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Allometry, Basal Area Growth, and Volume Equations for *Quercus mongolica* and *Quercus variabilis* in Gangwon Province of Korea

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Abstract : Allometry, basal area equations, and volume equations were developed with various tree measurement variables for the major species, *Quercus mongolica* and *Quercus variabilis*, in Korean natural hardwood forests. For allometry models, the relationships between total height-DBH, crown width-DBH, height to the widest portion of the crown-total height, and height to base of crown-total height were investigated. Multiple regression methods were used to relate annual basal area growth to tree variables of initial size (DBH, total height, crown width) and relative size (relative diameter, relative height) as well as competition measures (competition index, crown class, exposed crown area, percent exposed crown area, live crown ratio). For tree volume equations, the combined-variable and Schumacher models were fitted with DBH, total height and crown width for both species.

Key words : *mensuration, allometry, basal area growth, tree volume,* Quercus mongolica, Quercus variabilis

Introduction

Hardwood forests of Korea contain slightly over 2.50 million ha (38%) of total forest area, about 75% of which is in natural oak forests. Gangwon Province has the most hardwood forest area and oak resources among 9 Provinces of Korea (Korea Forest Service, 2006). Among 12 oak species, *Quercus mongolica* is the most dominant species through the Korean Peninsular and Gangwon Province. But wood quality tends to be generally poor with sweep and crook. *Quercus variablilis* ranked 2nd in dominance of oaks in Gangwon Province (3rd nationwide) with better stem quality and usefulness of wood, compared with *Quercus monogolica* (Korea Forest Service, 2006).

Oaks have been treated as useless wood for a long time in Korea, but recently they have been re-evaluated as value-added trees from an environmental and economic point of view. Therefore, oaks will potentially play a key role in the forest resources as well as forest industry of both Korea and Gangwon Province. For instance, the Korean Forest Service strives to formulate a management program with natural deciduous forests including oak forests. However, not many studies have been completed for oak forest management in terms of quantitative analysis of volume, growth, yield and silvicultural treatments in Korea although ecological and physiological research have been extensive in specific deciduous forests (Kim and Kim, 1995; Park et al., 2003; Suh and Lee, 1998).

Therefore, the first step for oak forest management is determining tree growth characteristics for major oaks species in Korea (Choi and Yoo, 2006; Kim and Lee 1970; Lee, *et al.*, 2004; Shin *et al.*, 2005). Furthermore, to scientifically diagnose stand characteristics for complicated natural deciduous forests with many species, not only are biological and environmental characteristics with various tree and stand measurement factors considered, but also detailed tree and stand structure are investigated (Belcher *et al.*, 1982; Cole and Lorimer, 1994; Choi *et al.*, 2001; Choi and Yoo, 2006).

Accordingly, the purpose of this study was to develop allometry relationships between tree measurement fac-

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tors and to develop basal area growth and volume equations with various tree measurement factors for *Quercus mongolica* and *Quercus variabilis*.

Materials and Methods

1. Data collection

Data were collected from two natural deciduous stands in Gangwon Province of Korea (Research forest of Kangwon National University and Yangyang Eco-observation Site of Korean Forest Service). Fifteen circular plots were established in two stands with plot radius equal to 3.5 times the mean crown radius of the 10 canopy trees (dominant, codominant, intermediate, as defined by Smith *et al.*, 1997) nearest to plot center. Subject trees, on which growth measurements were made, were all trees greater than or equal to 5 cm dbh within a radius 2.1 times the mean crown radius of the 10 canopy trees (Cole and Lorimer, 1994; Choi and Yoo, 2006). This plot design is efficient for data collection and gives approximately equal number of sample trees in stands of different ages.

Distance and azimuth from plot center were recorded for all live trees. Species, DBH, tree height and crown class were recorded for all subject and competitor trees. Height measurements were taken to the base, widest point, and top of each tree crown using a clinometer and height pole. The crown classes recognized were dominant, codominant, intermediate, and suppressed, as defined by Smith *et al.* (1997) and were coded 5, 4, 3, and 2, respectively. For subject trees, crown radii in four cardinal directions as well as radii of the exposed portion of the crown (the part not overtopped by adjacent trees) were measured by extending a tape measure horizontally from the bole center at ground level to the crown projection edge. A clinometer was used to sight the crown projection edge for all measurements.

