Tree crown ratio models for multi-species and multi-layered stands of southeastern British Columbia

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ABSTRACT

The ratio of live crown length to tree height (crown ratio; CR) is often used as an important predictor variable for tree level growth equations, particularly for multi-species and multi-layered stands. Also, CR indicates tree vigour and can be an important habitat variable. Measurement of CR for each tree can be time-consuming and difficult to obtain in very dense stands and for very tall trees where the base of live crown is obscured. Models to predict CR from size, competition and site variables were developed for several coniferous and one hardwood tree species growing in multi-species and multi-layered forest stands (complex stands) of southeastern British Columbia. Simple correlations indicated the expected relationships of CR decreasing with increasing height, and with increasing competition. A logistic model form was used to constrain predicted CR values to the interval [0,1]. Also, predictors were divided into tree size, stand competition, and site measures, and the contribution of each set of contributors was examined. For all models, height was an important predictor. The stand competition measure, basal area of larger trees, contributed significantly to predicting CR given that crown competition factor was also included as a measure of competition. Logical trends in CR versus size and competition variable groups were reflected by the models; site variable slightly improved predictions for some species. Much of the variability in CR was not accounted for, indicating that other variables are important for explaining CR changes in these complex stands.

Key words: crown ratio, multi-species stands, multi-layered stands, basal area of larger trees

RÉSUMÉ

Le ratio entre la longueur de la cime vivante par rapport à la hauteur de l'arbre (ratio de la cime; RC) est souvent utilisé en tant que variable importante de prédiction dans le cas d'équations de la croissance des arbres, spécialement pour les peuplements composés de nombreuses espèces et présentant plusieurs étages. De plus, le RC indique la vigueur de l'arbre et peut être une variable importante de l'habitat. La mesure du RC pour chaque arbre peut prendre beaucoup de temps et être difficile à obtenir dans des peuplements très denses et dans le cas d'arbres très grands pour lesquels la base de la cime vivante se retrouve dans l'ombre. Les modèles de prédiction du RC à partir des variables de diamètre, de compétition et de station ont été élaborées pour diverses espèces résineuses et pour une espèce feuillue retrouvées dans des peuplements composés de nombreuses espèces et présentant plusieurs étages (peuplements complexes) du sud-est de la Colombie-Britannique. Des corrélations simples ont démontré tel que prévu des relations de RC en décroissance avec l'augmentation de la hauteur et de l'augmentation de la compétition. Une forme de modèle logistique a été utilisée pour contraindre les valeurs prévues de RC selon un intervalle de [0,1]. De plus, les variables de prédiction ont été divisées selon le diamètre de l'arbre, la compétition au sein du peuplement et des mesures de la station, et la contribution de chaque ensemble de contributeurs a été étudiée. Pour tous les modèles, la hauteur constituait une variable de prédiction importante. La mesure de la compétition au sein du peuplement et la surface terrière des plus gros arbres ont contribué de façon significative à la prédiction du RC étant donné que le facteur de compétition des cimes était également inclus dans la mesure de la compétition. Les tendances logiques du RC comparativement aux groupes de variables de diamètre et de compétition ont été reflétées par les modèles; la variable de la station a légèrement amélioré les prédictions pour certaines espèces. La majeure partie de la variabilité du RC n'a pas été prise en considération, ce qui indique que d'autres variables sont déterminantes pour expliquer les changements de RC dans ces peuplements complexes.

Mots clés : ratio de la cime, peuplements composés de plusieurs espèces, peuplements comportant plusieurs étages, surface terrière des plus gros arbres

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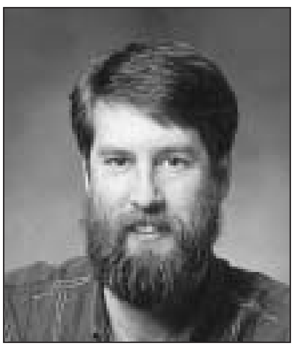

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Introduction

Trees retain live branches that contribute positively to net photosynthesis (Kramer and Kozlowski 1979). The presence of foliated lower branches in stand-grown trees reflects within-canopy light levels and shade tolerance; open grown trees typically have live crowns that extend to ground level. Crown ratio (CR), the ratio of live crown length to tree height, is widely used to predict growth and yield of trees and forests (Bella 1971, Sprinz and Burkhart 1987), including release following partial cutting (Bailey and Tappeiner 1998). CR is a useful indicator of tree vigour (Assmann 1970, Hasenauer and Monserud 1996), wood quality (Kershaw *et al.* 1990), stand density (Clutter *et al.* 1983), competition and survival potential (Oliver and Larson 1996), wind firmness (Navratil 1997), and is a feature of interest in management of many non-timber resources including wildlife habitat, recreation and visual quality (McGaughey 1997). However, measuring CR can be time-consuming resulting in measures on only a subset of trees in plots. Also, the base of the live crown is very difficult to see in very dense stands and for very large trees.

