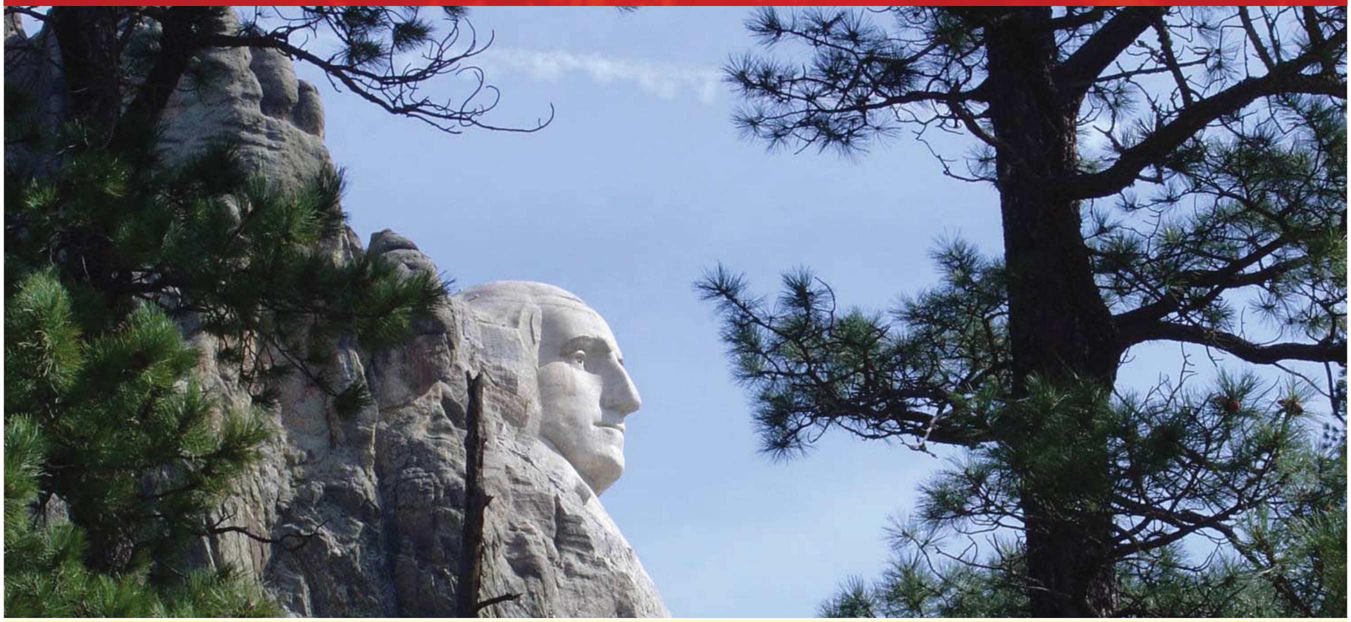
Joint Fire Science Program
Fire Science Brief
RESEARCH SUPPORTING SOUND DECISIONS



Black Hills National Monument in South Dakota.

Modifying the Model to Mitigate Crown Fire: Improving Estimates of Canopy Fuels for the Black Hills (and Beyond)

Summary

Managers of most coniferous forests in the western United States aim to create and maintain forest structures that are less susceptible to the initiation and spread of crown fire. To achieve this end, they use models that predict potential fire behavior, and these models rely on accurate estimates of canopy structure, including canopy base height (CBH) and canopy bulk density (CBD). Managers predict CBD through use of the Fire and Fuels Extension to the Forest Vegetation Simulator (FFE-FVS). However, the equations used by FFE-FVS to predict crown mass are based on estimates solely from northern Montana and Idaho, and therefore likely do not capture the variability in crown mass between different geographic regions. Moreover, an underlying assumption critical to the prediction of CBD in FFE-FVS is that crown biomass is distributed uniformly along the entire length of a tree's crown; however, in actuality, CBD is likely to be low at the top and bottom and highest somewhere in the middle, and the place where CBD is the highest is important because this is the place where crown fire would most likely spread. Thus, the procedure currently implemented in FFE-FVS can underestimate CBD because of (1) use of crown mass equations outside their appropriate geographic range and (2) the assumption of a uniform distribution of crown mass within the live crown. This project focused on ponderosa pine forests in the Black Hills National Forest (BHNF) of South Dakota and tested the effects of modified estimators of canopy fuel and canopy fuel distribution on the determination of canopy bulk density, canopy base height, and potential crown fire behavior as compared to the current methods of prediction in FFE-FVS. The project team developed improved methods—that can be applied throughout the United States—for estimating both the amount and vertical distribution of canopy fuels from forest inventory data that can be integrated into FFE-FVS.

