Influence of Crown Biomass Estimators and Distribution on Canopy Fuel Characteristics in Ponderosa Pine Stands of the Black Hills

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Abstract: Two determinants of crown fire hazard are canopy bulk density (CBD) and canopy base height (CBH). The Fire and Fuels Extension to the Forest Vegetation Simulator (FFE-FVS) is a model that predicts CBD and CBH. Currently, FFE-FVS accounts for neither geographic variation in tree allometries nor the nonuniform distribution of crown mass when one is estimating CBH and CBD. We develop allometric equations specific to ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) in the Black Hills to predict crown mass and use the Weibull distribution to model the vertical distribution of crown mass within individual trees. We present parameter prediction models that, in turn, predict the vertical distribution of crown mass based on stand- and tree-level attributes. With use of an FFE-FVS executable incorporating local crown mass equations and the parameter prediction models, new estimates of CBD and CBH were produced. Locally derived biomass equations predicted substantially greater estimates of foliage mass than currently predicted by FFE-FVS. The increase in CBD resulting from the local biomass and vertical distribution models averaged 78% over original estimates. Our results suggest that locally derived crown mass equations in addition to nonuniform estimates of crown mass distribution be used to calculate CBH and CBD as used in fire prediction models. FOR. SCI. 56(2): 156–165.

Keywords: canopy bulk density, canopy base height, crown allometry, fire hazard, crown biomass distribution

PONDEROSA PINE (*Pinus ponderosa* Dougl. ex Laws.) forests of the western United States are frequently managed to create and maintain structures that are less susceptible to the initiation and spread of crown fire (Peterson et al. 2005). Stand management prescriptions to design such forest structures are typically developed using models that estimate potential fire behavior under severe burning conditions associated with catastrophic wildfires (Rothermel 1972, Scott and Reinhardt 2001). Burning conditions are specified in terms of fuel moisture content, wind speed, and temperature. These models rely on descriptions of surface fuels and canopy structure to estimate potential fire behavior. For a surface fire to become an active crown fire in a mature forest stand, two conditions must be met. There must be sufficient canopy fuel close enough to the forest floor to carry flames vertically from the surface to the main forest canopy. Canopy base height (CBH) is a measure of proximity of canopy fuels to surface fuels. In addition, there must be sufficient proximity between crowns and combustible fuel (e.g., needles and small branches) to carry fire from tree crown to tree crown. Canopy bulk density (CBD) is a measure of how closely canopy fuels are packed, which reflects the likelihood that fire can move through the forest canopy. Fuel management treatments to reduce the likelihood of crown fire frequently involve thinning forests to increase CBH and decrease CBD (van Wagner 1977, Peterson et al. 2005). Measures of CBH and CBD are critical to producing reliable estimates of fire behavior as related to changes in stand structure and therefore effectiveness of fuels treatment. In this article, we develop explicit models that depict the vertical distribution of canopy fuels for ponderosa pine in the Black Hills of South Dakota and compare our results with techniques currently used in the Fire and Fuels Extension to the Forest Vegetation Simulator (FFE-FVS) (Reinhardt and Crookston 2003, Crookston and Dixon 2005).

A commonly used method for obtaining indirect estimates of CBH and CBD involves the use of individual tree allometries to estimate crown mass for individual trees and a process to distribute crown mass through the length of the live crown. Then, a summation procedure is used to determine the canopy mass per unit volume at vertical intervals through the forest canopy. FFE-FVS is a widely used tool to evaluate fuels treatment effectiveness that incorporates a version of this procedure. FFE-FVS predicts CBD and CBH from data gathered on individual trees during routine forest inventory. Allometric crown mass equations (Brown 1978) are used to predict foliage and fine branch biomass (0–0.64 cm diameter) of individual trees. FFE-FVS then creates a

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profile of the canopy fuel stratum within a stand and calculates the CBD using the weight of foliage plus one-half of the fine branchwood within each 0.3-m section of the individual crowns (Reinhardt and Crookston 2003). A 4-m running average (beginning at the point in the canopy where a minimum of 18.4 kg ha^{-1} m^{-1} of canopy fuels exists) of the CBD around those 0.3-m sections is calculated with the CBD of the stand computed as the maximum of those 4-m running averages (Scott and Reinhardt 2001). The prediction of CBH is determined from the vertical profile of CBD. In FFE-FVS, CBH is the minimum height at which a 0.9-m running average is $\leq$0.011 kg m^{-3} (Reinhardt and Crookston 2003).

Although FFE-FVS provides a working prediction of CBD and CBH, the underlying assumptions and equations used to calculate and predict CBD and CBH may not accurately represent CBD or CBH within a stand (Reinhardt et al. 2006). The equations used by FFE-FVS to predict crown mass for ponderosa pine are based on a small number of trees from northern Montana and Idaho (Brown 1978). These equations, therefore, may not reflect variability in crown allometry because of differences in physiographic region, site, or stand variability (Vose et al. 1994, Gilmore 2001, Gilmore and Seymour 2004). For example, Fulé et al. (2001a) found that allometric equations for ponderosa pine forests of northern Arizona predicted significantly lower crown biomass estimates than were predicted by Brown (1978). In five stands across the western United States, Reinhardt et al. (2006) found that Brown's (1978) allometric equations overpredicted canopy fuel load and that regional and crown class adjustments were necessary to obtain accurate predictions. In addition to differences in allometric relationships among regions, stand density can have a substantial impact on crown architecture within individual trees which, in turn, affects biomass allocation. Individual trees grown in open or low-density stands tend to have greater foliage and branch biomass than trees grown in high-density stands (Long and Smith 1990). The solution to this problem is to model crown biomass as a function of dbh along with some variable that incorporates the effects of stand density on individual tree growth and crown morphology (Dean and Long 1986, Long and Smith 1988). Crown length or crown ratio reflects the growing conditions a tree has been subjected to throughout a given period of time with trees growing in more open, low-density stands having longer crown lengths than trees grown in closed or high-density stands (Oliver and Larson 1996). Therefore, crown length or crown ratio is an indirect, but relatively accurate depiction of stand density and growing conditions.

