Canopy Fuel Treatment Standards for the Wildland-Urban Interface

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Abstract—*This paper describes a canopy fuel treatment standard based on models of crown fire flame size, initiation, spread rate, and firefighter safety. Site-specific prescriptions can be developed with NEXUS or nomograms. A general prescription designed to be effective at 20-ft windspeeds up to 25 mph during drought summer fine dead fuel moisture conditions (1-hr = 4%, 10-hr = 5%, 100-hr = 7%, live = 78%) calls for a crown-fire-free zone (CFFZ) 380 ft wide with a maximum canopy bulk density of 0.10 kg/m^3. Minimum canopy base height ranges from 2 to 18 ft depending on surface fuel conditions; for fuel model 10 (timber litter and understory), minimum canopy base height is 13 ft.*

Introduction

Houses and other structures can be ignited during a wildland fire by direct flame contact, radiation, or burning embers. The probability of structure ignition can be greatly reduced, but not eliminated, by surface fuel modification immediately adjacent to structures and by adherence to design and construction standards for the structure itself. However, except for an exceptionally well-designed structure, firefighter intervention is needed during the passage of a wildland fire to suppress incipient ignitions. Therefore, when designing fuel treatments for structure protection in the wildland-urban interface we should plan for the presence of firefighters at a structure during fire front passage.

Firefighters need a zone around the structure in which to lay hose, raise ladders to the roof, inspect the home exterior for ignitions, and suppress external structure ignitions. This immediate area around the structure should not allow a spreading surface fire. Surface fuels around this fire-free zone must be treated so that flame lengths allow firefighters to work safely.

Even in full protective wildland clothing, firefighters are more prone to burn injury from flames than a structure is prone to ignition by radiation (Cohen and Butler 1998). In other words, radiation from flames will injure a firefighter or homeowner before untreated wood siding would ignite. Therefore, fuel treatments around structures should be designed to protect firefighters, not structures. Fuels should be treated such that the structure is within a firefighter safety zone. This is the basis for defensible space—the area around a structure where firefighters can safely work (California State Board of Forestry 1996). Many surface fuel treatment standards for creating defensible space exist (for example: International Fire Code Institute 1997, Moore 1981). This paper presents a method for determining the size and characteristics of a coniferous forest canopy treatment.

Firefighter safety zone size, and thus the required area of canopy fuel modification around a structure, is a function of expected flame height. A physical

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heat transfer model suggests this distance must be about 4 times expected flame height, not including a factor of safety (Butler and Cohen 1998). Flame heights are always less than or equal to flame length. To be conservative and simplify, I assume that flame length equals flame height.

Crown fires present special problems for structure protection. They generate huge quantities of burning embers, some of which may travel long distances. Crown fires have very tall flames, which indicate need for a large safety zone and therefore wide fuel modification distance. Modifying canopy fuels to preclude crown fire near a structure is a critical part of ensuring firefighter safety during structure protection.

The guidelines presented here are not intended to be applied by firefighters assigned to structure protection during an active fire—they should be implemented by structure owners before fire threatens.

The Design Environmental Condition

Before prescribing a canopy fuel treatment one must first specify the design environmental condition—the most extreme condition under which the treatment is expected to produce the prescribed result. There are only two factors in the design condition: fine dead fuel moisture content and 20-ft windspeed.

Fine dead fuel moisture content can be set in either of two ways. One method is to identify a threshold condition from a local fire weather database, such as 90^{th}, 95^{th}, or 99^{th} percentile. Firefamily Plus (Bradshaw and McCormick 2000) is a good tool for such analysis. Where such data are not available, the design fine dead fuel moisture content can simply be set to a standard set of moistures, such as those used by Rothermel (1991) in his crown fire spread model (table 1). These values are for the northern Rocky Mountains; other regions may need to use a different set if fuel moistures vary significantly from these.

The design windspeed is more difficult to determine from a fire weather database. Many fire weather databases have a single daily windspeed observation, and this is often a 10-minute average. Windspeeds much higher than reported can occur at the station during other times of the day; the 10-minute average masks significant variability. If using windspeed data, I recommend setting the design windspeed to a value that represents the near maximum (95^{th} or 99^{th} percentile) 1-minute average windspeed that can occur at a site. The design windspeed can alternatively be set to a reasonable value based on expert knowledge of local conditions and the windspeed at which firefighters would discontinue operations. Design windspeeds between 20 and 40 mph are reasonable—I use 25 mph as a default.

Table 1—Rothermel's (1991) fine dead fuel moisture content scenarios. Values are component moisture content (percent).