Tree volume data were obtained from *Q. mongolica* and *Q. variabilis* felled subject trees. The diameters and log length over the stem were measured at 0%(stump), 2%, 4%, 6%, 8%, 10%, 15%, 20%, 25%, 30%, 40%, 50%, 60%, 70%, 75%, 80%, 90% and 100%(top) points from stump to tip of tree. A disk was cut at breast height for laboratory measurement of radial increment and tree age. The cross-sectional disks were air dried and sanded in the laboratory. The total number of rings was counted along radii of 4 cardinal directions and averaged to determine breast height age. Ring widths for the most recent 5 complete years were measured along 4 radii with an optical micrometer (to the nearest 0.01 mm) and averaged for estimates of annual diameter increment. Individual-tree basal area and basal area increments were calculated using the average diameter measurements and assuming circular stem form.

2. Numerical analyses

Annual basal area growth (ΔBA) was calculated as the average annual growth during the 5 year period preceeding the year of measurement. Total crown area (TCA) and exposed crown area (ECA) were calculated as the sum of the areas of four quarter ellipses, delimited by the four total and exposed crown radii, respectively. The percent exposed crown area (%ECA) was computed as the ratio of exposed to total crown projection area. For overtopped trees, a minimum %ECA of 2.0 was assigned to take into account sunflecks and small breaks in the canopy. ECAs for overtopped trees were therefore calculated as 2% of the measured TCA. Crown width (CW) was calculated by average total crown radii x 2 (Table 1).

Total age (AGE) was calculated as age at DBH plus 4.

Table 1. Tree variables calculated using tree measurements.

Variables	Unit	Formula*
Basal area growth (ΔBA)	cm^2/yr	
Diameter at breast height (DBH)	cm	
Total tree height (HT)	m	
Tree height to the widest portion of crown (HW)	m	
Tree height to base of crown (HB)	m	
Crown width (CW)	m	$2\left(\frac{a+b+c+d}{4}\right)$
Crown length (CL)	m	$HT\text{-}HB$
Tree age (AGE)		$(Age\ at\ DBH)+4$
Crown class (CC)		D, CD, I, S
Tree volume (V)	m^3	$\left(\frac{B+B'}{2}\right)L$
Live crown ratio (LCR)		$(HT\text{-}HB)/HT$
Total crown area (TCA)	m^2	$\frac{\pi}{4}(ab+bc+cd+da)$
Exposed crown area (ECA)	m^2	$\frac{\pi}{4}(a'b'+b'c'+c'd'+d'a')$
Percent exposed crown area (%ECA)	%	$(ECA/TCA)\times 100$
Relative diameter (RD)		$DBH/\overline{D}$
Relative height (RH)		$HT/\overline{H}$
Competition index (CI)		$\left(\sum_{j=1}^{n} D_j\right)/D_i$

*D: dominant(=5), CD: codominant(=4), I: intermediate(=3), S: suppressed(=2), B: cross-sectional area at large end of log, B': cross-sectional area at small end of log, L: log length, a,b,c,d: total crown radius to cardinal direction(m), a',b',c',d': exposed crown radius to cardinal direction(m), $\overline{D}$: average dbh of dominant and co-dominant trees on plot(cm), $\overline{H}$: average total height of dominant and co-dominant trees on plot(m), D_i: Dbh of subject tree(cm), D_j: dbhs of competitors(cm).

Relative diameter (RD) and relative height (RH) were calculated by dividing bole diameter or total tree height by the arithmetic mean diameter or height respectively, for all codominant and dominant trees on the plot. Live crown ratio (LCR) was defined as the ratio of live crown length to total tree height. A diameter-based competition index (CI) for each subject tree was also calculated using the following formula:

$$\left(\sum_{j=1}^{n} D_j\right)/D_i$$

where D_j is the diameter at breast height of competitor tree j and D_i is the subject tree diameter at breast height.

