

# Introduction to Fire Behavior Modeling

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## Introduction

Wildfire is at once a naturally occurring agent for ecological change and a potentially destructive natural phenomenon akin to earthquakes and floods. As wildfire occurrence has increased over the last several decades, so too has interest in the modeling of wildfire behavior. Wildfire behavior modeling is used across a variety of spatial and temporal scales, from planning the management of a wildfire incident over the next few days or weeks to land management planning over millions of acres for decades to come.

The information presented here is not a substitute for modeling experience gained during an apprenticeship under a master or journey-level fire behavior modeler. However, it does provide a solid foundation upon which to build such experience.

In this document, we refer to a variety of fuel and fire behavior modeling systems. An overview of these software tools is provided in Appendix C. Within the main text, we provide a few additional details and examples on the use of BehavePlus and Nexus. If you want to follow the examples in the software, please download and install these two fire modeling systems. Follow the links provided in Appendix C to download these software systems.

**Chapter 1** provides an overview of wildfire behavior modeling that defines “wildfire;” presents two ways of describing the morphology of a wildfire; defines four primary, quantitative wildfire behavior characteristics; and introduces five major influences on wildfire behavior simulations.

**Chapter 2** describes how surface fuel is characterized for wildfire behavior modeling. It includes an overview of fire behavior fuel models as used in fire behavior modeling systems, including a description of the required fuel model parameters, a description of the standard fire behavior fuel models available for use in any fire modeling project, and the need for and use of custom fuel models in BehavePlus and NEXUS.

**Chapter 3** defines and describes five canopy characteristics as they are used in fire behavior simulation and includes methods to estimate them.

**Chapter 4** discusses fuel moisture content inputs to fire behavior modeling systems. It includes sections on dead fuel moisture content, live herbaceous moisture content and its use in dynamic fuel modeling, live woody fuel moisture content, and foliar moisture content.

**Chapter 5** describes the slope characteristics—slope steepness and aspect—that directly or indirectly affect fire behavior simulations.

**Chapter 6** describes wind characteristics, including wind speed time-averaging period, reference height above the ground, and ways to specify wind direction in fire behavior modeling systems.

**Chapter 7** describes the prediction of surface fire behavior characteristics with Rothermel’s (1972) spread model. The components of the spread model and factors

affecting predicted rate of spread are described, as well as the application of the model in both BehavePlus and Nexus.

**Chapter 8** describes the development and application of Rothermel's (1991) statistical model to predict crown fire spread rate. The application of the model in BehavePlus and Nexus is also described.

Lastly, **Chapter 9** describes how separate surface and crown fire behavior simulations are integrated into a single overall prediction of fire behavior, including type of fire.

## Chapter 1: Background

This chapter is presented in four sections. In the first section, we define fire and distinguish it from other forms of combustion, and define wildfire and distinguish it from other kinds of fire. In the second section, we discuss two ways of describing the morphology of a wildfire—by shape and by relative spread direction. In the third section, we define four primary, quantitative wildfire behavior characteristics: flaming front spread rate, heat per unit area, fireline intensity, and flame size. Finally, in the last section of this chapter, we introduce the five major influences on wildfire behavior simulations: fuelbed structure, fuel moisture content, slope characteristics, wind characteristics, and relative spread direction.

The objectives of Chapter 1 are to:

- define fire and distinguish it from other forms of combustion,
- define wildfire and distinguish it from other kinds of fire,
- define and describe the morphology of a wildfire as recognized in fire operations (by shape) and its relationship to wildfire morphology as recognized in fire behavior modeling (by relative spread direction),
- list and describe the four primary quantitative wildfire behavior characteristics, and
- list and describe the five major influences on wildfire behavior simulations.

### What is wildfire?

Before jumping directly into a discussion of wildfire behavior modeling, it will be helpful to first put that topic into context. *Combustion*<sup>1</sup> is a complex process in which fuel is heated, ignites, and oxidizes rapidly, giving off heat in the process. *Fire* is a special case of combustion—self-perpetuating combustion characterized by the emission of heat and accompanied by flame and/or smoke. With fire, the supply of combustible fuel is controlled by heat given off during combustion.

Solid fuel particles are turned into combustible gasses through a process called *pyrolysis*—the breakdown of complex cellulose and lignin molecules into simpler, combustible matter through the application of heat. The result is a positive feedback in which combustion produces heat, and that heat produces combustible fuel, which then combusts to produce more heat, and so on.

To illustrate the difference between fire and other forms of combustion, consider two devices available for backyard cooking: the charcoal grill and the gas grill (Fig. 1-1). The combustion occurring in a charcoal grill is self-sustaining—the supply of combustible

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<sup>1</sup> Terms in italics are defined in the FireWords glossary of fire science terminology ([www.firewords.net](http://www.firewords.net)).

fuel is controlled by the heat generated by combustion—and therefore is considered fire. On the other hand, the supply of fuel in a gas grill is controlled by a valve, not by a positive-feedback from the heat of combustion. The combustion in a gas grill is not fire.



**Figure 1-1** – Fire is a self-sustaining process. The combustion in a charcoal grill (left) is self-sustaining—heat from combustion generates the combustion gasses needed for further combustion—and therefore qualifies as fire. The combustion in a gas grill (right) is controlled by a valve, not by self-sustaining feedback.

Two types of combustion associated with fire are recognized: *flaming combustion* and *smoldering combustion*. Flaming combustion is the combustion of gaseous fuel and is characterized by the emission of heat and light in the form of flames. Smoldering combustion (also called glowing combustion) is the combustion of solid fuel and is not necessarily associated with the presence of flames.

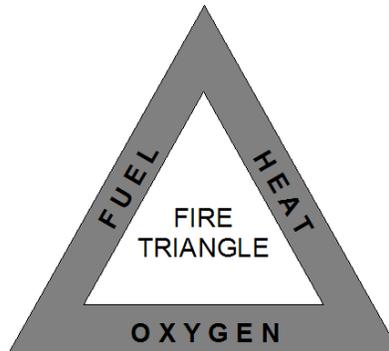
*Flames* are the visual evidence of the rapid reaction between fuel and oxygen—flaming combustion (Fig. 1-2). In a wildfire, flame is the portion of the plume of hot gasses above the combustion zone that radiates energy in the visible part of the electromagnetic spectrum, which occurs when plume temperature is above approximately 600° C (1100° F).



**Figure 1-2** – Flames are visual evidence of rapid oxidation. Combustion particles are visible (that is, they radiate energy in the visible portion of the electromagnetic spectrum) when they are above 600° C. The tip of flames is where the plume cools to below that temperature.

The three factors affecting the presence of fire have been organized into the fire triangle: fuel, heat, and oxygen (Fig. 1-3).

All three factors must be present in order to maintain fire. If any one factor is missing, the fire will go out. There must be a source of fuel available for combustion, a source of heat to promote the reaction (the fire itself), and oxygen in sufficient concentration to maintain the reaction.



**Figure 1-3** – The Fire Triangle. Fuel, heat, and oxygen are the required elements for fire. Remove any one of those elements and fire cannot continue.

Several different kinds of fire can occur, depending on the location of the fire and nature of the fuel source. A fire burning on or within a building constitutes a structure fire or building fire (Fig. 1-4). A fire burning within an enclosed space, such a room within a building, is a compartment fire (Fig. 1-4); the flow of oxygen to and heat away from the burning fuel in the compartment are controlling factors of a compartment fire. Backdraft and flashover are compartment fire phenomena of special concern to structural firefighters.



**Figure 1-4** – A structure fire (left) is any fire burning on or within a building. A compartment fire (right) is a special kind of structure fire that is burning within an enclosed space that limits the flow of oxygen to and heat and combustion gasses away from the burning fuel.

And, finally, there is wildfire<sup>2</sup>, which is an unfortunate misnomer since land need not be “wild” to experience a wildfire. In fact, combustion scientists who study fire in all its

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<sup>2</sup> A wildfire is an unplanned wildland fire; a prescribed fire is a planned wildland fire.

forms use the term vegetation fire or landscape fire instead of wildfire (Fig. 1-5). These terms better describe the essential characteristics of what we know as wildfire. First, vegetation and its detritus (litter) serve as the fuel source for all wildfires. The vegetation need not be natural or wild (consider a wildfire spreading across a field of cured wheat). Second, the term landscape fire alludes to an important trait of wildfire—that it can spread across a landscape. Nonetheless, the term wildfire is so well known that we will continue to use it. Wildfire is self-sustaining combustion of vegetation-derived fuel across some portion of the landscape.



**Figure 1-5** – A wildfire, also known as a vegetation fire or landscape fire, is the self-sustaining combustion of a vegetation-derived fuelbed. A wildfire spreads across the landscape in response to the fire environment, which includes fuel, weather, and topography.

## Wildfire morphology

The morphology of a wildfire is described in two ways: qualitatively by the different shapes that burned and unburned areas of a wildfire can form, and quantitatively by the orientation of the flaming front with respect to the direction of maximum spread, which is called the relative spread direction.

### *By shape*

A wildfire burning in constant wind and weather conditions on a uniform fire environment takes the shape of a simple ellipse (Fig. 1-6).



**Figure 1-6** – Like all wildfires burning in homogeneous conditions, each of these point-source fires, placed using aerial ignition during a prescribed fire, takes on the shape of a simple ellipse.

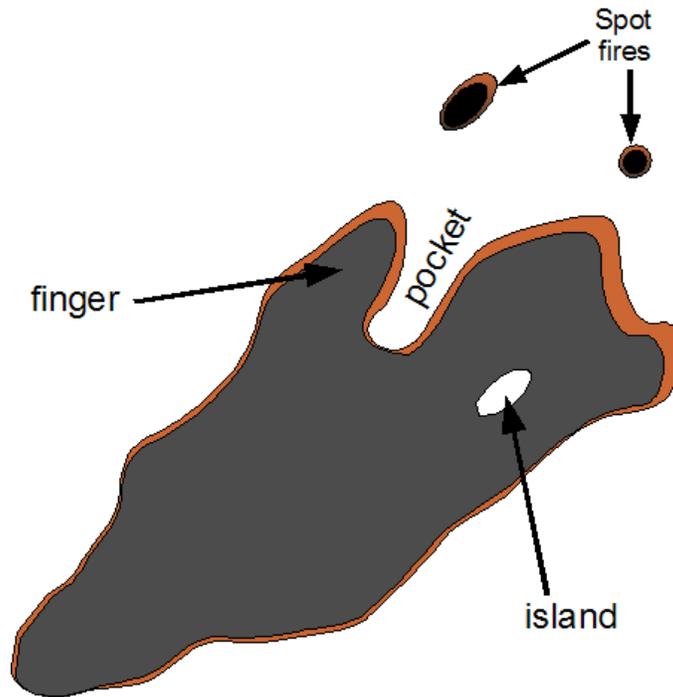
The fire environment can become quite variable once a fire grows beyond the immediate area of its origin. Different areas of the fire may be burning in different fire environments, such as different fuelbed structure, slope steepness, moisture content, wind speed, wind direction, etc. The result of such fire environment heterogeneity is that, even if each discrete section of the fire front spreads as a simple ellipse, the overall fire shape can be quite complex, especially when influenced by spot fires and barriers to fire spread.

A finger is a long, narrow extension of fire extending from the main body (Fig.1-7). Fingers of fire can form when the main fire spreads around a slower-burning or non-burnable patch of fuel, or when a small section of a fire perimeter encounters a fire environment through which fire spreads much faster than the main body (cured grass, for example), especially under the influence of strong wind or slope.

A pocket (Fig. 1-7) is an unburned indentation of the fire perimeter surrounded on three sides by the fire; often, two sides of a pocket are fingers. Pockets are formed when the main body of fire spreads around an unburnable or slow-burning patch of fuel. An island (Fig. 1-7) is an unburned area within a fire that is wholly surrounded by burned area. An island may be shrinking in size if the inner perimeter is active—an inward-burning fire perimeter—or the island perimeter may have extinguished naturally or by suppression. Unburned islands occur for several reasons. An island may not be covered by a sufficient quantity of fuel to burn under any condition (sparse or no vegetation cover). Other times, an island forms because the requirements for fire spread were not met at the time the fire arrived, even though it might have met those requirements at another time.

A spot fire (Fig. 1-7) is a fire ignited outside the main fire by a firebrand. While a spot fire is small, it usually takes on the simple elliptical shape, but as it grows, it can develop fingers, pockets, unburned islands, and even loft embers that ignite new spot fires. Spot

fires may coalesce as they grow into one another, and they are often overrun by the main fire.



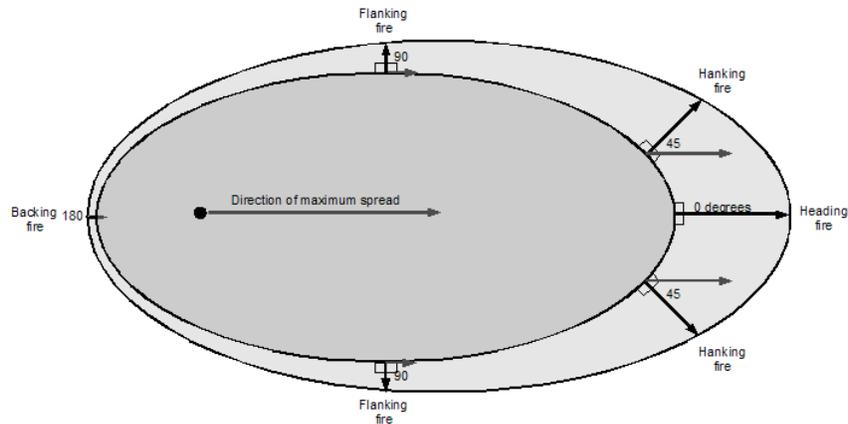
**Figure 1-7** – A finger is a long, narrow extension of the main body of fire. A pocket is an unburned indentation of the fire perimeter surrounded on three sides by the fire. An island is an unburned area within a fire that is wholly surrounded by burned area. A spot fire is a fire ignited outside the main fire by a firebrand.

These features can occur at many different scales. For example, a finger can be just a few feet across or more than a mile. There can be fingers on fingers and spot fires from spot fires.

Describing wildfire morphology by identifying the parts of a fire is very helpful during wildfire operations (as they can have significant effects on firefighter safety). However, shape-based morphological descriptions are not used in wildfire behavior modeling systems. Instead, fire modeling systems consider wildfire morphology as described by the relative spread direction, which can be calculated for any point on the fire perimeter.

#### *By relative spread direction*

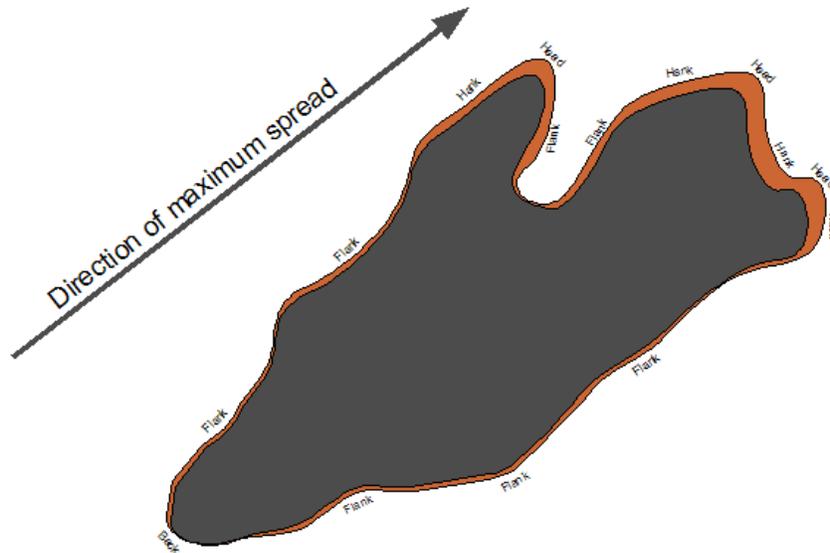
Recall that under a uniform fire environment, a wildfire perimeter takes on the shape of a simple ellipse with the long axis of the ellipse oriented in the direction of maximum fire spread, which is the heading direction (Fig. 1-8). Under spatially uniform fire environment conditions, the heading direction is the same on all parts of a fire. In Figure 1-8, the heading direction is indicated by gray arrows; all gray arrows point in the same direction— to the right side of the page—and is also indicated by the general orientation of the ellipse.



**Figure 1-8** – Sections of this simple fire perimeter can be classified by the orientation of the flaming front (dark arrows) with respect to the direction of maximum spread (gray arrows). The black dot represents the origin of the fire and is located at the rear focus of the ellipse.

The *relative spread direction* is the angle between the absolute flaming front orientation (dark arrows) and the direction of maximum spread, measured in degrees clockwise from the direction of maximum spread. Relative spread direction varies around the fire perimeter even in a uniform fire environment. At the head of the fire, the flaming front is oriented exactly in the heading direction, so relative spread direction is 0 degrees. At the opposite end of the wildfire—the rear, back, or heel of the fire—the relative spread direction is 180 degrees clockwise from the heading direction. The widest parts of the ellipse are called the flanks of the fire, and there the relative spread direction is 90 and 270 degrees clockwise from the maximum spread direction. As you will see later in this chapter, the change in fire behavior between the head and the flank of a fire is so great that it is helpful to describe fire behavior at a point on the perimeter between the head and the flank—the “hank” (Scott 2007), where the flaming front is oriented 45 degrees from the direction of maximum spread.

In a heterogeneous fire environment, the direction of maximum spread can vary around the perimeter. This description of wildfire morphology by relative spread direction can be related to fire shape by breaking down a complex wildfire perimeter into discrete points. Each perimeter point has its own fire environment and therefore its own direction of maximum spread. The relative spread direction is determined separately for each point on a fire perimeter, no matter how complex the fire shape (Fig. 1-9).



**Figure 1-9** – By examining the orientation of the flaming fire front with respect to the direction of maximum spread (heading direction; shown by arrow), wildfire morphology by relative spread direction can be related to fire shape. Perimeter points facing in the direction of maximum spread are head fires; those points facing 90 degrees off of the direction of maximum spread are on the flanks. Fire behavior modeling systems compute relative spread direction for each fire environment, usually in degrees clockwise from the direction of maximum spread.

The use of relative spread direction in fire behavior calculations is covered in more detail later in this chapter.

### Wildfire behavior characteristics

This section defines and describes the four primary, quantitative fire behavior characteristics: flaming front rate of spread (*ROS*), heat released per unit area (*HPA*), fireline intensity (*FLI*), and flame size—specifically, flame length (*FL*). These characteristics affect other important fire characteristics, such as fire effects (smoke production, crown scorch height, and fire severity) and fire-level fire characteristics (fire size and magnitude). Each of these wildfire behavior characteristics is described in the following sections.

We will use two contrasting fire environments—a coniferous forest stand and a grassland—to illustrate the calculation of each fire behavior characteristic. The characteristics of each fire environment are detailed in Table 1-1.

**Table 1-1**—Fire environment characteristics for two hypothetical fire environments: a coniferous forest stand and a grassland. Aspect is not applicable in these examples due to the flat terrain. Elevation is not applicable because it is used to estimate dead fuel moisture, which is arbitrarily set in this example. These major influences on wildfire behavior simulations are introduced later in this chapter and described in detail in subsequent chapters.

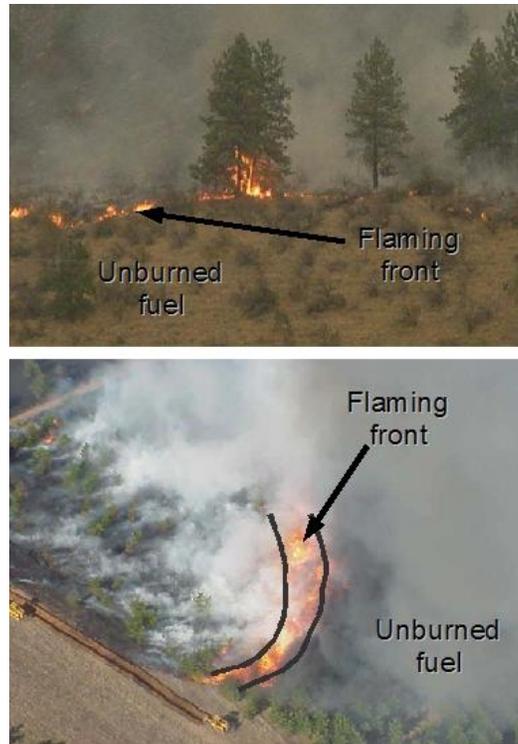
Major influence		Forest stand	Grassland
Fuelbed structure	Surface fuel <sup>a</sup>	Heavy load of timber litter (fuel model TL5)	Moderate load of grass (fuel model GR4)
	Canopy fuel	Low canopy base height; moderate canopy bulk density, 4 t/ac canopy fuel load	None
Slope characteristics	Slope steepness	Flat ground	Flat ground
	Aspect	n/a	n/a
	Elevation	n/a	n/a
Fuel moisture content	Dead fuel moisture	4% Dead fuel moisture content	4% dead fuel moisture content
	Live fuel moisture content	100% live woody fuel moisture content	45% live herbaceous moisture content
Wind characteristics	Wind speed	Moderate to strong (15 mi/h at 20-ft height above the canopy)	Moderate to strong (15 mi/h at 20-ft height above the surface)
	Wind direction	South	South

<sup>a</sup> TL5 and GR4 refer to surface fire behavior fuel models, which are covered in detail in Chapter 2.

The forest stand fire environment is typical of one with a well-developed understory of shrubs and small trees, resulting in a low canopy base height and making crown fire initiation a common occurrence. The canopy bulk density is moderate, making active crown fire a possibility under high wind speeds and low moisture contents. The grassland fire environment is much simpler, having uniform coverage of moderate grass load with no overstory trees. Flat ground is assumed for both scenarios. Both scenarios also use the same dead fuel moisture contents and open wind speeds.

### *Flaming front rate of spread (ROS)*

The flaming front of a wildfire is its leading edge, dominated by flaming combustion and spreading into previously unburned fuel (Fig. 1-10).



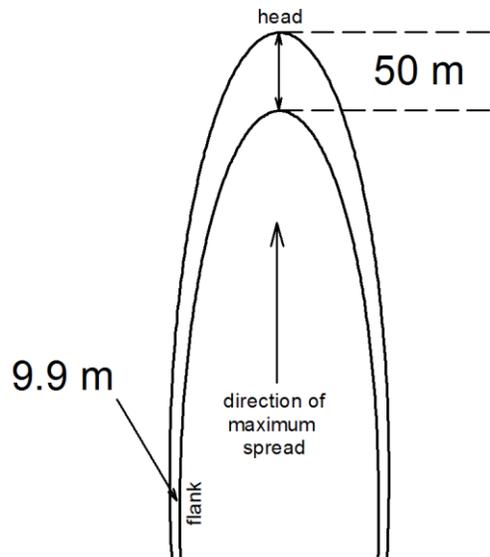
**Figure 1-10** – The flaming front of a wildfire is its leading edge, which spreads into unburned fuel and is dominated by flaming combustion.

The flaming front is located at all positions around the fire perimeter: head, flank, rear, and points in between. Flaming front rate of spread (*ROS*) is the linear rate of advance of a flaming front into unburned fuel in the direction perpendicular to the fire front. Figure 1-11 shows the position of a flaming front for the grassland fire environment (Table 1-1) at two points in time just one minute apart. Rate of spread is the distance between the two perimeters (in the direction perpendicular to the flaming front) divided by the time interval. Note that *ROS* varies around the perimeter of the fire. At the head of the fire, in the direction of maximum spread, the flaming front travelled 50 m during the one-minute time interval, so the *ROS* is 50 m/min (150 ch/h)<sup>3</sup>. On the flank, where the flaming front is oriented 90 degrees with respect to the maximum spread direction, the flaming front spread at only 9.9 m/min.

For the forest stand fire environment (Table 1-1), maximum flaming front rate of spread is 8.6 m/min (25.6 ch/h). The forest stand is experiencing a passive crown fire, so its *ROS* falls between the surface fire and potential crown fire *ROS* values<sup>4</sup>.

<sup>3</sup> Please refer to Appendix B for a comprehensive listing of unit conversion factors for this and other quantities presented in this document.

<sup>4</sup> More on how surface and crown fire *ROS* are integrated will be presented in Chapter 9.



**Figure 1-11** – The spread rate of the flaming front is its linear rate of advance in the direction perpendicular to the flaming front. The curving lines represent the position of the flaming front at two points in time that are just one minute apart. Spread rate is greatest at the head of the fire and decreases around the perimeter.

Spread rate of surface fires is predicted using Rothermel's surface fire spread model<sup>5</sup> (Rothermel 1972). Rothermel's (1991) crown fire spread model is used to predict crown fire spread rate. Surface and crown fire spread rate are covered in more detail in later chapters.

Rate of spread is an important fire behavior characteristic for two reasons. First, it contributes to how large the wildfire can become during a specified period of time, and that in turn influences the likelihood that a wildfire will reach certain places of concern on a landscape. Second, rate of spread is a significant factor affecting fireline intensity and flame size, which are important for determining fire effects.

Flaming front spread rate of free-burning wildfires varies over more than three orders of magnitude. A backing fire in a compact timber litter fuelbed may spread at less than 0.2 m/min (0.5 ch/hr); a fully active crown fire can spread faster than 100 m/min (300 ch/hr); and rate of spread in cured grass fuels can reach nearly 10 km/hr (6 mi/hr) under the influence of strong winds.

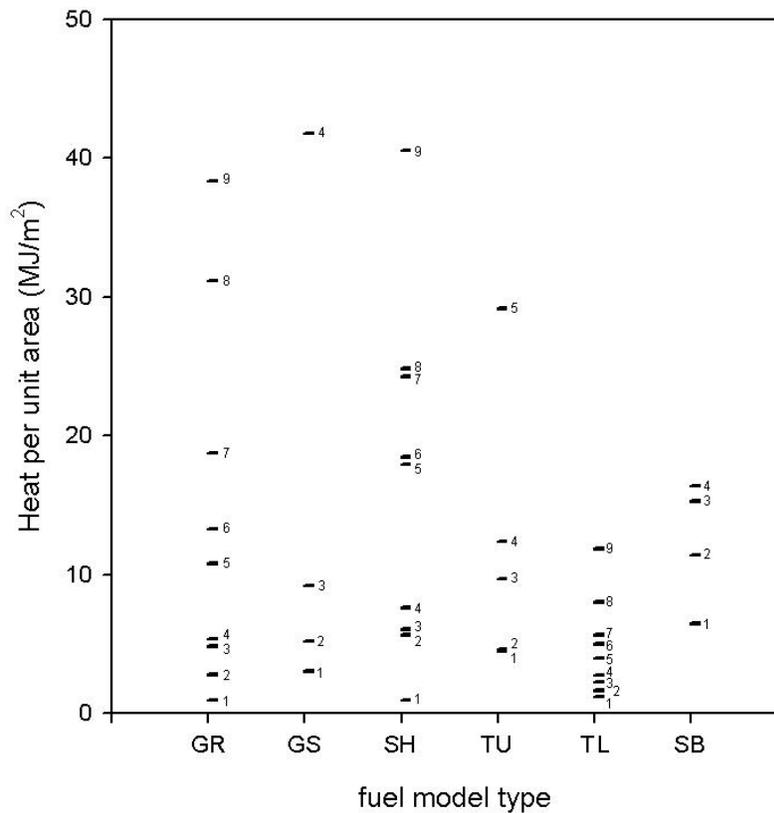
### *Heat per unit area (HPA)*

Heat per unit area (*HPA*) is the amount of heat released per unit area during the short period of continuous flaming. Flaming front residence time is typically on the order of seconds (for very fine fuel particles, such as grass) to a few minutes (for coarser woody

<sup>5</sup> All major fire modeling systems in the United States use Rothermel's surface fire spread model or some minor variation of it.

fuel particles). Post-frontal flaming and smoldering can continue for many hours or days after the flaming front has passed, but the heat released during that time is not included in *HPA*.

*HPA* can be thought of as the product of fuel particle heat content (*H*) and the fuel load consumed during passage of the flaming front (*W*)<sup>6</sup>. Although *H* has been shown to vary slightly among fuel particles derived from different species, it is functionally constant for most fire modeling simulations<sup>7</sup>, so variation in *HPA* is therefore a function primarily of variation in *W*. For surface fires, *HPA* is a function of the selected fuel model and live and dead fuel moisture contents (Fig. 1-12).



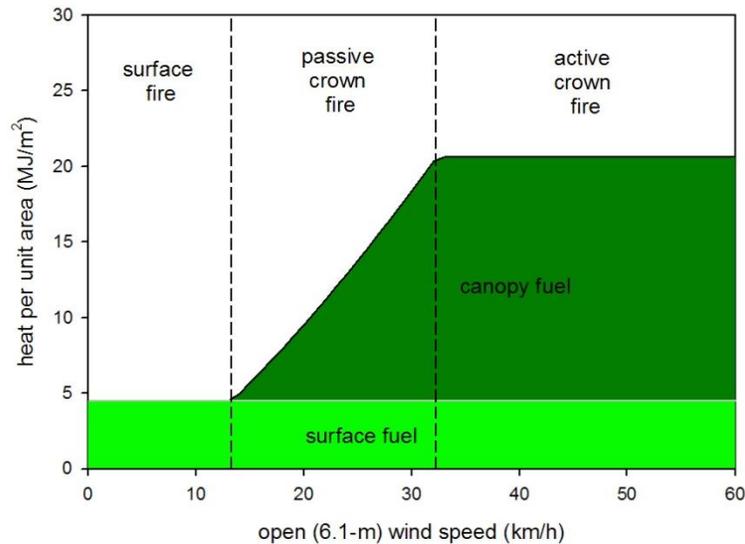
**Figure 1-12** – Surface fuel *HPA* values for the 40 fire behavior fuel models (Scott and Burgan 2005). Fuel models for each fuel model type are listed in a single column. This chart assumes 6% 1-hr, 7% 10-hr, and 8% 100-hr timelag moisture content values; live herbaceous moisture content is 60%; and live woody moisture content is 90%.

For crown fires, *HPA* includes the combined load of surface and canopy fuel consumed

<sup>6</sup> See Scott and Reinhardt (2001) for a discussion of conflicting terminology that has led to confusion in determining *W* for use in estimating fireline intensity.

<sup>7</sup> For surface fuel modeling, *H* is held constant at 18,593 kJ/kg (8,000 BTU/lb) for all fuel models except GR6, for which *H* is 20,917 kJ/kg (9,000 BTU/lb).

during passage of the flaming front. An active crown fire consumes nearly all of the available canopy fuel, while a passive or intermittent crown fire consumes only a portion (Van Wagner 1993). The relative contribution of surface and canopy fuel to overall *HPA* for the forest stand (Table 1-1) is shown in figure 1-13. At low wind speeds, where only surface fire is possible, overall *HPA* is equal to the surface fuel *HPA*. Overall *HPA* increases during the period of passive crowning as the fraction of canopy fuel consumed increases. By the time active crowning is possible, at a wind speed of 20 mi/h (33 km/h), all of the possible canopy fuel contribution is included in overall *HPA*.



**Figure 1-13** – Illustration of the contribution of surface fuel and canopy fuel to overall heat per unit area (*HPA*) as a function of increasing wind speed and type of fire for the forest stand described in Table 1-1. At low wind speeds, where only surface fire is possible, overall *HPA* is the surface fuel *HPA*. Where passive or active crown fire is possible, overall *HPA* is the combination of surface and canopy fuel *HPAs*. Within the passive crown fire type, canopy fuel *HPA* increases with wind speed as the fraction of canopy fuel burned increases. For reference, the *HPA* for the grassland is 5.7 MJ/m<sup>2</sup> at all wind speeds.

The Rothermel model does not estimate surface fuel *HPA* directly; only by combining reaction intensity, an intermediate parameter in the model, with a model of residence time (Anderson 1969) can the Rothermel spread model be used to estimate *HPA* (Andrews and Rothermel 1982). Nonetheless, the Rothermel surface fire spread model is the best choice currently available for surface fuel *HPA*.

### *Fireline intensity (FLI)*

Fireline intensity (also called Byram's fire intensity) is the rate of heat release per unit length of the fire front (Byram 1959). As with *HPA*, the heat released during post-frontal flaming and smoldering combustion is not included in the calculation of fireline intensity. Fireline intensity is a fundamental fire characteristic containing "...about as

much information about a fire's behavior as can be crammed into one number" (Van Wagner 1977). Byram (1959) defined fireline intensity as

$$FLI = H * W * ROS$$

where  $H$  is heat content and  $W$  is fuel load consumed in the flaming front. In the preceding section we defined  $HPA$  as  $H * W$ , so we can also express  $FLI$  as the product of  $HPA$  and  $ROS$ :

$$FLI = HPA * ROS$$

Adjustments to the above equation are necessary to make the units work out. For  $HPA$  expressed in  $\text{MJ}/\text{m}^2$  and  $ROS$  in  $\text{m}/\text{min}$ , the following equation produces  $FLI$  in  $\text{kW}/\text{m}$ .

$$FLI = (1000 * HPA) * \left(\frac{ROS}{60}\right)$$

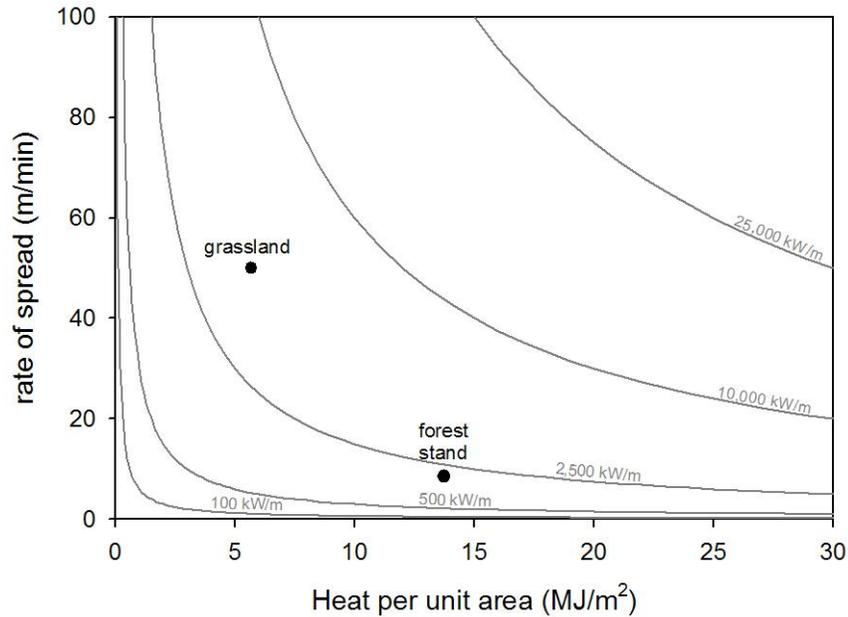
For example, recall from the earlier section that  $HPA$  for the grassland fire environment was  $5.68 \text{ MJ}/\text{m}^2$  and  $ROS$  was  $50 \text{ m}/\text{min}$ . The  $FLI$  calculation for the grassland is therefore

$$FLI = (1000 * 5.68) * \left(\frac{50}{60}\right) = 4733 \text{ kW}/\text{m}$$

And for the forest stand

$$FLI = (1000 * 13.76) * \left(\frac{8.57}{60}\right) = 1964 \text{ kW}/\text{m}$$

These results can be plotted on a fire behavior characteristics chart, which displays both  $HPA$  and  $ROS$ , along with curving reference lines indicating fireline intensity (Fig. 1-14). From this chart we see that the  $FLI$  values for these contrasting fire environments are actually somewhat similar—they straddle the  $2,500 \text{ kW}/\text{m}$  reference line, but for different reasons. The forest stand has a higher  $HPA$ , due to the contribution of canopy fuel, but a lower  $ROS$  than the grassland.