Crown ratio has been predicted using empirical models (Belcher *et al.* 1982, Wykoff *et al.* 1982, Dryer and Burkhart 1987, Maguire and Hann 1990, Hynynen 1995, Hasenauer and Monserud 1996). Most of these models include competition measures (e.g., density, crown competition factor), tree size (e.g., breast height diameter, tree height, age), and site (e.g., elevation, slope, aspect) variables (Wykoff 1986, Hynynen 1995, Hasenauer and Monserud 1996).

Stands of southeastern British Columbia (BC) are complex, with many species and a wide range of tree sizes. Species include shade-tolerant conifers such as grand fir (*Abies grandis* (Dougl.) Lindl.), subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.), and western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), semi-tolerant conifers such as Douglas-fir (*Pseudotsuga menziesii var. menziesii* (Beissn.) Franco) and interior spruce (*Picea glauca* (Moench) Voss and *P. engelmannii* Parry, and hybrids), and shade-intolerant conifers such as lodgepole pine (*Pinus contorta* var. *contorta* Dougl.), ponderosa pine (*Pinus ponderosa* Laws.), white pine (*Pinus monticola* Dougl.), and western larch (*Larix occidentalis* Nutt., L). These stands may also contain shade-intolerant hardwoods such as paper birch (*Betula papyrifera* Marsh.), trembling aspen (*Populus tremuloides* Michx.), and black cottonwood (*Populus trichocarpa* Torr. & Gray) (Meidinger and Pojar 1991). Multi-cohort stands result from frequent gap-making disturbances that lead to initiation of new groups of trees. In these stands, trees of various ages, species, sizes, vigour, crown classes, and shade tolerance levels co-exist. As a result, growth measures, including crown ratios, are more variable than in even-aged and/or single-species stands.

Crown ratio is used as an input variable to estimate growth and mortality of individual trees and also is used to display changes in the appearances of stands over time for habitat suitability and visual changes. The objective of this research was to develop and test a crown ratio prediction model for a selection of species growing in complex stands of southeastern BC, using tree size, stand-level competition, and site variables as possible predictor variables. These variables are commonly used for more homogeneous stands, such as even-aged, single-species stands. For these complex stands, an additional competition measure, basal area of larger trees, was included to better indicate competition.

Methods

Data

Fixed-area permanent sample plot (PSPs) data were supplied by the BC Ministry of Forests, Forest Practices Branch. A detailed description of the PSP establishment and the data collection can be found in BC Ministry of Forests (1995). These PSPs were installed and measured to document tree and stand growth and mortality over time in the Interior Douglas-fir (IDF) Biogeoclimatic Ecosystem Classification (BEC) zone for over 30 years. This BEC zone is typically diverse in structure, both vertically and horizontally, with a mix of hardwoods, conifers, and shrubs (Meidinger and Pojar 1991).

The 387 PSPs used in model fitting represent a variety of stand structures, species compositions, densities, and site qualities found in the IDF, ranging from 1200 to 2030 m in elevation, and from 7.7 to 63.5 m^2/ha in basal area. From these PSPs, the last measurement for each tree with measured crown lengths and heights was selected, thereby removing any time-related correlations among sample trees (13 471 trees). Five species were well represented in the dataset: aspen, paper birch, Douglas-fir, lodgepole pine, and hybrid spruce. Of these five species, spruce is considered the most shade-tolerant species, and Douglas-fir is considered more tolerant than the other species (Harlow *et al.* 1979). An independent dataset of trees measured for crown length was used to test fitted models. These data were used to verify forest inventory estimates. The independent data were collected in the IDF BEC zone and in stands that have similar structure and features as the modeling data. However, only Douglas-fir, lodgepole pine, and hybrid spruce were well represented in this independent dataset (more than 30 trees). The crown ratio was calculated for each tree in the model-fitting and model-testing datasets, and all data were checked for any obvious measurement errors by plotting pairs of variables.

Model description

Crown ratio values range from 0 (no crown, dead or defoliated) to 1 (crown extends over the entire tree bole). Since the logistic model is restricted to [0,1], an appropriate model for estimating tree crown ratio is:

$$\hat{CR} = \left[1 + e^{-\beta \times X}\right]^{-1} \qquad [1]$$

where $\hat{CR}$ is the estimated crown ratio, $\beta \times X$ is a linear equation with parameters β and independent variables X, and *e* is the Naperian constant.

Since CR is expected to vary by tree species, a separate CR model was fitted for each species. Possible predictor variables were then selected to represent size, competition, site, and stand structure. The linear combinations for the independent variables can be given as (after Hasenauer and Monserud 1996):

$$\beta \times X = \beta_0 + b \times X_1 + c \times X_2 + d \times X_3 \qquad [2]$$

where β_0 is intercept of the model, *b* to *d* are sets of parameters, X_1 refers to tree size variables, X_2 refers to measures (or indices) of competition including density, and X_3 refers to site variables.

