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# Estimating Canopy Bulk Density and Canopy Base Height for Interior Western US Conifer Stands

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Crown fire hazard is often quantified using effective canopy bulk density (CBD) and canopy base height (CBH). When CBD and CBH are estimated using nonlocal crown fuel biomass allometries and uniform crown fuel distribution assumptions, as is common practice, values may differ from estimates made using local allometries and nonuniform distributions. We estimated CBD and CBH for mostly pure, even-aged stands of seven conifer species by modifying the Fire and Fuels Extension to the Forest Vegetation Simulator to use nonuniform crown fuel distributions, which allowed us to determine whether distribution effects on CBD and CBH estimates were species specific or general. For two species, we also compared estimates from local and nonlocal allometries to ascertain whether there was a consistent bias in CBD and CBH estimates associated with application of allometries outside their geographic area of origin. Using nonuniform distributions caused consistent increases in average CBD estimates of ~10–30% for all species compared to estimates obtained using uniform distributions. Effects on CBH varied. Using local allometries did not result in CBD or CBH estimates that were consistently larger or smaller than those obtained using nonlocal allometries. We conclude that using nonuniform distributions invariably increases estimates of CBD for even-aged conifer stands, whereas effects on CBH estimates are difficult to predict and that allometric relationships vary widely among stands in the southern Rocky Mountains.

**Keywords:** canopy bulk density, canopy base height, crown fuel distribution, crown biomass allometry, Fire and Fuels Extension to the Forest Vegetation Simulator (FFE-FVS)

Large destructive wildfires and expansion of the wildland-urban interface have propelled crown fire hazard assessment to the forefront of management priorities for conifer forests in the western United States (Radeloff et al. 2005, Stephens and Ruth 2005). In Colorado alone, the 2012 and 2013 wildfire seasons each saw hundreds of homes destroyed, with insurance claims totaling hundreds of millions of dollars (Chaykowski 2013). Crown fire hazard assessment entails using models to predict potential fire behavior based on the canopy fuels complex (Scott and Reinhardt 2001). This type of assessment is used to prioritize stands for treatment, to compare alternative fuel treatment options in terms of their anticipated effects on crown fire behavior, to evaluate treatment effectiveness after the fact, and to assess risk to firefighters during suppression activities (Cruz and Alexander 2010).

All crown fire behavior models require as inputs some characterization of the amount of canopy fuels and their arrangement in space (Cruz et al. 2003). Canopy fuels are generally taken as that portion of the canopy likely to be consumed in a fire, which typically includes foliage and some portion of fine woody fuels (Call and Albini 1997). Predictions from most fire modeling systems used by land managers to evaluate crown fire hazard, e.g., FARSITE, NEXUS, and the Fire and Fuels Extension to the Forest Vegetation Simulator (FFE-FVS) (Rebain et al. 2010), depend substantially on two key canopy fuel inputs: canopy bulk density (CBD) and some stand-level representation of the crown base height of individual trees (canopy base height [CBH]) (Van Wagner 1977). CBD reflects how compactly fuels are packed in space and is thus a critical variable for evaluating the potential for fire to spread horizontally through canopies. When CBD is large, there is a high degree of connectivity between fuel particles that promotes fire spread through canopies by ensuring a continuous supply of fuel to advancing flames (Van Wagner 1977). CBD is influential in predictions of fire type (e.g., surface and active crown) from fire behavior models given a fixed slope, fuel moisture, and wind speed (Scott and Reinhardt 2001) and is thus useful for comparing alternative treatments in terms of their potential to reduce crown fire behavior. A threshold value of CBD (271 lb

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acre-ft$^{-1}$ [0.10 kg m$^{-3}$]) has been proposed as a target for thinning treatments intended to reduce the likelihood of crown fire (Keyes and O'Hara 2002). CBH is an important determinant of the degree of connectivity between surface fuels and tree crowns; it is thus reflective of the potential for fire to transition from surface to canopy fuels (Van Wagner 1993). CBD and CBH are frequently used to evaluate the potential influence of treatments such as thinning on fire behavior either directly or as inputs to calculations of various fire behavior indices (Long et al. 2010).

Although there are several techniques by which land managers can obtain estimates of CBD and CBH (e.g., Alexander and Cruz 2014), one of the most common approaches is to use FFE-FVS to generate estimates from tree inventory data. FFE-FVS is a semi-distance-independent forest growth modeling framework that is capable of characterizing changes in surface and canopy fuels over time as well as calculating several indices of potential fire behavior (Reinhardt et al. 2003, Crookston and Dixon 2005). While CBD can be calculated simply as the biomass of fuel in a volume of space (i.e., the "load over depth" method) (Reinhardt et al. 2006), estimated CBD from FFE-FVS is most correctly described as an estimate of *effective* CBD: the maximum 13 ft (4 m) running mean bulk density of predefined 1-ft (0.3 m)-thick canopy layers (Sando and Wick 1972). CBH is estimated in a similar fashion as the lowest height at which the running mean bulk density of canopy layers exceeds a predefined threshold of 30 lb acre-ft$^{-1}$ (0.011 kg m$^{-3}$) (Scott and Reinhardt 2001), although it too can be calculated simply as the average crown base height of trees in a stand or some similar value (Cruz and Alexander 2010). Because estimates of CBD and CBH from FFE-FVS are derived from estimates of the bulk density of canopy layers, their values depend not only on the biomass of canopy fuel and the canopy depth but also on the manner in which fuel is distributed vertically within the crowns of trees that make up the canopy (Keyser and Smith 2010).