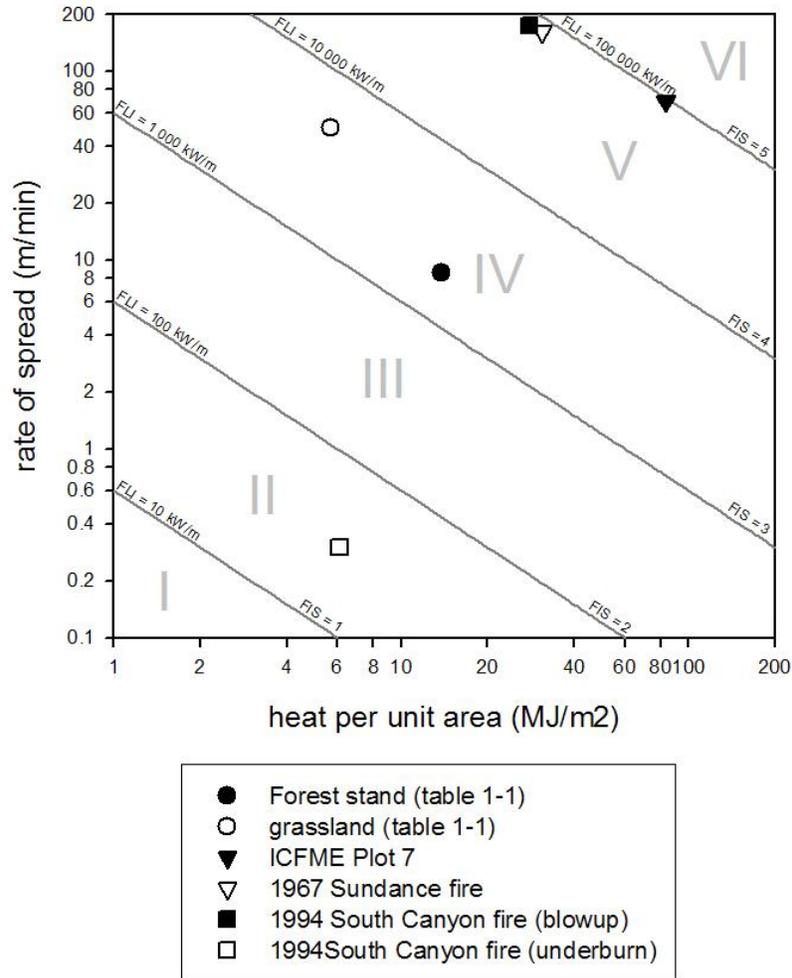
**Figure 1-14** – A fire behavior characteristics chart can depict three quantitative fire behavior characteristics at once. The Y-axis represents flaming front spread rate, the X-axis represents heat per unit area, and the curving lines represent fireline intensity.

Considering the full range of fire environments possible, potential values of fireline intensity span nearly five orders of magnitude, from less than 10 kW/m (3 BTU/ft-s) for a slow-spreading fire in light fuel to more than 100,000 kW/m (29,000 BTU/ft-s) for a fast-spreading fire in heavy fuel (crown fire or shrub-canopy fire). This very large range of fireline intensity values has made its interpretation difficult. To address this large range of *FLI* values, Scott (2006) used the common logarithm of *FLI* (specifically measured in kW/m) as a standard scale called the Fireline Intensity Scale (FIS).

$$FIS = \text{Log}_{10}(FLI)$$

The FIS is similar to the familiar Richter scale of earthquake magnitude in its use of a logarithmic scale; each unit increase in the FIS represents a meaningful 10-fold increase in fireline intensity. For the range of possible fireline intensity values noted above, FIS ranges from less than 1 (10 kW/m) to just greater than 5 (100,000 kW/m), suggesting six wildfire intensity classes—fire intensity classes I through VI.

Fig. 1-15 shows a fire behavior characteristics chart scaled for displaying FIS and the six corresponding fire intensity classes. Plotting those axes on a log-log scale straightens the lines of equal fireline intensity and reveals the large range of variability in fireline intensity values.



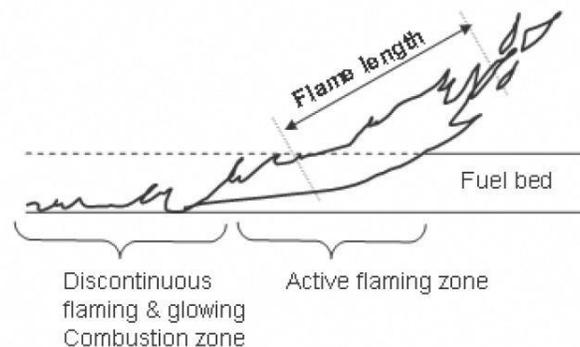
**Figure 1-15** – This fire characteristics chart is shown with a  $\log_{10}$  (common log) scale for both axes, resulting in straight lines for  $FLI$  and  $FIS$  values. Each reference line represents a 10-fold increase in fireline intensity, resulting in a natural classification of fireline intensity into six classes. Note that fireline intensity during the South Canyon fire blowup is in the upper end of intensity class V, among the highest intensities possible, whereas the underburn fire behavior before the blowup is in the middle of class II, more than three orders of magnitude lower intensity.

Fire behavior characteristics for a variety of simulated and observed wildfires are plotted on the chart. Our two hypothetical fire environments fall within wildfire intensity class IV, with  $FIS$  values of 3.7 for the grassland and 3.3 for the forest stand. Note that although the grassland  $FLI$  is more than double that of the forest stand, the  $FIS$  and the log-log fire behavior characteristics chart help to show that, given the huge range of  $FLI$  values possible, they are actually quite similar. At the high end of the scale, Plot 7 of the International Crown Fire Modeling Experiment (ICFME) produced a fireline intensity of 97,100 kW/m ( $FIS = 5.0$ ) in a jack pine stand. The 1967 Sundance fire in north Idaho briefly produced an estimated  $FLI$  value of 80,300 kW/m ( $FIS = 4.9$ ). The blowup period of the 1994 South Canyon fire, which burned under the influence of strong upslope winds in a fuelbed of tall shrubs, exhibited nearly the same fireline intensity (82,800 kW/m,  $FIS = 4.9$ ). Before the South Canyon fire blowup, a backing fire

that underburned the same fuelbed exhibited a fireline intensity of just 27 kW/m (FIS = 1.4), a difference of approximately 3.5 orders-of-magnitude.

### Flame size

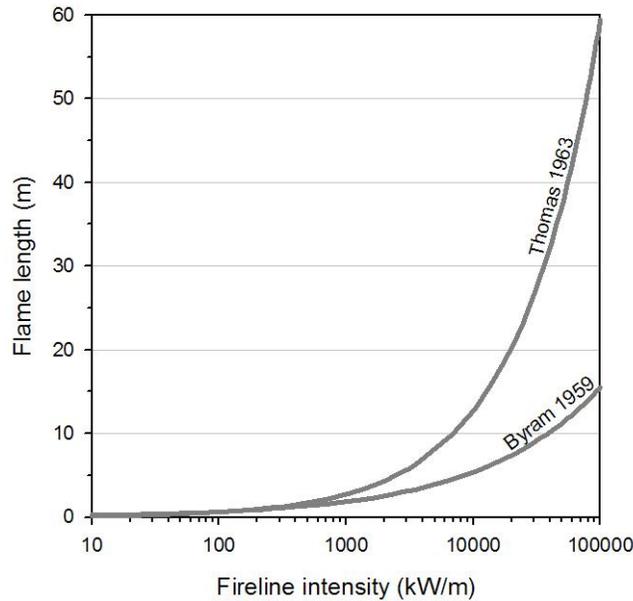
Recall from earlier in this chapter that flames are the visible manifestation of rapid combustion. Flame size is a measure of the physical dimensions of such flames. Two measures of flame size are available: flame height and flame length (Fig. 1-16). Flame height is used in a model of firefighter-injury threshold, but flame length has been more closely related to fireline intensity and is therefore more commonly used.



**Figure 1-16** – Flame length is the distance from the base of the flame zone to the tip of continuous flaming. Intermittent flaming occurs beyond the flame tip. Flame length is difficult to define, observe, and simulate when fuelbeds are deep in relation to the flame size, such as in crown fires and shrubland fires.

A variety of mathematical models have been constructed for relating flame length to fireline intensity as defined above, but only the Byram (1959) and Thomas (1963) models are in operational use in U.S. fire modeling systems (Fig. 1-17).

Flame length is presented as a fire behavior characteristic because it is so readily apparent to personnel on the ground, whereas fireline intensity is not. Calculating flame length is problematic, however, especially for passive or intermittent crown fires. A passive crown fire is the burning of a single tree or simultaneous burning of a small group of trees. For most of the time that a passive crown fire is spreading, surface fire behavior would be observed, with flame lengths represented by what the surface fuel alone is capable of producing. During the short period when trees are torching out, flames briefly increase in length by more than an order of magnitude. An intermittent crown fire—one that frequently alternates between surface fire and active crown fire—exhibits the same bimodal flame length distribution. Which of these observed flame lengths is the flame length of a passive or intermittent crown fire? Fireline intensity is a scientifically better measure of fire intensity, even if it cannot be readily observed in the field.



**Figure 1-17** – Two mathematical relationships are commonly used to estimate flame length from fireline intensity; the models provide very different estimates of flame length for *FLI* values greater than 1000 kW/m. Thomas' (1963) model is most commonly used for estimating crown fire flame length, whereas Byram's (1959) model is used for surface fires.

Deep fuelbeds also present a problem for interpreting flame length values. Flame length is defined as the distance from the base of the flames, the mid-height of the fuelbed, to the tip of the continuous flame. When flames are quite long in comparison to the fuelbed depth, there is little concern for making an adjustment for the mid-height of the fuelbed. When the fuelbed is deep, however, as in crown fires, this adjustment is critical. For crown fires, Byram suggested adding one-half of the fuelbed height (stand height) to the flame length values calculated using his model to obtain a better estimate of what might be observed. No such correction is suggested or needed when using Thomas' flame length model. For that reason, Byram's model is generally applied to surface fires (shallow fuelbeds) and Thomas' model to crown fires (deep fuelbeds)<sup>8</sup>.

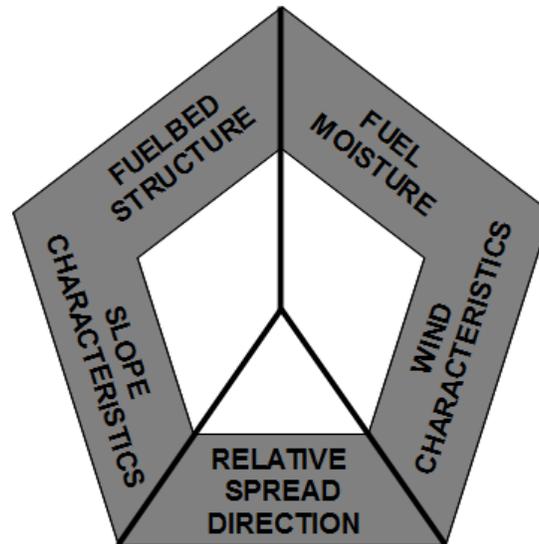
### Major influences on fire behavior simulations

Earlier in this chapter we introduced the fire triangle, the three factors that must be present to sustain fire: fuel, heat, and oxygen. In addition, many readers are familiar with the fire behavior triangle, the three primary factors affecting fire behavior: fuel, weather, and topography. The fire behavior triangle is a useful construct for a general discussion of the factors affecting fire behavior, but for a more specific discussion of

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<sup>8</sup> The exact implementation of this general rule varies between the fire behavior modeling systems.

wildfire behavior simulation, we have re-organized the factors into five major influences, displayed as a fire modeling pentagon (Fig. 1-18).



**Figure 1-18** – The fire modeling pentagon illustrates the five major influences on fire behavior modeling simulations. Fuelbed structure and slope characteristics are time-constant influences since those factors do not change during any single fire simulation (which typically lasts no more than a few weeks). Fuel moisture and wind characteristics are time-varying influences because those factors can vary by the minute, hour, day, and week, and thus affect all temporal fire growth simulations. Relative spread direction—heading, flanking, backing—has considerable effect on fire behavior.

Each of these five major influences will be introduced in the following subsections. Each will then also be discussed in more detail in specific chapters.

### *Fuelbed structure*

Fuelbed structure can be considered constant for the duration of any single fire behavior simulation. Fuelbed structure varies over longer time periods, however. Vegetation grows and dies, litter accumulates and decays, and intentional and unintentional fuel modifications occur, all of which affect fuelbed structure over the scale of years and decades. These longer-term changes in fuelbed structure are important in many fire management applications (planning fuel treatments, for example) but can safely be ignored for single-season fire behavior simulations. It is therefore possible to maintain geospatial fuelbed structure data and update them periodically, which is precisely what the LANDFIRE Program ([www.landfire.gov](http://www.landfire.gov)) has done.

Vegetation-derived fuelbeds (that is, wildland fuel) consist of three main strata: ground, surface, and canopy. The ground fuel stratum—duff and organic soil, for example—primarily influences fire effects (fuel consumption, smoke production, tree mortality,

mineral soil exposure, etc.) and does not significantly affect fire behavior modeling. For this reason, ground fuel stratum characteristics will not be discussed further in this document. On the other hand, surface and canopy fuel stratum characteristics affect fire behavior significantly. General characteristics of those strata will therefore be introduced here, and they will be discussed in greater detail later in chapters 2 and 3.

**Surface fuel** – All operational fire behavior modeling systems use Rothermel’s (1972) surface fire spread model. The major surface fuelbed factors in that model are: load, depth, surface-area-to-volume (SAV) ratio, extinction moisture content, and heat content.

Characterizing surface fuel for fire behavior modeling is described in Chapter 2 of this guide.

**Canopy fuel** – Fire behavior modeling systems use a combination of Van Wagner’s (1977) crown fire threshold models and Rothermel’s (1991) crown fire spread rate model to simulate crown fire initiation and spread behavior. The two major canopy fuel stratum characteristics that influence crown fire initiation and spread are: canopy base height (CBH) and canopy bulk density (CBD). In addition, simulation of crown fire intensity and flame length requires an estimate of canopy fuel load (CFL). Also, the canopy characteristics stand height (SH) and canopy cover (CC) indirectly influence both surface and crown fire behavior by affecting dead fuel moisture and mid-flame wind speed.

Characterizing canopy fuel for fire behavior modeling is described in Chapter 3 of this guide.

### *Fuel moisture content*

The moisture content of live and dead fuel particles is an important factor affecting wildfire behavior. Significant variability in fuel moisture content occurs within the time period of fire behavior simulations. Fine dead fuel moisture content, for example, varies significantly within a single day and from day to day. Live woody moisture content typically varies from week to week throughout the course of a season.

For use in fire modeling systems, fuel moisture is measured as “gravimetric” moisture content on a dry-mass basis. Translation: fuel moisture content is the mass of the moisture (water) in a fuel particle divided by the oven-dry mass of the fuel particle. Fuel moisture content is measured this way because it represents the ratio of heat sink to heat source. The moisture mass represents a heat sink—the heat required to evaporate that moisture—and the oven-dry mass represents the heat source available for combustion.

$$\frac{\text{heat sink}}{\text{heat source}} = \frac{\text{moisture mass}}{\text{dry fuel mass}}$$

As calculated with the above equation, moisture content is expressed as the moisture fraction<sup>9</sup>. In fire modeling applications, moisture content is typically expressed as a percentage. Multiply moisture fraction by 100 to express moisture content as a percentage.

Because moisture content is measured on an oven-dry basis, and because living fuel particles can contain more moisture mass than oven-dry fuel mass, moisture content values of live fuel particles may exceed 100 percent. For example, freshly emerged spring-time foliage may have a fuel moisture content of nearly 300 percent. This simply means that for every gram of oven-dry foliage there are 3 grams of water within the leaves. The ratio of heat sink to heat source is very high.

Fuel moisture content values are assigned to a variety of live and dead fuel classes. Dead fuel moisture content values are assigned separately to four different fuel particle diameter classes. These size classes are frequently labeled by their approximate timelag class (Table 1-2).

**Table 1-2**—Relationship between timelag class and fuel particle size class. A timelag is the length of time required for a fuel particle to move from its current moisture content to its equilibrium moisture content.

Timelag class	Size class (diameter)	
	in	mm
1-h	0 – 0.25	0 – 6
10-h	0.25 – 1.0	6 – 25
100-h	1 – 3.0	25 – 75
1000-h	> 3.0	> 75

The 1000-h timelag class is used in some fire modeling systems that predict fire effects (such as fuel consumption). However, this dead fuel particle diameter class is not used in the modeling of fire behavior itself when using the Rothermel spread model. Only the characteristics of fuel particles less than 3 inches (75 mm) in diameter are required to simulate fire behavior.

If held at a constant temperature and humidity, a dead fuel particle will eventually achieve its equilibrium moisture content (*EMC*). When temperature and/or humidity change – and therefore *EMC* changes – the moisture content of the fuel particle changes as well, but not instantaneously. The moisture content moves toward the new *EMC* value following an exponential function. After a few timelag periods, the moisture

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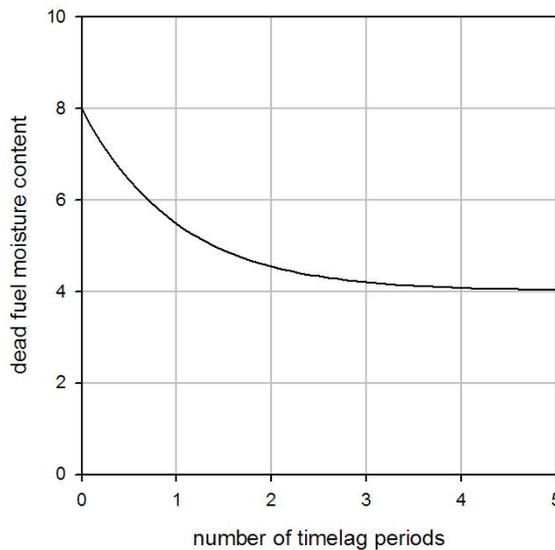
<sup>9</sup> Moisture fraction is used sometimes in the fire science literature but not in fire modeling applications.

content will have theoretically moved almost all the way to the new value (Table 1-3).

**Table 1-3**—Relative movement toward equilibrium moisture content as a function of the number of timelag periods. After just one timelag period, dead fuel moisture content will have moved 63.2 percent of the way from its original value to its equilibrium. After three timelag periods the moisture content is effectively equal to the equilibrium moisture content.

Number of timelag periods	Relative movement from current to equilibrium moisture content (percentage)
1	63.2
2	86.5
3	95.0
4	98.2
5	99.3

For example, let’s assume that dead fuel moisture content is currently 8 percent, and the equilibrium moisture content is 4 percent. After one timelag period, the moisture content will have fallen from 8 percent to 5.5 percent, and after three periods it is already down to 4.2 percent (Fig. 1-19).



**Figure 1-19**—During one timelag period, dead fuel moisture moves 63% of the way from the original fuel moisture to the new equilibrium moisture content.

How long does it take to reach the new *EMC* value in terms of hours? That depends on the diameter of the fuel particle, and that's where the timelag concept comes in. Smaller diameter fuel particles move more rapidly toward their *EMCs* than larger diameter particles. The rate of change is exponential—rapid at first, and then slower as the moisture content approaches *EMC* (Fig. 1-19). Timelag is the length of time required for the moisture content to change by an amount equal to about 63%<sup>10</sup>. A one-hour timelag fuel particle would gain or lose 63% of the difference between its current moisture content and its *EMC*. Ten-hour timelag particles take 10 hours to change by the same fraction.

Of course, *EMC* changes with temperature and humidity, so it is never constant for long enough to allow the fuel particle to actually come into equilibrium with it—*EMC* is a moving target that cannot be hit.

The timelag concept explains why fuel particle size classes are frequently labeled by timelag rather than by size class. Even though the timelag concept is not used in fire modeling systems, the size classes are still labeled as such—one-hour fuel load is the load of fuel particles less than 0.25 in diameter.

Live fuel moisture content values are assigned separately to three different live fuel categories; all three live fuel categories consist of fuel particles less than 0.25 in (6 mm) in diameter. Live herbaceous moisture content pertains to living, non-woody (grass and herbaceous) fuel particles. Live woody moisture content pertains to the leaves and fine stems (less than 0.25 in diameter) of shrubs and small trees in the surface fuel stratum. Live herbaceous and live woody moisture content are inputs to Rothermel's surface fire spread model. Foliar moisture content pertains to the needles of conifer trees in the canopy fuel stratum. Foliar moisture content is an input to Van Wagner's (1977) transition-to-crown fire model, which will be discussed in Chapter 9 of this guide.

The characterization of live and dead fuel moisture content is discussed in detail in Chapter 4 of this guide.

### *Slope characteristics*

Slope characteristics change at the geological time scale. With few notable exceptions (Mount St. Helens, for example), it is safe to assume that the slope characteristics present today will be here for the foreseeable future.

Two slope characteristics affect fire behavior simulations: slope steepness and aspect. Slope steepness is the vertical rise of terrain per unit of horizontal run. Slope steepness directly affects fire behavior: the steeper the slope, the faster and more intense the fire. Aspect is the compass direction that a slope faces. Aspect indirectly affects fire behavior by influencing dead fuel moisture and by interacting with wind direction. (At a coarser scale, aspect influences vegetation composition and therefore fuelbed structure.)

Slope characteristics are discussed in detail in Chapter 5 of this guide.

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<sup>10</sup> Why 63%? Because that is  $1-1/e$ , which comes from the formula for exponential decay.

### *Wind characteristics*

Wind characteristics vary greatly, even at very short time scales (seconds to minutes). Two wind characteristics are used in wildfire behavior simulations: wind speed and wind direction. Wind speed is the rate of movement of a parcel of air past a given point. There are two important considerations regarding the measurement of wind speed for fire behavior modeling: time-averaging and height above ground. The second important wind characteristic is wind direction—the direction that a parcel of air is travelling.

Wind characteristics are discussed in detail in Chapter 6 of this guide.

### *Relative spread direction*

The final element of the wildfire modeling pentagon is relative spread direction. The notion of relative spread direction—the angle between the flaming front orientation and the direction of maximum spread—was introduced in the “Morphology of a wildfire” section of this chapter. This section contains a few more details on how relative spread direction is used in fire behavior calculations.

The basic output of surface and crown fire spread rate models is applicable to the direction of maximum spread (the heading direction). Knowledge of relative spread direction (in combination with the length-to-breadth ratio of the assumed ellipse) allows a determination of the percentage of the maximum spread rate that occurs in the direction the flaming front is facing.

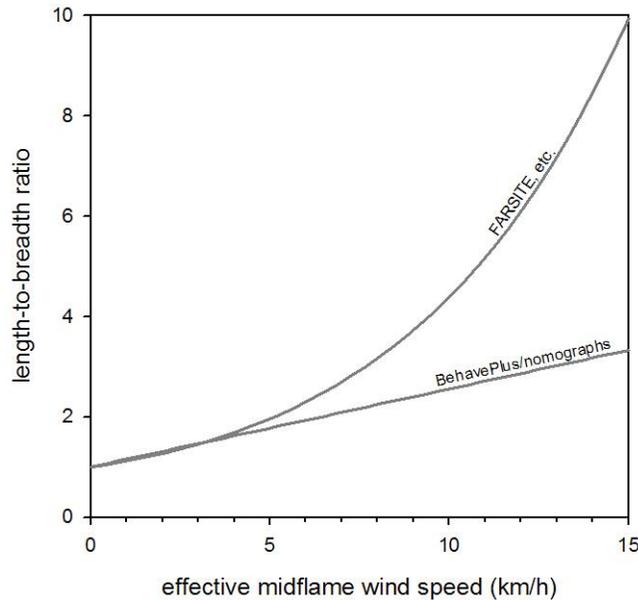
The length-to-breadth (L/B) ratio of an assumed elliptical fire has been related to effective mid-flame wind speed<sup>11</sup>. The higher the effective mid-flame wind speed, the more elongated the fire shape. Unfortunately, different fire modeling systems use different relationships between L/B ratio and effective mid-flame wind speed (Fig. 1-20).

The BehavePlus fire modeling system<sup>12</sup> uses a simple linear model (Andrews 1986), whereas Finney’s geospatial fire modeling systems (FARSITE, FlamMap, FSPro, and FSIM) use a modification of a different model (Anderson 1983). The fire behavior nomographs (Scott 2007) and the charts in this document are developed for the linear relationship that is implemented in the BehavePlus system. Results will vary in geospatial fire modeling systems.

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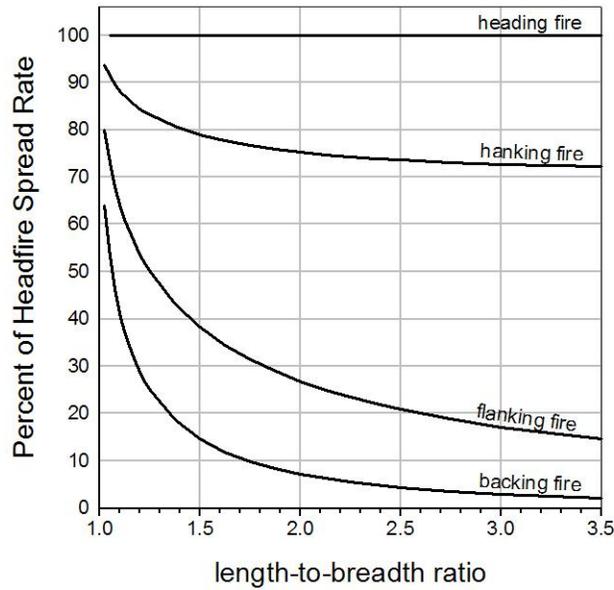
<sup>11</sup> Effective mid-flame wind speed is the combination of the effects of wind speed, slope steepness, and wind direction with respect to slope.

<sup>12</sup> Please see Appendix C for a summary of the fuel and fire behavior modeling software referenced in this chapter.



**Figure 1-20** – Two mathematical models of the length-to-breadth ratio of an assumed elliptical fire are used in fire behavior modeling systems. BehavePlus and the nomographs use a simple linear model, whereas geospatial fire modeling systems use a non-linear model. Results are functionally identical at effective mid-flame wind speeds below 5 km/h; above that wind speed, the model used in the geospatial systems predicts skinnier fires, which results in a greater decrease in fire behavior along the flanks of the fire compared to the model used in the nomographs and BehavePlus.

For the grassland fire environment described earlier (Table 1-1), the effective mid-flame wind speed is 10.5 km/h (6.5 mi/h). Using the BehavePlus relationship (Fig. 1-20), this means the L/B ratio is 2.6. The percentage of head fire spread rate that occurs at other parts of the fire perimeter is a function of the relative spread direction at each perimeter point. On the flank of this fire, where the relative spread direction is 90°, the ROS would be 20 percent of the head fire spread rate, 74 percent at the flank (45° relative spread direction), and 5 percent at the rear (Figure 1-21). The head fire spread rate is 50 m/min, so the resulting ROS values are adjusted accordingly (Table 1-4). For a more in-depth discussion of non-heading fire behavior, visit the Training section of [www.nifft.gov](http://www.nifft.gov), where you can learn about and register for the online course *Using Fire Behavior Nomographs to Estimate Fire Behavior Characteristics*.



**Figure 1-21** – Using the simple ellipse model of fire shape, spread rate around the perimeter of a fire can be related to the head fire spread rate. To use the chart, trace a vertical line from the X-axis, at the appropriate length-to-breadth ratio, to the desired spread direction—head, hank, flank, or rear (back). At the appropriate line, read the fraction of headfire spread rate from the Y-axis.

Note that *HPA* remains constant at these points around the perimeter, so *FLI* varies in direct proportion to *ROS*—if the *ROS* is reduced by half, so too is the *FLI*. Flame length is also affected by the reduction in *ROS* in non-heading directions, but not linearly because the relationship between *FLI* and *FL* is not linear (see Fig. 1-17).

**Table 1-4**—Tabulation of spread rate at four points on an assumed elliptically shaped wildfire for the grassland fire environment (Table 1-1).

Point on elliptical wildfire perimeter	Relative spread direction (degrees from maximum spread direction)	Percentage of head fire spread rate (Fig. 1-21)	Rate of spread (m/min)
Head	0	100	50
Hank	45	74	37
Flank	90	20	10
Rear	180	5	2.5

Geospatial fire modeling systems use this elliptical model. At every point on the landscape, the L/B ratio is determined from the effective mid-flame wind speed. Relative spread direction is determined from the orientation of the fire perimeter

relative to the direction of maximum spread. The simulated head fire spread rate is adjusted by the elliptical model in Figure 1-21 to obtain the spread-direction corrected spread rate.

## Chapter 1 summary

Combustion is a complex process in which fuel oxidizes rapidly, giving off heat in the process. Fire is a self-perpetuating form of combustion characterized by the emission of heat and accompanied by flame or smoke. Wildfire—better termed vegetation fire or landscape fire—is self-sustaining combustion in a vegetation-derived fuelbed.

Wildfires can attain complex shapes. There are two common ways of describing the morphology of a wildfire—by shape and by relative spread direction. For fire modeling, it is necessary to describe wildfire morphology by relative spread direction, which is the angle between the heading direction of a fire and the direction the flaming front faces. For a heading fire, the flaming front is facing directly in the heading direction. On the flank of a fire, the flaming front faces 90 degrees off of the heading direction (either clockwise or anti-clockwise). The flaming front at the rear of a fire faces directly opposite (180 degrees) the heading direction.

Flaming front rate of spread (*ROS*) is the linear rate of advance of a fire front into unburned fuel in the direction perpendicular to the fire front. Fireline intensity is the rate of heat release per unit width of fire front, regardless of its depth. Heat per unit area (*HPA*) is the amount of heat released per unit ground area during the relatively short duration of continuous flaming as the flaming front passes. Flame size is a measure of the physical dimension of flames (which themselves are the visible manifestation of rapid combustion), typically their length (*FL*).

Finally, the fire environment characteristics as illustrated in the fire behavior triangle—fuel, weather, and topography—have been reorganized into a pentagon of five major influences on wildfire behavior simulations. Fuelbed structure and slope characteristics are time-constant influences; they can be considered constant for all fire behavior simulations. Fuel moisture content and wind characteristics are time-varying influences related to weather. Except for very short duration fire simulations, the variability in dead fuel moisture and wind and direction must be considered. Finally, spread direction is a topological influence on fire behavior simulations, meaning that the spatial arrangement of the time-constant influences (as well as the temporal arrangement of time-varying influences) determines the orientation of the flaming front with respect to the heading direction as the fire front passes. Spread direction has a significant effect on simulated fire growth and behavior.

## Chapter 2: Characterizing Surface Fuel for Fire Behavior Modeling

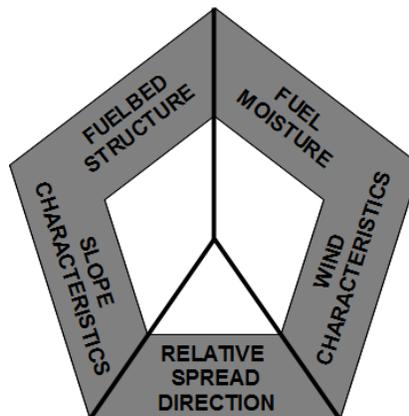
This chapter is presented in three sections. The first section is an overview of fire behavior fuel models as used in fire behavior modeling systems, including a description of the required fuel model parameters. The next section describes the standard fire behavior fuel models available for use in any fire modeling project. The final section describes the need for and use of custom fire behavior fuel models in the fire behavior modeling systems BehavePlus and NEXUS.

The objectives of Chapter 2 are to:

- list the components of a fire behavior fuel model,
- describe the history and characteristics of the original 13 fuel models,
- describe the history and characteristics of the 40 fuel models and their relationship to the original 13 fuel models,
- identify the reasons for using a custom fuel model,
- create and save a custom fuel model file in BehavePlus, and
- load and use a custom fuel model in NEXUS.

### Fire behavior fuel models

Recall from Chapter 1 that fuelbed structure functions as one of the five major influences on fire behavior simulations (Fig. 2-1). Fuelbed structure is comprised of surface fuel characteristics (described in this chapter) and canopy fuel characteristics (described in Chapter 3). Additional fuelbed structure characteristics are needed for modeling fire effects, including duff load and coarse woody debris characteristics. Those characteristics are not used in fire behavior modeling and are therefore not covered in this document.



**Figure 2-1** –The fire modeling pentagon illustrates the five major influences on fire behavior modeling simulations.

The Rothermel (1972) surface fire spread model is used in all fire modeling systems in the U.S. Therefore, the surface fuel characteristics that are needed to simulate wildland fire behavior are determined by the inputs for that model. The basic formulation of the Rothermel model consists of a small set of fuelbed inputs:

- Fine fuel load
- Fuelbed bulk density and packing ratio
- Fuelbed surface-area-to-volume (SAV) ratio
- Fuelbed heat content
- Moisture of extinction

This basic formulation was generalized to allow for the specification of fuel load and SAV ratio by size class and component (live and dead). Fuelbed bulk density and packing ratio are calculated from fuel load and fuelbed depth. The operational inputs to the spread model are therefore:

- Load of dead fuel particles up to 6 mm (0.25") diameter
- Load of dead fuel particles 6-25 mm (0.25-1.0") diameter
- Load of dead fuel particles 25-75 mm (1.0-3.0") diameter
- Load of live herbaceous fuel
- Load of fine live woody fuel (foliage and twigs up to 6 mm [0.25" diameter])
- SAV ratio of dead fuel particles less than 6 mm (0.25") diameter
- SAV ratio of live herbaceous fuel
- SAV ratio of live woody fuel
- heat content of dead fuel particles
- heat content of live fuel particles
- fuelbed depth
- dead fuel moisture of extinction

Rothermel called a complete set of these inputs a fire behavior fuel model. To aid in using the spread model, a set of 11 fire behavior fuel models was developed and published with the spread model in 1972. This set was revised and augmented by Albin (1976) and formalized by Anderson (1982), becoming what has been called the original 13 original fire behavior fuel models. A second complete set of fuel models, simply called the 40 fire behavior fuel models, was developed in 2005 by Scott and Burgan. These two fuel model sets are discussed in the following sub-sections.

According to Rothermel's definition, a fuel model includes all fuel inputs to the Rothermel surface fire spread model. Three fuel inputs have never been subject to control by a user when creating a custom fuel model: total mineral contents, effective mineral contents, and fuel particle density. In all fire behavior simulation systems that use the Rothermel model, total mineral content is 5.55 percent, effective (silica-free) mineral content is 1.00 percent, and oven-dry fuel particle density is 513 kg/m<sup>3</sup> (32 lb/ft<sup>3</sup>)<sup>13</sup>. In addition, the 10- and 100-hr SAV ratios were listed as model parameters for the original 13 fuel models, but they are generally not subject to control of the user

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<sup>13</sup> Please refer to Appendix B for a comprehensive listing of unit conversion factors for particle density and other quantities presented in this document.

when making custom fuel models in fire modeling systems. In all standard and custom fire behavior fuel models, the 10-hr dead fuel SAV ratio is  $3.58 \text{ cm}^2/\text{cm}^3$  ( $109 \text{ ft}^2/\text{ft}^3$ ), and the 100-hr SAV is  $0.098 \text{ cm}^2/\text{cm}^3$  ( $30 \text{ ft}^2/\text{ft}^3$ ).

### **Standard fire behavior fuel models**

Two separate sets of standard fire behavior fuel models are available for use in fire behavior modeling systems. These two sets are described in the following subsections.

#### *13 original fuel models*

Rothermel published 11 fuel models with his 1972 spread model. At that time, extinction moisture content was not listed for each fuel model separately, but instead was held at 30 percent for all models. Thus, variation in predicted spread rate among models could be attributed to fuel load by size class, fuelbed depth (and therefore bulk density and packing ratio), and fuel particle SAV ratio.

Albini (1976) refined those 11 fuel models and added two others: dormant brush and Southern Rough. His tabulated set became what is now called the “original” 13 fire behavior fuel models. Whereas extinction moisture content was held constant for Rothermel’s 11 fuel models, Albini’s fuel models specified this value separately for each fuel model. Like Rothermel, Albini noted that “other variables needed to complete the [fuel] descriptions are held constant for the entire set.”

Anderson (1982) described the 13 fuel models listed by Albini and provided aids to selecting a fuel model. Fuel model parameters did not change from Albini’s set. Anderson listed only fuel load by size class, fuelbed depth, and dead fuel extinction moisture.

The BEHAVE fire behavior prediction and fuel modeling system (Burgan and Rothermel 1984; Andrews 1986) included fuel heat content as a fuel parameter that could vary from model to model, whereas previously that parameter had been left constant. Geospatial fire modeling systems (Finney 1998) and BehavePlus (Andrews and others 2003) allow the user to specify separate live and dead heat content values. The ability to specify heat content is primarily employed for greater precision when building a custom fuel model; the original 13 fuel models still used a single value of  $18,622 \text{ kJ/kg}$  ( $8000 \text{ BTU/lb}$ ) for live and dead heat content for all fuel models.

Training on the original 13 fuel models is available in the National Wildfire Coordinating Group (NWCG) courses S-290, S-390, and S-490.

#### *40 fuel models*

The original 13 fire behavior fuel models are “for the severe period of the fire season when wildfires pose greater control problems...” (Anderson 1982). Those fuel models have worked well for predicting spread rate and intensity of active fires at the peak of the fire season in part because the associated dry conditions lead to a more uniform fuel complex—an important assumption of the underlying fire spread model (Rothermel 1972). However, they may be deficient for other purposes, including prescribed fire, wildland fire use, simulating the effects of fuel treatments on potential fire behavior, and simulating transition to crown fire using crown fire initiation models. Widespread

use of the Rothermel (1972) fire spread model and the desire for more options in selecting a fuel model led to the development of a set of 40 standard fire behavior fuel models (Scott and Burgan 2005).

Fuel models in the set of 40 are grouped by fire-carrying fuel type. The number of fuel models within each fuel type varies. Each fuel type has been assigned a mnemonic two-letter code. Non-burnable fuel models, even though not really a "fuel," were included in the set to facilitate consistent mapping of these areas on a fuel model map. Fuel types were ordered in a way similar to the original 13, with hybrid fuel types (such as Timber-understory) generally between the two types that comprise the hybrid. Fuel types are as follows:

- (NB) Non-burnable
- (GR) Grass
- (GS) Grass-shrub
- (SH) Shrub
- (TU) Timber-understory
- (TL) Timber litter
- (SB) Slash-blowdown

To facilitate both communication and computation, a two-part fuel model reference scheme was devised—a fuel model **number** (between 1 and 256, for use in computer code and mapping applications) and a fuel model **code** (three or four digits, used for oral and written communication and input to fire modeling systems). The fuel model number and fuel model code are directly related; the last digit of the fuel model code corresponds to the last digit of the fuel model number. For example, fuel model code GR1 is fuel model number 101.

