A Managers Guide to Canopy Fuels

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What are canopy fuels?

Coniferous forests of the western United States are frequently managed to create and maintain structures that are less susceptible to the initiation and spread of crown fire. Stand management prescriptions to design such forest structures are typically developed using models (e.g. FFE-FVS, NEXUS) that estimate potential fire behavior under severe burning conditions associated with catastrophic wildfires. Burning conditions are specified in terms of fuel moisture content, wind speed and temperature. These models rely on descriptions of surface fuels and canopy structure to estimate potential fire behavior. For a surface fire to become an active crown fire in a mature forest stand, two conditions must be met. There must be sufficient canopy fuel close enough to the forest floor to carry flames vertically from the surface to the main forest canopy. Canopy base height (CBH) is a measure of proximity of canopy fuels to surface fuels. In addition, there must be sufficient proximity between crowns and combustible fuel (e.g., needles and small branches) to carry fire from tree crown to tree crown. Canopy bulk density (CBD) is a measure of how closely canopy fuels are packed, which reflects the likelihood that fire can move through the forest canopy. Fuel management treatments to reduce the likelihood of crown fire frequently involve thinning forests to increase CBH and decrease CBD. Measures of CBH and CBD are critical to producing reliable estimates of fire behavior as related to changes in stand structure, and therefore effectiveness of fuels treatment. In this guide, we describe how canopy fuels are measured and how these measurements are translated into the information that fire behavior models need.

Why are canopy fuels hard to measure?

We generally want to know the same things about canopy fuel that we want to know about surface fuel – how much is there, what is the breakdown by fuel size class (e.g. 1h, 10 hr, etc.) and what type of fire behavior will it support. But canopy fuels are much more difficult to measure and characterize in ways that give us insight into likely fire behavior. First, canopy fuels are inaccessible for direct measurement – they are up in the air and we can't physically reach them for direct measurement. Direct measurement would require felling all the trees in a stand and then measuring them all as they lay on the ground, a process that is not practical. Second, canopy fuels have a complex 3-dimensional spatial distribution. Surface fuels are close to 2-dimensional, lying on or within a limited distance from the ground surface. But, canopy fuels are distributed over several feet to 10's of feet in depth. So, we can measure surface fuels with direct sampling such as Brown's transects or photoseries. We can't do this with canopy fuels, and have to rely on more complicated procedures of indirect measurement.

How do we measure how much fuel is in a forest canopy?

Because it is impractical to directly measure canopy fuel, we estimate it indirectly. The most common approach is to estimate how much a tree crown weighs and how much is in different fuel size classes, and then add up the weights for all the trees in an acre of a forest stand. There are several reasons why this approach is the standard. Foresters collect inventory information for forest stands that is based on collecting information for individual trees including DBH and height and how many trees of different sizes are in a forest stand. This sort of information is easy to collect, is widely available and is used in forest growth models like the Forest Vegetation Simulator (FVS). Then, we can estimate the weight of tree crowns as a whole and by size class using relations between crown weight and simple measures of tree size, like DBH and height. This is the same sort of procedure that foresters use to estimate tree volumes. The weights of the individual tree crowns can be added together for an average acre of a forest stand to estimate the amount of canopy fuel.

It is important to know the total mass of a tree crown and the mass of different fuel size classes. Figure 1 shows a top of a ponderosa pine tree cut at a diameter of 4 inches. For a top like this, the oven dry weight is 74 lbs, with 19 lbs in foliage and 1 hr fuel, 18 lbs in 10 hr, 21 lbs in 100 hr and 16 lbs in 1000 hr fuels. In a crown fire, only the needles and a portion of the 1 hr fuels would be likely to ignite. But, in a prescribed fire that would follow a harvest or fuel treatment, the amount of 10, 100 and 1000 hr fuels would also be important.

Figure 1. A ponderosa pine tree crown with a base diameter of 4 inches broken into fuel size classes. The crown is separated into foliage, 10 hr, 100 hr and 1000 hr fuels.

After sampling many trees, a relationship between tree dimensions and crown fuel mass can be developed (Figure 2). This relationship is used to estimate individual tree crown fuel mass from inventoried tree dimensions like DBH, tree height and live crown ratio.

