Estimating Canopy Fuels in Conifer Forests

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Crown fires occur in a variety of coniferous forest types (Agee 1993), including some that are not historically prone to crown fire, such as ponderosa pine (Mutch and others 1993). The head fire spread rate of a crown fire is usually several times faster than that of a surface fire burning under the same conditions, which leads to a significant increase in the number of acres burned during a given period. In addition, crown fires cause more severe and lasting damage than do surface fires. Consequently, predicting the behavior and effects of crown fire, determining the susceptibility of stands to crown fire, and designing treatments to mitigate the potential damage from crown fires are priorities for fire managers.

> Because the effects of crown fires are longer lasting and more severe than surface fires, learning more about crown fires is a priority for fire managers.

Systems and Models

Researchers have developed models of crown fire transition (Alexander 1998; Gomes da Cruz 1999; Van Wagner 1977) and crown fire spread (Albini 1996; Gomes da Cruz 1999; Grishin 1997; Rothermel 1991). Some of these models have been incorporated into computer systems to assess either surface and crown fire potential (NEXUS [Scott 1999]; FFE–FVS [Beukema and others 1997]) or surface and crown fire growth (FARSITE [Finney 1998]).

Both the computer systems and the models need a quantitative description of the canopy fuels; specifically, canopy bulk density (CBD) and canopy base height (CBH). CBD, usually expressed in kilograms per cubic meter, is the dry weight of the available canopy fuel per unit of canopy volume, including the spaces between the tree crowns. CBH is the lowest height above the ground at which there is enough available canopy fuel to propagate fire vertically into the canopy.

Available canopy fuel is the part that can burn in the flaming front of a crown fire. The foliage and some branch wood, which is less than 0.25 inches (0.6 cm) in length, are usually considered available canopy fuel. Larger fuel pieces in the canopy do not burn quickly enough to contribute to crown fire spread. CBD ranges from zero, where there is no canopy, to about 0.4 kg/m^3 in very dense stands.

Existing Methods

Currently, canopy fuel is estimated using instrument-based, inventory-based, and heuristic techniques. Instrument-based techniques use ground-based passive optical sensors to estimate the Leaf Area Index (LAI), which is the amount of foliage surface area per unit of ground area. LAI is used with estimates of specific leaf area and canopy depth to estimate CBD.

Inventory-based techniques use individual-tree allometric equations, which relate tree size to crown biomass, to predict the available canopy fuel loads for every tree in a stand. Available canopy fuel load divided by canopy depth yields CBD. A variation of this technique is to generate a vertical fuel profile of the stand. CBD is then computed as the maximum 15-foot (5-m) running mean predicted for each stand (Scott and Reinhardt 2001).

Heuristic methods rely on expert opinion to estimate CBD. For the Selway–Bitterroot Wilderness, tables of CBD by cover type and density class were developed using expert opinion, without quantitative measurements (Keane and others 1998).

None of the above methods have been tested against direct measurement (collecting and weighing the fuel), so we do not know if their estimates are reliable. Additionally, no previous studies have directly sampled CBD to provide ground-truth data to test the indirect methods.

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Canopy Fuel Project

The Joint Fire Sciences Program provided funding to the USDA Forest Service's Missoula Fire Sciences Laboratory to investigate the indirect methods of estimating canopy fuels by comparing them with the results of direct measurements. The primary study objective was to compare the results from the indirect methods against real data. Other objectives were to:

- Document the vertical, horizontal, and size-class distribution of canopy fuels for one stand in each of five forest types;
- Document the effects of progressive levels of tree removal on canopy fuels;
- Develop a preliminary canopy fuel photo guide; and
- Calibrate and compare several optical canopy sensors.

We chose study sites that are prone to crown fire in five major forest types. Although these sites provided a series of examples and a basis for future, more extensive work, they did not document the range of conditions within each type. The need to directly sample an area up to 2 acres (0.8 ha) in size prevented us from using sites in national parks or wilderness areas. Additionally, we chose only sites approved for tree removal or that could be exempted from environmental analysis. Four of the five sites that we used were on National Forest System land (table 1); one of these was in an experimental forest. The fifth site was in a State-owned university research forest. We sampled only one plot on each site.

We used two fixed-radius plot sizes: a 49-foot (15-m) radius for plots with low stem density and a 33-foot (10-m) radius for plots with higher stem density. We conducted a standard inventory of each plot, recording the species, diameter at breast height, tree height, crown base height, live crown ratio, tree health, and crown class for all trees taller than 4.5 feet (1.4 m). Smaller trees were tallied by species and height class on four subplots. After sampling, we collected a cross-section from the stump to determine tree age and we mapped the location of every tree. We measured surface fuels using eight planar-intercept fuel transects (Brown and others 1982) at each plot.

