ESTIMATING TREE CROWN WIDTHS FOR THE PRIMARY ACADIAN SPECIES IN MAINE

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ABSTRACT

In this analysis, data for seven conifer and eight hardwood species were gathered from across the state of Maine for estimating tree crown widths. Maximum and largest crown width equations were developed using tree diameter at breast height as the primary predicting variable. Quantile regression techniques were used to estimate the maximum crown width and a constrained nonlinear equation was developed for estimating the largest crown width. We noted an improvement in predictions in 11 of 14 species compared to currently-used largest crown width equations in the region. The models performed well across the wide range of stand conditions present in the dataset and proved effective when used in the computation of alternative measures of stand density (crown competition factor and percent canopy cover). Results from this analysis can be used in examining tree crown dynamics and assessing alternative measures of stand density.

INTRODUCTION

Accurately determining individual tree crown width has a broad applicability to forestry and natural resource sciences, yet, the measurement of crown width is lacking in most forest inventories. Estimating crown width can 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). Crown width variables have become integral in fields using airborne laser scanning technologies (e.g. Salas and others 2010). Tree diameter at breast height (dbh) generally accounts for much of the variability in predicting tree crown dimensions.

Open-grown trees are commonly selected to estimate maximum crown width (mcw). The mcw of a tree is generally defined as the potential crown width at a given diameter if the tree is open-grown. Methods for selecting trees in the field that display open-grown characteristics are available (Paine and Hann 1982), but making this determination can be laborious, often involves extensive traveling to subject trees, and may lend to subjectivity. Despite its importance, there are currently no regional mcw equations for most of the important commercial species in the northeastern U.S. Ek (1974) developed mcw equations for several species in the Lake States region but their applicability for use with trees found in Maine has not previously been assessed.

A forest-grown tree of a given species displays a horizontal crown extension that is less than that of an open-grown tree. This measure of crown width is termed the largest crown width (lcw). Hence, lcw equations differ from mcw equations in that they predict the crown widths of trees growing in forested settings. Bechtold (2003) developed lcw equations that covered a broad portion of the eastern U.S. The performance of the Bechtold (2003) equations to trees growing in Maine is unknown.

Crown width measurements are integral to estimating alternative measure of stand density used throughout forestry. Determining the mcw of trees is needed for estimating crown competition factor (CCF; Krajicek and others 1961), and lcw equations are needed to estimate percent canopy cover (PCC; Crookston and Stage 1999). CCF is an estimate of the area available to the average tree in the stand in relation to the maximum area it could use if it were open grown. PCC is defined as the percentage of the ground area that is covered by a vertical projection of tree crowns. Consequently, quantification of these stand density measures is an important component of many forest growth and yield models. As an example, the Forest Vegetation Simulator employs equations developed using open-grown trees to compute CCF, but uses separate equations developed with forest-grown trees for estimating PCC (Crookston and Dixon 2005).

The goal of this analysis was to employ data gathered from across Maine to determine tree crown width attributes for its primary species. The primary objectives were to: (1) develop mcw and lcw equations for seven conifer and eight hardwood tree species; (2) compare model predictions with existing equations used throughout the region; and (3) evaluate the crown width equations in the determination of measures of stand density.

METHODS

SPECIES

Maine is part of the Acadian forest, which is a transition zone between the conifer-dominant boreal forests of the

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north and the mixed hardwood forests of the south (Braun 1950, Rowe 1972). Forests are typically established under natural regeneration and are comprised of mixed-species stands with even- or uneven-aged stand structures. Common conifer species include balsam fir [*Abies balsamea* (L.)], red spruce [*Picea rubens* (Sarg.)], white spruce [*Picea glauca* (Moench) Voss.], eastern white pine [*Pinus 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) USDA Forest Service Forest Health Monitoring program (FHM); (2) USDA Forest Service Northern Research Station, Penobscot Experimental Forest (PEF); and (3) University of Maine Cooperative Forestry Research Unit (CFRU).

FHM—The FHM program collected information on 123 0.07-ha plots throughout each of the 16 counties in Maine from 1991-1999. Some of the trees in these plots were remeasured during this period. The maximum horizontal diameter of the widest axis of the tree crown and the distance perpendicular to this axis were measured. Crown measurements were collected on trees with a dbh greater than 12.7 cm.