Canopy fuel biomass is often quantified via summation of crown biomass calculations made at the tree level (e.g., Brown 1978), although other approaches have been developed (e.g., Alexander and Cruz 2014, Ruiz-González et al. 2015). FFE-FVS estimates crown fuel biomass for most western conifer species using allometries developed using data from mostly dominant and codominant trees located in northern Idaho and Montana (Brown 1978), and biomass is assumed to be uniformly distributed within crowns (Reinhardt and Crookston 2003). The crown fuel allometries used in FFE-FVS have been shown to overestimate canopy fuel load and CBD for pure and mixed-species conifer stands at various locations throughout the interior western United States (Reinhardt et al. 2006) and to underestimate the same values for pure ponderosa pine (*Pinus ponderosa* Douglas ex P. Lawson & C. Lawson) stands in South Dakota's Black Hills (Keyser and Smith 2010). These biases have been attributed to the use of allometries to predict biomass for trees that occupy different canopy positions or reside in geographic areas different from those used for model development (Reinhardt et al. 2006, Keyser and Smith 2010).

The assumption of uniform vertical distribution of fuel within crowns in FFE-FVS does not affect estimation of canopy fuel load (Reinhardt and Crookston 2003). However, it is inconsistent with observed crown fuel distributions (Ex et al. 2015) and has been shown to result in lower estimates of CBD for ponderosa pine stands in South Dakota's Black Hills than when nonuniform crown fuel distributions were used (Keyser and Smith 2010). This effect arises because using uniform crown fuel distributions in CBD estimation eliminates the potential for peaks of crown fuel distributions to overlap in the canopy profile, which has the effect of reducing the maximum running mean bulk density of canopy layers. CBH estimation could also be affected if uniformly distributing crown biomass caused the bulk density threshold to be exceeded at a different height, although work to date has not shown this to be true (Keyser and Smith 2010).

In this work, we investigated the effects of incorporating nonuniform crown fuel distributions and local crown biomass allometries in FFE-FVS on estimates of CBD and CBH. We used data from pure, even-aged stands of five interior western US conifer species: ponderosa pine, lodgepole pine (*Pinus contorta* Douglas ex Loudon), Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco), subalpine fir (*Abies lasiocarpa* [Hook.] Nutt.), and Engelmann spruce (*Picea engelmannii* Parry ex Engelm.), as well as mixed stands of two-needle pinyon (*Pinus edulis* Engelm.) and Rocky Mountain juniper (*Juniperus scopulorum* Sarg.). This study focused specifically on the CBD and CBH estimation methodologies implemented in FFE-FVS (Reinhardt and Crookston 2003) because this approach is used extensively throughout the western United States (Affleck et al. 2012). Specifically, we addressed the following questions: Are CBD estimates obtained using nonuniform distributions greater than estimates obtained using uniform distributions for even-aged stands of other conifers as has been demonstrated for ponderosa pine? Is there also a predictable effect on CBH? And, is there a consistent bias associated with geographic area in estimates derived using nonlocal crown fuel biomass allometries, or does bias vary widely between stands? We answered these questions by modifying the CBD and CBH estimation procedures in FFE-FVS to incorporate nonuniform vertical crown fuel biomass distributions and local biomass allometries.

## Methods

### Data Collection and Processing

We used data collected over a period of almost three decades from 59 mostly pure, even-aged conifer stands located throughout the interior western United States (Figure 1) to evaluate the generality of the effects of using nonuniform crown fuel biomass distributions on CBD and CBH estimates. Coordinates and physical characteristics of most of the stands are reported in Ex et al. (2015). Field methods and the remaining stands are described in detail in Ex et al. (2015), Long and Smith (1988), and Long and Smith (1989). A brief overview of field methods follows.

Stands were selected to represent broad ranges of average tree size and stand density for each species. Our data come from stands with quadratic mean diameters ranging from 1.3 to 17.2 in. (3.3 to 43.7 cm) and densities ranging from 55 to 10,324 trees acre$^{-1}$ (136 to 25,542 trees ha$^{-1}$) (Table 1).S In each stand, we established a single fixed-area plot that was sized to capture about 30 trees. Plot sizes ranged from 215 to 53,820 ft$^2$ (20 to 4,951 m$^2$) (Table 1). Height, crown base height, and dbh were recorded for all trees ≥0.4 in. (1 cm) dbh. Crown base height was designated as the height of the lowest whorl or as the height of the third lowest live branch in the compact live crown when the lowest whorl had fewer than three

S Supplementary data are available with this article at http://dx.doi.org/10.5849/forsci.15-118.

