Equations to Convert Compacted Crown Ratio to Uncompacted Crown Ratio for Trees in the Interior West

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ABSTRACT

Crown ratio is the proportion of total tree length supporting live foliage. Inventory programs of the US Forest Service generally define crown ratio in terms of compacted or uncompacted measurements. Measurement of compacted crown ratio (CCR) involves envisioning the transfer of lower branches of trees with asymmetric crowns to fill holes in the upper portion of the crown. Uncompacted crown ratio (UNCR) is measured without adjustment for holes in the crown and may be a more appropriate measurement when interest is on height to the first live branches in the crown. CCR is more commonly available because it is a standard measurement of the Forest Inventory and Analysis (FIA) program of US Forest Service, and UNCR is an optional measurement at the discretion of regional FIA units. The mean difference between UNCR and CCR of trees in the western United States (0.17 live crown) could be large enough to introduce biologically significant bias in applications that use crown ratio to derive height to crown base. Equations were developed to convert CCR to UNCR for 35 tree species in Idaho, Montana, Wyoming, Nevada, Utah, Colorado, Arizona, and New Mexico using data from the Interior West FIA unit. UNCR was modeled as a logistic function of CCR and tree diameter, and species-specific equations were fit by nonlinear regression. Root mean squared error for the regression equations ranged from 0.06 to 0.15 UNCR (mean absolute error, 0.04–0.12 UNCR). Equations for most species performed well when applied to test data that were not available at the time of model fitting.

Keywords: canopy fuel, crown modeling, FIA, forest inventory and analysis, nonlinear regression

Crown ratio is commonly measured in forest inventories as the proportion of total tree length supporting live foliage. Measuring crown ratio involves determining the base of the live crown. However, protocols for determining crown base vary, and some protocols require subjective judgment especially in the case of asymmetric crowns (Hasenauer and Monserud 1996, Soares and Tomé 2001). National inventory programs in the United States generally describe crown ratio measurements as either compacted or uncompacted (e.g., US Forest Service 2005, 2007a, 2007b, 2007c). Compacted crown ratio (CCR) is an ocular measurement that requires envisioning the transfer of lower live branches to fill in large holes in the upper portion of the tree until a full, even crown is visualized (US Forest Service 2005). Uncompacted crown ratio (UNCR) is measured without adjustment for holes in the crown. It is the proportion of total tree length that is between the base of the live crown (as defined by the particular inventory protocol) and the last live foliage at the crown top, without regard for the spatial arrangement of branches along the length of the crown. Both variables range from near 0 (very small crown) to 1 (crown reaches the ground) and are often expressed as percentages.

CCR is considered a surrogate for tree photosynthetic potential and has been used as a predictor of periodic increment in forest growth models (Wykoff et al. 1982, Monleon et al. 2004). However, UNCR may be a more appropriate measurement in other applications of crown ratio data, such as stand visualization, wildlife habitat models, and fire behavior prediction, where interest is on the distance from the ground to the first live branches in the forest canopy (Monleon et al. 2004). UNCR is also a predictor in crown width models (Bechtold 2003, 2004) and is known to influence allometric scaling between woody mass and foliage (Mäkelä and Valentine 2006).

Because forest inventories in the western United States often measure only CCR, Monleon et al. (2004) developed regression equations to predict UNCR from CCR and other tree attributes for 28 species in California, Oregon, and Washington. The objective of the present study was to develop comparable equations for 35 species occurring in eight Interior West states using data from the Forest Inventory and Analysis (FIA) program of the US Forest Service. Previous work (Monleon et al. 2004) documented a robust UNCR modeling approach by examining different regression techniques, data transformations, and predictor variables, so this phase of analysis did not need repeating. A test data set comprised of tree measurements not available at the time of model fitting was used to validate the equations for Interior West species.

A secondary objective was to test the equations for California, Oregon, and Washington (Monleon et al. 2004) against Interior West data for a subset of 10 species that also occurred in the Interior West states. Information on the performance of these equations

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when extrapolated geographically is useful given the lack of UNCR measurements in inventory data for the western United States. Also, comparing equations for the same species, developed for two geographic regions using data from different FIA units, helps to assess the robustness of the overall modeling approach.

Methods

Data

FIA conducts forest inventory using a network of systematically located permanent ground plots, with a spatial sampling intensity of approximately one plot per 6,000 ac. These plots, denoted as phase 2, are measured by field crews if any portion of the plot contains forestland, defined as land that is at least 10% stocked by forest trees of any size, or land formerly having such tree cover, and not currently developed for a nonforest use (Reams et al. 2005). A 1⁄16 subset of the phase 2 plots are referred to as phase 3 plots (previously denoted Forest Health Monitoring plots), resulting in a phase 3 sample intensity of approximately one plot per 96,000 ac (McRoberts 2005). Phase 3 plots include all of the measurements of phase 2 plots, plus additional measurements related to several different indicators of forest health. CCR is a national core variable for phase 2 plots, meaning it is measured by all FIA units following standard protocols (US Forest Service 2005, 2007b). However, UNCR is a core variable only on phase 3 plots; it is an optional variable for trees 5 in. or more in diameter on phase 2 plots, meaning its collection is at the discretion of the regional FIA units.