FFE-FVS bases its predictions of CBD and CBH on the assumption that crown biomass is equally distributed throughout the entire length of the tree crown (Figure 1A). It is widely recognized that foliage and branch biomass are not uniformly distributed throughout the crowns of individual trees. Reinhardt et al. (2006) found that procedures for estimating CDB based on a uniform vertical distribution of canopy fuel (e.g., dividing total fuel load by canopy length) were not accurate compared with CBD empirically determined by felled tree measurements in five dense stands across the West. Forest production research suggests that

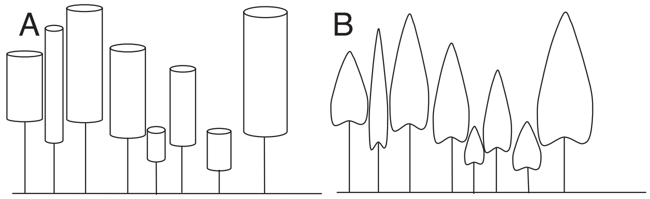

Figure 1. (A) Representation of the uniform distribution of crown biomass assumed by the Fire and Fuels Extension to the Forest Vegetation Simulator and (B) representation of hypothesized crown shape and crown biomass distribution.

crown biomass is a skewed normal distribution (e.g., Gillespie et al. 1994) with less mass at the top and bottom of a tree crown and most of the mass concentrated near the center of the crown (Figure 1B). Depending on stand conditions, the distribution of crown biomass can have a downward or upward shift. Several studies report that density has a significant influence on the distribution of foliage biomass within the crown profile. For example, Garber and Maguire (2005) reported that foliage distribution of ponderosa pine in central Oregon exhibits a downward shift (i.e., longer tail toward the top of the tree) in response to low stand density or dominant social or crown position. In contrast, the authors found that foliage distribution displayed an upward shift (i.e., longer tail toward the bottom of the tree) in the crowns of individual ponderosa pine trees in lower social positions (e.g., intermediate and suppressed). Reinhardt et al. (2006) observed upwardly skewed distributions of canopy mass in plots from five dense forest stands. They were able to produce vertical canopy profiles using site-adjusted allometric equations and plot-specific nonuniform crown profiles that closely matched empirically observed profiles.

The oversimplification of crown architecture and biomass distribution in FFE-FVS may introduce bias into the predicted estimates of canopy-level CBD and CBH. Downward shifts in crown biomass could lower CBH and concentrate more foliage in a smaller volume, increasing CBD. In contrast, if there is an overall upward shift in the distribution of crown biomass, CBH may be increased. However, the concentration of fuel mass in the smaller volume could still result in an increase in CBD. We hypothesize that current methods of predicting CBD underestimate both CBD and CBH because of the oversimplification of biomass distribution within crowns and canopies. Underestimating CBD or overestimating CBH could create situations in which fuels treatments do not reduce CBD and CBH below the critical thresholds required to minimize crown fire hazard. In contrast, overestimating CBD or underestimating CBH could cause overtreatment that could limit economic resources for additional fuels reduction projects. Integrating site-specific crown mass equations and a more realistic depiction of the distribution of crown biomass, as suggested by Reinhardt et al. (2006), would create a more accurate estimate of the forest canopy fuel structure and alleviate both of these potential biases. In this article, we (1) develop site-specific estimators of crown fuel mass for ponderosa pine in the Black Hills, South Dakota, (2) model the vertical distribution of the crown fuel mass for individual trees and determine the effect of stand density on the vertical distribution of biomass, (3) estimate the vertical distribution of canopy fuels within a stand from commonly available stand inventory information (Table 1); and (4) evaluate the effects of using site-specific crown mass equations and explicit models of the vertical distribution of canopy fuels to estimate CBH and CBD compared with current techniques used in FFE-FVS.

Methods

Study Sites

The study was conducted in the Black Hills National Forest (BHNF), South Dakota. The Black Hills are a forested uplift that rise ~900–1200 m above the surrounding Great Plains in southwestern South Dakota and northeastern Wyoming (Hoffman and Alexander 1987, Froiland 1990). Encompassing 1.3 million acres in southwestern South Dakota, 92% of the BHNF is forested and of that forest landbase, 85% is dominated by ponderosa pine (DeBlander 2002). The climate in the Black Hills is continental with cold winters and mild, moist summers (Johnson 1949). Mean daily temperatures range from −3.3°C in winter to 13.2°C in summer and yearly precipitation averages ~47 cm with 65–75% occurring between the months of April and October (Hoffman and Alexander 1987, Froiland 1990, Shepperd and Battaglia 2002).

Data Collection

Between June and August 2006, we measured tree dimensions and crown biomass on a total of 80 (≥5 cm dbh) ponderosa pine trees located in 16 stands throughout the BHNF to develop estimators of crown biomass and vertical distribution of biomass. All stands consisted of pure, second-growth ponderosa pine that had not received any notable disturbance in the last 25 years. Stands were identified using existing vegetation GIS data supplied by the BHNF and were selected to encompass a range of stand conditions (e.g., stand density and tree size) (Table 2).

Within each of the 16 stands, we randomly established one vegetation plot. Plot size varied based on a visual inspection of stand density and was designed to sample approximately 25 trees per plot. Plot size ranged from 0.04 ha in high-density stands to 0.2 ha in low-density stands.

Table 1. Abbreviations and associated definitions of tree- and stand-level variables

Variable	Description
dbh	Diameter at breast height (cm)
HT	Individual tree height (m)
BLC	Height to the base of the live crown (m)
CR	Crown ratio (1 − BLC/HT)
SDI	Reineke's stand density index
RD	Relative density (SDI_{stand}/SDI_{max})*
MHT	Mean height of sample trees within a given stand
FOL	Dry weight live foliage mass (kg)
1HF	Dry weight 1 h fuel mass (kg)
CBD	Canopy bulk density (kg/m^3)
CBH	Canopy base height (m)

* SDI_{max} for ponderosa pine = 1,112 (Long and Shaw 2005)

We inventoried each plot and recorded species, dbh (to the nearest 0.1 cm), total height (to the nearest 0.01 m), and height to the base of the live crown (BLC) (to the nearest 0.01 m) on each tree within the plot. FVS uses compacted crown ratio to model crown dynamics. Therefore, we measured the base of the live crown as the height to the base of the compacted live crown by "moving up" isolated lower branches until a full whorl was accumulated. Five trees ≥5 cm dbh were arbitrarily selected across the range of tree sizes present on each plot for destructive sampling (Table 3). All sample trees had intact and undamaged, single-stemmed (i.e., not forked) crowns. Crown class, determined following Oliver and Larson (1996), was recorded for 69 of the 80 sample trees.