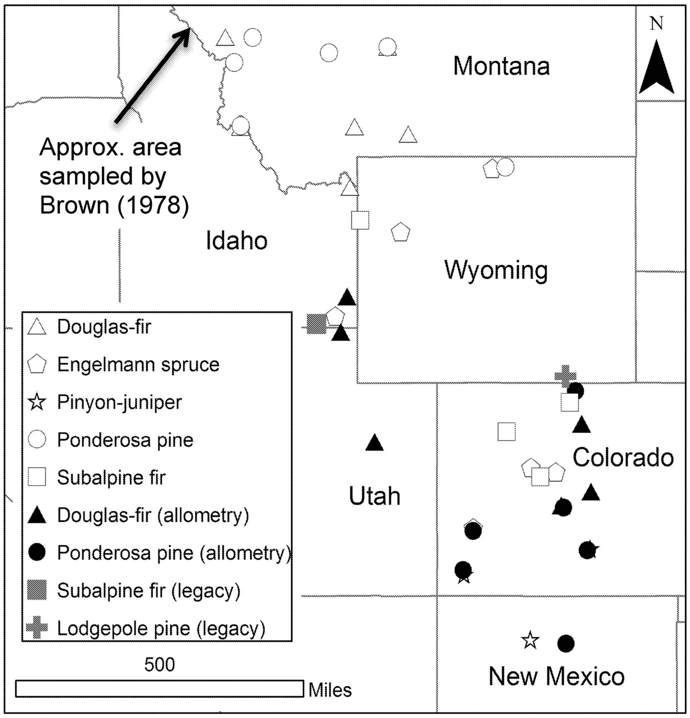


**Figure 1. Sampling locations. Black shapes are locations of 12 stands that were used to develop local biomass allometries. Gray shapes denote the approximate locations of 22 stands sampled by Long and Smith (1988, 1989).**

branches. Nonuniform crown fuel distributions were developed using data collected by destructively sampling five trees per stand that spanned the range of sizes present in the main stand canopy. We subjectively chose trees for destructive sampling that were free of forks, lopsided crowns, or other obvious abnormalities. All crown material from each destructively sampled tree was weighed in the field. Subsamples of foliage and several diameter classes of live and dead branches (Bradshaw et al. 1983) were then collected. Subsamples were dried and reweighed to permit development of ratios for estimation of the dry weight of crown material by size class.

Data from a subset of 12 of the 59 stands described above were used to evaluate whether there was consistent bias in CBD and CBH estimates from FFE-FVS that was associated with geographic area (Figure 1). The allometries in FFE-FVS were developed for stands in Montana and northern Idaho (Brown 1978). We developed corresponding allometries using data from six ponderosa pine and six Douglas-fir stands located in Colorado, New Mexico, Utah, and southern Idaho (Figure 1). We sampled this subset of stands specifically to obtain data sets for these two species from stands that were geographically distinct from those used to develop the allometries in FFE-FVS and that also spanned broad ranges of average tree size and stand density (Table 2).

Using the nonuniform fuel distributions and local biomass allometries, we modified the CBD and CBH calculation procedure in FFE-FVS in three ways: we incorporated nonuniform distributions, but retained crown biomass allometries from Brown (1978); we retained the uniform distributions from the production version of FFE-FVS but incorporated local biomass allometries, and we incorporated both nonuniform distributions and local biomass allometries (Figure 2). It is our assumption that the third modification offered the most accurate characterization of the amount and the arrangement of canopy fuels. We used the March 2015 version of the Central Rockies Variant of FVS for our analysis. For each cover type (Table 1), we obtained estimates of CBD and CBH using our modifications and compared them with estimates from the production version of FFE-FVS.

## Statistical Methods

We used a two-parameter Weibull distribution to describe the arrangement of fuel loads within tree crowns (Keyser and Smith 2010). Separate distributions were used for foliage and fine woody fuel biomass because the center of foliage biomass generally resides higher in crowns than the center of woody fuel biomass (Figure 3). A single set of foliage and fine woody fuel distributions were used for all species and stands except for the three pinyon-juniper stands, in which distributions of both foliage and fine woody fuel biomass were shifted downward within crowns compared with stands of other species. Distribution parameter values are reported in Ex et al. (2015).

We used an iterative, derivative-free least-squares algorithm to fit separate allometric models for biomass of foliage and combined live and dead fuel with diameter of <0.25 in. (0.64 cm), which is consistent with available fuel in FFE-FVS (Reinhardt and Crookston 2003). The form of the model was

$$y = b_0 x_1^{b_1} x_2^{b_2} \tag{1}$$

where $x_1$ is dbh, $x_2$ is either live crown ratio (the ratio of live crown length to total tree height) or tree height, and $b_0$, $b_1$, and $b_2$ are estimated parameters (Monserud and Marshall 1999). We chose