Timelag fuel component	Early spring before greenup	Late spring after greenup	Normal summer	Drought summer	Late summer severe drought
1-h	8	9	6	4	3
10-h	14	11	8	5	4
100-h	18	15	10	7	6
Live	65	195	117	78	70

Regardless of how the design condition is selected, it is important that this condition be communicated clearly to all responsible parties. It is the limit of effectiveness of the treatment—analogous to the load limit on a bridge.

Size of the Crown-Fire-Free Zone

There are three elements of the canopy fuel treatment standard: required size of the treated area, and within it, maximum allowable canopy bulk density, and minimum allowable canopy base height.

The first element of the canopy fuel treatment standard is the size of the treatment area, called the crown-fire-free-zone (CFFZ). The CFFZ size is a function of the expected flame size. For a site-specific treatment design, determine potential crown fire flame length for the design condition using Rothermel's (1991) nomograms or by using NEXUS (Scott 1999; www.fire.org / nexus / nexus.html), then multiply this estimate by 4 to get the minimum radius of the CFFZ. For designing a non-specific treatment, use the nomogram in figure 1, which uses drought summer fuel moistures (table 1) and requires an estimate of the total available surface and canopy heat per unit area (HPA) in the area surrounding the CFFZ. Surface and canopy fuel HPA have been combined into four categories encompassing the range likely to be encountered (table 2).

At the default design windspeed of 25 mph, drought summer fine dead fuel moisture (table 1), and high surface and canopy fuel HPA (table 2), the CFFZ must be a minimum of 380 ft radius in all directions from the structure (figure 1).

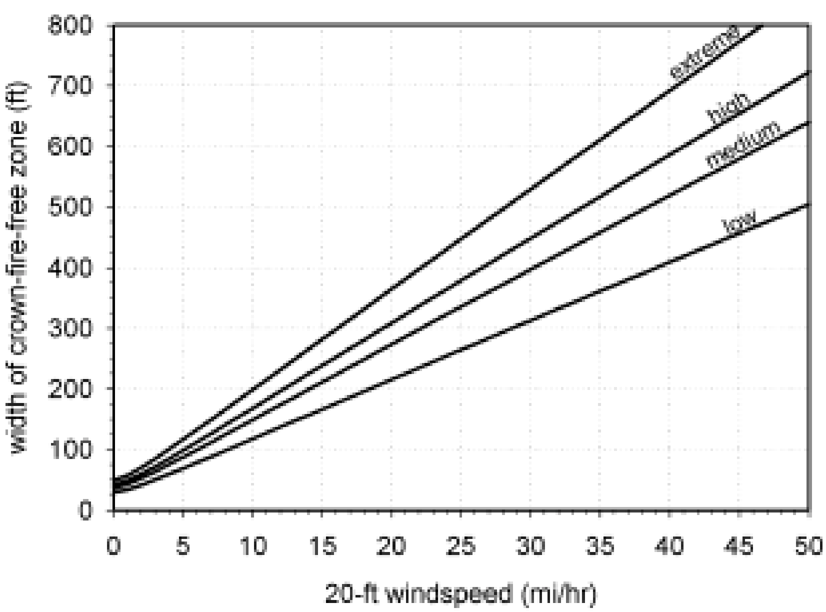

Figure 1—Minimum width of the crown-fire-free zone around a structure as a function of 20-ft windspeed for 4 categories of combined surface and canopy fuel heat per unit area (low = 3500 BTU/ft^2, medium = 5000 BTU/ft^2, high = 6000 BTU/ft^2, extreme = 7000 BTU/ft^2). This chart uses Rothermel's (1991) crown fire spread model to estimate flame length, and assumes level ground, drought summer fine dead fuel moisture conditions (1-hr = 4%, 10-hr = 5%, 100-hr = 7%, live = 78%). Width of the crown-fire-free zone is 4 times the estimated flame length.

Table 2—Stylized surface and canopy fuel loadings and heat per unit area, for estimating crown fire flame length in Rothermel's (1991) correlation. *Drought summer* fuel moisture is assumed (see table 1) for estimating heat per unit area of surface fuels. Available canopy fuel load can be estimated using tables in Rothermel (1991). Fire behavior fuel models (FBFM) are described in Anderson (1982).

