Maximum and Largest Crown Width Equations for 15 Tree Species in Maine

Matthew B. Russell and Aaron R. Weiskittel

ABSTRACT

An extensive statewide data set for seven conifer and eight hardwood species commonly occurring in Maine was used in the development of maximum and largest crown width equations. To establish the characteristics of open-grown trees, quantile regression was used to estimate the biological maximum crown width for a species at a given diameter. To predict crown widths of trees in forested settings, a constrained nonlinear equation was used, using the predicted maximum crown width, tree diameter, and crown ratio. The models performed well across the wide range of stand conditions present in the data set and improved predictions over the currently used crown width equations for most species (reduction of mean absolute error ranged from 1 to 23%). In general, predictions of largest crown width were not greatly improved with the inclusion of crown ratio, and there was a high amount of unexplained variation for shade-tolerant hardwood species, such as American beech (*Fagus grandifolia*) and sugar maple (*Acer saccharum*). The equations presented herein can be used in examining tree crown profiles, computing measurements of stand density, and investigating canopy dynamics for species common to the forests of Maine.

Keywords: crown diameter, crown profile, open grown, quantile regression

Measurement of crown width is not common in forest inventories, yet this value has wide applicability in forestry. Determining the biological potential for crown width of open-grown trees is needed for estimating stand-level metrics of density, such as crown competition factor (CCF) (Krajicek et al. 1961). Estimates of crown width can also be used to calculate stand canopy closure, which is important for assessing wildlife habitat suitability, fire risk, and understory light conditions for regeneration (Crookston and Stage 1999). Consequently, quantification of crown width attributes is an important component of many forest growth and yield models. As an example, the Forest Vegetation Simulator uses equations developed using open-grown trees to compute CCF but uses separate equations developed with forest-grown trees for estimating percentage of canopy cover (Crookston and Dixon 2005).

Although specific requirements for selecting open-grown trees are available (Paine and Hann 1982), finding trees that meet these criteria and making this determination can be laborious, and judgments are inherently subjective. Open-grown trees are commonly used in estimating maximum crown width (mcw), which is then related to tree dbh. Other variables, such as geographic location, appear to offer marginal improvement in estimating mcw (Paine and Hann 1982). Hasenauer (1997) found that the relationship between mcw and dbh was also influenced by site factors such as elevation, aspect, and slope. Despite the importance of mcw, there are currently no regional mcw equations for most of the important commercial species in the northeastern United States. Ek (1974) developed mcw equations for several species in the Lake States region, but their applicability for use with trees found in Maine is not known.

A forest-grown tree of a given species displays a horizontal crown extension that is less than that of an open-grown tree. The basic measure of crown width within a forested stand is the largest crown width (lcw) of a given tree (Hann 1998). Hence, lcw equations differ from mcw equations in that they predict the crown widths of trees growing in forested settings. This is important for estimating forest canopy cover (Gill et al. 2000) and understanding species differences in crown structure and implied canopy dynamics. Bechtold (2003) developed lcw equations that covered a broad portion of the eastern United States. Geographic location accounted for some of the observed variation in lcw; however, dbh alone explained much of this observed variability (Bechtold 2003). Although Hann (1998) found that including crown ratio was effective for improving predictions of lcw, other studies have found it to have a limited predictive power (Gill et al. 2000, Bechtold 2003). Including other variables, such as total height, did not significantly contribute in the estimation of tree crown widths for species growing in Spain (Condés and Sterba 2005). Bragg (2001) similarly found that the inclusion of stand basal area did not significantly improve model fit for the majority of species examined, as the adjusted R^2 increased by only 2.5%, on average. If stand-level measures are important in describing tree crown attributes, relative measures of stand density may outperform traditional measures like stand density index, number of trees per hectare, and stand basal area (Ducey 2009). Recently, Jordan and Ducey (2007) found the equation of Bechtold (2003) to consistently overpredict lcw for eastern white pine (*Pinus strobus* L.) trees grown in New Hampshire by 0.34 m. This led us to

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This article uses metric units; the applicable conversion factors are: centimeters (cm): 1 cm = 0.39 in.; meters (m): 1 m = 3.3 ft; hectares (ha): 1 ha = 2.47 ac.

question the applicability of using equations developed over broad geographic areas in more localized regions with specific growing conditions.

Model form and appropriate estimation of parameters are crucial for accurate and robust predictions. For both mcw and lcw equations, linear (e.g., Krajicek et al. 1961, Bechtold 2003), curvilinear (e.g., Paine and Hann 1982), or nonlinear functions (e.g., Ek 1974) have been used. Although no significant differences between linear and nonlinear model forms for predicting mcw have been reported (Leech 1984), a curvilinear or nonlinear model form in theory is more biologically logical, and the equations would seemingly produce reliable extrapolations. In addition, an lcw equation bound by the species mcw is reasonable, as it would not be plausible to allow a tree's lcw to be greater than its potential mcw. However, estimating the parameters of an mcw equation using ordinary least squares would be difficult, as the interest is in the maximum rather than the average crown width. Quantile regression has been used to determine stand maximum size-density lines (Zhang et al. 2005) and individual tree potential growth rates (Pretzsch and Biber 2010). This technique might also be effective for estimating the parameters for an mcw equation.

The goal of this analysis was to develop mcw and lcw equations for seven conifer and eight hardwood tree species found in three ecoregions throughout Maine. The primary objectives were to (1) assess the performance of the Ek (1974) and Bechtold (2003) equations for estimating mcw and lcw, respectively, in Maine; (2) use quantile regression to estimate parameters of species-specific mcw equations; and (3) evaluate the effectiveness of crown ratio for improving predictions of lcw.