**Table 1. Summary sample data for stands used to evaluate the effect of using non-uniform crown fuel distribution assumptions on CBD and CBH estimation.**

| Cover type[a] | Plot sizes ($ft^2$)[b] | Trees $acre^{-1}$[c] | N[d] | Basal area ($ft^2$ $acre^{-1}$)[c] | Quadratic mean diameter (in.)[c] |
|---|---|---|---|---|---|
| Subalpine fir | 237–10,764 | 2,238 (186–6,441) | 9 (34–83) | 210 (101–408) | 6.1 (3.4–10.0) |
| Pinyon-juniper[e] | 10,764–10,764 | 310 (246–421) | 3 (61–104) | 117 (72–190) | 7.7 (6.1–9.2) |
| Lodgepole pine | 215–9,419 | 3,788 (106–10,324) | 17 (23–51) | 151 (40–247) | 3.9 (1.3–11.5) |
| Engelmann spruce | 721–5,382 | 1,049 (515–1,813) | 6 (30–133) | 244 (109–441) | 6.7 (3.9–9.3) |
| Ponderosa pine | 1,346–53,820 | 443 (55–2,040) | 12 (32–90) | 130 (57–266) | 10.7 (3.2–17.2) |
| Douglas-fir | 2,153–10,764 | 1,166 (600–2,300) | 12 (30–67) | 168 (50–270) | 8.4 (5.3–13.4) |

See Supplemental Table S1 for data in SI units.
[a] After Eyre et al. (1980), excepting the Engelmann spruce-subalpine fir type which has been split into its constituent species here.
[b] Minimum − maximum.
[c] Mean (minimum − maximum).
[d] Number of stands followed by the minimum and maximum number of trees measured in a given stand.
[e] Two-needle pinyon and Rocky Mountain juniper were sampled together in mixed stands where they co-occurred. The basal area and quadratic mean diameter for these typically multstemmed species were calculated using diameter at the root crown instead of dbh.

Table 2. Summary data for stands from which trees were destructively sampled to develop local crown fuel biomass allometries.

| Species | Plot size ($ft^2$) | $N$ | Trees $acre^{-1}$ | BA ($ft^2$ $acre^{-1}$) | QMD (in.) | Fuel Production | Fuel Local | dbh (in.)[a] | Height (ft)[a] | Crown base (ft)[a] |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | . .(tons $acre^{-1}$) | . . | | | |
| Douglas-fir | 5,380 | 50 | 405 | 118 | 7.3 | 6.1 | 5.2 | 8.2 (2.0–14.2) | 38.3 (14.3–63.3) | 12.3 (2.5–23.7) |
| | 5,380 | 30 | 243 | 237 | 13.4 | 9.0 | 10.2 | 12.9 (5.2–21.5) | 64.6 (33.2–86.7) | 16.9 (6.7–27.4) |
| | 2,152 | 46 | 931 | 178 | 5.9 | 10.3 | 16.4 | 6.3 (2.4–10.1) | 32.5 (14.4–46.4) | 11.1 (4.7–21.3) |
| | 10,760 | 67 | 271 | 108 | 8.5 | 5.2 | 6.2 | 9.9 (1.7–17.7) | 39.2 (10.1–59.3) | 11.0 (2.8–15.5) |
| | 5,380 | 40 | 324 | 50 | 5.3 | 2.9 | 4.1 | 6.7 (3.2–10.5) | 33.7 (20.5–46.2) | 3.8 (1.9–5.5) |
| | 5,380 | 46 | 372 | 198 | 9.9 | 8.5 | 8.4 | 10.2 (3.6–15.8) | 65.1 (28.3–86.0) | 11.0 (8.0–16.2) |
| Ponderosa pine | 2,152 | 46 | 931 | 166 | 5.7 | 6.7 | 9.0 | 6.58 (3.6–9.7) | 31.4 (21.2–39.4) | 13.2 (9.0–16.2) |
| | 5,380 | 35 | 283 | 173 | 10.6 | 5.3 | 6.1 | 9.6 (3.4–14.9) | 53.8 (18.8–69.8) | 33.6 (10.6–45.2) |
| | 26,900 | 34 | 55 | 87 | 17.0 | 4.0 | 3.6 | 17.3 (13.4–21.4) | 75.9 (64.9–91.1) | 28.8 (19.2–33.7) |
| | 53,800 | 90 | 73 | 57 | 11.9 | 2.4 | 3.1 | 16.0 (9.4–21.2) | 53.2 (41.3–60.9) | 18.8 (13.9–28.5) |
| | 10,760 | 34 | 138 | 112 | 12.2 | 4.8 | 5.0 | 13.8 (8.8–19.0) | 54.4 (48.3–61.2) | 19.9 (12.3–29.5) |
| | 5,380 | 41 | 332 | 110 | 7.8 | 3.9 | 4.4 | 8.6 (5.3–12.0) | 44.0 (37.1–50.8) | 19.4 (11.0–30.1) |

$N$ is total number of trees in each plot (5 trees from each plot were destructively sampled, totaling 30 trees of each species), BA is basal area, QMD is quadratic mean diameter, fuel-production is canopy fuel load from the production version of FFE-FVS, fuel-local is canopy fuel load calculated using local allometries, and dbh, height, and crown base are characteristics of destructively sampled trees. See Supplemental Table S2 for data in SI units.
[a] Mean (minimum − maximum).