We computed basal area for each tree, sorted the trees by diameter, and assigned each tree to one of four treatments, which contained 25 percent of the initial basal area. In the first treatment, we sampled the smallest trees until reaching 75 percent of the initial basal area. In the second treatment, we sampled the next smallest trees up to 50 percent of the initial basal area, and so on. We remeasured canopy fuels with optical sensors and took photographs after each treatment. By sampling in stages, we crudely mimicked progressive intensities of low thinning and obtained more canopy conditions. Our treatment samples did not represent the canopy fuels of a stand with a naturally occurring basal area equal to a quarter of the sample stand. At each level of the treatment, we thinned a donut-shaped area surrounding the plot so that the trees outside the plot would not bias the optical sensors.

Table 1—*Location and characteristics of the canopy fuel study sites.*

Forest type	Location	Slope (percent)	Aspect	Elevation (feet [m])
Ponderosa pine/ Douglas-fir	Lolo National Forest, MT	6	NNE	3,450 (1,050)
Douglas-fir	Salmon-Challis National Forest, ID	25	SE	7,500 (2,300)
Climax ponderosa pine	Coconino National Forest, AZ	11	S	7,575 (2,308)
Sierra Nevada mixed conifer	Blodgett Forest Research Station, CA	7	NNE	4,250 (1,300)
Lodgepole pine	Tenderfoot Experimental Forest, Lewis and Clark National Forest, MT	7	NE	7,520 (2,290)

Measurements

We measured canopy characteristics using several instruments—Licor LAI 2000, Accupar Ceptometer, Nikon Hemiview digital camera, and CID Plant Canopy Imager.* We also estimated canopy cover with a concave mirror optometer (spherical densiometer) and a GRS densiometer. A GRS densiometer indicates whether a point is beneath the tree crown. The fraction of points along a transect (or in a grid) covered by the tree crowns equals the amount of canopy cover. Lastly, we photographed the stands using vertically oriented 35-mm color slides, with 28-mm and 50-mm lenses.

We used direct measurement to determine the spatial and size class distribution of the canopy fuel at each plot. For small trees up to about 16 feet (5 m) tall, we sampled each tree as a whole, recording the number of live branches, crown diameters, weight of live branches, and weight of dead branches for each meter in height above the ground. On about 10 percent of the small trees, we separately sorted the live and dead branches into size classes and components (table 2). We collected samples to determine the moisture content of live and dead fuels by size class. We used the moisture content data to correct the field weights to oven-dry weights for reporting and the size class proportions from the sorted trees to estimate the proportions on the remaining trees.

For large trees, we measured individual branches and will summarize to estimate the tree and stand biomass. We measured the diameter, length, width, foliated ratio, and field weight of every live branch greater than 0.4 inches (1 cm) in diameter within each meter in height. We noted the average vertical angle of branches for each meter and sorted a subsample of branches (7–10 percent, depending on the species) into size classes and components (fig. 1). We also recorded the weight of all sizes of dead branches and small live branches that were less than 0.4 inches (1 cm) and sorted a sample of dead and small live branches into size class and component.

Table 2—*Size classes and components for sorting branch biomass.*

Component/class		Live	Dead
Foliage		X	–
Lichen		X	–
Cones		X	
Branchwood diameter class (mm)	0–3*	X	X
	3–6	X	X
	6–10	X	X
	10–25	X	X
	25–50	X	X
	50–75	X	X
	75+	X	X

*Finer than the finest size class used in most previous studies.

Because it was important that branches were intact before measurement, we used special rigging equipment to lower trees that were up to about 40 feet (12 m) tall. We could not safely lower the larger trees, so we used spurs to climb the bole, cutting branches along the way. Ground crews tended the climber, measuring and weighing branches as they came off the tree (fig. 2). The climber topped the tree where the bole diameter reached about 4 inches (10 cm) (fig. 3). The top branches sustained little damage even when they were dropped from more than 110 feet (34 m).

Initial Results

On all five study sites, we sampled about 300 main canopy trees and 300 under- and middle-story trees. Our data include gross weight, size, and *x*-, *y*-, *z*-coordinates for all branches within the study plots—a total of about 12,000 branches weighing 14 tons (13,000 kg). We sorted more than 900 branches into size classes. Five conifer species were present at the study sites: ponderosa pine, Douglas-fir, lodgepole pine, incense cedar, and white fir. We measured a very small amount of subalpine fir at the lodgepole pine site.

