Largest-Crown-Width Prediction Models for 53 Species in the Western United States

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ABSTRACT: *The mean crown diameters of stand-grown trees 5.0-in. dbh and larger were modeled as a function of stem diameter, live-crown ratio, stand-level basal area, latitude, longitude, elevation, and Hopkins bioclimatic index for 53 tree species in the western United States. Stem diameter was statistically significant in all models, and a quadratic term for stem diameter was required for some species. Crown ratio and/or Hopkins index also improved the models for most species. A term for stand-level basal area was not generally needed but did yield some minor improvement for a few species. Coefficients of variation from the regression solutions ranged from 17 to 33%, and model R^2 ranged from 0.15 to 0.85. Simpler models, based solely on stem diameter, are also presented. West. J. Appl. For. 19(4):245–251.*

Key Words: Largest crown width, tree crown width, crown diameter, crown modeling.

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Crown-width models are commonly separated into two categories—models for open-grown trees and models for stand-grown trees. The dimensions of crowns in open settings approach maximum biological potential, while those of stand-grown trees are generally smaller due to the influence of competition. Terminology developed by crown modelers in the western United States identifies models based on open-grown trees as "maximum crown width" (MCW) models, and those derived from stand-grown trees as "largest crown width" (LCW) models (Hann 1997). Both types of models relate to the horizontal silhouette of a crown as defined by the vertical projection of its longest branch tips, hence the terms "maximum" and "largest." MCW and LCW approximate the mean diameter of this silhouette from field measurements of crown extension along two or more axes passing through the tree crown.

MCW models predict potential crown size and are primarily used to develop tree stocking guides (Smith and Gibbs 1970) and crown competition indices (Krajicek et al. 1961). LCW models predict the actual size of tree crowns in forest settings, resulting in a variety of applications that include estimations of crown surface area and volume (Zarnoch et al. 2004), forest canopy cover (Gill et al. 2000), tree-crown profiles (Hann 1999), and wildlife habitat indices (Hays et al. 1981).

LCW prediction models are appealing because the direct measurement of crown diameters in the field is costly, particularly for extensive inventories. The measurement of mean crown diameter with a logger's tape averages more than one minute per tree (Bechtold et al. 2002). The objective of this article is to use extensive tree- and stand-level data gathered by the USDA Forest Service Forest Health Monitoring program (FHM) in the western United States to develop regional LCW prediction models for as many tree species as possible. A similar study has recently been conducted for species endemic to the eastern United States (Bechtold 2004).

Previous Studies

Significant relationships between crown width and stem diameter are well established for open-grown and stand-grown trees of many species (Krajicek et al. 1961, Dawkins 1963, Hetherington 1967). Simple linear relationships between crown width and stem diameter are often adequate, but quadratic expressions of stem diameter are known to improve crown-width models for some species (Paine and Hann 1982). Although diameter at breast height (dbh) is the most common variable used in crown-width prediction models, LCW (and occasionally MCW) models have been supplemented with additional tree-level and stand-level variables. Moeur (1981) used total height and crown length in models for 11 species in the northern Rocky Mountains, as did Hann (1997) for 15 species in western Oregon. Bechtold et al. (2002) found vertical crown ratio to be significant in models for 13 tree species in North Carolina. Bragg (2001) improved crown-diameter models for 20 species in the upper lake states by adding a term for basal area competition. Crown width also has been shown to vary by geographic location. Paine and Hann (1982) improved

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crown-width models for 11 of 15 species in southwest Oregon with the introduction of coordinates relating trees to a geographic reference point. To summarize, these studies show that measures of vertical tree dimension, stand density, and geographic location can improve crown-width models for some species over the use of stem diameter alone.

Methods

The Data

Between 1992 and 1999, the FHM program established a network of 1/6-ac plots systematically distributed across eight western states (California, Colorado, Idaho, Nevada, Oregon, Utah, Washington, and Wyoming). In addition to crown diameters, a variety of other tree and stand parameters were measured for use as indicators of forest ecosystem productivity and sustainability. The FHM plot network has since been integrated with the Forest Inventory and Analysis (FIA) sampling grid (Stolte 2001). Between 1992 and 1999, some plots were remeasured multiple times during successive inventories. To avoid problems with autocorrelation, only the most recent measurement of each tree was used for this analysis. After deleting species with less than 25 observations and applying additional screening restrictions as discussed below, the FHM dataset yielded a total of 21,689 observations from 983 forested plots across 8 western states.

