Project Title: Estimating canopy fuels and their impact on potential fire behavior for ponderosa pine in the Black Hills, South Dakota.

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ABSTRACT

We evaluate whether current procedures used in fire behavior prediction models such as FVS-FFE provide predictions of CBD and CBH suitable for evaluating fire behavior in response to fuel treatments. Currently, FFE-FVS uses a geographic non-specific set of tree allometries and assumes a uniform distribution of crown mass when estimating CBH and CBD. We develop allometric equations to predict crown mass specific to ponderosa pine in the Black Hills (*Pinus ponderosa* Dougl. ex Laws.) from a sample of 80 felled trees in 16 forest stands spanning a wide range in tree size and stand. We develop a non-uniform description of vertical crown mass within individual trees using the Weibul distribution. We relate the parameters of the distribution to stand structure, so that a vertical canopy biomass profile can be estimated for any stand from standard inventory information. We modify the existing FVS-FFE program to include our results.

Estimates of CBD increased by an average of 78% when using our local biomass and non-uniform vertical distribution models compared to current procedures in FVS-FFE. On average, 47% of the underprediction of the current procedure compared to our new models resulted from site specific allometries and additional 31% of the under prediction resulted from a non-uniform distribution of crown mass. Our results suggest locally-derived crown mass equations in addition to non-uniform estimates of crown mass distribution should be used to calculate CBH and CBD as used in fire prediction models.

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. Of the 16 stands sampled in this study, only two had CBD estimates >0.100 kg m^{-3} (i.e. the CBD where active crown fire would be expected) as currently implemented in FFE-FVS. When local crown mass equations and distribution models were applied to the data, 12 out of the 16 stands had CBD estimates >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.

BACKGROUND AND PURPOSE

Long-term maintenance of fuels reduction treatments is a primary goal for forest management in the ponderosa pine (*Pinus ponderosa* Laws.) forests of the Black Hills, South Dakota. The Black Hills are dominated by young, dense, even-aged ponderosa pine stands and the prevalence of these stands can result in large, catastrophic wildfires, such as the 34,000 ha Jasper fire of 2000. Many of these stands are in the wildland – urban interface, where reducing the likelihood of crown fire behavior in the event of a wildfire is extremely important. Annually, ~2,300 ha are being treated to reduce the potential for crown fire, primarily by thinning to reduce canopy density. Fire resistant structures created by stand level fuels treatments are not static: canopy density increases with time as trees grow and regeneration is recruited into the overstory canopy. With this increased canopy density, active crown fire behavior again becomes likely. Accurate projections of how canopy density changes with initial treatment and how canopy density increases with time are crucial in determining how, when, and how often fuels treatments are preformed. We propose to develop improved methods for estimating the amount and vertical distribution of canopy fuels from forest inventory data and to integrate these estimators of canopy fuels with models of forest growth and fire behavior (i.e. the Forest Vegetation Simulator (FVS) and the Fire and Fuels Extension (FFE).

Fuels treatments to reduce crown fire behavior in Black Hills ponderosa pine forests are most commonly commercial or precommercial thinning to reduce stand density below 12 m^2/ha (50 ft^2/acre) of basal area. These densities are thought to reduce the amount of canopy fuels below the level that will support crown fire. Stands thinned to these densities will have high basal area growth rates, with rapid development of canopy density. Also, ponderosa pine regeneration will be prolific at these stand densities, and will create ladder fuels and increased canopy density as regeneration grows in height and crown size. Initial treatment effectiveness and longevity of treatment effects are evaluated using estimates of surface fuels and canopy structure in surface and canopy fire behavior models. Two types of crown fire behavior are predicted based on stand structure and weather conditions – passive or active crown fire. Passive crown fire occurs when there is a sufficient density of canopy fuels to spread surface fire vertically from lower to upper canopy reaches at a given wind speed. The height in a canopy where there are sufficient fuels to spread flames vertically is called the canopy base height (CBH). Active crown fire occurs when there is sufficient density of fine fuels (e.g. foliage and small branches) at any height in the canopy to indicate sufficient continuity of canopy fuel to carry fire from tree to tree at a given wind speed. The density (kg/m^3) of needles and small branches used to determine continuity of canopy fuels is called canopy bulk density (CBD).

