Models for Estimation and Simulation of Crown and Canopy Cover

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Abstract.—Crown width measurements collected during Forest Inventory and Analysis and Forest Health Monitoring surveys are being used to develop individual tree crown width models and plot-level canopy cover models for species and forest types in the Intermountain West. Several model applications are considered in the development process, including remote sensing of plot variables and stand modeling with the Forest Vegetation Simulator. The modeling process is intended to be data driven, consistent with crown architecture and stand dynamics concepts, and compatible with multiple end-user applications.

Introduction

Canopy cover is an important forest stand variable that is used in a wide variety of applications, including assessment of wildlife habitat characteristics, stand competition status, and susceptibility to damaging agents. Crown width and canopy cover measurements have been collected periodically in the Intermountain West as part of Forest Inventory and Analysis (FIA) and Forest Health Monitoring (FHM) sample designs. These data have not yet been used to their full potential. New applications have been made possible with the implementation of the mapped plot design (Birdsey 1995, Hahn *et al.* 1995). Measured or modeled crowns can be stem-mapped to provide estimates of projected canopy cover that can be compared to other canopy cover estimates, such as those measured by field crews or derived from aerial imagery. Spatially explicit crown projections also permit development of specific overlap curves for stands of different composition and structure. Crown data from surveys conducted between 1980 and 1999 are being used to develop individual tree crown models and plot-level canopy cover models for most species and forest types that occur in the Interior West FIA (IW-FIA) database. The suite of models generated by this research may lead to improvements in data collection methods, canopy cover estimates, and remote sensing applications.

This article describes the available data, analysis considerations, and process with which a comprehensive set of crown diameter and canopy cover models is being developed for trees and forest types in the Intermountain West. This modeling effort includes objectives, such as increasing field efficiency and improving accuracy of canopy cover estimates that are internal to the FIA program. Other objectives anticipate users' needs and build on recent research and applications that use crown and canopy cover data. For example, the canopy cover extension to the Forest Vegetation Simulator (FVS) produces overlap-adjusted canopy cover estimates, but cover estimates are based on the assumption that stems (and crowns) are in a random spatial arrangement for all stand compositions and structures (Crookston and Stage 1999). Data from mapped FIA plots can be compared to FVS estimates and may support the assumption of random arrangement or suggest alternative arrangements by forest type. Most crown modeling efforts (for example, Bechtold 2003, Bragg 2001) are focused on prediction of crown width based on stem diameter and other factors. Isolating and measuring individual trees using high-resolution imagery (for example, Gougeon 1995, Gougeon and Leckie 2003) is possible, however, increasing the ability to estimate stem diameters and stand basal areas using crown measurements. Therefore, models that are optimized for remote sensing applications—in other words, with stem diameter as the dependent rather than independent variable—will also be valuable.

Analysis Approach

The approach to crown modeling taken herein reflects the desire to anticipate end user needs and, at the same time, develop models that are based on an understanding of tree biology and

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stand dynamics. Local parameterization of the models is desirable to the extent that the data permit. The analysis plan consists of a progression from simple individual tree crown models to more complex single tree models, and ultimately plot-level canopy cover models. Analysis will be conducted in two phases. Phase 1 will address individual tree crowns, and phase 2 will address plot-level cover models.