The Interior West FIA (IWFIA) unit has periodically collected both CCR and UNCR of trees in its phase 2 plots across Idaho, Montana, Wyoming, Nevada, Utah, Colorado, Arizona, and New Mexico during the last 30 years. We queried the IWFIA regional instance of the FIA database (Miles et al. 2001) for trees with a 5-in. or more diameter from the most recent measurement of each plot as of 2005. This resulted in a total of 406,768 trees measured between 1978 and 2005. A subset of 205,583 trees had measurements of both CCR and UNCR. The availability of UNCR from phase 2 plots provided an increase in number of tree records of two orders of magnitude compared with the data available to Monleon et al. (2004) who used tree records only from phase 3 plots in Washington, Oregon, and California.

Of the tree records used in this analysis, 56% were from plots having the current national standard FIA plot design consisting of a cluster of four 24-ft fixed-radius subplots (Bechtold and Scott 2005). The remaining tree records were from older inventories using a variety of plot designs, including both variable- and fixed-radius plots.

Tree measurement protocols are described in the *Interior West Forest Inventory and Analysis Field Procedures* manuals (US Forest Service 2006). Diameters were measured at breast height (dbh) for most species. Diameters were measured at the root collar (DRC) for species with shrublike form designated as "woodland" by IWFIA. The dbh was measured to the nearest tenth of an inch at a point 4.5 ft aboveground on the uphill side of the tree. DRC was measured to the nearest tenth inch at the groundline or at the stem root collar, whichever was higher. UNCR was the ratio of live crown length to tree height. Live crown length was determined from the last live foliage at the crown top to the lowest foliage of the "obvious live crown base," defined as the lowest whorl with live branches in at least two quadrants around the circumference of the stem, exclusive of whorls not continuous with the main crown. Many times there were additional live branches below the obvious live crown base. These branches were only included if they had a basal diameter greater than 1 in. and were within 5 ft of the base of the obvious live crown. The live crown base was taken as the point on the main bole perpendicular to the lowest live foliage on the last branch that is included in the live crown. The live crown base was defined by the height of live foliage, not by the point where a branch intersected with the main bole (US Forest Service 2006, p. 171). CCR was determined by visually transferring lower live branches to fill in large holes in the upper portion of the tree until a full, even crown was visualized (US Forest Service 2006, p. 173). For multistemmed western woodland species, lower live foliage was visually transferred to fill large holes on all stems and form an even crown across the tree (US Forest Service 2006, p. 175). The field manual states that crowns should not be overcompacted beyond the full crown typical for a species. For example, if branches tend to average 2 ft between whorls for a given species, then the crown should not be compacted beyond the 2-ft spacing (US Forest Service 2006, p. 173). Both crown ratios were measured in 5% increments before 1995, but were subsequently measured to the nearest 1%.

Monleon et al. (2004) provided a statistical and a practical rationale for including only trees with CCR of 0.90 or less. UNCR can not be smaller than CCR, so UNCR is always between CCR and 1. For example, if CCR is 0.95, then UNCR must be between 0.95 and 1.0. Because UNCR is restricted to a small range of possible values, the variance for those observations is small, which would result in a nonconstant variance of the residuals from a regression equation. Also, once CCR is greater than 0.90, any estimate of UNCR will be within measurement error (Pollard et al. 2006).

After limiting the analysis to species with at least 100 observations, the model-fitting data set contained 35 species and 201,855 tree records from 11,766 forested plots across the 8 IWFIA states (Tables 1 and 2).

IWFIA resumed measuring UNCR of trees with a 5-in. or more diameter on phase 2 plots in 2006 after having not measured UNCR on phase 2 plots during 2003–2005. The new tree records from 2006 became available subsequent to fitting the models described later and were used as a test data set. Tree measurement protocols in 2006 were as described previously. Tree records from plots that were repeat measurements of plots included in the training data set were excluded from the test data set. Twenty-three Interior West species had at least 50 tree records from 2006 available for testing.

Model Development

The following logistic equation was fitted to the data for each species:

$$\mathrm{UNCR} = \frac{1}{1 + e^{-x\beta}} + \varepsilon,$$

where $x\beta$ is a linear combination of the predictor variables and e is the mathematical constant. Potential predictor variables considered were CCR, the natural logarithm of diameter, the natural logarithm of height, the height/diameter ratio, and stand-level basal area (BA).