Estimates of the amount and vertical distribution of canopy fuels are critical to accurate estimates of the threshold wind speed where passive or active crown fire will occur. The primary method by which federal land managers predict CBD is through the use of the growth and yield model, the Fire and Fuels Extension to the Forest Vegetation Simulator (FVS-FFE). While FVS-FFE provides a working prediction of CBD through time, the underlying assumptions and equations used to calculate and predict CBD may not accurately represent CBD or CBH. The equations used by FVS-FFE to predict crown mass for ponderosa pine created by Brown (1978) are based on trees from northern Montana and Idaho. These equations, therefore, may not capture variability in crown mass due to geographic, site, or stand variability. Currently, when calculating CBD, FVS-FFE uses a uniform distribution of foliage and branchwood within individual crowns (eg. crown mass divided by crown length). But, crown mass is not evenly distributed within individual tree crowns – crown mass is distributed as a skewed normal distribution, with less mass at the top and bottom a tree crown and most of the mass concentrated near the center of the crown . We hypothesize that both of these problems may result in the underestimation of CBH and CBD in FVS-FFE and therefore provide inaccurate estimates of potential fire behavior.

There are many potential benefits from this proposed research. First, accurately predicting crown mass is the foremost important step in calculating CBD. If current crown mass equations for ponderosa pine do not adequately describe crown mass in different geographic regions, current predictions of CBD may be inaccurate. By comparing crown mass equations for ponderosa pine in the Black Hills to those calculated by Brown (1978) and used in FVS-FFE, this research will help determine if there is a need for region specific crown mass equations for individual species. Second, by incorporating a correction factor for foliage distribution into CBD calculations, effects of density and canopy position on canopy fuel distribution will be taken into consideration vastly improving the accuracy of CBD predictions. We suggest that the proposed modifications to the current methodology for predicting CBD will greatly improve land managers ability to evaluate initial treatment effectiveness and to plan for maintenance of fuels treatment projects.

1. We develop equations to predict the amount of forest canopy fuels for Black Hills ponderosa pine to be used with standard forest inventory data and that are compatible with fire behavior models such as FVS-FFE. Equations currently used to estimate canopy fuels are based on a small sample size from a specific and limited geographic range. Our results identify whether current techniques produce sufficiently accurate estimates of canopy fuels to provide a realistic analysis of changed fire behavior from fuel treatments.

2. We develop a technique to accurately predict the vertical distribution of fuels within treated canopies and untreated canopies of Black Hills ponderosa pine. The current approach to estimate CBD from tree inventories assumes a uniform distribution of crown mass. This approach may cause an underestimate of canopy bulk density and an inaccurate estimate of canopy base height. Our results identify whether a more accurate technique for vertical distribution of fuels within tree crowns will improve estimates of canopy bulk density.

3. We test the effect of our estimators of canopy fuel and canopy fuel distribution on the determination of canopy bulk density, canopy base height, and potential crown fire behavior in stands treated for fuels reduction in Black Hills ponderosa pine as compared to the current methods of prediction in FVS-FFE. We will provide our results to the Forest Management Service Center as a set of equations and documentation intended for incorporation into the FVS-FFE model.

STUDY DESCRIPTION AND LOCATION

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 (Froiland 1990, Hoffman and Alexander 1987). 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. 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 (Shepperd and Battaglia 2002).

Data collection

We measured tree dimensions and crown biomass on a total of 80 [≥5 cm diameter at breast height (dbh)] ponderosa pine trees located in 16 stands throughout the BHNF to develop estimators of crown biomass and vertical distribution of biomass (Table 1). 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].

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. 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. All sample trees had intact and undamaged, single-stemmed (i.e., not forked) crowns.

Table 1. Stand-level summary statistics.

Stand	Density (trees ha^{-1})	Basal area (m^2 ha^{-1})	QMD (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	3780	47.2	12.6	1171	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	1157	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

Crown class, determined following Oliver and Larson (1996), was recorded on 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, 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) 1000 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, 10), we separated all live and dead branch material by the following four components: (1) foliage + 1 hours fuels (foliated twigs), (2) 10 hours fuels, (3) 100 hour fuels, and (4) 1000 hour fuels. The green weights (kg) of each of the three components in the odd-numbered crown sections and each of the four components in the even-numbered crown sections of each tree were measured in the field using a digital scale (Intercomp, CS200, 125 kg ± 0.05 kg).