Key Findings

- The relationship between tree diameter and crown mass differs depending on location.
- Fuel within a ponderosa pine tree crown is concentrated below the center of the live crown, and distribution changes with stand density.
- The existing estimator of crown biomass and non-uniform distribution of crown biomass currently used in FFE-FVS *significantly underestimate* canopy bulk density for ponderosa pine stands in the BHNF when compared to results using a local crown biomass estimators and a non-uniform distribution of crown mass.

Accurate measures for effective treatments

Managers of most coniferous forests in the western United States have an overarching common goal: reduce the likelihood of crown fire. To lessen the probability of crown fire, managers aim to create and maintain forest structures that are less susceptible to its initiation and spread. Stand management prescriptions to design such forest structures are typically developed using models that predict potential fire behavior, and the success of these models relies on accurate estimates of canopy structure to predict fire behavior.

But let's back up for a closer look at the ingredients for a crown fire. For a surface fire to become an active crown fire, two conditions must be met: First, there must be sufficient canopy fuel close enough to the forest floor to carry flames vertically from the surface to the main forest canopy. CBH is a measure of proximity of canopy fuels to surface fuels. Second, there must be sufficient proximity between crowns and combustible fuel (needles and small branches) to carry fire from tree crown to tree crown. CBD is a measure of how closely canopy fuels are packed, reflecting the likelihood that fire can move through the forest canopy.

Fuel management treatments to reduce the probability of crown fire frequently involve thinning forests to increase CBH and decrease CBD. Accurate measures of CBH and CBD are critical to producing reliable predictions of fire behavior related to changes in stand structure—and therefore critical to the effectiveness of fuel treatments.

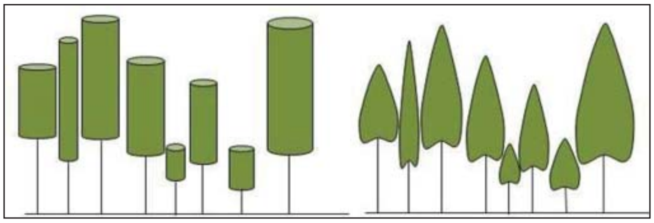
A typical managed ponderosa pine forest in the BHNF.

Rethinking the model

So, crown fire prediction models use CBD as the index by which to determine whether fire will initiate and spread through a forest canopy. For an even-aged forest stand, CBD would likely be low at the top and bottom and highest somewhere in the middle of the canopy. Dr. Frederick "Skip" Smith, lead investigator on the project, explains, "This relates to the biology of the way needles are distributed with height and the way trees grow. Near the top there's just not a lot of structure to hang needles on; as you come down, there are more branches—and bigger branches—so there's structure to support a lot of needles and still a lot of light availability to keep them alive; and then down further, there's still a lot of branch structure, but little available light." The place where canopy bulk density is the highest is of special interest because this is the place where crown fire would most likely spread from tree to tree. This is called "maximum CBD." It's the point of contagion of the canopy to crown fire—the point in the canopy that contains the highest density of flammable matter.