The crown diameters used for this analysis conform to the LCWs of stand-grown trees. To ensure that only stand-grown trees were included, those with an "open grown" crown class were deleted. For each sampled tree with a stem diameter of at least 5.0 in., field crews measured (with logger's tapes) the horizontal diameter of the widest axis of the crown, plus the dimension perpendicular to the widest axis. The arithmetic mean diameter calculated from these two field measurements is the dependent variable in the prediction equations that follow.

For most species, dbh was used as the independent variable for stem diameter. For species with shrub-like form designated as "woodland," diameter at rootcollar (drc) was substituted for dbh as the measure of stem diameter (USDA Forest Service 2002).

Live-crown ratio was investigated as a measure of vertical crown dimension potentially correlated with the crown diameters of species encountered in this study. Tree length, crown length, and height to crown base are similar variables used by other modelers but not available in the FHM dataset. The crown ratios used in this analysis adhere to the rules for "uncompacted" live crown ratio as specified by the USDA Forest Service (2002). The term "uncompacted" means that estimates of crown ratio were not reduced to compensate for gaps between the base of the live crown and the top of a tree.

Stand-level basal area/ac was selected to quantify the effect of stand density on crown diameter. Basal areas were computed from all live tally trees with stem diameters ≥ 5.0 in. For woodland species, drc was substituted for dbh in the basal area calculations.

Latitude, longitude, and elevation are potentially useful for integrating the effect of geographic location. Because there is much interaction between these variables in the complex topography of the western United States, an index comprised of all three was identified as an additional candidate variable. Hopkins (1938) studied the phenologic occurrence of springtime and concluded that relative to a given geographic position, spring is delayed by 1 day for every 100 ft of elevation, 4 days for every 1 degree of northward latitude, and by 1¼ days for every 1 degree of westward longitude. Based on these relationships, Hopkins bioclimatic index (i.e., the number of days spring is delayed) was computed for each tree sampled relative to the mean elevation (5,549 ft), latitude (42.16 degrees), and longitude (-116.39 degrees) of all plots in the 8-state region:

$$HI = \left(\frac{(E - 5449)}{100}\right)1 + (LAT - 42.16)4 + (-116.39 - LON)1.25 \quad (1)$$

where:

E = elevation (ft);
LAT = latitude (decimal degrees); and
LON = longitude (decimal degrees).

A positive H value means that spring is delayed relative to the reference position, while a negative value indicates that spring is advanced.

Regression Models

Mean LCW (in ft) was modeled as a function of one or more of the following terms associated with stem diameter, vertical crown dimension, stand density, and geographic location:

D = dbh (in.), or drc (in.) for woodland species;
CR = live crown ratio (%);
BA = stand-level basal area (ft^2/ac);
LAT = latitude (decimal degrees);
LON = longitude (decimal degrees);
E = elevation (ft); and
HI = Hopkins index (days).

The candidate variables then were evaluated with a series of fixed and stepwise regressions designed to identify the best model for each species. The ranges of the variables used in the final models resulting from the regression analyses are provided in Table 1.

Results and Discussion

Stem diameter and crown diameter are known to be highly correlated, so stem diameter was entered first into the ordinary least squares (OLS) regression:

$$LCW = b_0 + b_1(D), \quad (2)$$

where b_0 and b_1 are regression parameters estimated from the data.

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Table 1. Ranges of data used to fit crown-width prediction models for 53 species in the western United States.