Each sample tree was felled using a chainsaw with care taken to minimize damage during felling. We measured total height and height to the BLC. The crown (total height − BLC) was then divided into 10 sections of equal length. The boundary of each section was marked and numbered 1 through 10 with the topmost section as 1 and the BLC section as 10. Branches from all sections were then removed from the main bole and processed to measure biomass.

The degree of processing of branches depended on the section number. For odd-numbered sections (1, 3, 5, 7, and 9), we separated all live and dead branch material into three components: (1) foliage + 1-hour fuels (woody biomass <0.64 cm in diameter) + 10-hour fuels (woody biomass ≥0.64 cm but <2.54 cm in diameter); (2) 100-hour fuels (woody biomass ≥2.54 cm but <7.6 cm in diameter); and (3) 1,000-hour fuels (woody biomass ≥7.6 cm in diameter). This was done by cutting all branches at the appropriate diameter, working from the terminals of the branch to the base of the branch. For all even-numbered sections (2, 4, 6, 8, and 10), we separated all live and dead branch material by the following four components: (1) foliage + 1-hour fuels (foliated twigs); (2) 10-hour fuels, (3) 100-hour fuel, and (4) 1,000-hour fuels. The green weights (kg) of each of the three components in the odd-numbered crown sections and of each of the four components in the even-numbered crown sections of each tree were measured in the field using a digital scale (CS200, Intercomp; 125 ± 0.05 kg).

Random subsamples of foliated twigs were obtained from each even-numbered crown section and subsamples of 10-, 100-, and 1,000-hour fuels were obtained from sections 2, 6, and 10 of each sample tree. All subsamples were weighed in the field to the nearest gram using a portable field scale. Subsequent to weighing, subsamples were bagged and taken back to the laboratory where they were oven-dried at 70°C for 1 week to constant final weight. For foliated twigs, foliage was separated from wood and dry foliage, and wood weight was measured. Similarly, dry weights of 10-, 100-, and 1,000-hour fuels from each tree were measured. From the green and dry weight data, green to dry weight ratios as well as foliage to wood ratios were calculated for each fuel class. These ratios were used to estimate dry weight of foliage and wood for each fuel size class from green weights measured in the field.

Table 2. Stand-level summary statistics

Stand	Density (trees ha^{-1})	Basal area (m^2 ha^{-1})	Quadratic mean diameter (cm)	SDI	RD (%)	Average stand height (m)
1	398	24.1	27.8	466	42	17.4
2	773	29.3	22.0	621	56	14.9
3	3,780	47.2	12.6	1,171	100	9.9
4	472	25.9	26.4	509	46	16.5
5	746	35.6	24.7	710	64	16.9
6	868	31.2	21.4	673	60	13.2
7	535	21.9	22.9	397	36	10.4
8	348	28.0	32.0	514	46	16.7
9	286	15.5	26.3	306	27	14.8
10	286	5.8	16.1	140	13	6.0
11	325	25.1	31.4	439	40	16.0
12	526	32.7	28.1	622	56	17.2
13	234	23.2	35.5	382	34	16.3
14	1,157	37.9	20.4	830	75	15.3
15	894	20.7	17.2	465	42	7.9
16	908	22.3	17.7	489	44	10.2

Table 3. Mean (minimum, maximum) dbh, tree height, BLC, FOL, and 1HF of sample trees in each of the 16 stands

Stand	dbh (cm)	Height (m)	BLC (m)	FOL (kg)	1HF (kg)
1	27.0 (19.5, 37.0)	17.8 (16.6, 19.2)	10.2 (9.0, 11.9)	21.0 (6.5, 42.9)	0.00 (0.00, 0.00)
2	19.5 (13.4, 24.5)	13.7 (11.8, 15.2)	8.3 (7.0, 9.3)	7.4 (3.4, 14.6)	0.05 (0.00, 0.18)
3	15.6 (8.1, 24.1)	12.1 (9.8, 13.9)	6.9 (4.4, 8.2)	5.7 (0.5, 13.7)	0.07 (0.01, 0.12)
4	27.7 (17.3, 39.8)	16.7 (14.6, 17.5)	8.1 (4.9, 11.3)	25.8 (5.8, 64.1)	0.03 (0.00, 0.05)
5	27.5 (15.0, 39.0)	18.5 (10.2, 22.7)	10.2 (4.7, 12.6)	14.2 (3.2, 23.2)	0.05 (0.00, 0.13)
6	21.9 (15.5, 28.0)	14.8 (14.4, 15.7)	8.9 (8.5, 9.7)	9.9 (2.7, 19.9)	0.04 (0.00, 0.12)
7	29.7 (5.5, 46.9)	18.2 (4.4, 23.8)	7.3 (1.6, 10.3)	29.9 (1.5, 51.5)	0.03 (0.00, 0.05)
8	31.7 (24.0, 40.0)	17.8 (17.0, 19.1)	9.4 (8.2, 10.3)	32.5 (23.8, 53.2)	0.05 (0.00, 0.17)
9	26.2 (19.1, 34.8)	14.8 (17.0, 17.9)	5.8 (3.7, 8.3)	33.8 (15.7, 66.7)	0.10 (0.00, 0.30)
10	16.0 (11.0, 20.8)	5.7 (10.6, 6.5)	1.2 (1.0, 1.3)	15.9 (7.5, 29.0)	0.50 (0.10, 0.97)
11	46.8 (38.5, 53.6)	22.2 (4.6, 25.3)	8.3 (6.7, 10.3)	66.5 (54.8, 91.0)	0.22 (0.00, 0.42)
12	22.1 (11.5, 35.2)	15.7 (18.9, 19.70	8.8 (7.1, 11.5)	14.5 (3.6, 35.1)	0.21 (0.00, 0.73)
13	44.6 (32.8, 58.0)	23.5 (10.5, 25.0)	10.0 (7.2, 12.2)	63.4 (29.5, 116.0)	0.05 (0.00, 0.19)
14	17.2 (14.7, 19.9)	15.5 (22.7, 17.5)	10.7 (8.1, 12.3)	4.1 (2.8, 5.8)	0.04 (0.00, 0.10)
15	12.1 (10.8, 13.5)	6.4 (5.3, 7.9)	2.3 (1.7, 2.9)	5.6 (3.4, 6.5)	0.09 (0.04, 0.19)
16	12.2 (9.9, 14.0)	8.3 (6.5, 9.6)	4.5 (4.0, 4.9)	3.3 (2.0, 4.4)	0.13 (0.02, 0.38)