Random subsamples of foliated twigs were obtained from each even-numbered crown section and subsamples of 10, 100, and 1000 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 1000 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.

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). Sample trees did not contain any appreciable amount of dead foliage or dead 1 hour fuels; therefore these components were not modeled. Due to problems processing in the field, 2 trees were removed from the analysis, leaving a total a total of 78 trees available for the statistical analyses.

The 2-parameter Weibul model was used to model the vertical distribution of total crown fuel mass (FOL + 1HF) for each tree. The form of the cumulative Weibul distribution used was:

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

where Y = 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 = location within the crown (i.e. section number or relative distance from top of tree). 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 (Crookston and Dixon 2005, version 6.31-revision date 9.19.08, Reinhardt and Crookston 2003) that calculates stand-level canopy fuels profiles as well as estimates of CBD and CBH. Using individual-tree data collected as part of the stand inventory, we used FFE-FVS to compare (a) 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), (b) 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 (c) 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.

KEY FINDINGS

Local biomass estimator

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

$$FOL = 0.0865DBH^{1.8916}LCR^{1.1358}$$

The nonlinear relationship between FOL, DBH, and LCR explained 89% of the variation in the data (Fig. 1). Both DBH and LCR had a positive effect on FOL.

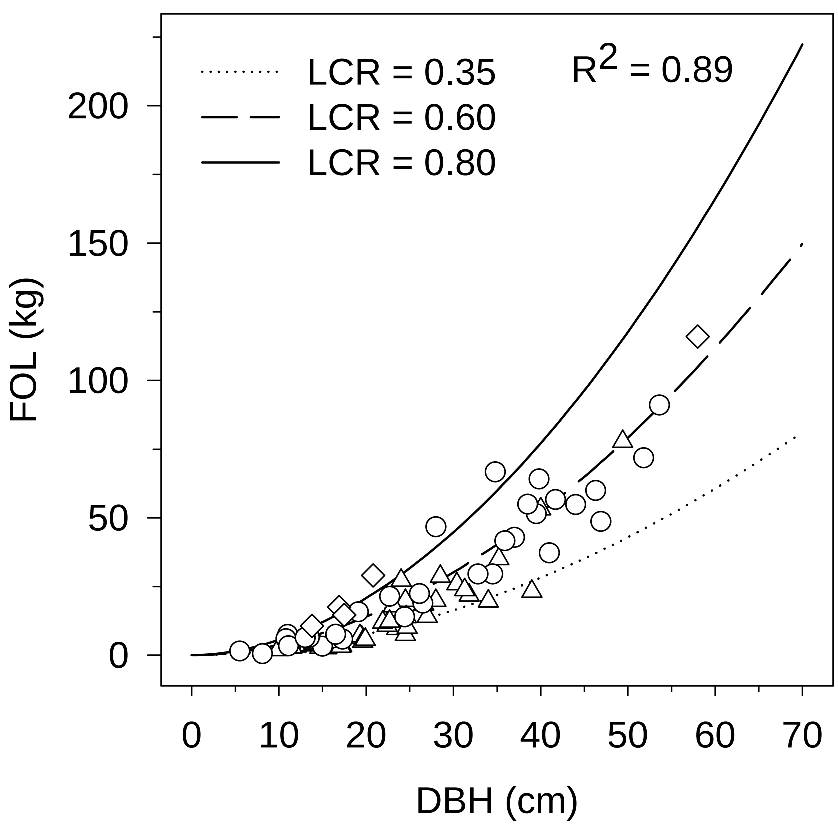

Figure 1. Relation between live foliage mass, DBH, and LCR. Open triangles represent trees whose LCR was between 0.25 and 0.50, open circles represent trees whose LCR was between 0.50 and 0.75, and open diamonds represent trees whose LCR ≥0.75.

Very little 1HF was observed with the 1HF ranging from 0.00 to 0.97 kg. The mass of 1 hour fuels was best predicted by the following equation:

$$1HF = 1.5439LCR^{5.6131}$$

Although DBH was not a significant predictor of 1HF ($P > 0.05$), LCR alone explained 76% of the variation in the data. Our equations predicted substantially greater FOL estimates and slightly lower 1HF estimates than predicted by the equations of Brown (1978) for the trees in our sample. Our equations predicted 23% greater foliage mass for dominant/co-dominant trees and 112% greater foliage mass for intermediate/suppressed trees than predicted by Brown (1978). In contrast, we predicted 90% less 1HF for dominant/co-dominant trees and 94% less 1HF for intermediate/suppressed trees than Brown's (1978) equations.