		Crown width[b] (ft)		Stem diameter[a] (in.)		Crown ratio (%)		Basal area[c] (ft^2/ac)		Latitude (decimal deg)		Longitude (decimal deg)		Elevation (ft)		Hopkins index[d] (days)	
Species[a]	n	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
Softwood species																	
Pacific silver fir	218	4	33	5.0	35.8	5	99	2	493	43.16	48.96	–123.95	–120.52	2100	5300	–9	26
White fir	855	3	35	5.0	62.6	10	99	4	445	34.08	46.11	–123.54	–104.95	322	10200	–40	19
Grand fir	610	4	35	5.0	43.9	5	99	12	496	40.54	48.91	–124.33	–114.58	295	6400	–48	20
Corkbark fir	68	5	15	5.2	18.3	45	99	70	222	37.02	41.44	–112.17	–105.15	8200	11200	1	28
Subalpine fir	1262	3	28	5.0	27.4	5	99	3	280	37.44	48.86	–123.05	–105.67	1600	11500	–14	44
California red fir	160	4	36	5.0	52.3	20	99	35	423	33.72	41.28	–123.46	–116.67	4600	9000	–35	26
Shasta red fir	63	6	26	5.0	40.1	40	99	38	288	41.47	43.70	–123.05	–121.60	5500	6600	3	17
Noble fir	50	4	29	5.2	46.0	20	99	85	354	43.94	48.86	–122.35	–119.96	2100	5600	–11	32
Port-Orford cedar	78	3	22	5.0	13.4	15	99	199	270	42.85	43.15	–124.46	–123.88	800	2800	–35	–15
California juniper (w)	28	6	31	5.2	42.6	35	99	47	101	34.82	41.56	–121.03	–118.28	4000	5837	–41	4
Western juniper (w)	302	3	36	5.0	45.3	10	99	8	218	36.35	44.93	–121.91	–113.01	200	9000	–71	27
Utah juniper (w)	402	1	30	5.0	29.7	10	99	8	221	34.32	44.93	–121.91	–104.86	4623	8600	–30	27
Rocky mtn. juniper (w)	144	5	29	5.0	38.1	5	99	5	277	37.02	44.91	–112.46	–103.60	3900	8725	–37	19
One-seed juniper (w)	98	2	28	5.7	36.5	10	99	11	512	37.13	38.53	–105.09	–103.11	4900	6700	–43	–17
Western larch	183	3	28	5.0	23.1	5	99	24	300	44.42	48.97	–121.20	–114.92	295	6400	–25	20
Incense cedar	220	3	32	5.0	42.0	5	99	12	445	35.72	44.71	–123.79	–118.33	1100	6800	–33	11
Engelman spruce	1205	3	29	5.0	35.9	5	99	2	391	37.02	48.89	–123.84	–105.15	295	12000	–25	44
Sitka spruce	53	7	43	5.1	39.2	20	99	12	307	40.54	47.77	–124.46	–123.30	0	2800	–46	–5
Whitebark pine	97	4	29	5.0	24.2	10	99	46	270	37.54	48.62	–123.05	–110.01	6200	10700	6	44
Bristlecone pine	26	7	25	5.0	18.9	65	99	24	121	37.31	39.45	–114.65	–105.06	8410	10700	9	25
Common pinyon (w)	278	5	27	5.0	25.5	30	99	3	500	35.12	40.14	–118.28	–103.32	4600	8725	–40	11
Lodgepole pine	2761	1	40	5.0	62.2	5	99	2	315	36.35	48.90	–124.18	–105.41	200	10900	–23	43
Limber pine	164	3	34	5.0	20.7	5	99	3	256	37.02	45.64	–115.76	–105.15	6400	11200	2	43
Jeffrey pine	108	5	44	5.1	48.1	5	99	12	345	36.10	42.19	–123.75	–118.33	1700	9000	–38	15
Sugar pine	118	5	49	5.0	44.9	15	99	28	445	34.08	42.73	–124.10	–116.94	1100	8200	–47	11
Western white pine	84	4	34	5.1	38.4	15	99	15	423	36.21	48.92	–124.18	–115.87	200	9200	–25	32
Ponderosa pine	1413	1	46	5.0	41.3	5	99	4	414	36.81	48.91	–123.57	–104.07	300	9800	–56	41
Grey pine	37	6	54	5.1	34.8	30	95	9	164	35.70	41.18	–122.90	–118.05	400	4900	–69	–4
Singleleaf pinyon (w)	323	4	30	5.0	22.7	20	99	7	206	34.32	40.26	–119.60	–112.16	200	8900	–71	15
Douglas-fir	4088	1	66	5.0	68.7	5	99	2	696	37.13	48.97	–124.46	–104.95	100	11000	–49	67
Redwood	55	3	31	5.1	35.6	5	99	104	353	37.07	40.68	–124.07	–122.17	400	1800	–55	–39
Western redcedar	439	3	38	5.0	62.0	15	99	13	493	37.90	48.97	–124.42	–109.76	200	8520	–25	49
Western hemlock	1008	4	54	5.0	63.5	5	99	12	496	42.68	48.96	–124.42	–115.93	0	8500	–34	49
Mountain hemlock	209	1	33	5.0	32.4	5	99	28	397	37.64	48.72	–123.55	–115.23	1600	9200	–10	27
Hardwood species																	
Bigleaf maple	106	8	57	5.1	34.1	10	99	37	405	39.82	48.33	–124.06	–121.38	100	8500	–36	49
Rocky mtn. maple (w)	70	8	39	5.0	26.2	25	99	10	288	40.75	48.64	–123.48	–110.95	1600	7200	–38	14
Bigtooth maple (w)	48	4	20	5.0	14.7	30	99	4	145	37.34	41.13	–112.75	–111.33	5400	8275	–11	11
Red alder	409	3	54	5.0	28.3	10	99	6	386	40.54	48.82	–124.46	–117.30	0	8100	–46	53
White alder	37	8	35	5.1	18.1	25	90	49	270	38.75	45.61	–123.92	–120.98	700	3000	–56	–2
Pacific madrone	164	1	43	5.0	29.7	5	99	13	369	37.21	45.33	–124.29	–121.06	700	6000	–55	15
Curlleaf mtn-mahogany (w)	227	3	29	5.0	24.0	10	99	10	174	34.32	45.05	–121.91	–109.70	495	9200	–37	27
Tanoak	534	2	41	5.0	31.0	5	99	57	353	37.07	42.52	–124.37	–121.06	300	6000	–55	15
Quaking aspen	1383	1	34	5.0	19.9	5	99	2	256	37.02	48.42	–119.27	–104.07	3200	10800	–9	33
Narrowleaf cottonwood	44	8	35	5.1	16.6	30	90	17	150	37.05	38.85	–108.65	–106.15	5400	8000	–26	–2
Coastal live oak	87	3	53	5.0	40.6	5	99	60	147	34.51	38.62	–122.63	–119.81	500	2000	–73	–54
Canyon live oak	440	5	49	5.0	53.2	5	99	10	696	34.08	42.43	–124.29	–116.94	700	8200	–60	–5
Blue oak	184	5	61	5.0	29.4	15	99	4	172	35.23	40.75	–122.99	–118.55	400	5900	–69	–2
Gambel oak (w)	248	1	19	5.0	15.4	5	99	9	149	37.02	40.16	–113.28	–104.73	6000	8500	–23	11
Oregon white oak	126	6	30	5.0	22.4	15	99	22	200	38.38	45.87	–123.34	–120.75	900	3700	–54	–11
California black oak	239	4	52	5.1	40.3	5	99	20	345	35.37	42.63	–123.65	–118.29	1100	6200	–47	–8
Valley oak	29	5	47	5.1	21.3	10	99	63	172	35.70	39.20	–122.99	–120.96	900	1800	–64	–44
Interior live oak	79	2	37	5.0	19.5	15	99	10	77	35.99	40.70	–123.21	–118.06	600	7300	–60	–5
California laurel	28	10	44	5.1	18.7	30	99	24	271	38.31	43.63	–124.06	–120.39	900	6000	–54	15