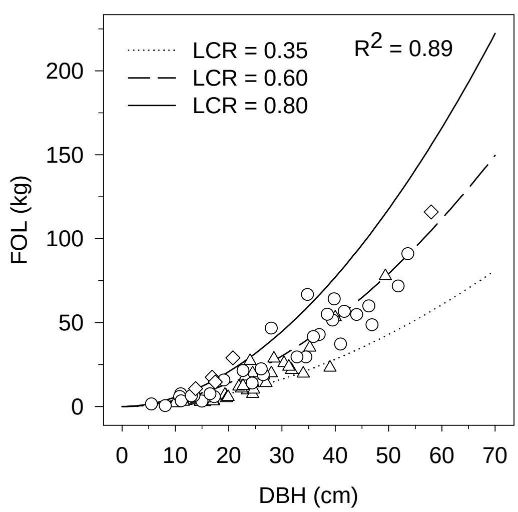

Figure 2. A relationship to estimate foliage mass for Black Hills ponderosa pine trees from tree DBH and tree live crown ratio

For a forestry inventory, the crown weights for all the trees in a stand can be added together to give an estimate of canopy fuel in units like tons per acre.

This process is easy in theory, but can be difficult in practice. The statistical relations between tree crown mass are built from labor intensive, time consuming felled tree sampling, where trees must be carefully dissected and the pieces weighed. It takes lots of trees of different sizes to adequately describe this relation for a tree species. And, trees of the same species grow differently in different geographic areas. So, an equation that is developed from ponderosa pine trees in Montana probably won't do a very good job when applied to ponderosa pine trees in Arizona. Work is underway to determine how far equations for particular species can be extended, and fill in the gaps that currently exist.

How do we determine canopy fuel measurements that are used to predict fire behavior?

Total weight is not used to in models that predict crown fire behavior. Rather, indices of overall canopy fuel characteristics are needed. In effect, we take a 3-dimensional forest canopy and evaluate whether there is sufficient quantity and proximity of fuel in tree crowns to initiate and carry crown fire through a forest canopy at a given fuel moisture content and windspeed. Specifically, crown fire prediction models use canopy bulk density (CBD) as the index of canopy fuel characteristics to determine whether fire will initiate and spread either vertically (i.e. torching) or horizontally (i.e. active crown fire) through a forest canopy. Canopy bulk density is based on fuels that are likely to ignite and be consumed in crown fire and are taken include foliage and 50% of 1 hr fuels. Then, for the canopy as a whole or for a portion of the canopy based on height, CBD is calculated by dividing the amount of fuel per unit area by the height of the canopy profile of interest. Units are lbs per cubic foot or kg per cubic meter.

To picture this process, think of starting at the very top of a forest canopy and collecting all of the foliage in the highest 1 foot of the canopy and weighing it. CBD for this segment would be determined by dividing this weight by the area of an acre (43,560 ft^2) to find the average fuel weight per cubic foot of the acre. This process could be repeated, foot by foot, going down the canopy. When done, we would know the CBD for each foot interval of the forest canopy. For and even-aged forest stand, it CBD would likely be low at the top and bottom, and highest somewhere in the middle. The place where canopy bulk density was the highest would be of special interest, because this would be the place where crown fire would most likely spread from tree to tree. This maximum CBD, sometimes called effective CBD, is used to determine the wind speed at which active crown fire would occur at a given fuel moisture content and slope. The threshold windspeed for crown fire initiation is the Crowning Index (CI). Effective CBD is higher in dense forest stands than in sparse stands, and we can lower effective CBD by reducing tree density in forest thinning.

The CBD near the ground is another point of special interest. This is the way that fire behavior models characterize ladder fuels. If CBD close to the surface is high enough to indicate that fuel will ignite and carry ignition from low in the canopy to higher levels of the canopy, torching or passive crown fire is predicted. The wind speed at which passive crown fire occurs is called Torching Index (TI). In terms of fire behavior, canopy base height (CBH) is defined as the height closest to the ground surface where there is sufficient CBD to transport fire vertically through the canopy. A CBD of 0.011kg/m^3 or above is often used as the threshold.

FFE-FVS is one of the most widely used models that estimates CBD from tree measurements and then uses this estimate to predict fire behavior. FFE uses a computational process to implement the general procedure described above. Once crown mass has been determined for all inventoried trees within the stand, models like FVS-FFE calculates what Scott and Reinhardt (2001) refer to as "effective" CBD. Effective CBD is the maximum ~4 m (13 ft) running average of CBD for layers 0.3 m (1 ft) thick (Reinhardt and Crookston 2003). An underlying assumption critical to the prediction of CBD in FFE-FVS is that crown biomass (foliage and fine branchwood) is equally distributed along the entire length of a tree's crown resulting in crown shape being modeled as a cylinder (Fig. 3). Here, the crown mass of a tree is divided by the length of the live crown, and this constant amount is set in each 1-foot segment of the trees crown.