Methods

Study Area

Maine comprises nine separate climatic zones, which strongly influence the composition and structure of its forests (Briggs and Lemin 1992). Across these zones, average annual precipitation is 110 cm, with a range of 95 to 125 cm, and mean growing degree-days (sum of temperature $>5°C$) is 2,133 (range, 1,508–2,976; Briggs and Lemin 1992). Glacial till is the principal soil parent material, with soil types ranging from well-drained loams and sandy loams on glacial till ridges to poorly and very poorly drained loams on flat areas between these low-profile ridges. In general, the northern conifer sites from which many of the trees sampled in this study were drawn are underlain by poorly to very poorly drained loams and silt loams.

Maine is part of the Acadian forest, which is a transition zone between the conifer-dominant boreal forests of the north and the mixed hardwood forests of the South (Braun 1950). Common conifer species include balsam fir (*Abies balsamea* [L.] Mill.), red spruce (*Picea rubens* Sarg.), white spruce (*Picea glauca* [Moench] Voss), eastern white pine (*P. strobus* L.), eastern hemlock (*Tsuga canadensis* [L.] Carr.), black spruce (*Picea mariana* [Mill.] B.S.P.), and northern white-cedar (*Thuja occidentalis* L.). Hardwoods commonly found include red maple (*Acer rubrum* L.), paper birch (*Betula papyrifera* Marsh.), gray birch (*Betula populifolia* Marsh.), yellow birch (*Betula alleghaniensis* Britt.), quaking aspen (*Populus tremuloides* Michx.), bigtooth aspen (*Populus grandidentata* Michx.), American beech (*Fagus grandifolia* Ehrh.), northern red oak (*Quercus rubra* L.), and sugar maple (*Acer saccharum* Marsh.). Red spruce, white spruce, and balsam fir dominate the relatively low-lying sites of poorer drainage, but the proportion of eastern hemlock and white pine increases as drainage improves.

Data

The data for this analysis came from three primary sources at a range of locations throughout Maine: (1) US Forest Service Forest Health Monitoring (FHM) program, (2) US Forest Service Northern Research Station, Penobscot Experimental Forest (PEF), and (3) University of Maine Cooperative Forestry Research Unit (CFRU). Each data set is further described below.

FHM

The FHM program collected information on one hundred twenty-three 0.07-ha plots throughout each of the 16 counties in Maine from 1991 to 1999. Some plots were remeasured during this period. The FHM data contained 7,042 observations representing 15 species of primary interest. All crown measurements were collected on trees with a dbh greater than 12.7 cm. The maximum horizontal diameter of the widest axis of the tree crown and the distance perpendicular to this axis were measured. A complete description of the FHM data can be found in Bechtold (2003).

PEF

The PEF, located in the towns of Bradley and Eddington, Maine, is a long-term experiment investigating effects of even-, two-, and uneven-aged silvicultural systems in the Acadian forest (Sendak et al. 2003). Dominated by northern conifers but also including hardwood species, the mixed-species stands found at the PEF are common to Maine's forests and represent a wide range of management strategies. Tree crown and height measurements have recently begun to be collected on a subset of continuous forest inventory (CFI) plots at the PEF. Crown measurements in this analysis were obtained from 2,993 individual trees on 81 plots (0.08 ha) across the PEF. In addition, 2,698 crown measurements were also made on 20 CFI plots across the PEF by Saunders and Wagner (2008) and were used in this analysis.

CFRU

The CFRU data set came from an early investigation of thinning in spruce-fir forests (McCormack 1989). It consisted of four locations across Maine: the townships of Lakeville Plantation, T5 R15 WELS, T11 R16 WELS, and T11 R13 WELS. Stand ages at time of establishment ranged from 17 to 70 years. Thirty-one plots of varying size were measured up to four times from 1978 to 1994 across these locations. The measurements were from 1,012 red spruce, 348 black spruce, 144 white spruce, and 95 balsam fir.

For all data sets, crown ratio was recorded as the proportion of live crown length measured from the top of the tree to the lowest live branch where it intersects the bole (i.e., uncompacted crown ratio). For the FHM data, ocular measurements of crown ratio were made in 5% increments. In both the PEF and CFRU data sets, tree dbh, total height, and height to crown base were recorded and crown radii (r) were measured from the center of the bole of each tree to the edge of its crown in each of the cardinal directions (N, S, E, W). For the FHM data, the maximum horizontal diameter of the widest axis of the tree crown and its perpendicular distance were each divided by two and considered as crown radii measurements. Quadratic mean crown width was computed as $2(\sqrt{(r_1^2 + r_2^2 + r_3^2 + r_4^2)/4})$ for all data sets to provide an unbiased estimation of crown area irrespective of crown shape (Gregoire and Valentine 1995, Figure 1).

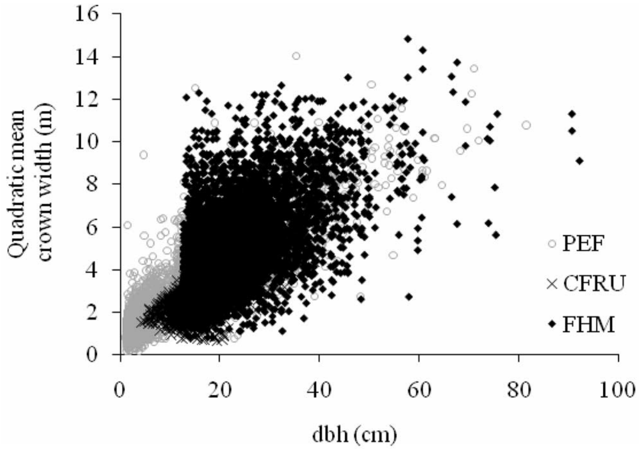

Figure 1. Quadratic mean crown width and tree dbh for Penobscot Experimental Forest (PEF), Cooperative Forestry Research Unit (CFRU), and Forest Health Monitoring (FHM) data.