[a] Species designated (w) are woodland species where stem diameter is diameter at rootcollar (drc) instead of diameter at breast height (dbh).

[b] Largest crown width of stand-grown trees (i.e., mean crown diameter).

[c] Stand-level basal area (trees with stem diameters 5.0-in. and larger).

[d] Hopkins index is the number of days spring is delayed relative to latitude 42.16°, longitude –116.39°, and elevation 5449 ft.

Examination of the residuals from the regression solutions indicated heteroscedasticity with respect to D for many species. A weighted least squares (WLS) approach thus was used for this and subsequent regressions to counter the effect of increasing variation with increasing stem diameter. Appropriate weights were determined by modeling the variance of the residuals from the OLS solutions as a function of D, as follows:

1. The LCW models were solved using OLS regression.
2. The absolute values of the OLS residuals (R) were modeled as a function of D:

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$$|R| = b_0 + b_1(D).$$

3. The LCW models were solved again using WLS, where each observation was weighted by w_i, the reciprocal of the estimated variance with respect to D_i:

$$w_i = 1/(b_0 + b_1(D_i))^2,$$

where $i = 1 \ldots n$.

The D coefficients for pacific yew (*Taxus brevifolia*) and golden chinkapin (*Castanopsis chrysophylla*) were not statistically significant at a P value of 0.05. Because the ability to develop biologically justifiable models was doubtful, and the numbers of observations were limited (30 each), these two species were deleted from the analysis. The number of species available for modeling thus was reduced to 53 from a previous total of 55.

Further examination of the residuals from Equation 2 indicated that a quadratic term might improve the models for some species. All species were thus re-fitted with the model

$$LCW = b_0 + b_1(D) + b_2(D^2), \qquad (3)$$

using WLS regression, and the quadratic term was retained for 14 species where the P-value associated with the D^2 coefficient was significant at $P = 0.05$.

On fixing D and D^2 in those models where significant (i.e., retaining these terms in subsequent regressions), all models then were re-fitted with an additional term for crown ratio (CR):

$$LCW = b_0 + b_1(D) + b_2(D^2) + b_3(CR). \qquad (4)$$

CR then was retained for 39 species where its coefficient was significant ($P = 0.05$). At this stage, the signs of all coefficients were consistent and biologically reasonable. The coefficients associated with D were all positive, confirming a positive correlation between stem diameter and crown diameter. The coefficients associated with D^2 all were negative, meaning that crown diameter approaches an upper biological limit as stem diameter increases. The coefficients associated with CR all were positive, indicating that large crowns tend to be large in all dimensions.