Coefficient Estimation

Monleon et al. (2004) used weighted nonlinear regression with weights set to the inverse of UNCR $\times$ (1 $-$ UNCR), which is proportional to the inverse of the variance of a binomial distribution. In the present study, weighting the regression in this way resulted in poor fits for some species as indicated by diagnostic plots

Table 1. Scientific and common names of 35 tree species in the Interior West model-fitting data set.

Scientific name	Common name
Abies concolor (Gord. & Glend.) Lindl. ex Hildebr.	White fir
Abies grandis (Douglas ex D. Don) Lindl.	Grand fir
Abies lasiocarpa (Hook.) Nutt.	Subalpine fir
Abies lasiocarpa (Hook.) Nutt. var. arizonica (Merriam) Lemmon	Corkbark fir
Betula papyrifera Marsh.	Paper birch
Cercocarpus ledifolius Nutt.	Curlleaf mountain-mahogany
Juniperus deppeana Steud.	Alligator juniper
Juniperus monosperma (Engelm.) Sarg.	Oneseed juniper
Juniperus occidentalis Hook.	Western juniper
Juniperus osteosperma (Torr.) Little	Utah juniper
Juniperus scopulorum Sarg.	Rocky Mountain juniper
Larix occidentalis Nutt.	Western larch
Picea engelmannii Parry ex Engelm.	Engelmann spruce
Picea pungens Engelm.	Blue spruce
Pinus albicaulis Engelm.	Whitebark pine
Pinus aristata Engelm.	Bristlecone pine
Pinus contorta Douglas ex Louden	Lodgepole pine
Pinus edulis Engelm.	common pinyon
Pinus flexilis James	Limber pine
Pinus jeffreyi Balf.	Jeffrey pine
Pinus monophylla Torr. & Frém.	Singleleaf pinyon
Pinus monticola Douglas ex D. Don	Western white pine
Pinus ponderosa C. Lawson	Ponderosa pine
Pinus strobiformis Engelm.	Southwestern white pine
Populus angustifolia James	Narrowleaf cottonwood
Populus deltoides Bartram ex Marsh. ssp. monilifera (Aiton) Eckenwalder	Plains cottonwood
Populus tremuloides Michx.	Quaking aspen
Populus trichocarpa Torr. & A. Gray ex Hook.	Black cottonwood
Pseudotsuga menziesii (Mirb.) Franco	Douglas-fir
Quercus gambelii Nutt.	Gambel oak
Quercus grisea Liebm.	Gray oak
Quercus macrocarpa Michx.	Bur oak
Thuja plicata Donn ex D. Don	Western redcedar
Tsuga heterophylla (Raf.) Sarg.	Western hemlock
Tsuga mertensiana (Bong.) Carrière	Mountain hemlock

of weighted residuals and model performance statistics (see Model Evaluation). Therefore, for each species, models were fitted with and without the weights and the model evaluation criteria described later were used to select the best set of coefficients.

To reduce the influence of outliers, models were fitted using robust nonlinear regression by iteratively reweighted least squares (Motulsky and Ransnas 1987, Venables and Ripley 2002). Model fitting was done in R 2.4.0 (R Development Core Team 2006) using the nlrob function in the *robustbase* package (Rousseeuw et al. 2006). Initial approximations for each parameter were based on the coefficients from Monleon et al. (2004).

Model Evaluation

Fitted models were evaluated using visual techniques, including diagnostic plots of weighted residuals (Draper and Smith 1981) and plots of observed (y) versus predicted ($\hat{y}$) values relative to the 1:1 line (Mayer and Butler 1993). Precision of the models was assessed with the root mean squared error (RMSE) and mean absolute error (MAE):

$$\mathrm{RMSE} = \{[\sum (y_i - \hat{y}_i)^2]/n\}^{1/2} \quad \mathrm{MAE} = (\sum |y_i - \hat{y}_i|)/n,$$

where n is the number of observations for the species being evaluated, y_i is the observed UNCR for tree i, and $\hat{y}_i$ is the predicted UNCR for tree i.

Bias was assessed with the mean error (ME):

$$\mathrm{ME} = \sum (y_i - \hat{y}_i)/n.$$

It was also informative to create groups of residuals by dividing the range of the primary predictor variable CCR into three equal-length subranges (denoted as low, medium, and high CCR) and examine ME for each subrange (Donatelli et al. 2004).

Model efficiency (Loague and Green 1991, Vanclay and Skovsgaard 1997) was calculated as

$$\mathrm{EF} = 1 - \frac{\sum (y_i - \hat{y}_i)^2}{\sum (y_i - \bar{y})^2}.$$

This statistic provides an index of model performance on a relative scale, with 1 indicating perfect fit, 0 indicating model fit no better than a simple average, and negative values indicating poor fit. Efficiency statistic (EF) is similar to R^2 but is measured against the line $y = \hat{y}$ (Mayer and Butler 1993). It has been used as a goodness-of-fit statistic in the case of simulation and nonlinear regression models (e.g., Yang et al. 2000, Soares and Tomé 2001, Calama et al. 2003, Pinjuv et al. 2006).