Statistical Analyses

The equations used to predict CBD and CBH in FFE-FVS are based on tree-level predictions of both live and dead foliage mass and the mass of live and dead 1-hour fuels. Consequently, we limit our analyses to those particular crown components. We used nonlinear regression (PROC NLIN, SAS Institute, Inc.) to develop equations to predict total dry mass (kg) of live foliage (FOL) and live 1-hour fuels (1HF) based on individual tree attributes including dbh and live crown ratio (LCR). Based on previous research (e.g., Monserud and Marshall 1999), we modeled biomass using the general allometric model,

$$Y = b_0 X_1^{b1} X_2^{b2} + \varepsilon, \tag{1}$$

where Y is total dry mass, X_1 and X_2 are dbh and LCR, respectively, and b_0, b_1, and b_2 are estimated coefficients for the model. By using nonlinear regression, we excluded the bias introduced by the more common logarithmic approach to allometric modeling (Baskerville 1972) as well as present the response variable in terms more easily interpreted by the reader. Sample trees did not contain any appreciable amount of dead foliage or dead 1-hour fuels; therefore, these components were not modeled. In the case of FOL, weighted nonlinear regression was used to fulfill the assumption of normality and homoscedasticity. The form of the weighting function used was dbh^{-3}. All parameters were significant at the $\alpha = 0.05$ level. We report r^2 values as a goodness-of-fit measure where $r^2 = 1 -$ (residual sum of squares/corrected total sum of squares) (Monserud and Marshall 1999). Because of problems processing in the field, 2 trees were removed from the analysis, leaving a total of 78 trees available for the statistical analyses.

The two-parameter Weibull model was used to model the vertical distribution of total crown fuel mass (FOL + 1HF) for each tree. The form of the cumulative Weibull distribution used was

$$Y = 1 - \exp[-(X/\beta)^{\alpha}], \tag{2}$$

where Y is the cumulative proportion of canopy fuel mass at a specific location within the crown, α and β are the estimated shape and scale parameters, respectively, and X is the location within the crown (i.e., section number or relative distance from top of tree). The Weibull was chosen because of its success in modeling the vertical distribution of both foliage and branch mass (e.g., Schreuder and Swank 1974, Vose 1988, Gillespie et al. 1994, Xu and Harrington 1998). When $\alpha = 3.6$, the distribution of canopy fuels approximates a normal distribution. When $\alpha < 3.6$, the distribution of canopy fuel biomass within a crown is bunched toward the bottom of the crown (i.e., negatively skewed). In this study, the distribution began at the top of the tree so that a relative height of 1.0 represented the BLC.

Models to predict FOL and 1HF as well as equations to predict the vertical distribution of canopy fuels for individual trees were coded into a FFE-FVS stand-alone executable (version 6.31, revision date Sept. 19, 2008; Crookston and Dixon 2005) that calculates stand-level canopy fuel profiles as well as estimates of CBD and CBH. With individual-tree data collected as part of the stand inventory, we used FFE-FVS to compare original estimates of CBD and CBH based on Brown's (1978) crown mass equations and the uniform distribution of canopy fuels within the crown (hereafter referred to as original), modified estimates of CBD and CBH calculated using site-specific crown mass equations and the uniform distribution of canopy fuels within the crown (hereafter referred to as local biomass only), and modified estimates of CBD and CBH calculated using site-specific crown mass equations in conjunction with models depicting the distribution of canopy fuel mass within individual tree crowns (hereafter referred to as local biomass distribution) for each of the 16 sample stands.

Results and Discussion

Biomass Prediction

Across all stands, observed FOL ranged from 0.5 to 116.0 kg (Table 3). The best model for predicting FOL for our sample trees in the Black Hills was

$$FOL = 0.0865 dbh^{1.8916} LCR^{1.1358}. \quad (3)$$

The nonlinear relationship between FOL, dbh, and LCR explained 89% of the variation in the data (Figure 2). Both dbh and LCR had a positive effect on FOL. Very little 1HF was observed with the 1HF ranging from 0.00 to 0.97 kg (Table 3). The mass of 1-hour fuels was best predicted by the equation,

$$1HF = 1.5439 LCR^{5.6131}. \quad (4)$$

Although dbh was not a significant predictor of 1HF ($P > 0.05$), LCR alone explained 76% of the variation in the data (Figure 3).

Our equations predicted substantially greater FOL estimates and slightly lower 1HF estimates than those predicted by the equations of Brown (1978) for the trees in our sample. We found that Equation 3 predicted 23% greater FOL estimates for dominant/codominant trees and 112% greater FOL estimates for intermediate/suppressed trees than predicted by Brown (1978). In contrast, Equation 4 predicted 90% less 1HF for dominant/codominant trees and 94% less 1HF for intermediate/suppressed trees than Brown's (1978) equations.

Site differences, including nutrient and water availability as well as temperature within and across physiographic regions, can all contribute to local and regional variability in allometric relationships (Brix 1981, Vose et al. 1994). For example, Long and Smith (1988) suggest that differences in precipitation, soil depth, and soil water holding capacity may be responsible for differences in leaf area-sapwood relations observed in lodgepole pine (*Pinus contorta* Dougl. ex. Loud.) between Utah and Wyoming. Similarly, substantial geographic differences in crown allometry have been noted for both balsam fir (*Abies balsamea* [L.] Mill.) (Gilmore and Seymour 2004) and larch (*Larix* spp.) species (Gilmore 2001) in the eastern United States. For ponderosa

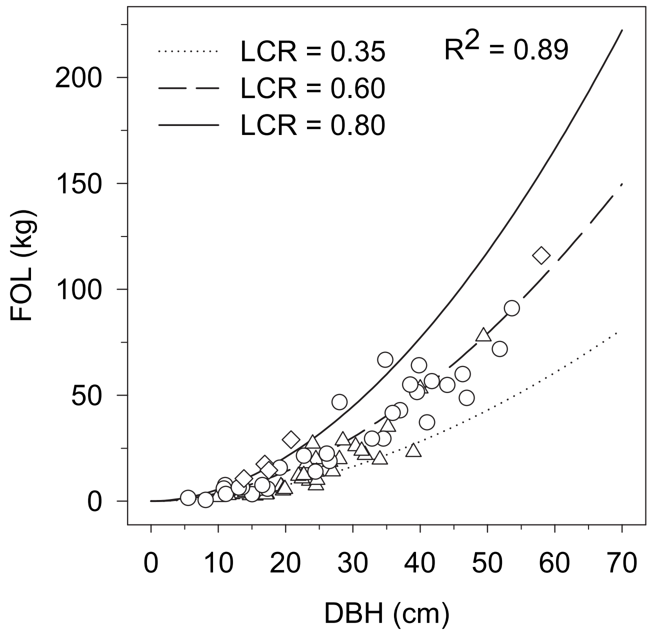

Figure 2. Relation between live foliage mass, dbh, and live crown ratio (LCR) (Equation 3). △, trees whose LCR was between 0.25 and 0.50; ○, trees whose LCR was between 0.50 and 0.75; ◇, trees whose LCR ≥ 0.75.