Mining Historic Data

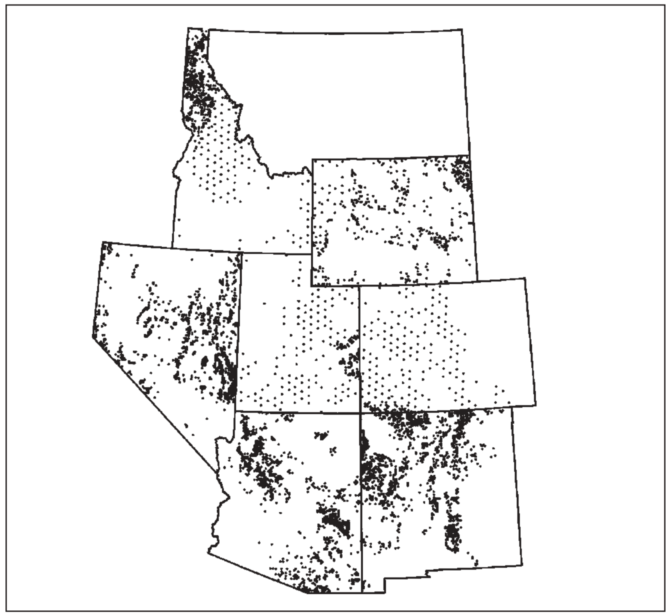
This study was conceived with the intent of using data collected from past surveys. The number of usable records was unknown, however. Twenty-two surveys conducted by FIA from 1980 to 1988 and by FHM from 1991 to 1999 were identified as potentially including crown width measurements based on field manual documentation. Crown width data from the oldest surveys were retrieved from digital tape archives. The surveys covered all, or major portions of, seven of the eight states in the IWFIA analysis area: Arizona, Colorado, Idaho, Nevada, New Mexico, Utah, and Wyoming (fig. 1). No crown data from past surveys were available for Montana.

At a minimum, species, diameter, and two crown width measurements were required to constitute a usable record. Diameter was recorded to the nearest 0.1 inch in all surveys. For most species, diameter was measured at breast height (d.b.h.), but for woodland species (species of short stature and, commonly, a multistem habit), diameter was measured at the root collar (d.r.c.). For individuals with multiple stems, the method described by Chojnacky (1988) was used to calculate an equivalent diameter at root collar. Crown widths were measured to the nearest foot; further discussion of crown width data follows.

Other variables under consideration include number of stems (woodland species only), compacted or uncompacted live crown ratio (measured or calculated), density measures (basal area or stand density index), elevation, and various geographic or political divisions (for example, National Forest unit or ecoregion).

The analysis data set includes 108,946 usable records for 59 species or species groups (table 1). The number of usable records varies widely by species, however, and complete sets of the potential additional variables could not be compiled for some species. This situation may limit the potential for geographic stratification for some species. For 17 species with a low number of observations, only preliminary models (or no models at all) may be developed. The distribution of observations appears to reflect the relative abundance of species across the area of interest, however, and less demand for models of rarer species is assumed. Some locally abundant species with limited geographic ranges, such as Arizona cypress (*Cupressus arizonica*), are not represented in the data. The analysis data set contains 43 species with $n \geq 30$, 38 species with $n \geq 50$, 33 species with $n \geq 100$, 22 species with $n \geq 500$, and 17 species with $n \geq 1{,}000$. Based on this distribution of observations and the behavior of the stem diameter-crown width relationship, developing reliable general crown width models for at least 32 species and local (in other words, geographically stratified) crown width models for at least 17 species should be possible.

Figure 1.—*Locations of sample plots that include crown width measurements.*



Data Considerations

Because the data include observations for which two crown width measurements were obtained, some assumptions must be made about crown shape to determine the appropriate value for use in crown diameter modeling. FIA field manuals usually specify that the long crown axis should be measured first and

Table 1.—*Species included in the crown width database and number of observations for each.*