The primary method by which land managers predict CBD and thus fire behavior is through the use of the tree growth model the FFE-FVS, developed by Reinhardt and Crookston. However, the equations used by FFE-FVS to predict crown mass are based on estimates solely from northern Montana and Idaho (founded on data from Brown's, *Weight and Density of Crown of Rocky Mountain Conifers* in 1978). These equations, therefore, likely do not capture the variability in crown mass between different geographic regions. Site differences, including nutrient and water availability as well as temperature within and across geographic regions, can all contribute to local and regional variability in the relationship between tree diameter and crown mass. For example, in 2001, Fulé and others developed equations specific to ponderosa pine in northern Arizona that predicted lower foliage and small branch biomass estimates than Brown's equations for Montana and Idaho. And Reinhardt and others found that Brown's equations miscalculated crown mass for ponderosa pine in five different geographic areas around the western United States. Moreover, an underlying assumption critical to the prediction of CBD in FFE-FVS is that crown biomass is distributed uniformly along the entire length of a tree's crown, resulting in crown shape being modeled as a cylinder. But, as discussed, crown mass is *not* evenly distributed within individual tree crowns—

mass is concentrated near the center of the crown. In short, the procedure currently implemented in FFE-FVS can underestimate CBD because of (1) use of crown mass equations outside their appropriate geographic range and (2) the assumption of a uniform distribution of crown mass within the live crown. And herein lays the crux of the problem: the success of long-term maintenance of fuel reduction treatments to mitigate crown fire potential relies on accurate model estimates of CBD and therefore fire behavior—but the model is currently missing the mark.



Distribution of canopy bulk density assumed by the FFE-FVS model at left versus actual distribution from measured stands on the right.

A Black Hills case study

With funding from the Joint Fire Science Program, the project team focused their study on ponderosa pine (*Pinus ponderosa*) forests in the BHNF, which is 92 percent forested, that encompass 1.3 million acres in southwestern South Dakota. Of that forest land base, 85 percent is populated by ponderosa pine.

BHNF is dominated by young, dense, even-aged ponderosa pine stands, and the prevalence of these stands can result in large, devastating wildfires, such as the 34,000-hectare (84,000-acre) 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 imperative for protecting lives and property. Annually, approximately 2,300 hectares (5,700 acres) are treated to reduce the potential for crown fire, primarily by thinning to reduce canopy density. But fire-resistant forest structures created by stand-level fuel treatments are not static: canopy density increases with time as trees grow and the canopy regenerates, so crown fire behavior again becomes likely.

In current practice, thinning to reduce CBD in BHNF ponderosa pine forests aims to lower stand density below 12 square meters per hectare (50 square feet per acre) of basal area—a size-weighted measure of stand density. These densities (on which initial treatment effectiveness and longevity of treatment effects are based) are evaluated using estimates of surface fuels and canopy structure through FFE-FVS, and have, up until recently, been thought to reduce the amount of canopy fuels below the level that will support crown fire. However, experience has shown that stands thinned to these densities will have high post-treatment basal area growth rates with rapid development of canopy density. Smith explains, "There are two goals you want to achieve through a fuels treatment: you want to lower the threshold below the level that would support wildfire, and you want that effect to persist. If 50 square feet per acre gets you just below the threshold, but a year later you have to treat again, the effectiveness is lost. So these numbers aren't really achieving the long-term goal—especially if you're using a model that underestimates CBD and hence fire hazard." He continues, "Fire and vegetation managers intuitively knew there was a problem, but the science wasn't helping them. There's what the model was telling them, and they were saying 'no, that isn't enough.'"

Jasper Fire in 2000 in BHNF. Credit: Blaine Cook.

And here's where the project comes in. Through a case study of ponderosa pine in BHNF, the research team set out to develop improved methods for estimating both the amount and vertical distribution of canopy fuels from forest inventory data and to integrate these estimators of canopy fuels into FFE-FVS.

A nationwide scope

Of special note is that improvements resulting from the research team's study can be applied outside BHNF, as well. If the crown mass equations for ponderosa pine currently employed in FFE-FVS do not adequately describe crown mass and therefore CBD in BHNF, it's likely that the current equations do not provide accurate estimations in other geographic regions of the country, either. By comparing crown mass equations for ponderosa pine in BHNF to those calculated by Brown and used in FFE-FVS, this research will help determine if there is a need for region-specific crown mass equations for individual species. Further, by incorporating a correction factor for foliage distribution into CBD calculations, the effects of canopy fuel distribution will be taken into consideration, vastly improving the accuracy of CBD predictions and thus land managers' ability to evaluate initial treatment effectiveness and to plan for maintenance of fuels treatment projects—for BHNF and beyond.