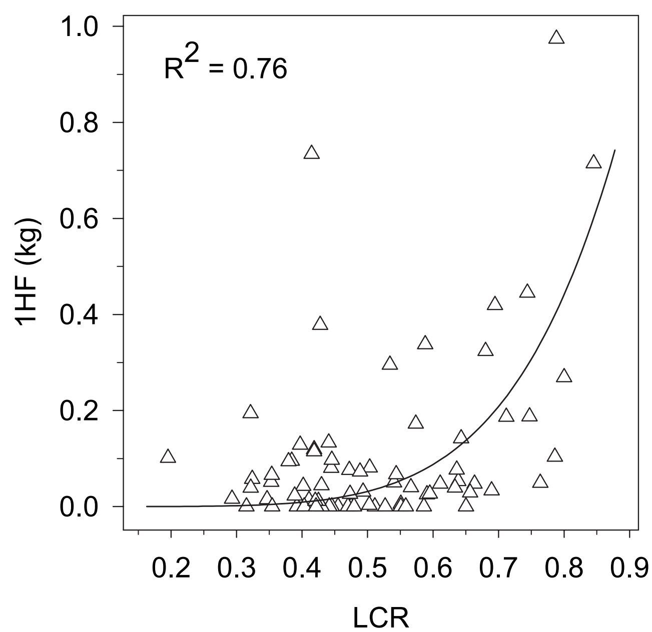

Figure 3. Live 1-hour fuel mass as a function of live crown ratio (LCR) (Equation 4).

pine, Fulé et al. (2001a) developed allometric equations specific to northern Arizona that predicted lower foliage and small branch (<0.64 cm) biomass estimates than those developed in Montana by Brown (1978). Reinhardt et al. (2006) found that Brown's equations overpredicted crown mass for ponderosa pine in different geographic areas. Given the results presented here, in conjunction with past studies, it is apparent that crown allometry varies among geographic regions and that no one set of allometric equations is applicable across the range of ponderosa pine.

Vertical Distribution of Crown Fuel Biomass

Currently, FFE-FVS uses allometric estimates of crown biomass that assume an even vertical distribution of crown fuel mass for individual trees to estimate CBH and CBD. We wanted to determine whether this assumption was warranted and, further, whether the vertical distribution of crown fuel mass was affected by tree size and stand density. If this was the case, we wanted to develop a relationship to estimate the vertical distribution of crown fuel mass that reflected this relationship.

We modeled the vertical distribution of crown fuel mass using the Weibull distribution individually for the 78 sample trees ($P < 0.0001$ for all 78 trees). The minimum and maximum scale (β) and shape (α) parameters predicted by Equation 2 for individual trees ranged from 4.4 to 7.9 and 1.4 to <3.6, respectively. The distribution of crown fuel mass on 78 sample trees was skewed (shape parameter < 3.6). Clearly, canopy fuels are not evenly distributed within the crown of an individual tree, and the manner of the distribution could potentially have a significant impact on determination of CBH and CBD for forest canopies. Within a given stand, we observed little effect of crown class (e.g., dominant/codominant, intermediate/suppressed) on the distribution of crown fuel mass for the 69 trees on which tree crown class was recorded. For the limited number of stands in which intermediate/suppressed trees were sampled, the confidence interval surrounding the estimated shape parameters for intermediate/suppressed trees overlapped that of dominant/codominant trees within a given stand causing us not to reject the null hypothesis that the distribution of crown fuel biomass within a tree crown is different between crown positions. These findings are in contrast to those reported for ponderosa pine in central Oregon by Garber and Maguire (2005), who found an upward shift in crown mass with decreasing crown class due, in part, to decreasing light availability and loss of epinastic control (Maguire and Bennett 1996). Although our sample size was large (n = 78), only 16 of the trees were sampled from intermediate/suppressed canopy positions. It is possible that we were unable to detect differences in crown fuel mass distribution between crown classes because of the limited sample of intermediate/suppressed trees from these stands.

Next, we wanted to determine whether the vertical distribution of crown fuels was related to tree- or stand-level characteristics. Although the shape and scale parameters varied among the 78 sample trees, within a given stand we observed little variability in the vertical distribution of crown fuel mass as the confidence intervals of the α and β parameters of individual trees within a stand in the vast majority of cases overlapped. A negative relationship between the average shape parameter and relative density (RD) was observed with the shape parameter averaging 1.9665 in the highest density stand to 3.2458 in the lowest density stand (Figure 4). The dependence of the average shape and scale parameters (Table 4) on tree- and/or stand-level attributes (Table 1) was investigated using a system of parameter prediction models. The best models for predicting the average distribution of crown fuel mass on trees within a stand based on stand-level attributes were

$$M\beta = 7.1386 - 0.0608 * \text{MHT}, \qquad (5)$$

$$M\alpha = 3.3126 - 0.0214(\text{MHT}) - 1.1622(\text{RD}), \qquad (6)$$

where $M\beta$ and $M\alpha$ are the average scale and shape parameters for a stand, MHT is the average stand height, and RD is relative density. Average height explained 51% of the variation in the scale parameter, whereas the combination of average height and RD explained 72% of the variation in the shape parameter.