Non-uniform distribution of crown fuel biomass

Currently, FFE-FVS uses allometric estimates of crown biomass that assume an uniform vertical distribution of crown fuel mass for individual trees to estimate CBH and CBD. We wanted to determine if 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 Weibul 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 eq. [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/co-dominant trees within a given stand causing us not to reject the null hypothesis that there the distribution of crown fuel biomass within a tree crown is different between crown positions.

Next, we wanted to determine if 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. The dependence of the average shape and scale parameter on tree- and/or stand-level attributes 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:

$$M\beta = 7.1386 - 0.0608*MHT \qquad R^2 = 0.51$$

$$M\alpha = 3.3126 - 0.0214(MHT) - 1.1622(RD) \quad R^2 = 0.72$$

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 [5] whereas the combination of average height and RD explained 72% of the variation in the shape parameter [6]. 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;

Comparing currently used procedures for estimating CBD and CBH with locally-derived biomass equations and non-uniform crown fuel distributions in FVS/FFE

We wanted to evaluate whether using local biomass equations to predict crown fuels along with a non-uniform vertical distribution of fuels within individual tree crowns would result in significant changes in CBH and CBD compared to 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: (a) the original FFE-FVS code; (b) the local biomass equation; and (c) the local biomass equations and a non-uniform vertical distribution of biomass based on estimates of Weibul shape and scale parameters 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 (Fig. 2). 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 is in sharp contrast to stands 8 and 14 where RD was 46% and 75% and where 36% and 63% of canopy fuel biomass was located in the upper 50% of the stand, respectively.

Compared to 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 CBD using local biomass equations compared to unmodified, original estimates of CBD averaged 47%, and the increase ranged from 15 to 84% for the 16 stand sampled. Use of the local biomass equations and the Weibul vertical distribution of crown fuel mass model increased CBD by estimates by an additional 31% when compared to using the local biomass equation alone, and the increase varied from 5 to 61%.

Results presented here, in addition to results reported in Reinhardt et al. (2006), suggest that indirect estimates of CBD that incorporate a non-uniform distribution of crown fuel mass should be used when using tree inventory information to estimate CBD. The percent increase in CBD that resulted from incorporating both local biomass equations and the vertical distribution of canopy fuels was positively related to QMD. For example, in stand 13 QMD was 35.5 cm and the increase in CBD was 139%. Compare this to stand 3 where QMD was 12.6 cm and the increase in CBD was only 20%

