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DBH growth model for *Pinus densiflora* and *Quercus variabilis* mixed forests in central Korea

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Abstract

This study presents an individual tree diameter at breast height (dbh) growth model for mixed *Pinus densiflora* (Red pine) and *Quercus variabilis* (Oak) uneven-aged stands in central region of Korean peninsula. The different model components, including the effects of tree age, tree size, competition and growing site are evaluated for both Red pine and Oak. The aim is to understand and model the individual growth patterns of the two species. Based on sensitivity analysis of radial growth using a variety of combinations of independent variables, the conclusion could be reached that the size and aspect components have a positive effect on radial growth, while the other variables such as age, competition index, elevation, and slope have a negative influence. All model component effects, except the effect of elevation, are greater in pine than in Oak, indicating that Red pine is relatively less suppressed than Oak in the study area. Among the topographic variables, slope appears to be an important critical factor for Red pine. For Oak, elevation is the primary critical factor and other variables have no great effect. These interrelationships between radial growth and the age, size, competition, and site variables correspond quite well with ecological expectations and silvicultural experience of the two species in Korea.

Keywords: Individual tree; dbh growth model; Mixed stand; Uneven-aged stand; *Pinus densiflora*; *Quercus variabilis*

1. Introduction

Pinus densiflora (Red pine) is one of the most important tree species in Korea, both in terms of high-value wood products and cultural significance. Red pine stands, either planted or naturally regenerated after clear cutting, cover about 27% of the total forest area in South Korea (Forest Administration of Korea, 1999). The majority of these forests are even-aged and intensively managed. However, irregular forest structures resulting from non-intensive management or various biotic and abiotic damages are increasingly found.

Among the native tree species found in South Korea, Oaks are rather prominent. Most of the Oak stands, occupying about 26% of the total forest area in South Korea, originated through natural regeneration, especially from sprouting and their growth rates are comparable with Red pine. Various Oak species may occur in the understory of Red pine stands, despite efforts to

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remove them. Left to grow, the Oak will compete with the Red pine and eventually will become the dominant species.

The management of mixed stands of Red pine and Oak is of increasing importance to foresters in South Korea and a crucial factor for sound management of these stands is the knowledge of the growth at individual tree level, of the different species. Stand level growth models using population mean values have proved useful for managing even-aged pure stands. Such models have already been developed and are widely used in South Korea (Kim, 1963; Kim and Lee, 1970; Lee, 1971; Yoo and Noh, 1987; Yoo et al., 1986). But they are of limited use in mixed uneven-aged forests, where species and sizes of individual trees are very diverse. The required individual tree growth models are not yet available in South Korea, except for two single-tree diameter growth models for even-aged and monospecies stands of *P. densiflora* (Lee, 1996; Lee and Gadow, 1997) and *Pinus koraiensis* (Lee et al., 1999). Analyzing the growth of mixed stands requires a modeling approach that relates the growth of individual trees to the resources available to them and thus the required models simulate each individual tree as a basic unit and sum the resulting estimates to produce stand-level values (Vanclay, 1994; Gadow and Hui, 1999; Bartelink, 2000; Porté and Bartelink, 2002).

This study presents an individual tree diameter at breast height (dbh) growth model for mixed Red pine and Oak stands in central region of Korean peninsula. The different model components, including the effects of tree age, tree size, competition and growing site are evaluated for both Red pine and Oak, in order to give clear understanding about individual dbh growth patterns of the two tree species.

2. Materials

Individual tree growth models can be developed using data either from "permanent" sample plots observed over long time periods (Monserud and Sterba, 1996), from temporary sample plots complemented with increment cores (Wykoff, 1990) or from short-term "interval plots" which represent a compromise between the two, producing one growth rate for a large number of initial states within a reasonably short period of time (Gadow et al., 1998). Because of the lack of data from either permanent plots or interval plots, this study is based on observations from temporary sample plots complemented with tree ring measurements from increment cores.

The data were collected from mixed stands of *P. densiflora* (Red pine) and *Quercus variabilis* (Oak) in central region of Korean peninsula. Sixty-eight temporary sample plots covering between 0.01 and 0.02 ha were installed in Red pine and Oak mixed stands which had remained untouched during at least 10 years preceding the measurements. The diameters outside bark at breast height and the heights of all trees were

Table 1
Description of the variables used in the diameter growth model

Variables	*Pinus densiflora* (181 trees)				*Quercus variabilis* (190 trees)			
	Mean	Minimum	Maximum	S.D.	Mean	Minimum	Maximum	S.D.
Age (years)	59	20	84	12	44	16	75	16
dbh (cm)	29.5	10.7	52.0	9.1	20.5	5.2	40.6	6.4
Height (m)	13.2	6.0	23.6	3.5	13.3	6.9	23.1	3.1
CINo	5.8	1.0	12.0	2.0	5.7	1.0	10.0	1.9
HgCI	1.68	0.17	7.55	1.12	2.14	0.41	12.08	1.66
PAI (cm)	0.123	0.021	0.736	0.088	0.192	0.040	0.508	0.100
Ao (years)	58	18	69	11	41	18	65	15
Ho (m)	15.9	10.7	22.4	3.3	16.2	10.6	22.6	3.2
Aspect (°)	226	0	351	94	226	0	351	94
Aspect index	0.95	0.00	2.00	0.66	0.95	0.00	2.00	0.66
Elevation (m)	434	250	590	107	434	250	590	107
Slope (°)	32.9	17.0	48.0	4.2	32.9	17.0	48.0	4.2

CINo: number of competitor trees, HgCI: Hegyi's competition index, PAI: periodic annual increment of tree radius, Ao: dominant stand age, Ho: dominant stand height. Aspect index $= 2 \times |1 - \text{aspect}/180|$.

measured in each sample plot. The tree coordinates were established by measuring distance and azimuth from the plot center to individual trees. The plots were selected to cover a large range of ages, tree sizes, and competition situations. Between two and six sample trees were randomly selected for each tree species in each plot. A total of 181 Red pine and 190 Oak sample trees were available. Increment cores were taken from sample trees and tree rings were measured to 1/100 mm using the tree ring measurement system Johann Type II.