Results and Discussion

The mean difference between field-measured UNCR and CCR for trees in the Interior West was 0.17, ranging from 0.08 for quaking aspen (*Populus tremuloides*) to 0.27 for narrowleaf cottonwood (*Populus angustifolia*). These results are similar to those reported by Monleon et al. (2004) for trees in California, Oregon, and Washington, where the mean difference between UNCR and CCR over all species was 0.16. The magnitude of differences between UNCR and CCR of western tree species can lead to biased estimates in modeling applications. For example, simulated crown fire potential was significantly lower if CCR instead of UNCR was used to derive stand-level crown fuel parameters in several forest types of the Pacific Northwest (Monleon et al. 2004). Estimates of stand-level crown base height, in particular, could be biased high if CCR is used to derive the height to the first live branches of individual trees in a stand (Reeves et al. 2006, Toney et al. 2007).

Monleon et al. (2004) fit two sets of equations to predict UNCR: one set used only CCR and the natural logarithm of diameter as potential predictors, while the second set also included the natural logarithm of height and the height/diameter ratio as potential predictors. However, for nearly one-third of the species the height variables were not significant at an $\alpha = 0.05$ level in the second set of equations and were, therefore, not retained by the stepwise regression procedure. Furthermore, improvement in prediction errors was negligible for most species in cases where one or both of the height variables were retained. We tested height variables for some of the more common species in the IWFIA data set and also found negligible improvement in prediction errors. We also tested stand-level BA (squared feet per acre) as a potential predictor in the equations for all species. BA was significant at the $\alpha = 0.05$ level in equations for 28 of the 35 species; however, decreases in RMSE caused by the addition of BA were less than 0.01 UNCR for all species (mean decrease in RMSE of 0.002 UNCR), while the mean increase in EF was 0.01 and no differences in residual plots between equations with and without BA were discernible. The model-fitting objective of the present study was to convert crown ratio measurements from one form (CCR) into another (UNCR), which differs

Table 2. Number of plots and trees in the model-fitting data set, and minimum (min), average (mean), maximum (max), and standard deviation (SD) of tree variables by species.