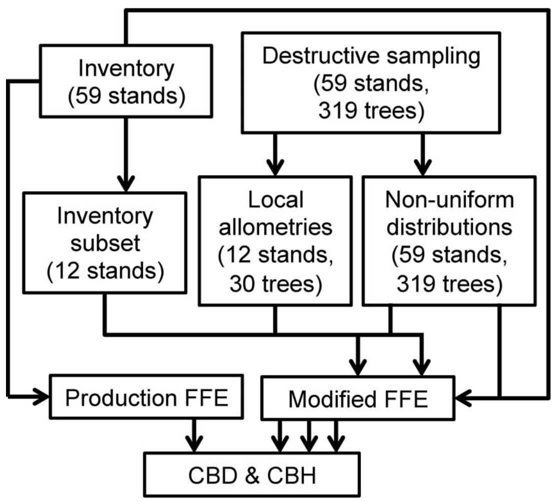


**Figure 2. Diagram of the four CBD and CBH estimation procedures evaluated in this study.**

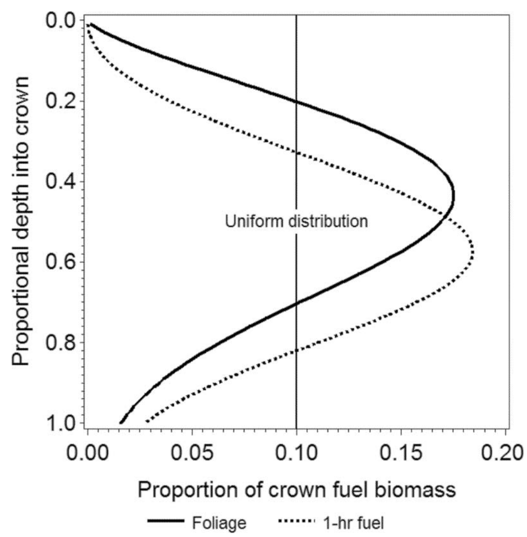


**Figure 3. Nonuniform distributions used to describe foliage and fine woody fuel biomass distribution within crowns with a uniform distribution (the vertical line) for comparison. Distribution parameters are reported in Ex et al. (2015).**

between potential combinations of predictor variables by first comparing competing models using the form

$$\log_e y = b_0 + b_1 \log_e x_1 + b_2 \log_e x_2 \quad (2)$$

with Akaike's information criterion corrected for small sample sizes (AICc) (Burnham and Anderson 2010). Models with differences in AICc of <2 were considered equivalent. We fit Model 1 using estimated values of $b_1$ and $b_2$ from Model 2 as starting values for weighted nonlinear regression and $x_1^{-3}$ as a weighting factor where necessary to satisfy the assumption of homoscedasticity (according to Keyser and Smith 2010). Final model selection was based on residual plots from nonlinear regression and goodness of fit: the model with the lowest root mean square error was deemed the best (Table 3).

After obtaining estimates of CBD and CBH from the production version of FFE-FVS as well as from modified calculations that incorporated nonuniform distributions and local biomass allometries, we used means comparisons to determine whether differences in estimated CBD and CBH were statistically significant. We used paired two-sample $t$-tests when error was normally distributed, and Wilcoxon signed-rank tests when the assumption of normality was violated.

## Results

Local allometries predicted larger canopy fuel loads than nonlocal allometries for most stands, but the sign and magnitude of differences varied among stands for both species (Table 2). The difference between predictions from local and nonlocal allometries ranged from <1% to almost 60% of the total predicted canopy fuel load, but was generally ~10–40% (Table 2).

The data showed that estimates of CBD generated using nonuniform crown fuel biomass distributions were consistently 13–27% larger than estimates from the production version of FFE-FVS. The difference was statistically significant for stands in all cover types except pinyon-juniper (Table 4). Unlike CBD, the estimates of CBH did not always increase. Average differences between estimates of CBH from the production version of FFE-FVS and

**Table 3. Model 1 parameter estimates for predicting biomass in pounds of foliage and fine woody fuels in tree crowns.**

| Species | Biomass component | Variables | $b_0$ | $b_1$ | $b_2$ | Bias[a] | RMSE | $R^{2b}$ |
|---|---|---|---|---|---|---|---|---|
| Douglas-fir | Foliage | dbh (in.), CR | 1.6319 | 1.5870 | 1.5223 | −0.03 | 18.1 | 0.74 |
| | Fine wood | dbh (in.), CR | 0.8696 | 1.5060 | 1.1188 | 0.39 | 9.0 | 0.68 |
| Ponderosa pine | Foliage | dbh (in.), CR | 0.2631 | 2.3263 | 0.8964 | 0.12 | 23.8 | 0.86 |
| | Fine wood | dbh (in.), HT | 0.1001 | 3.3272 | −1.2232 | −0.28 | 3.3 | 0.59 |

See Supplemental Table S3 for data presented in SI units. All parameters were significant at $\alpha = 0.05$. RMSE, root mean square error; CR, crown ratio (proportion); HT, height (ft).
[a] Predicted − observed.
[b] The $R^2$ nonlinear fit statistic is 1 − sum of squared residual error/sum of squared error relative to mean observed value.