Table 2. Parameter estimates (standard errors in parentheses) by species for predicting the maximum crown width (mcw) (m) using tree dbh (cm) for seven conifer and eight hardwood species growing in Maine.

Species	a_1	a_2
Conifers		
Balsam fir	1.37 (0.039)	0.572 (0.021)
Black spruce	0.535 (0.21)	0.742 (0.14)
Eastern hemlock	2.44 (0.42)	0.408 (0.055)
Eastern white pine	1.24 (0.49)	0.585 (0.10)
Northern white-cedar	1.63 (0.44)	0.436 (0.087)
Red spruce	1.80 (0.46)	0.461 (0.075)
White spruce	1.50 (0.46)	0.496 (0.10)
Hardwoods		
American beech	2.93 (0.65)	0.434 (0.077)
Gray birch	2.24 (1.8)	0.382 (0.28)
Northern red oak	4.08 (2.0)	0.310 (0.16)
Paper birch	1.48 (0.24)	0.623 (0.056)
Quaking aspen	1.31 (0.24)	0.586 (0.059)
Red maple	2.17 (0.19)	0.491 (0.030)
Sugar maple	3.31 (0.66)	0.356 (0.06)
Yellow birch	4.04 (0.79)	0.308 (0.062)

Model is mcw = $a_1 \text{dbh}^{a_2}$.

Tree data according to species are summarized in Table 1. Observations that were coded as displaying a broken or dead top or greater than 50% crown dieback were excluded from this analysis. Data were obtained on sites representing each of the three ecoregions occurring in Maine as described in Bailey (1980): the Laurentian mixed forest (212), Adirondack-New England mixed forest (M212), and eastern broadleaf (oceanic) forest provinces (221). The data encompassed a range of geographic locations, stand conditions, and management strategies common to Maine's forests.

Model Development

Maximum Crown Width

To determine a species mcw at a given tree diameter, multiple measurements from open-grown trees are required. However, determining whether a tree is open-grown is not necessarily common, and the qualifications of the "open-grownness" of trees in forested stands may lend themselves to some subjectivity. One approach to circumvent this is to use quantile regression techniques to estimate a species-specific mcw for a given tree diameter. Least-squares regression techniques estimate a response variable that is conditioned solely on the statistical mean, whereas quantile regression methods allow estimation of response variables for any quantile of the data (Koenker and Hallock 2001). Given that the data comprised a wide range of tree crown widths (both open- and forest-grown) and that the interest is in estimating the maximum potential crown width for a species at a given dbh, the 99th quantile was fit to represent the maximum crown width for open-grown trees. A nonlinear allometric equation was used

$$\text{mcw} = a_1 \text{dbh}^{a_2}, \tag{1}$$

where dbh is tree dbh (cm) and a_i values are coefficients estimated from the 99th percentile used to represent maximum crown width

Table 1. Summary statistics and species proportion within each data set for data used to fit crown width models for seven conifer and eight hardwood species occurring in Maine.

			dbh				Quadratic mean crown width				Crown ratio (proportion)				Species proportion		
Species	Code	n	Mean	SD	Min	Max	Mean	SD	Min	Max	Mean	SD	Min	Max	FHM	PEF	CFRU
			(cm)				(m)										
Conifers																	
Balsam fir	BF	3605	12.2	7.0	1.1	40.1	2.8	1.3	0.3	12.5	0.57	0.21	0.02	1.00	0.30	0.67	0.03
Black spruce	BS	400	14.6	3.5	4.3	23.6	2.4	0.7	0.8	5.2	0.63	0.17	0.17	1.00	0.13		0.87
Eastern hemlock	EH	1127	23.1	11.1	1.3	57.4	5.3	2.0	1.2	12.1	0.65	0.18	0.02	0.99	0.37	0.63	
Eastern white pine	WP	866	25.6	15.7	1.4	92.2	5.0	2.4	0.6	14.8	0.54	0.20	0.10	0.99	0.65	0.35	
Northern white-cedar	WC	866	22.7	7.6	1.6	59.7	3.7	1.2	0.8	10.5	0.64	0.17	0.01	0.99	0.78	0.22	
Red spruce	RS	2994	19.7	7.2	1.2	56.9	3.6	1.4	0.7	12.1	0.52	0.18	0.04	1.00	0.40	0.26	0.34
White spruce	WS	339	17.4	7.1	1.5	40.6	3.5	1.2	0.6	9.3	0.67	0.19	0.15	1.00	0.36	0.21	0.43
Hardwoods																	
American beech	AB	325	21.3	6.7	11.9	43.4	6.0	2.0	1.4	12.2	0.60	0.20	0.15	0.99	0.99	0.01	
Gray birch	GB	251	6.4	4.7	1.3	25.4	2.1	1.3	0.2	9.4	0.43	0.15	0.08	0.95	0.14	0.86	
Northern red oak	RO	102	24.3	10.3	12.7	66.8	6.3	2.3	2.1	13.1	0.48	0.10	0.15	0.75	1.00		
Paper birch	PB	576	16.4	8.4	1.3	37.3	4.3	2.1	0.2	14.0	0.44	0.15	0.01	0.95	0.65	0.35	
Quaking aspen	QA	353	18.2	7.5	1.3	45.4	4.2	1.7	0.4	10.7	0.39	0.15	0.10	0.99	0.73	0.27	
Red maple	RM	1785	18.2	8.6	1.3	54.9	4.9	2.1	0.2	12.2	0.49	0.15	0.07	0.99	0.61	0.39	
Sugar maple	SM	355	24.4	9.6	12.7	73.9	6.2	2.0	2.4	14.3	0.55	0.14	0.30	0.90	0.98	0.02	
Yellow birch	YB	388	23.6	8.9	1.5	54.1	6.3	2.2	1.9	13.0	0.58	0.17	0.15	0.95	0.97	0.03	

Min, minimum; max, maximum; FHM, Forest Health Monitoring; PEF, Penobscot Experimental Forest; CFRU, Cooperative Forestry Research Unit.