The lower shape parameter observed in higher density stands suggests that crown fuel mass is shifted slightly upward on trees in high-density stands relative to trees growing in more open stand conditions; a shift that probably occurs in response to decreasing light availability in lower portions of the canopy in dense stands (Smith et al. 1991). Stand density has been shown to have a significant effect on the distribution of crown mass for numerous species including balsam fir (Gilmore and Seymour 1997), loblolly pine (Xu and Harrington 1998), Douglas-fir (Maguire and Bennett 1996), and ponderosa pine (Garber and Maguire 2005), whereas others (e.g., Gillespie et al. 1994) have found no effect of stand density on biomass distribution. Reinhardt et al. (2006) observed an upward shift in canopy profiles for

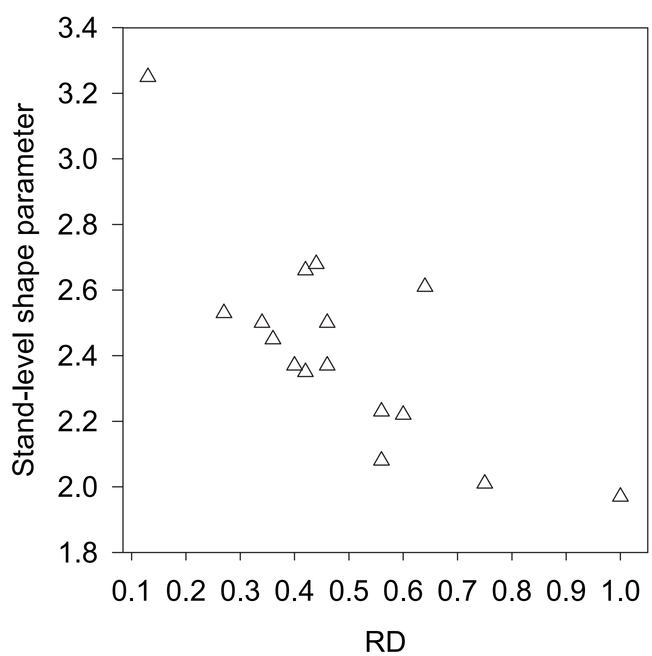

Figure 4. Relation between the stand-level average shape (α) parameter (Equation 2) and relative density (RD).

Table 4. Mean scale and shape parameter estimates for each of the 16 sample stands

Plot	n	Shape parameter (α)	Scale parameter (β)
1	5	2.3534	6.2937
2	4	2.0828	5.7264
3	5	1.9665	6.1573
4	5	2.4968	5.9704
5	5	2.6121	6.5302
6	5	2.2188	6.1151
7	6	2.4478	5.7808
8	5	2.3709	6.0755
9	5	2.5291	6.3097
10	5	3.2458	7.1226
11	5	2.3738	5.6601
12	5	2.2263	6.0008
13	5	2.5015	6.1512
14	5	2.0138	5.8977
15	4	2.6593	6.7465
16	4	2.6789	7.0076

dense stands of species including ponderosa pine, Douglas-fir, and lodgepole pine. Similar to patterns observed by Garber and Maguire (2005) for ponderosa pine in Oregon, the distribution of crown fuel biomass within individual trees grown in higher density stands displayed the greatest upward shift of canopy fuels mass within individual crowns (Figure 5).

Estimating CBD and CBH for Forest Canopies

We wanted to evaluate whether using local biomass equations to predict crown fuels (i.e., FOL and 1HF) along with realistic estimates of the vertical distribution of fuels within individual tree crowns would result in significant changes in CBH and CBD compared with current techniques. We used procedures in FFE-FVS (Reinhardt and Crookston 2003) to conduct this comparison. As currently configured, the procedures calculate CBH and CBD using Brown's (1978) biomass equations for crown fuels for ponderosa pine trees in Montana and assume an even distribution of fuel within a tree crown. We modified the calculation procedures in the stand-alone executable to determine CBH and CBD based on the original FFE-FVS code, the local biomass equation (Equations 3 and 4), and the local biomass equations (Equations 3 and 4) and a nonuniform vertical distribution of biomass based on estimates of parameters derived from Equations 5 and 6 and inventory information from our vegetation plots.

The incorporation of site-specific biomass and crown fuel distribution models within individual trees produced a substantial impact on stand-level, canopy fuels profiles (Figure 6). For example, in the lowest density stand (RD = 13%), on average 23% of the canopy fuel biomass was located in the upper 50% of the stand. This result is in sharp contrast to stands 8 and 14 for which RD was 46 and 75% and 36 and 63% of canopy fuel biomass was located in the upper 50% of the stand, respectively.

Compared with the local biomass distribution model, which we assume to most accurately represent actual CBD, the original and local biomass only methods were biased and underpredicted CBD. Across all stands, the increase in