Within each of the above fuel types, the fuel models are ordered (by number and code) by increasing heat per unit area at a reference fuel moisture condition (at 8 percent dead and 75 percent live fuel moisture content). Wind speed and slope steepness do not affect heat per unit area.

The dead fuel extinction moisture assigned to the fuel model defines the weighted-average dead fuel moisture content at which the fire will no longer spread in the Rothermel model. This modeling parameter is generally associated with climate (humid vs. dry), although fire science research has yet to fully explain the mechanism for the association. Fuel models for dry climates tend to have lower dead fuel moistures of extinction, while fuel models for humid-climate areas tend to have higher moistures of extinction. Fuel model names (and the fuel model selection guide) include reference to the general climate where the fuel model is found.

In the set of 40 fuel models, all fuel models that have a live herbaceous component are "dynamic," meaning that their herbaceous load is allocated dynamically between the live and dead components. More information on the dynamic fuel model process is included in Chapter 4. None of the original 13 fire behavior fuel models is dynamic.

More information on the 40 fuel models, including a guide to selecting a fuel model and a crosswalk from the original 13 fuel models, is available in the online course "Introduction to the 40 Fire Behavior Fuel Models" at [www.nifft.gov](http://www.nifft.gov).

## Custom fire behavior fuel models

Although the availability of 53 standard fire behavior fuel models covers a wide variety of surface fuelbeds, certain situations may still require the use of a custom fuel model. Reasons for using custom fuel models include:

- Slight modification to a standard fuel model is desired
- No standard fuel model produces the observed fire behavior characteristics
- Simulating fire behavior for specific fuel inventory parameters

Creating a custom fuel model is a difficult task. In most cases, the need for a custom fuel model is identified only after discovering significant differences between fire behavior observations and predictions made with one or more standard fuel models. The custom fuel model must be calibrated with those observations. A standard fuel model, on the other hand, should not be expected to match fire behavior observations perfectly because it has been designed for general application. Moreover, fire behavior simulation results are sensitive to small changes in fuel model parameters that are difficult to quantify (fuelbed depth, for example).

The following subsections demonstrate how to create and use custom fuel models in BehavePlus and NEXUS<sup>14</sup>.

Inputting custom fuel model parameters into BehavePlus and NEXUS is simple compared to coming up with the proper parameters<sup>15</sup>. For the following examples we will create a custom fuel model that is a variation of fuel model TL5. The custom fuel model will have exactly double the load in every class and component, and double the fuelbed depth. All other fuel model parameters will remain unchanged from TL5. We'll call this custom fuel model TL13 (193). Note that by doubling both the loads and the depth, fuelbed bulk density and packing ratio will remain unchanged. The fuel model parameters for standard fuel model TL5 and custom fuel model TL13 are listed in Table 2-1.

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<sup>14</sup> Please see Appendix C for an overview of the fuel and fire behavior modeling software referenced in this chapter.

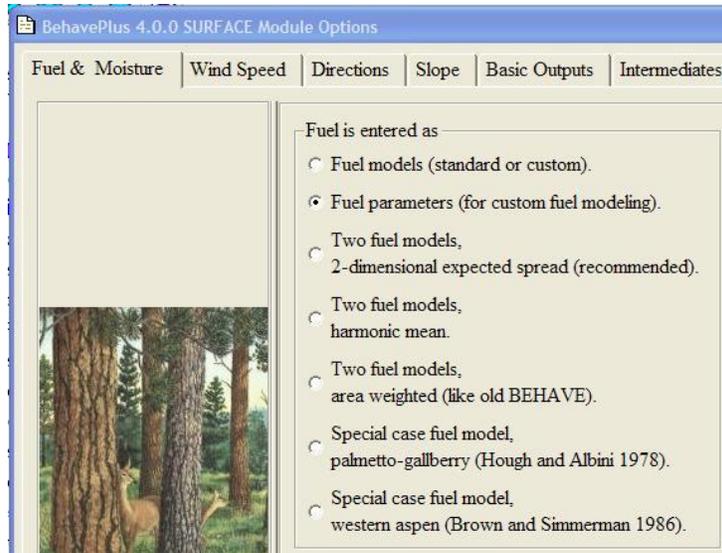
<sup>15</sup> Developing the parameters of a custom fuel model is a challenging task that is not covered in this document.

**Table 2-1** – Fuel model parameters for the standard fuel model TL5 and for a custom fuel model with exactly double the fuel load in each class and double the fuelbed depth.

	Standard fuel model TL5	Custom fuel model TL13
Fuel model type	“S”	“S”
1-hr fuel load (kg/m <sup>2</sup> )	0.2578	0.5156
10-hr fuel load (kg/m <sup>2</sup> )	0.5604	1.1208
100-hr fuel load (kg/m <sup>2</sup> )	0.9863	1.9726
Live herbaceous fuel load (kg/m <sup>2</sup> )	0.00	0.00
Live woody fuel load (kg/m <sup>2</sup> )	0.00	0.00
1-hr SAV ratio (cm <sup>2</sup> /cm <sup>3</sup> )	65.62	65.62
Live herbaceous SAV ratio (cm <sup>2</sup> /cm <sup>3</sup> )	n/a	n/a
Live woody SAV ratio (cm <sup>2</sup> /cm <sup>3</sup> )	n/a	n/a
Fuelbed depth (cm)	18.3	36.6
Dead fuel moisture of extinction (%)	25	25
Dead fuel heat content (kJ/kg)	18,622	18,622
Live fuel heat content (kJ/kg)	n/a	n/a

### *BehavePlus*

To create the custom fuel model TL13 in BehavePlus, first set the BehavePlus configuration to use fuel entered as fuel parameters, as follows: **Configure > Module Selection > Surface Fire Spread (SURFACE) Options > Fuel & Moisture tab > Fuel Parameters** (for custom fuel modeling). The properly set option on the Fuel and Moisture tab of the Surface Fire Spread dialog box is shown in Figure 2-2.



**Figure 22-2** – The SURFACE module options dialog box is used to specify how fuel is entered. To create a custom fuel model in BehavePlus, first set the “Fuel is entered as” button to “Fuel parameters (for custom fuel modeling)”.

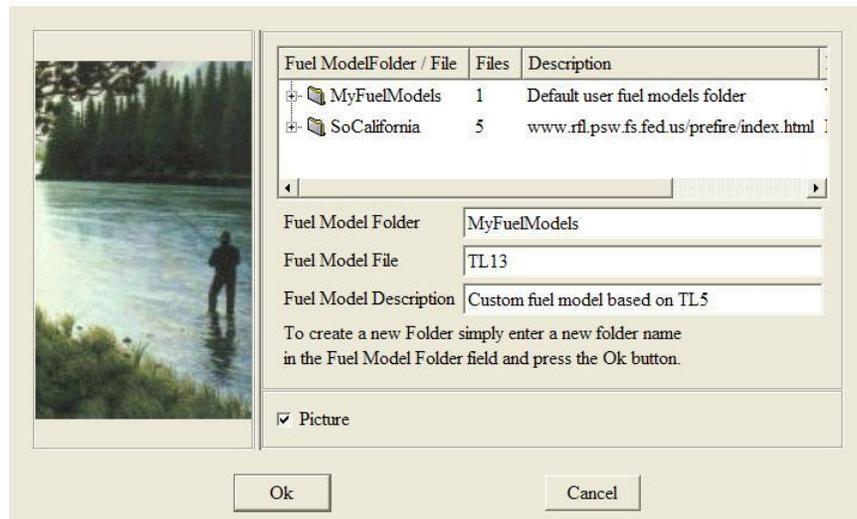
Next, enter the fuel model parameters for custom fuel model TL13 using the inputs listed in Table 2-1 above. The fuel model type is “S” (static) because there is no live herbaceous fuel to transfer. The fuel inputs should appear as shown in Figure 2-3.

Fuel/Vegetation, Surface/Understory		Initialize from a Fuel Model
Fuel Model Type		S
1-h Fuel Load	kg/m <sup>2</sup>	0.2578
10-h Fuel Load	kg/m <sup>2</sup>	0.5604
100-h Fuel Load	kg/m <sup>2</sup>	0.9863
Live Herbaceous Fuel Load	kg/m <sup>2</sup>	0.0000
Live Woody Fuel Load	kg/m <sup>2</sup>	0.0000
1-h SA/V	cm <sup>2</sup> /cm <sup>3</sup>	65.62
Live Herbaceous SA/V	cm <sup>2</sup> /cm <sup>3</sup>	
Live Woody SA/V	cm <sup>2</sup> /cm <sup>3</sup>	
Fuel Bed Depth	cm	18.3
Dead Fuel Moisture of Extinction	%	25
Dead Fuel Heat Content	kJ/kg	18622
Live Fuel Heat Content	kJ/kg	

**Figure 2-3** – Fuel model parameters for custom fuel model TL13 entered in BehavePlus.

Now, save these fuel model parameters to the BehavePlus format: **File > Save as a fuel model >BehavePlus format**. Save this custom fuel model in the MyFuelModels folder;

name it TL13 and give it a brief description (Fig. 2-4). Once you have saved the custom fuel model it is automatically available for selection in the current BehavePlus session<sup>16</sup>.



**Figure 2-4** – Dialog box for saving custom fuel model in BehavePlus.

The fuel model you just created, plus any others in the MyFuelModels folder, is now available for use in BehavePlus; it will now appear in the fuel model Input Guide after the 53 standard fuel models (Fig. 2-5).

185	tl5	High load conifer litter (S) (185)
186	tl6	Moderate load broadleaf litter (S) (186)
187	tl7	Large downed logs (S) (187)
188	tl8	Long-needle litter (S) (188)
189	tl9	Very high load broadleaf litter (S) (189)
201	sb1	Low load activity fuel (S) (201)
202	sb2	Moderate load activity or low load blowdown (S) (202)
203	sb3	High load activity fuel or moderate load blowdown (S) (203)
204	sb4	High load blowdown (S) (204)
TL13	TL13	Custom fuel model based on TL5

**Figure 2-5** – Custom fuel models appear below the standard fuel models in BehavePlus.

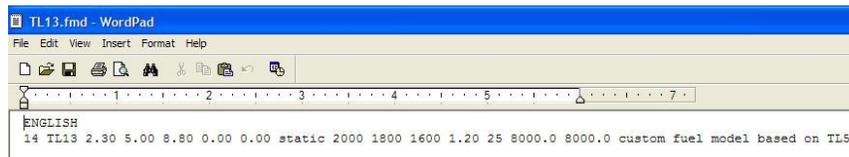
You may have noticed that BehavePlus can save the custom fuel model in FARSITE format. The FARSITE fuel model file format is also used by all geospatial fire modeling systems and NEXUS. To save a custom fuel model in the FARSITE format, go back and save the custom fuel model TL13: **File > Save as a fuel model > FARSITE format**.

<sup>16</sup> In later sessions, you will have to attach this fuel model before you can use it. To do so, select **Configure > Fuel model set selection > MyFuelModels**.

Navigate to a folder you can find again easily (typically not the default) and name the file “TL13” (the file extension “fmd” will be added automatically). The FARSITE file format is a simple text file. We’ll explore that format in the following section on NEXUS because it reads the same file format. BehavePlus does not allow the user to specify the fuel model number; we’ll edit the automatically created number later. Also note that the FARSITE format fuel model file is saved in English units, even though we entered metric units in BehavePlus.

### NEXUS

NEXUS uses the FARSITE file format for importing custom fuel models. It is an ASCII text file format, so creating or editing one is very easy. The file consists of two or more lines of ASCII text. The first line indicates whether the values are in English or metric units. Each of the following lines consists of 16 data fields, separated by one or more spaces. Each data line in the file represents a custom fuel model. Figure 2-6 below illustrates the contents of TL13.fmd, a fuel model file consisting of just one custom fuel model.



**Figure 2-6** – Contents of ASCII format TL13.fmd, a custom fuel model file created in BehavePlus.

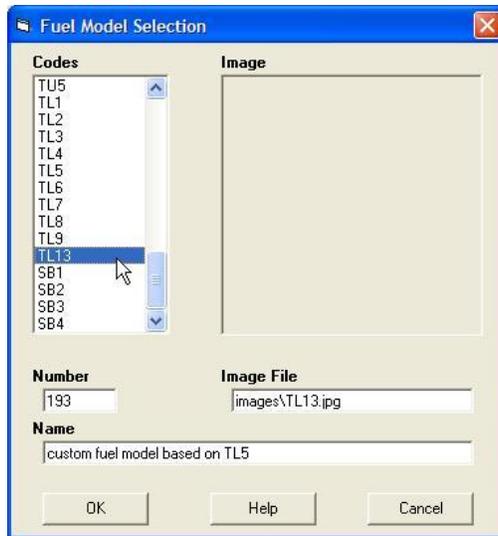
The fields, in order from left to right, are shown in Table 2-2 below.

**Table 2-2** – Fields in the FARSITE custom fuel model file, which is also used in NEXUS.

Field	Variable	English units	Metric units
1	Fuel model number	–	–
2	Fuel model code	–	–
3	1-hr dead fuel load	t/a	tonnes/ha
4	10-hr dead fuel load	t/a	tonnes/ha
5	100-hr dead fuel load	t/a	tonnes/ha
6	Live herbaceous fuel load	t/a	tonnes/ha
7	Live woody fuel load	t/a	tonnes/ha
8	Fuel model type	–	–
9	1-hr SAV ratio	ft <sup>2</sup> /ft <sup>3</sup>	cm <sup>2</sup> /cm <sup>3</sup>
10	Live herbaceous SAV ratio	ft <sup>2</sup> /ft <sup>3</sup>	cm <sup>2</sup> /cm <sup>3</sup>
11	Live woody SAV ratio	ft <sup>2</sup> /ft <sup>3</sup>	cm <sup>2</sup> /cm <sup>3</sup>
12	Fuelbed depth	ft	cm
13	Dead fuel extinction moisture	percent	percent
14	Dead fuel heat content	BTU/lb	kJ/kg
15	Live fuel heat content	BTU/lb	kJ/kg
16	Description	–	–

Notice that the TL13.fmd custom fuel model file contains only one custom fuel model – TL13 – which we created using BehavePlus in the previous section. BehavePlus automatically assigned a fuel model code of “14.” We want this fuel model to be number 193, which you can do by opening the file in any text editor, making the change, and then saving the edited file.

Let’s now attach this edited custom fuel model file to NEXUS by selecting **Tools > Custom fuel models**. Navigate to and select the TL13.fmd custom fuel model file. The fuel model is now available for use in NEXUS. To confirm this, click on the “Low FM” button to open the Fuel Model Selection dialog box. Scroll down to the TL fuel models; TL13 should be found between the TL and TU fuel models (Fig. 2-7) because this list is sorted by fuel model number.



**Figure 2-7** – The NEXUS fuel model selection dialog box. The fuel model list is sorted by fuel model number.

Results of BehavePlus and NEXUS simulations illustrate the effect of creating a custom fuel model that doubles the loads and depth, as we did with TL13. A detailed examination of Rothermel’s spread equation, shown later in Chapter 7, indicates that such a fuel model should experience exactly twice the spread rate and twice the HPA (see Chapter 1). Sure enough, these simulations—for 5 percent dead fuel moisture content, no slope, 5 mi/h mid-flame wind speed—show exactly that result (Fig. 2-8).

### TL5 vs. TL13

Fuel Model	ROS (max) ch/h	Heat per Unit Area Btu/ft <sup>2</sup>	Fireline Intensity Btu/ft/s	Flame Length ft
tl5	5.0	370	34	2.3
TL13	10.0	741	135	4.3

**Figure 2-8** – BehavePlus results for fuel model TL5 and custom fuel model TL13, which has double the fuel loads and double the fuelbed depth as TL5 – keeping bulk density identical for both fuel models. Five percent dead fuel moisture content, zero slope, and 5 mi/h mid-flame wind speed were used.

Now let’s take a look at the fireline intensity values. Fireline intensity is 4 times greater for TL13 than TL5, even though we only doubled the load and depth. Why would that be? It’s because fireline intensity is the product of spread rate and HPA, and each of those was itself doubled when using the custom fuel model. Therefore, fireline intensity

is proportional to the square of the load/depth factor. In this case, we doubled load and depth, so fireline intensity increases by a factor of  $2^2$ , or 4.

Finally, take a look at the flame length values. Flame length is not quite doubled, even though both spread rate and *HPA* were doubled. Why is that? Recall from Chapter 1 that flame length is a function of fireline intensity. Specifically, fireline intensity is raised to the power 0.46 in the equation, which is very nearly equal to the square root of fireline intensity. If the exponent were exactly equal to 0.5 – corresponding to the square root – then flame length would be doubled as well. Instead, flame length is proportional to just less than the load/depth factor, no matter the wind speed or fuel moisture used in the simulation.

### **Chapter 2 summary**

Fire behavior modeling systems used in the U.S. rely on Rothermel's surface fire spread model, which itself requires a host of fuelbed parameters. Those 13 parameters are organized into fuel models. Two sets of standard fire behavior fuel models are available: the original 13 and the new 40 fuel models. In addition, custom fuel models can be created for use in point-based and geospatial fire modeling systems.

Detailed information about the 40 fire behavior fuel models is available through a course developed and hosted by the National Interagency Fuels, Fire, and Vegetation Technology Transfer Team (NIFTT) at [www.nifftt.gov](http://www.nifftt.gov).

## Chapter 3: Characterizing a Forest Canopy for Fire Behavior Modeling

This chapter is presented in five sections that define and describe the five canopy characteristics as used in fire behavior simulations, including methods to estimate the characteristics.

The objectives of Chapter 3 are to:

- list, define, and describe five canopy characteristics and their use in surface and crown fire behavior modeling and
- describe methods of estimating of canopy characteristics.

Obtaining reliable estimates of forest canopy characteristics is essential for accurately simulating both surface and crown fire behavior in fire behavior modeling systems. Canopy characteristics influence surface fire behavior by sheltering the surface fuelbed from wind and sun, which reduces the wind speed measured 20 feet above the tree-top level to the mid-flame wind speed and affects dead fuel moisture content. Canopy characteristics influence crown fire occurrence and behavior by determining the environmental conditions that lead to crown fire initiation and spread.

There are five characteristics of a forest canopy that directly or indirectly influence simulations of surface or crown fire behavior (Table 3-1): canopy fuel load (*CFL*), canopy base height (*CBH*), stand height (*SH*), canopy bulk density (*CBD*), and canopy cover (*CC*).

**Table 3-1** – The primary and secondary effects of canopy characteristics on surface and crown fire behavior simulations.

Canopy characteristic	Primary effect(s)	Secondary effect(s)
Canopy fuel load (CFL)	<ul style="list-style-type: none"> <li>Crown fire intensity (NEXUS<sup>17</sup>)</li> </ul>	n/a
Canopy base height (CBH)	<ul style="list-style-type: none"> <li>Crown fire initiation (all modeling systems)</li> </ul>	<ul style="list-style-type: none"> <li>Active crown fire spread (geospatial systems<sup>18</sup>)</li> <li>Wind adjustment factor (BehavePlus)</li> </ul>
Stand height (SH)	<ul style="list-style-type: none"> <li>Wind adjustment factor (all modeling systems)</li> </ul>	<ul style="list-style-type: none"> <li>Spotting distance (FARSITE, BehavePlus)</li> </ul>
Canopy bulk density (CBD)	<ul style="list-style-type: none"> <li>Active crown fire spread (all modeling systems)</li> </ul>	n/a
Canopy cover (CC)	<ul style="list-style-type: none"> <li>Wind adjustment factor (all modeling systems)</li> <li>Dead fuel moisture (FARSITE, FlamMap)</li> </ul>	n/a

Each of these five canopy characteristics will be discussed in further detail in the following sections.

All of the methods of estimating these canopy characteristics involve calculations based on the use of a treelist to describe the nature and density of trees at a sample point. A treelist comprises a listing of the attributes of trees present in a sample area. At a minimum, the attributes included in a treelist include: species, tree expansion factor (the number of trees per unit area represented by the tree), diameter at breast height, tree height, and crown base height<sup>19</sup>. Additional tree attributes, such as crown position (crown class) and health status, may also be listed for each tree. Treelists are created by inventorying trees in a given area using established forest mensuration techniques. Databases of treelists are becoming available for use within fuel modeling systems.

<sup>17</sup> Canopy fuel load (CFL) is a direct input into NEXUS. In BehavePlus and the geospatial fire modeling systems, CFL is computed from canopy bulk density, canopy base height, and stand height.

<sup>18</sup> Most geospatial fire modeling systems in the have two crown fire modeling options: Finney (1998) and Scott and Reinhardt (2001). This secondary effect applies only when using the Finney (1998) crown fire modeling method.

<sup>19</sup> Crown base height is a property of an individual tree, whereas canopy base height is a property of the sample point or stand.

Throughout this chapter we will use an example treelist sampled using a 10-m fixed-radius plot in a stand composed of Douglas-fir and lodgepole pine on the Salmon-Challis National Forest in Idaho (Scott and Reinhardt 2005). Canopy bulk density was destructively sampled in 1-m deep layers at this site, so the additional step of estimating canopy biomass is not necessary for this example. The sample plot consisted of 65 living trees of just two species: Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) and lodgepole pine (*Pinus contorta* Douglas ex Loudon). Because all trees were sampled from a single fixed-radius plot, the tree expansion factor (*TEF*) is identical for each tree (Table 3-2). On fixed-area plots, *TEF* is the inverse of plot size. The plot was 10-m in radius, so its area is  $\pi \cdot 10^2 = 314.16 \text{ m}^2$ , or 0.031416 ha (0.0776 ac). The inverse of this is 31.83, so each tree recorded on this plot represents 31.83 trees per ha (12.88 trees per ac).

Diameter at breast height (*DBH*) is the diameter of the tree bole measured outside the bark at breast height (1.37 m; 4.5 ft) above ground. Tree height is the vertical distance from the ground to the tip of the tree. Crown base height is the vertical distance from the ground to the bottom-most branches of the tree crown. Crown position is a classification of relative tree position based on a tree crown's position relative to those of adjacent trees (Helms 1998).

**Table 3-2** – A basic treelist for a Douglas-fir / lodgepole pine stand on the Salmon-Challis National forest (Scott and Reinhardt 2005). Species codes: PSEMEN = Douglas-fir; PINCON = lodgepole pine. Crown position codes: S = suppressed; I = intermediate; C = codominant; D = dominant. Sixty-five live trees were present on a 10-m radius plot. Basal area is 37.67 m<sup>2</sup>/ha (164.1 ft<sup>2</sup>/ac), stem density is 2,069 trees per ha (837 trees per ac), and quadratic mean diameter is 15.2 cm (6.0 in).

Tree Number	Species	Expansion Factor (Trees/ha)	DBH (cm)	TH (m)	CBH (m)	crown position
1	PSEMEN	31.83	5.3	3.5	2.5	S
2	PSEMEN	31.83	20.1	14.0	2.0	C
3	PSEMEN	31.83	16.2	19.0	5.0	C
4	PSEMEN	31.83	21.0	20.4	5.7	C
5	PSEMEN	31.83	8.0	10.0	6.0	I
6	PSEMEN	31.83	29.1	21.0	10.0	C
7	PSEMEN	31.83	20.0	14.0	7.0	C
8	PSEMEN	31.83	9.4	10.0	3.0	I
9	PSEMEN	31.83	13.0	10.0	5.0	I
10	PSEMEN	31.83	23.3	15.0	8.0	C
11	PSEMEN	31.83	23.1	17.0	10.0	C
12	PSEMEN	31.83	4.5	5.0	1.5	S
13	PSEMEN	31.83	23.9	17.0	10.0	C
14	PSEMEN	31.83	4.1	5.0	2.0	S
15	PSEMEN	31.83	3.1	4.5	2.0	S
16	PSEMEN	31.83	15.4	12.0	5.0	C
17	PINCON	31.83	4.2	6.0	4.0	S
18	PSEMEN	31.83	18.5	18.0	4.0	C
19	PSEMEN	31.83	0.9	2.0	1.0	S
20	PSEMEN	31.83	24.3	17.2	8.0	C
21	PSEMEN	31.83	10.1	12.0	6.0	I
22	PSEMEN	31.83	32.6	14.5	8.0	C
23	PINCON	31.83	7.9	12.5	9.0	I
24	PSEMEN	31.83	11.7	12.5	8.0	I
25	PSEMEN	31.83	14.2	14.0	9.0	C
26	PSEMEN	31.83	27.6	17.0	9.0	C
27	PSEMEN	31.83	6.7	7.0	3.0	I
28	PSEMEN	31.83	8.7	8.0	5.5	I
29	PSEMEN	31.83	11.4	12.5	8.0	I
30	PSEMEN	31.83	9.2	7.8	1.0	I
31	PSEMEN	31.83	19.3	14.0	4.0	C
32	PINCON	31.83	24.3	16.0	3.0	C
33	PSEMEN	31.83	22.4	16.4	2.5	C
34	PSEMEN	31.83	8.5	10.0	7.0	I
35	PSEMEN	31.83	2.0	3.0	2.0	S
36	PSEMEN	31.83	23.1	16.0	8.0	C
37	PSEMEN	31.83	17.3	16.0	8.0	C
38	PSEMEN	31.83	3.5	4.0	2.5	S
39	PINCON	31.83	15.9	14.0	7.0	C
40	PSEMEN	31.83	8.5	8.5	1.5	I
41	PINCON	31.83	13.1	15.0	8.0	I
42	PINCON	31.83	14.9	15.0	8.0	I
43	PSEMEN	31.83	4.6	5.0	2.0	I
44	PSEMEN	31.83	2.4	4.0	3.0	S
45	PINCON	31.83	14.3	14.0	9.0	C
46	PINCON	31.83	8.0	12.5	8.0	I
47	PINCON	31.83	14.5	13.5	9.0	C
48	PSEMEN	31.83	23.1	13.6	7.0	C
49	PSEMEN	31.83	5.4	4.0	2.0	S
50	PSEMEN	31.83	3.2	3.5	1.5	S
51	PSEMEN	31.83	15.5	10.4	5.0	C
52	PSEMEN	31.83	3.9	6.0	2.0	S
53	PSEMEN	31.83	8.5	8.0	5.0	S
54	PSEMEN	31.83	11.5	7.0	2.0	I
55	PSEMEN	31.83	5.9	7.0	3.0	I
56	PINCON	31.83	18.5	14.0	9.0	C
57	PSEMEN	31.83	7.6	9.0	7.0	S
58	PINCON	31.83	13.5	11.0	7.0	I
59	PINCON	31.83	8.8	7.0	4.0	S
60	PSEMEN	31.83	13.7	10.4	6.0	I
61	PINCON	31.83	21.5	17.2	7.8	C
62	PINCON	31.83	14.0	14.6	8.0	C
63	PINCON	31.83	18.2	14.0	8.0	C
64	PSEMEN	31.83	7.2	10.0	7.0	S
65	PSEMEN	31.83	15.9	13.0	6.0	C

### Canopy fuel load (CFL)

Canopy fuel load (CFL) is the oven-dry mass of available canopy fuel per unit ground area. Available canopy fuel is that which is consumed in the short-duration flaming front of a crown fire. For the purposes of this guide, we will consider canopy fuel load to consist of live and dead foliage, 0- to 3-mm live branchwood, 0- to 6-mm dead branchwood, plus any lichen and moss. The contribution of foliage to canopy fuel load dominates available fine branchwood in the canopy fuel load for most conifer species; some analyses therefore include only foliage and do not consider the contribution of fine branchwood.

In fire modeling, canopy fuel load is used only to determine the canopy fuel contribution to the fireline intensity of a crown fire; the greater the CFL, the greater the canopy fuel contribution to fireline intensity. Only NEXUS requires this value as a direct user input; the other fire modeling systems estimate CFL from other canopy characteristics.

Canopy fuel load is also used in several methods of estimating canopy bulk density, described in a later section of this chapter.

#### *Estimating canopy fuel load*

Canopy fuel load is relatively simple to estimate from a treelist. A treelist contains the information about each tree needed to estimate its available biomass from allometric equations. Such equations relate measures of a tree's size (height, DBH) and other characteristics (species, crown position, etc.) to the biomass of its crown components: foliage and branchwood by diameter class. Canopy fuel load is estimated by summing the product of each tree's canopy fuel mass (kg) and its tree expansion factor across all trees in a treelist:

$$CFL_{plot} = \sum_i^n \frac{CF_i * TEF_i}{10000}$$

where  $i$  refers to each tree in a treelist. The factor "10,000" is needed to express CFL in kg/m<sup>2</sup>. For the example plot (Table 3-1), the available canopy fuel was sampled directly for a study of canopy fuel characteristics. The example calculations in this chapter use those measured values rather than estimates from allometric equations wherever possible. Canopy fuel load in the example stand was measured to be 2.09 kg/m<sup>2</sup> (Table 3-3) This value includes live 0-3 mm branchwood and dead 0-6 mm diameter branchwood. Foliage load alone was 1.59 kg/m<sup>2</sup> at the plot; Douglas-fir has a significant proportion of branchwood less than 3-mm diameter that is included as canopy fuel load.

The Canopy Fuel Stratum Characteristics Calculator (CFSCC) Version 1.0<sup>20</sup>, which implements the equations presented in Cruz and others (2003), estimates a CFL value of 1.45 kg/m<sup>2</sup> for this stand. The Cruz and others (2003) analysis included only foliage in

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<sup>20</sup> Canopy Fuel Stratum Characteristics Calculator Version 1.0 is an Excel spreadsheet that implements the equations presented in Cruz and others (2003) and is available at [www.frames.gov](http://www.frames.gov).

the biomass regression, so this result compares quite favorably with the measured 1.59 kg/m<sup>2</sup>.

**Table 3-3** – CFL for a Douglas-fir / lodgepole pine stand on the Salmon-Challis National Forest.

Calculation option		CFL (kg/m <sup>2</sup> )
A	$\sum \frac{CF * TEF}{10000}$	2.09
B	CFSCC Version 1.0	1.45

Although all fuel modeling software systems produce estimates of *CFL*, only the NEXUS fire behavior modeling system uses that input independently. The other systems—BehavePlus and the geospatial systems—compute *CFL* internally from other canopy characteristics by rearranging the equation used to calculate *CBD* by the box method.

$$CFL = CBD * (SH - CBH)$$

This is a reasonable method to use when *CFL* cannot be calculated directly in a fuel modeling system, but this method may overestimate *CFL* in certain circumstances. First, if *CBD* is estimated by the maximum running-mean method, as most fuel modeling systems currently do, then using this method will overestimate *CFL*. For example, the maximum running-mean *CBD* for the example treelist, as you will see later in this chapter, is 0.255 kg/m<sup>3</sup>; so, according to this equation, *CFL* would be estimated as 4.08 kg/m<sup>2</sup>—nearly double the actual value.

Fortunately, *CFL* is not a critical crown fire behavior simulation parameter; it is used only to estimate the contribution of canopy fuel to crown fire intensity. It is not an input used in any other calculation, so the consequence of any error is small. Nonetheless, dividing such estimates of *CFL* by two is likely to produce estimates of *CFL* that more closely match the treelist calculation.

### Canopy base height (*CBH*)

Canopy base height (*CBH*) is the lowest height above the ground at which there is sufficient canopy fuel to propagate fire vertically; if foliage can be ignited at this height, then a tree or small group of trees is assumed to torch. *CBH* is a property of a plot, a stand, or a group of trees, not of an individual tree (which would be the crown base height). For fire behavior modeling, *CBH* is an effective value that incorporates ladder fuel, such as tall shrubs, small understory trees, low-hanging branches, lichen, moss, and needle drape. No direct, repeatable field measurement of *CBH* exists; different observers will estimate different values in the same stand, often considerably so.

The primary influence of *CBH* is on the determination of environmental conditions needed for crown fire initiation. The lower the *CBH*, the milder the conditions can be in order to initiate a crown fire. Secondarily, in geospatial modeling systems, *CBH* also determines the incidence and ultimate spread rate of active crown fires (when using the

native Finney 1998 crown fire simulation method). Lower *CBH* leads to more prevalent and faster-spreading active crown fires. In addition, *CBH* affects the with-cover wind adjustment factor in BehavePlus. Higher *CBH* means there is less foliage beneath the canopy to interfere with the wind, so wind adjustment factor is greater.

### *Estimating canopy base height*

Stand- or plot-level *CBH* is only generally observable in the field—different observers can make drastically different estimates—so indirect measurement from a treelist is recommended. Several options for estimating *CBH* from a treelist exist (Table 3-4).

**Table 3-4** – *CBH* estimates for the Douglas-fir / lodgepole pine stand example plot using a variety of methods.

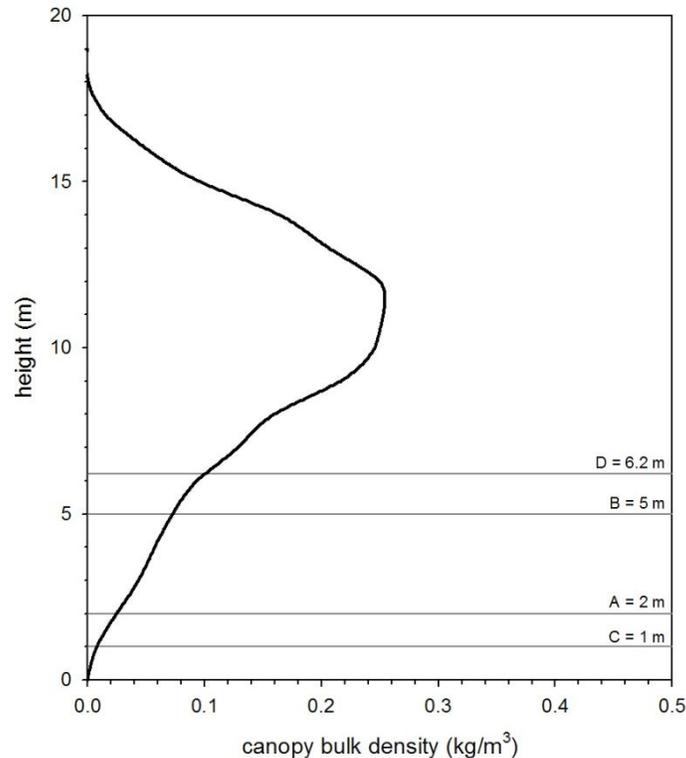
Calculation option		<i>CBH</i> (m)
A	25 <sup>th</sup> percentile tree crown base height	2.0
B	Mean tree crown base height	5.0
C	Height of threshold CBD	1.0
D	CFSCC (Version 1.0)	6.2

The simplest treelist method is to estimate the stand-level *CBH* by summarizing the individual crown base height values in the treelist. For example, *CBH* has been estimated as the 25<sup>th</sup> percentile crown base height (2.0 m for the example treelist) or the mean crown base height (5.0 m). Cruz and others (2003) produced regression equations for estimating *CBH* from summary characteristics of a plot (basal area and mean tree height<sup>21</sup>). For this example, stand BA = 37.67 m<sup>2</sup>/ha and mean tree height = 11.3 m, producing a *CBH* estimate of 6.2 m.

Using a method adapted from Sando and Wick (1972), *CBH* has been calculated—based on a vertical distribution of canopy fuel (Fig. 3-1)—as the lowest height above the ground at which at critical density of available canopy fuel is present (Reinhardt and Crookston 2003; Scott and Reinhardt 2005).

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<sup>21</sup>Cruz and others (2003) list this parameter as stand height, but a subsequent clarification (Cruz and others 2011) indicates that the variable is best described as mean tree height (including all trees of any size in the calculation). Measures of stand height typically focus on the dominant overstory trees in a plot and exclude sub-dominant trees.



**Figure 3-1** – Canopy base height as estimated using several methods for a destructively sampled canopy fuel profile for a Douglas-fir / lodgepole pine stand on the Salmon-Challis National Forest. The 25<sup>th</sup> percentile crown base height (A) is 2 m. The mean crown base height (B) is 5 m. The height above ground where canopy bulk density exceeds 0.01 kg/m<sup>3</sup> (C) is 1 m. The CFSCC Version 1.0 estimates *CBH* for this stand as 6.2 m.

In this case, the threshold bulk density is reached at a height of just 1 m.

The profile of canopy bulk density needed to estimate *CBH* by this treelist method can be estimated using the FuelCalc, FFE-FVS, and FMAPlus software programs. These programs automatically calculate *CBH* as the height at which a threshold *CBD* is reached.

Because of the difficulty of defining a repeatable measure of *CBH*, and because of the wide range of estimates produced by different indirect measures, it is sometimes identified by working backwards from observed or expected crown fire initiation to the *CBH* that would produce that result. In other words, if experience suggests that a certain fire fuel complex would experience a transition to crown fire under a certain fuel moisture and wind speed combination, then the *CBH* that produces that result can be assigned to the fuel complex.