Comparing canopies: Current model vs. modified model estimators

The team measured tree dimensions and crown biomass on a total of 80 (≥5 centimeters [2 inches] diameter at breast height) ponderosa pine trees located in 16 stands throughout the BHNF, and the study centered on three main objectives. First, the team would develop FFE-FVS-compatible equations to predict the amount of forest canopy fuels for Black Hills ponderosa pine. Results would identify whether current techniques produce sufficiently accurate estimates of canopy fuels to provide a realistic analysis of changed fire behavior from fuel treatments in the BHNF. Second, they would develop a technique to accurately predict the vertical distribution of fuels within canopies of BHNF ponderosa pine. Results would determine whether a more accurate technique for estimating vertical distribution of fuels within tree crowns will improve estimates of canopy bulk density. Third, the researchers would test the effect of the modified estimators of canopy fuel and canopy fuel distribution on the determination of canopy bulk density, canopy base height, and potential crown fire behavior in BHNF ponderosa pine stands as compared to the current methods of prediction in FFE-FVS. The project team would then present their results to the Forest Management Service Center (the Forest Service entity that maintains FFE-FVS and collaborates on improvements to the model) as a set of equations and documentation intended for incorporation into the FFE-FVS model.

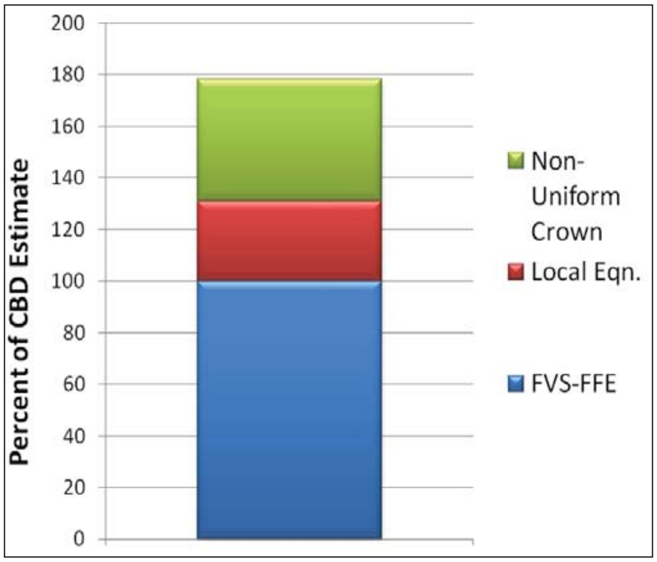
Radical results

First, the team found that the relationship between tree diameter and crown mass did indeed differ depending on location. For example, the amount of burnable fuels for a given ponderosa pine of a certain diameter was different in Montana than in South Dakota. Smith elaborates, “This means there are limits regarding how far you can take these sorts of relationships for widespread tree species like ponderosa pine. They need to be verified and tested in different locations.”

Second, the researchers developed a mathematical equation to describe the non-uniform distribution of needles in a tree crown. But in addition, they found that distribution changes according to stand density: The denser the stand, the more crown mass is shifted toward the top of the tree because of less available light; and conversely, the sparser the stand, the more it’s shifted to the bottom. Smith tells the story: “So, we had to develop an equation that would allow us to describe the general shape crown mass distribution according to geographic location for individual trees, and then we also had to be able to describe how different stand types would affect that distribution in order to accurately estimate maximum CBD.”

Third, the researchers modified the current algorithm in FVS that determines CDB and CBH to use local biomass estimates and estimates of non-uniform canopy fuel distribution for Black Hills ponderosa pine. They then compared the estimates of CBD using these modified techniques with those currently employed in FFE-FVS. Smith reports, “We found that the estimates were drastically different. The existing procedures significantly underestimated CBD and thus fire hazard—with all associated management implications.” Astoundingly, CBD increased by an average of 47 percent using locally derived biomass estimators compared to Brown biomass equations. Moreover, CBD increased by an additional 31 percent when CBD was estimated used non-uniform canopy fuel distribution models. In total, CDB increased by an average of 78 percent between the current estimates in FFE-FVS and the combined effects of using local biomass estimators and a non-uniform crown mass distribution.

