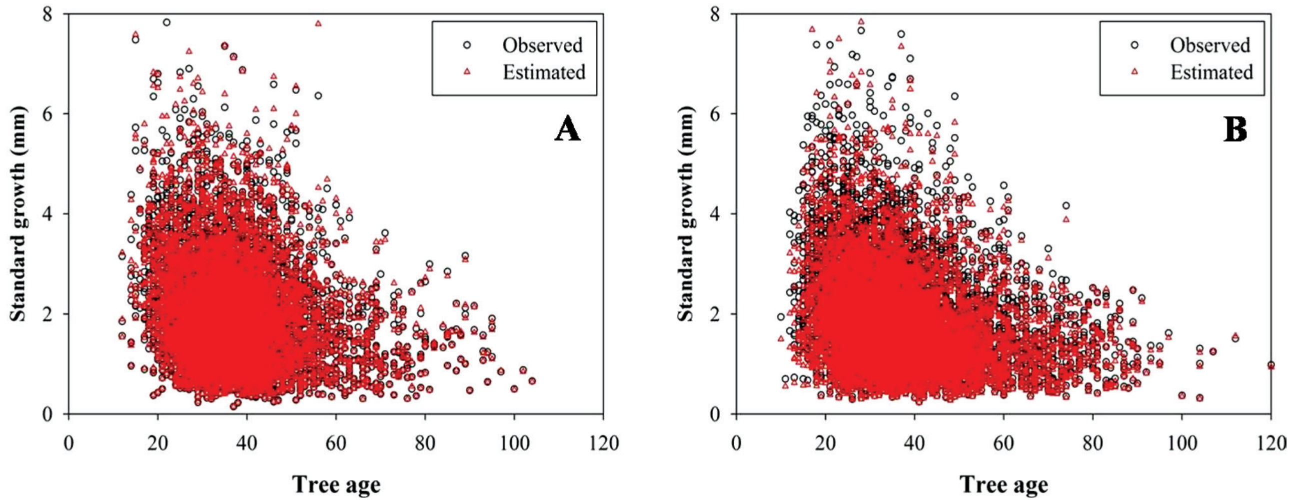


Figure 5: clouds of observed and estimated radial growth for (A) *P. densiflora* and (B) *Q.* spp.