Species	n	Species	n	Species	n
Conifers		*Pinus flexilis*	991	*Cercocarpus montanus*	18
Abies concolor	815	*Pinus strobiformis*	49	*Cercocarpus breviflorus*	19
Abies grandis	1,818	*Pinus jeffreyi*	62	*Cornus nuttallii*	1
Abies lasiocarpa	2,563	*Pinus leiophylla*	16	*Olneya tesota*	95
Abla var. arizonica	385	*Pinus ponderosa*	7,088	*Platanus californica*	2
Juniperus erythrocarpa	21	*Pinus monophylla*	9,663	*Populus spp.*	72
Juniperus californica	20	*Pinus discolor*	270	*Populus angustifolia*	174
Juniperus deppeana	3,598	*Pinus monticola*	200	*Populus deltoides*	18
Juniperus occidentalis	263	*Pseudotsuga menziesii*	5,605	*Populus tremuloides*	3,822
Juniperus osteosperma	19,181	*Thuja plicata*	1,102	*Populus trichocarpa*	45
Juniperus monosperma	8,312	*Tsuga heterophylla*	437	*Prosopis spp.*	871
Juniperus scopulorum	2,748	*Tsuga mertensiana*	27	*Prunus spp.*	21
Larix occidentalis	569	**Hardwoods**		*Quercus spp.*	214
Picea engelmannii	2,962	*Acer macrophyllum*	20	*Quercus spp. (evergreen)*	2,634
Picea pungens	80	*Acer negundo*	25	*Quercus arizonica*	1,061
Pinus albicalus	153	*Acer glabrum*	128	*Quercus emoryi*	571
Pinus aristata	71	*Acer grandidentata*	49	*Quercus gambelii*	3,843
Pinus edulis	19,648	*Alnus rubrum*	12	*Quercus oblongifolia*	45
Pinus contorta	5,527	*Alnus rhombifolia*	5	*Robinia neomexicana*	33
Pinus coulteri	1	*Betula papyrifera*	118		
Pinus engelmannii	11	*Cercocarpus ledifolius*	784		

the short axis of the crown be measured perpendicular to the long axis and centered on the bole. In some field manuals, this method was specified in the text, but accompanying illustrations suggested that the second measurement should be taken where the crown was at its minimum width, regardless of the angle. The perpendicular measurement method was therefore assumed because measurement angles were not recorded.

When both crown width measurements are equal, the issue of diameter calculation is trivial. The issue becomes somewhat more important, however, as the difference between the two crown width measurements increases—in other words, crown shape is more eccentric. Typically, the value used in diameter crown width modeling efforts has been the arithmetic mean of two (or occasionally more) crown width measurements (Bechtold 2003, Bragg 2001). This value has no mathematically intrinsic relationship, however, to crowns that are not round. If the true shape of a crown with differing width measurements is assumed to be an ellipse, crown area is calculated using equation 1.

$$K = \pi ab \qquad (1)$$

where:

K is projected crown area, and

a and b are the major and minor radii of the ellipse.

Sensitivity to calculation of "average" diameter when the radii are unequal can be shown by a simple example (table 2). Three trees with crowns of varying eccentricity are used in the

Table 2.—*Area and diameter calculations for three hypothetical crowns of varying eccentricity.*

Wl	Ws	Wx	a	b	K	e	We	Percent area
8	8	8	4	4	50.3	0.00	8.0	1.000
10	6	8	5	3	47.1	0.40	7.7	0.938
12	4	8	6	2	37.7	0.47	6.9	0.750

Note: Wl and Ws are the long and short axes of the crown; Wx is the arithmetic mean of crown width; a and b are the long and short radii of the ellipse representing the crown; K is ellipse area in square feet; e is the eccentricity of the ellipse; We is the diameter of a circle with an area equal to the area of the ellipse; and percent area is the ratio of the area of the ellipse to the area of a circle with diameter Wx.

example. In the trivial case, both diameter measurements are equal (8 ft). In this case, eccentricity (e) equals 0, and area (K) equals 50.3 ft^2—in other words, the area of a circle with a 4-ft radius. In the other cases, crown widths vary, but the arithmetic mean remains equal to 8 ft. As eccentricity increases, K decreases. The projected area of a crown with major and minor diameters of 12 and 4 ft is only 75 percent that of a round crown, although the arithmetic mean diameters are equal.

An argument can be made that this difference is biologically important, given that the projected crown area (and likewise, the surface area of the crown paraboloid) bears some relationship to the potential exposed photosynthetic area (Oliver and Larson 1990). Implications also exist with respect to packing of crowns in closed or nearly closed canopy stands. This suggests that considering the difference during analysis may be important.