The study sites varied in initial density and tree size (table 3). The main canopy in all stands was even aged. The ponderosa pine/Douglas-fir and Sierra Nevada mixed conifer stands had younger age classes of Douglas-fir or white fir in the understory, as reflected in their estimated vertical fuel profiles. The

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Figure 1—*A lodgepole pine sample branch before (above) and after (below) being sorted into size classes. Photo: Joe Scott, Systems for Environmental Management, Missoula, MT, 2001.*

stands without an understory—lodgepole pine, ponderosa pine, and Douglas-fir—had bell-shaped vertical distributions of available canopy fuels. The stands with an understory—Sierra Nevada mixed conifer and ponderosa pine/Douglas-fir—had canopy fuel under the main canopy (fig. 4).

Based on allometric equations, the highest available canopy fuel load was in the ponderosa pine stand, while the lowest load was in the ponderosa pine/Douglas-fir stand (table 4). Similar to the available canopy load, CBD was highest in the ponderosa pine stand and lowest in the ponderosa pine/Douglas-fir stand. The Sierra Nevada mixed conifer stand had the second highest load but had the second lowest bulk density because the fuel was distributed throughout a deep canopy. In all stands, the maximum 1-foot (0.3-m) CBD was only slightly higher than the maximum 15-foot (5-m) running mean.

We completed fieldwork during the summers of 2000 and 2001. Data entry and analysis are underway, and the results should be available soon.

Discussion and Conclusion

Allometric estimates of canopy fuels reveal interesting relationships among the stands. The ponderosa pine stand had the highest canopy fuel load and the highest bulk density; several possible explanations exist. We located the plot in the highest density portion of a high-density stand—the basal area was 50 percent higher in this stand than the next highest basal area. This plot does not characterize the ponderosa pine forest type. The high density implies that we should expect high canopy fuel estimates. However, because the trees grow at such a high density, the allometric equations might overestimate individual-tree biomass.

Using developed allometric relationship for dominant and codominant trees, we made assumptions about the biomass of subdominant trees. In stands that are dense, the biomass of dominant trees might be overpredicted by relationships derived from trees of similar size from less dense stands. Our direct measurements will shed light on whether canopy fuels are really that high in this stand, or if the allometric equations were overestimated.

Quantitative estimates of canopy fuels are needed to predict crown fire occurrence and behavior effectively, and to assess and mitigate crown fire hazard. The canopy fuel study is testing several indirect methods by comparing them with direct measurement. This paper reports the initial results that were based on allometric methods. We will report the comparison with direct measurement when all the data are available.

For more information, visit the canopy fuels project Website at <www.firelab.org>. Links to canopy fuels project publications will be posted as available.

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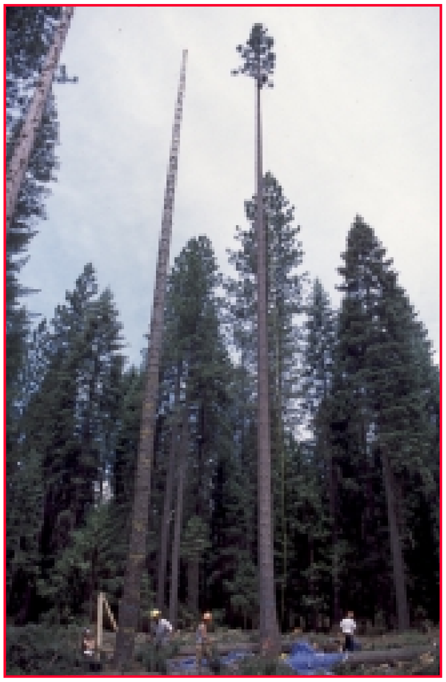

Figure 2—*The ground crew measured and weighed branches sent down by the climber, who used a self-rewinding tape to measure branch height. Photo: Joe Scott, Systems for Environmental Management, Missoula, MT, 2001.*

Figure 3—*After cutting all the branches on the way up, the climber made a topping cut at about 4 inches (10 cm) in diameter. Even when dropped from more than 110 feet (34 m), there was very little damage to the top branches. Photo: Joe Scott, Systems for Environmental Management, Missoula, MT, 2001.*

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Table 3—*Stand characteristics of the canopy fuel study site plots.*