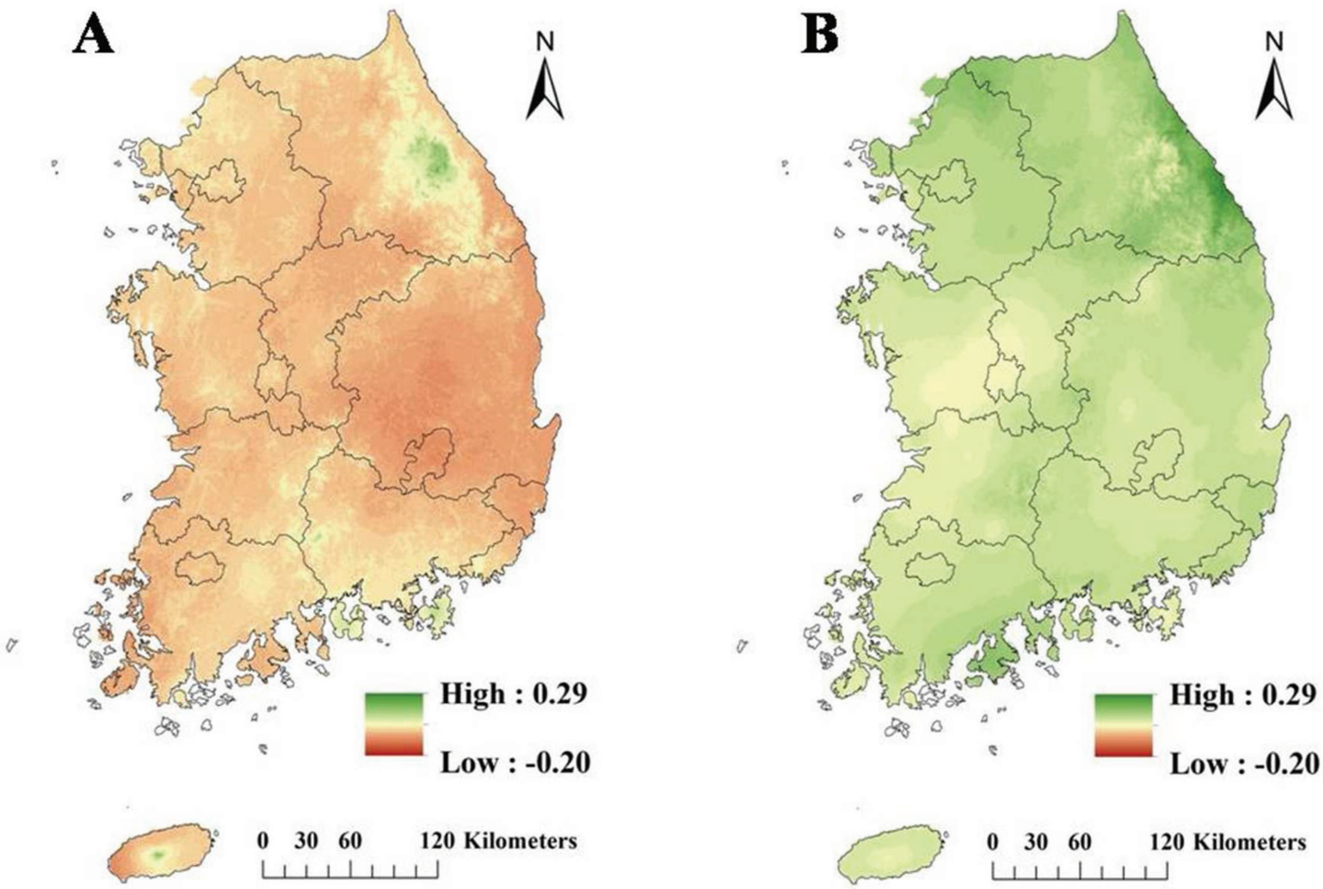


Figure 6: the distribution of sensitivity-species of (A) *P. densiflora* and (B) *Q.* spp. estimated by equation 8.

of *Q.* spp. can be encouraged in most area in South Korea as models by Choi *et al.* (2011) and Yim (1977). Therefore, the distribution of *P. densiflora* may be limited to high elevated area due to narrow-ranged WI, while the *Q.* spp. will be distributed all over low elevated area.

The characteristics of radial growth in the present and future represented that the sensitivity of *P. densiflora* was higher than *Q.* spp. (Fig. 7). Therefore, *P. densiflora* in South Korea may be gradually replaced by *Q.* spp. due to the temperature rising in the future because high sensitivity