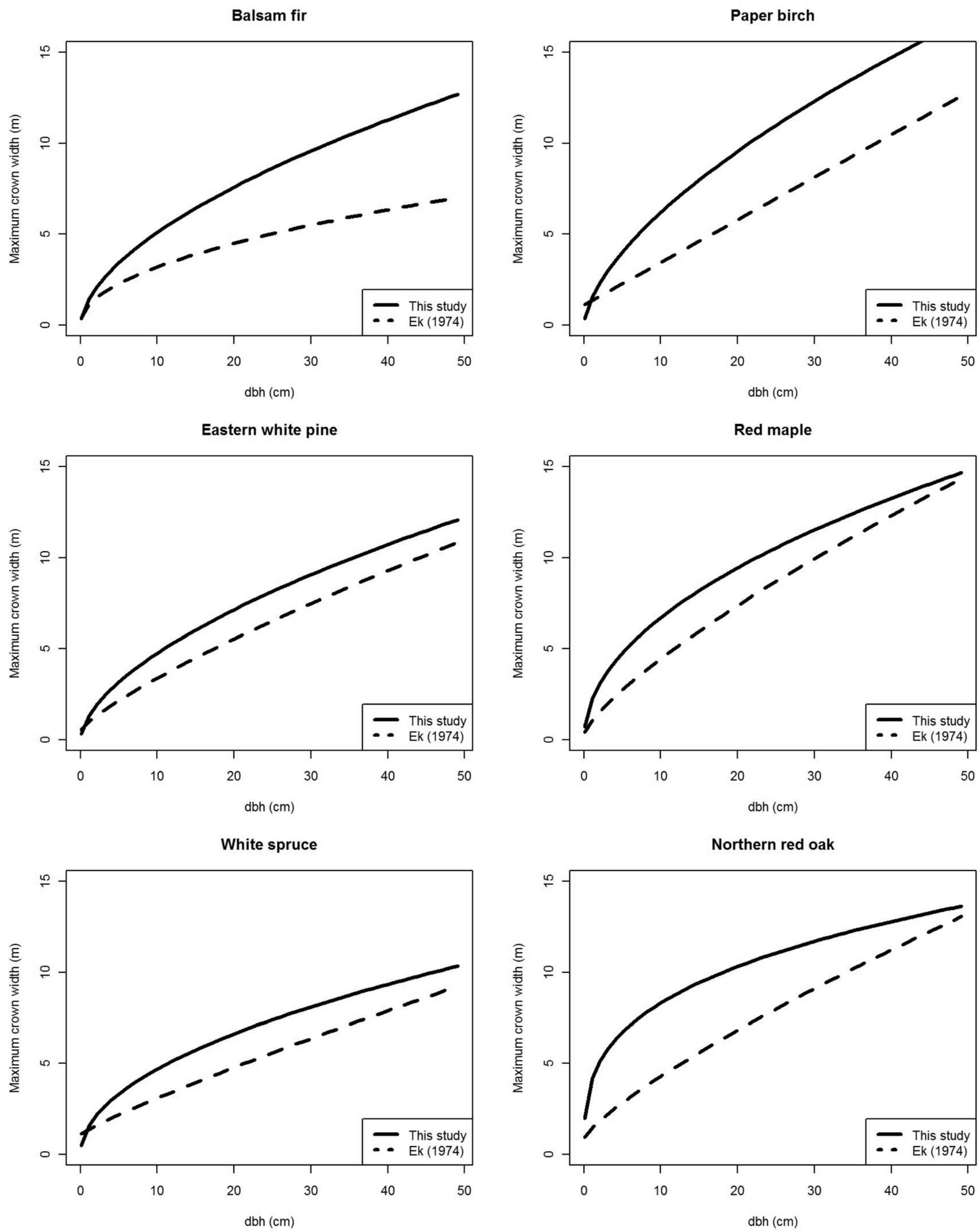

Figure 2. Predicted maximum crown width (m) across a range of tree dbh values (cm) using the equations developed in this study and those of Ek (1974) for several conifer and hardwood species.

(m) for each species. Preliminary analysis indicated that this mcw model form performed better than the one used by Ek (1974).

Largest Crown Width

Whereas Equation 1 predicts the biological maximum crown width for a species at a given dbh, lcw predicts crown size for trees that are not able to reach their biological maximum because they grow in denser forested stands. Recognizing the relationship between open-grown and forest-grown trees, constrained predictions of lcw were made to be less than or equal to that of the mcw curve. A nonlinear equation was fit to the data that took the form,

$$\mathrm{lcw} = \frac{\mathrm{mcw}}{b_1 \mathrm{dbh}^{b_2}}, \tag{2}$$

where mcw is the predicted maximum crown width of the tree at its corresponding dbh (Equation 1) and b_i values are estimated coefficients. Bechtold (2003) found that including tree live-crown ratio decreased the root mean square error by 9 and 3% on average for

Table 3. Parameter estimates (standard errors in parentheses) by species with fit index (FI) and mean absolute error (MAE) for predicting the largest crown width (lcw) (m) using tree diameter at breast height (dbh) (cm) and crown ratio (cr) for seven conifer and eight hardwood species growing across three ecoregions in Maine. Comparisons of MAEs with those of Bechtold's (2004) Equations 4 and 5 are also presented.