After fixing D, D^2, and CR in models where these terms were significant, all models were then re-fitted with an additional term for stand-level basal area (BA):

$$LCW = b_0 + b_1(D) + b_2(D^2) + b_3(CR) + b_4(BA). \qquad (5)$$

The BA term was statistically significant ($P = 0.05$) in models for 19 species. A negative correlation between stand density and crown diameter was expected, but the additional term exhibited a mixture of positive and negative coefficients. In the few models with BA coefficients that were negative and statistically significant, the partial R^2 values resulting from the addition of BA generally were less than 0.02. Because D and CR are tree-level variables highly correlated with stand density, the general instability and weak significance of the BA term was attributed to collinearity with D and CR. As a result, the utility of the BA term in any of these models is questionable, but it did yield minor improvement for a few species. The BA term thus was retained for nine species where it was statistically significant and the coefficient was negative.

Again after fixing D, D^2, CR, and BA in models where significant, all models were re-fitted with stepwise regressions where additional terms for LAT, LON, and E were entered as candidates. The stepwise procedure selected one or two of these geographic variables as statistically significant for many species, but there was no clear consistency. Different geographic terms were selected for different species, coefficient signs fluctuated between positive and negative for a given geographic variable, and some of the model intercepts changed dramatically. Over-parameterization, as well as interactions among latitude, longitude, and elevation made it impractical to include up to three different terms for geographic location, so Hopkins' (1938) bioclimatic index was investigated as an alternative.

Because Hopkins index was developed in the eastern United States, its applicability to western states is uncertain. The relationship between latitude, elevation, and climatic condition seemed reasonable for the West, but the negative effect of westward longitude was suspect—possibly attributable to distance from the moderating climatic effect of the Atlantic Ocean in the region where the index was developed. Theorizing that crown diameters generally should be smaller under climatic conditions where spring is delayed, correlations between LCW and latitude, longitude, and elevation were checked to verify a negative correlation between LCW and elevation, a negative correlation between LCW and latitude, and a positive correlation between LCW and longitude. Among individual species, there was considerable fluctuation in the signs of the correlation coefficients for each of these variables (again attributed to latitude, longitude and elevation interactions); but when averaged across all 53 species, the means of the correlation coefficients exhibited signs that were consistent with Hopkins (1938).

With D, D^2, CR, and BA fixed in models where significant, all models were then re-fitted with an additional term for Hopkins index (HI)

$$LCW = b_0 + b_1(D) + b_2(D^2) + b_3(CR) + b_4(BA) + b_5(HI), \qquad (6)$$

and HI was retained for 31 species for which its coefficient was significant ($P = 0.05$). Most of the coefficients associated with HI were negative, confirming that tree crowns generally are smaller in harsher climates where spring is delayed, but a few of the coefficients were positive. This was attributed to the possibility that competing species may drop out of the stand-level species mix as climatic conditions become more extreme.

Equation 6 thus was chosen as the best biologically justifiable model attainable from the available data, with

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Table 2. Model statistics and parameter estimates from crown-width prediction Equation 6, for 53 species in the western United States.