Fuel complex heat per unit area class	Surface fuel model	Additional coarse fuels (tons/ac)	Available canopy fuel load (tons/ac)	Heat per unit area (BTU/ft^2)
Low	FBFM 8			
	Compact timber litter		8	3500
Medium	FBFM 10			
	Timber litter and understory		10	5000
High	FBFM 10			
	Timber litter and understory	30	12	6000
Extreme	FBFM 12			
	Medium logging slash		12	7700

Canopy Fuel Characteristics in the CFFZ

Two canopy fuel characteristics must be controlled in the CFFZ: canopy bulk density (CBD) and canopy base height (CBH). Canopy bulk density, the mass of available canopy fuel per unit of canopy volume, must be low enough to cause an active crown fire to cease when entering the CFFZ. Canopy base height must be high enough to preclude initiation of passive crown fire within the CFFZ.

Maximum Allowable Canopy Bulk Density

Fuels within the CFFZ must be managed so that an active crown fire spreading to the zone would cease. This is accomplished by reducing canopy bulk density (CBD) below a threshold value (figure 2). The threshold CBD is determined by linking separate models of crown fire spread rate (Rothermel 1991) and critical conditions for active crown fire spread (Van Wagner 1977).

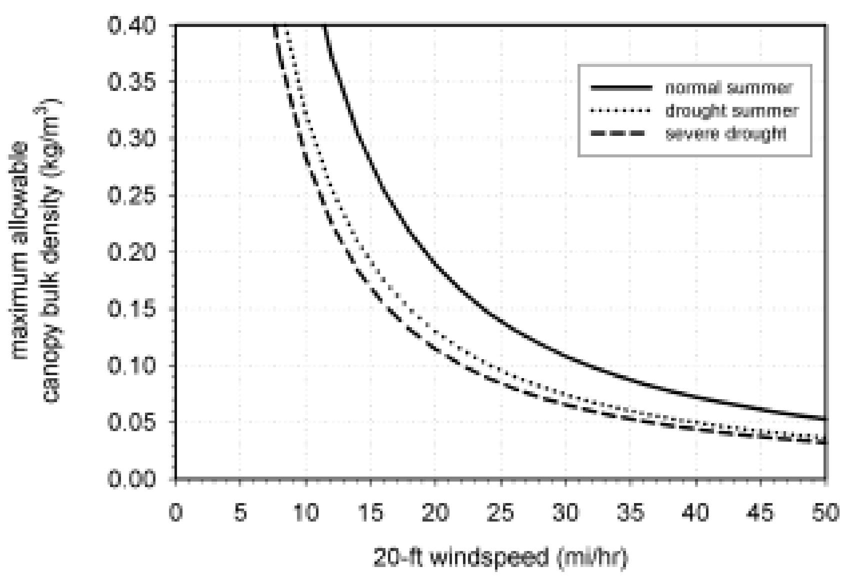

Figure 2—Maximum allowable canopy bulk density as a function of 20-ft windspeed, for a range of fine dead fuel moisture content scenarios. Level ground is assumed.

It is largely a function of the design windspeed (Scott and Reinhardt 2001). At the design condition of drought summer fuel moisture and 25 mph open windspeeds, the maximum allowable CBD is approximately 0.10 kg / m^3.

Unfortunately, CBD is difficult to estimate and prescribe in a treatment. CBD can be determined from indirect measures such as leaf area index, stand biometrics, or from optical sensors (Scott and Reinhardt 2001). Currently, the best method of estimating CBD is to use modified allometric equations that relate tree species and size to crown biomass. The Fuels Management Analyst Plus suite (www.fireps.com) contains the program Crown Mass, the only tool available to help managers estimate CBD from allometric equations. For a site-specific treatment specification that includes fine dead fuel moistures not included in table 1, the user must use NEXUS.

Minimum Allowable Canopy Base Height

To minimize the amount of individual-tree torching that occurs, the CFFZ must be resistant to crown fire initiation. Van Wagner's (1977) model of crown fire initiation determines the fireline intensity necessary to initiate crowning based on canopy base height and foliar moisture content. Foliar moisture content is not a significant factor in the model and can be held constant at 100 percent (Scott 1998b). Because fireline intensity is related to flame length (Byram 1959), we can express the minimum allowable canopy base height as a function of expected surface fire flame length (figure 3). The nomograms produced by Scott and Reinhardt (2001) are useful for computing this threshold crown base height directly from fuel model and fuel moisture condition. NEXUS can be used for conditions not represented by the nomograms. For generic treatment planning, use the chart in figure 4, which assumes drought summer fuel moistures and a wind adjustment factor of 0.25 to represent the more open conditions of a treated stand. For the design condition of fire behavior fuel model 10, drought summer fuel moisture, and a 25 mph 20-ft windspeed, the minimum allowable CBH is 13 ft (figure 4).