	Equation 2: $\text{lcw} = \text{mcw}/(b_1 \text{dbh}^{b_2})$					Equation 3: $\text{lcw} = \text{mcw}/(c_1 \text{dbh}^{c_2} \text{cr}^{c_3})$					
				MAE[b]						MAE[b]	
Species	b_1	b_2	FI[a]	This study	Bechtold (2004) Equation 4	c_1	c_2	c_3	FI[a]	This study	Bechtold (2004) Equation 5
Conifers											
Balsam fir	1.49 (0.017)	0.105 (0.0050)	0.55	0.58	0.65	1.17 (0.020)	0.159 (0.0057)	−0.187 (0.012)	0.57	0.56	0.60
Black spruce	—	0.174 (0.0045)	0.35	0.46	0.47	1.34 (0.027)	—	−0.346 (0.038)	0.49	0.40	0.41
Eastern hemlock	1.90 (0.058)	−0.057 (0.010)	0.56	1.01	1.06	1.77 (0.055)	−0.055 (0.0097)	−0.145 (0.022)	0.58	1.00	1.11
Eastern white pine	—	0.147 (0.0033)	0.56	1.18	1.08	1.30 (0.021)	—	−0.304 (0.022)	0.68	0.98	1.01
Northern white-cedar	2.19 (0.20)	−0.080 (0.029)	0.27	0.77	0.79	1.52 (0.024)	—	−0.249 (0.030)	0.34	0.74	0.76
Red spruce	4.33 (0.21)	−0.264 (0.015)	0.43	0.77	0.96	3.51 (0.16)	−0.260 (0.014)	−0.284 (0.015)	0.50	0.71	0.92
White spruce	2.09 (0.16)	−0.069 (0.027)	0.51	0.59	0.64	2.19 (0.17)	−0.123 (0.029)	−0.239 (0.040)	0.57	0.56	0.70
Hardwoods											
American beech	—	0.194 (0.0058)	0.12	1.52	1.58	1.49 (0.042)	—	−0.342 (0.047)	0.28	1.37	1.41
Gray birch	3.10 (0.27)	−0.214 (0.04)	0.49	0.62	—	3.10 (0.27)	−0.214 (0.04)	—	0.49	0.62	—
Northern red oak	4.10 (0.89)	−0.272 (0.065)	0.43	1.31	1.29	4.10 (0.89)	−0.272 (0.065)	—	0.43	1.31	1.30
Paper birch	2.10 (0.13)	−0.035 (0.021)	0.59	1.00	1.04	1.67 (0.056)	—	−0.153 (0.037)	0.61	0.98	1.04
Quaking aspen	2.65 (0.26)	−0.157 (0.034)	0.57	0.87	0.88	2.17 (0.20)	−0.171 (0.032)	−0.242 (0.037)	0.60	0.83	0.86
Red maple	2.63 (0.11)	−0.132 (0.014)	0.56	1.05	1.15	2.22 (0.098)	−0.123 (0.014)	−0.190 (0.021)	0.58	1.03	1.14
Sugar maple	—	0.161 (0.0049)	0.17	1.44	1.38	1.43 (0.052)	—	−0.234 (0.055)	0.27	1.34	1.32
Yellow birch	4.23 (0.51)	−0.294 (0.037)	0.41	1.33	1.58	3.46 (0.42)	−0.275 (0.036)	−0.248 (0.045)	0.45	1.27	1.52

[a] $\text{FI} = 1 - [\sum_{i=1}^{n}(y_i - \hat{y}_i)^2 / \sum_{i=1}^{n}(y_i - \bar{y}_i)^2]$.
[b] $\text{MAE} = \sum_{i=1}^{n} |y_i - \hat{y}_i| / n$.