To avoid the problem of measurement errors of annual tree ring widths, the periodic annual increment of the preceding 5 years was used in the analysis as the annual radial increment (Δr). Tree age was defined as the number of tree rings at breast height plus 5. Basic statistics for the dataset are given in Table 1.

3. Method

3.1. Model component

Vegetation simulators such as PROGNOSIS (Stage, 1973; Wykoff et al., 1982), STEMS (Belcher et al., 1979) or TWIGS (Miner et al., 1989), developed in North America and similar distance independent tree models, such as BWIN (Nagel, 1999) and PROGNAUS (Monserud and Sterba, 1996; Hasenauer, 2000) which are used in Europe, usually depict individual tree growth as a function of initial tree size, competition, and site characteristics (Sterba et al., 2002).

This paper presents a first attempt to individual tree growth modeling in Korea, using a similar, albeit more comprehensive approach. We assume that the annual radial growth of a tree depends on tree age, tree size, competition, and site quality at stand level (Eq. (1)):

$$growth = f(age, size, competition, site) \quad (1)$$

In general, individual tree growth has been modeled using either basal area (Wykoff, 1990; Quicke et al., 1994; Monserud and Sterba, 1996; Jõgiste, 2000; Rose and Lynch, 2001) or diameter increment (Pukkala, 1989; Lee, 1996; Lee et al., 1999; Gourlet-Fleury and Houllier, 2000; Rautiainen et al., 2000). West (1980) concluded that no a priori reason exists for expressing growth as diameter increment or basal area increment. In this analysis, annual radial increment at breast height (Δr) was selected as the dependent variable for the diameter growth model.

Tree age is an important influencing variable on radial growth, but it is simply not available in practice. In some models, tree age was not included (Pukkala, 1989; Wykoff, 1990; Hasenauer and Monserud, 1996; Monserud and Sterba, 1996; Gourlet-Fleury and Houllier, 2000). We also attempted to exclude tree age to make the model more practical. But models without age variables show poor statistical performance in our analysis. Thus, we include the tree age as an independent variable.

Tree size can be described by a variety of attributes, such as breast height diameter, total height or crown length. Crown variables are not included because their assessment in the field is expensive. Initially, the use of height as a size component was explored, but the final model did not include height as the size variable, because one of the size variables (dbh or height) was not significant and the model fit could not be improved as much as expected.

A competition component, assuming values in the interval [0, 1], is used as an influencing factor on radial growth. We apply Hegyi's competition index (HgCI in Eq. (2)) which is calculated from dbh ratio and distance between subject tree and competitor trees (Hegyi, 1974). HgCI does not require any information of tree height and crown, and can be used in many situations where information about tree height and crown is not available. In this study, the competitors were selected using the iterative search method developed by Lee and Gadow (1997) which differentiates between active competitors facing the reference tree and passive competitors which are positioned behind an active competitor when viewed from the subject tree.

In even-aged forests, the effect of site quality on tree growth is generally accounted for by using site index which is derived from stand age and dominant height (e.g. Schroeder, 2000). Sometimes, stand age and dominant height are incorporated for indirectly considering the effect of site quality on tree growth (Lee, 1996; Lee et al., 1999). A simple and unique index for site quality in uneven-aged and mixed stand is generally not available. In this paper we distinguish between (1) a site quality-independent model and (2) a site quality-dependent model. For the site quality-dependent model, the dominant height and age were included in the model as independent variables for representing site index. An alternative approach is to directly include specific attributes of the growing site (Wykoff, 1990; Hasenauer and Monserud, 1996; Monserud and Sterba, 1996; Sterba et al., 2002). Wykoff (1990) used aspect, slope, elevation, habitat type and geographic location as indicators of site quality for mixed species stands. Hasenauer and Monserud (1996), Monserud and Sterba (1996), and Sterba et al. (2002) incorporated also elevation, slope and aspects into the individual tree growth model for mixed stands. We also introduce topographic variables, such as an aspect index (calculated by $2 \times |1 - \text{aspect}/180|$), elevation, and slope which represent site attributes that are relevant for the specific conditions in Korea.

3.2. Radial and diameter growth model

A range of models with exponential and power functions was evaluated, using a variety of combinations of independent variables. Different functions were fitted to the datasets and statistical performance and biological consistency considered. The resulting system of diameter growth models was then classified according to whether tree height and site quality are included or not, as follows:

11	Tree height-independent and site quality-independent model
121	Tree height-independent and site quality-dependent model with dominant height and age
122	Tree height-independent and site quality-dependent model with topographic index

As a result of the above considerations, the following general radial increment model was selected.