*CBH* is a difficult parameter to observe or measure, and is also difficult to map because it is not well related to landscape characteristics that can be measured with remote sensing. It is among the least reliable fire modeling inputs to estimate, so adjustment of this parameter may be necessary in order to obtain reasonable fire modeling results.

## Stand height (*SH*)

Stand height can be defined as the average or typical height of the largest trees in a forest stand.

Stand height primarily influences the wind adjustment factor as simulated in all fire modeling systems. Taller forest stands lead to greater reduction of wind speed. Secondly, *SH* influences spotting distance in geospatial modeling systems and BehavePlus. Taller trees can lead to longer spotting distances because the embers are lofted higher.

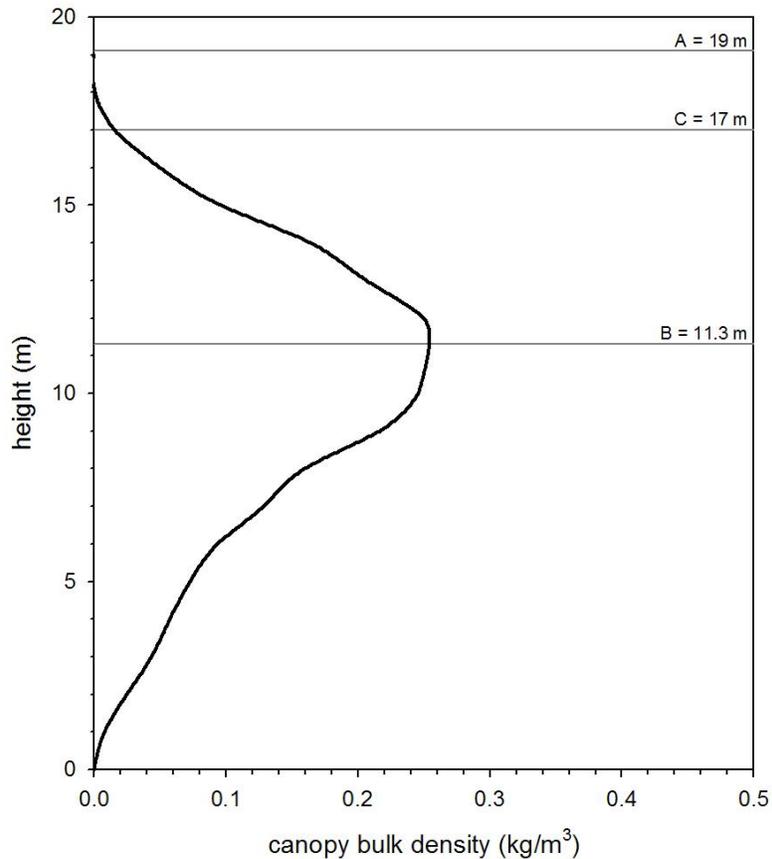
### *Estimating stand height*

In the field, *SH* can be estimated by computing the average height of a sample of the dominant (or tallest) trees in the stand. In our example, the average of the five tallest trees (A) was 19.1 m (Fig. 3-2). The mean height of all trees on the plot (B) was just 11.3 m. This is not a common measure of stand height, but we have included it here because it is the definition used by Cruz and others (2003). Notice that for this example stand, the mean tree height falls very near the height at which the greatest bulk density occurs, and more than 40% of the *CFL* occurs above this height.

**Table 3-5** – Stand height for a variety of calculation options.

Calculation option		<i>SH</i> (m)
A	Mean of 5 tallest trees	19.1
B	Mean <i>tree height</i>	11.3
C	Height of threshold <i>CBD</i>	17

The vertical profile of available canopy fuel provides a method of estimating *SH* analogous to the estimation of *CBH*. Rather than find the height where the profile first exceeds a threshold bulk density value, for *SH* we find the height where the profile falls below the same threshold (C). In this example, that height is 17 m. Methods A and C are adequate for determining stand height for use in fire behavior modeling systems.



**Figure 3-2** – Three estimates of stand height (SH) for a Douglas-fir / lodgepole pine stand on the Salmon-Challis National Forest.

### Canopy bulk density (CBD)

Canopy bulk density (CBD) is the mass of available canopy fuel per unit canopy volume (Scott and Reinhardt 2001). Canopy bulk density is a bulk property of a plot, stand, or group of trees, not of an individual tree. Basic methods for estimating canopy bulk density use a treelist in conjunction with allometric equations to predict individual-tree biomass. The biomass data are then summarized by any of several methods to provide an estimate of bulk density or to create a vertical profile of bulk density in horizontally thin layers.

Canopy bulk density is used to predict whether an active crown fire is possible. The product of canopy bulk density and rate of spread is mass-flow rate; a minimum mass-flow rate is hypothetically required to maintain an active crown fire.

Canopy bulk density influences fire behavior simulations by determining the environmental conditions needed to sustain an active crown fire. The higher the CBD, the milder the conditions can be (lower wind speeds, higher fuel moistures) in order to sustain active crown fire spread through the forest canopy.

### Estimating canopy bulk density

Like *CBH*, *CBD* is a bulk property of a stand of trees—including the gaps between trees—not of an individual tree. There are two general methods for calculating *CBD*: the maximum running-mean method and the box method.

**Table 3-6** – *CBD* estimates for the example plot for a variety of calculation options.

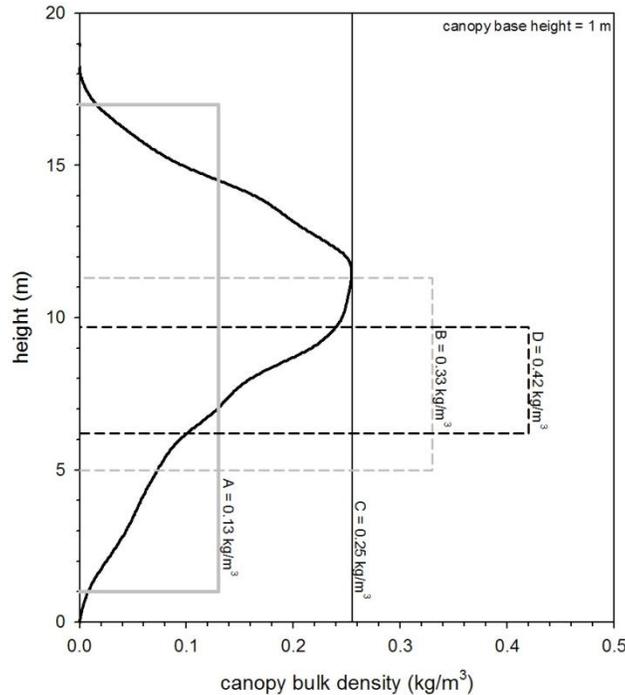
Calculation option		<i>CBD</i> (kg/m <sup>3</sup> )
A	$\frac{CFL}{(SH - CBH)}$	0.13
B	$\frac{CFL}{\text{mean}CL}$	0.33
C	Maximum running mean <i>CBD</i>	0.26
D	CFSCC Version 1.0	0.42

The box method (Table 3-6, options A and B) is the simplest estimation of *CBD*; simply divide canopy fuel load (*CFL*) by canopy depth (*CD*). Canopy depth can be estimated in several ways. As seen in Figure 3-1 (option A), *CD* can be determined from *SH* and *CBH*, so

$$CBD = \frac{CFL}{SH - CBH}$$

This calculation results in the average bulk density of the vertical fuel profile shown previously in Figure 3-1. On that chart, the area “under the curve”—to the left of the curve in this case—represents *CFL*. This calculation method is equivalent to making a rectangle of the same area (see Fig. 3-3). For the example stand, *CFL* was 2.09 kg/m<sup>2</sup>, *SH* was 17 m, and *CBH* was 1 m, so *CBD* calculated with this method is 0.13 kg/m<sup>3</sup>.

$$CBD = \frac{2.09 \text{ kg/m}^2}{(17 - 1)\text{m}} = 0.13 \text{ kg/m}^3$$



**Figure 3-3** – Canopy fuel profile with a rectangular box of area equivalent to the area under the profile curve. The location of this box on the X-axis indicates the estimated CBD. In this example, CBD is 0.13 kg/m<sup>3</sup>.

Alternatively, Cruz and others (2003) calculated canopy depth as the mean crown length. For this example, mean crown length is 6.3 m, so an estimate of *CBD* by that approach would be

$$CBD = \frac{2.09 \text{ kg/m}^2}{6.3 \text{ m}} = 0.33 \text{ kg/m}^3$$

Note that this estimate of *CBD* is greater than the highest bulk density anywhere in the profile, indicating that mean crown length is perhaps not a good indicator of canopy depth. Cruz and others (2003) produced equations to estimate *CBD* from stem density and basal area. That equation results in an estimate of 0.42 kg/m<sup>3</sup>, higher still than simply applying their method to the fuel profile data.

Note that the actual profile does not exhibit uniformity like the assumed rectangle of the box methods. No plot, not even a plantation with trees of uniform size, results in such a uniform vertical fuel profile. There is always a peak layer within the vertical fuel profile. In this example, the profile was smoothed with a running-mean of 3-m depth, so the peak represents the maximum running-mean *CBD*; individual layers could have a slightly larger *CBD* value. Following the hypothesis that crown fire spread could be controlled by the density of the densest layers of the canopy (not the average density as indicated option A), FuelCalc, FFE-FVS and FMAPlus all estimate plot-level *CBD* as this maximum running-mean *CBD*. For the example in Figure 3-3, the density of the densest layers corresponds to a value of 0.255 kg/m<sup>3</sup>, nearly double that of the box method, but still much lower than the estimate from the Cruz and others equation.

FFE-FVS, FuelCalc, and FMAPlus all estimate CBD using the maximum running-mean method. The Canopy Fuel Stratum Characteristics Calculator Version 1, option D, uses a method based on calculations using the box method (option B). The LANDFIRE program ([www.landfire.gov](http://www.landfire.gov)) has produced nationwide geospatial data of *CBD* using a prototype version of FuelCalc, which also uses the maximum running-mean method.

### Canopy Cover (*CC*)

Canopy cover is the relative amount of ground area covered by the vertical projection of tree crown perimeters. Canopy cover is commonly expressed as a percentage of total ground area. For example, at 50 percent canopy cover, half of the total ground area is covered by the vertical projection of tree crowns. Unless otherwise specified, canopy cover refers to non-overlapping canopy cover. Two overlapping tree crowns are not counted twice, so the theoretical maximum attainable canopy cover value is 100 percent. Values of overlapping canopy cover, used in ecological applications, can exceed 100 percent.

Canopy cover is not synonymous with canopy closure, which is a point measure of canopy coverage or an ecological measure of site occupancy by vegetation—a canopy can be “closed” (fully occupied) at less than 100 percent canopy cover.

Fire modeling systems use *CC* (in conjunction with *SH*) to estimate the with-cover wind adjustment factor; the greater the cover, the greater the reduction in wind speed. Canopy cover also influences simulations of dead fuel moisture content when using the fuel moisture tables or any of the geospatial modeling systems. The greater the canopy cover, the greater the shading and the higher the dead fuel moisture content will be.

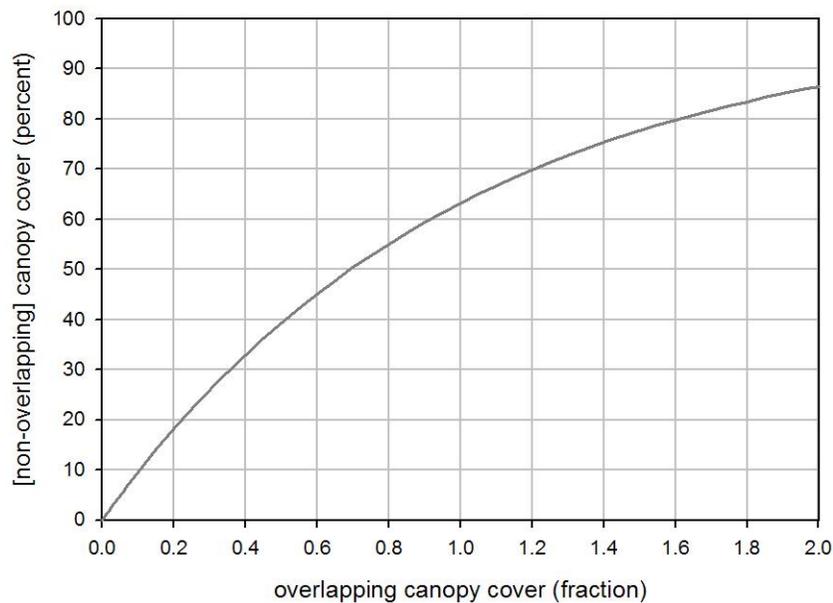
#### *Estimating canopy cover*

Canopy cover can be estimated in the field using a variety of tools ranging from handheld densitometers to hemispherical photography and other light-sensing techniques. Canopy cover can also be calculated from treelist data. From the treelist, the crown area (*CA*) for each tree is first estimated from a regression equation. Next, the overlapping canopy cover (*OCC*) is estimated by summing *CA* for all trees on the plot. For *CA* in meters and *TEF* in hectares, the *OCC* equation divides by 10,000 to result in a fraction.

$$OCC = \sum_i^n \frac{TEF_i * CA_i}{10000}$$

An *OCC* fraction of 1.0 means that the total overlapping crown area equals the ground area. Finally, the canopy cover (percent) is estimated from the overlapping canopy cover (Fig. 3-4). Canopy cover is estimated using this method in FFE-FVS and FuelCalc.

$$CC = 100 * (1 - e^{-OCC})$$



**Figure 3-4** – Estimating non-overlapping canopy cover (percent) from overlapping canopy cover (fraction) in FFE-FVS and FuelCalc.

### Chapter 3 summary

Five characteristics of a forest canopy are essential fuel characteristics for integrating surface and crown fire behavior simulations: canopy base height, canopy bulk density, canopy fuel load, canopy cover, and stand height. These fire modeling inputs affect everything from dead surface fuel moisture and wind adjustment factor to crown fire initiation and spread.

A variety of field-based methods forestimating these characteristics is available. In addition, the fuel modeling software systems FFE-FVS, FuelCalc, and FMAPlus estimate these characteristics from treelist data.

## Chapter 4: Characterizing Fuel Moisture Content

This chapter is presented in four sections. The first section describes methods of estimating dead fuel moisture content for use in fire modeling systems. The next section describes live herbaceous moisture content, its use in dynamic fuel modeling, and its uniquely strong effect on fire simulations. The third section describes live woody fuel moisture content and its influence on fire behavior simulations. The final section describes foliar moisture content and its use in fire simulations.

The objectives of Chapter 4 are to:

- define and describe dead fuel moisture content,
- describe the relative importance of timelag class fuel moisture contents on surface fire behavior in Rothermel's (1972) surface fire spread model,
- list two general methods of estimating dead fuel moisture content for fire behavior modeling,
- define and describe live herbaceous moisture content and its influence on fire behavior simulations,
- define and describe live woody moisture content and its influence on fire behavior simulations, and
- define and describe foliar moisture content and its influence on fire behavior simulations.

Chapter 1 identified fuel particle moisture content as a time-varying influence on fire behavior. While both dead and live fuel particles vary temporally in moisture content, they do so at different rates and in response to different factors. Dead fuel moisture content in fine fuel particles (less than ¼-inch in diameter) can change significantly in just one hour, responding to ambient temperature and relative humidity. Live fuel particles do not change so quickly. Typically, live herbaceous, live woody, and live foliage fuel particles change their moisture content in response to plant life-cycle events that take place over the course of weeks to months.

### Dead fuel moisture content

In Chapter 1 we introduced the concept of fuel particle timelag and timelag classes—1-hr, 10-hr, and 100-hr—where the timelag represents the time it takes a fuel particle to change 63% of the difference between the current moisture content and the equilibrium moisture content. Coarser (larger diameter) dead fuel particles change moisture content more slowly than finer fuel particles.

Dead fuel moisture is estimated from environmental factors such as temperature, relative humidity, time of day, slope steepness, and aspect. Two dead fuel moisture content estimation approaches are in common use. First is the use of tables for

estimating fine dead fuel moisture produced at the Rocky Mountain Station for use in the S-390 Introduction to Wildland Fire Behavior Calculations course. These tables were meant for field use by Fire Behavior Analysts and have therefore been called “FBA tables” for estimating fine dead fuel moisture. The tables were published in Rothermel’s 1983 guide on fire behavior prediction. The tables are still in use in BehavePlus and NEXUS, so we will discuss them briefly in this chapter. The second approach is the use of a mathematical dead fuel moisture simulation model (Nelson 2000), which is available for use in geospatial fire modeling systems such as FARSITE and FlamMap. Unfortunately, that same moisture model is not embedded within any non-geospatial fire behavior modeling system, so learning the model’s sensitivity to its inputs is difficult. In this chapter, we provide generic simulations with that model to illustrate its sensitivity.

### *Relative importance of 1-, 10- and 100-hr timelag class moisture contents*

Although fire behavior modeling systems require the input of moisture content values for the 1-, 10-, and 100-hr timelag classes, those separate values are condensed into a single characteristic value before use in the surface fire spread model<sup>22</sup>. Those three separate moisture content (*MC*) values are combined into a characteristic *MC* value by computing a weighted average, where the weighting factors are the relative contribution of each class to the overall fuel particle surface area of the fuelbed. The 1-hr timelag class has much more surface area per unit mass or volume than the 10-hr class particles, and the 10-hr particles have more surface area than the 100-hr particles. The relative weighting factors on the three timelag classes depend on the fuel load in each class and on the surface-area-to-volume (*SAV*) ratio for each class.

Let’s illustrate this weighted-average calculation for fuel model GS2, which has load in both live herbaceous and live woody classes. The herbaceous load in GS2 is dynamic, meaning that its fuel load is allocated to live and dead categories. For this example, we’ll assume that half of the herbaceous load is dead and the remaining half is live. Therefore, fuel load by class and component is as shown in Table 4-1 below.

Fuel particle volume per unit fuelbed area is derived by dividing fuel load by fuel particle density, a constant at 513 kg/m<sup>3</sup>. Multiplying that value by fuel particle *SAV* ratio produces the total fuel particle surface area per unit fuelbed area for each class. Finally, the dead fuel particle weighting factor is the fuel particle surface area for the class divided by the total dead fuel particle surface area for all size classes in the dead fuel category. A separate calculation produces weighting factors for the live herbaceous and live woody classes.

For this example, dead herbaceous fuel receives 33.9% of the weight, dead 1-hr timelag particles receive 62.7%, and 10-hr particles 3.4% (100-hr particles receive no weight because this class is not present in GS2). By convention, dead herbaceous fuel particles are given the same *MC* as 1-hr timelag particles, so the effective weight given to the 1-hr timelag *MC* is 96.6%.

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<sup>22</sup> Likewise, live herbaceous and live woody moisture content values are collapsed into a single effective value representing live fuel.

Assuming the 1-hr timelag class *MC* is 4% and the 10-hr *MC* is 6%, the characteristic dead fuel *MC* is 4.1%—nearly identical to the 1-hr timelag class because so much of the fuel particle surface area is in the dead herbaceous and dead 1-hr classes.

Similarly, live herbaceous fuel accounts for 23.1 % of the live fuel surface area, and live woody fuel accounts for the remaining 76.9%. Assuming live herbaceous *MC* is 75 percent and live woody *MC* is 90 percent, the characteristic live fuel *MC* is 86.5 percent.

**Table 4-1** – Calculation of weighted-average dead fuel moisture content for fuel model GS2. For this and all other fuel models, the weighted average moisture content is nearly identical to the 1-hr moisture content value because most of the weight is placed on that class.

Fuel particle category	Fuel particle class	Fuel load (kg/m <sup>3</sup> )	Fuel particle volume per unit fuelbed area (m <sup>3</sup> /m <sup>2</sup> )	Fuel particle SAV ratio (m <sup>2</sup> /m <sup>3</sup> )	Fuel particle SA per unit fuelbed area (m <sup>2</sup> /m <sup>2</sup> )	Fuel particle class weighting factor	Moisture content (percent)
Dead fuel	herb	0.0673	0.0001312	5905	0.775	0.3387	4
	1-hr	0.1121	0.0002187	6562	1.435	0.6272	4
	10-hr	0.1121	0.0002187	358	0.078	0.0342	6
	100-hr	0.0000	0.0000000	98	0.000	0.0000	8
	<b>subtotal</b>	<b>0.2914</b>	<b>0.0005685</b>	<b>6127</b>	<b>2.288</b>	<b>1.0000</b>	<b>4.1</b>
Live fuel	herb	0.0673	0.0001312	5905	0.775	0.2308	75
	woody	0.2242	0.0004373	5905	2.583	0.7692	90
	<b>subtotal</b>	<b>0.2914</b>	<b>0.0005685</b>	<b>5905</b>	<b>3.357</b>	<b>1.0000</b>	<b>86.5</b>

Note that the dead fuel weighting factors depend primarily on the allocation of fuel load among the timelag classes, but also on the level amount of herbaceous load allocated to the dead fuel category. In fuel models with an herbaceous component, as the level of curing changes so do the weighting factors on dead fuel timelag classes.

Weighting factors for each of the standard fuel models are listed in Table 4-2 below (under the assumption that herbaceous components are fully cured).

**Table 4-2** – Weighting factors used to combine 1-, 10-, and 100-hr timelag class moisture contents into a single characteristic dead fuel moisture content. Live herbaceous fuels are assumed to be fully cured. With few exceptions, the moisture content of the 1-hr timelag class dominates the calculation of characteristic dead fuel moisture content.

Fuel model	Weighting factors		
	1-h	10-h	100-h
1	1.00	0.00	0.00
2	0.98	0.02	0.00
3	1.00	0.00	0.00
4	0.95	0.04	0.01
5	0.97	0.03	0.00
6	0.89	0.09	0.02
7	0.89	0.09	0.02
8	0.94	0.03	0.02
9	0.99	0.01	0.00
10	0.94	0.03	0.02
11	0.77	0.17	0.06
12	0.75	0.19	0.06
13	0.76	0.18	0.06
GR1	1.00	0.00	0.00
GR2	1.00	0.00	0.00
GR3	0.98	0.02	0.00
GR4	1.00	0.00	0.00
GR5	1.00	0.00	0.00
GR6	1.00	0.00	0.00
GR7	1.00	0.00	0.00
GR8	0.99	0.01	0.00
GR9	0.99	0.01	0.00
GS1	1.00	0.00	0.00
GS2	0.97	0.03	0.00
GS3	0.99	0.01	0.00
GS4	1.00	0.00	0.00
SH1	0.97	0.03	0.00
SH2	0.90	0.09	0.01
SH3	0.69	0.31	0.00
SH4	0.93	0.07	0.00
SH5	0.92	0.08	0.00
SH6	0.93	0.07	0.00
SH7	0.80	0.18	0.02
SH8	0.80	0.19	0.01
SH9	0.96	0.04	0.00
TU1	0.84	0.11	0.05
TU2	0.89	0.09	0.02
TU3	0.99	0.01	0.00
TU4	1.00	0.00	0.00
TU5	0.92	0.07	0.01
TL1	0.85	0.10	0.05
TL2	0.90	0.08	0.02
TL3	0.76	0.18	0.06
TL4	0.78	0.13	0.10
TL5	0.85	0.10	0.05
TL6	0.97	0.03	0.01
TL7	0.60	0.15	0.24
TL8	0.98	0.01	0.00
TL9	0.96	0.03	0.01
SB1	0.82	0.09	0.09
SB2	0.94	0.05	0.01
SB3	0.97	0.03	0.01
SB4	0.95	0.03	0.01

Note that with few exceptions, the moisture content of the 1-hr timelag class dominates the calculation of characteristic dead fuel moisture content. Nearly half of the standard fuel models give a weight of at least 0.95 to the 1-hr timelag class; 95% of the fuel

models give the 1-hr timelag class a weight of at least 0.75. In other words, size matters; smaller fuel particles matter a whole lot more than larger particles when computing the characteristic dead fuel moisture content value<sup>23</sup>. In fire behavior modeling, this means that we can focus our effort on estimating the 1-hr timelagMC, because the 10- and 100-hr timelagclass MCs have relatively little influence on fire behavior simulations.

### Fuel moisture tables

The FBA fuel moisture tables refer to “fine dead fuel moisture,” not to any specific timelag size class. Fine dead fuel moisture can be assumed equivalent to the 1-hr and 10-hr timelag classes. Because those two classes dominate the calculation of characteristic MC, the fuel moisture tables can also be used to approximate the characteristic MC used in Rothermel’s surface fire spread model. As such, the FBA tables can be applied to all three timelag classes in fire behavior modeling systems<sup>24</sup>.

When using the fuel moisture tables, estimated fine dead fuel moisture content is the sum of reference fuel moisture and a moisture correction. Reference fuel moisture is a function of air temperature and relative humidity. As can be seen in Figure 4-1, relative humidity has a much stronger effect on reference fuel moisture than air temperature does.

		RELATIVE HUMIDITY (PERCENT)																				
Dry Bulb Temperature (°F)		0	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
		4	9	14	19	24	29	34	39	44	49	54	59	64	69	74	79	84	89	94	99	
10 - 29		1	2	2	3	4	5	5	6	7	8	8	8	9	9	10	11	12	12	13	13	14
30 - 49		1	2	2	3	4	5	5	6	7	7	7	8	9	9	10	10	11	12	13	13	13
50 - 69		1	2	2	3	4	5	5	6	6	7	7	8	8	9	9	10	11	12	12	12	13
70 - 89		1	1	2	2	3	4	5	5	6	7	7	8	8	8	9	10	10	11	12	12	13
90-109		1	1	2	2	3	4	4	5	6	7	7	8	8	8	9	10	10	11	12	12	13
109+		1	1	2	2	3	4	4	5	6	7	7	8	8	8	9	10	10	11	12	12	12

**Figure 4-1** – Reference fuel moisture table. The reference dead fuel moisture content can be derived by locating the intersection of temperature and relative humidity. Note that relative humidity has a much greater effect on reference moisture content than air temperature. The final estimated fine dead fuel moisture content is determined by adding a correction to the reference moisture content.

For example, the reference moisture content for a relative humidity of 25 percent and temperature of 85 degrees Fahrenheit is 4 percent.

<sup>23</sup> See BehavePlus tip

([http://www.firemodels.org/downloads/behaveplus/tips/BehavePlus\\_Tips-CharMois.pdf](http://www.firemodels.org/downloads/behaveplus/tips/BehavePlus_Tips-CharMois.pdf)) on the relative importance of 1- and 10-hr moisture content values.

<sup>24</sup> BehavePlus allows the user to specify a single MC value for the dead fuel category that is equivalent to specifying the same MC value to each of the three classes separately.

The moisture correction is a function of season, time of day, elevation of the projection point relative to the weather observation<sup>25</sup>, slope steepness class, aspect, and whether the fuelbed is shaded (by a forest canopy or persistent cloud cover). Separate tables are provided for: early summer (May, June, July), spring and fall (February, March, April; August, September, October), and early winter (November, December, January). Although the reference moisture content table is designed for universal application, the dead fuel moisture content correction tables are tuned for use in the mid-latitudes of the northern hemisphere.

To use the dead fuel moisture content correction tables, first decide whether the dead fuels are shaded (greater or less than 50% shaded). The top half of the table will be used for exposed fuelbeds, and the bottom half for shaded fuelbeds.

For exposed fuelbeds, identify the set of three columns associated with the specified time of day and intersect that with the pair of rows associated with the specified aspect. Doing so narrows the results down to six possible results. Choose the result associated with the specified slope steepness and whether the projection point is located above, level with, or below the weather observation used for the reference condition. For shaded fuelbeds, follow the same procedure, noting that slope is not a factor.

For example, if it is late afternoon (between 4 and 6 pm) in early summer (May, June or July) and the projection point is at the same level as the weather observation used in the reference condition on a steep, un-shaded slope on a south aspect, then the moisture correction is 1 percent. The final estimate of fine dead fuel moisture content is the reference fuel moisture plus the moisture correction:  $4 + 1 = 5$  percent.

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<sup>25</sup> The weather observation should be within 2,000 vertical feet of the projection point.

**DEAD FUEL MOISTURE CONTENT CORRECTIONS**

**MAY JUNE JULY**

		EXPOSED - LESS THAN 50% SHADING OF SURFACE FUELS																		
		0800 >			1000 >			1200 >			1400 >			1600 >			1800 >			
		B	L	A	B	L	A	B	L	A	B	L	A	B	L	A	B	L	A	
N	0-30%	2	3	4	1	1	1	0	0	1	0	0	1	1	1	1	1	2	3	4
	31%+	3	4	4	1	2	2	1	1	2	1	1	2	1	2	2	3	4	4	
E	0-30%	2	2	3	1	1	1	0	0	1	0	0	1	1	1	2	3	4	4	
	31%+	1	2	2	0	0	1	0	0	1	1	1	2	2	3	4	4	5	6	
S	0-30%	2	3	3	1	1	1	0	0	1	0	0	1	1	1	1	2	3	3	
	31%+	2	3	3	1	1	2	0	1	1	0	1	1	1	1	2	2	3	3	
W	0-30%	2	3	4	1	1	2	0	0	1	0	0	1	0	1	1	2	3	3	
	31%+	4	5	6	2	3	4	1	1	2	0	0	1	0	0	1	1	2	2	
		SHADED - GREATER THAN OR EQUAL TO 50% SHADING OF SURFACE FUELS																		
N	0%+	4	5	5	3	4	5	3	3	4	3	3	4	3	4	5	4	5	5	
E	0%+	4	4	5	3	4	5	3	3	4	3	4	4	3	4	5	4	5	6	
S	0%+	4	4	5	3	4	5	3	3	4	3	3	4	3	4	5	4	5	5	
W	0%+	4	5	6	3	4	5	3	3	4	3	3	4	3	4	5	4	4	5	

NOTE: A = 1000'-2000' above site  
 L = ±1000' of site location  
 B = 1000'-2000' below site

Figure 4-2 – Table of dead fuel moisture content corrections for the months of May, June, and July in the mid-latitudes of the northern hemisphere.

**DEAD FUEL MOISTURE CONTENT CORRECTIONS**

**FEBRUARY MARCH APRIL/AUGUST SEPTEMBER OCTOBER**

		EXPOSED - LESS THAN 50% SHADING OF SURFACE FUELS																		
		0800 >			1000 >			1200 >			1400 >			1600 >			1800 >			
		B	L	A	B	L	A	B	L	A	B	L	A	B	L	A	B	L	A	
N	0-30%	3	4	5	1	2	3	1	1	2	1	1	2	1	2	3	3	3	4	5
	31%+	3	4	5	3	3	4	2	3	4	2	3	4	3	3	4	3	3	4	5
E	0-30%	3	4	5	1	2	3	1	1	1	1	1	2	1	2	3	3	3	4	5
	31%+	3	3	4	1	1	1	1	1	1	1	2	3	3	4	5	4	5	6	
S	0-30%	3	4	5	1	2	2	1	1	1	1	1	1	1	2	3	3	3	4	5
	31%+	3	4	5	1	2	2	0	1	1	0	1	1	1	2	2	3	4	5	
W	0-30%	3	4	5	1	2	3	1	1	1	1	1	1	1	2	3	3	3	4	5
	31%+	4	5	6	3	4	5	1	2	3	1	1	1	1	1	1	3	3	4	
		SHADED - GREATER THAN OR EQUAL TO 50% SHADING OF SURFACE FUELS																		
N	0%+	4	5	6	4	5	5	3	4	5	3	4	5	4	5	5	4	5	6	
E	0%+	4	5	6	3	4	5	3	4	5	3	4	5	4	5	6	4	5	6	
S	0%+	4	5	6	3	4	5	3	4	5	3	4	5	3	4	5	4	5	6	
W	0%+	4	5	6	4	5	6	3	4	5	3	4	5	3	4	5	4	5	6	

**Figure 4-3** – Table of dead fuel moisture content corrections for the early spring (February, March, and April) and early fall (August, September, and October) in the mid-latitudes of the northern hemisphere.

**DEAD FUEL MOISTURE CONTENT CORRECTIONS**

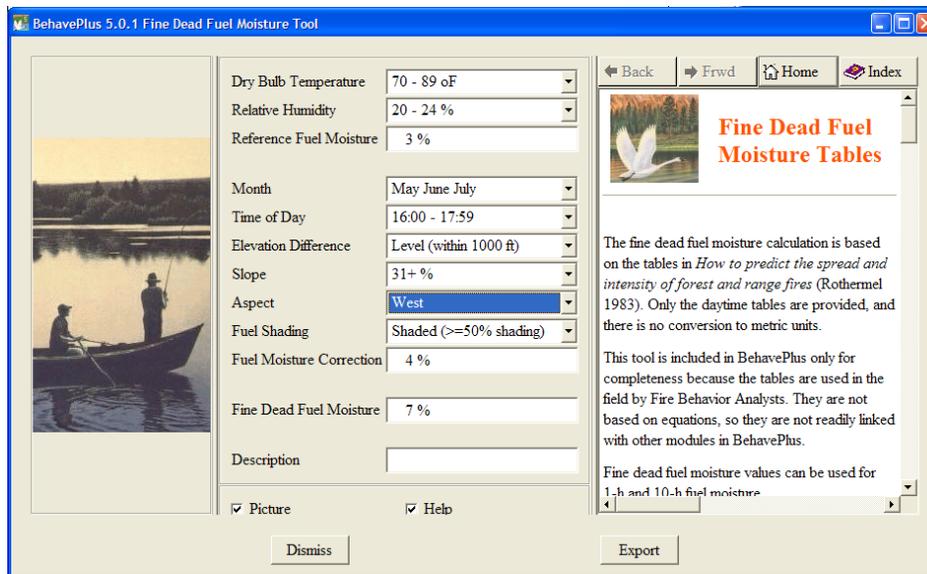
**NOVEMBER DECEMBER JANUARY**

		EXPOSED – LESS THAN 50% SHADING OF SURFACE FUELS																	
		0800 >			1000 >			1200 >			1400 >			1600 >			1800 >		
		B	L	A	B	L	A	B	L	A	B	L	A	B	L	A	B	L	A
N	0-30%	4	5	6	3	4	5	2	3	4	2	3	4	3	4	5	4	5	6
	31%+	4	5	6	4	5	6	4	5	6	4	5	6	4	5	6	4	5	6
E	0-30%	4	5	6	3	4	4	2	3	3	2	3	3	3	4	5	4	5	6
	31%+	4	5	6	2	3	4	2	2	3	3	4	4	4	5	6	4	5	6
S	0-30%	4	5	6	3	4	5	2	3	3	2	2	3	3	4	4	4	5	6
	31%+	4	5	6	2	3	3	1	1	2	1	1	2	2	3	3	4	5	6
W	0-30%	4	5	6	3	4	5	2	3	3	2	3	3	3	4	4	4	5	6
	31%+	4	5	6	4	5	6	3	4	4	2	2	3	2	3	4	4	5	6
		SHADED – GREATER THAN OR EQUAL TO 50% SHADING OF SURFACE FUELS																	
N	0%+	4	5	6	4	5	6	4	5	6	4	5	6	4	5	6	4	5	6
E	0%+	4	5	6	4	5	6	4	5	6	4	5	6	4	5	6	4	5	6
S	0%+	4	5	6	4	5	6	4	5	6	4	5	6	4	5	6	4	5	6
W	0%+	4	5	6	4	5	6	4	5	6	4	5	6	4	5	6	4	5	6

**Figure 4-4** – Table of dead fuel moisture content corrections for the months of November, December, and January in the mid-latitudes of the northern hemisphere.

The fuel moisture tables are presented here because they are still useful for getting a ball-park idea of fine dead fuel moisture content for use in non-spatial fire behavior modeling applications as well as because they are used to estimate fine dead fuel moisture in the Cruz and others (2005) crown fire spread rate model described in Chapter 8. Geospatial fire modeling systems such as FlamMap and FARSITE use Nelson’s (2000) mathematical model, which is described in the next section.

In BehavePlus, the fuel moisture tables are accessed through the **Tools > Fine Dead Fuel Moisture** menu option. Selections are made using drop-down menus; results are updated automatically after each variable is selected.



**Figure 4-5** – Fine dead fuel moisture utility within BehavePlus. To access the utility, select **Tools > Fine Dead Fuel Moisture**.

In NEXUS, the fine dead fuel moisture tables are accessed through the **Tools > FBA Tables** menu option. As in BehavePlus, selections are made using drop-down menus, and results are updated automatically after each variable is selected.

The screenshot shows a window titled "Moisture Table Lookup" with the following parameters:

- Day or Night?: Day time
- Temperature: 80 fahrenheit
- Humidity: 22 %
- Reference FM: 3 %
- Season: Summer
- Shading: Shaded
- Time of day: 4pm - 6pm
- Elevation: Level
- Aspect: West
- Slope: Flat/Steep
- FM correction: 4 %
- Fine Dead FM: 7 %

Buttons for "Help" and "Exit" are located at the bottom of the window.