**Table 4. Average difference in estimated CBD and CBH from modified and production versions of FFE-FVS (average percentage change follows each value in parentheses).**

| Cover type | FFE-FVS modification | CBD Δ (lb acre ft$^{-1}$) | CBD Δ significance | CBH Δ (ft) | CBH Δ significance |
|---|---|---|---|---|---|
| Ponderosa pine | Local allometries | 62 (16) | $z = 9.5$, $P = 0.06$ | −1.5 (−17) | $t(5) = -1.6$, $P = 0.16$ |
| Douglas-fir | | 92 (21) | $z = 5.5$, $P = 0.31$ | −0.8 (−19) | $t(5) = -2.1$, $P = 0.09$ |
| Subalpine fir | Nonuniform distributions | 201 (23)[a] | $t(8) = 7.6$, $P < 0.01$[a] | 0.8 (22) | $z = 5.0$, $P = 0.13$ |
| Ponderosa pine | | 76 (27)[a] | $t(11) = 12.3$, $P < 0.01$[a] | 2.1 (17)[a] | $t(11) = 2.8$, $P = 0.02$[a] |
| Pinyon-juniper | | 52 (13) | $t(2) = 2.4$, $P = 0.14$ | −0.3 (−11) | $t(2) = -1.0$, $P = 0.42$[a] |
| Lodgepole pine | | 49 (13)[a] | $t(15) = 4.8$, $P < 0.01$[a] | 0.6 (9)[a] | $z = 14.5$, $P = 0.05$ |
| Engelmann spruce | | 149 (17)[a] | $t(5) = 5.0$, $P < 0.01$[a] | 0.5 (23) | $z = 3.0$, $P = 0.25$ |
| Douglas-fir | | 103 (24)[a] | $t(11) = 7.1$, $P < 0.01$[a] | 1.4 (18) | $z = 15.0$, $P = 0.08$ |
| Ponderosa pine | Local allometries and nonuniform distributions | 144 (48)[a] | $z = 10.5$, $P = 0.03$[a] | −0.3 (−9) | $t(5) = -0.2$, $P = 0.87$ |
| Douglas-fir | | 179 (44)[a] | $z = -10.5$, $P = 0.03$[a] | −0.2 (−7) | $t(5) = -0.3$, $P = 0.74$ |

Values were calculated as modified − production. Significance columns are test statistics ([$t(df)$] for paired two-sample $t$-tests and $z$ for Wilcoxon signed-rank tests) and $P$ values. See Supplemental Table S4 for data presented in SI units.
[a] Significant differences at $\alpha = 0.05$.

estimates from versions that used nonuniform crown fuel distributions ranged from −11% to +23% and were in most cases nonsignificant (Table 4).

Although estimates of CBD and CBH generated using local crown fuel biomass allometries were sometimes substantially different from estimates from the production version of FFE-FVS (Supplemental Table S5), there was no statistical difference between estimates from the different methodologies (Table 4). This was because in some stands estimates of canopy fuel load from local allometries were larger than estimates from nonlocal allometries, causing estimates of CBD to increase and potentially causing estimates of CBH to decrease, whereas in other stands the opposite was true (Table 2).

On average, combining nonuniform crown fuel distributions and local crown fuel biomass allometries (the most accurate characterization of the amount and arrangement of canopy fuels) resulted in larger estimates of CBD than when either nonuniform distributions or local allometries were used alone. Estimates of CBD were 44–48% greater than estimates from the production version of FFE-FVS (Table 4). When local allometries predicted greater canopy fuel loads, they amplified the increase in estimated CBD from using nonuniform distributions. When they predicted less canopy fuel, the increase was diminished (Figure 4). CBH estimates obtained by combining nonuniform fuel distributions and local crown fuel biomass allometries were not significantly different from estimates from the production version (Table 4).

## Discussion

This study forms the basis for a general description of how crown fuel distribution assumptions and the provenance of crown fuel biomass allometries affect estimation of CBD and CBH using the methodology implemented in FFE-FVS. To our knowledge only two other studies have directly addressed the influence of these factors on CBD and CBH estimation (Reinhardt et al. 2006, Keyser and Smith 2010). Our results indicate that incorporating nonuniform vertical crown fuel distributions in FFE-FVS essentially always increases estimates of CBD relative to estimates from the production version of FFE-FVS for pure, even-aged conifer stands. In contrast, the effect on CBH estimation is inconsistent. Although estimates of CBH usually increased or stayed the same, for some stands they decreased. Nonlocal allometries did not consistently over- or underestimate crown fuel biomass relative to local allometries, which suggests that allometric relationships vary widely among stands in the southern Rockies.