$$\Delta r_{t,j} = a_0 A_{t,j}^{a_1} D_{t,j}^{a_2}\, \mathrm{e}^{b\mathrm{HgCI}_{t,j}^{0.5}}\, \mathrm{SQ}_t \tag{2}$$

where $\Delta r_{t,j}$ is annual radial increment at breast height of tree j at time t (cm); $A_{t,j}$ is tree age (years); $D_{t,j}$ is tree diameter at breast height (cm); $\mathrm{HgCI}_{t,j}$ is Hegyi's competition index of tree j at time t

$$\mathrm{HgCI}_i = \sum_{i=1}^{n} \frac{d_j/d_i}{\mathrm{Dist}_{ij}}$$

d_i is diameter at breast height of reference tree (cm); d_j is diameter at breast height of competitor tree (cm); Dist_{ij} is distance between reference tree and competitor tree (m); SQ_t is stand level site quality, $\mathrm{SQ}_t = \mathrm{Ao}_t^{c_1}\mathrm{Ho}_t^{c_2}$ for SQ-dependent model with growth factors (121); Ho is stand dominant height (mean height of 3–5 highest trees; m); Ao is stand dominant age (mean age of 3–5 highest trees; years); $\mathrm{SQ}_t = \mathrm{e}^{c_1\mathrm{AI}_t^{0.5}+c_2\mathrm{EL}_t^{0.5}+c_3\mathrm{SL}_t^{0.5}}$ for SQ-dependent model with topographic factors (122); AI is aspect index: $\mathrm{AI} = 2\times |1 - \text{aspect}/180|$ with values ranging from 0 (south) to 2 (north); EL is elevation (m); SL is slope (°).

Diameter growth is directly derived from radial increment. The tree diameter after n years ($D_{t+n,j}$) can be estimated from the current diameter ($D_{t,j}$) and the n-year periodic radial increment which is calculated as the sum of twice the annual radial increment predicted from age, dbh, competition index, and site quality, as follows:

$$D_{t+n,j} = D_{t,j} + 2\sum_{k=t}^{t+n-1} \Delta r_{k,j} \tag{3}$$

3.3. Model fitting and statistical analysis

The entire model was fitted directly to the dataset and all parameters of Eq. (2) were simultaneously estimated using the SAS NLIN procedure (SAS Institute, 1998). To ensure the statistical reliability of the parameter estimates, different variable combinations were tested and the statistical performance of the model was evaluated.

4. Results and discussion

In this section we present the statistical performance of the model, the plausibility of the effects of the independent variables, the plausibility of growth projections and applicability of the model.

4.1. Statistical performance of the models

The parameter estimates and related statistics are presented in Table 2. The models show relatively good performance in explaining the variation in radial growth, all with coefficient of determination (R^2) ranging from 0.60 to 0.69 for Oak and from 0.55 to 0.59 for Red pine, and with standard error of estimate (S.E.E.) ranging from 0.058 to 0.064 for Oak and from 0.059 to 0.060 for Red pine, respectively. The site quality-dependent models (121, 122)

Table 2
Parameter estimates and related statistics for radial growth model (Eq. (2))

Parameters	Models					
	Red pine			Oak		
	11	121	122	11	121	122
a_0	27.09*	19.41*	125.0 (ns)	5.242***	2.008*	6.948**
a_1	−1.6722***	−1.647***	−1.550***	−0.9419***	−0.5886***	−0.6508***
a_2	0.5295**	0.4569*	0.4808*	0.1969*	0.2208*	0.2645*
b	−0.3952***	−0.4238***	−0.3998**	−0.3389***	−0.2764***	−0.2545***
c_1		−0.08307 (ns)	0.1908 (ns)		−0.4039***	0.1456 (ns)
c_2		0.3052 (ns)	−0.04852*		0.3468**	−0.07737***
c_3			−0.1752**			−0.04724 (ns)
S.E.E.	0.05989	0.05992	0.05866	0.06377	0.06014	0.05774
R^2	0.55	0.55	0.57	0.60	0.65	0.68

ns: non-significant. S.E.E.: standard error of estimate.
* Significant at a level of 0.05.
** Significant at a level of 0.01.
*** Significant at a level of 0.001 or 0.0001.

show slightly better statistical performance than site quality-independent model (11). The model with topographic variables (122) shows the best statistical performance. Through adding site quality variables to the model, the Oak model was significantly improved in comparison to the Red pine model.

Because of differences in the data structure, the statistical performance of our model could not be directly compared with similar models from North America and Europe. We did find that the model results are reasonable and in agreement with local silvicultural experience in the specific ecological conditions in Korea. Regarding the biological and silvicultural plausibility, our results were compared with those of similar models focusing on approximately the same problems.

Parameters for age and competition were found to be all significant. All terms included in the site quality-independent model (11) were significant at a probability level of 0.05. However, the parameters of dominant age and height in the site quality-dependent model (121) are all significant in Oak, but not in Red pine. The site index problem in individual tree growth models is illustrated by Quicke et al. (1994) who pointed out that a site index term was not required once dbh and age were added to the model. Age and dbh seems to capture the influence of the site on individual tree growth quite well (Lemon and Schumacher, 1962; Cole and Stage, 1972). Wykoff and Monserud (1988) showed also that a diameter increment model using measured site index did not perform better than a model that used habitat type, location, slope, aspect, and elevation to represent site effects. Peng (2000) also insisted that site quality using site index, or dominant age and height, is questionable because of the initial suppression of the smaller trees. Therefore, the classical site index derived from mean age and dominant height and used in even-aged forest models is not applicable in uneven-aged multi-species forests. Our analysis of the model performance confirms this finding.

The parameters of the topographic variables in the site quality-dependent model (122) show similar performance in the two tree species. For Red pine, the parameters for elevation and slope were significant at a level of 0.01 or 0.05 but the parameter for the aspect index was found to be non-significant. For Oak, only the parameter for elevation was significant at a level of 0.0001 while the parameters for aspect index and slope were non-significant. This differs from the findings of Monserud and Sterba (1996) in which Oak growth was only affected by aspect.

4.2. Plausibility of effects of independent variables on diameter growth

To evaluate the plausibility of model performance, the sign of the parameters and the value of each component were examined (Fig. 1).