	Equation 6[a]: $LCW = b_0 + b_1(D) + b_2(D^2) + b_3(CR) + b_4(BA) + b_5(HI)$								
	Model statistics[c]			Parameter estimates[d]					
Species[b]	RSQ	RMSE	CV	b_0	b_1	b_2	b_3	b_4	b_5
Softwood species									
Pacific silver fir	0.43	3.8	28	7.7763	0.5960	–	–	–	–0.0705
White fir	0.62	2.7	21	2.4789	0.9317	–0.0128	0.0327	–	–0.1178
Grand fir	0.58	3.3	22	3.0335	0.9752	–0.0113	0.0548	–	–0.0597
Corkbark fir	0.15	2.1	24	6.0730	0.3756	–	–	–	–
Subalpine fir	0.52	2.3	24	2.6068	0.6145	–	0.0417	–	–0.0698
California red fir	0.78	2.6	21	2.3660	0.5472	–	0.0316	–	–0.0702
Shasta red fir	0.83	2.2	19	4.0524	0.6423	–	–	–	–
Noble fir	0.72	3.0	20	2.7761	0.7311	–	0.0476	–	–0.0756
Port-Orford cedar	0.38	2.6	25	1.0365	0.7943	–	0.0399	–	–
California juniper (w)	0.76	3.2	22	–0.6303	1.6960	–0.0225	–	–	0.1166
Western juniper (w)	0.65	3.8	28	–0.0037	1.3526	–0.0165	–	–	–
Utah juniper (w)	0.50	3.0	31	–5.9542	1.1877	–0.0256	0.0857	–0.0095	–
Rocky mtn. juniper (w)	0.60	3.1	25	–4.1599	1.3528	–0.0233	0.0633	–	–0.0423
One-seed juniper (w)	0.70	2.7	23	–0.7915	0.5975	–	0.0890	–0.0094	–
Western larch	0.36	3.8	31	1.5995	0.7675	–	0.0750	–	–
Incense cedar	0.67	2.8	22	2.0872	0.9281	–0.0094	0.0332	–	–
Engelman spruce	0.55	2.5	23	4.1348	0.5694	–	0.0403	–	–0.1014
Sitka spruce	0.65	4.7	24	8.8087	0.7825	–	–	–	–
Whitebark pine	0.53	3.2	31	0.5223	0.7432	–	–	–	0.0829
Bristlecone pine	0.58	3.1	20	–12.7069	0.9571	–	0.2177	–	–
Common pinyon (w)	0.67	2.6	21	–5.4647	1.9660	–0.0395	0.0427	–	–0.0259
Lodgepole pine	0.61	2.7	28	–1.5440	1.3828	–0.0200	0.0396	–0.0083	–
Limber pine	0.56	3.3	28	3.4094	0.8638	–	0.0592	–0.0105	–0.0956
Jeffrey pine	0.85	2.7	19	1.2784	0.7937	–	0.0334	–	–0.0887
Sugar pine	0.77	3.7	25	3.1052	0.8049	–	–	–	–0.1230
Western white pine	0.74	3.2	25	4.8643	0.6949	–	–	–	–0.0974
Ponderosa pine	0.73	3.0	23	–0.3459	1.1110	–0.0080	0.0566	–0.0094	–0.0362
Grey pine	0.81	4.3	20	–2.4909	1.0716	–	0.0648	–	–0.1127
Singleleaf pinyon (w)	0.66	2.4	23	2.1556	0.8302	–	0.0299	–0.0195	–0.0272
Douglas-fir	0.57	4.2	26	3.2346	1.1158	–0.0112	0.0442	–0.0057	–0.0237
Redwood	0.46	4.4	23	–15.1653	0.3182	–	0.1349	–	–0.4682
Western redcedar	0.37	4.2	25	5.2911	1.0612	–0.0153	0.0469	–	–
Western hemlock	0.63	4.4	26	–0.4624	1.0429	–0.0078	0.1018	–	–0.0271
Mountain hemlock	0.60	3.3	29	–0.3362	0.7142	–	0.0414	–	–
Hardwood species									
Bigleaf maple	0.45	7.5	33	–1.9386	1.2250	–	0.1622	–	–0.1417
Rocky mountain maple (w)	0.34	5.0	28	5.9765	0.8648	–	0.0675	–	–
Bigtooth maple (w)	0.31	2.6	23	4.0040	1.0604	–	–	–	–
Red alder	0.60	4.7	28	–0.7294	1.2885	–	0.1307	–	–
White alder	0.38	4.8	24	4.6188	0.9135	–	0.1019	–	–
Pacific madrone	0.44	4.8	33	4.9133	0.9459	–	0.0611	–	0.0523
Curlleaf mtn-mahogany (w)	0.48	2.8	26	4.0105	0.8611	–	–	–	–0.0431
Tanoak	0.52	3.9	27	3.1150	0.7966	–	0.0745	–0.0053	–0.0289
Quaking aspen	0.59	2.5	21	–0.5095	1.2318	–	0.0744	–	0.0233
Narrowleaf cottonwood	0.52	4.0	24	4.1687	1.5355	–	–	–	0.1275
Coastal live oak	0.76	5.6	27	–16.1696	1.7456	–	0.0925	–	–0.1956
Canyon live oak	0.45	4.0	28	0.2738	1.0534	–	0.0350	–	–0.1385
Blue oak	0.76	4.5	23	2.7110	1.5159	–	0.0415	–0.0271	–
Gambel oak (w)	0.32	2.5	27	0.3309	0.8918	–	0.0510	–	–
Oregon white oak	0.42	3.7	24	–1.3160	2.9311	–0.0866	–	–	–
California black oak	0.47	5.7	33	1.6306	0.9867	–	0.0556	–	–0.1199
Valley oak	0.78	3.7	17	–2.1068	1.9385	–	0.0860	–	–
Interior live oak	0.56	4.4	24	0.7146	1.5460	–	–	–	–0.1121
California laurel	0.58	4.7	24	2.4247	1.3174	–	0.0786	–	–

[a] LCW = largest crown width of stand-grown trees (i.e., mean crown diameter); D = dbh for non-woodland species, or diameter at rootcollar for woodland species; CR = uncompacted vertical crown ratio (percent); BA = stand-level basal area, trees with stem diameters 5.0-in. and larger (ft^2/acre); and HI = Hopkins Index (days spring is delayed relative to latitude 42.16° longitude –116.39°, and elevation 544 ft).