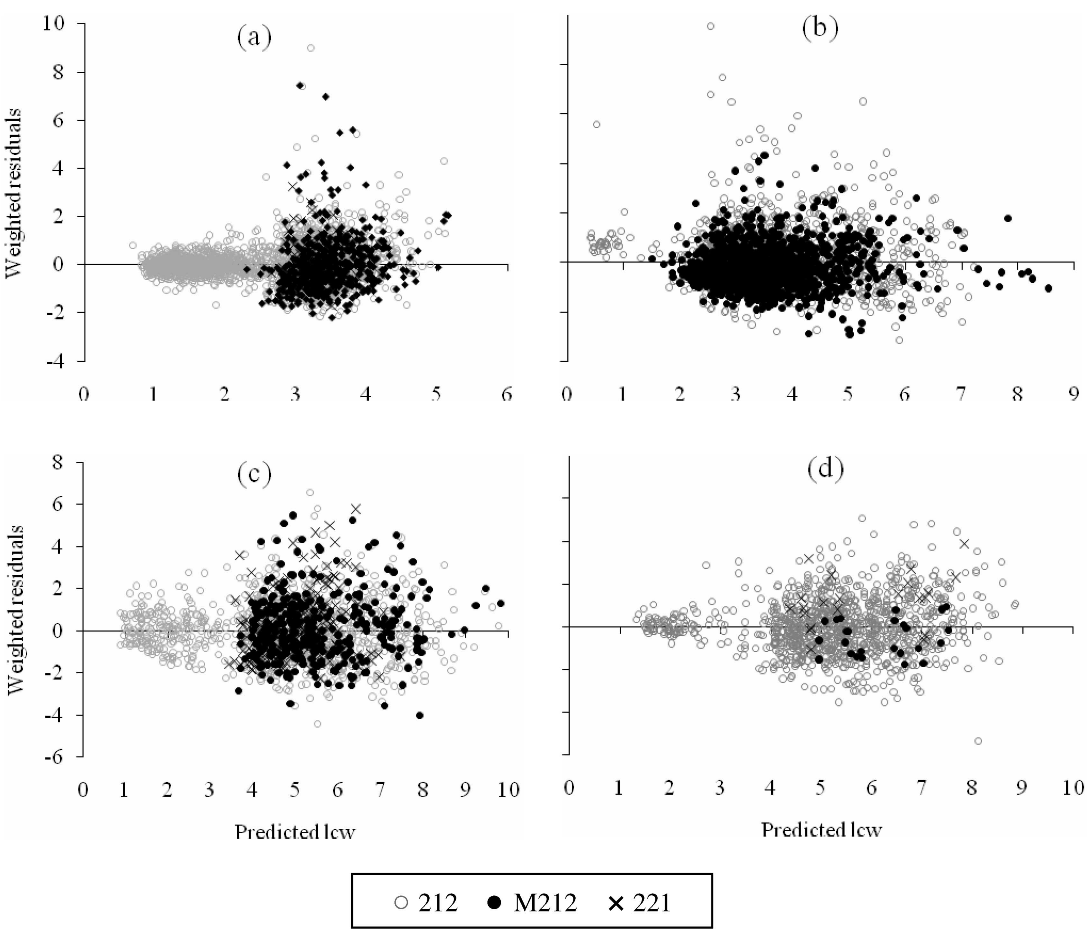

Figure 3. Weighted residuals and predicted lcw values for balsam fir (a), red spruce (b), red maple (c), and eastern hemlock (d) occurring in three ecoregions in Maine (Bailey 1980): Laurentian mixed forest (212), Adirondack–New England mixed forest (M212), and eastern broadleaf (oceanic) forest provinces (221).

conifer and hardwood species, respectively. Therefore, the relationship between crown ratio and lcw was investigated. Initially, the model form including crown ratio used by Hann (1998) was tested, but it resulted in unreliable extrapolations. Recognizing that crown ratio, whether made by ocular or direct measurement, is often a covariate used for predicting lcw, an equation of the following form was also fit:

$$\text{lcw} = \frac{\text{mcw}}{c_1 \text{dbh}^{c_2} \text{cr}^{c_3}}, \tag{3}$$

where cr is the crown ratio of the tree ($0 < \text{cr} \leq 1$), and c_i values are estimated coefficients. Unconstrained model forms of Equations 2 and 3 that did not include mcw in the numerator were also tested, but there was no indication of model improvement in terms of fit index or mean squared error for the majority of species examined.

The mcw and lcw model parameters were estimated in R using the nonlinear quantile regression (nlrq) and generalized nonlinear least-squares (gnls) functions, respectively. Although the data displayed a hierarchical structure (i.e., trees within plots within data set), preliminary analysis indicated that the use of mixed-effects analysis did not improve model fits. For the lcw models, a power function of dbh was used to weight the observations and overcome problems with heteroscedasticity in the data, i.e., $\text{Var}(\varepsilon_i) = \sigma^2 \text{dbh}_i^{\delta}$, where $\text{Var}(\varepsilon_i)$ is residual variance for tree i, σ^2 is the residual sums of squares, and δ is the variance function coefficient.

Results

Maximum Crown Width

All coefficients were positive, indicating that mcw increases nonlinearly with dbh (Table 2). Of all the species, northern red oak and yellow birch had the highest intercepts, whereas black spruce, eastern white pine, and paper birch had the steepest slopes. Drastic differences between the mcw equations developed in this analysis and the equations of Ek (1974) were observed for several species (Figure 2). Values derived from mcw equations in this analysis were 45% higher than those of Ek (1974). The greatest differences were for balsam fir and paper birch.

Largest Crown Width

A strong positive correlation was observed between dbh and cr ($p < 0.001$). Crown ratio was not a significant predictor of crown width for two of the species examined (gray birch and northern red oak; Table 3). Surprisingly, cr alone proved to be a better predictor than dbh for six other species. Analysis of residuals did not indicate any trends in model predictive ability in each of the three ecoregions studied (Figure 3). For the dbh-only equation, fit index (FI) ranged from 0.12 to 0.59, and mean absolute error (MAE) (m) ranged from 0.46 to 1.52. For Equation 3, FI ranged from 0.27 to 0.68, and MAE ranged from 0.40 to 1.37. Including crown ratio as an additional predictor on average increased FI by 0.06 and lowered MAE by 0.05 m. Compared with previously published equations using similar variables (Bechtold 2003), reductions in MAE were observed in 12 of 14 species; MAE ranged from 1 to 19% and 1 to 23% using Equations 2 and 3, respectively. The improved predictions were greatest for red spruce, yellow birch, balsam fir, and red maple. American beech and sugar maple had the lowest FIs of any species.

Maximum and lcw curves for one conifer and one hardwood species are shown in Figure 4. Equations show that trees with a greater crown ratio will display an lcw curve that is closer to the mcw for the species. Coefficients from Equations 1–3 were regressed against species shade tolerance (Niinemets and Valladares 2006), and a mild correlation was observed between shade tolerance and the power coefficient associated with the dbh term in Equations 2 and 3 (Figure 5).