Aside from the biological argument, another practical reason exists to consider projected crown area as the basis for calculating crown width. Determination of crown area is far more practical than determination of crown width in remote sensing applications. With the increasing availability of high-resolution imagery (in other words, $\leq$ 3 ft) and current image processing capabilities, isolating and measuring individual trees (for example, Gougeon 1995, Gougeon and Leckie 2003, Maltämo *et al.* 2004) is possible. The irregular nature of tree crowns makes it difficult (or computationally inefficient) to determine an "average" diameter for remotely sensed crowns. The area of individual crowns can be measured (or estimated) easily, however, whether by raster- or vector-based methods.

Based on the potential advantages of using crown area as the basis for measure instead of an arithmetic mean of diameters, a crown width value (We in table 2) was calculated from elliptical crown area using equation 2. In simple terms, crown width for an eccentric crown is defined as the diameter of a circular crown with a projected area equal to the projected area of the elliptical crown.

$$CW = 2(\sqrt{(K/\pi)}) \quad (2)$$

where:

CW is crown width, and

K is crown area according to equation 1.

By calculating crown width this way, one of the primary goals of this study—to produce compatible stem diameter-crown width and crown width-stem diameter models—is possible. Also, crown width-stem diameter models are effectively "optimized" for the variable—crown area—that is more likely to be used in remote sensing applications.

Crown width data are notoriously variable, with hardwood species typically more variable than conifer species (Bechtold 2003, Bragg 2001). In the Intermountain West, woodland species (hardwoods and conifers), and especially those with multistemmed growth habits, tend to be the most variable. Analysis of the stem diameter-crown width relationship revealed three basic patterns into which each species could be grouped: (1) a well-behaved, apparently linear relationship, (2) a well-behaved, apparently nonlinear relationship, and (3) a highly variable pattern that masked the relative linearity of any underlying relationship, assuming one exists (fig. 2).

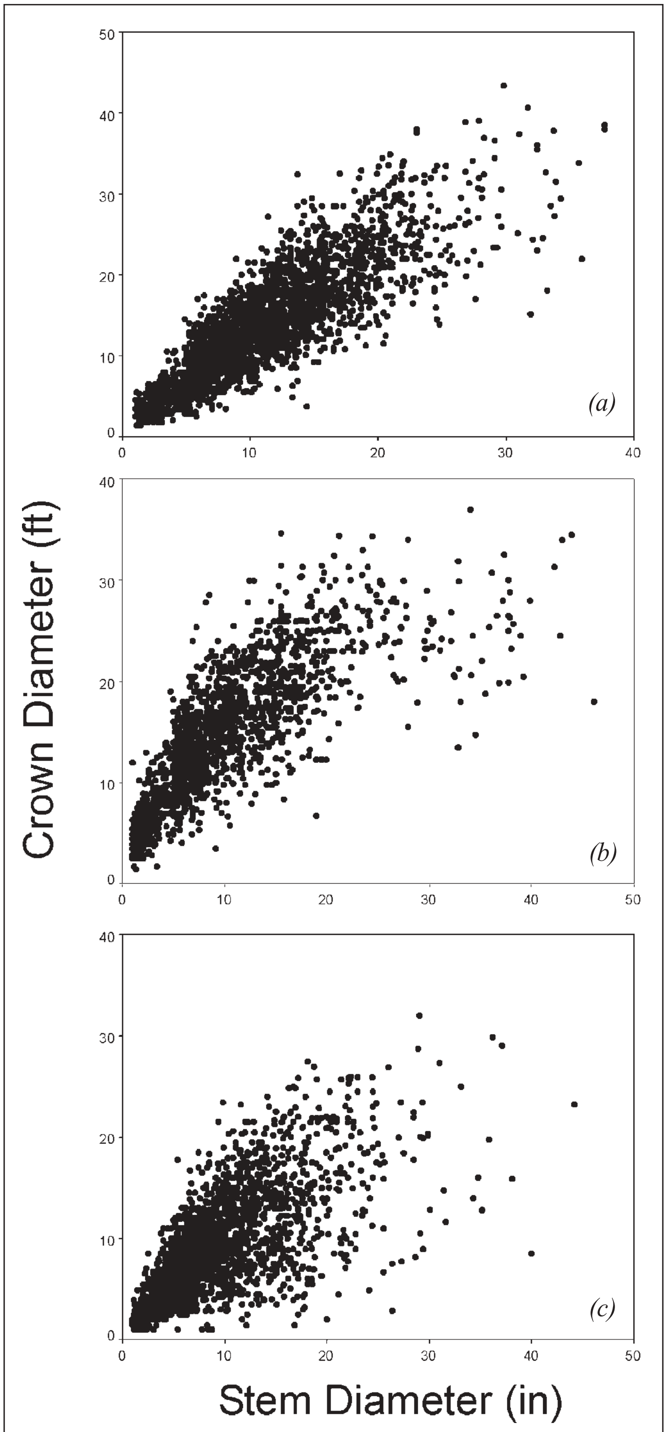
Scatter plots such as those in figure 2 show that the variance is not homogeneous across the ranges of diameter and crown width. For some species, the need for data transformation is obvious, but for others, such as ponderosa pine (fig. 2A), the need is not as clear. As a result, log10 (diameter) and log10 (crown width) were added to the data set. The decision of whether to use transformed or untransformed values in the models was deferred until the model fitting process, at which time the decision would be based on model behavior and residuals analysis.