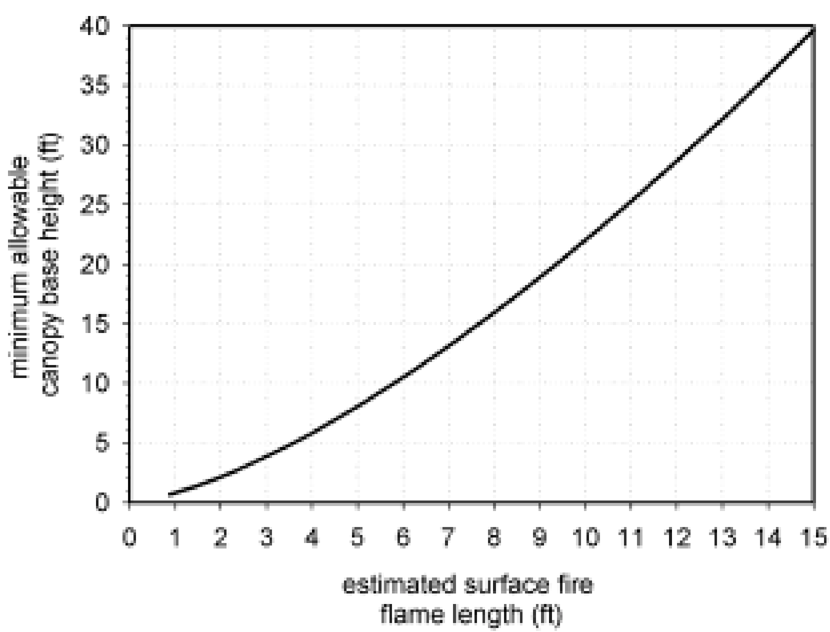

Figure 3—Minimum allowable canopy base height as a function of surface fire flame length, as predicted from Van Wagner's (1977) crown fire initiation model and Byram's flame length model.

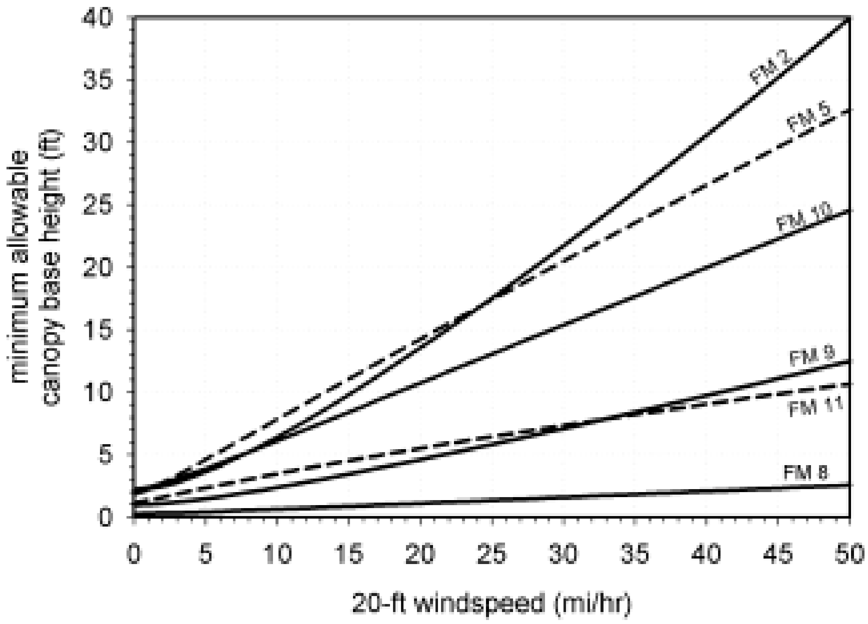

Figure 4—Minimum allowable canopy base height as a function of 20-ft windspeed, for a variety of fire behavior fuel models, assuming level ground, wind adjustment factor 0.25 (represents treated stand condition), and drought summer fine dead fuel moisture conditions (1-hr = 4%, 10-hr = 5%, 100-hr = 7%, live = 78%).

Discussion

Previous work based on similar models suggests fuels need to be treated a maximum of only 130 ft from a structure (Cohen and Butler 1998). However, that recommendation is based on preventing piloted ignition of wood by radiation, not protecting firefighters or the homeowner who may be present during fire front passage. Because structures are so susceptible to ignition by firebrands, if exterior ignitions are to be suppressed, people may need to be present. The treatment standard presented in this paper is designed to protect those people.

The default maximum allowable CBD in this analysis falls within the range of 0.074 to 0.125 kg / m^3 found by Agee (1996) to cause cessation of the crown fires reported by Rothermel (1991). Agee also found an empirical threshold of 0.10 kg / m^3 on the 1994 Wenatchee fires, which coincides exactly with the value from this analysis for drought summer fuel moisture and 25 mph 20-ft winds.