Tree size has been used to predict CR (e.g., Hasenauer and Monserud 1996). Measures of size included were diameter outside bark at breast height (DBH; 1.3 m above ground), expressed as DBH squared to better represent tree basal area, tree height (HT), and tree slenderness (HDR) resulting in:

$$b \times X_1 = \beta_1 \times HDR + \beta_2 \times HT + \beta_3 \times DBH^2 \qquad [3]$$

where β_1 to β_3 are parameters to be estimated.

Competition can be expressed by a variety of stand measures such as crown competition factor (CCF). The maximum crown area equations developed by Wykoff *et al.* (1982) were used in this study. For complex stands, Wykoff *et al.* (1982), Wykoff (1986), and Ritchie and Hann (1987) suggested that basal area per ha for trees larger than the subject tree (BAL) (m^2/ha) would help indicate competition. Using these two variables resulted in:

$$c \times X_2 = \beta_4 \times BAL + \beta_5 \times \ln(CCF) \qquad [4]$$

where β_4 and β_5 are parameters to be estimated. The relationship between CR and CCF is likely nonlinear as noted by Wykoff *et al.* (1982) and, therefore, the logarithm of CCF was used for this study. Other tree level measures of competition requiring inter-tree distances (spatial measures of competition) could have been included to improve CR predictions for these complex stands; however, these measures are not commonly available for all stands.

Site was represented by elevation (ELEV), slope (SL), aspect (ASPECT in radians) in the following model:

$$\begin{aligned} d \times X_3 = {} & \beta_6 \times ELEV + \beta_7 \times ELEV^2 \\ & + \beta_8 \times SL + \beta_9 \times SL^2 + \beta_{10} \times SL \\ & \times \sin(ASPECT) \\ & + \beta_{11} \times SL \times \cos(ASPECT) \end{aligned} \qquad [5]$$

where β_6 to β_{11} are parameters to be estimated. The combined effect of slope and aspect (e.g., on light availability) is represented by the "slope-aspect transformation" as was outlined by Stage (1976) and Hasenauer and Monserud (1996).

Given that the crown ratio model is intended for multi-species and multi-layered stands, site index was intentionally excluded from the model. Also, tree age was excluded since this is often measured only on a small subset of trees, and tree ages are quite variable in multi-layered stands.

Model fitting, interpretation, and evaluation

Eq. [2] to [5] were then inserted into Eq. [1] and the parameters β_0 to β_{11} were estimated for aspen, paper birch, Douglas-fir, lodgepole pine, and hybrid spruce, separately. Initially, multiple linear regression fit (PROC REG; SAS Institute Inc. 1999) was used to fit the linear version of the model (logarithmic transformation), as follows (after Hasenauer and Monserud 1996):

$$\ln\left(\frac{1}{CR} - 1\right) = \beta_0 + b \times X_1 + c \times X_2 + d \times X_3 \qquad [6]$$

To avoid undefined values in Eq. [6], trees with a crown ratio of 1.0 were reset to 0.99. There were no trees without crowns (CR = 0) in the dataset. The parameter estimates from the linear least squares fit were then used as starting parameters for the nonlinear least squares, Marquardt optimization technique in PROC NLIN (SAS Institute Inc. 1999).

Models were also fit for each variable subset separately (e.g., X_1, X_2, and X_3), using the linear versions to obtain starting parameters for the nonlinear models, to evaluate the contribution of each set, and to indicate interactions among sets of variables. Since BAL was included to account for stand complexity, the contribution of BAL alone was also examined by removing BAL from the X_2 equation.

For all nonlinear fits of models, the following statistics were calculated:

1. Estimated standard error of estimates ($S\hat{E}E$) (Zar 1999):

$$S\hat{E}E = \sqrt{\sum_{i=1}^{n} \frac{\hat{e}_i^{\,2}}{n-k}}$$

2. Proportion of variance explained (I^2):

$$I^2 = 1 - \frac{SSE}{SSY} = \frac{\sum_{i=1}^{n} \hat{e}_i^{\,2}}{\sum_{i=1}^{n} (y_i - \bar{y})^2}$$

where: $\hat{e}_1$ is the difference between the observed (y_i) and estimated crown ratio values ($\hat{y}_i$); $\bar{y}$ is the average of observed crown ratio values; n is the number of trees in the model-fitting data set; and k is the number of coefficients in the fitted equation. Residual plots for each fitted model were used to check for lack of fit and normality plots were used to check for normality of residuals.

To produce a more parsimonious model, linear least squares stepwise selection with $\alpha = 0.05$ for both entry and removal of variables (PROC REG; SAS Institute Inc. 1999) for Eq. [6] was used to select subsets of variables. Since the two variables, SL X sin(ASPECT) and SL X cos(ASPECT), together represent aspect, these were removed or retained as a group. The equations were fit again using nonlinear least squares including only the selected variables and using the estimated coefficients from the stepwise linear fit as starting parameters for the nonlinear least squares solution.

Model validation

Using the independent data, the predictive abilities of the final fitted crown ratio models were evaluated using $S\hat{E}E$ and I^2, as for the model-fitting data, as well as average difference (bias), defined as:

$$bias = \sum_{i=1}^{n} \frac{\hat{e}_i}{n}$$

where predicted values are based on the fitted model, applied to the test data.