Phase 1: Individual Tree Models

Phase 1 of the study involved the development of crown width models that relate crown width to stem diameter and other variables. Commonly, crown width studies produce "basic" models that predict crown width solely as a function of stem diameter and "complex" models that use one or more explanatory variables. The latter set of models assumes that the additional variables have been measured or can be calculated from other variables. Geographic location may be coded in the data set as a categorical variable (Crookston n.d.) or as a continuous variable such as latitude-longitude or Universal Transverse Mercator coordinates (Bechtold 2003). Significant variables may be selected using stepwise regression methods or by applying information efficiency criteria.

Simple equations used to predict crown width can have linear or nonlinear forms. Some investigators have made *a priori* decisions with respect to selection of linear or nonlinear models

Figure 2.—*Three scatter plots that are representative of the patterns observed for species included in this study: (a) linear and well-behaved (ponderosa pine), (b) apparently nonlinear (grand fir), and (c) highly variable (Rocky Mountain juniper).*



based on assumptions about the stem diameter-crown width relationship. Equations 3 and 4 are examples of simple crown width equations, and both models have been used with and without the intercept term (b0).

$$CW = b_0 + b_1D \quad (3)$$

$$CW = b_0 + b_1D^{b2} \quad (4)$$

where:

CW is mean crown width in feet,

D is d.b.h. for forest species and d.r.c. for woodland species, in inches, and

b_0, b_1, and b_2 are parameters to be estimated.

These equations are starting points for the model building process used in this study. As mentioned above, crown width data usually have heterogeneous variance, and transformations and weights have been used in previous studies. One such option is to use a log-transformed version of equation 4 that excludes the intercept term (equation 5). Although this equation provides a simultaneous transformation and linearization of the equation, the equation is technically (but perhaps not practically) inconsistent with crown width data because it produces a crown width of 0 at 0 d.b.h. Because crown width is measured at an unspecified height, trees shorter than breast height (4.5 ft) have a measurable crown width. The lack of an intercept term, however, should present no inconsistencies for species that have diameter measured at the root collar.

$$\log CW = b_1 + b_2(\log D) \quad (5)$$

By taking these considerations into account, the model building process used in this study will be data-driven and, at the same time, will attempt to develop the simplest appropriate model for a particular species. The steps may be summarized as follows:

1. Fit the linear model (that is, equation 3) to the data.
2. Evaluate residuals for homogeneity.
3. If transformation is warranted, refit model using transformed variables.
4. Evaluate residuals for linearity.
5. If nonlinear model is warranted, refit using nonlinear model (equation 4).
6. Evaluate performance of linear versus nonlinear model.