[b] Species designated (w) are woodland species where stem diameter (D) is diameter at rootcollar (drc).

[c] RSQ = adjusted R^2; RMSE = root mean squared error from the regression solutions; CV = coefficient of variation from the regression solutions; CV = (RMSE/mean LCW)*100, where mean LCW = mean crown diameter.

[d] Terms where parameter estimates are missing were excluded from the regression solutions due to nonsignificance. Nonsignificant model intercepts were retained in the solutions.

terms included or excluded for various species on the empirical basis of whether or not their associated coefficients were significant ($P = 0.05$).

Fit statistics and parameter estimates from the solutions of Equation 6 are presented in Table 2. Parameter estimates with missing values were excluded from the regressions for

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Table 3. Model statistics and parameter estimates from crown-width prediction Equation 3, for 53 species in the western United States.

	Equation 3[a]: $LCW = b_0 + b_1(D) + b_2(D^2)$					
	Model statistics[c]			Parameter estimates[d]		
Species[b]	RSQ	RMSE	CV	b_0	b_1	b_2
Softwood species						
Pacific silver fir	0.42	3.8	28	7.3037	0.5909	–
White fir	0.51	3.0	24	4.4965	0.9238	–0.0120
Grand fir	0.50	3.6	23	5.7545	1.1196	–0.0147
Corkbark fir	0.15	2.1	24	6.0730	0.3756	–
Subalpine fir	0.44	2.5	26	3.9629	0.6469	–
California red fir	0.75	2.8	23	4.7623	0.5222	–
Shasta red fir	0.83	2.2	19	4.0524	0.6423	–
Noble fir	0.67	3.3	21	6.3260	0.6588	–
Port-Orford cedar	0.33	2.7	26	2.3625	0.9974	–
California juniper (w)	0.68	3.7	25	–2.1213	1.7308	–0.0243
Western juniper (w)	0.65	3.8	28	–0.0037	1.3526	–0.0165
Utah juniper (w)	0.24	3.6	38	2.4349	0.9000	–0.0177
Rocky mtn. juniper (w)	0.54	3.3	27	2.1431	1.3447	–0.0228
One-seed juniper (w)	0.46	3.6	31	5.7367	0.4932	–
Western larch	0.30	4.0	33	4.5176	0.7931	–
Incense cedar	0.65	2.9	23	4.1207	0.9773	–0.0107
Engelman spruce	0.47	2.8	25	5.1218	0.5547	–
Sitka spruce	0.65	4.7	24	8.8087	0.7825	–
Whitebark pine	0.53	3.2	31	2.6531	0.8015	–
Bristlecone pine	0.41	3.7	24	7.4251	0.8991	–
Common pinyon (w)	0.65	2.7	21	–1.2638	1.9922	–0.0410
Lodgepole pine	0.54	2.9	30	–1.1994	1.5154	–0.0232
Limber pine	0.35	4.0	34	4.0181	0.8528	–
Jeffrey pine	0.83	2.9	20	4.2675	0.7714	–
Sugar pine	0.72	4.1	27	4.8657	0.7890	–
Western white pine	0.69	3.5	28	4.2840	0.6949	–
Ponderosa pine	0.66	3.3	25	2.3089	1.1388	–0.0089
Grey pine	0.71	5.2	25	4.3699	1.2524	–
Singleleaf pinyon (w)	0.55	2.8	26	2.5093	0.8503	–
Douglas-fir	0.51	4.4	27	5.7753	1.0639	–0.0109
Redwood	0.27	5.1	27	12.0128	0.4576	–
Western redcedar	0.33	4.3	26	8.1993	1.1134	–0.0165
Western hemlock	0.50	5.1	31	5.0036	1.1808	–0.0107
Mountain hemlock	0.58	3.3	29	3.2343	0.6927	–
Hardwood species						
Bigleaf maple	0.27	8.6	38	10.0915	1.1139	–
Rocky mountain maple (w)	0.28	5.2	29	10.5451	0.9493	–
Bigtooth maple (w)	0.31	2.6	23	4.0040	1.0604	–
Red alder	0.47	5.5	32	4.7027	1.3537	–
White alder	0.26	5.2	26	9.7927	0.9006	–
Pacific madrone	0.40	5.0	34	5.7785	0.9832	–
Curlleaf mtn-mahogany (w)	0.46	2.9	27	3.5082	0.8770	–
Tanoak	0.40	4.4	31	6.7864	0.8443	–
Quaking aspen	0.50	2.8	24	2.5515	1.2029	–
Narrowleaf cottonwood	0.47	4.2	25	2.8848	1.5866	–
Coastal live oak	0.74	5.8	28	0.5740	1.8475	–
Canyon live oak	0.35	4.4	30	6.1397	1.0109	–
Blue oak	0.76	4.5	23	3.9281	1.5550	–
Gambel oak (w)	0.23	2.7	28	3.0334	0.9834	–
Oregon white oak	0.42	3.7	24	–1.3160	2.9311	–0.0866
California black oak	0.38	6.2	36	7.0284	1.0470	–
Valley oak	0.77	3.8	17	2.9954	1.9137	–
Interior live oak	0.52	4.6	25	5.1005	1.6359	–
California laurel	0.47	5.2	27	7.3204	1.4420	–