PEF—The PEF, located in the towns of Bradley and Eddington, ME, is a long-term experiment investigating impacts of even-, two-, and uneven-aged silvicultural systems in the Acadian forest (Sendak and others 2003). Tree crown and height measurements have been collected since 2000 on a subset of continuous forest inventory (CFI) plots at the PEF. Crown measurements in this analysis were obtained from individual trees on 81 plots (0.08-ha in size) across the PEF. In addition, 2,698 crown measurements made on 20 CFI plots across the PEF were used in this analysis (Saunders and Wagner 2008).

CFRU—The CFRU dataset came from an early investigation of thinning in spruce-fir forests (McCormack 1989). It consisted of four locations across Maine in 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.

In the PEF and CFRU datasets, tree dbh was 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 for all datasets to provide an unbiased estimation of crown area irrespective of crown shape (Gregoire and Valentine 1995). Crown width by dbh and dataset is presented in Figure 1. Depending on the minimum size dbh measured in the inventory and the relative distribution of species, crown width and dbh vary according to dataset.

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 percent crown dieback were excluded in this analysis.

MODEL DEVELOPMENT

To develop mcw equations, open-grown trees are often used in model development. This can be problematical as the determination of “open-grownness” could lend to subjectivity, is not always specified in the field, and datasets of open-grown trees are often comprised of small sample sizes. One approach to overcome this is to employ 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, while 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 of the following form was used:

$$mcw = a_1 dbh^{a_2} \quad [1]$$

where dbh is tree diameter at breast height (cm) and a_i’s were coefficients estimated from the 99th percentile used to represent maximum crown width (m) for each species.

An lcw equation predicts the crown width for trees that are not able to reach their biological maximum due to competition in a stand. 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:

$$lcw = \frac{mcw}{b_1 dbh^{b_2}} \qquad [2]$$

where mcw is the predicted maximum crown width of the tree at its corresponding dbh (Eq. [1]) and b_i's were estimated coefficients. The b1 parameter was non-significant for four species. To evaluate the lcw equations, we computed fit index (FI) and mean absolute error (MAE):

$$FI = 1 - \left(\sum_{i=1}^{n} (y_i - \hat{y}_i)^2 \Big/ \sum_{i=1}^{n} (y_i - \bar{y})^2 \right)$$

$$MAE = \sum_{i=1}^{n} | y_i - \hat{y}_i | / n$$

where y_i, $\hat{y}_i$, and $\bar{y}$ are observed, predicted, and mean lcw, respectively, and *n* is number of trees in a species. The mcw and lcw model parameters were estimated in R using the nonlinear quantile regression (**nlrq**) and generalized nonlinear least squares (**gnls**) functions, respectively. Further analysis indicated that incorporating tree crown ratio as an additional predictor showed a minor improvement in fit index for some species.

To assess the crown width equations in terms of computing stand density measures, data from the Penobscot Experimental Forest (PEF) long-term silvicultural study were obtained. The permanent sample plots within these stands represent differing silvicultural practices with a variety of stand compositions and structures (Sendak and others 2003). The mcw equation (Eq. [1]) was used to compute maximum crown area for each individual tree, and crown competition factor (CCF) was calculated (Krajicek and others 1961). The lcw equation (Eq. [2]) was used to compute percent canopy cover (PCC) with a correction for crown overlap (Crookston and Stage 1999). CCF and PCC were were also estimated for the PEF plots using the Ek (1974) and Bechtold (2003) equations, respectively. These estimates of CCF and PCC were compared with plot basal area ($m^2\ ha^{-1}$).

RESULTS

All coefficients were positive in estimating mcw, indicating that mcw increases nonlinearly with dbh (Table 2). Differences between the mcw equations developed in this analysis and the equations of Ek (1974) were observed for several species (Figure 2). Generally, the predicted mcw using equations developed in this analysis were 45 percent higher than mcw predicted from the equations of Ek (1974). For the lcw equations, increasing dbh resulted in a larger predicted lcw (Table 3). For conifers, fit index (FI) ranged from 0.25 for northern white-cedar to 0.56 for eastern hemlock and eastern white pine. For hardwoods, FI ranged from 0.12 for American beech to 0.59 for paper birch. Mean absolute error (MAE) for conifers ranged from 0.46 m for black spruce to 1.18 m for eastern white pine. For hardwoods, MAE ranged from 0.46 m for gray birch to 1.52 m for American beech. Compared to previously published equations (Bechtold 2003), reductions in MAE were observed for 6 of 7 conifer species, with the exception of eastern white pine. For hardwoods, we observed reductions in MAE when compared to Bechtold's (2003) equations for 5 of 7 species, with the exceptions of northern red oak and sugar maple.