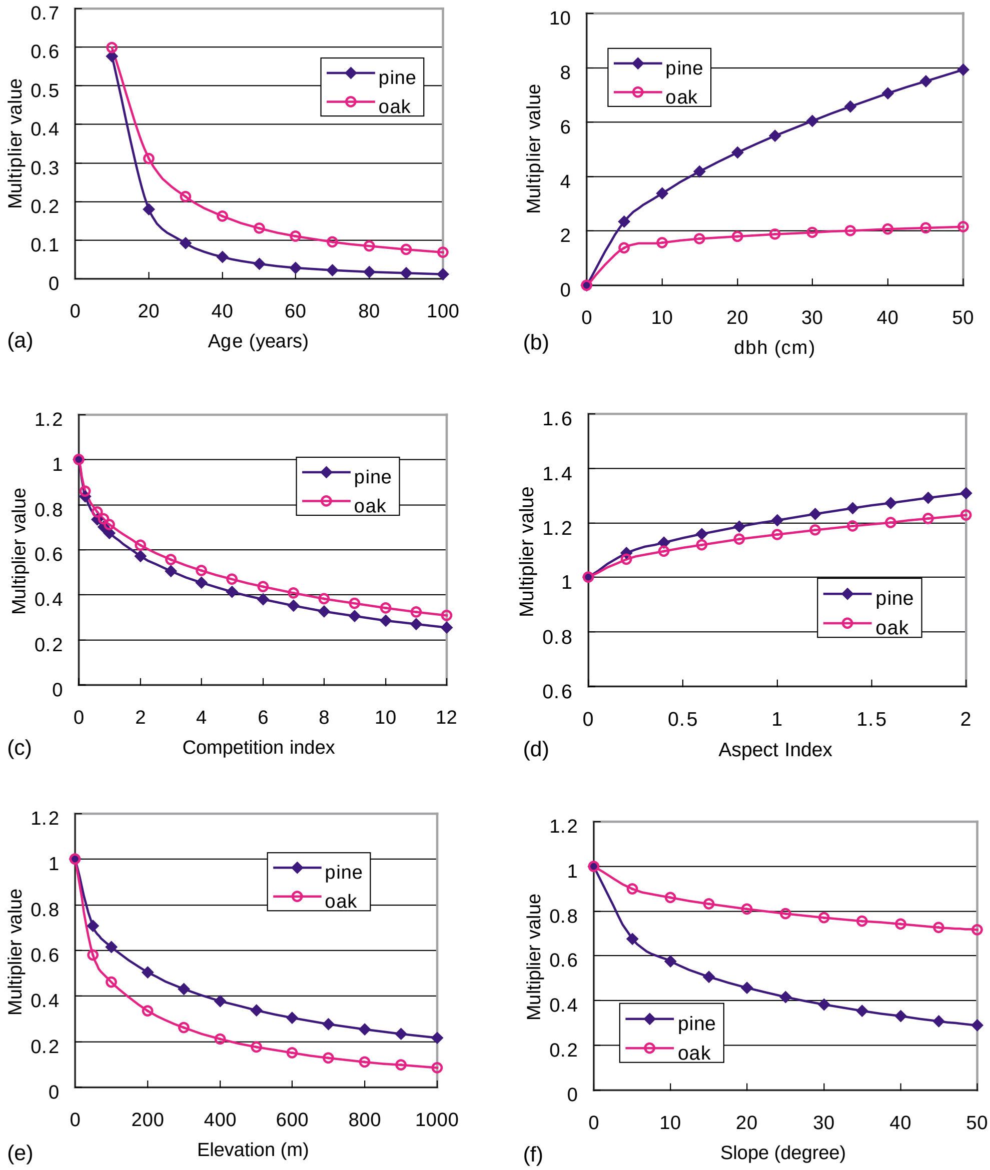

Fig. 1. Relationships between different variables and corresponding multiplier values.

4.2.1. *Tree age*

Similar as in other individual tree growth models (Quicke et al., 1994; Lee, 1996; Lee et al., 1999; Jõgiste, 2000), the coefficient for tree age is negative, indicating that annual radial growth decreases with increasing age, if other variables remain constant, which is consistent with general experience. This observation is valid for the observed range of tree ages (20 years for Red pine and 16 years for Oak). The rate of decrease is determined by the coefficients a_0 and a_1, and the effect of tree age on the radial growth is greater in Red pine than in Oak (Fig. 1a). This effect can be explained by the stand structure in the study area, where Oak is more suppressed than Red pine (see competition index in Table 1).

4.2.2. Tree size

The coefficient of the size component dbh is positive. Radial growth increases with increasing tree size, which confirms numerous other studies (Wykoff and Monserud, 1988; Wykoff, 1990; Quicke et al., 1994; Hasenauer and Monserud,0 1996; Monserud and Sterba, 1996; Lee, 1996; Jõgiste, 2000; Sterba et al., 2002). The positive effect of tree size on radial growth can be explained by the fact that size reflects the effects of past competition and/or vigor on tree growth.

The positive effect of current diameter on radial growth is greater in Red pine than in Oak (Fig. 1b). A possible explanation may be the assumption that Oak trees, which usually occur in the understory, would invest more in height growth than in diameter growth. While ages and diameters of Oak trees show low values, their heights are almost the same as those of Red pine (see Table 1).

4.2.3. Competition

As expected, all significant competition coefficients are negative, which is plausible because radial growth can be expected to decrease with increasing competition. The negative effect of competition on tree growth is confirmed by numerous other growth studies (Wykoff, 1990; Holmes and Reed, 1991; Quicke et al., 1994; Biging and Dobbertin, 1995; Hasenauer and Monserud, 1996; Lee, 1996; Monserud and Sterba, 1996; Jõgiste, 2000; Sterba et al., 2002) in which increment decrease with increasing competition. Fig. 1c shows the effect of the competition index (CI) on radial growth if all other independent variables remain constant. As the value of CI decreases, the value of CI component and radial growth increases. The value of CI component decreases more rapidly in Red pine than in Oak, indicating that Red pine is more sensitive than Oak to changes of CI. This effect may be explained by the extreme shade-intolerance which is characteristic of Red pine. Under a canopy of Red pine, Oak can grow, but Red pine can often hardly stay alive under a canopy of Oak.