In this index, competitors are defined to include all trees equal or higher in crown class than the subject tree and within a radius equal to 3.5 x the mean crown radius of dominant-codominant trees. Tree volume (V) was calculated by Smalian's formula with stem measurement data (Table 1). The basic statistics for the tree measurement dataset are given in Table 2.

3. Model forms

Allometric equations for this study such as total height versus DBH, crown width versus DBH, height to widest crown versus total height, and height to base of crown versus total height functions were developed for both species using Eqs. (1), (2) and (3), which are traditionally used in forest allometry studies (Avery and Burkhart, 2002). Equation forms that were evaluated include:

$$Y = b_0 + b_1 X \tag{1}$$

$$lnY = b_0 + b_1 lnX \tag{2}$$

$$lnY = b_0 + b_1 X^{-1} \tag{3}$$

where ln = natural logarithm, b_0 and b_1 = regression coefficients.

Predictive equations for annual basal area growth were developed based on an *a priori* hypothesis that a model of the form

Annual growth = f(initial size, relative size, local stocking or competition) (4)

would generally give the most accurate predictions when simple tree measurements were used as predictor variables (Cole and Lorimer, 1994). For this study, initial size included DBH, total height, and crown width. Relative sizes were relative diameter and relative height. Competition terms consisted of competition index, crown class, exposed crown area, percent exposed crown area, and live crown ratio.

For stem volume equation, the combined-variable model (Eq. 5) and Schumacher and Hall (1933) model (Eq. 6) were used; these models have been widely applied in past studies for predicting tree volume (Avery and Burkhart, 2002).

$$V = b_0 + b_1 D^2 H \tag{5}$$

$$lnV = b_0 + b_1 lnD + b_2 lnH \tag{6}$$

where V is total outside bark stem volume from ground to tip (m^3), D is diameter at breast height over bark (cm)

Table 2. The attributes of *Quercus mongolica* and *Quercus variabilis*.

Variables	*Q. mongolica* (n=144)				*Q. variabilis* (n=119)			
	Mean	Min.	Max.	S.D	Mean	Min.	Max.	S.D
AGE (years)*	37	21	53	11	40	15	70	15
ΔBA (cm^2/yr)*	4.5	0.09	13.7	3.5	6.4	1.08	26.5	5.2
V (m^3)*	0.1280	0.0140	0.4385	0.1023	0.1584	0.0177	0.6144	0.1487
DBH (cm)	16.0	6.0	49.5	8.0	17.8	6.5	40.0	7.2
HT (m)	11.5	3.7	23.7	3.9	12.1	5.2	19.0	3.5
HW (m)	9.5	2.7	21.1	3.5	10.1	4.6	17.9	2.9
HB (m)	6.9	1.1	16.4	2.6	7.4	1.9	12.6	2.6
CL (m)	4.5	0.9	17.4	2.6	4.8	0.7	9.7	2.0
CW (m)	3.6	0.8	10.4	1.7	3.8	0.6	8.6	1.7
TCA (m^2)	12.1	0.5	84.8	12.2	13.1	0.3	56.0	11.2
RD	0.83	0.27	1.57	0.25	0.93	0.42	1.90	0.32
RH	0.89	0.30	1.40	0.21	0.93	0.44	1.38	0.20
CI*	7.02	1.16	22.12	4.99	7.39	0.53	25.25	5.63
CC	3.8	2.0	5.0	1.18	4.1	2.0	5.0	1.04
ECA (m^2)*	6.8	0.02	25.5	7.5	7.1	0.01	28.2	7.8
%ECA*	52.0	2.0	100.0	44.6	59.8	2.0	100.0	38.8
LCR	0.39	0.07	0.86	0.14	0.40	0.11	0.80	0.13

*Subject trees only: 43 trees for *Quercus mongolica* and 40 trees for *Quercus variabilis*.

and H is total tree height (m).