Using the independent data, the predictive abilities of the crown ratio models were also evaluated by visually comparing differences between observed and predicted crown ratio values over selected independent variables.

Results and Discussion

Data summary

The model-fitting and testing datasets covered a wide range of tree sizes and basal area per ha values (Table 1). However, small trees less than 12.5 cm DBH were not available in the test data. Although paper birch and aspen were represented in the model fitting data, little data were available for these species in the test dataset.

Simple correlations were obtained to give insights into the relationships between CR and each variable. Plots of CR versus each variable indicate nonlinear trends with CCF, and the logarithm of CCF was obtained. Based on simple correlations using the model fitting dataset, crown ratio was inversely related to the DBH^2, except for Douglas-fir, and to HT, with greater negative correlations given for HT (Table 2). The relationship with HDR was negative, except for

Table 1. Number (No.) of trees, minimum (Min), average (Mean), maximum (Max), and standard deviation (STD) of diameter at breast height (DBH), height, crown ratio, crown competition factor (CCF), and basal area per ha by species for model building and test data sets.

Species	No. of Trees	DBH(cm)				Height(m)				Crown Ratio				CCF				Basal Area (m^2) per ha			
		Min	Mean	Max	STD	Min	Mean	Max	STD	Min	Mean	Max	STD	Min	Mean	Max	STD	Min	Mean	Max	STD
Model data																					
Aspen	380	2.0	13.4	33.8	6.8	2.4	14.2	32.2	6.0	0.10	0.32	0.80	0.16	26.39	151.87	285.35	54.12	4.19	30.92	51.52	10.28
Paper birch	567	2.1	14.5	41.0	7.6	3.1	15.7	30.0	6.0	0.10	0.47	0.90	0.17	1.39	164.79	302.80	49.78	0.19	35.00	64.36	11.05
Douglas-fir	8664	2.0	22.2	102.4	12.8	1.9	16.8	43.2	7.7	0.10	0.52	1.00	0.19	15.38	168.91	302.80	50.43	4.23	32.45	64.36	9.33
Lodgepole pine	3367	2.0	17.5	49.2	7.80	2.0	16.6	39.8	6.28	0.10	0.42	1.00	0.21	1.39	152.54	302.80	59.26	0.19	30.16	57.13	11.43
Hybrid spruce	492	2.1	16.4	63.6	11.50	2.1	14.2	35.0	8.74	0.10	0.68	1.00	0.20	72.89	164.47	244.59	41.36	13.17	35.41	52.61	9.08
Test data																					
Douglas-fir	468	12.5	24.9	84.9	14.07	6.7	17.2	40.9	5.82	0.20	0.58	0.90	0.16	70.00	169.90	293.00	64.48	0.20	13.73	46.58	10.56
Lodgepole pine	176	12.5	19.9	49.0	6.41	4.3	17.1	29.3	4.50	0.10	0.40	0.90	0.17	70.00	154.98	264.00	51.82	0.20	13.04	43.70	8.72
Hybrid spruce	52	13.0	21.8	59.2	8.85	11.4	18.4	32.5	4.65	0.30	0.66	0.90	0.20	94.00	150.33	263.00	41.04	0.22	17.29	44.81	10.25

Table 2. Pearson's correlations between crown ratio and predictor variables. Correlations that are significantly different from zero (? = 0.05) are indicated by *

Species	No. of Trees	HT/ DBH	HT	DBH^2	BAL	LN(CCF)	ELEV.	SLOPE	SL X SIN (ASPECT)	SL X COS (ASPECT)
Aspen	380	0.168*	-0.476*	-0.218*	-0.441*	-0.528*	0.319*	-0.141*	0.070	-0.036
Paper birch	567	-0.137*	-0.234*	-0.065*	-0.272*	-0.374*	-0.102*	0.101*	0.003	-0.309*
Douglas-fir	8664	-0.383*	-0.112*	0.061*	-0.209*	-0.423*	0.177*	-0.052*	-0.014	-0.095*
Lodgepole pine	3367	-0.384*	-0.466*	-0.116*	-0.424*	-0.558*	0.017	0.003	-0.051*	-0.312*
Hybrid spruce	492	-0.413*	-0.176*	-0.014	-0.262*	-0.267*	-0.067	0.102*	-0.024	-0.065

Notes: HT/DBH is height to diameter at breast height (DBH) ratio; ln is natural logarithm, CCF is crown competition factor, BAL is the basal area in larger trees in m^2/ha, SL is slope percent expressed as a ratio, SL X sin(ASPECT) is product of slope and the sine (ASPECT in radians); SL_COS(ASPECT) is product of slope and the cosine of stand (ASPECT in radians).