Using this process, developing the most parsimonious model for each species should be possible while ensuring that the model form best matches the data. The use of nonlinear models may be precluded by the lack of an adequate number of observations in some cases because the models may be "over-fitted" and unduly influenced by outlying observations. After the underlying pattern for a species is established, the influence of other factors on crown width can be weighed. This may require the assumption that the general stem diameter-crown width relationship for a species follows the same pattern in all parts of its geographic range.

Phase 2: Plot-Level Cover Models

The second phase of this study involves development of canopy cover models according to forest type or species compositional mixture. Overlap of crowns can be approximated on fixed-area, stem-mapped plot designs, such as the one currently used in FIA surveys (Birdsey 1995, Hahn *et al.* 1995). Measured or modeled crown diameters can be located according to stem location coordinates, allowing the calculation of a total canopy cover estimate that includes crown overlap. This should allow for improvement of the Canopy Cover Extension that is currently used with the FVS (Crookston and Stage 1999).

Crookston and Stage (1999) assumed a random stem distribution in their calculation of overlap-adjusted canopy cover (equation 6). This assumption may be inappropriate for some species, especially those that are shade intolerant or have been shown to exhibit crown shyness (for example, Long and Smith 1992). Equation 6 also has some practical limitations that are discussed below.

$$Co = 100[1-\exp(-xC')] \quad (6)$$

where:

Co is adjusted canopy cover,

C' is unadjusted canopy cover, and

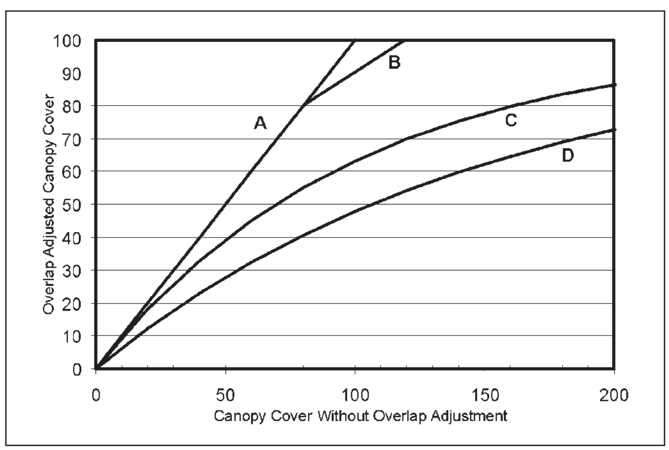
x is 0.01 for a random stem arrangement.

Crookston and Stage (1999) recognized the limitations of a fixed model and stated that the "ability to represent uniform distributions and some special attraction and repelling of canopies (to clump trees or clump openings, as the case may be) would depend on empirical relations not currently available" (Crookston and Stage 1999, 2). They appeared somewhat pessimistic about prospects for improving the model, however, stating "experience shows that little accuracy would be gained by including more refinements" (Crookston and Stage 1999, 2). In any case, because such a simple model is unlikely to adequately represent all forest compositions and structures, exploring alternative models is sensible.

When considering the appropriate overlap model, consider also the function of the model in conceptual terms. The hypothesized space, in terms of the relationship between unadjusted and adjusted canopy cover, that the model should be capable of predicting can be determined using a few benchmarks and simple assumptions. When a sufficiently flexible model has been developed, the only remaining question is whether the patterns produced by different cover types can be distinguished (i.e., a statistically significant difference exists). The overlap relationship is explored in figure 3.