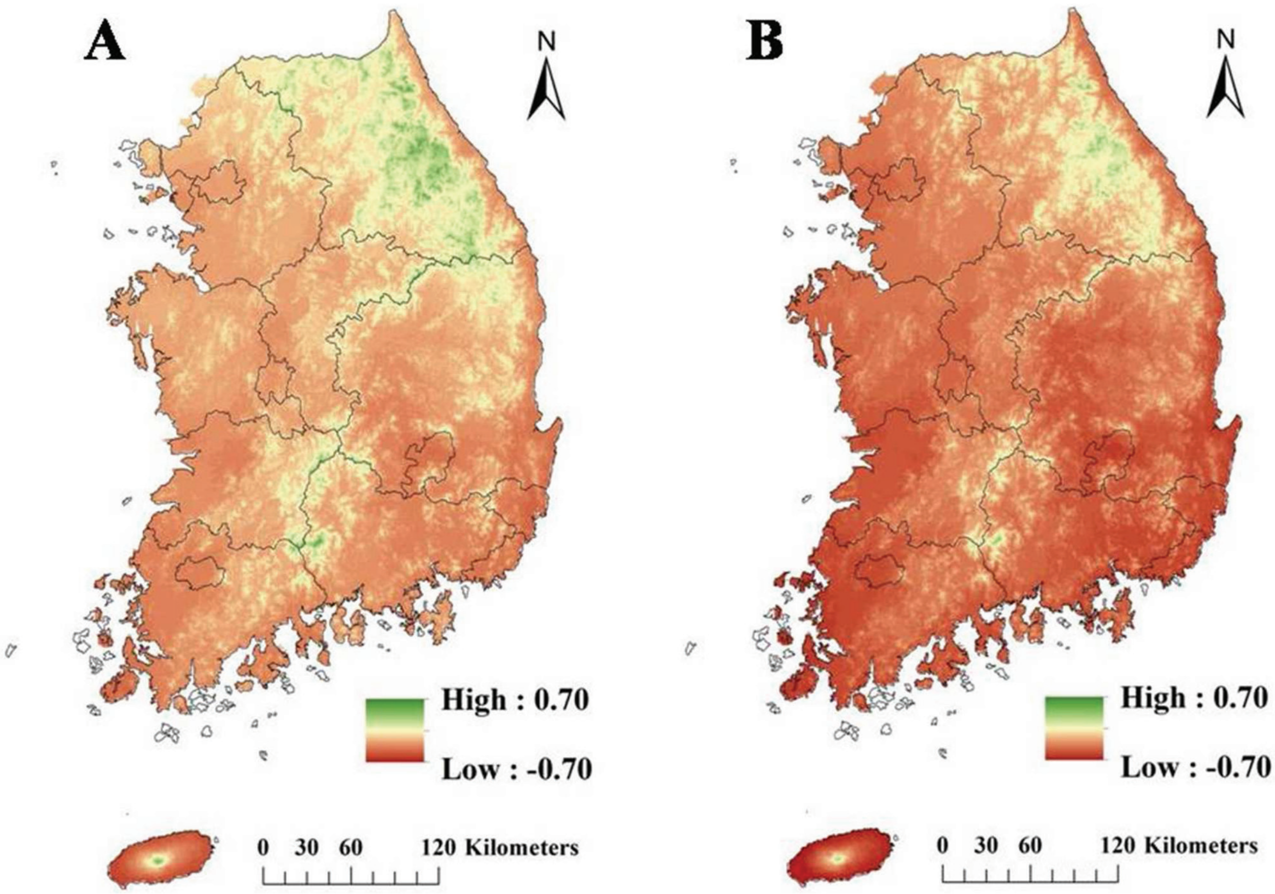


Figure 7: the distribution of sensitivity-relative in (A) the present and (B) the future estimated by equation 9.

accompanies the high probability of such change. Even if these results are preliminary, they suggest it would be useful to prepare adequate forest adaptation plans in response to climate change.

CONCLUSIONS

The objective of this study was to develop radial growth models for *P. densiflora* and *Q.* spp. and to predict the possibility of changes in forest type using tree-ring estimates prepared with NFI data, and future climatic data from the IPCC. We developed the standard radial growth model, for which standard radial growth is defined as radial growth at age 30, and analysed the relationship between standard radial growth and TWI, temperature and precipitation by GAM. Our results showed that rising temperature had a negative impact on the radial growth of *P. densiflora* and a positive influence on that of *Q.* spp. On the other hand, predicted increases in precipitation had a positive impact on radial growth of both tree species. Therefore, *P. densiflora* would be more sensitive than *Q.* spp. to climate change, and habitats currently occupied by *P. densiflora* may be gradually changed into *Q.* spp. forests in eastern coastal and southern parts of South Korea. *P. densiflora* may potentially be replaced by *Q.* spp. in the majority of South Korean forest, except for northern and high mountainous areas.

Quantification of the relationships between tree growth and climate has been conducted by various researchers in plant science. However, the results of these studies differ according to tree species, topography, climate and methodologies; the relationship between tree growth and climate cannot be explained by a limited number of investigations, including this study. Therefore, research on this topic should proceed employing a variety of tree species and environmental factors in other regions. Nevertheless, the findings and predictions presented in this study will be helpful for understanding the impact of climatic factors on tree growth and for predicting future changes in distribution of dominant tree species under climate change.

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