Table 3. Fit statistics for full model with all variables and models with size, competition (Comp), and site variables, separately

Species	Number of trees	I^2				$\hat{SEE}$			
		All	Size	Comp	Site	All	Size	Comp	Site
Aspen	380	0.57	0.38	0.32	0.18	0.11	0.13	0.13	0.15
Paper birch	567	0.29	0.15	0.15	0.14	0.14	0.16	0.16	0.16
Douglas-fir	8664	0.34	0.24	0.19	0.05	0.17	0.17	0.17	0.19
Lodgepole pine	3367	0.48	0.41	0.35	0.23	0.16	0.16	0.17	0.19
Hybrid spruce	492	0.36	0.22	0.03	0.16	0.16	0.17	0.19	0.18

aspen, indicating that trees that were tall and slender had lower CR values. For all tree species, CR decreased with an increase of both competition variables. For spruce, the most shade-tolerant of the five species, correlations between CR and competition variables were lower than for other species. The commonly used competition measure CCF (included as ln(CCF)) appeared to relate well to CR, even in these multi-species and multi-layered stands. The variable BAL generally had weaker correlations with CR than did ln(CCF), but stronger correlations than most other variables. Correlations were generally low for CR with site variables, except for aspen where the correlation between CR and elevation was slightly over 0.3, and the directions of correlations were not consistent among species. Simple correlations were positive for CR with elevation and slope for some species and negative with others. Correlations between the size variables were quite high (absolute value more than 0.6), as were correlations between the two competition variables; correlations between site variables were generally less than 0.3 in absolute value (not shown). Across variable groups, size variables were moderately to strongly related to competition variables for all species.

Model evaluation and interpretation

Only minor changes in SEE were noted between using all variables, versus using size, competition, or site variables, separately (Table 3). Since CR is constrained to the interval [0,1], SEE differences were, necessarily, small. Competition variables alone had I^2 values similar to the size variables alone, except for the more shade-tolerant species, spruce. Since diameter differences are largely due to competition, much of the effects of competition on CR are likely already accounted for by the tree size variables, even for multi-species and multi-layered stands. Dropping BAL from the competition variables resulted in little change, indicating that this variable did not improve results once CCF was in the model, even for these complex stands. Using only site variables resulted in I^2 values that were generally smaller than for the size or competition variable groups, except for spruce. Hasenauer and Monserud (1996) found that the site variables contributed less than 10% for all tree species considered in their study. For this study, site variables accounted for 5% (Douglas-fir) to 23% (lodgepole pine) of the variability in crown ratio.

Based on the stepwise linear least squares regression of Eq. 6, a subset of variables was selected. Eq. 2 was refitted using nonlinear least squares with the reduced set of variables (Table 4). For all species, HDR and HT, representing tree size, and ln(CCF), representing competition, were selected. The coefficient for HT was always positive, unlike the simple correlations between CR and HT (Table 2), indicating that the size variables cannot be interpreted separately. Similarly, the coefficient with ln(CCF) was positive, unlike the simple correlations. However, taking the size variables as a group and using Eq. 3, as well as the competition variables as a group using Eq. 4, CR decreased with increasing size and competition for each species, as demonstrated for Douglas-fir in Fig. 1. Similar trends were found by Hasenauer and Monserud (1996). Generally, crowns are expected to be longer for lower densities (e.g., Oliver and Larson 1996, Clutter *et al.* 1983). Conversely, trees with close neighbours on all sides maintain small live CR and eventually slow in diameter growth. The interpretation of the size variable is a bit more complex, since slenderness (HDR) was included. To examine this relationship further, slenderness was isolated from SIZE, and a graph of the relationship

Table 4. Parameter estimates for CR model by species. Only significant variables were included (α = 0.05).

					Tree size variables			Competition variables				Site variables			
Species	Number of trees	I^2	$\hat{SEE}$	Inter-cept	HT/ DBH (m/cm)	Height (m)	DBH^2 (cm^2)	BAL (m^2/ha)	ln (CCF)	ELEV	$ELEV^2$	SL (%/ 100)	SL^2 (%/ $100)^2$	SL X sin (ASP)	SL X cos (ASP)
Aspen	380	0.56	0.109	-0.9316	-0.7360	0.0781	-0.00168	0.0215	0.3847		-0.00515				
Paper birch	567	0.25	0.148	-3.1768	0.5736	0.0302			0.4414			-0.4121		0.1041	0.5181
Douglas-fir	8664	0.34	0.156	-5.8511	1.6929	0.0263	-0.0001	-0.00629	0.8405		-0.00192		0.1379	-0.1376	-0.0626
Lodgepole pine	3367	0.48	0.155	-4.5926	0.7209	0.0655	-0.00065	0.00618	0.5035	0.2668	-0.017	-0.4512		0.0594	0.1837
Hybrid spruce	492	0.33	0.164	-4.9339	1.4023	0.0427		0.0241	0.3179						

Notes: HT/DBH is height to diameter at breast height (DBH) ratio; ln is natural logarithm, CCF is crown competition factor, BAL is the basal area in larger trees in m^2/ha, ELEV is elevation in hectometres (100 metres); SL is slope percent expressed as a ratio, SL X sin(ASP) is product of slope and the sine (aspect is in radians) and SL_COS(ASP) is product of slope and the cosine of stand.