CCF and PCC were found to be positively correlated with plot-level basal area (BA) for permanent sample plot data at the Penobscot Experimental Forest (Figure 3). The Pearson correlation coefficients of CCF-BA and PPC-BA were 0.56 and 0.70, respectively. The Pearson correlation coefficient for CCF-BA using the equations of Ek (1974) was 0.45. The correlation coefficient for PPC-BA using the equations of Bechtold (1974) was 0.61.

DISCUSSION

For the primary species occurring across Maine, mcw and lcw relationships appear to be adequately captured using tree dbh. Using quantile regression provides the ability to model the biological maximum of tree crown width, hence, determining whether or not trees are open-grown is not required in developing mcw equations. Adapting the mcw estimate using a nonlinear equation form results in an accurate and constrained estimate of lcw. For most species, improved predictions resulted when compared to previously published equations developed at more broad scales.

The large differences in the presented mcw equations with those of Ek (1974) likely arise from three primary sources. First, geographic differences that influence tree crown attributes are likely apparent, as the Ek (1974) equations were developed using trees grown in the Lake States. Second, the data used in this analysis included trees with a full range of crown widths and dbh, including measurements of trees with a minimum dbh of around 1.4 cm for most species. Lastly, employing 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. Shade tolerant hardwoods like sugar maple and American beech likely had low FI's for lcw because a limited number of trees were used for those species and a complete range of diameters was not available when compared to other species.

Predicted crown widths from the developed equations appear to adequately represent alternative measures of stand density. We observed a stronger correlation between CCF and basal area and PPC and basal area using the crown width equations developed herein when compared to CCF and PCC using crown width equations found in Ek (1974) and Bechtold (2003). This speaks to the importance of an accurate and reliable estimate of individual tree crown width in determining stand density measures. Stand basal area is extensively used in growth models because it is easy to measure and is highly correlated with volume, but it is often confounded with site quality and stand age. Alternatively, the mcw equations can be used in computing CCF, a measure that is assumed to be independent of site and age and can be applied to both even- and uneven-aged stands. CCF is an effective measure of stand density because the determination of crown width is species-specific. Hence, CCF is a metric that takes into account the contribution of individual species to stand density. PCC has implications not only in forestry but also in assessing wildlife habitat suitability and evaluating fire risk potential. The computation of PCC, however, does not taken into account the spatial distribution of trees and as a percentage is constrained to be between 0 and 100%, which may prove difficult in quantifying competition. Field measurements of canopy cover and/or derived canopy cover estimates from LiDAR could aid in further evaluating the performance of the crown width equations.

Methods developed for developing mcw equations do not require the discernment between open- and forest-grown trees. Provided that trees are sampled across a wide range of stand conditions, estimating maximum crown width using quantile regression performs well. Bounding a tree's crown width by its potential maximum is biologically logical and resulted in accurate estimates of largest crown width. The equations of Bechtold (2003) performed well when using data from Maine, however we did find improvements for most species examined. Results from this analysis can be used in exploring measurements of stand density, examining tree crown profiles, and investigating canopy dynamics for species common to these forests.