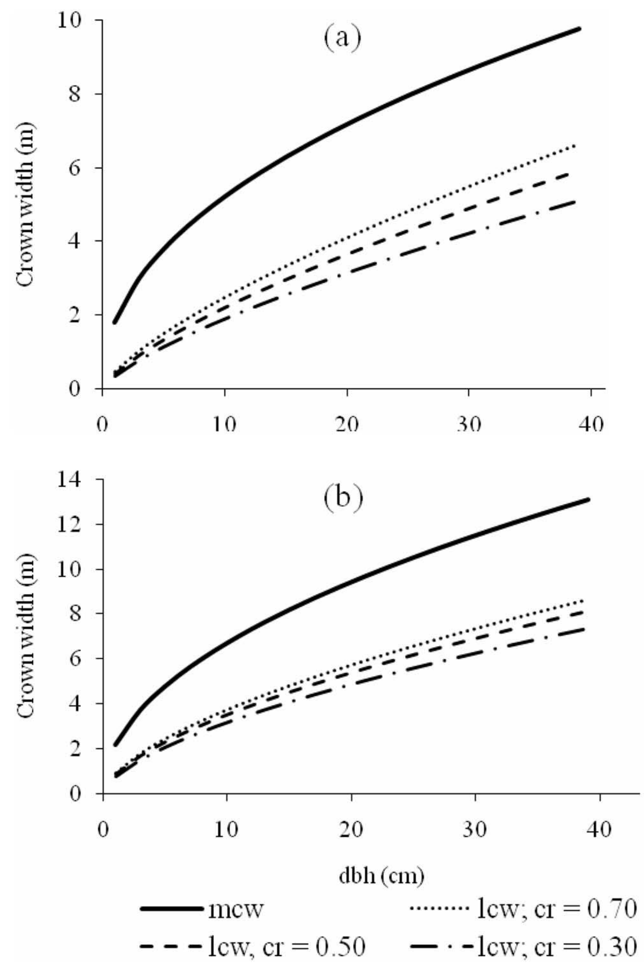

Figure 4. Predicted maximum crown width (mcw) and largest crown width (lcw) at crown ratios (cr) of 0.70, 0.50, and 0.30 for common conifer (red spruce [a]) and hardwood (red maple [b]) species growing in Maine.

Discussion

For the primary species occurring across Maine, mcw and lcw relationships appear to be adequately captured using tree dbh and cr. Quantile regression techniques provide the ability to capture the biological maximum of crown potential. Adapting this estimate using a nonlinear equation results in an accurate and constrained estimate of lcw. For most species, predictions were improved compared with previously published equations developed at more broad scales. These findings agree with Condés and Sterba (2005), who showed the effectiveness of using models driven by dbh for predicting crown widths. Although we did not directly test the influence of stand-level covariates (e.g., basal area per hectare) or geographic position on the crown width relationship, other studies have found that they do not drastically improve predictions. For example, Bragg (2001) found that including stand variables increased crown width prediction by only 2.5%, whereas Bechtold (2003) noted an increase in R^2 of only 1% when geographic position was included.

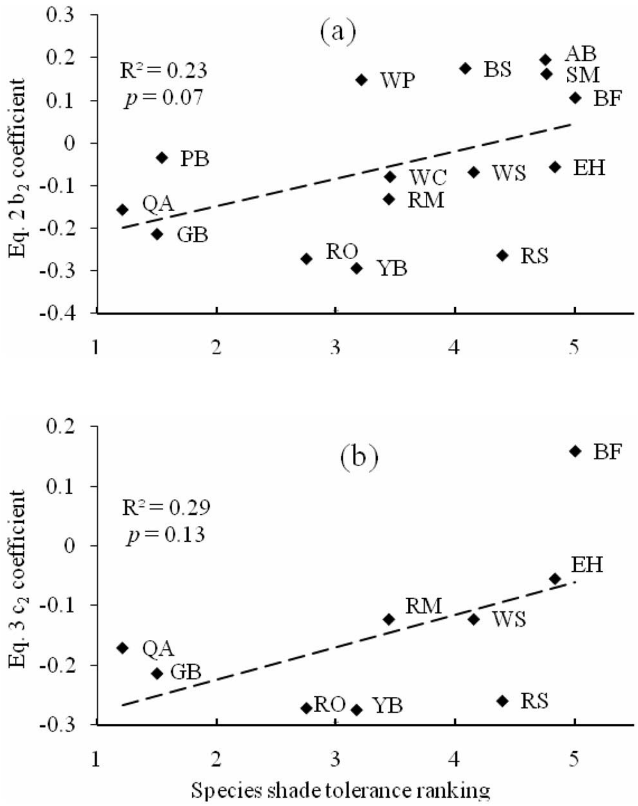

Figure 5. Comparisons of dbh power coefficient from Equations 2 (a) and 3 (b) for predicting the largest crown width with species-specific shade tolerance ranking (Niinemets and Valladares 2006). Species codes are as defined in Table 1.

Ease of use in model selection is an important criterion for equations that predict crown width (Jordan and Ducey 2007), and models that use tree dbh and cr offer wide applicability across multiple settings.

Tree dbh alone captured much of the variability in predicting the lcw for the 15 species examined, and the improvement when including cr (FI increased on average by 0.06) was close to the value that was found by Bechtold (2003). The fact that cr alone was a better predictor than diameter for some species may be because we did not have a wide range of diameters compared with other species (Table 1). The fact that cr alone proved to be a better predictor than dbh for six of the species examined is likely due to the strong positive correlation observed between dbh and cr. The lack of drastic improvements in the predictions due to crown ratio for other species could be attributed to the different methods of measurement in the various data sets. For example, cr was measured by sight in the FHM data set but was measured directly in PEF and CFRU data sets. However, an initial assessment using a mixed-effects model did not indicate that any bias could be attributed to the method of measurement.

The large differences between the presented mcw equations and those of Ek (1974) likely arise from three primary sources. First, geographic differences that influence tree crown attributes are likely apparent, as the Ek equations were developed using trees grown in the Lake States. Second, the data in this analysis used trees with a full range of crown widths and dbh, including measurements of trees with a minimum dbh of approximately 1.4 cm for most species. Finally, using quantile regression allowed for a quantitative estimation of the maximum potential crown width, whereas Ek (1974) used least-squares procedures conditioned solely on the statistical mean of the data. The findings of this study are similar to those of Bragg (2001), who found a mild trend between species shade tolerance and the regression coefficients associated with predicting lcws (Figure 5). Shade-tolerant hardwoods, such as sugar maple and American beech, likely had low FIs for lcw because a limited number of trees were used for those species. Additionally, a complete range of diameters was not available, in contrast to other species. The reported results further illustrate the biological importance of shade tolerance as it relates to tree crown attributes.