Keyser and Smith (2010) found that incorporating nonuniform crown fuel distributions in FFE-FVS increased estimates of CBD by 31% on average over estimates from the production version of FFE-FVS for managed, even-aged ponderosa pine stands in South Dakota's Black Hills. In this study, incorporating nonuniform distributions in FFE-FVS caused CBD estimates to increase by 13–27% on average for mostly pure, unmanaged, even-aged conifer stands of varying composition (Table 4). The magnitude of the increase in CBD depended on the amount of overlap between crowns in the vertical canopy profile (i.e., the amount of variation in tree heights and crown ratios). In very uniform, managed stands like those in the Black Hills, peaks in nonuniform distributions overlap substantially, amplifying the effect of adopting nonuniform distributions on CBD estimation compared to less uniform stands. This highlights the possibility that incorporating nonuniform crown fuel distributions in FFE-FVS may have unpredictable effects on CBD estimates for multiaged or multispecies stands with more complex canopy profiles than the even-aged stands investigated in this work. However, these issues may be irrelevant, as CBD estimates are presumably near meaningless for stands with complex canopy profiles

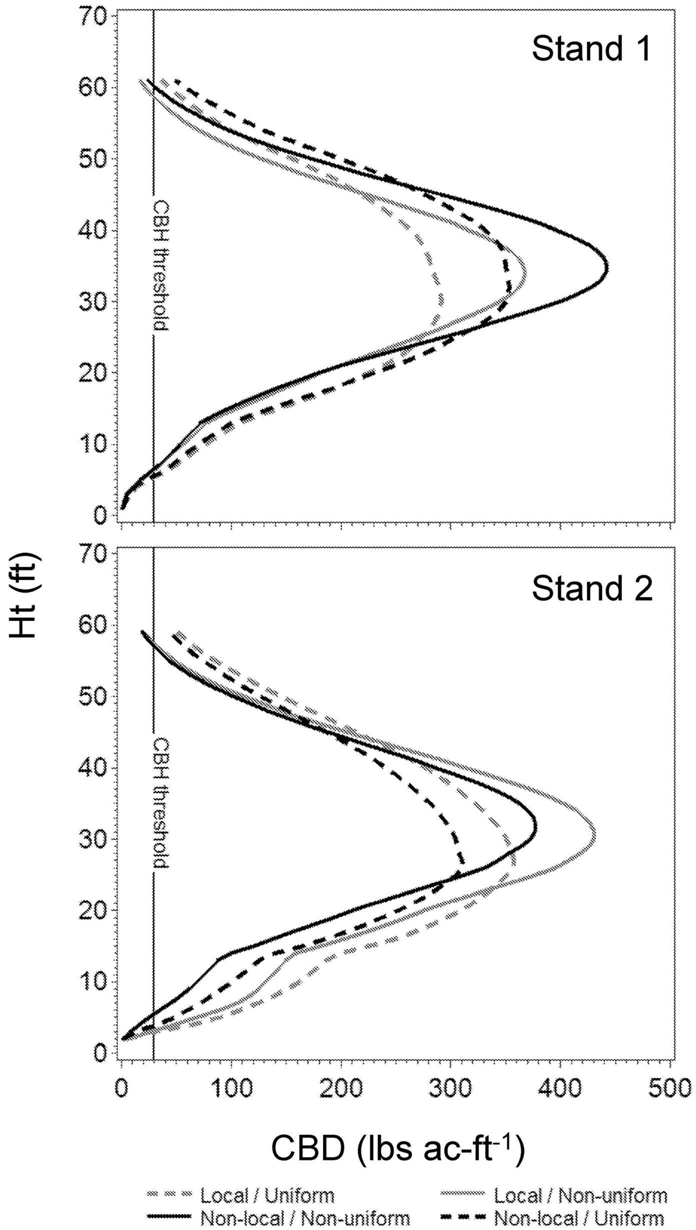


**Figure 4. Canopy fuel profiles for two Douglas-fir stands created using modified CBD and CBH calculations that incorporated local biomass allometries and uniform crown fuel distributions, local allometries and nonuniform distributions, nonlocal allometries and uniform distributions, and nonlocal allometries and nonuniform distributions. Local allometries decreased the estimate of crown fuel biomass for Stand 1 and increased the estimate for Stand 2. See Supplemental Figure S1 for SI units.**

regardless of crown fuel distribution characteristics because using a metric like CBD for fire hazard assessment makes the implicit assumption that the canopy profile is homogeneous. Canopy fuel metrics like CBD and CBH warrant reevaluation as indicators of fire hazard for restoration treatments that increasingly emphasize creation of complex stand and canopy structures in fire-prone forests of the interior western United States (e.g., Churchill et al. 2013, Underhill et al. 2014). Fire behavior modeling studies suggest that assumptions of homogeneous fuel distribution are generally problematic: Both the horizontal arrangement of trees within stands (Hoffman et al. 2012) and the three-dimensional arrangement of fuels within individual tree crowns (Parsons et al. 2011) have been shown to influence potential fire behavior.