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Table 1—Summary statistics for data used in the development of crown width models for seven conifer and eight hardwood species in Maine

Species	Code	n	dbh (cm)				Quadratic mean crown width (m)			
			Mean	SD	Min	Max	Mean	SD	Min	Max
Conifers										
Balsam fir	BF	3605	12.2	7.0	1.1	40.1	2.8	1.3	0.3	12.5
Black spruce	BS	400	14.6	3.5	4.3	23.6	2.4	0.7	0.8	5.2
Eastern hemlock	EH	1127	23.1	11.1	1.3	57.4	5.3	2.0	1.2	12.1
Eastern white pine	WP	866	25.6	15.7	1.4	92.2	5.0	2.4	0.6	14.8
Northern white-cedar	WC	866	22.7	7.6	1.6	59.7	3.7	1.2	0.8	10.5
Red spruce	RS	2994	19.7	7.2	1.2	56.9	3.6	1.4	0.7	12.1
White spruce	WS	339	17.4	7.1	1.5	40.6	3.5	1.2	0.6	9.3
Hardwoods										
American beech	AB	325	21.3	6.7	11.9	43.4	6.0	2.0	1.4	12.2
Gray birch	GB	251	6.4	4.7	1.3	25.4	2.1	1.3	0.2	9.4
Northern red oak	RO	102	24.3	10.3	12.7	66.8	6.3	2.3	2.1	13.1
Paper birch	PB	576	16.4	8.4	1.3	37.3	4.3	2.1	0.2	14.0
Quaking aspen	QA	353	18.2	7.5	1.3	45.4	4.2	1.7	0.4	10.7
Red maple	RM	1785	18.2	8.6	1.3	54.9	4.9	2.1	0.2	12.2
Sugar maple	SM	355	24.4	9.6	12.7	73.9	6.2	2.0	2.4	14.3
Yellow birch	YB	388	23.6	8.9	1.5	54.1	6.3	2.2	1.9	13.0

Table 2—Parameter estimates (standard errors in parentheses) by species for predicting the maximum crown width (mcw; m) using tree diameter at breast height (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)

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) for seven conifer and eight hardwood species in Maine. Comparisons of MAE with those of Bechtold (2003) equation [4] is presented

Species	b_1	b_2	FI	MAE	
				This Study	Bechtold (2003) Eq. [4]
Conifers					
Balsam fir	1.49 (0.017)	0.105 (0.0050)	0.55	0.58	0.65
Black spruce	-	0.174 (0.0045)	0.35	0.46	0.47
Eastern hemlock	1.90 (0.058)	-0.057 (0.010)	0.56	1.01	1.06
Eastern white pine	-	0.147 (0.0033)	0.56	1.18	1.08
Northern white-cedar	2.19 (0.20)	-0.080 (0.029)	0.27	0.77	0.79
Red spruce	4.33 (0.21)	-0.264 (0.015)	0.43	0.77	0.96
White spruce	2.09 (0.16)	-0.069 (0.027)	0.51	0.59	0.64
Hardwoods					
American beech	-	0.194 (0.0058)	0.12	1.52	1.58
Gray birch	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
Paper birch	2.10 (0.13)	-0.035 (0.021)	0.59	1.00	1.04
Quaking aspen	2.65 (0.26)	-0.157 (0.034)	0.57	0.87	0.88
Red maple	2.63 (0.11)	-0.132 (0.014)	0.56	1.05	1.15
Sugar maple	-	0.161 (0.0049)	0.17	1.44	1.38
Yellow birch	4.23 (0.51)	-0.294 (0.037)	0.41	1.33	1.58

Model is: $lcw = mcw / (b_1 dbh^{b_2})$

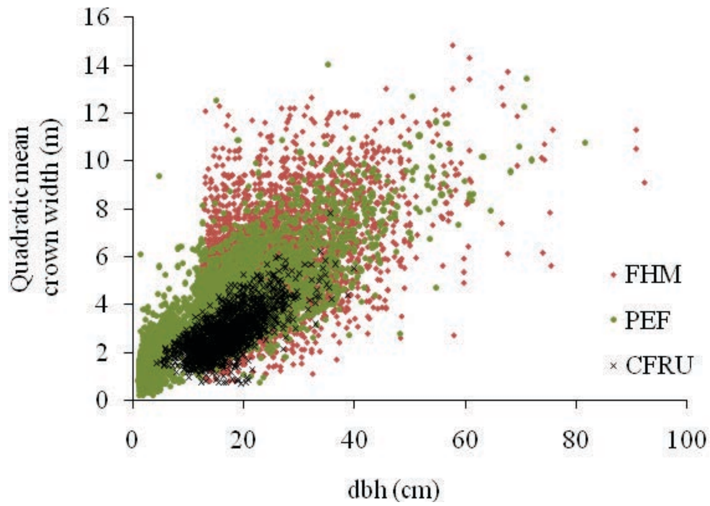

Figure 1—Quadratic mean crown width and tree diameter at breast height (dbh) for Penobscot Experimental Forest (PEF), Cooperative Forestry Research Unit (CFRU), and Forest Health Monitoring (FHM) data.