The methods presented do not require discernment of open- and forest-grown trees. Provided that trees are sampled across a wide range of stand conditions, estimating the crown width of open-grown trees using quantile regression performs well. Using the maximum (open-grown) crown width for each species, the largest (forest-grown) crown width, using tree dbh and cr, can be predicted. Although this study used data gathered from the three primary ecoregions in Maine, the ecoregions examined expand across much of the northeastern United States and Lake States (Bailey 1980) and well into the Canadian Maritime Provinces. We suggest that these equations be evaluated for use in these regions along with those of Ek (1974) and Bechtold (2003). Equations 1–3 presented herein can be used in further examining tree crown profiles, exploring measurements of stand density, and investigating canopy dynamics for species common to these forests.

Literature Cited

Bailey, R.G. 1980. *Description of the ecoregions of the United States.* USDA Misc. Pub. 1391. Washington, DC. 77 p.

Bechtold, W.A. 2003. Crown-diameter prediction models for 87 species of stand-grown trees in the eastern United States. *South. J. Appl. For.* 27(4): 269–278.

Bragg, D.C. 2001. A local basal area adjustment for crown width prediction. *North. J. Appl. For.* 18(1):22–28.

Braun, E.L. 1950. *Deciduous forests of eastern North America.* Hafner, New York, NY. 596 p.

Briggs, R.D., and R.C. Lemin. 1992. Delineation of climatic regions in Maine. *Can. J. For. Res.* 22(6):801–811.

Condes, S., and H. Sterba. 2005. Derivation of compatible crown width equations for some important tree species of Spain. *For. Ecol. Manag.* 217(2–3):203–218.

Crookston, N.L., and G.E. Dixon. 2005. The Forest Vegetation Simulator: A review of its applications, structure, and content. *Comp. Electr. Agric.* 49:60–80.

Crookston, N.L., and A.R. Stage. 1999. *Percent canopy cover and stand structure statistics from the Forest Vegetation Simulator.* US For. Ser. Gen. Tech. Rep. RMRS-GTR-24. 11 p.

Ducey, M.J. 2009. Predicting tree shape from simple stand variables. *J. Sustain. For.* 28(1–2):5–21.

Ek, A.R. 1974. *Dimensional relationships of forest and open grown trees in Wisconsin.* School of Natural Resources, University of Wisconsin, Madison, WI. Forestry Research Notes. 7 p.

Gill, S.J., G.S. Biging, and E.C. Murphy. 2000. Modeling conifer tree crown radius and estimating canopy cover. *For. Ecol. Manag.* 126(3):405–416.

Gregoire, T.G., and H.T. Valentine. 1995. A sampling strategy to estimate the area and perimeter of irregularly shaped planar regions. *For. Sci.* 41(3):470–476.

Hann, D.W. 1998. *Equations for predicting the largest crown width of stand-grown trees in western Oregon.* Res. Cont. 17. Forest Research Laboratory, Oregon State University, Corvallis, OR. 14 p.

Hasenauer, H. 1997. Dimensional relationships of open-grown trees in Austria. *For. Ecol. Manag.* 96(3):197–206.

Jordan, G.J., and M.J. Ducey. 2007. Predicting crown radius in eastern white pine (*Pinus strobus* L.) stands in New Hampshire. *North. J. Appl. For.* 24(1):61–64.

Koenker, R., and K.F. Hallock. 2001. Quantile regression. *J. Econ. Persp.* 15(4):143–156.

Krajicek, J.E., K.A. Brinkman, and S.F. Gingrich. 1961. Crown competition—A measure of stand density. *For. Sci.* 7:35–42.

Leech, J.W. 1984. Estimating crown width from diameter at breast height for open-grown radiata pine trees in South Australia. *Aust. J. For. Res.* 14:333–337.

McCormack, M.L. 1989. Thinning spruce and spruce-fir stands. P. 9–10 in *1989 Annual report of the Cooperative Forestry Research Unit.* Maine Agricultural and Forest Experiment Station, Orono, ME.

Niinemets, U., and F. Valladares. 2006. Tolerance to shade, drought, and waterlogging of temperate northern hemisphere trees and shrubs. *Ecol. Monogr.* 76(4):521–547.

Paine, D.P., and D.W. Hann. 1982. *Maximum crown width equations for southwestern Oregon tree species.* Res. Pap. 46. Forest Research Laboratory, Oregon State University, Corvallis, OR. 20 p.

Pretzsch, H., and P. Biber. 2010. Size-symmetric versus size-asymmetric competition and growth partitioning among trees in forest stands along an ecological gradient in central Europe. *Can. J. For. Res.* 40(2):370–384.

Saunders, M.R., and R.G. Wagner. 2008. Height–diameter models with random coefficients and site variables for tree species of Central Maine. *Ann. For. Sci.* 65(2):1–10.

Sendak, P.E., J.C. Brissette, and R.M. Frank. 2003. Silviculture affects composition, growth, and, yield in mixed northern conifers: 40-year results from the Penobscot Experimental Forest. *Can. J. For. Res.* 33(11):2116–2128.

Zhang, L., H. Bi, J.H. Gove, and L.S. Heath. 2005. A comparison of alternative methods for estimating the self-thinning boundary line. *Can. J. For. Res.* 35(6):1507–1514.