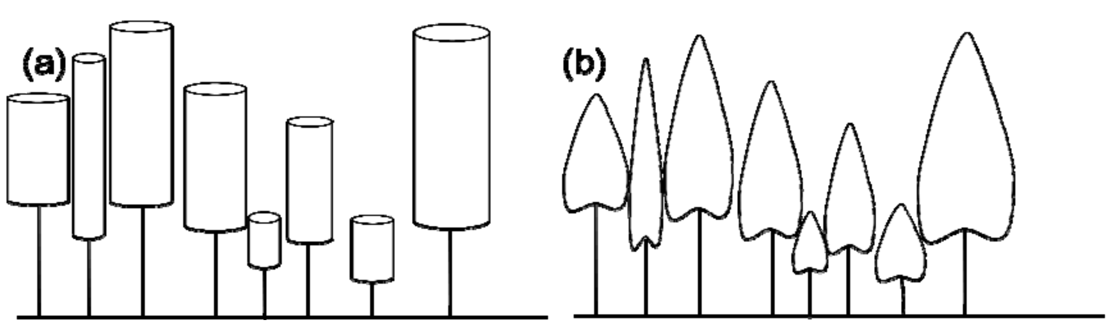

Figure 3. A representation of the uniform distribution of crown mass (a) currently used by FFE-FVS compared to a non-uniform distribution of crown mass (b).

FFE-FVS creates a profile of the canopy fuel stratum (i.e. crown biomass) within a stand. The model then calculates the CBD using the weight of foliage plus 0.5 times the 1 hr fuel branchwood (0-0.25 inch) in diameter within each 0.3 m section of the individual crowns (Reinhardt and Crookston 2003). A 4 m running average of the CBD within those 0.3 m sections is then calculated (Fig. 4). The final CBD of the stand is the maximum CBD of those 4 m running averages. The prediction of CBH is based off of CBD. In FFE-FFE, CBH is simply the minimum height where CBD is greater than or equal to 0.011 kg/m^3 (Reinhardt and Crookston 2003). Due to the relationship between CBD and CBH in FVS-FFE and the influence CBH has on the initiation of crown fire, it is imperative to the success and long-term maintenance of fuels reduction treatments that model predictions of CBD are an accurate estimate of actual CBD.

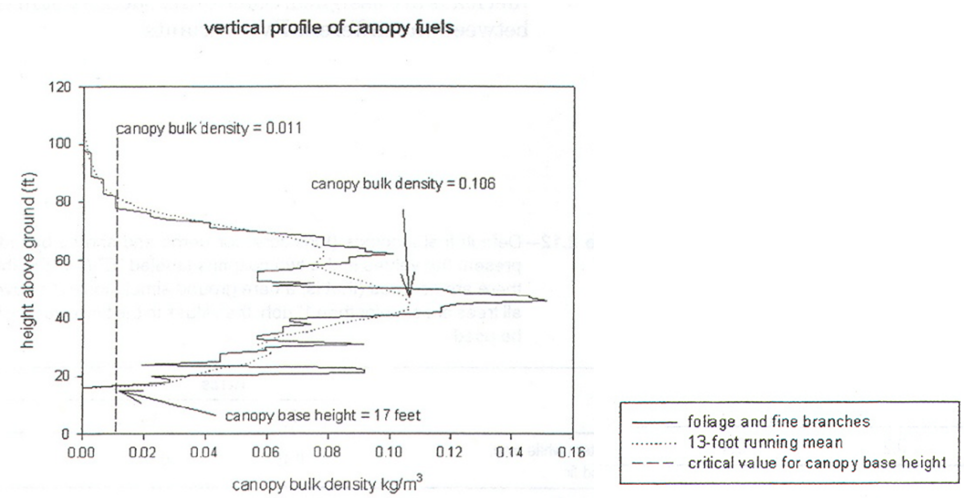

Figure 4. Vertical distribution of canopy fuels taken from Reinhardt and Crookston (2003). Canopy bulk density if the maximum ~4 m running average of canopy layers 0.3 m deep whereas canopy base height is defines as the point at which CBD is greater than 0.011 kg/m^3.

Recent work (Keyser and Smith 2009) has shown that this procedure can underestimate CBD because of: 1) the assumption of a uniform distribution of crown mass within the live crown;

and 2) use of crown mass equations outside their appropriate geographic range. Work is underway to correct these problems.

For More Information

There are several key references that describe the role of canopy fuels in fire behavior and fire behavior modeling and the techniques used to measure and quantify canopy fuels. We have used these references extensively in developing this guide. We highly recommend reading these references to develop a full understanding of the role canopy fuels in fire behavior prediction and the techniques used to measure them.

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Joint Fire Science Program