**Figure 4-6** – Fine dead fuel moisture utility within NEXUS. To access the utility, select **Tools > FBA Tables**.

### *Fuel conditioning*

Fuel conditioning is a feature of geospatial fire modeling systems in which fine dead fuel moisture content is simulated, both temporally and geospatially, based on terrain, vegetation cover, season, latitude, and near-term weather history. Weather factors include temperature, relative humidity, precipitation amount and timing, and cloud cover. Terrain factors include slope steepness, aspect, and elevation (which is used to adjust temperature and relative humidity adiabatically to elevations different from the elevation of the weather observations). Season (date) determines day length and, in conjunction with latitude, solar radiation.

The main purpose of fuel conditioning is to establish realistic dead fuel moisture content values across a heterogeneous landscape: Moisture content in fuelbeds on north slopes should be different than those on south slopes, fuelbeds under dense forest cover different than exposed fuelbeds, and so on. Secondly, fuel conditioning allows for the simulation of MC at different points in time. Dead fuel MC is driest at different times of the day, on different aspects, and in different seasons. Although fuel conditioning is an optional feature of geospatial fire modeling systems, it is so important to fire behavior modeling that it should be included in every simulation.

Geospatial fire behavior modeling systems use Nelson's (2000) fuel moisture model to simulate moisture content of the 10-hr timelag class. Although Nelson's model can also be used to simulate 1-hr timelag MC, it would be very computationally intensive to do

so. Instead, geospatial fire modeling systems estimate 1-hr MC as a weighted average of the simulated 10-hr MC and the 10-hr equilibrium moisture content (EMC)

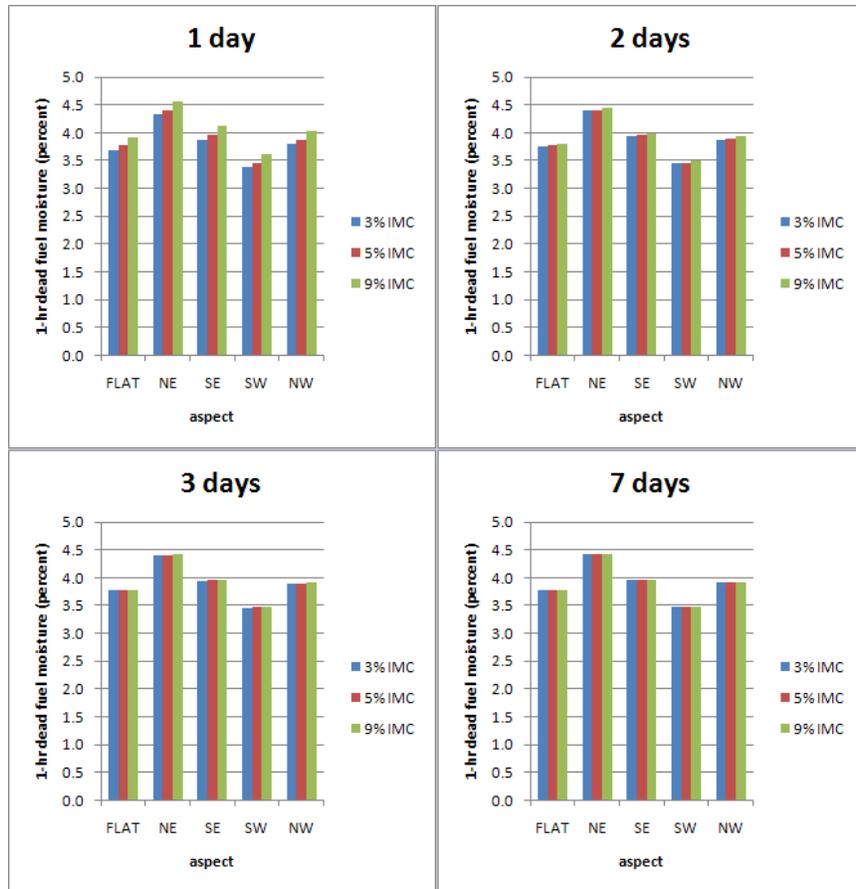
$$MC_{1h} = 0.2 * MC_{10h} + 0.8 * EMC_{10h}$$

where 20 percent of the weight is placed on the 10-hr MC and the remaining 80 percent of the weight is placed on the equilibrium 10-hr MC.

To illustrate the sensitivity of 1-h MC as it is simulated in geospatial fire modeling systems, it was simulated using FlamMap for a series of identical days, each of which reaches a high of 90 degrees Fahrenheit, a low relative humidity (RH) of 10 percent, and which had 10 percent cloud cover. Overnight low temperature was 60° F with recovery to 50% RH. Conditioning period ranged from one day to seven days. Initial 10-hr dead fuel moisture content ranged from 5% to 11%<sup>26</sup>. Results shown below are for 2 pm on a 40% slope with 50% canopy cover.

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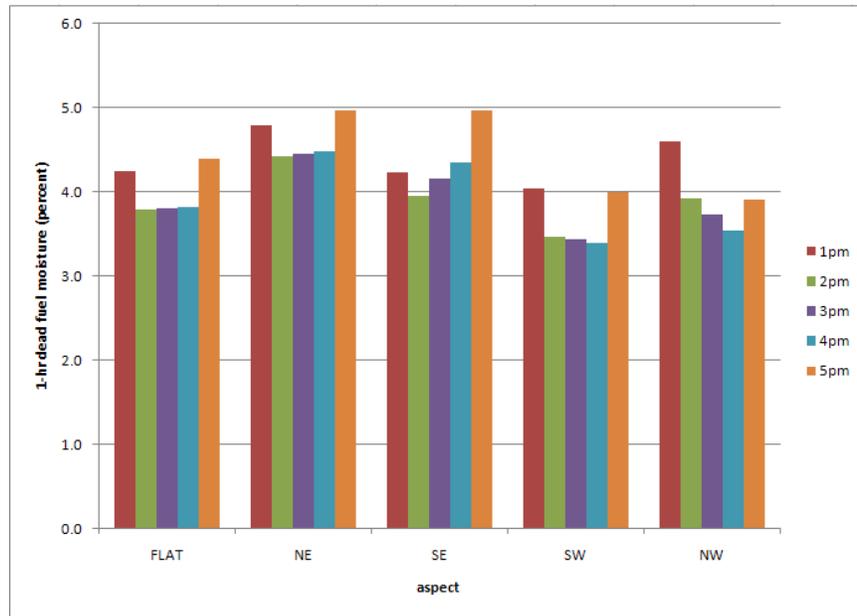
<sup>26</sup> Recall that FlamMap simulates 1-hr MC as a function of 10-hr MC, so initialization of fuel conditioning is based on the 10-hr value rather than the 1-hr value.



**Figure 4-7**– Effects of initial MC and length of conditioning period on 1-hr timelag class moisture content. Final 1-hr MC stabilizes after just 1-3 days, regardless of initial MC. Inputs: 50 percent canopy cover, 40 percent slope, 2 pm, hot, dry conditions.

After just one day of fuel conditioning, 2 pm 1-hr dead fuel MC has nearly equilibrated, even though the initial MC value varies from the ultimate value. Improvements in fuel moisture estimates by lengthening the conditioning period are insignificant after two days.

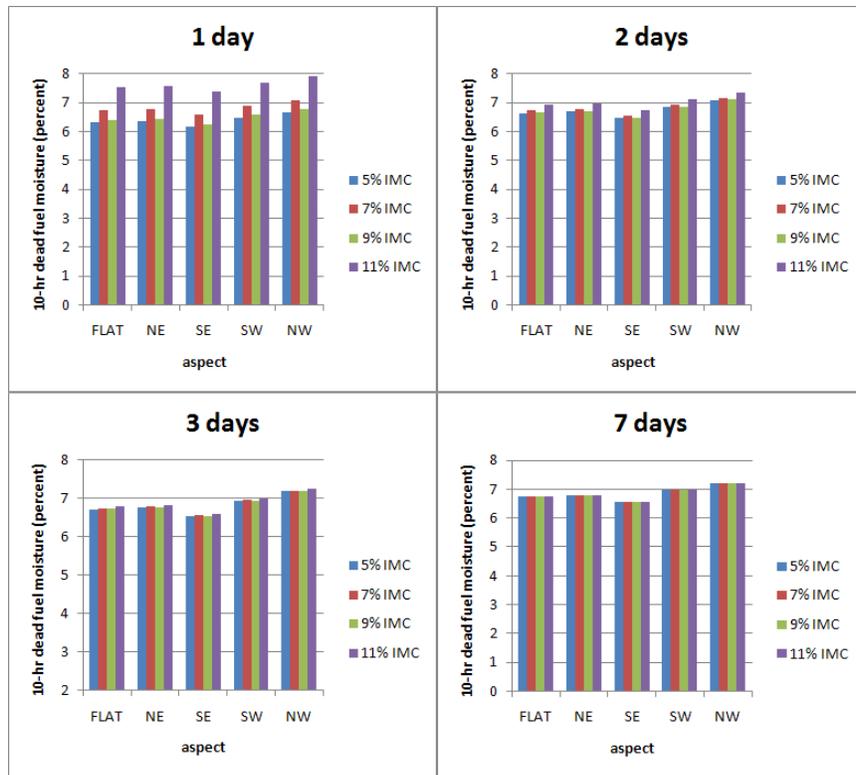
The above results are for 2 pm in early July. What about other times of day?



**Figure 4-8** – Effect of time of day on 1-hr timelag class moisture content. Different aspects experience their lowest 1-hr MC at different times of day, and moisture content can change quickly in just one hour.

The time of day for the end of the conditioning period appears to hold more significance in determining 1-hr dead fuel MC than does the initial MC or the length of the conditioning period. Depending on aspect, 1-hr dead fuel MC can jump more than half a percentage point. For example, on a SW aspect, MC increases from 3.4 percent to 4.0 percent between 4pm and 5pm. This would have a much greater effect on simulated fire behavior than the very small errors associated with initial MC values and short conditioning periods.

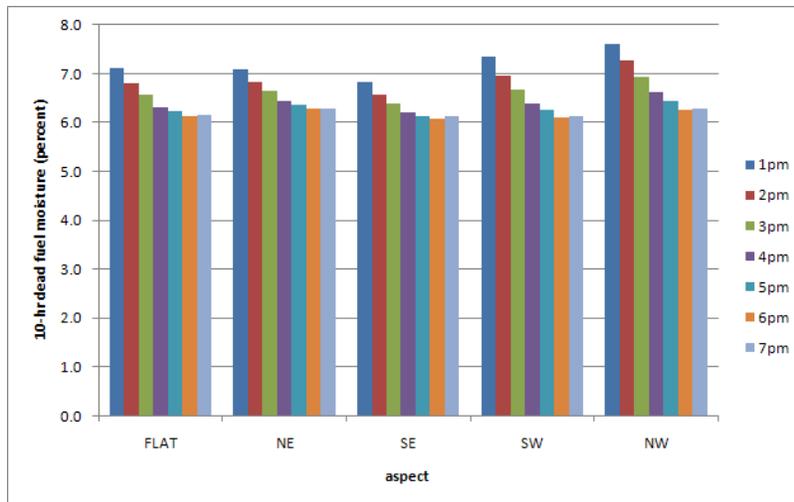
10-hr timelag fuel particles respond more slowly to diurnal weather patterns, but the practical results are the same as for the 1-hr timelag class.



**Figure 4-9** – Effects of initial MC and length of conditioning period on 10-hr timelag class moisture content. Final 10-hr MC stabilizes after about 3 days, regardless of initial MC. Inputs: 50 percent canopy cover, 40 percent slope, 2 pm, hot, dry conditions.

After seven days, the 10-hr fuels are fully conditioned, but after just two days, the 10-hr class fuel particles are sufficiently conditioned for use in fire behavior modeling.

Time of day affects 10-hr fuel particles, too. These coarser fuel particles continue to lose moisture content later into the afternoon and evening than the finer 1-hr timelag particles.



**Figure 4-10** – Effect of time of day on 10-hr timelag class moisture content. 10-hr timelagMC reaches its minimum later in the day than 1-hr MC.

The hourly variation in 10-hr timelagMC is less than for 1-hr timelag particles. Because the 10-hr MC contributes much less to the characteristic MC than the 1-hr MC, and because inter-hour variation is less for 10-hr timelag fuel particles, modelers should select the ending time for fuel conditioning based on the response of the 1-hr timelagMC, not the 10-hr.

Following are the “take-home messages” regarding fuel moisture conditioning:

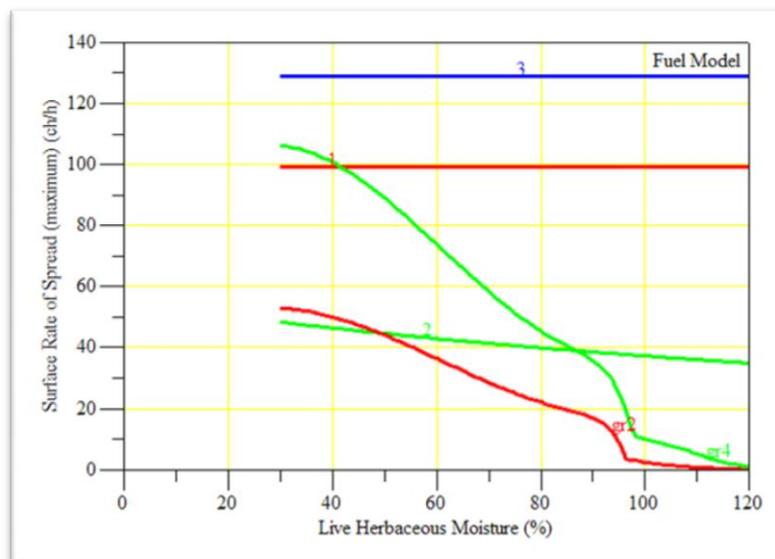
1. Don’t worry about initial dead fuel moisture content values; using the same set of reasonable default values for every simulation should produce reasonable results. (But watch out for the live herbaceous and live woody values in the initial moisture content file; those are critically important.)
2. Don’t worry about conditioning fuels beyond three days unless it is necessary to condition coarser fuel particles for use in the post-frontal fuel consumption model in FARSITE. Surface fire behavior is driven by the 1-hr MC, and 1-hr MC is driven by recent weather. (The exception to this rule is precipitation; if it has rained, results could be different.) On an incident, focus on the weather forecast rather than what has occurred in the past because the current day’s weather has a greater effect on dead fuel MC than the past weather.
3. The time of day the conditioning period ends can be significant, so choose carefully. Different aspects achieve their lowest MC at different times of day, and the time of lowest MC is likely a function of the time of year. Focus on 1-hr timelagMC when selecting the time of day.

Note that the results shown in the above figures are for a particular latitude and time of year. Other locations and times of year could produce different results; nonetheless, the above “take-home messages” generally hold true.

## Live herbaceous fuel moisture content

Live herbaceous moisture content (*LHMC*) refers to the oven-dry moisture content of living non-woody plant material: grasses and forbs. While still alive and green, herbaceous fuel particles may consist of a greater water mass than oven-dry fuel mass. In other words, the moisture content of live herbaceous fuel can exceed 100 percent. In fact, freshly flushed herbaceous fuel can have a moisture content approaching 300 percent; that is, the mass of water in the fuel particle is three times the oven-dry mass of the particle itself.

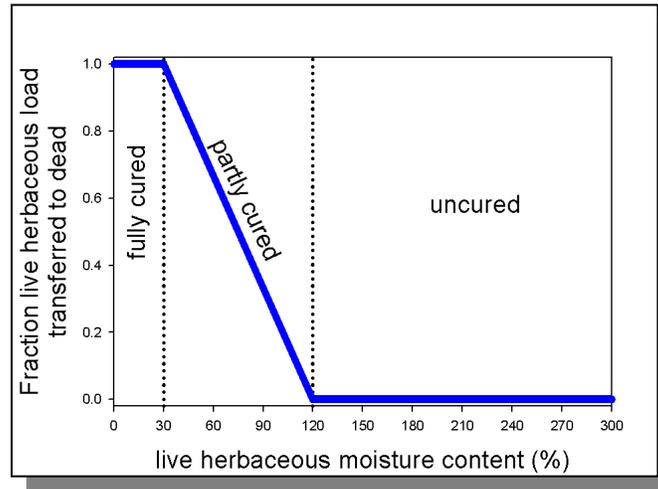
Live herbaceous moisture content was not a significant input factor in U.S. fire behavior modeling systems prior to the development of the set of 40 fire behavior fuel models (Scott and Burgan 2005). Of the original 13 fuel models, only FM2 had a live herbaceous component. Fuel models FM1 and FM3—both pure-grass fuel models—do not have a live herbaceous component; all of the grass fuel in those fuel models is dead and included in the dead 1-hr timelag (0–¼-inch) class. As a result, fire behavior characteristics for FM1 and FM3 do not vary with *LHMC* (Fig. 4-11). Moreover, the herbaceous component of FM2 is “static,” meaning that the load of live herbaceous fuel does not change dynamically to represent curing of the herbaceous fuel. The oven-dry load of live herbaceous fuel is fixed for all simulations, so fire behavior characteristics vary only moderately when *LHMC* is varied (Fig. 4-11).



**Figure 4-11** – Surface fire rate of spread as a function of live herbaceous moisture content (*LHMC*). Fuel models 1 and 3 do not have a live herbaceous component and therefore are unaffected by *LHMC*. Fuel model 2 is a static model, so the effect of *LHMC* is small. Fuel models GR2 and GR4 are dynamic, so rate of spread is strongly affected by *LHMC*.

Live herbaceous moisture content is treated much differently in the 40 fuel model set.

For one, 17 of the 40 fuel models—all nine GR and four GS fuel models plus SH1, SH9, TU1 and TU3—have a live herbaceous component<sup>27</sup>. More importantly, all of those 17 fuel models are “dynamic,” not “static” like FM2, meaning that the herbaceous load is dynamically allocated to the live and dead categories to simulate seasonal curing. This dynamic allocation of the herbaceous load is made as a very simple function of the live herbaceous moisture content (Fig. 4-12)<sup>28</sup>.



**Figure 4-12**—Operational fire modeling systems use this simple straight-line relationship between live herbaceous moisture content and the fraction of load transferred to the dead category.

The result of this dynamic load allocation is that fuel models in the 40 fuel model set that have an herbaceous component are much more sensitive to *LHMC* than is FM2 (Fig. 4-11). This significant difference requires fire behavior modelers to pay close attention to *LHMC* when using any of the 40 fuel models with a significant herbaceous component (the GR and GS fuel models). Guidelines for choosing an *LHMC* value for FM2 were no different than those for choosing a moisture content value for live woody fuel particles (Table 4-3).

<sup>27</sup> In many of these fuel models, the load of the live herbaceous component is a relatively small fraction of the total fuel load. See Table 7 in Scott and Burgan (2005) for a listing of live herbaceous fuel load in relation to total fuel load.

<sup>28</sup> BehavePlus allows the user to override this function, but all other fire behavior simulation systems allocate herbaceous load to live and dead categories as a function of live herbaceous moisture content.

**Table 4-3** – Guidelines for choosing a live fuel moisture content based on stage of vegetation development (Rothermel 1983).

Moisture	Stage of Vegetative Development
300%	Fresh foliage, annuals developing, early in growing cycle
200%	Maturing foliage, still developing with full turgor
100%	Maturing foliage, new growth complete and comparable to older perennial foliage
50%	Entering dormancy, coloration starting, some leaves may have dropped from the stem
30%	Completely cured, treat as dead fuel

Because only FM2 used the *LHMC* input, and because FM2 was not particularly sensitive to it, the guidelines in Table 4-3 proved sufficient. However, the use of dynamic fuel models in the set of 40 fuel models suggests the need for a different way to estimate *LHMC* for fire behavior modeling. The dynamic herbaceous load transfer from live to dead has a larger effect on simulated fire behavior characteristics than the *LHMC* itself. For that reason, it is usually best to first identify the approximate level of curing in the herbaceous fuelbed, then work backward to determine the *LHMC* value that results in that curing level (Table 4-4).

**Table 4-4** – Live herbaceous moisture content associated with level of curing according to the straight-line model in Figure 4-12. This table can be used to estimate the level of curing from live herbaceous moisture content or to determine an appropriate live herbaceous moisture content to use for a given level of curing.

level of curing		live herbaceous moisture content
uncured	0 percent	120 percent or more
one-quarter	25	98
one-third	33	90
one-half	50	75
two-thirds	66	60
three-quarters	75	53
fully cured	100	30 or less

For example, if the grass fuelbed is fully cured (that is, no green or living grass remains), use a value of 30 percent or less for *LHMC*; all herbaceous load will then be transferred to the dead category. If approximately 50 percent of the standing herbaceous component is live and the other 50 percent is dead (that is, a 50% level of curing), then use an *LHMC* value of 75 percent.

Further difficulties arise when setting *LHMC* for geospatial fire modeling because *LHMC* can only be specified separately for each fuel model, and those values are then applied to the whole landscape. Different aspects and elevations cannot be given different *LHMC* values even though they may cure out at different times.

**Live woody fuel moisture content**

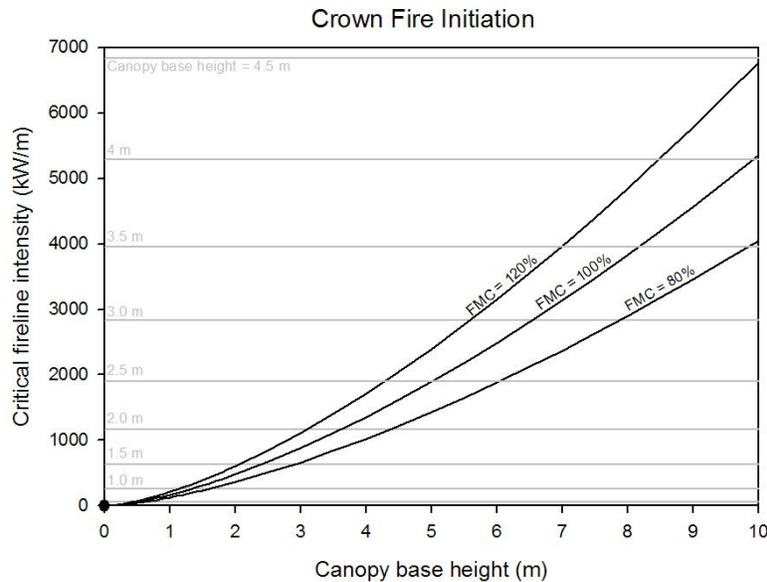
Live woody moisture content (*LWMC*) is a required input for 18 of the 40 (and 4 of the 13) fire behavior fuel models—all of the GS, SH and TU fuel models. Live woody fuel particles consist of fine live branchwood (less than ¼ inch diameter) and live shrub and small tree foliage.

Although there is no dynamic fuel modeling in live woody fuel particles, the 40 fuel models that have a live woody component are in general more sensitive to *LWMC* than the original 13. The reason for this increased sensitivity is a generally higher ratio of live fuel load to dead fuel load in the 40 fuel models than in the 13. A higher proportion of live fuel means that the moisture content of that component has increased importance. The nature of how the live fuel component is incorporated into the Rothermel surface fire spread model further increases the sensitivity. Therefore, again, setting *LWMC* is more important with the 40 fuel models than with the original 13.

Table 4-3 above provides general guidelines for selecting a value for *LWMC* for use in fire behavior modeling. Live woody fuel *MC* monitoring programs may provide further insight for a region or locality.

**Foliar moisture content**

Foliar moisture content (*FMC*) refers to the oven-dry moisture content of the trees over the surface fuel layer, if present. *FMC* is used in fire behavior modeling to determine how much surface fire intensity is needed to ignite crown foliage (Fig. 4-13).



**Figure 4-13** – Critical (threshold) fireline intensity required to initiate crown fire as a function of canopy base height and foliar moisture content (*FMC*).

Across its normal range of variability, foliar moisture content has less influence over crown fire initiation than does canopy base height. Numerous studies of *FMC* have been conducted throughout North America. Moisture content of conifer foliage varies among species and seasons, but not from day to day or year to year. The Forestry Canada Fire Danger Group (1992) related the timing of seasonal changes in *FMC* to latitude, longitude, and elevation.

In old foliage (at least 1 year old), the lowest *FMC* values are near 75 percent. These low *FMC* values occur during early spring, which is outside the fire season in many parts of the United States. Highest old-foliage moisture content values are near 150 percent. The range of old-foliage *FMC* for most species straddles 100 percent, so this value has been used as a default *FMC* if no other information is available.

Larger errors in estimating effective *FMC* probably result from variable amounts of dry dead fuels and lichen in the canopy. Van Wagner (1993) estimated effective *FMC* by computing the loading-weighted average moisture content of the foliage and fine dead canopy fuels. Unless better local data are available, using 100 percent for *FMC* is a reasonable approach, especially given the relative insensitivity of the models to this parameter.

### Chapter 4 summary

A variety of dead fuel and live fuel moisture content values are needed for simulating wildfire behavior. Dead fuel moisture content values are needed for each of the three timelag classes: 1-hr, 10-hr, and 100-hr. Although fire behavior models require moisture content values for all three timelag classes, the Rothermel surface fire spread model places most of the emphasis on the moisture content of the 1-hr timelag class because it contains most of the fuel particle surface area (even though the longer timelag classes may contain a larger share of the load). The 1-hr timelag class moisture content is therefore the most important to estimate accurately. Moisture content of the 1-hr timelag class changes quickly in response to changes in temperature and relative humidity, so it is primarily the current and immediate-past weather that determines 1-hr moisture content. Weather conditions older than approximately a day or two do not strongly affect 1-hr moisture content.

Two dead fuel moisture estimation approaches are currently used in fire behavior modeling: fuel moisture tables and fuel conditioning. The fuel moisture tables return a moisture content value that can be used for all three timelag classes and are appropriate for use with non-spatial fire modeling applications such as BehavePlus, NEXUS, and nomographs. The second approach, fuel conditioning, is used in geospatial fire modeling systems. Fuel conditioning uses Nelson's fuel moisture model to simulate dead fuel moisture content through time as a function of site characteristics and temporally changing weather. Long conditioning periods are typically not needed because the 1-hr timelag class—the most important for fire behavior modeling—responds so quickly to changes in the weather. For the same reason, the initial fuel moisture content values are largely irrelevant. Two to three days are typically sufficient for conditioning dead fuel moisture across the landscape, regardless of the initial moisture content values used. Because 1-hr timelag class moisture content values

change so quickly, the time of day selected for moisture conditioning is more important than the initial moisture content values.

Three classes of live fuel moisture content are required for fire behavior modeling: live herbaceous, live woody, and foliage moisture content. Live herbaceous moisture content is particularly important because it is used to allocate the herbaceous load between live and dead categories. In most cases, it is best to determine live herbaceous moisture content by working backward from the observed level of herbaceous fuel curing. Live woody moisture content can be estimated from the stage of vegetation development. Foliar moisture content is determined primarily by time of year and species. Except where fire season coincides with the springtime period of low foliar moisture content, *FMC* can be set to 100 percent.

## Chapter 5: Characterizing Slope Steepness and Aspect

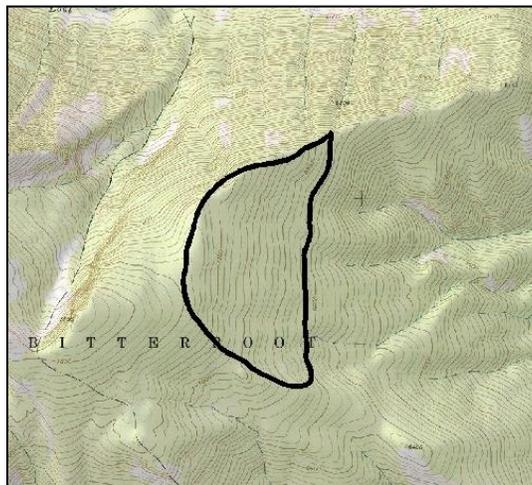
This chapter is presented in a single section on slope characteristics. A slope is a terrain feature of uniform steepness and aspect. Slope steepness and aspect are important characteristics that directly or indirectly affect fire behavior simulations.

The objectives of Chapter 5 are to:

- list and define two slope characteristics and
- describe the direct and indirect effects of slope characteristics on fire behavior simulations.

### Slope characteristics

A *slope* is a geographic terrain feature of uniform steepness and aspect (Fig. 5-1). A large or steep slope may span a wide elevation band. For fire management application, a slope has two important characteristics: steepness and aspect. Slope steepness is the inclination of a slope with respect to the horizontal. Aspect is the direction a slope faces with respect to North. The effects of these two slope characteristics on fire modeling simulations are discussed in the following subsections.



**Figure 5-1** – A slope is a terrain feature of uniform steepness and aspect. The area shown here is a slope that is east-facing and at a uniform steepness of 30 percent.

### *Slope steepness*

Slope steepness at a point is measured in the direction of the steepest inclination from that point (the fall line). Slope steepness can be measured in the field with a clinometer, estimated from a topographic map, or inferred from a digital elevation

model (DEM). Fire management applications do not distinguish between inclination (angle up from the horizontal) and declination (angle down from horizontal, often represented as a negative slope angle). Positive numbers are used to represent slope steepness.

In many fields, angle of inclination is typically measured in degrees, but fire management applications have used the forestry standard of measuring slope steepness as a percent: vertical rise (elevation change) as a percent of horizontal run.

$$\text{slope (percent)} = \frac{\text{vertical rise}}{\text{horizontal run}} * 100$$

If slope is measured in degrees, it can be converted to percent by taking the tangent of the slope in degrees. A 45 degree slope is the same as a 100 percent slope

$$\text{slope (percent)} = \tan(\text{slope(degrees)}) * 100$$

The conversion between slope steepness in percent and degrees is also shown in tabular form (Table 5-1).

**Table 5-1** – Conversion factors for slope steepness measured in degrees and percent.

percent	degrees	degrees	percent
0	0.000	0	0.000
5	2.862	5	8.749
10	5.711	10	17.63
15	8.531	15	26.80
20	11.31	20	36.40
25	14.04	25	46.64
30	16.70	30	57.74
35	19.29	35	70.02
40	21.80	40	83.91
45	24.23	45	100.0
50	26.57		
60	30.96		
70	34.99		
80	38.66		
90	41.99		
100	45.00		

None of the direct or indirect influences of slope steepness on fire modeling simulations is sensitive to small changes in steepness. A measurement error of  $\pm 10$  percent—within the margin of error for practiced ocular estimation—would not result in significant change in modeling results.

Slope steepness affects flaming front rate of spread in the Rothermel spread model and therefore also affects fireline intensity and flame length (see Chapter 1). However, in the Rothermel (1972) surface fire spread model, slope steepness has no effect on fuel consumption at the flaming front.

Slope steepness is a minor influence on dead fuel moisture content (see Chapter 4). Typically, steeper slopes that are facing the sun are subject to greater solar radiation than shallower slopes, and therefore exhibit lower dead fuel moistures under those conditions. In other conditions (shaded, or on an aspect facing away from the sun) slope steepness has almost no effect on dead fuel moisture content.

The combination of slope steepness, aspect, wind speed, and wind direction together determine the direction of maximum spread (*DMAX*) and effective mid-flame wind speed. Other inputs being equal, changing slope steepness usually results in a very small change in *DMAX*—wind direction, wind speed and aspect are stronger influences on *DMAX* than slope steepness. Likewise, unless wind speed is very low, slope steepness contributes relatively little to effective mid-flame wind speed<sup>29</sup>.

### Aspect

*Aspect* is the direction that a slope faces. This direction can be described as a cardinal direction or in degrees clockwise from North. The relationship between these two directions is shown in Table 5-2.

**Table 5-2** – Relationship between aspect as measured as a cardinal direction and as degrees clockwise from North.

Cardinal direction	Degrees clockwise from North
N	0
NE	45
E	90
SE	135
S	180
SW	225
W	270
NW	315

<sup>29</sup> More on effective mid-flame wind speed is presented in Chapter 6.

To determine aspect at any point on a slope, face down the steepest part of the slope (the fall line)—the direction you are facing is the aspect. If the slope faces to the east, you are on an east aspect.

Aspect can be easily measured in the field using a compass or generated within a geographic information system (GIS) using information from a digital elevation model (DEM).

Aspect affects fire behavior only indirectly. First, aspect affects dead fuel moisture content. Aspect determines the amount of solar radiation received by a slope by changing the angle between the sun and the slope. During the afternoon, when temperatures are high and solar radiation is strong, the driest fuel moistures will be found on slopes that face the afternoon sun, which would be the south and southwest aspects in the northern hemisphere. East aspects face the morning sun and therefore are the first to dry out from the overnight period. Information regarding how aspect affects dead fuel moisture content was presented in Chapter 4.

Second, aspect affects how wind direction combines with slope steepness and wind speed to determine the effective wind speed and direction of maximum spread. Wind direction is specified by meteorologists as the direction the wind is coming from with respect to North, but fire simulations are sensitive to relative wind direction (wind direction relative to the upslope direction). A south wind is a wind blowing from the south to the north. That wind will produce a greater effective wind speed if it is blowing up a slope than down it because the wind and slope are in alignment. A south wind and a south aspect are in alignment, because both factors increase fire spread in the northerly direction. More information about how aspect and wind direction interact is presented in Chapter 6.

### **Chapter 5 summary**

A slope is a terrain feature that is relatively uniform in two fire behavior modeling characteristics: steepness and aspect. Slope steepness is the inclination of a slope with respect to the horizontal and is measured as a percent ( $\text{rise/run} \times 100$ ) or in degrees. Slope steepness is always a positive number—there is no distinction between an angle measured as upslope or downslope. Slope steepness affects simulated flaming front rate of spread and therefore also fireline intensity and flame length. Slope steepness does not affect heat per unit area.

Aspect is the direction a slope faces with respect to North and is measured in degrees clockwise from north or as four (N, S, E, W) or eight (N, NE, E, SE, S, SW, W, NW) cardinal directions. Aspect affects dead fuel moisture content and relative wind direction (with respect to upslope).

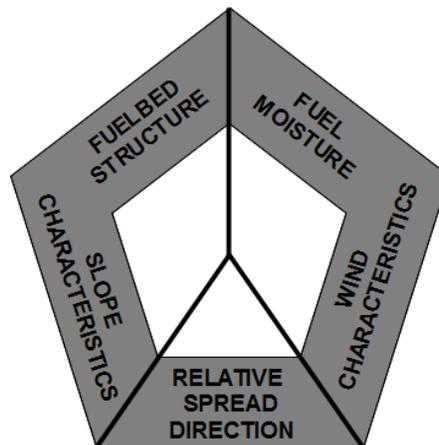
## Chapter 6: Characterizing Wind Speed and Direction

This chapter is presented in three sections. In the first section we define the wind speed time-averaging periods used for reporting wind speed data, and identify the time-averaging period most appropriate for fire modeling applications. In the second section we identify the different reference heights above the ground where wind speed is measured and make conversions among them using a wind adjustment factor. Finally, in the last section we identify two ways to specify wind direction in fire behavior modeling systems.

The objectives of Chapter 6 are to:

- define the different time-averaging periods typically recorded at weather stations and identify the most appropriate time-averaging period for fire modeling,
- identify the different heights above the ground where wind speed is measured and adjust wind speed between these heights, and
- identify two ways of specifying wind direction in fire behavior modeling systems and determine which systems use which approaches.

Wind is air in motion relative to the Earth's surface. Two characteristics of wind—its speed at a reference height above ground and its direction of travel—are important time-varying influences affecting fire behavior simulations (Fig. 6-1). Wind speed and direction can vary greatly by the second, minute, hour and day. Given such variability, analyzing wind speed and direction data for fire behavior modeling can be difficult.



**Figure 6-1** – Wind characteristics—speed and direction at a reference height—are important time-varying influences on fire behavior simulations.

In addition to varying with time, wind characteristics also vary spatially, though the ability of fire modeling systems to use spatial information on wind characteristics varies widely. (No current operational fire behavior modeling system simultaneously addresses spatially and temporally variable wind characteristics with precision.)

### **Wind speed time-averaging period**

Wind speed time-averaging period is the time period over which wind speed is averaged for reporting.

Instantaneous wind speed is the wind speed occurring at an instant in time, or the average speed over a very short period of time (about 1 second). This time period is too short to use for fire modeling. A fire cannot respond to changes in wind speed at that frequency, and too much data are required for even very short duration simulations.

Gust wind speed is the mean wind speed occurring during a wind gust—a brief period of elevated wind speed. Gust wind speed is defined variously, but typically refers to the maximum 3- to 5-second average wind speed occurring during a reporting period. In many cases, a gust wind speed is simply recorded as the maximum instantaneous wind speed. The short duration of a wind gust is not long enough to significantly affect fire behavior; a fire needs a period of time—roughly one minute—to respond to the higher wind speed.

The 1-minute average wind speed is the mean wind speed occurring over a period of one minute. The 1-minute average wind speed can be calculated by computing the mean of a sample of instantaneous wind speeds during a one-minute period, or by dividing the total distance of air traveling past an anemometer by the 1-minute time period. This, along with the 2-minute average wind speed, is an appropriate time-averaging period for use in fire modeling; it is not so long that important periods of high or low wind speeds are averaged out, nor is it so short that the fire cannot respond to it.