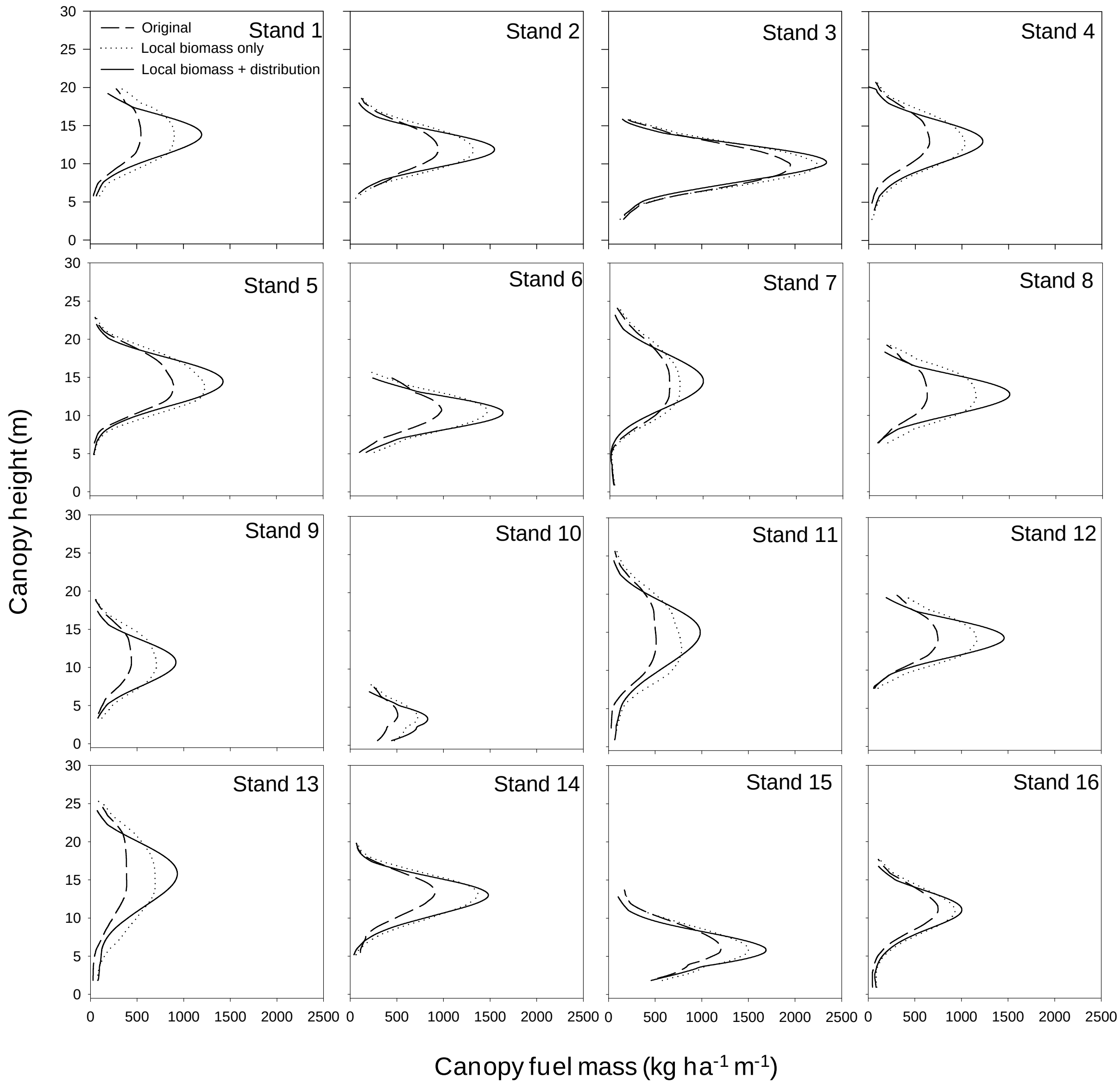

Figure 2. Canopy fuel profiles created from the 4 m running mean of canopy fuel mass (FOL + 0.5 * 1HF) for all 16 stands using the original, local biomass only, and local biomass-distribution FFE-FVS executables. Computation of the 4m running average was initiated when at least 18.4 kg ha^{-1} m^{-1} of canopy fuels were present as outlined in Reinhardt and Crookston (2003).

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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, within a given stand, substantial variability in CBH estimates 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 (eqs [3] and [4]) simply resulted in a greater amount of potential canopy fuel. Second, in the estimation of CBD, when an explicit, non-uniform 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.

MANAGEMENT IMPLICATION S

Importance of local biomass estimators

The most common techniques used to determine canopy fuels use tree allomotries to estimate the amount of biomass in tree crowns based on tree dimensions measured in inventory and/or extrapolated over time in forest growth models. Currently, a set of fuel biomass equations for ponderosa developed by Brown (1978) in Montana and Idaho are used in most fire behavior modeling across the western United States. Our results show that there are substantial differences in estimates of crown mass for Black Hills ponderosa pine trees and forests when using Brown's allometries compared to our locally derived equations. Our equations predicted 23% greater foliage mass estimates for dominant/co-dominant trees and 112% greater foliage mass estimates for intermediate/suppressed trees than predicted by Brown (1978). When we applied these techniques to our 16 sampled stands, our site-specific Black Hills allometries produced CBD estimates averaging 47% greater than those produced by Brown's (1978) allometries from the Inland Empire.

The magnitude of these differences in fuel mass and CBD estimates for Black Hills ponderosa pine are very large, and will have an impact on assessment of fire hazard and potential fire behavior. Here, current procedures for estimating crown mass in fire prediction systems will cause a substantial underestimate of canopy fuel and fire behavior. This should be corrected by applying our local crown biomass estimators in fire behavior prediction systems like FVS-FFE.