			UNCR				CCR				Diameter (in.)			
Species	Plots (*n*)	Trees (*n*)	Min	Mean	Max	SD	Min	Mean	Max	SD	Min	Mean	Max	SD
Abies concolor	513	3,891	0.03	0.74	1.00	0.17	0.02	0.56	0.90	0.18	5.0	11.1	45.0	5.8
Abies grandis	798	5,931	0.05	0.66	1.00	0.19	0.02	0.50	0.90	0.18	5.0	11.8	51.4	6.6
Abies lasiocarpa	2,759	19,925	0.03	0.78	1.00	0.16	0.01	0.60	0.90	0.18	5.0	9.6	43.6	4.3
Abies lasiocarpa var. arizonica	129	1,466	0.03	0.76	1.00	0.16	0.02	0.59	0.90	0.17	5.0	8.3	25.7	3.2
Betula papyrifera	101	303	0.10	0.49	0.87	0.16	0.05	0.37	0.82	0.15	5.0	8.3	32.0	3.2
Cercocarpus ledifolius[a]	87	597	0.05	0.68	0.99	0.22	0.05	0.53	0.90	0.21	5.0	9.2	27.0	3.6
Juniperus deppeana[a]	32	177	0.30	0.79	0.99	0.16	0.02	0.56	0.90	0.20	5.1	9.8	52.7	5.6
Juniperus monosperma[a]	96	449	0.25	0.89	0.99	0.11	0.05	0.69	0.90	0.19	5.0	13.0	42.1	6.8
Juniperus occidentalis	56	434	0.05	0.82	0.98	0.08	0.05	0.74	0.90	0.14	5.0	13.4	57.0	8.3
Juniperus osteosperma[a]	1,004	7,553	0.05	0.79	0.99	0.14	0.05	0.68	0.90	0.16	5.0	12.2	62.9	6.1
Juniperus scopulorum[a]	194	654	0.05	0.82	0.99	0.18	0.05	0.62	0.90	0.21	5.0	9.8	36.8	4.8
Larix occidentalis	795	3,475	0.04	0.48	0.98	0.17	0.01	0.36	0.90	0.14	5.0	14.8	49.9	7.6
Picea engelmannii	2,516	18,915	0.05	0.78	1.00	0.15	0.01	0.60	0.90	0.17	5.0	12.5	50.6	6.4
Picea pungens	75	467	0.23	0.81	0.99	0.12	0.10	0.66	0.90	0.16	5.0	11.7	45.3	6.3
Pinus albicaulis	809	5,866	0.05	0.72	1.00	0.18	0.02	0.51	0.90	0.19	5.0	11.2	56.0	5.9
Pinus aristata	39	253	0.05	0.83	0.99	0.13	0.05	0.66	0.90	0.19	5.0	13.4	64.5	8.3
Pinus contorta	2,840	35,302	0.01	0.54	1.00	0.21	0.01	0.39	0.90	0.18	5.0	8.8	53.0	3.1
Pinus edulis[a]	256	1,924	0.10	0.87	0.99	0.13	0.05	0.66	0.90	0.18	5.0	9.2	34.3	3.6
Pinus flexilis	637	2,881	0.05	0.74	1.00	0.20	0.01	0.53	0.90	0.21	5.0	10.6	58.4	5.8
Pinus jeffreyi	16	107	0.15	0.59	0.93	0.19	0.05	0.45	0.85	0.17	5.8	16.4	48.5	7.4
Pinus monophylla[a]	659	5,238	0.05	0.75	0.99	0.13	0.05	0.66	0.90	0.14	5.0	9.4	37.0	3.8
Pinus monticola	165	359	0.05	0.67	0.99	0.19	0.05	0.50	0.90	0.20	5.0	13.4	50.3	7.3
Pinus ponderosa	3,016	25,360	0.02	0.62	1.00	0.17	0.01	0.49	0.90	0.17	5.0	11.8	66.1	6.2
Pinus strobiformis	130	444	0.21	0.71	1.00	0.17	0.15	0.56	0.90	0.18	5.0	10.6	29.4	5.0
Populus angustifolia	45	253	0.15	0.74	0.95	0.17	0.05	0.47	0.86	0.17	5.0	14.9	37.7	7.8
Populus deltoids spp. monilifera	24	282	0.15	0.60	0.95	0.18	0.05	0.42	0.78	0.16	5.1	16.0	60.4	7.8
Populus tremuloides	1,497	14,479	0.01	0.35	1.00	0.15	0.01	0.27	0.88	0.13	5.0	8.4	25.2	2.8
Populus trichocarpa	68	295	0.15	0.58	0.99	0.19	0.05	0.42	0.85	0.17	5.0	17.1	55.4	8.9
Pseudotsuga menziesii	4,700	38,368	0.05	0.69	1.00	0.19	0.01	0.52	0.90	0.18	5.0	13.5	65.0	7.1
Quercus gambelii[a]	85	580	0.10	0.67	0.99	0.18	0.01	0.43	0.90	0.17	5.0	7.1	25.2	2.6
Quercus grisea[a]	30	212	0.35	0.82	0.99	0.14	0.02	0.57	0.90	0.18	5.0	9.8	36.3	4.2
Quercus macrocarpa	38	294	0.01	0.74	0.99	0.13	0.01	0.57	0.88	0.17	5.0	6.9	15.2	1.8
Thuja plicata	391	2,877	0.05	0.67	1.00	0.18	0.02	0.51	0.90	0.17	5.0	13.5	94.7	8.9
Tsuga heterophylla	213	1,320	0.10	0.71	0.99	0.17	0.03	0.53	0.90	0.18	5.0	11.0	38.5	5.6
Tsuga mertensiana	87	935	0.20	0.77	1.00	0.15	0.05	0.58	0.90	0.17	5.0	12.2	46.5	6.4

[a] Indicates woodland species for which diameter was measured at the root collar.

from studies designed to predict crown ratio solely from other tree and stand attributes (e.g., Hasenauer and Monserud 1996, Soares and Tomé 2001, Temesgen et al. 2005). In the present study, CCR provided most of the information for predicting UNCR, while the addition of other tree and stand-level variables provided only negligible improvement in the performance of the equations. For this reason, we chose to present only the simpler set of equations that predict UNCR from CCR and ln(diameter).

The final fitted equation was

$$\mathrm{UNCR_{pred}} = 1/(1 + e^{-[a+b\cdot \mathrm{CCR}+c\cdot \ln(\mathrm{diameter})]}), \qquad (1)$$

where $\mathrm{UNCR_{pred}}$ is the predicted UNCR for a given tree, and a, b, and c are coefficients estimated from the data (Table 3). Table 4 shows fit statistics for these equations computed from the model-fitting data. The RMSE of predicted UNCR for the equations fit in this study (hereafter, the "Interior West equations") was similar to results obtained by Monleon et al. (2004) for trees in California, Oregon, and Washington. RMSE ranged from 0.06 to 0.15 UNCR (MAE, 0.04 to 0.12 UNCR).