Table 5. Prediction statistics for the percent live crown ratio model using the test data set

		Fit statistics		
Species	Number of Trees	bias	$\hat{SEE}$	I^2
Douglas-fir	468	0.019	0.13	0.35
Lodgepole pine	176	-0.037	0.16	0.20
Hybrid spruce	52	-0.044	0.20	0.06

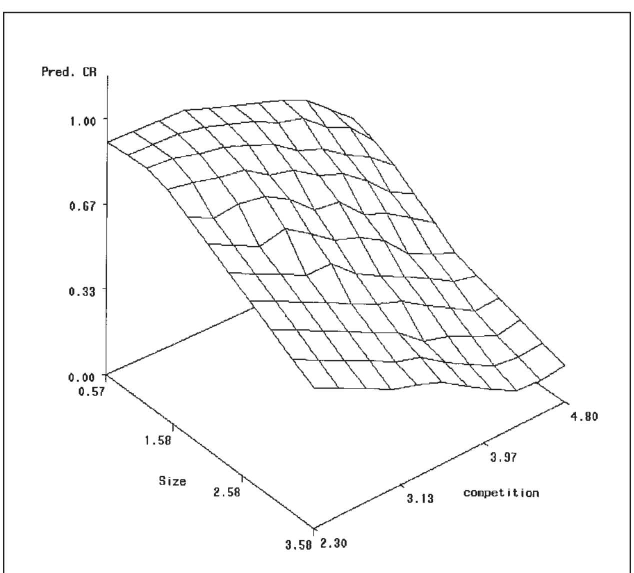


Fig. 1. Predicted crown ratio (Pred. CR) versus size (Eq. 3) and competition (Eq. 4) groups of variables for Douglas fir (n = 8664).

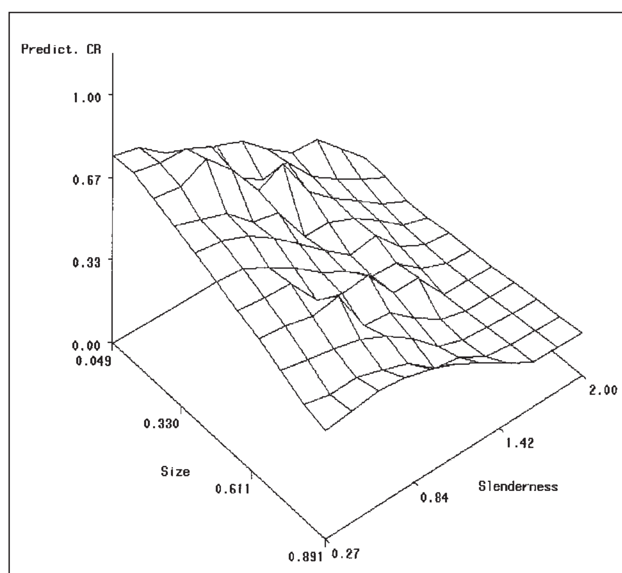
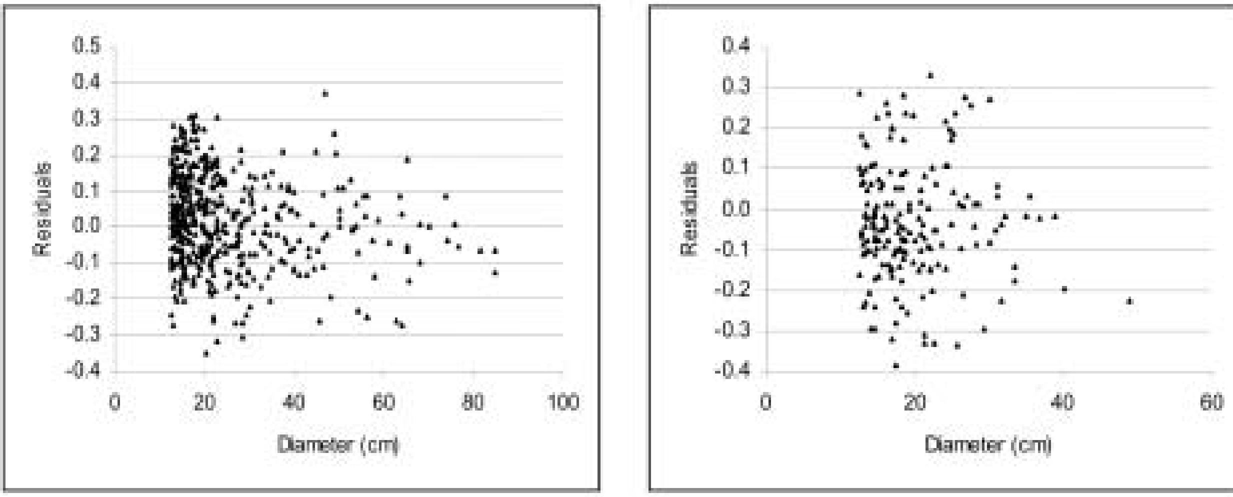
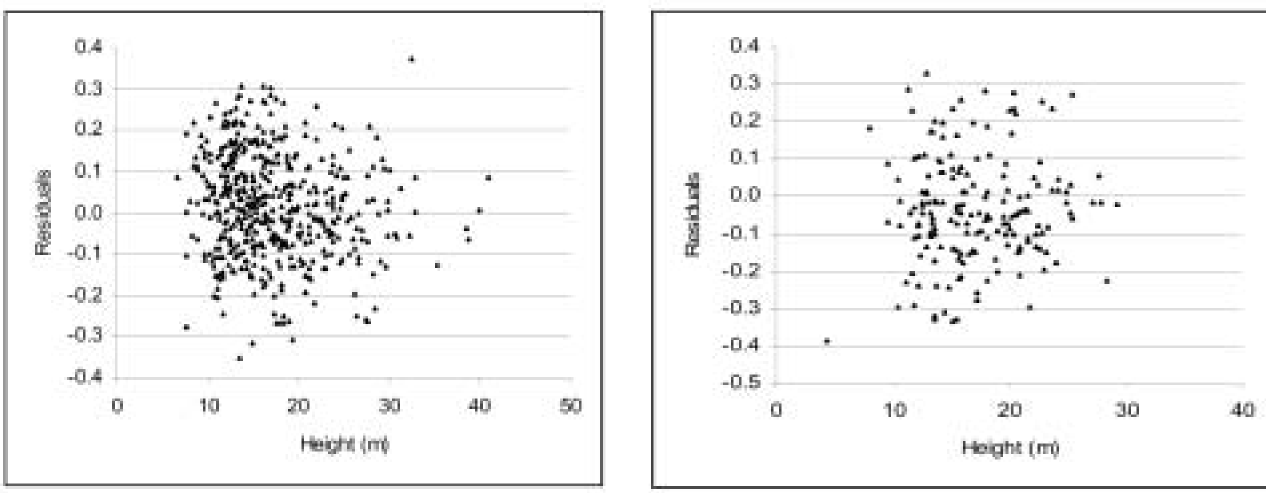