The following statistical measures of fit for model forms were used for this study: coefficient of determination (R^2) and standard error of estimate ($S_{y.x}$). Also, for multiple regressions, variance inflation factors (VIF) were checked to determine how much the variances of the estimated regression coefficients are inflated as compared to when the predictor variables are not linearly related. The variance inflation factor is defined as follows;

$$VIF_j = \frac{1}{1-R_j^2} \quad J = 1,2,3,\ldots,k \tag{7}$$

where R_j^2 is the coefficient of multiple determination when X_j is regressed on the other predictor (X) variables in the model.

Result and Discussion

1. Allometry equations

The allometric model is very useful in forest management, as it gives an approximately correct expression of a number of relations, such as DBH versus total height and DBH versus crown width. To estimate total height as a function of DBH for the two species, Eqs. (2) and (3) were considered for simple linear regression models. The power function, Eq. (2), was more suitable for *Q. mongolica* whereas Eq. (3) was a better fit for *Q. variabilis* based on R^2 and standard error of estimate. These species-specific allometric relationships were highly significant for both species ($P < 0.0001$). The residuals showed equal variance pattern in both equations. Regarding the total height and DBH for *Q. mongolica* and *Q. variabilis*, total height showed a positive trend with increasing DBH in both species. The correlation was, however, relatively weak (R^2=0.52), compared to conifer species in Korea (Kim and Choung, 1988; Lee, 1980; Lee, 2000).

In allometric relationships between crown width with several variables, DBH was the strongest variable (r=0.79-0.86) for both species. Power function Eq. (2) was suitable for both species. *Q. mongolica* had higher R^2 value (0.73) than that of *Q. variabilis* (0.61). The DBH-CW equations were highly significant for both species ($P < 0.0001$) with the exponents in the power function being close to 1.0 (actual range 0.925-1.017) (Table 3).

To estimate the height to the widest part of the crown and the height to base of crown, for both species, total height as the predictor variable was the most suitable. The height to the widest point of the crown significantly increased with increasing total height for both species and the correlation was strong (r=0.89-0.94) even without transformation. Eq. (1) was suitable (R^2 of 0.81-0.85) for both species and it exhibited the highest R^2 among other allometric relationships. The height to base of crown and total height also had a linear pattern when employing Eq. (1). However, the R^2 (0.60-0.68) decreased for both species when compared to the allometry with HW versus HT (13-25 percentage points) (Table 3).

Table 3. Allometric equations for *Quercus mongolica* and *Quercus variabilis*. All equations have significant *F*-values (p<0.0001). R-square and standard error of estimate were computed on the arithmetic scales for total tree height and crown width.

Species	Equation	R^2	$S_{y.x}$
Q. mongolica (n=144)	$\ln HT = 0.976 + 0.528 \ln DBH$	0.52	2.76
	$\ln CW = -1.305 + 0.925 \ln DBH$	0.73	0.91
	$HW = 0.135 + 0.814\ HT$	0.85	1.35
	$HB = 1.215 + 0.500\ HT$	0.60	1.63
Q. variabilis (n=119)	$\ln HT = 3.002 - 8.338\ DBH^{-1}$	0.52	2.41
	$\ln CW = -1.637 + 1.017 \ln DBH$	0.61	1.06
	$HW = 0.893 + 0.756\ HT$	0.81	1.27
	$HB = -0.069 + 0.611\ HT$	0.68	1.46

2. Basal area growth equations

Coefficients of determination between basal area growth and single predictor variables are shown in Table 4. Initial size variables generally had higher R^2 values than other variables, in which diameter had the highest coefficient of determination for both species (0.59 and 0.68). Relative size gave R^2 values of 0.43 to 0.46 except relative height (0.18) for *Q. variabilis*. Exposed crown area and crown class had the highest R^2 value of any competition terms for the two species. The lowest correlation among single predictor variables was for live crown ratio for both species (Table 4).