4.2.4. Growing site

Site quality can be determined if the age and the height of the dominant trees are known. The negative coefficient of age and the positive coefficient of dominant height confirm the experience that height growth is superior on better sites. In our site quality-dependent model which includes the topographic index, the traditional site index (stand age and height relationship) was not used. We follow Monserud and Sterba (1996) who pointed out that, in individual tree models, the size variable dbh is a useful compound measure of age, site quality, and past competition.

Topographic factors could be useful for modeling site effects on tree growth in uneven-aged forests. The coefficient of the aspect index (AI) which increases from south to north, is positive. This means that north facing slopes are more favorable for tree growth. Similar results were reported by Monserud and Sterba (1996). Their aspect coefficient was significant and tree growth improved from south to north. For the same aspect index, the AI multiplier of Red pine is greater than that of Oak (Fig. 1d). Thus, radial growth of Red pine is more affected by aspect than that of Oak. Regarding the aspect effect, water availability plays an important role. Chung et al. (1998) reported that the water potential is greater in Oak than in Red pine. Red pine with a relatively lower water potential may be more sensitive to changes in water availability.

The coefficients of slope and elevation are negative, and trees are considered to grow better in lower and flatter areas. Monserud and Sterba (1996) reported similar results for Spruce, Scots pine, and Stone pine. The effect of elevation was quadratic, with growth first increasing and then decreasing as elevation increased. For Larch and Beech the elevation effect was negatively linear, with growth decreasing with increasing elevation. However, Hasenauer and Monserud (1996) reported an insignificant influence of site factors on the growth of Stone pine and Oak in Austria. The elevation multiplier of Oak in Korea is lower than that of Red pine (Fig. 1e) reflecting a greater sensitivity of Oak radial growth to increasing elevation than of Red pine. This coincides with the observation that appearance and growth of Red pine is less dependent on elevation (Forest Research Institute, 1999).

Radial increment decreases with increasing slope, which confirms the findings of Monserud and Sterba (1996). In Korea, Red pine appears to be more sensitive to slope change than Oak (Fig. 1f). The difference in the decrease in radial growth with increasing slope can be attributed also to the water potential which is greater in Oak than in Red pine. The steeper and drier slopes are not favorable for Red pine which has a lower water potential.

A direct comparison with other growth models for Red pine and Oak mixed stands was not possible, because our analysis represents the first attempt to model the dynamics of a multi-species forest in Korea. The dataset is unique concerning the particular species and ecological conditions found in Korea. The comparison of each model component with those of other individual tree growth models in other countries does not reveal any implausible contradiction. The effects of the different model components are found to be reasonable and consistent.

4.3. Plausibility of growth projection

4.3.1. Maximum diameter growth

Similar to the approach followed by Quicke et al. (1994), there is no predefined potential growth function imposed on the model. Maximum dbh growth can be determined from the interaction between age and dbh of individual trees, while the CI multiplier is equal to 1. To estimate the maximum dbh growth of a free-growing tree, the competition index was set to zero. dbh development was then predicted for the biggest trees in each age class. The predicted maximum dbh growth curves are above the observed growth values (Fig. 2).

4.3.2. Interaction effects of independent variables

Three dimensional graphs are useful for evaluating the combined effects of two independent variables (McFadden and Oliver, 1988; Quicke et al., 1994; Jõgiste, 2000). This is illustrated in Fig. 3 for age and size, using model 11. The competition index was held constant at a value of 1.5.

Radial growth decreases, as tree age increases and, for a given age, radial growth increases, as dbh increases. The size effect is greater at lower tree ages. The negative effect of tree age and the positive effect of tree size is greater in Red pine than in Oak.

Using model 122, annual radial growth was simulated for different aspects and slopes (Fig. 4) while other variables were held constant: competition index at 1.5, tree age at 30 years, dbh at 20 cm, and elevation at 300 m.

There are no great differences in radial growth for different aspects, however the slope effect is considerable. While, no differences in slope effect on radial growth are observed in Oak, radial growth decreases considerably with increasing slope in Red pine. The slope effect in Red pine is greater at northerly aspects (high values of AI).

Annual radial growth for different combinations of elevation and slope was simulated using model 122 (Fig. 5) while the other variables were held constant: competition index at a value of 1.5, tree age at 30 years, dbh at 20 cm, and aspect index at 1.

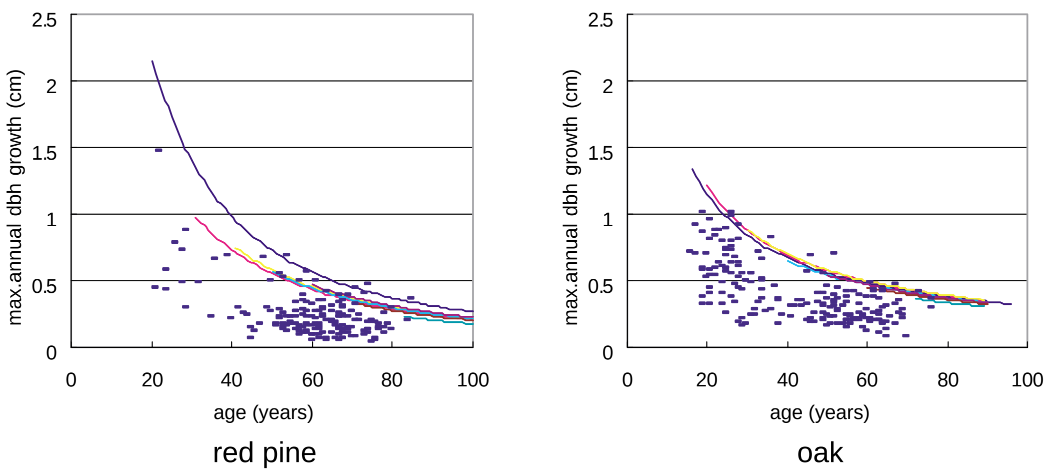

Fig. 2. Potential diameter growth with maximum dbh and minimum age for each 20-year age class, and observed dbh growth.