Development of a technique for describing non-uniform crown mass distribution

Estimates of CBD and CBH require that that a canopy profile be constructed so that the point of the 'contagion' of the canopy to crown fire can be determined as the point in the canopy that contains the highest density of flammable (e.g. foliage and 1 hr fuels) can be identified. CBD is then used in conjunction with fuel moisture and wind speed to determine if crown fire will occur. Currently, vertical distribution of fuel within a tree is taken as uniform and calculated for each interval of the live crown as crown mass / crown length. We demonstrated that canopy fuel for ponderosa pine is not uniformly distributed through the live crown and , further, that the distribution of crown mass is affected by stand density. We develop a procedure whereby this non-uniform distribution of crown fuel mass can be determined for an individual tree based on its size and the stand density. This procedure uses commonly available tree and stand statistics that are measured in inventory and/or generated by forest growth models such as FVS.

We provide the foundation to incorporate a non-uniform distribution of crown mass in fire behavior modeling systems such as FVS-FFE. As these models were built, the simplified assumption of a uniform distribution was used in the absence of a more accurate alternative. Our system of equations describing the vertical distribution of canopy fuel and its relation with stand structure can be easily incorporated into fire behavior modeling systems that use forest inventory as the basis for estimating canopy fuels.

Impacts of locally-derived biomass equations and non-uniform crown fuel distributions on estimating CBD and CBH in FVS/FFE

We modified the current algorithm in FVS that determines CDB and CBH to use our local biomass and our estimates of non-uniform canopy fuel for individual Black Hills ponderosa pine trees. We then compared the estimates of CBD using our techniques with those currently produced by FVS-FFE (Fig. 3). CBD increased by an average or 47% using locally derived biomass estimators compared to the Brown (1978) biomass equations. CBD increased by an additional 31% when CBD was estimated used our non-uniform canopy fuel distribution models over those currently predicted using FVS-FFE. In total, CDB increased by an average of 78% between the current estimates in FVS-FFE and the combined effects of using local biomass estimators and a non-uniform crown mass distribution.

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. 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 2003). Of the 16 stands sampled in this study, only two 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 out of the 16 stands had CBD estimates above 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.