Alternative linear regressions for predicting basal area growth of each species are shown in Table 5. Natural logarithm transformations of predictor and response variables generally produced better residual patterns and higher correlations with basal area growth than inverse transformations and untransformed data; thus logarithmic transformed variables were used throughout the remaining basal area growth analyses. The basal area growth equations were derived based on a priori hypothesis in Eq. (4) as well as considering high R^2 and low $S_{y.x}$ (Table 4). The basal area growth equation with all 3 terms (initial size, relative size, competition) for *Q. mongolica* included DBH, RH, and CI, and had R^2 equal 0.69 and $S_{y.x}$ equal 0.58. In the case of *Q. variabilis*, the variables included were HT, RH, and CC which accounted for 65% of observed variation in growth (Table 5).

However, the competition index in the equation with DBH, RH, and CI for *Q. mongolica* had a positive coef-

Table 4. Coefficients of determination (R^2) for basal area growth and single predictor terms based on the model $\ln(\Delta BA)=b_0+b_1\ln(X)$. All equations have significant F-values ($P<0.05$) except where noted.

Species	Initial size			Relative size		Competition				
	DBH	HT	CW	RD	RH	CI	CC	ECA	%ECA	LCR
Q. mongolica (n=43)	0.59	0.28	0.43	0.43	0.44	0.33	0.43	0.46	0.40	0.01*
Q. variabilis (n=40)	0.68	0.50	0.56	0.46	0.18	0.16	0.46	0.40	0.17	0.01*

*P-values for the LCR parameter in *Quercus mongolica* and *Quercus variabilis* are 0.58 and 0.57.

Table 5. Linear equations for predicting annual basal area increment (ΔBA, cm^2 per year). All equations have significant F-values ($P<0.0001$) and significant individual parameter estimates ($P<0.05$) except where noted. The value in parenthesis is variance inflation factor (VIF).

Species	Equations	R^2	$S_{y,x}$
Q.mongolica (n=43)	$\ln(\Delta BA) = -5.02 + 2.18\ln(DBH) + 1.47\ln(RH) + 0.48\ln(CI)$ (3.16) (1.72) (3.37)	0.69	0.58
	$\ln(\Delta BA) = -3.94 + 1.57\ln(DBH) + 0.89\ln(CC)$ (1.50) (1.50)	0.66	0.60
	$\ln(\Delta BA) = -2.63 + 1.55\ln(DBH) + 1.20\ln(RH)$ (1.56) (1.56)	0.65	0.61
	$\ln(\Delta BA) = -2.75 + 1.54\ln(DBH) + 0.11\ln(ECA)$ (1.90) (1.90)	0.63	0.63
	$\ln(\Delta BA) = -3.43 + 1.65\ln(DBH) + 0.14\ln(\%ECA)$ (1.60) (1.60)	0.63	0.63
	$\ln(\Delta BA) = 0.21 + 1.04\ln(CW) + 1.81\ln(RH)$ (1.17) (1.17)	0.63	0.63
	$\ln(\Delta BA) = -4.08 + 2.07\ln(DBH)$	0.59	0.65
Q. variabilis (n=40)	$\ln(\Delta BA) = -2.59 + 1.29\ln(DBH) + 0.51\ln(CC)$* (1.88) (1.88)	0.70	0.44
	$\ln(\Delta BA) = -2.07 + 1.33\ln(DBH) + 0.07\ln(ECA)$* (1.64) (1.64)	0.70	0.44
	$\ln(\Delta BA) = -2.66 + 1.57\ln(DBH)$	0.68	0.45
	$\ln(\Delta BA) = 0.95 + 0.78\ln(CW) + 0.84\ln(RD)$ (1.49) (1.49)	0.65	0.47
	$\ln(\Delta BA) = -4.88 + 1.83\ln(HT) - 1.14\ln(RH) + 1.31\ln(CC)$ (2.01) (2.33) (2.07)	0.65	0.48
	$\ln(\Delta BA) = -0.36 + 0.78\ln(CW) + 0.79\ln(CC)$ (1.70) (1.70)	0.63	0.49
	$\ln(\Delta BA) = -1.63 + 1.41\ln(HT) + 0.92\ln(RD)$ (1.47) (1.47)	0.61	0.50

*P-values were 0.09 for CC and 0.09 for ECA.