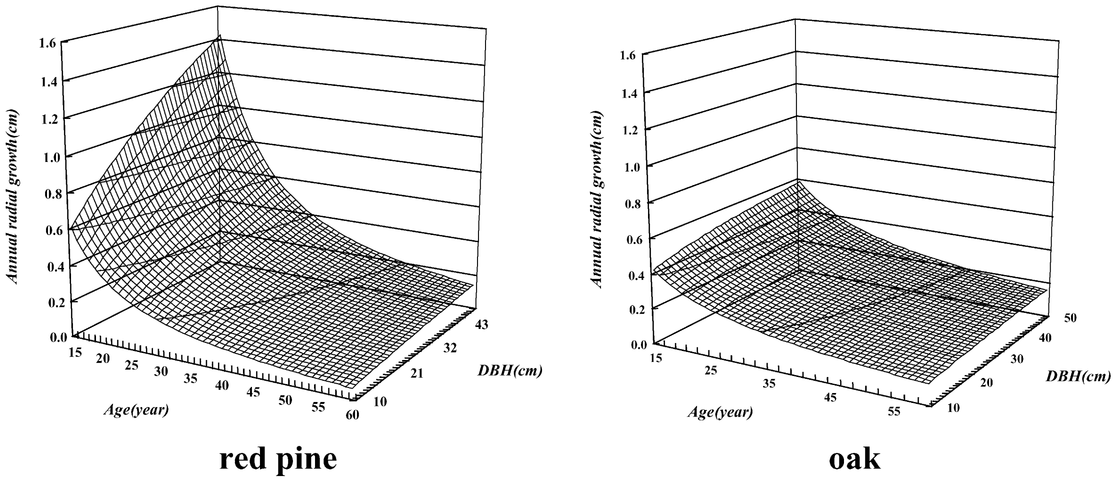

Fig. 3. Annual radial growth for different ages and diameters for Red pine and Oak, predicted using model 11. CI was held constant at a value of 1.5.

Radial growth of Red pine was found to be as a whole higher than that of Oak, except at lower elevations and steeper slopes. The decreasing rate of radial growth with increasing elevation is greater in Oak than in Red pine. At a given elevation, the radial growth of Red pine improves greatly with decreasing slope, while there is no slope effect in Oak. Among the topographic variables, slope appears to be an important critical factor for Red pine. For Oak, elevation is the primary critical factor and other variables have no great effect.

Using model 11, annual dbh growth was predicted for different combinations of tree age and competition index. The results are shown in Fig. 6. In the prediction, the variable d12 was held constant at a value of 15 cm. The age effect is greater at lower CI values while the CI effect is greater at younger ages. Age and CI effects are greater in Red pine than in Oak.

The annual dbh growth was also predicted for different combinations of competition index and dbh, with a constant tree age of 30 years. The results show that the dbh effect is great at lower CI values while the

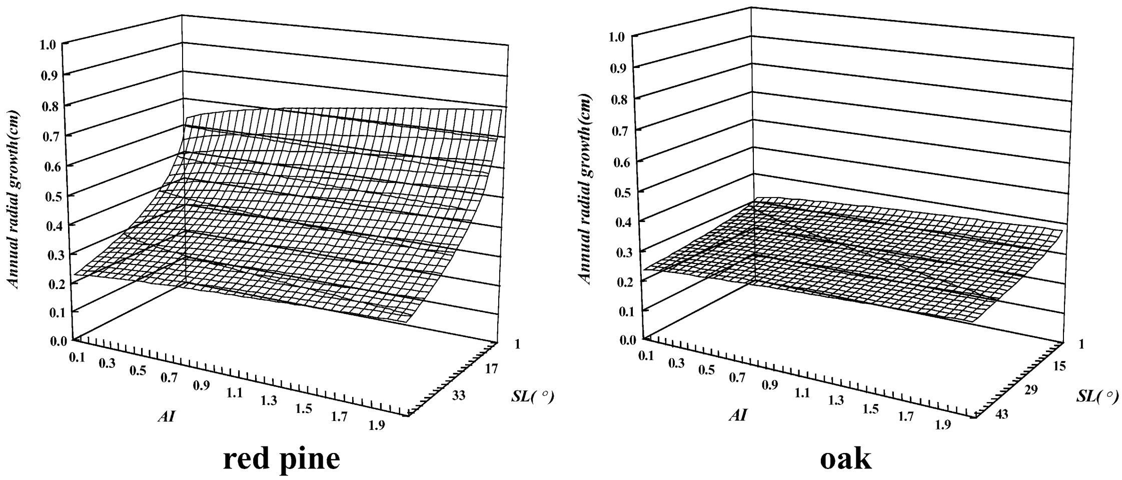

Fig. 4. Annual radial growth by tree aspect index (AI) and slope (SL) for Red pine and Oak, predicted using model 122 under keeping age in 30 years, dbh in 20 cm, elevation in 300 m, and CI in 1.5.