The 10-minute average wind speed is the mean wind speed occurring over a 10-minute time span. There is too much wind speed variability hidden by the 10-minute average to be of use in fire modeling. The 10-minute averaging period is too long because fire behavior responds non-linearly to wind speed, so short periods of high wind speed would have greater effect on fire growth than implied by simply averaging those values into the 10-minute average. This effect is exacerbated by transitions to crown fire behavior across a wind speed threshold; the 10-minute average wind speed may be below the crowning threshold, but significant portions of the 10-minute period could be above the threshold, and those crowning periods could greatly influence fire behavior.

Unfortunately, 10 minutes is the standard time-averaging period for most weather stations. Some adjustment to 10-minute average wind speed may be required for use in fire modeling applications. Using just the gust wind speed would greatly over-predict fire behavior if it were used for a time period much longer than the duration of the gust. When analyzing wind speed records for fire modeling, the appropriate wind speed probably falls somewhere between the 10-minute average and the gust wind speeds. Because the 1-minute average is a reasonable time period for fire behavior modeling, a good approach is to convert the 10-minute average to the probable maximum 1-minute average wind speed. The National Oceanic and Atmospheric Administration (NOAA) has prepared the following table of conversion factors (Table 6-1).

**Table 6-1** – Table for converting 10-minute average wind speed to probable maximum 1-minute average wind speed.

10-minute average wind speed (mi/h)	Probable 1-minute average wind speed (mi/h)	10-minute average wind speed (mi/h)	Probable 1-minute average wind speed (mi/h)
1	3	16	21
2	5	17	22
3	6	18	23
4	8	19	24
5	9	20	25
6	10	21	26
7	11	22	27
8	12	23	28
9	13	24	29
10	14	25	30
11	15	26	31
12	17	27	32
13	18	28	33
14	19	29	34
15	20	30	35

Although these conversions were published in tabular form, the following simple mathematical relationship describes the tabular data well:

$$\text{for } W_{10} < 12, W_1 = 1.27W_{10} + 2$$

$$\text{for } W_{10} \geq 12, W_1 = W_{10} + 5$$

where  $W_{10}$  is the 10-minute average wind speed and  $W_1$  is the 1-minute average wind speed (mi/h). Converting 10-minute average wind speed data to 1-minute average using the above relationship should improve fire behavior simulation results.

## Reference height above ground

Another consideration regarding wind speed for fire modeling is the height above the ground of the measurement or prediction. Due to friction with the Earth's surface, wind speed typically increases with height above the ground. So the height of the wind speed measurement is important.

Eye-level wind speed is the wind speed measured at eye level, about 5-6 feet (1.5 m) above the ground. This is the field-measurement standard because handheld anemometers can easily be held at this height.

Mid-flame wind speed is the wind speed acting on the flame structure. In fire modeling, mid-flame wind speed is not measured as the wind speed at the mid-flame height but is instead quantified as the mean wind speed in the vertical space from the top of the surface fuelbed to the top of the flame structure<sup>30</sup>. As flame height varies, so too does mid-flame wind speed—in theory. Mid-flame wind speed is often interchanged with eye-level wind speed, especially when measured during fire operations. Fire modeling applications, however, can better estimate wind speed at the mid-flame height, but even then the estimation is only approximate.

The open wind speed is the wind speed at a standard height above the ground and any obstructing vegetation. The standard height for fire management applications is 20 feet (6.1 m) in the United States, and 10 m (33 feet) elsewhere<sup>31</sup>. Obstructing vegetation includes not only shrubs but also trees, no matter how tall. For a stand of trees that is 100 ft (30 m) tall, the 20-ft wind speed is measured 20 ft above those trees, or 120 ft above the ground.

The Rothermel surface fire spread model is inherently based on mid-flame wind speed, so wind observations at other reference heights must be adjusted. Eye-level wind speed observations are typically used in place of mid-flame wind speed without adjustment. Open wind speed observations, such as those recorded at weather stations, must be adjusted to the mid-flame height for use in fire modeling systems. Fire modeling systems currently assume a linear adjustment in which the mid-flame wind speed is simply the 20-ft wind speed multiplied by a wind adjustment factor (*WAF*).

$$\text{midflame wind speed} = 20 \text{ ft wind speed} * \text{WAF}$$

Some fire modeling systems allow (or require) the user to skip the adjustment process and directly enter mid-flame wind speed, others allow (or require) the user to determine the *WAF* manually (with guidelines), while others determine *WAF* automatically from vegetation characteristics (Table 6-2).

Two mathematical models of *WAF* are currently used in fire modeling systems, one for situations in which the fuelbed is sheltered by a forest canopy (the “with-canopy”

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<sup>30</sup> The difference between these two measurements is small.

<sup>31</sup> Being higher above the ground, the 10-m wind speed is greater than the 6-m wind speed. A standard exists to convert wind speed between these two heights. Divide the 10-m wind speed by 1.15 to get the 6-m wind speed; multiply the 6-m wind speed by 1.15 to estimate the 10-m wind speed (Turner and Lawson 1978).

model) and another for instances where there is no forest canopy (the “no-canopy” model). Both models assume flat terrain; they do not account for the effects of complex terrain on wind sheltering or exposure.

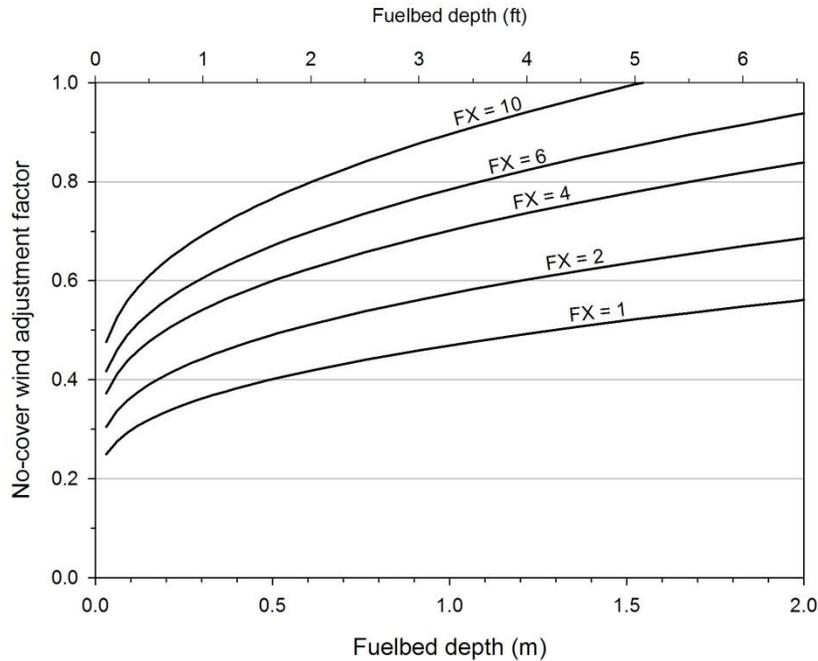
**Table 6-2** – Available methods for specifying mid-flame wind speed in fire behavior potential modeling systems.

	Direct entry of mid-flame wind speed	Manual WAF determination	Automatic WAF determination
Nomographs	Yes	Allowed, with guidelines	No
NEXUS	No	Required, with guidelines	No
BehavePlus	Yes	Allowed, with guidelines	Yes
Geospatial systems	No	No	Yes

### *No-cover wind adjustment*

The no-cover model of wind adjustment factor is for use when there is no forest overstory present to shelter the surface fuel. No-cover *WAF* is based on a physical model of wind speed with height above the ground; *WAF* is the ratio of the mean wind speed from the top of the surface fuelbed through the top of the flame structure to the 20-ft wind speed. Note that this model cannot be applied directly in fire modeling due to a circular relationship—flame height is a function of *WAF*, and *WAF* is a function of flame height. The solution was to assume flame height is just a simple function of flame extension (*FX*) above the top of the fuelbed. Flame extension is the number of fuelbed depths by which flame height extends above the fuelbed. If *FX* equals 1, the flames extend one fuelbed-depth above the top of the fuelbed, so flame height is twice the fuelbed depth. Fuelbed depth is taken directly from the fire behavior fuel model under consideration.

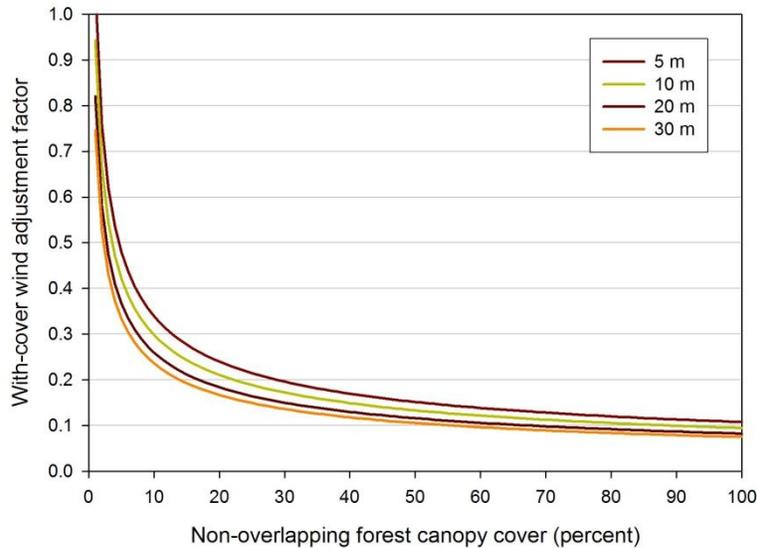
When first applying this model in FARSITE, Finney (1998) assumed flame extension = 1 for all fuel models (Fig. 6-2), meaning that flame height was assumed to be twice the fuelbed depth of the fuel model. That same assumed flame extension ratio value is used in the no-cover *WAF* calculations in all modeling systems of the FARSITE family, in BehavePlus, for the guidelines in NEXUS, and for the new fire behavior nomographs (Scott 2007).



**Figure 6-2** – No-cover wind adjustment factor as a function of fuelbed depth, where flame height above the fuelbed is assumed to be a multiple ( $FX$ ) of fuelbed depth. All fire modeling systems assume  $FX = 1$ , where flame height is twice the fuelbed depth.

### *With-cover wind adjustment*

The with-cover model of wind adjustment factor is based on the fact that a forest canopy will reduce the speed of the wind reaching the surface fuelbed—the denser and taller the forest canopy, the greater the wind reduction (Fig. 6-3). Different fire modeling systems implement this model in slightly different ways. The implementation used in the geospatial models assumes that trees have crowns that extend to the ground (crown ratio = 1), which may over-estimate the wind-reducing effect of the forest canopy. BehavePlus allows the user to specify a stand-level crown ratio in order to avoid the assumption that crowns extend to the ground, resulting in slightly higher estimates of  $WAF$  (unless crown ratio actually equals 1).



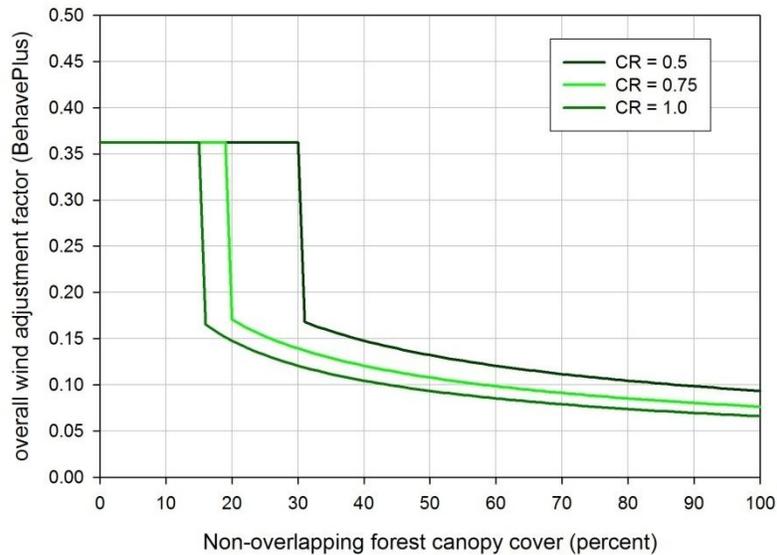
**Figure 6-3** – With-cover wind adjustment factor as a function of canopy cover (percent) for three different stand heights. This chart is for a crown ratio of 1.0, which is assumed in FARSITE and its related geospatial fire modeling systems.

### Overall wind adjustment

The two wind adjustment factor models described above must be somehow combined into a single value for use in fire modeling. Again, BehavePlus and the FARSITE family use different approaches.

FARSITE and other geospatial modeling systems apply the with-cover model for all situations with canopy cover greater than zero (see Fig. 6-3). In certain circumstances, this approach can produce illogical results. For example, if canopy cover and stand height are very low, with-cover *WAF* could exceed the no-cover value, implying that adding cover would increase mid-flame wind speed. Fortunately, these illogical results occur only if canopy cover is very low, usually less than 5 percent. Such low canopy cover values occur rarely in spatial data sets unless they have been manipulated to produce some other effect (such as to force spotting from a surface fuelbed).

In order to avoid the possibility of that illogical result, BehavePlus applies a threshold crown filling fraction (*CFF*) of 5 percent to determine which *WAF* model to use. (Crown filling fraction is the three-dimensional equivalent of canopy cover). If *CFF* is greater than 5 percent, then the with-cover model is used; if *CFF* is less than 5 percent, then the no-cover model is used. Unfortunately, this approach results in an artificial discontinuity in predicted *WAF* that occurs at canopy cover values of approximately 15-30 percent (depending on crown ratio; see Fig. 6-4).



**Figure 6-4** – BehavePlus’ overall wind adjustment factor as a function of canopy cover for three values of crown ratio (CR). Stand height is 30 m. The discontinuity in WAF occurs where crown filling fraction falls below 5 percent.

The discontinuity in the BehavePlus approach results in simulations where the mid-flame wind speed can nearly double with just a small reduction in canopy cover, with an even greater change in spread rate and fireline intensity. Moreover, this discontinuity occurs in the range of commonly observed canopy cover values.

A third possibility for integrating the no-cover and with-cover models is to simply take the smaller of those two *WAF* values, so that the with-cover *WAF* does not exceed the no-cover *WAF*. This approach is not currently used in any currently available fire behavior modeling system.

### Specifying wind direction

The meteorology standard describes wind direction as the direction the parcel of air is travelling *from*. Wind direction can be specified in degrees clockwise from North or as a cardinal direction (Table 6-3).

**Table 6-3** – Relationship between wind direction measured as a cardinal direction and measured as degrees clockwise from North.

Cardinal wind direction category	Degrees clockwise from North
N	0
NE	45
E	90
SE	135
S	180
SW	225
W	270
NW	315

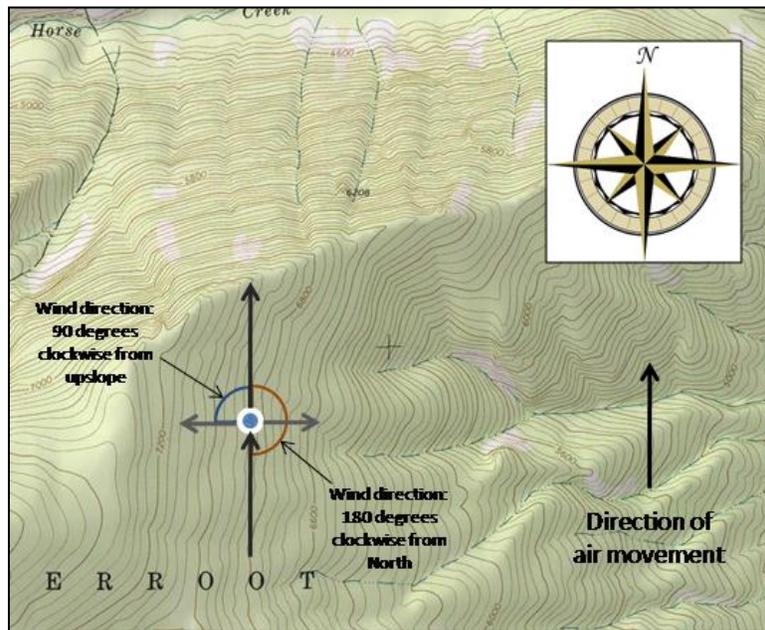
The fire modeling standard (native to the internal workings of fire models) describes wind direction as the relative direction the parcel of air is travelling *toward* with respect to the upslope direction, either as a category or as degrees clockwise from upslope (Table 6-4).

**Table 6-4** – Relationship between relative wind direction as categories and as degrees clockwise from upslope.

Relative wind direction category	Degrees clockwise from upslope
Upslope	0
Quarter-upslope	45, 315
Cross slope	90, 270
Quarter-downslope	135, 225
Downslope	180

Figure 6-5 illustrates the difference between these two ways of describing wind direction. In this example, the air is moving from the south to the north, and the slope

is facing the east. Meteorologically, this is a south wind, quantified as 180 degrees clockwise from north.



**Figure 6-5** – Illustration of cardinal wind direction (with respect to north) and relative wind direction (with respect to slope).

The upslope direction is toward the west, opposite the aspect. And the downwind direction is opposite the direction the wind is coming from. So, for fire modeling purposes, this is a cross-slope wind direction (90 degrees clockwise from upslope; see Fig. 6-5).

Another common option for specifying wind direction in fire modeling applications is to assume the worst case wind direction—upslope—regardless of whether another relative wind direction would occur given the cardinal wind direction and aspect.

Fire modeling systems that simulate potential fire behavior vary in the ways they can receive wind direction data (Table 6-5). The new fire behavior nomographs (Scott 2007) can be used when the relative wind direction is known (including the special case of upslope wind direction), but not for wind direction specified with respect to North. BehavePlus is the most flexible of the fire modeling systems and can accept wind direction data in any of the described formats. NEXUS, like the nomographs, is based on the fire modeling standard of relative wind direction, including upslope, but not with respect to North. FlamMap (basic) uses wind direction with respect to North along with aspect, a required input, to compute relative wind direction. In FlamMap, the user can choose the upslope relative wind direction, but not other relative wind directions (such as cross-slope).

**Table 6-5** – Methods of specifying wind direction in fire behavior potential modeling systems.

	Upslope wind direction	Wind direction with respect to North	Relative wind direction
Nomographs	yes	no	yes
BehavePlus	yes	yes	yes
NEXUS	yes	no	yes
FlamMap (basic)	yes	yes	no

Fire growth simulations take place over space and time, so wind speed and direction inputs should, in theory, vary both spatially and temporally. However, the ability of geospatial fire modeling systems to accommodate temporal and spatial variability in wind speed and direction data varies greatly (Table 6-6).

**Table 6-6** – Different geospatial fire modeling systems handle temporal and spatial variability in wind characteristics differently.

	Temporal variability	Spatial variability
FARSITE	Wind speed and direction can vary by the minute	Different portions of the landscape can be assigned different wind speeds and directions; terrain-adapted winds difficult to accommodate.
FlamMap (Minimum Travel Time [MTT])	One wind speed and direction per simulation (usually one or two burning periods).	Allows the use of terrain-adapted wind speed and direction data (from WindWizard or WindNinja).
FSPPro	One wind speed and direction per burning period.	Daily wind speed and direction applies across the whole landscape.
FSIM	One wind speed and direction per burning period.	Daily wind speed and direction applies across the whole landscape.

FARSITE allows the highest frequency of specification of wind speed and direction of any fire modeling system. FARSITE uses an event-driven input format for wind data,

meaning that a specified speed and direction is used in the simulation until a change in speed or direction is specified. Those changes can take place as often as once every minute, but more typically take place once or twice per hour. The intervals between changes in wind speed and direction need not be equal. However, such high temporal precision in wind data is not compatible with high spatial resolution. FARSITE accommodates gridded wind data—maps of wind speed and direction at high spatial resolution—but cannot simultaneously use high temporal and spatial resolution data.

The simple fire growth simulation tool in FlamMap (MTT) allows only one wind speed and direction for the whole simulation, which typically lasts up to one burning period. However, MTT does allow the use of terrain-adapted gridded winds produced by WindWizard or WindNinja.

Like MTT, FSPro (for Fire Spread Probability) and FSIM (for the Large Fire Simulator) only allow one wind observation per burning; but, unlike MTT, they cannot use terrain-adapted gridded wind data.

## Chapter 6 summary

Wind is air in motion, and it is characterized by its speed at a specified reference height above the ground (or vegetation cover) and direction with respect to North (or with respect to the upslope direction).

Wind speed varies in time almost continuously and is therefore averaged over a period of time for reporting. The 1- or 2-minute average wind speed is an appropriate time-averaging period for fire modeling applications. The standard 10-minute average is too long because it hides potentially important periods of higher-than-average wind speed. The gust wind speed—sometimes quantified simply as the peak wind speed—occurs over too short a time period for use in fire modeling applications because the brief time period is too short for the fire to respond.

Two general wind speed reference heights are used in fire modeling applications: mid-flame wind speed and open wind speed. Mid-flame wind speed is the mean wind speed occurring in the vertical space between the top of the surface fuelbed and the top of the flame structure. Eye-level (1.5 m; 5-6 ft) wind speed is often substituted for mid-flame wind speed when measuring wind speed in the field. Open wind speed is the wind speed at a standard height above obstructing vegetation. The standard height is 20 ft (6.1 m) in the United States and 10 meters elsewhere.

Fire modeling systems inherently need mid-flame wind speed, but wind speed observations are recorded at the 20-ft height. Therefore, a wind adjustment factor (*WAF*) is used to convert between wind speeds at the 20-ft and mid-flame reference heights. If a forest canopy is present, *WAF* is a function of canopy cover and stand height. If a forest canopy is not present, *WAF* is a function of flame height, which is assumed in fire modeling systems to be twice the fuelbed depth.

Wind direction within fire modeling systems is specified as relative wind direction—degrees clockwise from upslope. Some fire modeling systems also allow the user to specify wind direction as the wind direction with respect to North—degrees clockwise from north—and automatically compute the relative spread direction as long as aspect is known.

## Chapter 7: Simulating Surface Fire Behavior

Wildland fire scientists recognize three general types of fire—ground, surface and crown—depending on the fuel stratum that is burning. Separate models of fire behavior exist for each type of fire. The behavior of ground fires, which burn very slowly in duff, roots, buried logs, and other below-surface fuel components, is not addressed in this document. This chapter addresses the behavior of surface fires, which burn in the litter, grass, shrubs, and small trees near the ground.

The objectives of Chapter 7 are to:

- describe the purpose and development of the Rothermel surface fire spread model,
- describe the components of the fire spread model and the factors affecting rate of spread,
- describe how fireline intensity is estimated when using Rothermel’s model, and
- demonstrate the simulation of surface fire behavior with BehavePlus and NEXUS.

In this chapter, we integrate information presented in several earlier chapters. In Chapter 1 we introduced the fire modeling pentagon, which divides the factors that influence fire behavior into five categories: relative spread direction (Chapter 1), fuelbed structure (chapters 2 and 3), fuel moisture (Chapter 4), slope characteristics (Chapter 5), and wind characteristics (Chapter 6). In this chapter, we will show how those factors are used in the Rothermel (1972) spread model. We begin with an overview of the spread model itself, followed by a description of how the model is used to estimate fireline intensity. Finally, we demonstrate the simulation of surface fire behavior with BehavePlus and NEXUS.

### Rothermel spread model

The Rothermel model is a semi-physical model, meaning that it has components that rely on the physics of combustion and components that rely on laboratory experimental results. The basic model formula is quite simple: the rate of spread of a free-burning fire is simulated as the ratio of heat source to heat sink.

$$ROS = \frac{\text{heat source}}{\text{heat sink}}$$

Of course, for this model to work, the units must be just right. The heat source term represents the rate of heat generated per unit fuelbed area, and the heat sink represents the heat required to raise to ignition temperature a unit volume of fuelbed. The dimensional units are as follows:

$$ROS = \frac{BTU/ft^2 s}{BTU/ft^3}$$

The “BTU” and some of the “ft” terms cancel out, leaving:

$$ROS = \frac{ft}{s}$$

Fire modeling software converts *ROS* results in these units to the more familiar units of ch/hr or mi/h (or m/min or km/h). We'll now take a closer look at the heat source and sink terms.

Let's first simplify some of the fuel model parameters described in Chapter 2. Although there are 12 parameters for each fuel model, those parameters are combined into just six fuelbed characteristics before being used in the Rothermel spread model (Table 7-1). Those characteristics are:

- total fuel load (*L*)
- characteristic moisture content (*MC*)
- characteristic surface-area-to-volume ratio (*SAV*)
- fuelbed bulk density (*BD*)
- fuel particle heat content (*H*)
- dead fuel moisture of extinction ( $M_x$ )

**Table 7-1** – Relationship between the six summary fuelbed characteristics and the 12 fuel model parameters.

Fuel model parameter	Fuelbed characteristic					
	<i>L</i>	<i>MC</i>	<i>SAV</i>	<i>BD</i>	<i>H</i>	$M_x$
1-hr load	√	√	√	√		
10-hr load	√	√	√	√		
100-hr load	√	√	√	√		
Live herbaceous load	√	√	√	√		
Live woody load	√	√	√	√		
1-hr SAV ratio			√			
Herbaceous SAV ratio			√			
Live woody SAV ratio			√			
Dead fuel heat content					√	
Live fuel heat content					√	
Fuelbed depth				√		
Dead fuel moisture of extinction						√

In a later section, we will show where these six fuelbed characteristics are used in the spread equation and how each affects *ROS* and *FLI*.

### Heat source

The heat source term of the spread equation consists of four main factors:

$$\text{heat source} = I_R * R_{pf} * (1 + W + S)$$

where  $I_R$  is the reaction intensity,  $R_{pf}$  is the propagating flux ratio, and the  $W$  and  $S$  terms represent the effects of wind and slope on spread rate. Because the heat source term is the numerator of the spread equation, increasing any of these factors increases the modeled rate of spread. Each of these factors will be described in the following paragraphs.

Reaction intensity represents the rate of heat release per unit fuelbed area. Reaction intensity is a function of several fire environment factors: increasing fuel load and heat content increases  $I_R$ . Increasing bulk density and moisture content decreases  $I_R$ .

Propagating flux ratio is a measure of how much of the reaction intensity contributes to forward fire spread by heating fuel ahead of the flaming front. Most of the heat represented by reaction intensity is transferred straight to the atmosphere by convection, where it cannot contribute to forward spread. The  $R_{pf}$  term accounts for this fact. It is a function of fuel particle fineness and fuelbed bulk density. Finer fuel particles capture a larger fraction of the total energy, as do more compact fuelbeds.

The final two factors represent the effects of wind and slope. The  $W$  term is a function of mid-flame wind speed and fuel particle fineness. The  $S$  term is a function of slope steepness and fuelbed bulk density. On flat ground and with no wind,  $W$  and  $S$  are 0 and the heat source term reduces to  $I_R * R_{pf}$ . Otherwise, the  $W$  and  $S$  terms are combined using vector addition. In the case of upslope winds (that is,  $W$  and  $S$  operate in the same direction, upslope),  $W + S$  is the simple arithmetic sum of a wind coefficient and a slope factor. When the wind is blowing any direction other than upslope,  $W + S$  is determined using vector algebra, which uses the angle between the downwind and upslope directions to determine the effective sum. This vector addition is done automatically in all fire behavior modeling systems.

### Heat sink

The heat sink term is a bit simpler than the heat source term, with only three variables:

$$\text{heat sink} = BD * E_H * Q_{ig}$$

where  $BD$  is the fuelbed bulk density,  $E_H$  is the effective heating number, and  $Q_{ig}$  is the heat of ignition. Note that because these three factors are in the denominator of the spread equation, increasing them (for example, increasing  $BD$  by packing the fuel mass to a lower depth) will reduce the modeled rate of spread.

Fuelbed  $BD$  is a measure of fuelbed compactness—how much fuel mass is packed into a given volume. Fuelbed  $BD$  is calculated by dividing total fuel load by fuelbed depth:

$$BD = \frac{\text{total fuel load}}{\text{fuelbed depth}}$$

Total fuel load is the sum of live and dead fuel load values from the fire behavior fuel model. Fuelbed depth also comes from the fire behavior fuel model, so each fuel model has its own *BD* value.

Effective heating number represents the fraction of the total fuel load that must be heated to ignition. Nearly all of very fine fuel particles like grass stems must be heated to ignition temperature, so fuelbeds consisting of grass stems have effective heating numbers close to 1. Only the outer portion of coarse fuel particles such as branches and stems needs to be heated to ignition, so fuelbeds consisting of coarse fuel particles have smaller effective heating numbers. In practice, the effective heating number does not have a strong effect on predicted fire behavior compared to other factors.

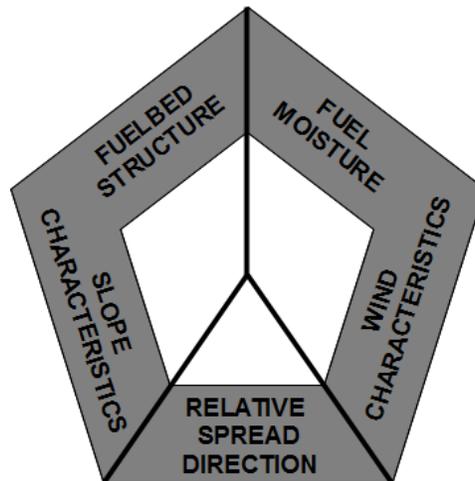
Finally,  $Q_{ig}$  is the amount of heat required to heat a given mass of fuel to its ignition temperature. This is a function of moisture content because the moisture must be driven off—vaporized—before raising the temperature to ignition.

### *Spread equation*

Combining the separate heat source and heat sink equations yields the final spread equation:

$$ROS = \frac{I_R * R_{pf} * (1 + W + S)}{BD * E_H * Q_{ig}}$$

Four of the five elements of the fire modeling pentagon (Fig. 7-1) are represented in this final equation. The fifth element, relative spread direction, is handled outside of the spread equation (see Chapter 1).



**Figure 7-1** – The fire modeling pentagon illustrates the five major influences on fire behavior modeling simulations. Fuelbed structure and slope characteristics are time-constant influences since those factors do not change during any single fire simulation (which typically lasts no more than a few weeks). Fuel moisture and wind characteristics are time-varying influences because those factors can vary by the minute, hour, day, and week, and thus affect all temporal fire growth simulations. Spread direction—heading, flanking, backing—has a considerable effect on fire behavior.

Notice from Table 7-2 that increasing most fire environment characteristics increases *ROS*. The exceptions to this rule are fuelbed bulk density and moisture content. Increasing moisture content increases the heat of ignition, which has a damping effect on *ROS* and also reduces  $I_R$  by increasing the moisture damping coefficient. Increasing fuelbed bulk density affects several variables in both the heat source and heat sink portions of the spread equation. Increasing bulk density reduces the propagating flux ratio (so less heat is available for fire spread) and reduces the effects of both wind and slope. Increasing bulk density also increases the heat sink. Fuelbed bulk density is not a direct fuel model parameter; instead, it is calculated by dividing total fuel load by fuelbed depth. Fuelbed depth is therefore a critically important fuel model parameter.

**Table 7-2** – The effects of summary fuelbed characteristics, organized by major fire modeling influence, on heat source and heat sink terms of the Rothermel surface fire spread equation. Arrows indicate the effect of increasing the fuelbed characteristic on how each term affects *ROS* (that is, arrows for the heat sink terms indicate their effect on *ROS*, not the heat sink term itself). Only *BD* does not have a unanimous effect on *ROS*. Nevertheless, the net effect of increasing *BD* is a reduction of *ROS*.

Major fire modeling influence	Fire environment characteristic	Heat source			Heat sink			Overall <i>ROS</i> effect
		$I_R$	$R_{pf}$	$W+S$	<i>BD</i>	$E_H$	$Q_{ig}$	
Fuelbed structure	<i>L</i>	↑						↑
	<i>SAV</i>	↑	↑	↑		↑		↑
	<i>BD</i>	↓	↓	↓	↓			↓
	<i>H</i>	↑						↑
	$M_x$	↑						↑
Fuel moisture	<i>MC</i>	↓					↓	↓
Wind speed	<i>W</i>			↑				↑
Slope steepness	<i>S</i>			↑				↑

### Fireline intensity

Recall from Chapter 1 that fireline intensity is the rate of heat release per unit length of fire front. Conceptually, fireline intensity is the product of spread rate and the heat per unit area released during flaming front passage:

$$FLI = HPA * ROS$$

In practice, *HPA* cannot be measured in the field because the amount of fuel consumption that takes place after the flaming front passage cannot be separated from

what occurs during flaming. Rothermel's model was constructed primarily to estimate *ROS*, but can also be used to estimate *HPA* as the product of *I<sub>r</sub>* and duration. That is, multiplying reaction intensity (kW/m<sup>2</sup>) by the residence time (*T<sub>r</sub>*) of flaming (seconds) results in *HPA* (kJ/m<sup>2</sup>). Residence time is a simple function of characteristic fuelbed particle fineness. Fuelbeds that consist of very fine particles—grass, for example—have short residence times (around 10 seconds). Fuelbeds characterized by coarser woody fuel particles have longer residence times (around 30 seconds as simulated with this model).

$$HPA = I_r * T_r$$

So fireline intensity is calculated in modeling systems that use Rothermel's model as:

$$FLI = ROS * I_r * T_r$$

Because *I<sub>r</sub>* is one of the factors affecting *ROS*, the same fire modeling factors that affect *I<sub>r</sub>* also affect *FLI* in the same way (see Table 7-2). Residence time gets shorter as *SAV* increases (finer fuel particles), which works opposite the effect on *ROS*. The overall net effect of *SAV* is uncertain—increasing *SAV* can increase or decrease fireline intensity, depending on other factors, especially packing ratio.

Flame length for surface fires is a function of *FLI*, so the same effects on *FLI* apply to flame length.

### Using non-spatial modeling systems

In the following two sections, we will demonstrate the basic use of the non-spatial fire modeling systems BehavePlus and NEXUS to simulate surface fire behavior. We'll use the same fire environment inputs for both (Table 7-3).

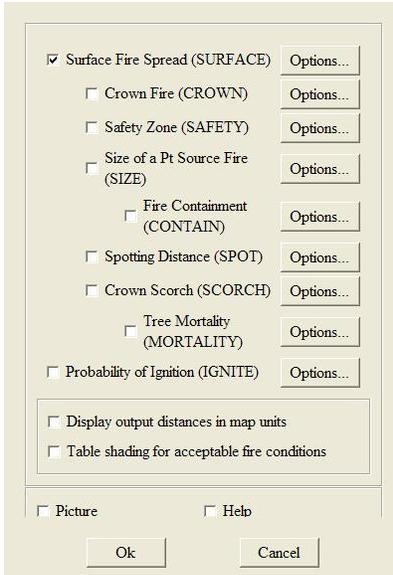
**Table 7-3** – Summary of fire modeling inputs to be used to demonstrate surface fire modeling in BehavePlus and NEXUS.

Fire modeling influence	Fire model input	Input
Fuelbed structure	Fuel model	TU5
Moisture content	1-hr timelag	4 %
	10-hr timelag	5%
	100-hr timelag	6%
	Live herb	n/a
	Live woody	90%
Wind characteristics	Wind speed	15 mi/h
	WAF	0.12
	Wind Dir.	Upslope
Slope	Steepness	20 %

### *BehavePlus*

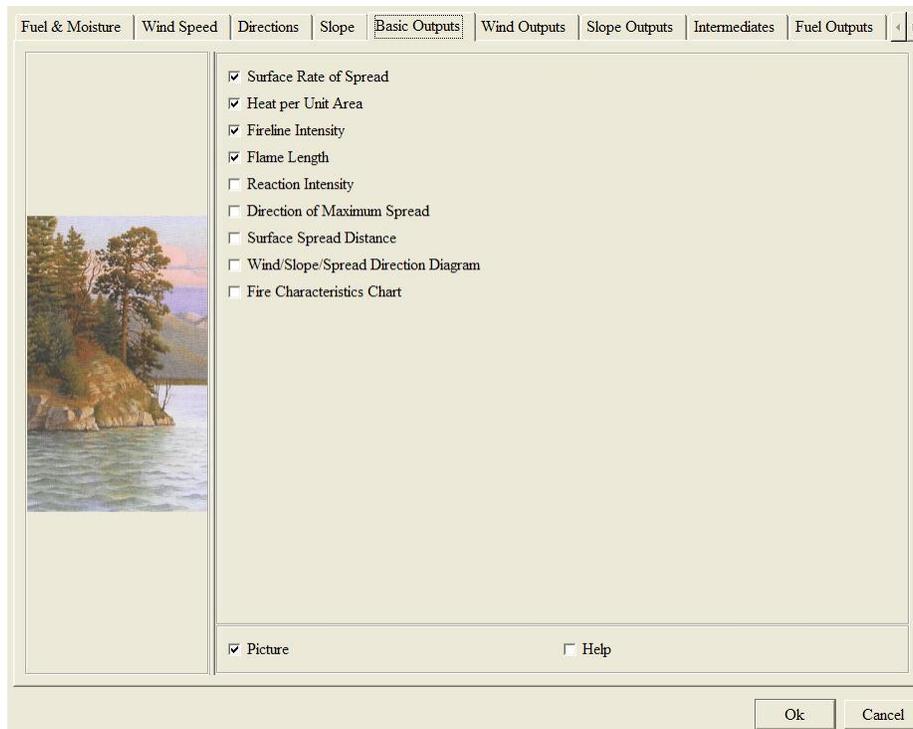
BehavePlus is a highly flexible non-spatial computer application for modeling the fire environment, behavior, and effects. It models surface fire and crown fire behavior separately. This section focuses on using BehavePlus to model, for surface fires only, the four primary fire behavior characteristics described in Chapter 1: *ROS*, *HPA*, *FLI* and *FL*.