The relationship between tree diameter and crown mass differ depending on location.



Canopy bulk density increased by an average of 78 percent between the current estimates in FFE-FVS and the combined effects of using local biomass estimators and a non-uniform crown mass distribution.

Another surprising finding relates to management efforts to increase CBH and reduce CBD below the threshold where crown fire can be initiated and carried through the tree canopy. Current recommendations prescribe that CBD be maintained at values <0.100 kilogram per cubic meter (kg m-3) to lessen the likelihood of crown fire. Of the 16 stands sampled in the study, only two had CBD estimates >0.100 kg m-3 as currently calculated in FFE-FVS. But when local crown mass equations and non-uniform distribution models were applied to the data, *12 out of the 16 stands* had CBD estimates above the 0.100 kg m-3 threshold. (In contrast to the substantial impact the local crown mass equations and vertical distribution model had on CBD, virtually no effect was observed on CBH. This is due, in part, to the low threshold FFE-FVS requires to determine CBH.) For additional technical details, see the final report for Project #06-3-3-13 located at the Joint Fire Science Program's website: http://www.firescience.gov/JFSP_Search_Advanced.cfm.

Beyond the Black Hills

The project results clearly identify a need to change the procedures used to estimate canopy biomass and CBD in FFE-FVS. However, because these results represent a case study focusing on Black Hills ponderosa pine, two critical research needs remain: (1) a comprehensive evaluation of the performance of biomass equations used in FFE-FVS for major forest species by geographic region, and (2) the development of non-uniform biomass distribution models for major tree species and their relation to stand structure by geographic region.

First, many published biomass estimators for species by geographic area exist. However, there is considerable variability in their formulation and quality, limiting the potential utility of existing estimators for use in FFE-FVS. Nonetheless, a systematic review of existing estimators would be useful in determining the availability of alternatives to the widely used Brown's set. In the case where local equations are not available or produce substantively different results from Brown's, additional field work would be warranted to develop local equations to produce reliable estimates of canopy fuel mass.

Second, 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, and these should be evaluated for their potential adaptation to describing the vertical distribution of canopy fuel. These distributions 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 FFE-FVS. For important species where suitable models are not available, field work should be undertaken to develop such models.

So, managers, stay tuned. Yes, the model is flawed. But the fix is in the works and coming soon to a forest near you.

Management Implications

- FFE-FVS, as presently formulated, would misdiagnose crown fire hazard in a substantial number of Black Hills ponderosa pine stands. Further, where FFE-FVS is used to design and evaluate fuel treatments, it is probable that either the amount of density reduction necessary to achieve a desired effect will be underestimated, and/or the longevity of effectiveness of a given treatment will be overestimated.
- Managers on the BHNF can currently use the updated model that incorporates the new local biomass and non-uniform distribution estimators for much more accurate predictions of CBD and thus fire behavior.
- This project represents a case study conducted on the BHNF, but the findings can be extrapolated to other parts of the United States.
- Managers need to be aware that (1) FFE-FVS is currently not estimating CBD and thus fire behavior accurately and (2) the model is being improved to more accurately estimate CBD and potential fire behavior.

Further Information: Publications and Web Resources

Keyser, Tara and Frederick W. Smith. 2010. Influence of crown biomass estimators and distribution on canopy fuel characteristics in ponderosa pine stands of the Black Hills. *Forest Science 56*(2):156-165.

Scientist Profile

Dr. Skip Smith is Professor of Silviculture and Forest Ecology in the Department of Forest, Rangeland and Watershed Stewardship at Colorado State University. His research interests include improving canopy fuel estimation techniques and enhancing the effectiveness and longevity of fuel treatments through silvicultural techniques.

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Results presented in JFSP Final Reports may not have been peer-reviewed and should be interpreted as tentative until published in a peer-reviewed source.

The information in this Brief is written from JFSP Project Number 06-3-3-13, which is available at www.firescience.gov.

An Interagency Research, Development, and Applications Partnership

JFSP *Fire Science Brief*
is published monthly.
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