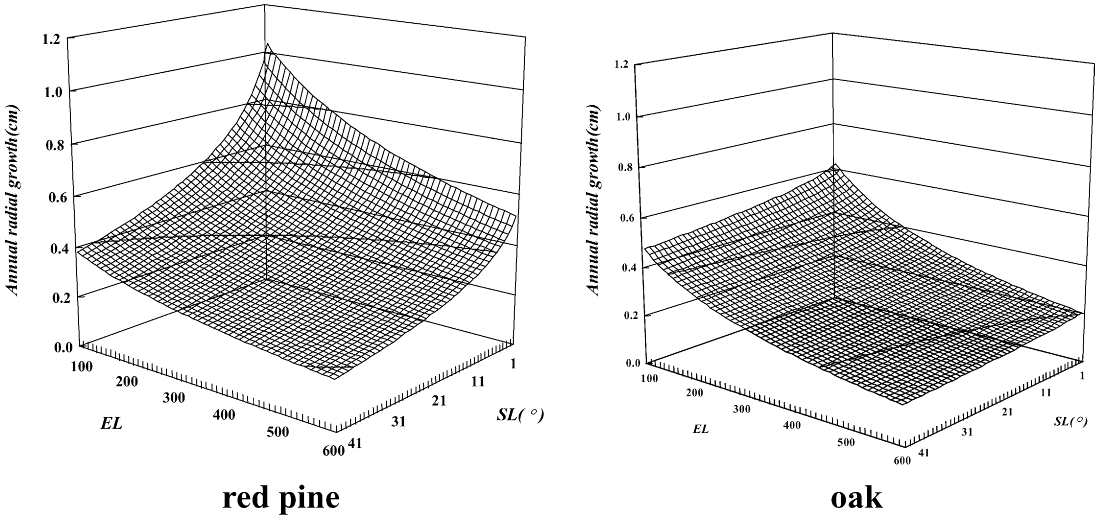

Fig. 5. Annual radial growth for various combinations of elevation (EL) and slope (SL) for Red pine and Oak, predicted using model 122.

CI effect increases with increasing dbh. dbh and CI effects are greater in Red pine than in Oak.

4.3.3. dbh growth prediction

Fig. 7 illustrates the dbh growth of trees with various values of competition index and age, starting with a dbh of 10 cm at age 15. The highest growth line shows dbh growth for open grown trees without competition with CI equal to zero. Without competition, the dbh of Red pine reaches 70 cm at age 100 and that of Oak 60 cm. And as expected, the dbh growth decreases, as competition increases, and this effect is greater in Red pine than in Oak.

4.4. Applicability of the model

Besides evaluating the statistical performance and plausibility of the mixed species model, special emphasis was put on its practicability in Korean forest ecosystems. The growth model presented in

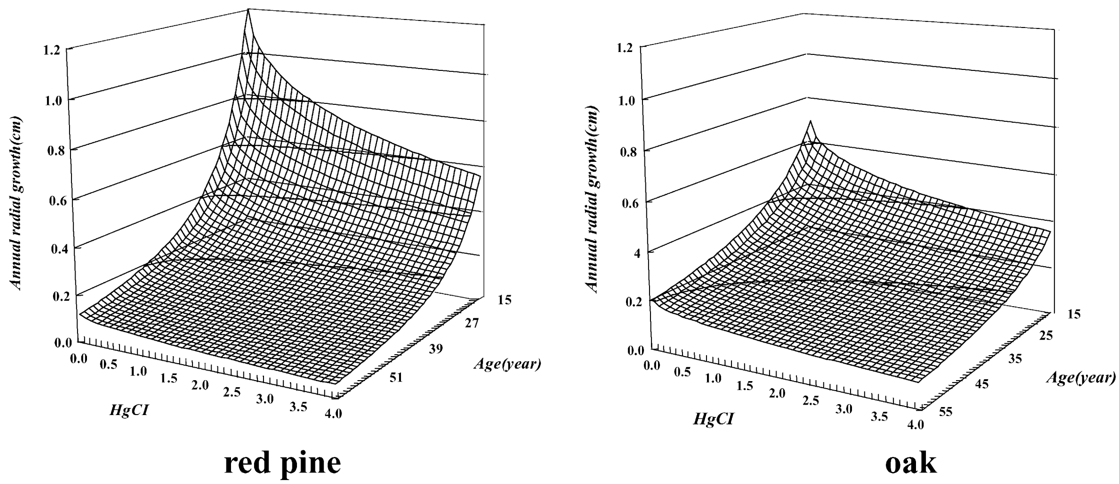

Fig. 6. Annual radial growth for different combinations of Hegyi's competition index (HgCI) and age for Red pine and Oak, predicted using model 11.