In figure 3, the x-axis represents unadjusted canopy cover, or, simply, the sum of the projected cover of all individual trees. The y-axis represents adjusted cover, or that which accounts for overlap of individual trees. Line A represents an obvious boundary, which represents the 1:1 relationship between unadjusted and adjusted canopy cover. In such a stand, trees might be evenly spaced, but more important, the crowns would be sufficiently plastic so that the projected canopy cover achieved 100 percent before any two individual crowns began to overlap.

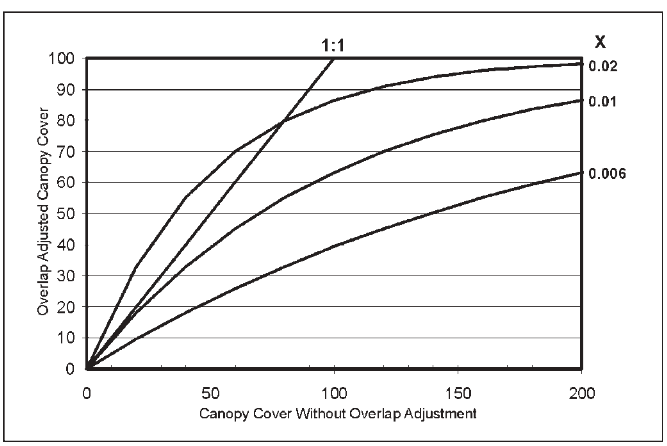
Figure 3.—*Relationship between the sum of cover of individual trees (unadjusted canopy cover) and canopy cover that accounts for overlap (adjusted canopy cover).*



Imagining plantation-grown trees behaving this way is easy, at least to a point. Mitchell and Popovich (1997) showed a 1:1 relationship and the point at which adjusted canopy cover breaks away from the 1:1 line for natural ponderosa pine stands in the Front Range of Colorado. Other species, such as lodgepole pine, have been shown to exhibit crown shyness and are unlikely to achieve 100-percent canopy cover in a mature, even-aged stand before understory reinitiation begins (Long and Smith 1992). Such stands may achieve their peak canopy cover at a relatively young age, because crowns are effectively trimmed back by abrasion caused by wind-driven sway as the stand grows taller (Long and Smith 1992).

Although achieving 100-percent cover without overlap may be theoretically possible, such an achievement is unlikely for most forest types; thus, an unknown boundary exists (fig. 3, line B) that probably varies by forest type. Line C in figure 3 represents the cover relationship for a random stem distribution, as modeled by Crookston and Stage (1999). This might be considered an average or typical model that lies somewhere between evenly spaced and clumpy crown arrangements. Therefore, the conceptual model can be completed by the addition of a lower boundary (line D) that represents some degree of clumpiness. The possible space occupied by the relationship between unadjusted and adjusted canopy cover is therefore bounded by lines A and D, with the likelihood that conditions do not exist in nature above line B.

Figure 4.—*Curve behavior for three values of x in the equation Co = 100[1-exp(-xC')], where Co is adjusted canopy cover, C' is unadjusted canopy cover, and x is 0.01 for a random stem arrangement.*