Fig. 2. Predicted crown ratio (Pred. CR) versus height to diameter ratio (HDR) and size based on diameter and height only for Douglas fir (n = 8664).



a) b)

Fig. 3a. Differences between observed vs. predicted (residuals) crown ratio over diameter for Douglas-fir (a) and lodgepole pine (b), using test data.



a) b)

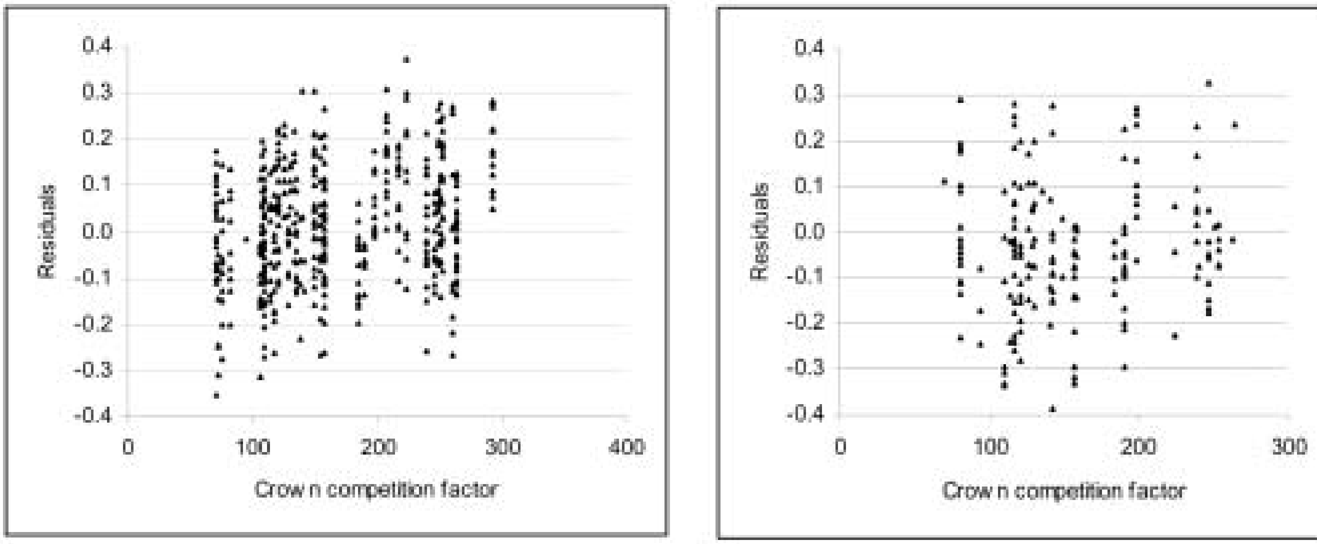
Fig. 3b. Differences between observed vs. predicted (residuals) crown ratio over tree height for Douglas-fir (a) and lodgepole pine (b), using test data

between predicted crown ratio versus SIZE based on DBH and height only, and slenderness was obtained (Fig. 2). As DBH and height increased, SIZE increased, resulting in a reduction in predicted crown ratios. As slenderness values increased, the predicted crown ratios also declined, indicating that taller, narrower trees have shorter crowns. This is expected, since taller, narrower trees are often the result of increased competition among stems.