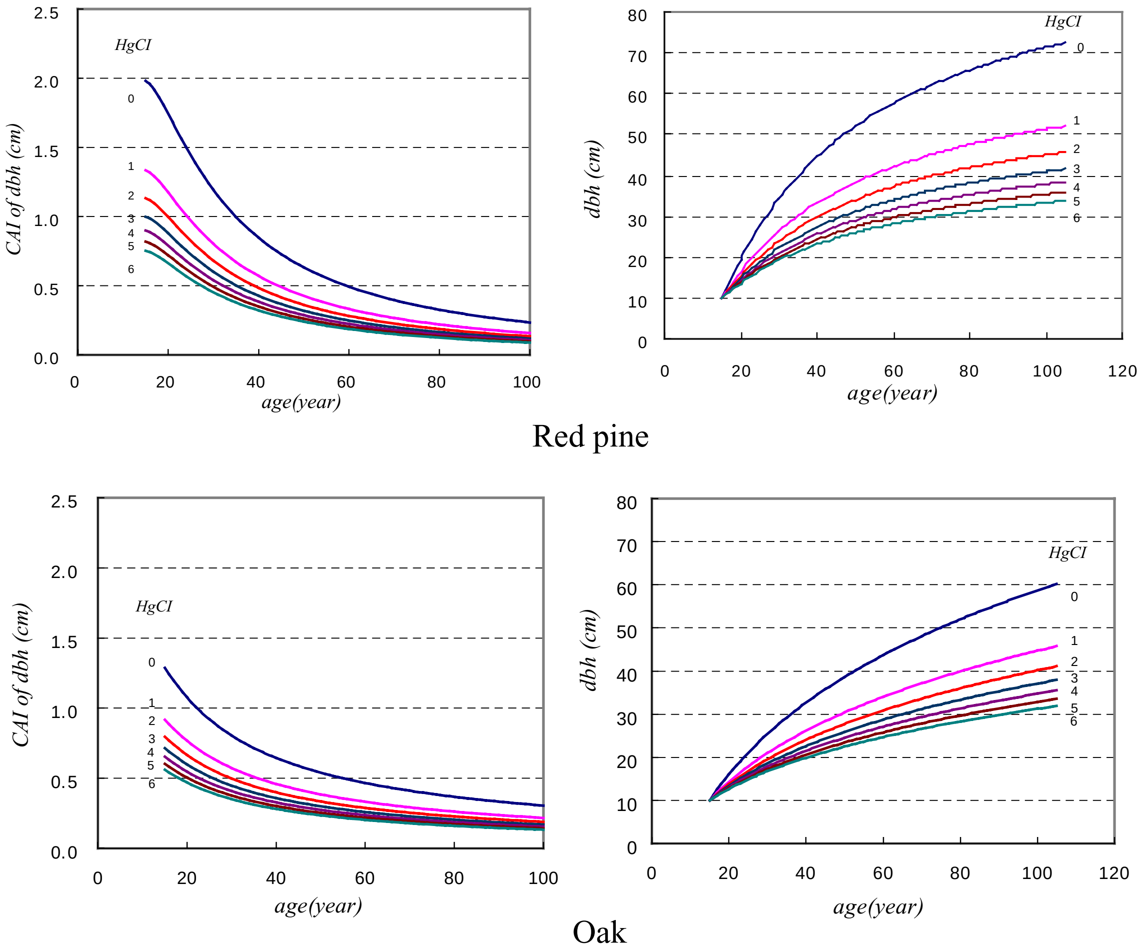

Fig. 7. Current Annual Increment (CAI) of dbh and dbh growth of trees with various competition index and age, beginning with a dbh of 10 cm at age 15.

this study encompasses variables which are generally available: tree size, competition, growing site and age. An attempt to exclude tree age failed. The poor statistical performance of the models without tree age made it necessary to include the age as a predictor variable. To enhance the applicability of the model, only diameter which is always available was used as a size component. Tree height which is not always available (especially in mixed stands) was intentionally excluded. The use of the size ratio competition index again aimed at making the model more applicable for the specific pine-oak mixed forest system. Tree diameters and distances (using the approaches developed by Hui et al., 2003; Gadow et al., 2003) will be readily available after field sampling.

Our attempt to make the model more applicable was continued to employ Hegyi's competition index using only distance and dbh ratio between subject tree and competitor trees. So our model appears theoretically less accurate than the models which require information of tree height or crown for calculating competition index (Biging and Dobbertin, 1992; Pretzsch, 1995; Hasenauer and Monserud, 1996; Monserud and Sterba, 1996; Bachmann, 1997), but can be more widely used in many situations where information about tree height and crown is not available.

Special emphasis was put on how to take characteristics of the growing site into account, and three approaches were tried. The site quality independent model has a lower statistical accuracy but can be easily applied when data about the growing site is not available. The site quality-dependent model with site index can be applied in the even-aged forests where the site index can be easily assessed from age and dominant height. The classical site index approach is not applicable in uneven-aged multi-species forests (Wykoff and Monserud, 1988; Peng, 2000; Sterba et al., 2002). Consequently, the model with site index cannot be applied. The site quality-dependent model with topography index has the advantage of accessing growing site with the same unit for different tree species. Therefore, the site quality-dependent model with the topography index can be applied in any arbitrary mixed stand. Our this knowledge presents a new solution to the difficult problem of predicting individual tree growth in pine-oak mixed forests, using variables which are readily available.

5. Conclusions

This study presents a first individual tree diameter growth model for mixed *P. densiflora* (Red pine) and *Q. variabilis* (Oak) forests in Korea. Using few independent variables which are usually available in the field, the model explains the variation in radial growth, with R^2 ranging from 0.60 to 0.69 for Oak and from 0.55 to 0.59 for Red pine, and with S.E.E. ranging from 0.058 to 0.064 for Oak and from 0.059 to 0.060 for Red pine, respectively. The site quality-dependent model variants show slightly better statistical performance than the site quality-independent one (11). All terms included in the site quality-independent model were significant at a probability level of 0.05, while variables for site quality in the site quality-dependent model show quite different significant levels. Dominant age and height variables were found to be significant in Oak but not significant in Red pine. The parameters for elevation and slope were significant in Red pine, and only the parameter for elevation was found to be significant in Oak.

The analysis of each multiplier does not reveal any conflicts with established experience in other countries. The effects of the different model components on radial growth are found to be reasonable and consistent. Based on sensitivity analysis of radial growth using a variety of combinations of independent variables, the conclusion could be reached that the size and aspect components have a positive effect on radial growth, while the other variables such as age, competition index, elevation, and slope have a negative influence. All model component effects, except elevation, are greater in pine than in Oak, indicating that Red pine is relatively less suppressed than Oak in the study area (and elsewhere in Korea). Among the topographic variables, slope appears to be an important critical factor for Red pine. For Oak, elevation is the primary critical factor and other variables have no great effect.

The interrelationships between radial growth and the age, size, competition, and site variables correspond quite well with ecological expectations and silvicultural experience of the two species in central Korea. The understanding derived from the model can serve as an important prerequisite for developing reasonable management regimes for mixed pine and Oak stands in central Korea.

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