Unlike estimates of CBD, those of CBH did not consistently increase when nonuniform crown fuel distributions were incorporated in FFE-FVS (Supplemental Table S5). For the CBH estimation methodology implemented in FFE-FVS, the effect of adopting nonuniform crown fuel distributions on CBH estimates depends on how fuel is distributed throughout the canopy profile. For example, when the bulk density of the lowest canopy layer just meets the bulk density threshold for CBH, incorporating a nonuniform distribution can cause the CBH estimate to increase by, in effect, shifting crown material upward and reducing bulk density of the lowest canopy layer to less than the threshold value (Figure 4). Alternatively, when bulk density of the lowest canopy layer greatly exceeds the threshold, incorporating a nonuniform distribution would have no effect on estimated CBH provided that the bulk density of the lowest nonzero canopy layer continued to exceed the threshold even after some material was shifted upward. The CBH estimate could decrease when there are canopy layers that have bulk densities that are below the threshold value at lower heights in the canopy than the layer in which the CBH threshold is met if concentrating fuel in lower canopy layers causes the threshold value to be exceeded at a lower height. This dependence on the canopy fuel profile explains why there was no consistent effect of incorporating nonuniform distributions on CBH estimates. There are alternative methods of estimating CBH that avoid these threshold effects, for example, estimating CBH using a regression approach from factors such as stand density (Alexander and Cruz 2014), although this approach may not perform well in treated stands (Reinhardt et al. 2006). Using a mean or lower quartile value from observed crown base height measurements is arguably the simplest approach and may also be the most conceptually sound, as it is similar to the CBH delineation method used to develop the most widely used crown fire initiation model (Cruz and Alexander 2010).

Allometric scaling relationships are subject to site-level variation that arises from differences in site quality, level of competition, and disturbance history (Ducey 2012); thus, allometric model bias is largely a product of specific sites and stands, rather than broader geographic areas. Although it is widely acknowledged that site-specific allometries are ideal, they are rarely available, especially for the specific size classes of canopy fuels used as inputs to fire behavior models (Affleck et al. 2012). Furthermore, Keyser and Smith (2010) found incorporating local crown biomass allometries in FFE-FVS caused consistent increases in CBD estimates for Black Hills ponderosa pine stands of 15–84%, which suggests that there is some potential for improvement by adjusting predictions for specific geographic areas, assuming consistent biases are the norm. Using local allometries caused CBD estimates to increase for many of the southern Rockies stands investigated in this study; however, in some cases they decreased (Supplemental Table S5; Figure 4). This result probably reflects greater variation in site characteristics among the stands in this study than among the stands investigated by Keyser and Smith (2010). Substantial variation in allometric relationships between dbh and crown biomass within our set of southern Rockies stands necessitated the inclusion of live crown ratio or tree height as an explanatory variable in Model 1. The allometric estimators in the production version of FFE-FVS rely solely on dbh and thus were unable to account for this variation in allometric relationships within our data set. The lack of consistent regional bias in CBD estimates for southern Rockies stands suggests that more flexible allometric model forms (Weiskittel et al. 2015) or site-specific adjustment factors (Reinhardt et al. 2006) are necessary to improve crown fuel biomass estimates for the varied sites in this region.

The most accurate characterizations of canopy fuel profiles in this study were obtained using nonuniform crown fuel distributions and local crown fuel biomass allometries. The net effect of combining nonuniform distributions and local allometries is a modification of the predictable effects of adopting nonuniform distributions (increased CBD) by stand- or forest-specific effects of local allometries. The effect of adopting nonuniform distributions is enhanced when local allometries predict greater amounts of crown fuel biomass than the allometries implemented in the production version of FFE-FVS (Figure 4). This scenario accounts for the 20–139% increase in estimated CBD reported by Keyser and Smith (2010) for Black Hills ponderosa pine. Alternatively, increases in estimated CBD from adopting nonuniform distributions are diminished or reversed when local allometries predict lesser amounts of crown fuel biomass (Figure 4). The net effect of incorporating both nonuniform distributions and local allometries on CBH estimation using FFE-FVS depends on the canopy fuel profile (see above) and on the sign and magnitude of any differences in biomass estimates from local and nonlocal allometries. CBH predictions may increase or decrease dramatically for a given stand, yet be unchanged for others (Supplemental Table S5).

## Conclusion

This work showed that incorporating nonuniform crown fuel distributions in FFE-FVS causes estimates of CBD for even-aged conifer stands to increase by ~10–30% regardless of species composition. The major implication of this consistent increase in estimated CBD is a subsequent decrease in estimates of the critical spread rate required to sustain the spread of fire from tree to tree through canopies from fire behavior models (Scott and Reinhardt 2001). An exploratory analysis (not described) using the data in this study suggested that this decrease was generally on the order of 10 ft $\text{min}^{-1}$ (3 m $\text{min}^{-1}$), but it varied considerably among stands. Percent changes in CBH from incorporating nonuniform distributions can be of a similar order of magnitude as changes in CBD and occasionally much larger, but the direction and amount of change are difficult to predict for a given stand. Adopting local biomass allometries in FFE-FVS could potentially change the estimates of CBD and CBH as much as adopting nonuniform crown fuel distribution assumptions. However, good estimates of CBD and CBH for southern Rocky Mountain stands require the use of allometric models that are capable of accounting for stand-to-stand variation in the relationship between dbh and crown fuel biomass. It should be noted here that alternative CBD and CBH estimation methodologies that do not rely on tree-level allometries or crown fuel distributions have been developed for even-aged stands (e.g., Alexander and Cruz 2014, Ruiz-González et al. 2015) and are unaffected by the specific issues addressed in this article. However, these approaches do not satisfy the tree-level data needs of physical fire models that are increasingly used to characterize fire behavior in stands with complex structures (Parsons et al. 2011, Pimont et al. 2011).

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