Start by opening the *Module Selection* dialog box (**Configure > Module selection**). Make sure that "Surface Fire Spread" is the only box checked (Fig. 7-2).



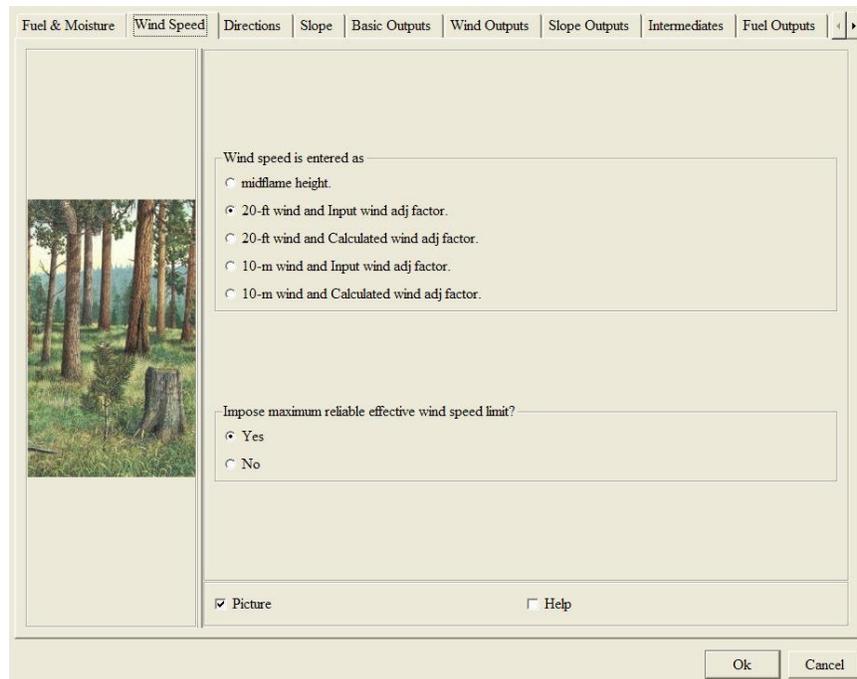
**Figure 7-2** – The BehavePlus Module Selection dialog box. For surface fires, make sure the Surface Fire Spread (SURFACE) option is checked.

Next, open the *SURFACE Module Options* dialog box by clicking the **Options...** button. On the *Basic Outputs* tab, check the top four fire behavior characteristics (Fig. 7-3).



**Figure 7-3** – The *SURFACE Module Options* dialog box. For our example, we will select just the four main fire behavior characteristics described in Chapter 1.

Next you need to check a few other surface fire modeling options. Here, we will only cover options that need to be changed from the default or those that should be checked to confirm the setting. Under the *Fuel & Moisture* tab, note that fuel will be entered as fuel models, that dynamic fuel load transfer will be calculated from live herbaceous fuel moisture, and fuel moisture will be entered by individual size class. Next, under the *Wind Speed* tab, check *20-ft wind and Calculated wind adj factor*, but leave the wind speed limit imposed (Fig. 7-4).



**Figure 7-4** – For this example we specify the 20-ft wind speed and input a wind adjustment factor, so check that option and click **OK** to continue.

Now, click on the *Directions* tab. We will not change any of these settings, but note that spread direction is in the direction of maximum spread (the heading direction) and wind is assumed to be in the upslope direction. On the *Slope* tab, note that slope steepness is measured in percent, and it will be specified in the input worksheet. The conversions between these units of measure are defined in Chapter 5. No other tabs contain options that are checked by default, so now click **OK** to return to the *Module Selection* dialog box, and then click **OK** again. The input worksheet will now be updated to reflect our settings (Fig. 7-5).

BehavePlus 5.0.1 Page 1

**Inputs: SURFACE**

Description [ ]

**Fuel/Vegetation, Surface/Understory**

Fuel Model [ ]

**Fuel Moisture**

1-h Moisture % [ ]

10-h Moisture % [ ]

100-h Moisture % [ ]

Live Herbaceous Moisture % [ ]

Live Woody Moisture % [ ]

**Weather**

20-ft Wind Speed (upslope) mi/h [ ]

Wind Adjustment Factor [ ]

**Terrain**

Slope Steepness % [ ]

---

**Run Option Notes**

Maximum reliable effective wind speed limit IS imposed [SURFACE].

Calculations are only for the direction of maximum spread [SURFACE].

Fireline intensity, flame length, and spread distance are always for the direction of the spread calculations [SURFACE].

Wind is blowing upslope [SURFACE].

---

**Output Variables**

Surface Rate of Spread (maximum) (ch/h) [SURFACE]

Heat per Unit Area (Btu/ft<sup>2</sup>) [SURFACE]

Fireline Intensity (Btu/ft/s) [SURFACE]

Flame Length (ft) [SURFACE]

Workspace C:\PROGRAM~1\BEHAVE~1\DefaultDataFolder\ (Page 1 of 1)

**Figure 7-5** – Once the modules and options are selected, the BehavePlus input worksheet is automatically updated to reflect the required inputs. Fuel moisture inputs are grayed out until a fuel model is selected, then only the required moisture content values are shown as required.

Now we are ready to enter values for a simulation. Starting at the top of the worksheet and working toward the bottom, enter values for each required input. You can also use the arrow button to open a dialog box that assists in entering the input value. The completed input worksheet should appear as in Figure 7-6.

BehavePlus 5.0.1 Sun, Feb 12, 2012 at 12:25:48 Page 1

**Inputs: SURFACE**

Description

**Fuel/Vegetation, Surface/Understory**

Fuel Model tu5

**Fuel Moisture**

1-h Moisture % 4

10-h Moisture % 5

100-h Moisture % 6

Live Herbaceous Moisture %

Live Woody Moisture % 90

**Weather**

20-ft Wind Speed (upslope) mi/h 15

Wind Adjustment Factor .12

**Terrain**

Slope Steepness % 20

**Run Option Notes**

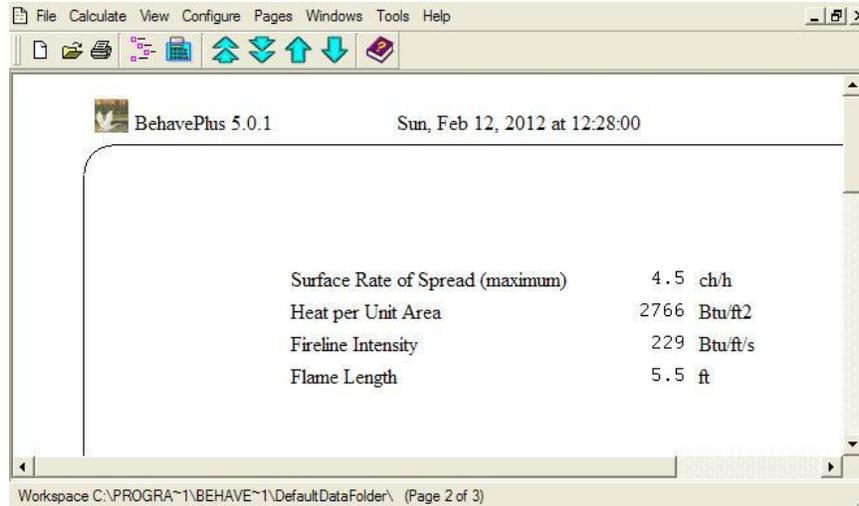
Maximum reliable effective wind speed limit IS imposed [SURFACE].  
 Calculations are only for the direction of maximum spread [SURFACE].  
 Fireline intensity, flame length, and spread distance are always  
 for the direction of the spread calculations [SURFACE].  
 Wind is blowing upslope [SURFACE].

**Output Variables**

Surface Rate of Spread (maximum) (ch/h) [SURFACE]  
 Heat per Unit Area (Btu/ft<sup>2</sup>) [SURFACE]  
 Fireline Intensity (Btu/ft/s) [SURFACE]  
 Flame Length (ft) [SURFACE]

**Figure 7-6** – Completed BehavePlus inputs worksheet for our surface fire modeling example. Live herbaceous moisture content is not required because it is not a component of fuel model TU5.

You are now ready to calculate the selected outputs. To do so, select **Calculate > Calculate** from the menu, or click the calculator icon. The outputs are presented on a new page (Fig. 7-7).



**Figure 7-7** – BehavePlus results page for the surface fire modeling example.

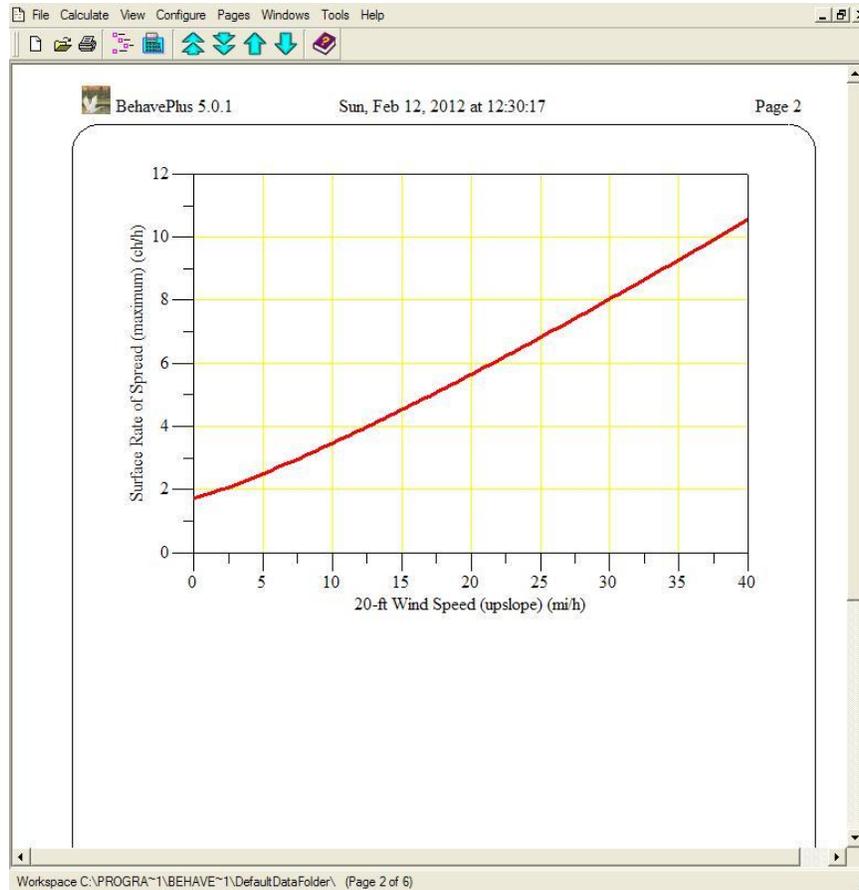
BehavePlus can also calculate outputs for a range of input values (for one or two input variables at a time). For our example, let's calculate fire behavior over a range of 20-ft wind speeds from 0 to 40 mi/h. To do that, return to the input worksheet and click on the arrow next to the 20-ft Wind Speed input. When the input guide opens, set the 20-ft wind speed variable to range from 0 to 40 mi/h in steps of 5 mi/h and then click **OK** (Fig. 7-8).



**Figure 7-8** – Input guide for setting 20-ft wind speed to range from 0 to 40 mi/h by steps of 5 mi/h.

The input worksheet will now show a series of nine entries for 20-ft wind speed, each separated by a comma. Clicking the calculate button opens a *Calculate Results* dialog box. Click **OK** to display both tabular and graphical results. Now, instead of a single page with results for all four fire behavior characteristics, there are five pages of results. The first page is a table of results over the range of wind speeds, and the following four

pages consist of graphs of each characteristic over wind speed. Either use screen-capture software to save the image (Fig. 7-9), or choose **File > Save as an image** to save each chart within the BehavePlus workspace.



**Figure 7-9** – Surface fire rate of spread over a range of 20-ft wind speeds.

To save the tabular results, choose **File > Export results**. The results are saved in html format, which can then be opened in Excel.

### Using NEXUS

NEXUS is a simple software application that simulates surface and crown fire behavior and rates crown fire potential for a specified fire environment. NEXUS can integrate surface fire and crown fire behavior models. This section focuses on using it to model the four primary fire behavior characteristics for surface fires only.

After starting the NEXUS program, simply fill out the inputs for Scenario A, starting from the top and working to the bottom of the inputs. Click on the **A** scenario button to give the scenario a name, if you wish. Next, check the simulation type. In this case, we want it to remain with the default of “surface.” Now, select the fuel model to use for the simulation by clicking on the **low FM** button and selecting TU5. Notice that many of the

input boxes are grayed out. This is because those inputs are not needed for surface fire modeling or are not needed for the selected fuel model.

Next, enter the wind adjustment factor (0.12) in the box labeled *WND/low*. Leave the three simulation multipliers at their default values of 1; these are used to adjust the model to better match observed behavior. Now, enter the fuel moisture content values. A value is not needed for live herbaceous moisture content because it is not used by fuel model TU5. Finally, enter the 20-ft wind speed, slope steepness, and wind direction in the last three input cells. Notice that outputs appear in the output pane as soon as a valid input set is complete. NEXUS automatically computes a complete set of fire behavior characteristics; there is no need to specify which ones are desired. The resulting NEXUS inputs and outputs should appear as in Figure 7-10.

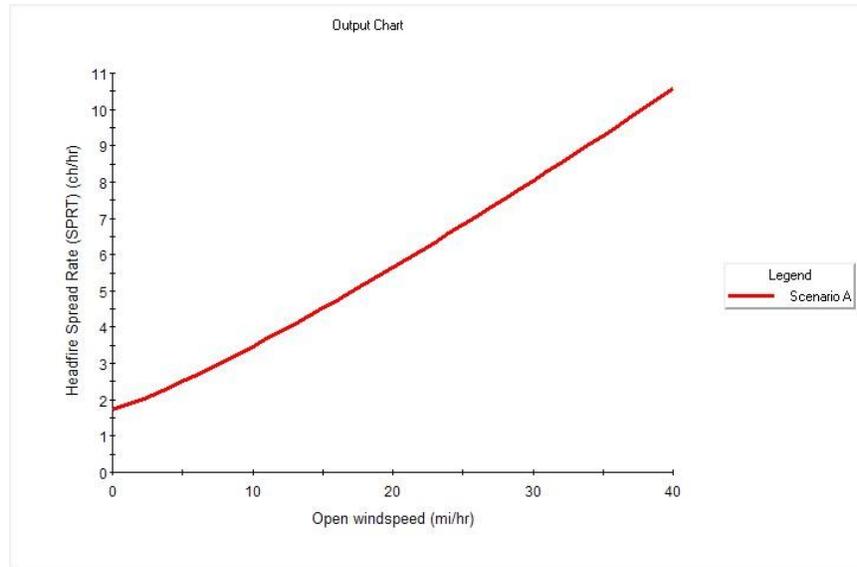
Input		A	B	C	D	Units
Scenario		A	B	C	D	
Simulation Type		surface	surface	surface	surface	
Low fuel model		FMCDlow	TU5	Low FM	Low FM	Low FM
WND/low		12	0.1	0.1	0.1	fraction
ROS/low		1	1	1	1	fraction
LAD/low		1	1	1	1	fraction
FLM/low		1	1	1	1	fraction
High fuel model		FMCDhigh	High FM	High FM	High FM	High FM
WND/high						fraction
ROS/high						fraction
LAD/high						fraction
FLM/high						fraction
Dead moisture		MC01	4			
		MC10	5			percent
		MC100	6			percent
Live moisture		MCLH				percent
		MCLW	90			percent
Canopy fuels		ACBD				kg/m <sup>3</sup>
		CABH				feet
		ACFL				ton/acre
		FDMC				percent
Misc		STFL				meters
Wind and slope		DW/ND	15			mi/hr
		SLOP	20			percent
		WDIR	0			degrees

Output		A	B	C	D	Units
Scenario		A	B	C	D	
FTYP		surface				nominal
CRFB		0				fraction
SPRT		4.53				ch/hr
HPUA		2766				BTU/ft
FLIN		229				BTU/ft
FIS		2.9				
FLML		5.5				feet
EMFW		2.2				mi/hr
Crown Fire Indices						
TORI						mi/hr
CRNI						mi/hr
SURI		0				mi/hr
Critical Initiation						
FLIN/Initiation		0				BTU/ft
FLML/Initiation		0				feet
SPRT/Initiation		0				ch/hr
Critical Active						
ACBD/active		0				kg/m <sup>3</sup>
SPRT/active		0				ch/hr
Cessation						
DW/ND/cessation		0				mi/hr

Figure 7-10 – Enter the input values in the *Input* page of the NEXUS screen; outputs are automatically produced in the Output pane.

Note that the NEXUS results match the BehavePlus results exactly. Just like BehavePlus, NEXUS can produce a graph of any of these outputs over a range inputs. To do this, simply click on the *Output Chart* tab, select the output variable and units on the Y-axis and the input variable, units, and range on the X-axis. To match the BehavePlus graph we created in the previous section, the only change to the default is to make the upper-end of the wind speed input range 40 mi/h. Type “40” in the box and press **Tab**. The chart updates automatically. Click the **Capture Chart** button to save the chart as an image file (Fig. 7-11).



**Figure 7-11** –Graphical NEXUS output showing simulated surface fire rate of spread over a range of 20-ft wind speed.

To see the data values that produced the chart, click on the *Output Table* tab. The settings from the *Output Chart* tab carry over to this tab, so there should be nothing to change. Click the **Text File** button to save the data set in comma-separated value (CSV) format.

### Chapter 7 summary

All fire behavior modeling systems used operationally in the United States use Rothermel's surface fire behavior model—a semi-physical/semi-empirical (laboratory) model—to simulate surface fire behavior. The model calculates forward rate of spread as the ratio of a fire's heat source to its heat sink. The Rothermel model uses inputs from four of the five elements of the fire modeling pentagon. Important fuelbed characteristics include fuel load, fuelbed bulk density, characteristic surface-area-to-volume ratio, fuel particle heat content, and dead fuel moisture of extinction. Moisture content of both live and dead fuel particles, wind speed and direction, and slope steepness are also important fire modeling influences.

## Chapter 8: Simulating Crown Fire Spread Rate

Wildland fire scientists recognize three general types of wildfire—ground, surface and crown—depending on the fuel stratum that is burning. Separate models of fire behavior exist for each type of fire. The behavior of ground fires, which burn very slowly in duff, roots, buried logs, and other below-surface fuel components, is not addressed in this document. Chapter 7 addressed surface fire behavior. This chapter addresses the behavior of crown fires, which burn in the canopy fuel stratum that overlies the surface fuel stratum. In Chapter 9, we will integrate surface and crown fire models into a single, integrated simulation of wildfire behavior.

The objectives of Chapter 8 are to:

- describe the development and application of the Rothermel crown fire spread correlation for simulating the long-range average and near-maximum crown fire spread rate,
- describe the development and application of the short-range crown fire spread rate potential,
- describe the factors affecting whether spotting from crown fires contributes to fire growth, and
- demonstrate the simulation of crown fire spread rate with BehavePlus and NEXUS.

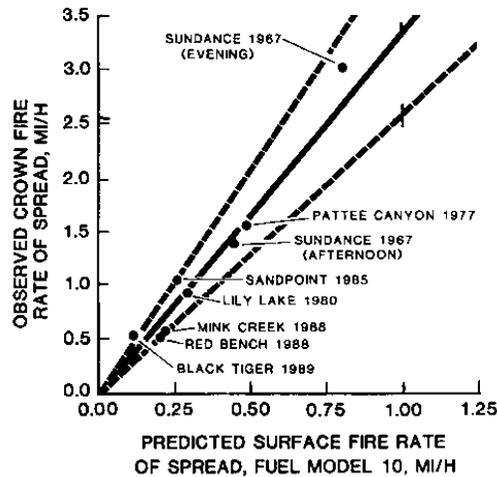
Detailed understanding of the nature of crown fires—how they start, spread, and cease—is not yet available to scientists or managers. Nonetheless, simulating the spread rate of crown fires in coniferous forests has been possible for more than two decades. New models of crown fire spread rate have recently become available, but are not yet included in fire behavior modeling used in the United States.

### **Rothermel correlation**

Following the active 1998 wildfire season in the northern Rocky Mountains, Rothermel and fire behavior scientists noted that the 1972 surface fire spread model was clearly inadequate when fires moved into the tree crowns. Unfortunately, no method of predicting crown fire behavior existed, so fire behavior analysts used a calibration approach to modify predictions made with the surface fire model.

Rothermel (1991) formalized that approach by developing a linear regression model. The model related crown fire spread rate on eight wildfires to predictions made with the surface fire spread model. The surface fire predictions were made with very specific inputs, not necessarily representing surface fuel where the fire was burning. For example, for the correlation, fuel model 10 (Anderson 1982) was used, and the wind adjustment factor was set to 0.4 for all eight fires because that value gave a good result

(Fig. 8-1), even though it would not necessarily have been used for surface fire predictions in those conditions.



**Figure 8-1** – Wildfire data points used in Rothermel's (1991) correlation between observed crown fire spread rate and predicted surface fire spread rate (using certain inputs).

The linear regression produced the following relationship:

$$ROS_{crown} = 3.34 * ROS_{FM10}$$

where  $ROS_{FM10}$  is calculated using a wind adjustment factor of 0.4. That is, those nine crowning wildfires spread at an average of 3.34 times the rate predicted with the surface fire spread model using fuel model 10 and  $WAF = 0.4$ .

This simple model of crown fire spread rate is used in all operational fire behavior modeling systems used in the U.S.

### Model of short-term potential

Rothermel's correlation described above simulates the average crown fire rate of spread over the course of several hours, and consequently many miles. He also produced a simple model of short-term "near-maximum" crown fire spread rate by calculating  $R_{max}/R$ , the ratio between the maximum and average crown fire spread rates, observed on five of the eight crowning wildfires.  $R_{max}/R$  varied from 1.23 to 2.0, with an average of 1.7. Therefore, multiplying  $ROS_{crown}$  by 1.7 produces an estimate of the near-maximum crown fire spread rate.

None of the operational fire behavior modeling systems directly implements this short-term near-maximum potential crown fire spread rate. However, NEXUS has "multipliers," or adjustment factors, that allow the user to easily replicate this model of short-term potential crown fire rate of spread by specifying a value of 1.7 for the crown fire spread rate multiplier.

## Spotting and crown fire growth

Spotting—new fires igniting downwind of the main fire due to firebrands—is well known to influence fire growth and behavior when certain fuel types burn at high intensity, including crown fires in coniferous forests. Embers lofted from other fuel types, such as grass, burn out so quickly that the main fire overruns any spot fires very quickly.

In order for spot fires to influence the growth of a crowning wildfire, the firebrands must travel far enough that the resulting spot fires are not overrun by the main fire before becoming established. Under conditions of uniform fuel and wind speed, the factors affecting whether spot fires influence crowning fire growth include: the length of time embers remain airborne, their downwind rate of travel, their burnout time, their likelihood of igniting a spot fire, the delay between ember contact with the ground and flaming fire growth, and the acceleration from point-source fire to steady state line fire. Compared to the predicted average crown fire spread rate, nearly all potential spot fires would be overrun by the main fire if wind speed and fuels are constant.

However, variability in the fire environment—temporally changing wind speed, or spatially varying fuel characteristics—will tend to result in a greater influence of spotting on fire growth. This is because variability has little influence on lofted embers—they tend to be lofted during the brief period of strong wind but remain aloft so briefly that they are not influenced by wind speed lulls. The crowning wildfire, in contrast, will spread much slower during wind lulls, and may even fail to spread as an active crown fire during that time. Also, the crowning wildfire can spread into a fuel complex unable to support high crown fire spread rates, whereas the embers can sail over such fuel complexes.

Fortunately, these factors are considered implicitly in many fire growth modeling systems, such as FARSITE.

## Using non-spatial modeling systems

In the following two sections, we will demonstrate the basic use of the non-spatial fire modeling systems BehavePlus and NEXUS to simulate crown fire rate of spread. We'll use the same fire environment inputs for both (Table 8-1).

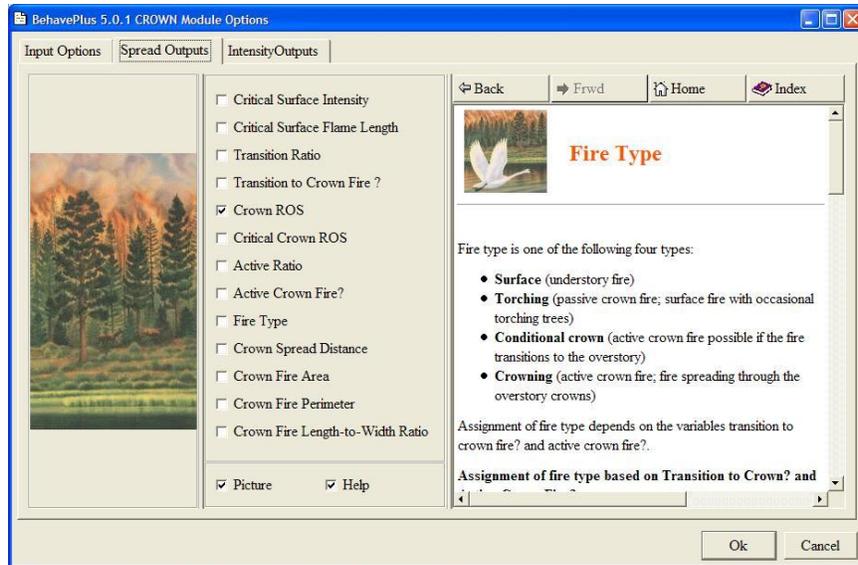
**Table 8-1** – Summary of fire modeling inputs to be used to demonstrate crown fire spread rate modeling in BehavePlus and NEXUS.

Fire modeling influence	Fire model input	Input
Fuelbed structure	Fuel model	n/a
Moisture content	1-hr timelag	4 %
	10-hr timelag	5%
	100-hr timelag	6%
	Live herb	n/a
	Live woody	90%
Wind characteristics	Wind speed	0-50 mi/h
	WAF	n/a
	Wind Dir.	Upslope
Slope	Steepness	20 %

### *BehavePlus*

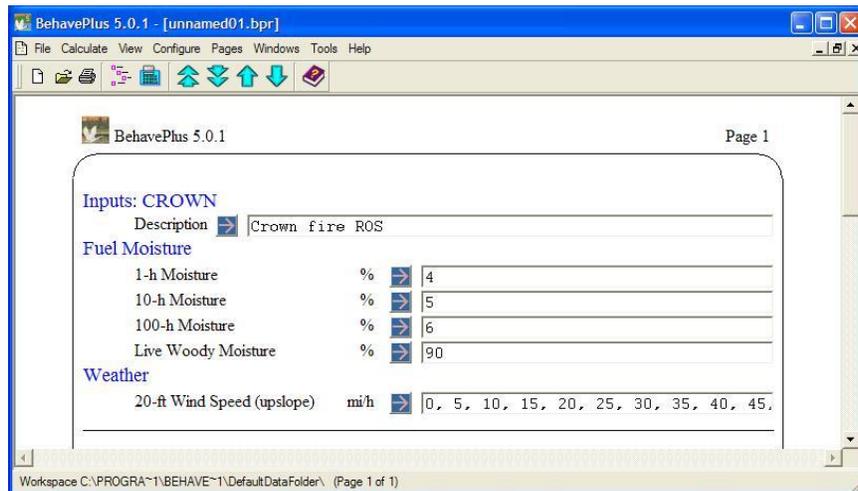
BehavePlus is a highly flexible non-spatial computer application for modeling the fire environment, behavior, and effects. It models surface fire and crown fire behavior separately. This section focuses on using BehavePlus to model crown fire spread rate.

Start by opening the *Module Selection* dialog box (**Configure > Module selection**). Make sure that "Crown Fire (CROWN)" is the only box checked, and then click the **Options** button next to the crown fire module. In this dialog box, uncheck all options except "Crown ROS" (Fig. 8-2).



**Figure 8-2** – The BehavePlus *CROWN Module Options* dialog box. For our example, we need to select only Crown ROS.

The resulting worksheet requires only two inputs: fuel moisture and wind speed. BehavePlus does not use slope steepness in its calculation of crown fire rate of spread, so that input does not appear on the worksheet. Enter values from Table 8-1 into the appropriate spaces in the worksheet. The completed worksheet should appear as in Figure 8-3. You can use the right-arrow button next to the wind speed input to open an input guide to help select wind speed values from 0 to 50 mi/h.



**Figure 8-3** – The completed BehavePlus worksheet for simulating only crown fire rate of spread, which is a function of fuel moisture and wind speed. BehavePlus does not include slope steepness as a factor affecting crown fire rate of spread, but NEXUS does.

You are now ready to calculate the selected outputs. To do so, select **Calculate > Calculate** from the menu or click the calculator icon. For now, let's display only the table results. The outputs are presented on a new page (Fig. 8-4).

### Crown fire ROS

20-ft Wind mi/h	Crown Fire ROS ch/h
0	3.1
5	11.4
10	25.4
15	42.9
20	63.2
25	85.7
30	110.4
35	136.8
40	165.0
45	194.7
50	225.8

**Figure 8-4** – BehavePlus results for crown fire rate of spread as a function of wind speed. (Fuel moisture inputs are as shown in Figure 8-3). Because BehavePlus does not include slope steepness, the resulting spread rate values are slightly lower than in NEXUS.

To save the tabular results, choose **File > Export results**. The results are saved in html format, which can then be opened in Excel.

### NEXUS

NEXUS is a simple software application that simulates surface and crown fire behavior and rates crown fire potential for a specified fire environment. NEXUS can integrate surface fire and crown fire behavior models. This section focuses on using it to model crown fire rate of spread only. Because NEXUS is designed to integrate surface and crown fire models, a non-standard use of it is required to replicate just the crown fire spread rate portion. We will demonstrate two ways to accomplish that task.

After starting the NEXUS program, we will fill out three of the available scenarios to illustrate several ways to simulate crown fire rate of spread. First, we will use Scenario A to apply a literal approach, using a surface fire prediction made with inputs to exactly match Rothermel's correlation. To do this, choose "surface" for the Simulation Type, fuel model 10 for the "Low fuel model," 0.4 for the wind reduction factor (*WDR<sub>low</sub>*), 3.34 for the rate of spread multiplier (*ROS<sub>low</sub>*), and the remainder of the inputs as described in Table 8-1. The inputs should appear as in Scenario A below (Fig. 8-5).

Scenario		A	B	C	D	Units
Simulation Type		surface	conifer	conifer	surface	
Low fuel model	FMCDlow	10	TU5	TU5	Low FM	
	WNDRlow	.4	.2	.2	0.1	fraction
	ROSMlow	3.34	1	1	1	fraction
	LADMlow	1	1	1	1	fraction
	FLIMlow	1	1	1	1	fraction
High fuel model	FMCDhigh	High FM	10	10	High FM	
	WNDRhigh	0.1	0.1	0.1	0.1	fraction
	ROSMhigh	T	1	1.7	T	fraction
	LADMhigh	T	T	T	T	fraction
	FLIMhigh	T	T	T	T	fraction
Dead moisture	MC01	4	4	4		percent
FBA Tables	MC10	5	5	5		percent
	MC100	6	6	6		percent
Live moisture	MCLH					percent
	MCLW	90	90	90		percent
Canopy fuels	ACBD	T	1	1		kg/m <sup>3</sup>
	CABH	T	1	1		feet
	ACFL	4	4	4		ton/acre
	FOMC	100	100	100	100	percent
Misc	STFL					meters
Wind and slope	OWND	20	20	20		mi/hr
	SLOP	20	20	20		percent
	WDIR	0	0	0		degrees

**Figure 8-5** – To illustrate the simulation of crown fire rate of spread, enter input values in scenarios A, B, and C, as shown here. Outputs are produced automatically.

In Scenario B, we will let NEXUS integrate surface and crown fire models. In order to look at crown fire rate of spread, we need to make sure the simulation transitions to active crown fire almost immediately. To do that, first select “conifer” for Simulation Type (representing crown fire in coniferous forest), fuel model TU5, and a wind reduction factor of 0.2. In the *Canopy fuels* input section, enter 1 kg/m<sup>3</sup> for canopy bulk density (*ACBD*; even though such a value is much too high for reality), 1 foot for canopy base height (*CABH*), 4 tons/ac for canopy fuel load (*ACFL*), and 100 for foliar moisture content (*FMC*). The wind and slope inputs are the same as those for Scenario A.

Scenario C will be the same as Scenario B but with one change: enter a rate of spread multiplier of 1.7 for *ROSMhigh*. This will modify the crown fire spread rate prediction by 1.7, which reproduces Rothermel's near-maximum crown fire spread rate prediction. Entries for the three scenarios should appear as in Figure 8-5.

To view the results, switch to the *Output Table* tab. In the *Row Input* box, make sure the variable is open wind speed and the units are mi/hr, and then set the minimum value to 0, the maximum to 50, and the step to 5. This will allow comparison to the BehavePlus simulation of the previous section. The resulting table should appear as in Figure 8-6.

The screenshot shows the 'Output' window in NEXUS. The 'Variable' is set to 'Headfire Spread Rate (SPRT)' and the 'Units' are 'ch/hr'. Below is a table with the following data:

Input	A	B	C	D
.000	5.400	4.300	9.200	
5.000	13.700	13.700	23.200	
10.000	27.700	27.700	47.100	
15.000	45.200	45.200	76.900	
20.000	65.500	65.500	111.400	
25.000	88.200	88.200	149.900	
30.000	112.800	112.800	191.800	
35.000	139.400	139.400	236.900	
40.000	167.600	167.600	284.900	
45.000	197.300	197.300	335.500	
50.000	228.600	228.600	388.600	

**Figure 8-6** – The NEXUS output table results for literal simulation of crown fire rate of spread (column A), simulation using the integrated crown fire modeling approach (column B), and simulation of the near-maximum crown fire rate of spread using the integrated approach (column C).

Note that for windspeeds at or above 5 mi/h, the results for scenarios A and B are identical. Scenario A is an exact simulation of Rothermel's crown fire model; Scenario B incorporates transitions to crown fire. The transition to crown fire is not complete when the wind speed is zero. Now, also note that these spread rate values are slightly higher than the BehavePlus results in Figure 8-4. The reason for the difference is slope steepness. BehavePlus assumes zero slope for the crown fire simulation, whereas NEXUS uses the 20% slope (upslope direction, in this case), which adds a little to the predicted rate of spread. Finally, Scenario C shows the predicted near-maximum crown fire spread rate, which is simply 1.7 times that of the predictions for scenarios A and B.

To save the data to a file, click the **Text File** button to save the data set in comma-separated value (CSV) format.

## Chapter 8 summary

All fire behavior modeling systems used operationally in the United States use Rothermel's (1991) correlation to estimate crown fire rate of spread. The correlation is based on the relationship between the observed rate of spread and predictions made with the surface fire spread model using certain inputs. The results for eight crowning wildfires produced the simple model that crown fire spread rate could be predicted as 3.34 times the spread rate predicted for surface fuel model 10 when using a wind adjustment factor of 0.4. For a subset of those fires, the near-maximum crown fire rate of spread was found to be 1.7 times this long-run average rate.

BehavePlus and NEXUS both apply this correlation for simulating crown fire spread rate. BehavePlus does not use slope steepness in its calculation of crown fire spread rate, whereas NEXUS does. The difference is minor unless the slope is steep and the wind is light.

Crown fire rate of spread is an important factor when integrating surface and crown fire models, which will be discussed in the next chapter.

## Chapter 9: Integrating Surface and Crown Fire Behavior Models

Wildland fire scientists recognize three general types of wildfire—ground, surface and crown—depending on the fuel stratum that is burning. Separate models of fire behavior exist for each type of fire. The behavior of ground fires, which burn very slowly in duff, roots, buried logs, and other below-surface fuel components, is not addressed in this document. Chapter 7 addressed surface fire behavior. Chapter 8 addressed the behavior of crown fires. In this chapter, we will integrate surface and crown fire models into a single, integrated simulation of wildfire behavior.

The objectives of Chapter 9 are to:

- describe the general process for integrating surface and crown fire spread rates,
- describe the crown fire initiation model used in fire behavior modeling systems,
- define and describe two indices of the potential for crown fire initiation: Torching Index and Transition Ratio,
- describe the threshold for sustained active crown fire,
- define and describe two indices of the potential for active crown fire: Crowning Index and Active Ratio,
- list and define the types of wild fire as recognized in fire behavior modeling systems, and
- demonstrate the simulation of surface-through-crown fire behavior using BehavePlus and NEXUS.