		Basal area		*Quadratic mean diameter*		*Density of trees >10 cm (4 in)*		*Stand height*	
Forest type	*Species*	*m^2/ha*	*ft^2/ac*	*cm*	*in*	*#/ha*	*#/ac*	*m*	*ft*
Ponderosa pine/ Douglas-fir	Ponderosa pine	22.7	98.7	24.5	9.6	240.3	97.3	22	72
	Douglas-fir	7.8	33.9	6.5	2.6	240.3	97.3		
	Total	30.5	132.6	–	–	480.7	194.6		
Douglas-fir	Douglas-fir	29.2	127.2	15.3	6.0	859.1	347.8	17	56
	Lodgepole pine	8.5	36.9	15.0	5.9	350.0	141.7		
	Total	37.7	164.1	–	–	1,209.1	489.5		
Ponderosa pine	Ponderosa pine	69	300	18.8	7.4	2,067.4	837	15	49
	Total	69	300	–	–	2,067.4	837		
Sierra Nevada mixed conifer	White fir	22.8	99.1	33.7	13.3	169.7	68.7	34	112
	Incense cedar	14.7	64.2	28.3	11.1	113.1	45.8		
	Ponderosa pine	8.9	38.6	63.1	24.8	28.2	11.4		
	Douglas-fir	0.4	1.7	19.0	7.5	14.1	5.7		
	Total	46.8	203.6	–	–	325.1	131.6		
Lodgepole pine	Lodgepold pine	42.7	185.8	15.5	6.1	1,145.3	463.7	19	64
	Subalpine fir	0.009	0.04	2.0	0.8	0	0		
	Total	42.7	185.8	–	–	1,145.3	463.7		

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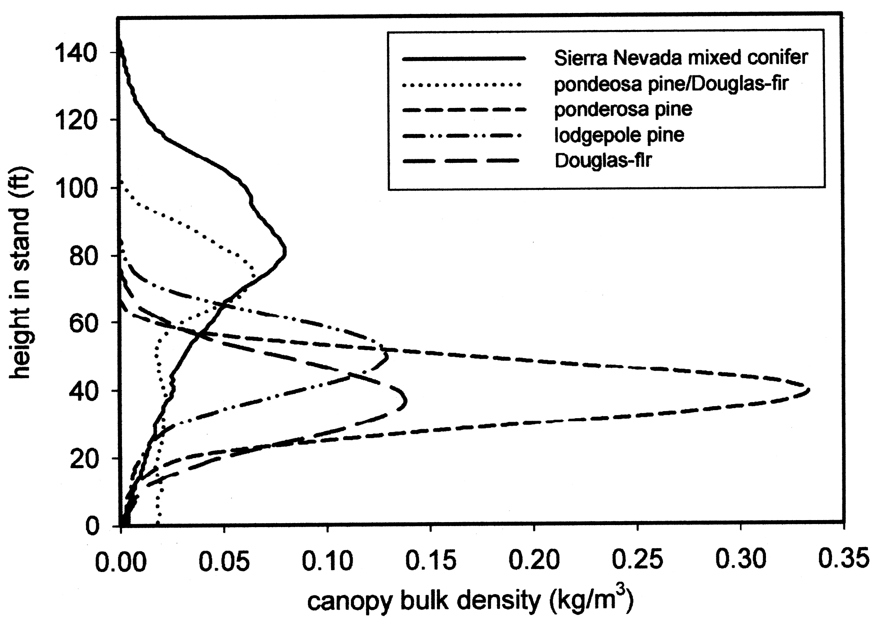

Figure 4—*Estimates of the vertical profiles of canopy bulk density in 1-foot (0.3-m) layers for each sample stand. Curves for each site represent a 15-foot (5-m) running mean. These estimates are summarized from allometric equations for individual trees, not from direct measurement. When available, direct measurements will be used to validate the accuracy of the estimates. The ponderosa pine site was in a very dense portion of a dense stand; available allometric equations probably overestimate its canopy biomass.*

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Table 4—*Initial canopy fuel load and bulk density estimates. The estimates of canopy fuel load and canopy bulk density were made using existing allometric equations for individual-tree biomass, not with the direct measurements made during this study.*

	Available canopy fuel load		***Canopy bulk density (CBD)****		***Maximum 0.3-m (1-ft) CBD***		***Height of maximum CBD***	
Forest type	***kg/m²***	***t/ac***	***kg/m³***	***lb/ft³***	***kg/m³***	***lb/ft³***	***m***	***ft***
Ponderosa pine/Douglas-fir	0.859	3.83	0.065	0.00406	0.082	0.00512	23	75
Douglas-fir	1.255	5.60	0.138	0.00862	0.153	0.00955	11	36
Ponderosa pine	2.241	10.0	0.333	0.02079	0.400	0.02497	12	39
Sierra Nevada mixed conifer	1.379	6.15	0.080	0.00499	0.085	0.00531	25	82
Lodgepole pine	1.255	5.60	0.129	0.00805	0.136	0.00849	15	49

*The maximum 15-foot (5-m) vertical running mean predicted for each stand.