ficient, although it should be negative theoretically. Therefore muticollinearity was suspected among the variables used to express competition. Variance inflation factors (VIF) were checked to see how much the variances of the estimated regression coefficients are inflated as compared to when the predictor variables are not linearly related (SAS, 2006). The VIF values of DBH, RH and CI were 3.16, 1.72 and 3.37, respectively. DBH and CI had not only the highest VIF values but also had higher correlation coefficient of 0.81, so this equation would not be qualified as the best model. In the same case, the equation with HT, RH, and CC for *Q. variabilis* also had a negative coefficient for RH (should be positive) with the highest VIF value being 2.33 among the variables. Although the VIF value of relative height was not higher than that of the previous equation involving DBH, RH, and CI for *Q. mongolica*, it was still suspicious for multicollinearity. Likewise, it did not appear to be a good equation for predicting basal area growth either. The other basal area models did not exhibit strong muticollinearity; no VIFs were greater than 2.0 for either species (Table 5).

Use of DBH as a measure of initial size resulted in a substantial improvement in R^2 and $S_{y.x}$ for both species. With the present data, diameter alone was a fairly good predictor variable, especially for *Q. variablilis*, explaining 68% of the variation in basal area growth (Table 5). However, other variables added with DBH were mostly

Table 6. Coefficients of determination (R^2) for volume and single predictor terms based on the model $\ln(V)=b_0+b_1\ln(X)$. All equations have significant *F*-values ($P<0.05$) except where noted.

Species	Initial size			Relative size		Competition				
	DBH	HT	CW	RD	RH	CI	CC	ECA	%ECA	LCR
Q. mongolica (n=43)	0.94	0.69	0.79	0.43	0.21	0.66	0.25	0.51	0.38	0.002*
Q. variabilis (n=40)	0.96	0.77	0.69	0.47	0.30	0.14	0.49	0.46	0.18	0.01*

**P*-values for the LCR parameter in *Quercus mongolica* and *Quercus variabilis* are 0.81 and 0.48.

not significant in the case of *Q. variabilis*. Although total height and total crown area as initial size were not as good as predictors as DBH for both species, they were more highly correlated with relative terms and competition terms especially for *Q. variables* (Table 5).

Considering relative sizes (RD and RH) for *Q. mongolica*, relative height was the only significant variable with initial size. Relative height, in conjunction with DBH, explained 65% of the variation in basal area increment, whereas RH with crown width accounted for 63%. For *Q. variabilis*, relative diameter was a good term with initial size variables. When relative diameter was used with crown width, the R^2 for basal area increment was 65%; total height plus RD gave a R^2 of 61%. The addition of an explicit relative height term in the function involving DBH increased the coefficient of determination by 6 percentage points for *Q. mongolica*. But no additional relative size variables were found to be significant in the functions including DBH for *Q. variabilis;* however, the addition of explicit relative diameter in the function involving crown width increased R^2 by 9 percentage points over a function involving CW only (Table 5).

The effectiveness of competition terms in a model is often evaluated by how much predictive power is increased when competition terms are added to a model containing only initial DBH as the independent variable (e.g. Bella, 1971; Biging and Dobbertin, 1995). With the present data, initial size alone was a fairly good variable by itself, explaining 43-68% of the variation in basal area increment (Table 4, except total height for *Q. mongolica*). However, the addition of an explicit competition term in functions with DBH increased the coefficient of determination by 4-7 percentage points for *Q. mongolica*, but only 2 percentage points for *Q. variabilis* (Table 5). Generally, crown class and exposed crown area as competition terms were strong variables, but competition index and live crown ratio were found to be weak variables for both species.

From the present data, DBH was not only better than total height and crown width, but also was correlated with crown class for both species, so that functions with DBH and CC could be a candidate for the best model. The present data tended to be similar to basswood and white ash of northern hardwoods in the United State in terms of bivariate regressions, in which initial size and exposed crown area of northern hardwood species had slightly better R^2 values (Cole and Lorimer, 1994; Choi *et al.*, 2001).