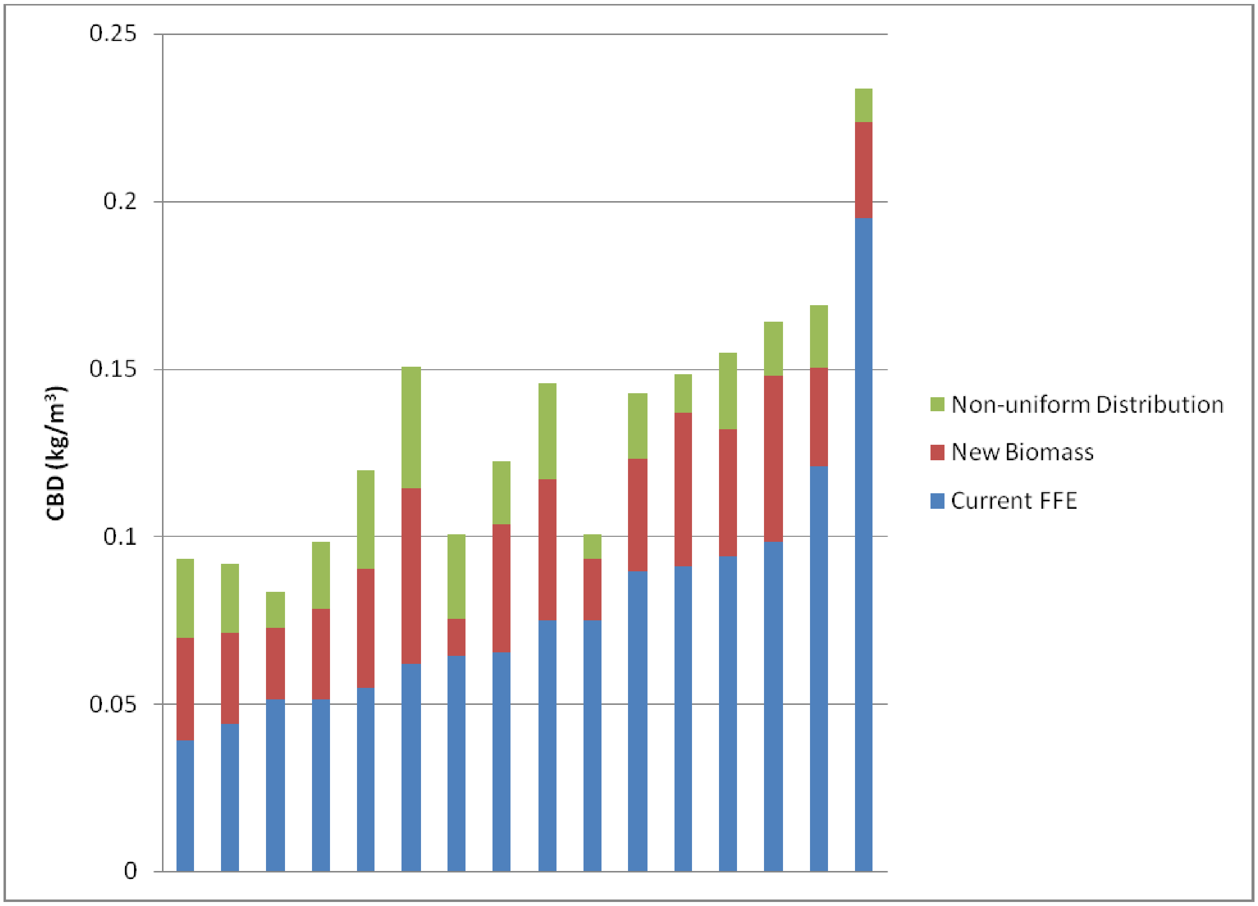

Figure 3. The increase in CBD for 16 ponderosa pine stands in the Black Hills resulting from our local biomass allometries and the non-uniform distribution of crown mass. Crown fire becomes likely where CBD >0.1 kg/m^3.

RELATIONSHIP TO RECENT FINDINGS AND ONGOING WORK

Our work confirms the findings of Reinhardt et al. 2006) and develops procedures for correcting biases in estimates of canopy fuel mass, CBD and DBH inherent in current procedures used in fire modeling systems. 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. 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 when compared to CBD empirically determined by felled tree measurements in five dense stands across the West. Reinhardt et al. (2006) observed upwardly skewed distributions of canopy mass in plots from five dense forest stands of species including ponderosa pine, Douglas-fir and lodgepole pine. They were able to produce vertical canopy profiles using site-adjusted allometric equations and plot-specific non-uniform crown profiles that closely matched empirically observed profiles.

While Reinhardt et al. (2006), suggest that indirect estimates of CBD that incorporate a non-uniform distribution of crown fuel mass should be used when indirectly estimating CBD, they did not develop a systematic procedure that could be incorporated modeling systems. Also, their work covered several geographic areas in the west, but did not have sufficient samples to produce geographically general biomass estimators. While they observe that canopy mass was skewed in dense stands, they did not have a sample suitable to describe a relationship between vertical biomass distribution and stand structure. Our procedures, that use site-specific crown mass equations and a more realistic depiction of the distribution of crown biomass, as suggested by Reinhardt et al. (2006), create a more accurate estimate of the forest canopy fuel structure and alleviate both of these potential biases.

Our results confirm observations that tree allometries for a species can vary by geographic region. 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 pine, Fulé et al. (2001) developed allometric equations specific to northern Arizona that predicted lower foliage and small branch (<0.64 cm) biomass estimates than 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.

Our work is consistent with studies of forest production and structure which document non-uniform canopy biomass distributions and the affect of stand structure on the distribution. 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), while 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 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.

FUTURE WORK NEEDED

Our results clearly identify a need to change the procedures used to estimate canopy biomass, CBD and CBH in fire behavior modeling systems. In the case of Black Hills ponderosa pine forests, biomass estimators commonly used in fire behavior modeling systems result in substantial underestimates of canopy fuels for individual trees, and an underestimate of CBD by an average of 47%. Current procedures that use a uniform distribution of biomass throughout a tree crown result in an additional 31% underestimate of CBD. In sum, using non-local biomass estimators and a uniform crown mass distribution results in an average underestimate of 78% in CBD in FVS-FFE for Black Hills ponderosa pine. Our results are a test case using Black Hills ponderosa pine and they confirm results of Reinhardt et al. (2006) who found discrepancies between empirical measurements of crown mass and CBD and estimates produced by widespread extrapolation of tree allometries. We see 2 critical research needs based on these works: 1) a comprehensive evaluation of the performance of biomass equations used in fire behavior modeling systems for major forest species by geographic region; and 2) development of non-uniform biomass distribution for major tree species and their relation to stand structure by geographic region.