Mean bias was near zero for most species. Bias in predicted UNCR was often large within certain subranges of CCR when the model EF was near or below the mean EF across all species of 0.49. For example, the equation for subalpine fir (*Abies lasiocarpa*) has ME of 0.009, but below-average EF of 0.45. Examination of the subrange residuals shows large bias in predicted UNCR at low values of CCR for subalpine fir. The equations for juniper species generally have similar problems. Subalpine fir and western juniper (*Juniperus occidentalis*) were also found difficult to model by Monleon et al. (2004) because of small sample sizes and limited ranges of UNCR. Trees of pinyon and juniper species in the Interior West (e.g., western juniper, Utah juniper, common pinyon, and singleleaf pinyon) tended to cluster around certain CCR–UNCR value pairs (e.g., large numbers of observations with CCR = 0.65 and UNCR = 0.65), which may be partially responsible for the relatively poor fit of these models. Users should be cautious applying equations with relatively low EF values (below about 0.49) and should assess the potential impact of the bias characteristics on their particular applications.

Using the Models

UNCR can be predicted using the coefficients in Table 3 as follows: if CCR is more than 0.9, $\mathrm{UNCR_{pred}} = \mathrm{CCR}$, otherwise, use Equation 1. The first step in this procedure could introduce bias because UNCR will be slightly larger on average than CCR even when CCR is more than 0.9. The mean difference between UNCR and CCR for trees with CCR more than 0.9 was 0.02 in our model-fitting data ($P < 0.001$). This value is small relative to the overall mean difference between UNCR and CCR and relative to measurement error (Pollard et al. 2006). However, an adjustment of $\mathrm{UNCR_{pred}} = \mathrm{CCR} + 0.02$ if CCR is more than 0.9 is probably

Table 3. Estimated coefficients for the regression of uncompacted crown ratio (UNCR) on compacted crown ratio (CCR) and ln(diameter) for 35 species in the Interior West.

	Equation: $UNCR_{pred} = 1/[1 + e^{-[a+b \cdot CCR+c \cdot \ln(diameter)]}]$			
Species	*a*	*b*	*c*	Weighting
Abies concolor	−1.2822	4.0171	0.0672	None
Abies grandis	−1.6358	5.0325		$(UNCR \times (1 - UNCR))^{-1}$
Abies lasiocarpa	−0.8519	3.8709	−0.0552	None
Abies lasiocarpa var. arizonica	−1.1664	4.0738		None
Betula papyrifera	−1.7752	4.5088		$(UNCR \times (1 - UNCR))^{-1}$
Cercocarpus ledifolius	−1.2751	4.6838	−0.1698	None
Juniperus deppeana	−0.3830	3.2962		None
Juniperus monosperma	0.9801	1.7931		None
Juniperus occidentalis	−0.0622	2.2242		None
Juniperus osteosperma	−0.1831	2.2050		None
Juniperus scopulorum	−1.2970	4.0726	0.2536	None
Larix occidentalis	−1.8661	4.9547		$(UNCR \times (1 - UNCR))^{-1}$
Picea engelmannii	−0.9834	3.9661	−0.0353	None
Picea pungens	−0.6458	3.2623		None
Pinus albicaulis	−0.9327	3.8231		None
Pinus aristata	0.1920	2.2287		None
Pinus contorta	−2.1683	5.4651	0.1434	$(UNCR \times (1 - UNCR))^{-1}$
Pinus edulis	0.3196	2.5716		None
Pinus flexilis	−1.4409	4.4130	0.0940	None
Pinus jeffreyi	−1.7532	5.0047		$(UNCR \times (1 - UNCR))^{-1}$
Pinus monophylla	−0.3956	2.0098	0.0681	None
Pinus monticola	−1.1662	3.7536		None
Pinus ponderosa	−1.6296	4.5654		$(UNCR \times (1 - UNCR))^{-1}$
Pinus strobiformis	−1.3658	4.1807		None
Populus angustifolia	−0.5266	3.5578		None
Populus deltoides spp. monilifera	−0.6962	3.6653	−0.1797	None
Populus tremuloides	−1.9832	4.7645		None
Populus trichocarpa	−0.5066	4.3659	−0.3041	$(UNCR \times (1 - UNCR))^{-1}$
Pseudotsuga menziesii	−1.4162	5.3576	−0.1156	$(UNCR \times (1 - UNCR))^{-1}$
Quercus gambelii	−1.3748	3.0274	0.4001	None
Quercus grisea	−0.4639	3.5862		None
Quercus macrocarpa	−0.0178	1.9683		None
Thuja plicata	−1.5641	4.9260		$(UNCR \times (1 - UNCR))^{-1}$
Tsuga heterophylla	−1.3381	4.7160		$(UNCR \times (1 - UNCR))^{-1}$
Tsuga mertensiana	−0.4151	3.8778	−0.2361	None

Blank entries imply the estimate was not significant at the $\alpha = 0.05$ level. Nonsignificant intercept terms were retained. Weighting indicates whether the regressions were weighted proportional to the inverse of the variance of a binomial distribution.

reasonable for most species, and could be considered as an alternative to the first step mentioned previously.

Tests of the Models with New Data

UNCR was predicted for trees in the 2006 test data set following the procedure described previously for using the models, including the adjustment $UNCR_{pred} = CCR + 0.02$ if CCR is more than 0.9. Ten species had coefficients available from Monleon et al. (2004), and these were also tested against the 2006 IWFIA data. Table 5 shows model performance statistics for the test data set.