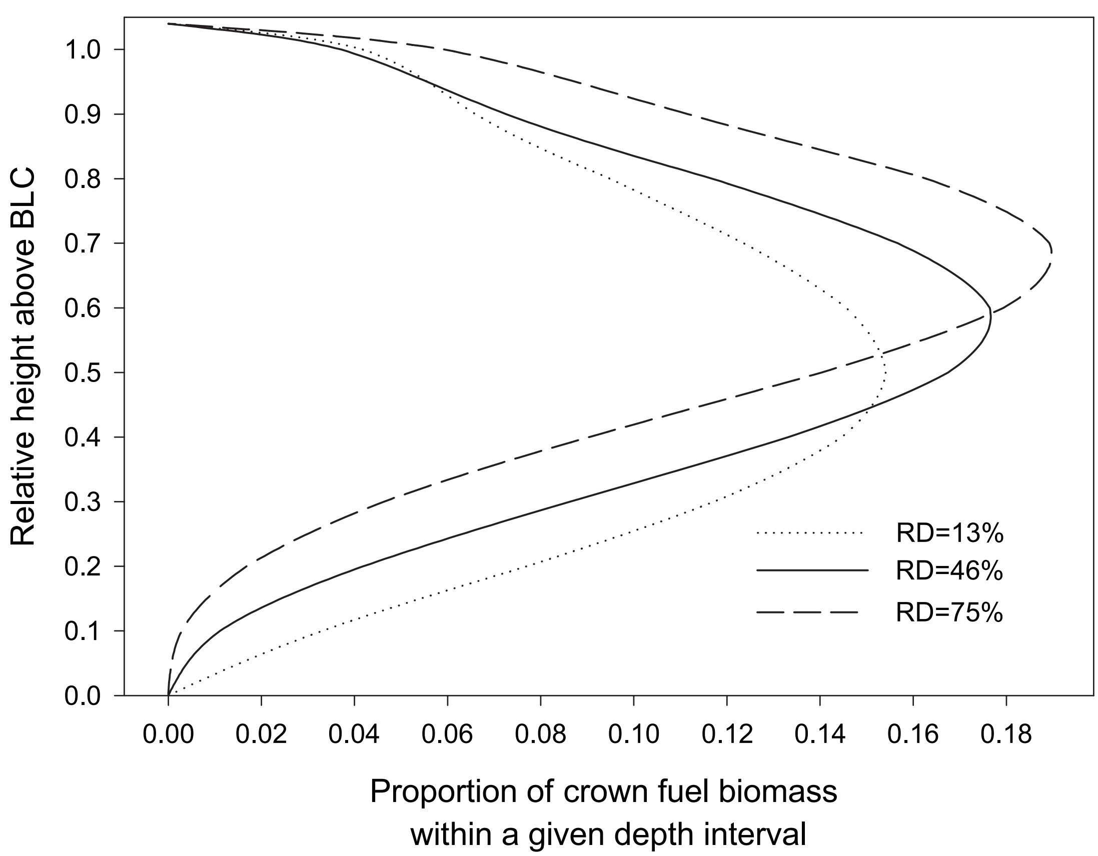

Figure 5. Predicted (Equation 2) crown fuel distribution on a dominant/codominant tree in stands of varying relative density (RD). For relative height in crown, 1.0 signifies the top of the tree and 0 represents the base of the live crown (BLC).

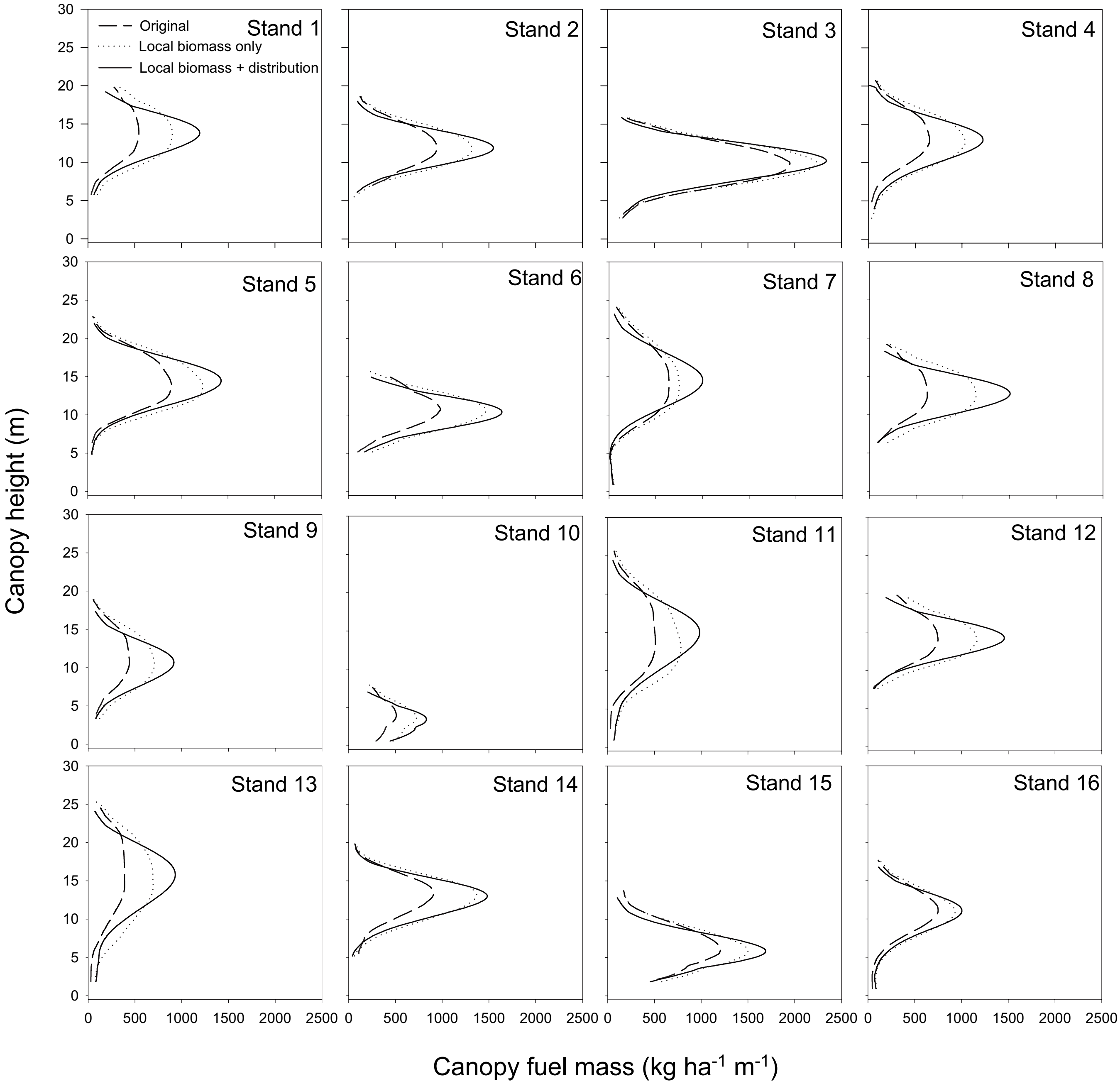

Figure 6. Canopy fuel profiles created from the 4-m running mean of canopy fuel mass (FOL + 0.5 × 1HF) for all 16 stands using the original, local biomass only, and local biomass-distribution Fire and Fuels Extension to the Forest Vegetation Simulator executables. Computation of the 4-m running average was initiated when at least 18.4 kg ha^{-1} m^{-1} of canopy fuels were present as outlined in Reinhardt and Crookston (2003).

CBD using local biomass equations (Equations 3 and 4) compared with unmodified, original estimates of CBD averaged 47%, and the increase ranged from 15 to 84% for the 16 stands sampled (Figure 7). Use of the local biomass equations and the Weibull vertical distribution of crown fuel mass model (Equations 5 and 6) increased CBD by estimates by an additional 31% compared with use of the local biomass equation alone, and the increase varied from 5 to 61%. Neither the modified biomass equations by themselves nor the modified biomass and nonuniform distribution models resulted in a decrease in CBD in any of the 16 stands sampled. Results presented here, in addition to results reported in Reinhardt et al. (2006), suggest that indirect estimates of CBD that incorporate a nonuniform distribution of crown fuel mass should be used when CBD is estimated indirectly. The percent increase in CBD that resulted from incorporating both local biomass equations and the vertical distribution of canopy fuels was positively related to quadratic mean diameter (QMD). For example, in stand 13 QMD was 35.5 cm and the increase in CBD was 139%. Compare this to results for stand 3 for which QMD was 12.6 cm and the increase in CBD was only 20%.