For the test dataset, the estimated SEE values (Table 5) were similar to those of the model building dataset (Table 4). Bias values were quite low. The I^2 value for hybrid spruce was very low (0.06), but there were only 52 hybrid spruce trees in the test dataset. It should be noted that there was a lack of small tree data (DBH < 12.5 cm) in the test dataset, and the hardwood species were not well represented.

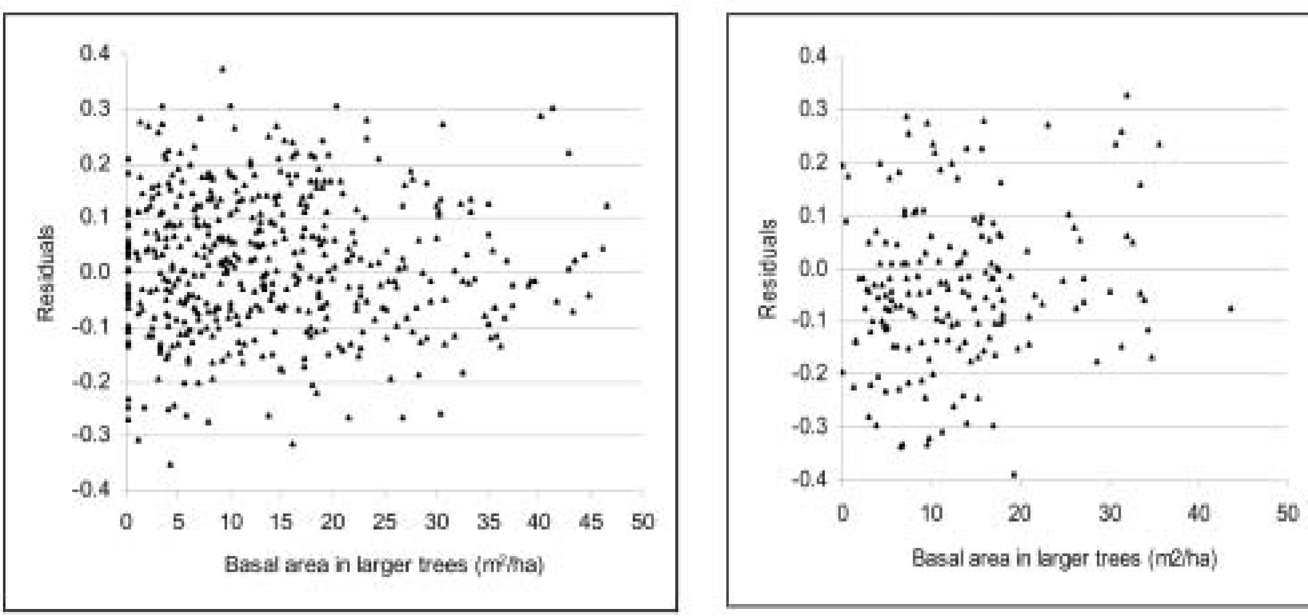
Moreover, when differences between observed and predicted crown ratio values were compared over tree size and competition measures, no evidence of lack of fit was found. The models predict crown ratio across tree sizes and relative positions of trees (in a stand) reasonably well (Fig. 3a to 3d) for both the modeling and the independent test data.

The CR models included predictor variables that are commonly measured and affect or indicate changes in CR. The addition of BAL to reflect competition in complex



a) b)

Fig. 3c. Differences between observed vs. predicted (residuals) crown ratio over basal area in trees larger than the subject tree for Douglas-fir (a) and lodgepole pine (b), using test data.



a) b)

Fig. 3d. Differences between observed vs. predicted (residuals) crown ratio over crown competition factor for Douglas-fir (a) and lodgepole pine (b), using test data.

stands did not improve the results over using CCF alone. A simple investigation incorporating structural indices of diversity in size and species within a stand (Staudhammer and LeMay 2001) indicated no real improvements in CR predictions for these complex stands. However, other variables that reflect differences in available growing space (e.g., spatial competition measures) might improve the accuracy of CR prediction for these complex stands, if these measures are available at a lesser cost than measuring CR directly.

Conclusion

Live crown ratio models for five species growing in multi-species and multi-layered stands of southeastern BC were fitted using easily measured variables of size, competition, and site. Logical trends in CR versus size and competition variable groups were reflected by the models, and the inclusion of site variables resulted in improvements for some species. Variables used were similar to those previously used for even-aged, single-species stands, except for basal area of larger trees. Size variables were, generally, the best predictors of CR variability, corresponding with other studies in more homogeneous stands. Since size variables do reflect differences in competition and site productivity, this may partly explain the lesser influence of competition and site variables in the CR models. The developed crown ratio models will be incorporated into existing growth models such as Prognosis^{BC} where crown ratio measures are not available. Improvements to model prediction may be obtained using spatial competition measures if these can be obtained at reasonable cost.

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