3. Tree volume equations

Coefficients of determination between tree volume and single predictor variables are shown in Table 6. Predictor variables are also classified into three categories corresponding to the three terms; initial size, relative size and competition. Among initial size variables, diameter had the highest coefficient of determination (0.94 and 0.96) for both species. Next, crown width and total height were significant for *Q. mongolica* and *Q. variabilis*, respectively (R^2=0.77 and 0.79). Relative diameter had the largest R^2 value (0.43 to 0.47) of relative terms for both species. Competition index and crown class had the highest R^2 value (0.49 to 0.66) among the competition terms for both species *Q. monogolica* and *Q. variabilis*. In general, initial size variables had much better R^2 values than other variables for both species (Table 6).

Prediction of stem-volume for each species was estimated by the combined variable and Schumacher models. These volume equations have been widely applied in past studies for predicting tree volume (Avery and Burkhart, 2002). For this study, DBH, total height and crown width as dependent variables were used for estimating tree volume for both models. For comparison of fit statistics, R^2 and standard error of estimate were computed on a volume scale for the Schumacher model (Table 7).

For *Q. mongolica*, DBH and HT had the highest R^2 of 0.98 and the lowest standard error of 0.016 in both models (Table 7). The combined-variable model with DBH and CW had a greatly decreased R^2 of 0.87. Also the Schumacher model with DBH and CW had a low R^2 and crown width was not significant (p=0.32) with a high VIF of 5.20. Likewise, functions with DBH, HT, and CW also had high VIF values for DBH and CW (6.53 and 5.21, respectively). Overall, the combined-variable and Schumacher models with DBH and HT were the best for esti-

Table 7. Linear equations for predicting tree volume (V, m^3). All equations have significant *F*-values ($P<0.0001$) and significant individual parameter estimates ($P<0.05$) except where noted. R-square and standard error of estimate were computed on a volume scale. The value in parenthesis is variance inflation factor (VIF).

Species	Equations	R^2	$S_{y.x}$
Q. mongolica (n=43)	$V = 0.00651 + 0.0000404(DBH^2)(HT)$	0.98	0.016
	$V = 0.0199 + 0.000129(DBH^2)(CW)$	0.87	0.037
	$\ln(V) = -9.51 + 1.94\ln(DBH) + 0.85\ln(HT)$ (2.12) (2.12)	0.98	0.016
	$\ln(V) = -8.29 + 2.22\ln(DBH) + 0.18\ln(CW)^*$ (5.20) (5.20)	0.91	0.031
	$\ln(V) = -9.10 + 1.68\ln(DBH) + 0.86\ln(HT) + 0.22\ln(CW)^¶$ (6.53) (2.12) (5.21)	0.97	0.017
Q. variabilis (n=40)	$V = 0.0182 + 0.0000335(DBH^2)(HT)$	0.97	0.024
	$V = 0.0467 + 0.0000834(DBH^2)(CW)$	0.91	0.046
	$\ln(V) = -9.04 + 1.80\ln(DBH) + 0.79\ln(HT)$ (3.09) (3.09)	0.98	0.023
	$\ln(V) = -7.87 + 2.01\ln(DBH) + 0.20\ln(CW)$ (2.78) (2.78)	0.96	0.030
	$\ln(V) = -8.71 + 1.64\ln(DBH) + 0.76\ln(HT) + 0.17\ln(CW)$ (4.54) (3.12) (2.81)	0.98	0.022

**P*-values was 0.32 for CW, ¶*P*-values was 0.07 for CW.

mating tree volume of *Q. mongolica* (Table 7).

For *Q. variablilis*, the combined-variable and Schumacher models with DBH and HT were almost equivalent in terms of R^2 (0.97-0.98) and the standard error of estimate (0.024-0.023). DBH and CW were not strongly significant as compared to DBH and HT for *Q. variabilis*. The Schumacher model with DBH, HT, and CW had the highest fit statistics (R^2=0.98, $S_{y.x}$=0.022) but VIF of DBH had a high value of 4.54 and R^2 was not improved with crown width (Table 7).

The mensurational equations presented here should prove valuable in efforts to better manage oak forests in Gangwon Province.

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