The three elements of the standard do not have an explicit factor of safety attached. There is no built-in safety factor for the prescribed CBD or CBH. However, several factors lead to a built-in margin of safety in the treatment size.

Flame length is used in place of flame height. Models of flame angle and flame height are now being developed, but not yet available. Using flame length in place of height slightly overestimates the required treatment.

The radiation model assumes that the flames radiate directly onto firefighters, but in reality any remaining trees in the CFFZ block some of the radiation before it reaches firefighters at the structure. The amount of blocking is not modeled, but may be significant. Blocked radiation by trees leads to a margin of safety.

The treatment assumes that active crowning is possible outside the CFFZ. If only passive crowning is possible outside the CFFZ, then flame length is over-predicted by the method.

Existing surface fuel treatment standards suggest larger treatment distances on steeper slopes, and generally only on the downslope side of the house. This standard suggests treating the same distance in all directions, regardless of slope steepness. Steeper slopes are well known to increase fireline intensity and spread rate, with the greatest effect in the uphill direction. However, windspeed usually has an even greater effect on fireline intensity and spread rate than slope steepness, but the direction of the effect is not known before the fire. Fire-carrying winds can be from any direction. In many cases a downslope wind would overpower the effect of slope steepness. If the direction of fire-carrying winds is well established for a site, then treatment distance from a structure could be reduced on the downwind side.

The models used in this method suggest very wide canopy fuel treatment areas. However, in many cases the canopy fuels are already within CBD and CBH limits, so no treatment will be necessary. In other cases a light treatment will reduce CBD to the desired level. In no case is complete removal of the forest canopy required to mitigate crown fire potential near a structure.

This standard also makes a structure less prone to ignition from embers. Ember exposure is reduced by eliminating crown fire immediately near the structure. Firebrand research has focused on maximum spotting distance from surface and crown fires, as fire-starting embers can travel very long distances in a convection column. However, little is known about the distribution of spotting distances from a crown fire or torching trees. It is likely that, while long spotting distances are attainable, most embers capable of igniting a structure do not travel very far at all. Therefore, reducing crown fire activity in the vicinity of a structure reduces its exposure to firebrands and thus its potential for ignition.

The cost of modifying canopy fuels to comply with this standard will vary widely. It depends in part on timber markets, terrain and stand conditions, method of treatment, and type of activity fuel treatment. In comparing three alternative treatments to reduce canopy fuels in second-growth ponderosa pine, Scott (1998a) found positive net returns of $156 to $832 per acre treated, depending on logging method, volume of trees removed and type of activity fuel treatment. However, those same treatments applied in different stands might not produce the same revenue.

Modifying canopy fuels as prescribed in this method may lead to increased surface fire intensity and spread rate under the same environmental conditions, even if surface fuels are the same before and after canopy treatment. Reducing CBD to preclude crown fire leads to increases in the wind adjustment factor (the proportion of 20-ft windspeed that reaches midflame height). Also, a more open canopy may lead to lower fine dead fuel moisture content. These factors increase surface fire intensity and spread rate. Therefore, canopy fuel treatments reduce the potential for crown fire at the expense of slightly increased surface fire spread rate and intensity. However, critical levels of fire behavior (limit of manual or mechanical control) are less likely to be reached in stands treated to withstand crown fires, as all crown fires are uncontrollable. Though surface intensity may be increased after treatment, a fire that remains on the surface beneath a timber stand is generally controllable.

If left untreated, activity fuel created while reducing CBD can exacerbate this increase in surface fire intensity and spread rate. Whole-tree harvesting or pile burning or broadcast burning of activity fuel is recommended following canopy fuel treatment to reduce surface fuel flammability.

Conclusion

Existing fuel treatment standards adequately address surface fuel only; they are assumed to be effective in creating defensible space at a structure. This paper presents a simple method of designing canopy fuel treatments likely to protect firefighters and homeowners in the wildland-urban interface. Firefighters attempting structure protection during passage of a fire front can work only within a safety zone. These guidelines create a crown-fire-free zone large enough that the tall flames from an active crown fire are unlikely to injure people protecting structures during a fire.

This method requires the manager to specify the design environmental conditions for the treatment. This design condition represents the limit of effectiveness of the treatment and should be communicated to homeowners and firefighters.

Acknowledgments

This research was supported in part with funds provided by the Joint Fire Sciences Program, the USDA Forest Service Rocky Mountain Research Station, and Systems for Environmental Management.

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