[a] LCW = largest crown width of stand-grown trees (i.e., mean crown diameter); D = dbh for non-woodland species, or diameter at rootcollar for woodland species.

[b] Species designated (w) are woodland species where stem diameter (D) is diameter at rootcollar (drc).

[c] RSQ = adjusted R^2; RMSE = root mean squared error from the regression solutions; CV = coefficient of variation from the regression solutions; CV = (RMSE/mean LCW*100).

[d] Terms where parameter estimates are missing were excluded from the regression solutions due to nonsignificance. Nonsignificant model intercepts were retained in the solutions.

species where they were determined to be nonsignificant. Although some of the model intercepts were also nonsignificant, these were retained to ensure that the resulting models were BLUE (best linear unbiased estimators).

The root mean squared errors (RMSE) shown in Table 2 provide estimates of the error in crown-diameter predictions in terms of feet. RMSE, a common measure of model performance, is most useful for comparing similar models

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for similar species among different studies. Comparisons among models involving dissimilar species are facilitated with the coefficient of variation (CV), which re-expresses RMSE as a percentage of the mean of the dependent variable:

$$CV = RMSE/\overline{LCW}*100, \quad (7)$$

where

$RMSE$ = the root mean squared error from the regression solution; and
$\overline{LCW}$ = mean LCW from the model predictions.

Comparisons of model performance among species has utility for applications such as the FIA program, which occasionally debates the merits of measuring versus modeling various inventory attributes. Species with models that yield low CVs and other satisfactory diagnostic statistics might be identified as candidates where model predictions can be used in lieu of field measurements. By species, coefficients of variation from the regression solutions ranged from 17 to 33%. The mean CV across all 53 species was 25%. Little difference was observed in the proportion of variation captured by the models among hardwood, softwood, woodland and nonwoodland species groups. The mean CV for each of these groups was about 25%.

Model R^2 values from the solution of Equation 6 ranged from 0.15 for corkbark fir (*Abies lasiocarpa var. arizonica*) to 0.85 for jeffrey pine (*Pinus jeffreyi*). Mean R^2 values across all species resulting from regression solutions of Equations 3, 4, 5, and 6 were 0.50, 0.55, 0.56, and 0.57, respectively. This suggests that the addition of crown ratio (to species where it was found to be statistically significant) increases partial R^2 values by an average of 0.05 across the 53 species tested here. The further addition of a term for basal area and geographic location (Hopkins index) each add another 0.01.

Because crown-ratio and geographic location data may not be available to some users and the gains from additional variables beyond stem diameter are only marginal for some species, the regression solutions from Equation 3 also are provided (Table 3). Gering and May (1995) built a case for simplicity when modeling the crown diameters of four species groups in Tennessee. Gill et al. (2000) concluded that dbh was the only predictor needed to model the crown radius of 13 species of western conifers, even though additional independent variables slightly improved some of their models. By individual species, gains in model precision resulting from the addition of crown ratio, basal area, and Hopkins index can be evaluated by comparing model statistics from Equation 3 in Table 3 with Equation 6 in Table 2.

Conclusions

Stem diameter is the strongest predictor of crown diameter for most tree species in the western United States. Stem diameter in quadratic form and additional terms for vertical crown ratio and geographic location improve the models for many species. Because stem diameter and crown ratio are correlated with stand density, an additional term for stand density is not generally needed but does yield minor improvement for a few species. Although model performance for some species can be enhanced by the addition of independent variables beyond stem diameter, the additional data may not be available to some potential users and the gains are marginal for some species, so there is also utility in presenting simpler models based solely on stem diameter.

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