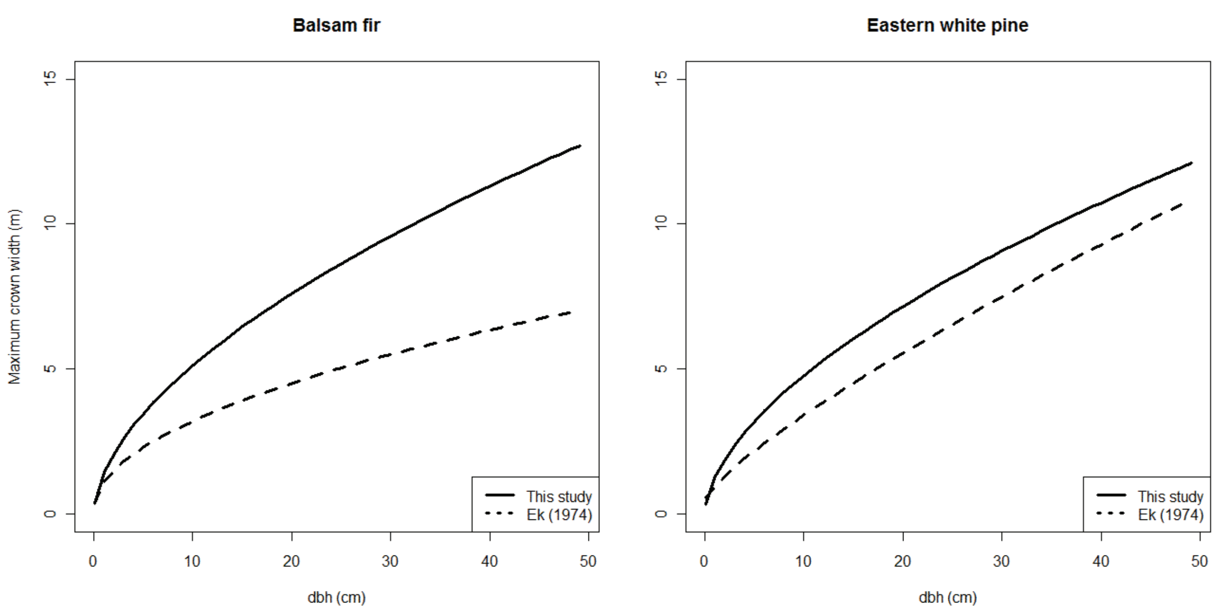

Figure 2—Predicted maximum crown width using tree diameter at breast height (dbh) for the equation developed in this study and that of Ek (1974) for balsam fir and eastern white pine.

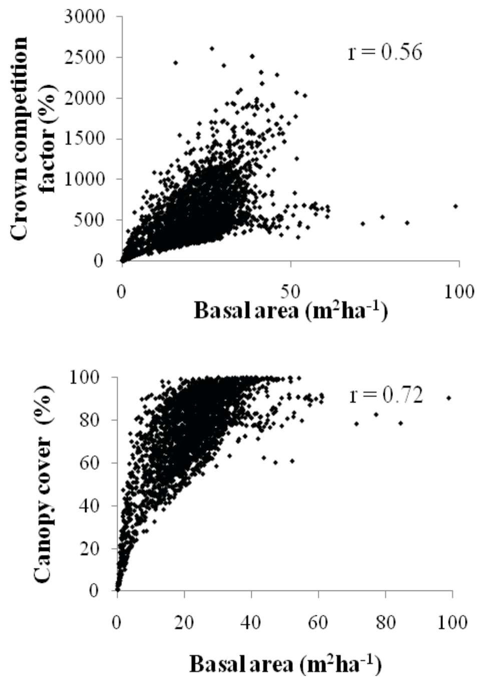

Figure 3—Crown competition factor and percent canopy cover related to basal area using permanent sample plots obtained from the Penobscot Experimental Forest, Bradley and Eddington, Maine.