The Interior West equations for most species performed well when applied to the test data. As expected, the equations for most pinyon and juniper species tended to perform little better than a simple average as indicated by low EF statistics. The equation for singleleaf pinyon (*Pinus monophylla*) was especially problematic and is not recommended for use. The equations for several common conifer species, including subalpine fir, western larch (*Larix occidentalis*), lodgepole pine (*Pinus contorta*), ponderosa pine, Douglas-fir (*Pseudotsuga menziesii*), and western redcedar (*Thuja plicata*) had MAE of 0.092 or less UNCR with low bias.

Comparison with the Monleon et al. (2004) equations serves as a model selection tool in that the Interior West equations should perform at least as well as the equations already available in the literature. This comparison also helps to assess whether the Monleon et al. (2004) equations are transportable to the Interior West, given that this application of their models extrapolates not only geographically but also across FIA operational units. In general, the Monleon et al. (2004) equations performed well when applied to the IWFIA 2006 tree data. The Interior West equations for Douglas-fir, western larch, and western redcedar performed slightly better than the Monleon et al. (2004) equations for these species applied to the test data, while the Monleon et al. (2004) equation for white fir (*Abies concolor*) performed slightly better than the Interior West equation.

The performance of the Monleon et al. (2004) equations applied to trees in the Interior West and the close agreement between the Monleon et al. (2004) and Interior West equations for 10 species compared helps to confirm the robustness of the overall modeling approach. This is important because of the limited availability of UNCR measurements in large forest inventories of the western United States. IWFIA is presently the only FIA unit measuring UNCR on phase 2 plots; UNCR is presently not measured on phase 2 plots in California, Oregon, Washington, and states east of the IWFIA region. The new Interior West equations for species previously lacking an equation for CCR–UNCR conversion may be transportable to these areas, although users should carefully consider potential implications of geographic extrapolation and test the equations in their areas if possible. The equations may also be applicable to other forest inventory data sets containing CCR if measurement

Table 4. Root mean square error (RMSE), mean absolute error (MAE), and mean error (ME), mean error for three equal-length subranges of compacted crown ratio (CCR), and model efficiency statistic (EF) for the regression coefficients in Table 3, computed from the model-fitting data.

Species	RMSE	MAE	ME	ME-low CCR	ME-medium CCR	ME-high CCR	EF
Abies concolor	0.122	0.091	0.010	0.051	0.012	−0.002	0.49
Abies grandis	0.110	0.084	−0.017	0.028	−0.020	−0.035	0.66
Abies lasiocarpa	0.116	0.086	0.009	0.081	0.007	0.003	0.45
Abies lasiocarpa var. arizonica	0.116	0.087	0.010	0.066	0.015	−0.002	0.47
Betula papyrifera	0.093	0.058	0.016	0.034	0.009	−0.017	0.68
Cercocarpus ledifolius	0.149	0.110	0.019	0.068	0.016	0.002	0.56
Juniperus deppeana	0.125	0.098	0.004	0.008	0.009	−0.003	0.39
Juniperus monosperma	0.104	0.080	−0.009	−0.053	−0.017	−0.003	0.18
Juniperus occidentalis	0.062	0.037	−0.001	−0.115	0.045	−0.003	0.42
Juniperus osteosperma	0.123	0.096	0.002	0.039	0.078	−0.013	0.22
Juniperus scopulorum	0.138	0.107	−0.006	0.024	0.017	−0.023	0.44
Larix occidentalis	0.089	0.064	0.006	0.025	−0.003	−0.018	0.72
Picea engelmannii	0.103	0.077	0.006	0.027	0.014	−0.002	0.53
Picea pungens	0.088	0.066	0.001	−0.001	−0.001	0.002	0.47
Pinus albicaulis	0.134	0.102	0.011	0.046	0.006	0.001	0.47
Pinus aristata	0.110	0.078	−0.004	−0.073	0.008	−0.003	0.33
Pinus contorta	0.120	0.088	−0.002	0.027	−0.014	−0.046	0.67
Pinus edulis	0.111	0.086	−0.007	−0.051	−0.003	−0.006	0.25
Pinus flexilis	0.139	0.103	0.012	0.044	0.017	−0.005	0.53
Pinus jeffreyi	0.106	0.089	−0.016	0.030	−0.026	−0.034	0.70
Pinus monophylla	0.112	0.096	0.004	0.009	0.082	−0.012	0.20
Pinus monticola	0.129	0.093	0.016	0.086	−0.011	0.018	0.53
Pinus ponderosa	0.100	0.078	−0.006	0.030	−0.005	−0.031	0.66
Pinus strobiformis	0.104	0.079	0.010	0.021	0.006	0.009	0.64
Populus angustifolia	0.140	0.112	−0.004	−0.029	0.016	−0.045	0.33
Populus deltoides spp. monilifera	0.141	0.103	0.018	0.069	0.001	0.006	0.41
Populus tremuloides	0.069	0.049	0.008	0.007	0.011	−0.022	0.78
Populus trichocarpa	0.151	0.117	−0.026	0.021	−0.052	−0.009	0.39
Pseudotsuga menziesii	0.116	0.089	−0.030	0.023	−0.034	−0.043	0.63
Quercus gambelii	0.143	0.113	0.004	0.009	0.006	−0.014	0.36
Quercus grisea	0.111	0.087	0.005	0.050	−0.015	0.014	0.40
Quercus macrocarpa	0.100	0.072	−0.002	0.007	−0.015	0.008	0.34
Thuja plicata	0.110	0.085	−0.025	0.028	−0.032	−0.035	0.61
Tsuga heterophylla	0.105	0.082	−0.021	0.025	−0.025	−0.031	0.61
Tsuga mertensiana	0.100	0.075	0.007	0.034	0.006	0.004	0.55