Across all stands, the average CBH obtained using the original, modified biomass only, and modified biomass-distribution versions of FFE-FVS were 6.2, 5.4, and 5.8 m, respectively. Although there was no effect on average CBH,

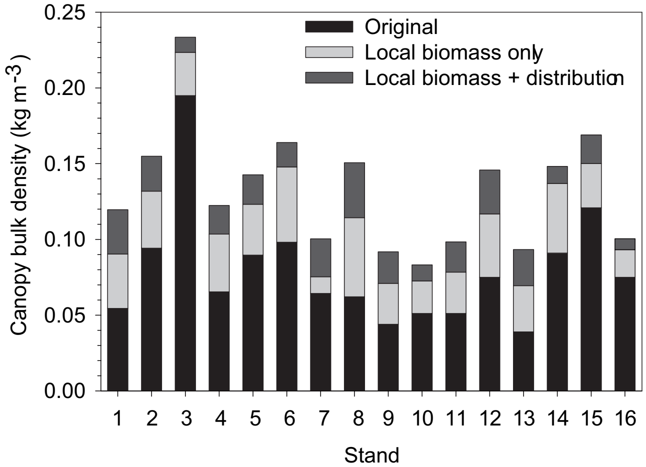

Figure 7. Predicted canopy bulk density (CBD) values for each of the 16 sample stands calculated using Brown's (1978) biomass equations and assuming a uniform distribution of biomass (original) and those predicted using local crown mass Equations 3 and 4 and models of biomass distribution within individual tree crowns (Equations 5 and 6). Light and dark gray bars represent the increase in CBD estimates due to the local biomass only procedure and the local biomass-distribution procedure, respectively.

within a given stand, substantial variability in CBH estimates was observed. Compared with the local biomass-distribution model, the original and local biomass only models were slightly biased with the original model overpredicting CBH and the local biomass only model underpredicting CBH. The percent difference in CBH estimates produced using the modified biomass-distribution versus original FFE-FVS model within individual stands ranged from −55% in stand 13 to 59% in stand 3. Unlike CBD for which the percent increase was related to stand structure (e.g., QMD), no relationship between the percent difference in CBH and stand structure was observed.

There are two underlying factors responsible for the increase in CBD. First, greater estimates of FOL predicted by crown mass equations specific to the Black Hills (Equation 3) simply resulted in a greater amount of potential canopy fuel. Second, in the estimation of CBD, when an explicit, nonuniform vertical distribution of crown fuel biomass is incorporated into the estimation procedure, biomass is concentrated near the center of the live crown for an individual tree. For even-aged stands, this will result in a greater maximum 4-m running average of canopy biomass, and, hence, a greater stand-level estimate of CBD than would be estimated if the fuel was evenly distributed within tree crowns. In contrast to the substantial impact the local crown mass equations and vertical distribution model had on CBD, little effect was observed on CBH. This is due, in part, to the low threshold FFE-FVS requires to determine CBH (to 0.011 kg m^{-3}) (Reinhardt and Crookston 2003).

Current management efforts to create stand structures more resistant to the initiation and spread of crown fire include increasing CBH and reducing CBD below the threshold where crown fire can be initiated and carried through the tree canopy. Lowering CBD and increasing CBH are often accomplished through various forms of thinnings (Agee 1996, Peterson et al. 2005). Although the threshold for CBD can vary under specific conditions, current recommendations are that CBD should be maintained at values <0.100 kg m^{-3} to decrease the likelihood of active crown fire (Keyes and O'Hara 2002, Peterson et al. 2005). Of the 16 stands sampled in this study, only 2 had CBD estimates >0.100 kg m^{-3} as currently implemented in FFE-FVS. When local crown mass equations and distribution models were applied to the data, 12 of the 16 stands had CBD estimates greater than the 0.100 kg m^{-3} threshold. Consequently, FFE-FVS, as presently formulated, would misdiagnose fire hazard in a substantial number of Black Hills ponderosa pine stands. Further, where FFE-FVS is used to design and evaluate fuels treatments, it is probable that either the amount of density reduction necessary to achieve a desired effect will be underestimated or the longevity of effectiveness of a given treatment will be overestimated.

Fuels management decisions are not made based solely on estimates of CBD. Rather the decision to thin and at what intensity is often made using CBD and CBH in combination with other indicators of fire behavior including the torching index (TI) and crowning index (CI). TI is defined as the windspeed at 6.1 m at which fire is carried from the surface into the crown (often referred to as passive crown fire or torching) and is strongly influenced by surface fuel loading and moisture content, foliar moisture content, wind reduction by the canopy, slope, and CBH (Scott and Reinhardt 2001). CI, on the other hand, is the 6.1-m windspeed at which crown fire can be actively carried from tree crown to tree crown (e.g., active crown fire) and is largely a function of surface fuel moisture content, slope, and CBD (Scott and Reinhardt 2001). Both of these crown fire hazard indices are estimated in FFE-FVS. The results from this study suggest that the effect of incorporating a local biomass-distribution model into FFE-FVS on TI may be stand-specific, depending on how the biomass-distribution model affects CBH, whereas the effect on CI, which has been shown to largely be a function of CBD (Fulé et al. 2001b) may be great and consistent (i.e., lower CI values).

Conclusions

We found substantial differences in estimates of CBD resulting from changes in the specific procedures used to estimate the amount and distribution of crown fuel mass for the even-aged ponderosa pine stands in our study. When tree allometries are used to estimate crown fuel variables in FFE-FVS, the technique for ponderosa pine is to apply one set of biomass equations across the entire geographic range and assume a uniform distribution of crown biomass (Reinhardt and Crookston 2003). When we applied local crown biomass estimators, CBD increased by an average of 47% compared with original, unmodified estimates, and use of a nonuniform crown mass distribution accounted for an additional 31% increase in CBD compared with a uniform distribution. However, the effect of these changes on CBH varied greatly within individual stands.

Based on our results, we suggest that wide geographic use of tree mass allometries be verified for different tree species and development of local allometries be undertaken where substantial differences in canopy fuel mass estimates occur. We also suggest that explicit, nonuniform estimates of vertical crown mass distribution be used when tree crown mass is aggregated to identify the position and amount of canopy mass to calculate CBH and CBD as used in fire prediction models.

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