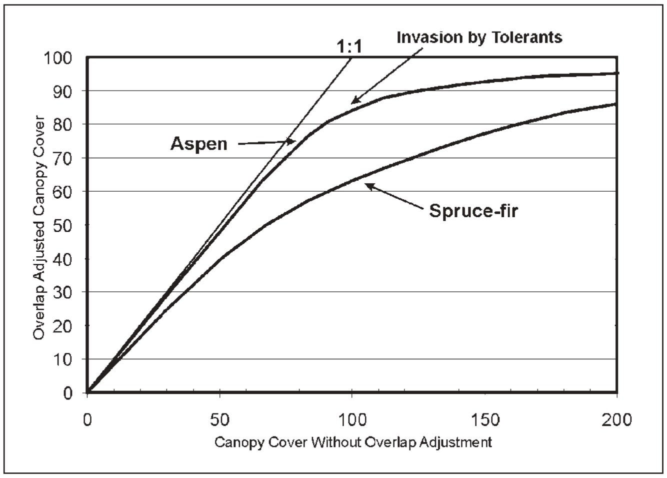
The primary limitations of equation 6 are that only a single parameter (x) exists in the model, and curves produced by the model are asymptotic to 100-percent adjusted canopy cover. By decreasing the value of x (fig. 4), curves representing increasingly clumpy crown arrangements can be produced but not the 1:1 cover relationship. Increasing x produces curves that cross above the 1:1 line and therefore represent an impossible condition—in other words, adjusted canopy cover that exceeds the sum of the individual trees.

Many options exist for producing canopy cover models with sufficient flexibility to reflect the conditions defined by the conceptual space in figure 3. Equation 6 may be modified, for example, by removing the constraint imposed by the asymptote of 100-percent cover. A flexible asymptote would permit the lower segments of some curves to closely follow the 1:1 line, although such curves could also cross into impossible space (adjusted cover > 100 percent). Mitchell and Popovich (1997) accomplished the transition between the 1:1 relationship and overlapping crowns using a segmented model. A full treatment of model options is not possible here, but the conceptual space in figure 3 can be likely modeled adequately.

The potential ability of a flexible canopy cover model can be explored by examining the stand dynamics that are expected to occur in contrasting forest types. The aspen and spruce fir types of the Intermountain West represent opposite ends of the shade tolerance range found among forest types of the region, with aspen being very intolerant, subalpine fir being very tolerant, and Engelmann spruce somewhat less tolerant than the fir (Long 1995). As with figure 3, certain benchmarks can be plotted in the space that represents the relationship between unadjusted and adjusted canopy cover in these two forest types (fig. 5).

Following fire, logging, or other disturbances, aspen commonly regenerate in large numbers by suckering. Regeneration on the order of 10,000 stems per acre or more is not uncommon (Long 1995). Considering that at maturity, perhaps in 50 years or less, the same stand will be at a density of a few hundred stems per acre, the sensitivity of aspen to competition is immediately apparent. Because of this sensitivity, expecting minimal crown overlap is logical, regardless of stand age. As noted earlier, an upper limit may exist to the amount of unadjusted cover that precludes adjusted cover from reaching 100 percent, at least as long as the stand remains pure and even-aged. Aspen stands are

Figure 5.—*Hypothetical relationships between unadjusted and adjusted canopy cover for aspen (shade intolerant) and Engelmann spruce-subalpine fir (shade tolerant) stand types.*



subject to invasion by a number of conifers that are more shade tolerant, however, including Engelmann spruce and subalpine fir (Mueggler 1987). Although the addition of more aspen canopy is unlikely, compositional change due to succession may increase unadjusted and adjusted canopy cover (fig. 5).

On the other hand, spruce fir stands tend to be clumpy. Engelmann spruce seedlings have difficulty surviving in open conditions and typically require shelter to regenerate successfully. This characteristic tends to influence the spatial arrangement of stems, making the distribution of crowns in spruce fir stands characteristically different from that in aspen stands. Modeling canopy cover for stands that behave similarly to those illustrated in figure 5 should be possible, based on stand composition and structure.

Conclusions

The modeling effort described in this article is multifaceted. Some of the anticipated outcomes are based on conceptual models, but the ability to achieve the desired results will depend, in part, on whether the data are sufficiently well behaved. Preliminary results suggest that the desired results can be achieved. Despite the large numbers of crown measurements available for analysis, comprehensive treatment of the species in the Intermountain West cannot be accomplished in this study. Additional data are needed for species that are poorly represented in the collected database. Preliminary analysis also suggests that regional differences are important. Therefore, crown width data are needed for Montana because models developed for the other states may not be applicable there.

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