Table 5. Model performance statistics computed from a test data set comprised of Interior West forest inventory and analysis field measurements taken in 2006.

		Equation: $UNCR_{pred} = 1/[1 + e^{-[a + b \cdot CCR + c \cdot \ln(diameter)]}]$							
		Coefficients from Table 3				Coefficients from Monleon et al. (2004)			
Species	Trees (n)	RMSE	MAE	ME	EF	RMSE	MAE	ME	EF
Abies concolor	244	0.125	0.097	0.035	0.45	0.122	0.095	0.014	0.48
Abies grandis	155	0.115	0.077	0.008	0.68	0.117	0.080	0.001	0.67
Abies lasiocarpa	1,466	0.123	0.091	0.036	0.47	0.124	0.091	0.020	0.46
Cercocarpus ledifolius	192	0.128	0.093	0.000	0.57				
Juniperus deppeana	129	0.113	0.080	0.024	0.24				
Juniperus monosperma	386	0.086	0.060	0.031	0.18				
Juniperus osteosperma	3,632	0.152	0.123	0.088	0.15				
Juniperus scopulorum	433	0.110	0.077	0.015	0.45				
Larix occidentalis	71	0.077	0.057	0.001	0.85	0.087	0.062	0.032	0.81
Picea engelmannii	2,062	0.122	0.094	0.046	0.48	0.126	0.091	0.045	0.45
Pinus albicaulis	131	0.149	0.109	0.047	0.33				
Pinus aristata	53	0.113	0.098	0.062	0.11				
Pinus contorta	2,380	0.117	0.085	0.016	0.76	0.120	0.085	0.031	0.75
Pinus edulis	1,892	0.102	0.072	0.010	0.37				
Pinus flexilis	175	0.181	0.133	0.077	0.32				
Pinus monophylla	252	0.151	0.123	0.105	−0.40				
Pinus ponderosa	805	0.107	0.079	0.027	0.70	0.106	0.083	0.011	0.71
Populus tremuloides	1,541	0.077	0.049	0.018	0.76				
Pseudotsuga menziesii	1,800	0.119	0.092	−0.010	0.64	0.128	0.091	0.044	0.58
Quercus gambelii	482	0.166	0.135	0.003	0.31				
Quercus grisea	157	0.113	0.083	0.011	0.40				
Thuja plicata	84	0.122	0.084	−0.004	0.43	0.129	0.094	−0.028	0.37
Tsuga heterophylla	78	0.090	0.076	−0.040	0.85	0.099	0.072	0.050	0.82

UNCR, uncompacted crown ratio, RMSE, root mean square error; MAE, mean absolute error; ME, mean error; EF, efficiency statistic.

protocols are similar to those used by FIA (e.g., US Forest Service 2007a).

Conclusions and Recommendations

A comprehensive set of equations now exists to convert CCR to UNCR in forest inventory data sets for the western United States. The present study provides coverage for species in eight Interior West states and complements the equations presented by Monleon et al. (2004) for species in California, Oregon, and Washington. These equations should be of particular interest to users of FIA data because of significant gaps in the availability of UNCR in most western states, especially in the data collected since 2000. Because the average difference between CCR and UNCR for western trees is approximately 0.17, biologically significant bias could be introduced in applications that use crown ratio to derive height to live crown. For these applications, it should be desirable to "uncompact" crowns before further data processing.

UNCR or height to live crown should be a standard measurement in forest inventories, especially considering the little additional time it would take (Monleon et al. 2004). UNCR appears to be a more repeatable measurement than CCR in the Interior West (Pollard et al. 2006), so it is probably more efficient to measure UNCR or height to live crown directly and estimate CCR using regression equations. Precise measurements of UNCR or height to live crown could benefit a variety of applications including crown fuel estimation and fire behavior modeling.

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