An evaluation of the performance of biomass estimators would require a review of available allometries and subsequent field testing and development, where need was identified. There are many published biomass estimators for species by geographic area. But, there is considerable variability in their formulation and quality. Some measure biomass components that are consistent with fuels measurements (e.g. 1 hr, 10 hr, etc. classes), but many do not. Some use independent variables that are consistent with tree inventories (e.g. DBH, height, etc.) while others use variable not commonly used in inventory (e.g. sapwood area). Further, there is considerable variability in the samples on which these allometries are based, including sample size, geographic extent, range of tree size and range of stand conditions. Any and all of these limit the potential utility of existing estimators for use in canopy fuel estimation systems. However, a systematic review of available estimators would be useful in determining availability of existing alternative to the widely used Brown’s (1978) set of allometries. Further, these could be used to test for consistency with Brown’s estimators. In the case where local allometries are not available or produced substantively different results from Brown’s, additional field work would be warranted to develop local allometries to produce reliable estimates of canopy fuel mass.

Statistical descriptions of the non-uniform vertical distribution or crown fuel mass are needed for major species in geographic areas where fire behavior modeling is important. There are several available studies describing vertical crown biomass distributions for individual trees. These should be evaluated for their potential adaptation to describing the vertical distribution of canopy fuel. Again, most of these studies were conducted for purposes other than modeling canopy biomass for fuels and fire behavior modeling. To be useful, they should describe the distribution of crown mass in terms that are used in fire behavior modeling (e.g. foliage mass and 1 hr fuels). These distributions should have a flexible form and should be able to reflect shifts in biomass in response to changes in stand structure. For species and geographic areas where these models are available, they should be adapted and used to formulate procedures for estimating CBD in models such as FVS-FFE. For important species where suitable models are not available, field work should be undertaken to develop such models.

DELIVERABLES CROSSWALK TABLE

Deliverable	Product
Local biomass equations for Black Hills ponderosa pine	We developed an allometric equation based on measurement 78 large trees from the Black Hills
Protocol for estimating a non uniform distribution of canopy fuels	We developed a statistical description of the non-uniform vertical crown mass distribution of ponderosa pine and a system of parameter recovery models to describe its relation with stand structure
Evaluate the impact of our findings on estimates of canopy fuels	We demonstrate that current procedures underestimate CBD by an average of 78% for Black Hills ponderosa pine. Adoption of our procedures will have a substantial impact on evaluation of fire hazard and on design of fuel treatments to reduce fire hazard.
Publish results	We have a manuscript entitled "INFLUENCE OF CROWN BIOMASS ESTIMATORS AND DISTRIBUTION ON CANOPY FUEL CHARACTERISTICS IN PONDEROSA PINE STANDS OF THE BLACK HILLS" by Tara L. Keyser and Frederick W. Smith currently in review with Forest Science
Work with Forest Management Service Center to incorporate findings into FVS-FFE	We have been in discussion with the FMSC throughout the project and are working with them to get our procedures implemented in FVS-FFE. We are working to have implementation of these procedures included in the 2009-2010 plan of work for the unit. The Black Hills National Forest has requested that this action be a high priority for the unit.
Guide for managers	The guide will occur in 2 steps. First, the Forest Science publication includes a review and description of procedures to estimate canopy fuel. Second, as our procedures are incorporated into FVS-FFE, they will be documented in the supporting material for FFE that are widely available to fire and fuel managers We have modified the existing FVS-FFE computer code to incorporate our procedures. This can readily be incorporated into FVS-FFE or into other applications that use forest inventory to determine canopy fuel amounts.
Dissemination of results to managers in workshops	The results have been communicated to Black Hills fire and fuels managers at the Continuing Education in Fuels Management (CEFM course held in May 2009 in Custer SD. This session was attended by over 25 fire and fuels managers from the Black Hills. Results were communicated to managers in a paper presented at the 2009 National Silviculture Workshop in Boise ID attend by over 100 vegetation managers. The results were disseminated in CEFM courses held in Sacramento CA, Bend OR, and Custer SD to over 120 fire and fuel managers from across the country.

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