No single integrated model of surface and crown fire behavior exists yet in operational form. The few physics-based wildfire behavior models that integrate surface-through-crown fire behavior in a single simulation require several orders of magnitude more computing power than the current surface and crown fire models and are not yet ready for routine use. Therefore, operational fire behavior simulation systems must integrate separate models of surface fire and crown fire behavior, discussed in the previous two chapters. This integration is accomplished by using two transition models. One transition model identifies the conditions under which a surface fire can transition to some kind of crown fire, and the second model determines the type of crown fire.

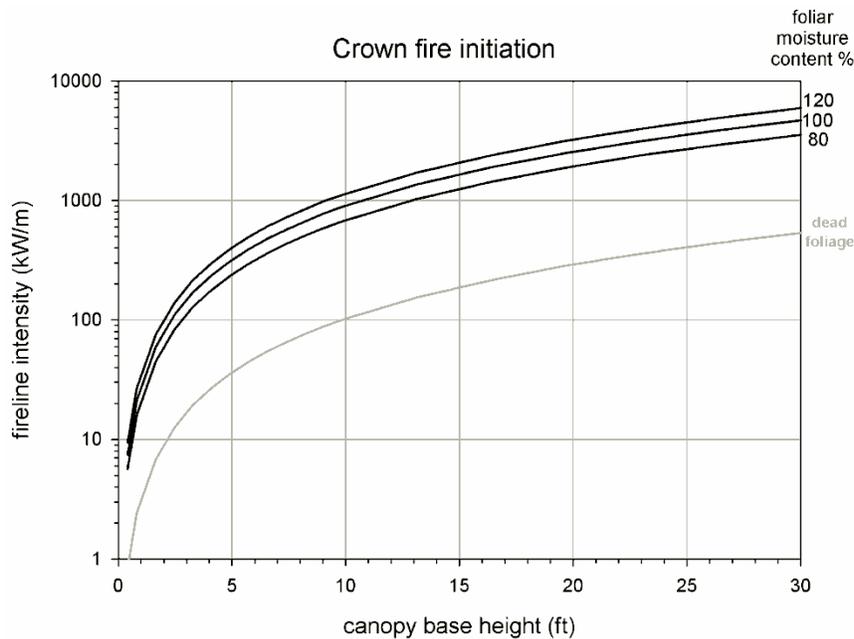
In this chapter, we will continue to use the example fire environment described in previous chapters (Table 9-1).

**Table 9-1** – Example fire modeling environment variables used in this chapter.

Fire modeling influence	Fire model input	Input
Fuelbed structure	Fuel model	TU5
	<i>CBH</i>	5 ft
	<i>CBD</i>	0.15 kg/m <sup>3</sup>
Moisture content	1-hr timelag	4 %
	10-hr timelag	5%
	100-hr timelag	6%
	Live herb	n/a
	Live woody	90%
	<i>FMC</i>	100%
Wind characteristics	Wind speed	0-50 mi/h
	<i>WAF</i>	0.12
	Wind Dir.	Upslope
Slope	Steepness	20 %

### Crown fire initiation

Crown fire initiation is the transition from surface fire to some kind of crown fire, either torching trees (passive crown fire) or fully-active crown fire. Fire behavior modeling systems in the United States use Van Wagner's (1977) model of crown fire initiation, which identifies the critical threshold fireline intensity at which the transition occurs as a function of canopy base height (CBH) and foliar moisture content (Fig. 9-1).



**Figure 9-1** – Van Wagner's (1977) crown fire initiation model determines the threshold fireline intensity required to initiate crown fire from canopy base height and foliar moisture content (*FMC*). Typical values of *FMC* range from 80-120 percent and have little effect on critical fireline intensity. Dead foliage still attached to branches has much lower moisture content (here assumed to be 10%) and therefore is more prone to ignition.

For the example fire modeling environment described in Table 9-1, the threshold fireline intensity is 317 kW/m. For use in fire behavior modeling systems, this threshold value is compared with the fireline intensity simulated using Rothermel's surface fire spread model (see Chapter 7). If the simulated surface fire intensity exceeds the threshold, then the transition to crown fire is assumed to take place.

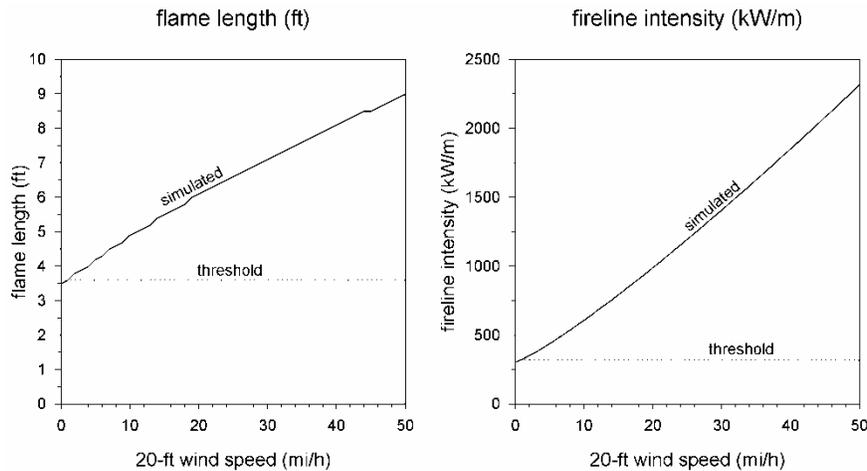
Foliar moisture content, within the normal range for living foliage, has a small effect on the threshold for crown fire initiation. Foliage of recently killed trees exhibits much lower moisture content, so the threshold for crown fire initiation can be quite low while the dead needles remain in the trees. *CBH* has the strongest effect on the threshold surface fire intensity. Unfortunately, *CBH* is a difficult parameter to measure at a plot and is even more difficult to map. It is therefore critical to examine how *CBH* and predicted fire behavior interact to simulate the threshold between surface fire and crown fire. Two options are available to aid that examination: Torching Index (NEXUS) and Transition Ratio (BehavePlus).

### *Torching Index*

The Torching Index (*TI*) is defined as the 20-ft wind speed at which the simulated surface fireline intensity (calculated with Rothermel's model) equals the critical threshold intensity (calculated with Van Wagner's model). The *TI* integrates the whole array of fire environment variables in the fire modeling pentagon (see Chapter 1). If the *TI* is low—transition to crown fire can occur at low wind speeds—then the crown fire hazard

is high. High values of  $TI$  mean that transition to crown fire will occur with higher wind speeds, so the hazard is low.

The Torching Index can be visualized graphically by plotting the simulated and threshold fireline intensity values over a range of wind speeds. For convenience, the simulated and threshold fireline intensity values can be converted to the equivalent flame length as well (Fig. 9-2). The threshold value does not change with wind speed, so it is represented as a flat line, but the simulated behavior increases with wind speed. The wind speed at which the simulated value crosses the threshold is the Torching Index. In this example, the transition occurs when the wind speed is between 0 and 1 mi/h. In other words, crown fire initiation can occur with little or no wind.

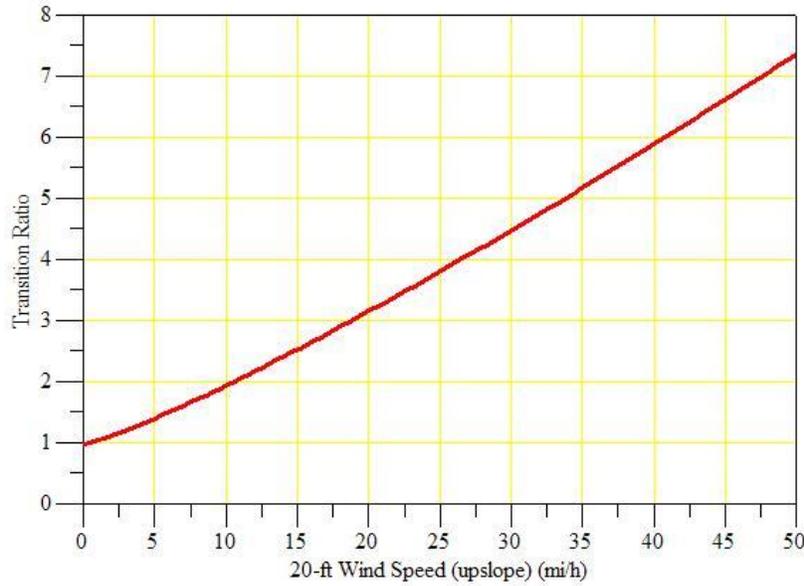


**Figure 9-2** – The Torching Index is the 20-ft wind speed at which the simulated fireline intensity (or flame length) equals the threshold value. In this example (see Table 9-1), this transition occurs when the wind speed is between 0 and 1 mi/h. In other words, crown fire initiation can occur with little or no wind.

The Torching Index is calculated in NEXUS, but not BehavePlus.

### *Transition Ratio*

BehavePlus does not calculate the Torching Index, but instead calculates the Transition Ratio ( $TR$ ), the ratio of the simulated to threshold fireline intensity. When the  $TR$  is less than 1, transition to crown fire does not occur. When  $TR$  is greater than 1, transition to crown fire occurs (Fig. 9-3).



**Figure 9-3** – The Transition Ratio calculated in BehavePlus is the ratio of the simulated to threshold fireline intensity. Although BehavePlus does not directly calculate the Torching Index, it can be seen here as the 20-ft wind speed at which  $TR = 1$ , which is again between 0 and 1 mi/h.

Because BehavePlus and NEXUS use the same underlying models,  $TI$  and  $TR$  are perfectly consistent. The wind speed at which  $TR = 1$  is also the Torching Index (see figures 9-2 and 9-3).

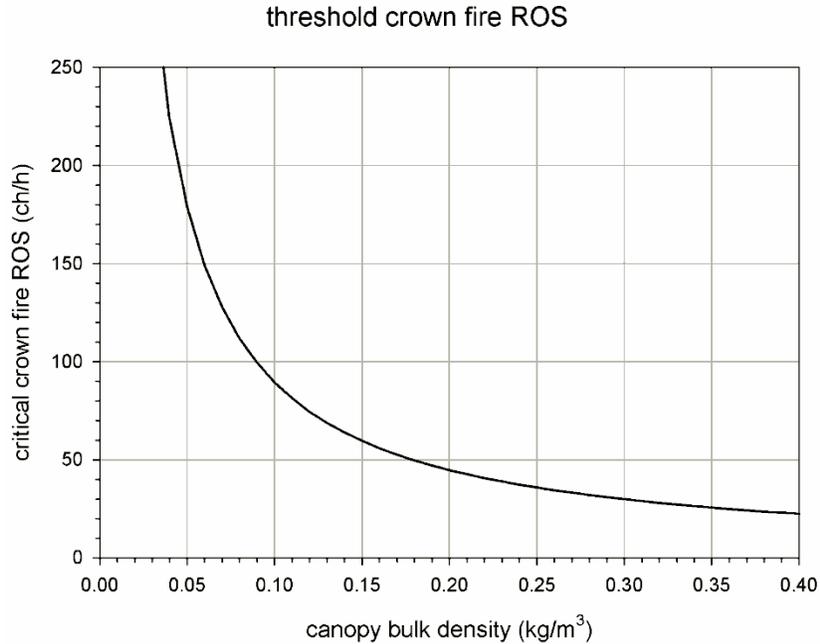
The Transition Ratio is calculated in BehavePlus, but not NEXUS.

### Sustained active crown fire spread

All operational fire behavior modeling systems use Van Wagner's (1977) model that identifies the minimum mass-flow rate needed for sustained active crown fire spread. The model is very simple: if the estimated mass-flow rate through the forest canopy exceeds a minimum value, then active crown fire is possible; otherwise only passive or intermittent crowning can be expected. Van Wagner's minimum mass-flow rate, estimated after observing a single crown fire thought to be near the threshold between passive and active crown fire, is  $3.0 \text{ kg/m}^2\text{-min}$ . Mass-flow rate is the product of canopy bulk density ( $CBD$ ) and rate of spread ( $ROS$ ), so the threshold can be expressed as the minimum crown fire spread rate as a function of  $CBD$  (Fig. 9-4):

$$ROS_{critical} = \frac{3}{CBD}$$

where  $ROS$  is measured in  $\text{m/min}$  and  $CBD$  in  $\text{kg/m}^3$ .



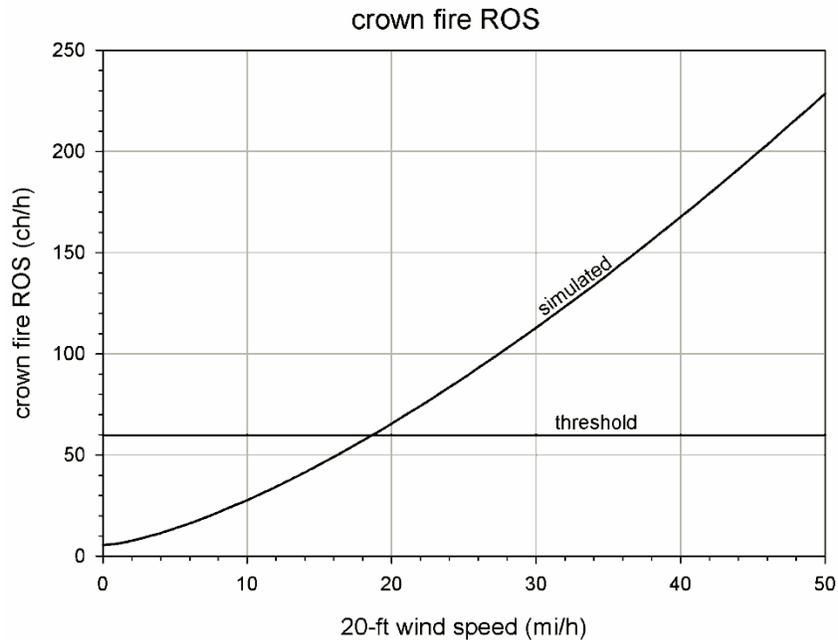
**Figure 9-4** – The critical (threshold) crown fire rate of spread is a function of canopy bulk density. Fully active crown fire is possible when the simulated crown ROS exceeds this threshold value. For our example fire modeling environment ( $CBD = 0.15 \text{ kg/m}^3$ ), the threshold crown fire ROS = 59.7 ch/h (20 m/min).

If the simulated crown fire ROS (see Chapter 8) is greater than this critical value, then an active crown fire is possible; otherwise, only torching or intermittent crown fire is possible. In this example ( $CBD = 0.15 \text{ kg/m}^3$ ), the threshold crown fire ROS is 59.7 ch/h (20 m/min).

### *Crowning Index*

The criterion for active crowning is a function of mass-flow rate through the canopy space. Mass-flow rate is a function of crown fire ROS. Crown fire ROS is primarily a function of wind speed. Therefore, crown fire potential can be rated by finding the wind speed that produces the ROS that results in the threshold mass-flow rate, called the Crowning Index ( $CI$ ). If the  $CI$  is low—meaning that active crown fire can occur at low wind speeds—then the crown fire hazard is high. High values of  $CI$  mean that active crown fire requires high wind speeds, so the hazard is low.

The Crowning Index can be visualized graphically by plotting the simulated and threshold crown fire ROS values over a range of wind speeds (Fig. 9-5). The threshold value does not change with wind speed, so it is represented as a flat line, but the simulated ROS increases with wind speed. The wind speed at which the simulated value crosses the threshold is the Crowning Index. In this example, the  $CI$  is 18.6 mi/h.



**Figure 9-5** – The Crowning Index is the 20-ft wind speed at which the simulated crown fire rate of spread (*ROS*) equals the threshold crown fire *ROS*. In this example, that occurs at a wind speed of 18.6 mi/h (for crown fire *ROS* as simulated in NEXUS).

The Crowning Index is calculated in NEXUS, but not BehavePlus.

### *Active Ratio*

BehavePlus does not calculate the Crowning Index, but instead calculates the Active Ratio (*AR*), which is the ratio of the simulated to threshold crown fire *ROS*. When *AR* is less than 1, active crown fire is not possible. When *AR* is greater than 1, fully active crown fire is possible (Fig. 9-6).



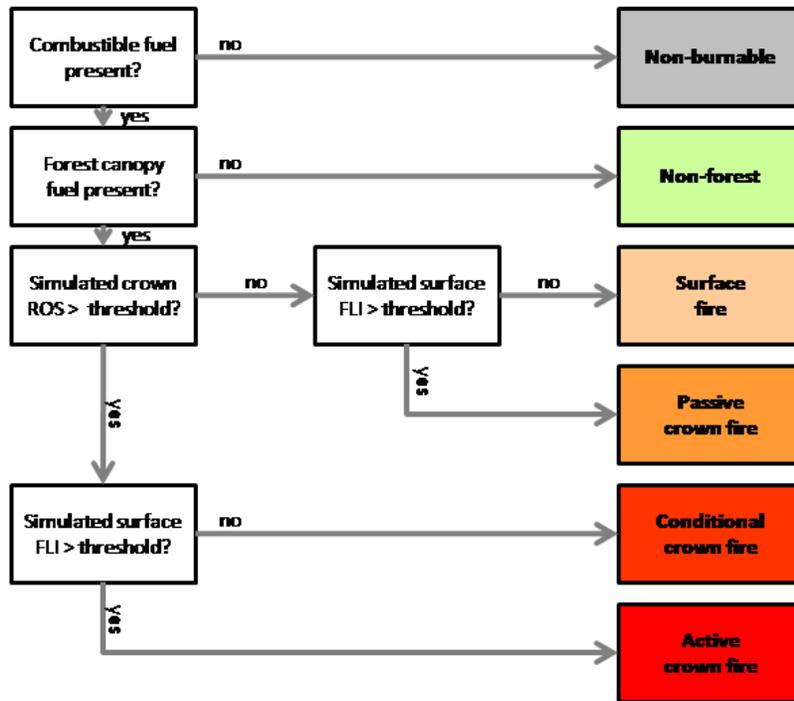
**Figure 9-6** – The Active Ratio calculated in BehavePlus is the ratio of the simulated to threshold crown fire rate of spread (ROS). Although BehavePlus does not directly calculate the Crowning Index (CI), it can be seen here as the 20-ft wind speed at which  $AR = 1$ , which is 19.1 mi/h. BehavePlus does not use slope steepness in its calculation of crown fire ROS, whereas NEXUS does, so the NEXUS-calculated CI is 18.6 mi/h.

Because BehavePlus and NEXUS use the same underlying models, *CI* and *AR* are *almost* perfectly consistent. The wind speed at which  $AR = 1$  is also the Crowning Index. The only reason the two systems are not perfectly consistent is that BehavePlus does not use slope steepness in its prediction of crown fire *ROS*, whereas NEXUS does. In this example (slope steepness = 20 percent),  $AR = 1$  at a wind speed of 19.1 mi/h, whereas the Crowning Index as calculated in NEXUS is 18.6 mi/h, a small difference.

The Active Ratio is calculated in BehavePlus, but not NEXUS.

### Type of fire classification

Fire behavior modeling systems use either a three- or four-class model for classifying type of fire. BehavePlus and NEXUS both use the four-class model, so that will form the foundation of the type of fire classification in this chapter. However, some geospatial fire analysts have suggested a more broadly applicable six-class model, adding new classes for “non-burnable” and “non-forest” fire. The non-burnable type (Figure 9-7) is used for completeness when displaying type of fire results on a map.



**Figure 9-7** – The expanded six-class model of wildland fire types. The new non-burnable type is for completeness in mapping fire modeling results; the non-forest type is to distinguish between a fire environment that has no potential to become a crown fire due to lack of an overlying combustible canopy (non-forest) and one that could potentially become a crown fire, but not in the modeled conditions (surface fire).

A non-forest fire is a fire that does not have an overlying forest canopy, such as grassland or shrubland. The reason for this new class is to distinguish between a surface fire that cannot be anything but a surface fire, because there is no canopy above it, and an under-burning surface fire that is burning in conditions that do not support any type of crowning.

A surface fire is one for which neither the simulated crown fire ROS nor surface fire FLI exceeds their respective threshold values. A surface fire is an underburn, but significant tree mortality and fuel consumption is still possible.

A passive crown fire is one for which the surface fire FLI exceeds the threshold value, but the crown fire ROS does not. A passive crown fire is also called intermittent crowning or torching, and encompasses a wide range of behavior, from little more than a surface fire to nearly active crown fire.

An active crown fire is one that meets both the crown fire initiation criterion and the criterion for sustained active crown fire. Active crown fires spread at the rate predicted using the model described in Chapter 8.

A conditional crown fire is one that exceeds the threshold for crown fire ROS but not for surface fire intensity. In other words, a conditional crown fire is a fire environment that could be expected to support active crowning, but cannot initiate one; active crowning

is thus conditioned on the type of fire that exists immediately before the modeled fire environment. If fire enters the stand as a crown fire, then it could be expected to remain a crown fire. If fire enters the stand as a surface fire, then it could be expected to remain a surface fire. NEXUS simulates the behavior characteristics of a conditional crown fire—rate of spread, fireline intensity, and flame length—as if it were an active crown fire to avoid a potentially serious under-prediction. The conditional crown fire type is relatively rare on most landscapes, requiring a fire environment with high *CBH* (high Torching Index) and high *CBD* (low Crowning Index). Note that conditional crown fire type is a fire modeling construct, not an observable phenomenon. What is observed is either a surface fire or active crown fire.

### Integrating surface and crown fire models

The final step in the integration of surface and crown fire models is to simulate the final, or overall, fire behavior characteristics. BehavePlus provides most of the essential components required for this integration, but falls short of actually doing so. Therefore, this section focuses on the method used in NEXUS. The final integrated rate of spread is computed as:

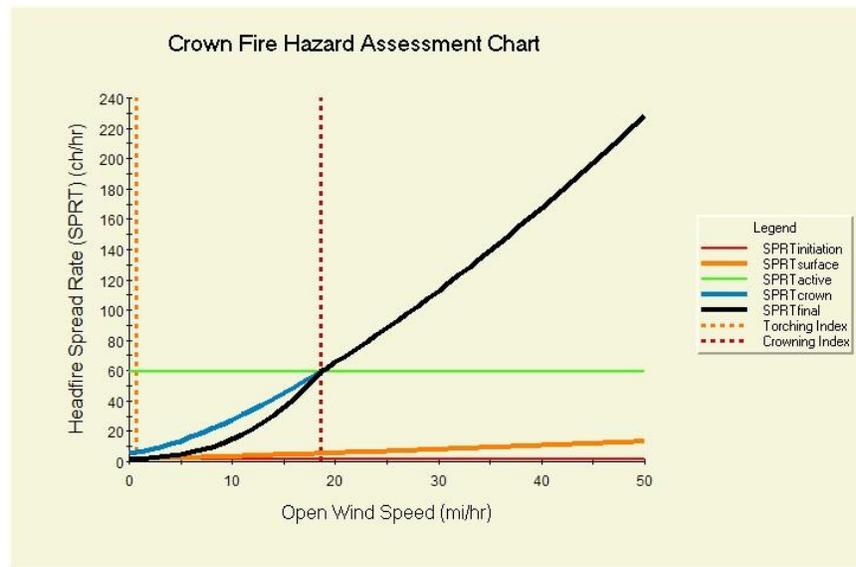
$$R_{final} = R_{surface} + CFB * (R_{crown} - R_{surface})$$

where *CFB* is a transition function that ranges from 0 for surface fires to 1 for a fully active crown fire. ( $R_{surface}$  and  $R_{crown}$  are as described in chapters 7 and 8.) Note that *CFB* is essentially a weighting factor for averaging  $R_{surface}$  and  $R_{crown}$ . When  $CFB = 0$ , all weight is placed on  $R_{surface}$ ; when  $CFB = 1$ , all weight is placed on  $R_{crown}$ ; and when  $CFB = 0.5$ , equal weight is placed on  $R_{surface}$  and  $R_{crown}$ .

Different models have been used to estimate *CFB*; NEXUS uses a simple straight-line model form. If the type of fire is “active crown fire” or “conditional crown fire,” then  $CFB = 1$ , meaning that  $R_{final} = R_{crown}$ . If the type of fire is “non-forest” or “surface fire,” then  $CFB = 0$ , meaning that  $R_{final} = R_{surface}$ . Finally, if type of fire is “passive crown fire,” then *CFB* is calculated as:

$$CFB = \frac{R_{surface} - R'_{init}}{R'_{surface} - R'_{init}}$$

where  $R'_{init}$  is the threshold surface fire rate of spread for crown fire initiation, and  $R'_{surface}$  is the surface fire spread rate that occurs when the wind speed equals the Crowning Index. In other words,  $CFB = 0.5$  when the predicted surface fire spread rate is halfway between the spread rate where initiation occurs and the spread rate where fully active crown fire occurs.  $R_{final}$  can be plotted on a crown fire hazard assessment chart along with the simulated and threshold spread rates (Fig. 9-8). Type of fire can also be visualized on this chart. When the wind speed is below the TI, surface fire is simulated; between the TI and CI is passive crown fire; and above the CI is active crown fire.



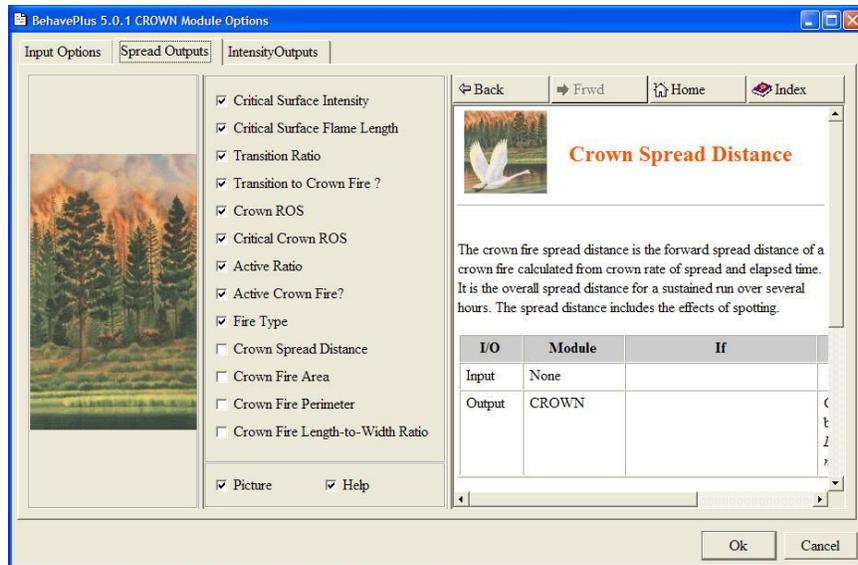
**Figure 9-8** – Crown fire hazard assessment chart in NEXUS for the example fire modeling environment, showing the TI and CI as dotted vertical lines and the final (overall) rate of spread as a black line.

## Using non-spatial modeling systems

In this section, we will illustrate how BehavePlus and NEXUS incorporate surface and crown fire models in their simulations of type of fire, indices of crown fire potential, and overall fire rate of spread.

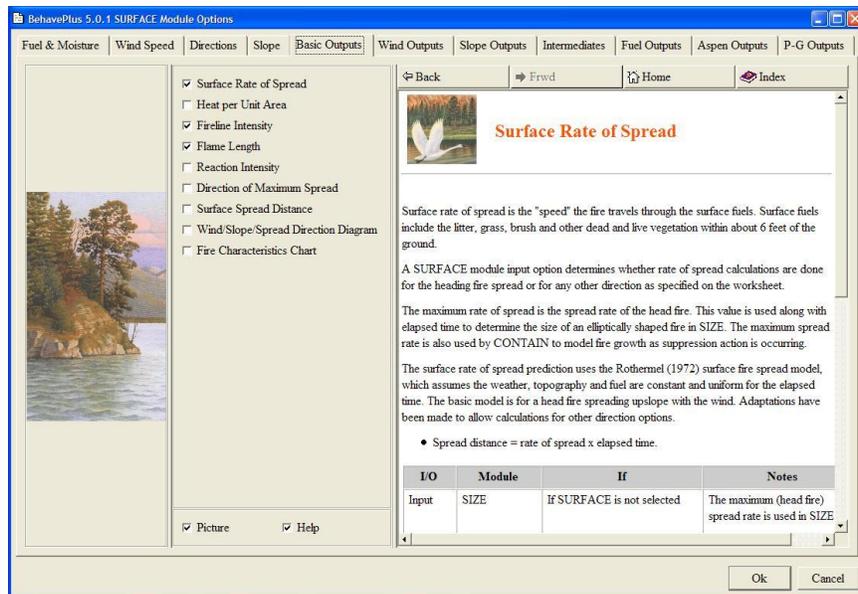
### *BehavePlus*

A few options in addition to those used in Chapter 8 are required to demonstrate how BehavePlus integrates surface and crown fire models. Begin by opening the *CROWN Module Options* dialog box, and then check all Spread Outputs but the last four (Fig. 9-9).



**Figure 9-9** – The *CROWN Module Options* dialog box in BehavePlus. For our example, choose all but the last four outputs.

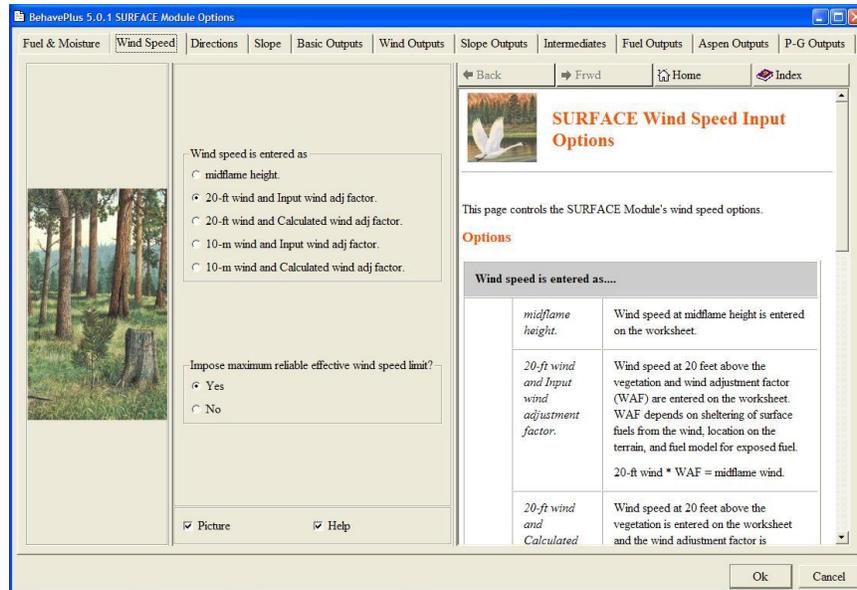
We also need to set the SURFACE Module Options so that Surface Rate of Spread, Fireline Intensity, and Flame Length are checked (Fig. 9-10). These simulated values will be compared to the threshold (critical) values generated in the CROWN module.



**Figure 9-10** – The *SURFACE Module Options* dialog box in BehavePlus. For comparison with CROWN Module results, select surface fire rate of spread, fireline intensity, and flame length outputs.

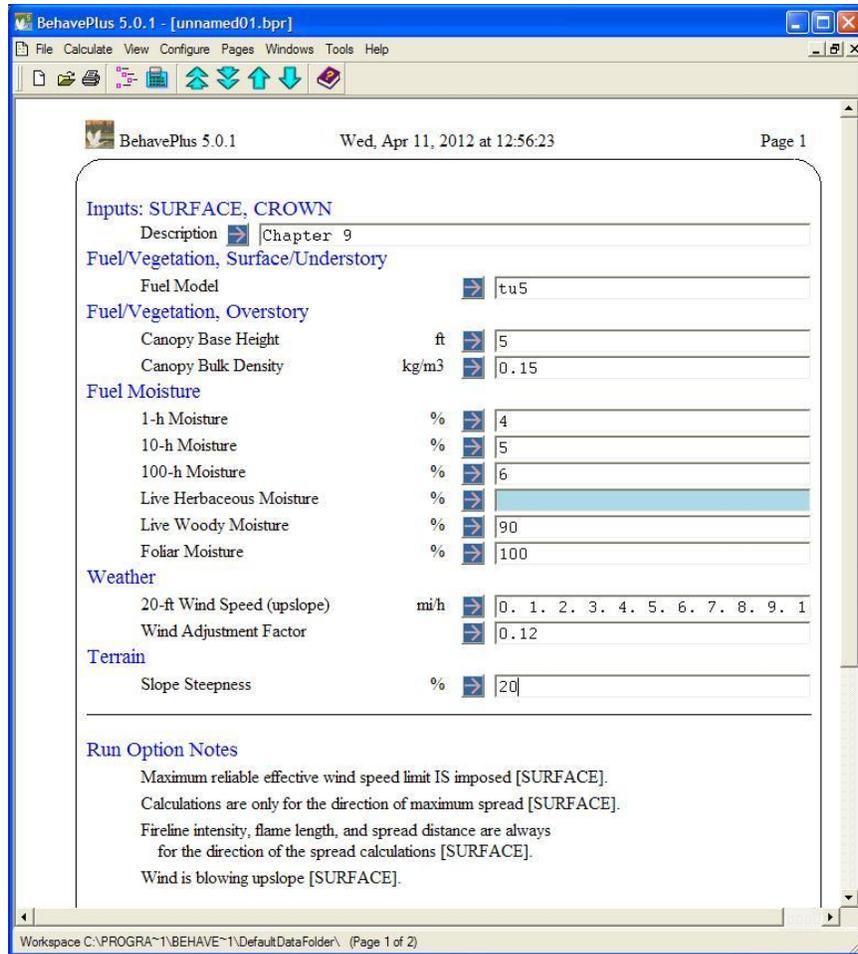
Finally, we need to ensure that both the SURFACE and CROWN modules work with wind speed measured at the 20-ft height. The best way to do that is to set, in the SURFACE

module, the wind speed to be entered as “20-ft wind speed and Input wind adj factor.” Select that option (Fig. 9-11).



**Figure 9-11** – The wind speed tab of the *SURFACE Module Options* dialog box in BehavePlus. To ensure consistency between the SURFACE and CROWN modules, wind speed must be entered as 20-ft wind speed and a wind adjustment factor. For consistency with NEXUS, choose the option for “20-ft wind and Input wind adj factor.”

The resulting worksheet can then be populated with the appropriate inputs. For wind speed, use a range from 0 through 50 mi/h in increments of 1 mi/h (Fig. 9-12).



**Figure 9-12** – The BehavePlus worksheet resulting from the settings described in figures 9-9 through 9-11. Use the guide button (arrow) to enter 20-ft wind speed values from 0 through 50 mi/h in steps of 1 mi/h.

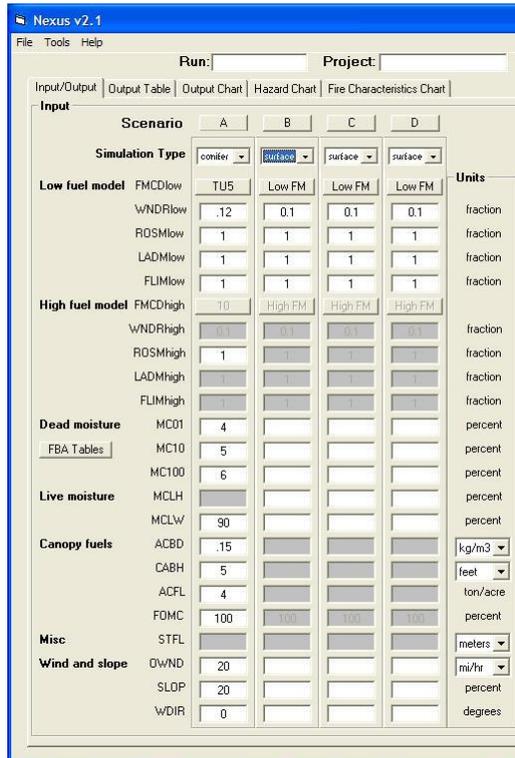
The results are presented in Table 9-2. Note that if the simulated surface fire flame length (column *d*) is greater than the threshold (critical) flame length (column *f*), then 'Transition to Crown?' is yes, the Transition Ratio will be 1.0 or greater, and Fire Type will be Torching or Crowning. Similarly, if the Crown ROS (column *i*) equals or exceeds the threshold (critical) crown ROS (column *j*) then the Active Ratio will be 1.0 or greater, 'Active Crown?' will be yes, and Fire Type will be Crowning or Conditional.

**Table 9-2 – BehavePlus results for the integrated SURFACE and CROWN modules.** Column *a* is the 20-ft wind speed, which ranges from 0-50 mi/h, as desired. Columns *b-d* display the outputs from the SURFACE module: rate of spread, fireline intensity, and flame length. Columns *e-h* display the outputs from the CROWN module related to transition to crown fire; columns *i-m* display outputs related to active crown fire.

(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)	(j)	(k)	(l)	(m)
20-ft Wind (mi/h)	Surface ROS (ch/h)	Fireline Intensity (BTU/ft/s)	Flame Length (ft)	Critical Surf Int (BTU/ft/s)	Critical Flame Len (ft)	Trans Ratio	Transition to Crown?	Crown ROS (ch/h)	Critical Crown ROS (ch/h)	Active Ratio	Active Crown?	Fire Type
0	1.7	88	3.5	91	3.6	1.0	No	3.1	59.7	0.1	No	Surface
1	1.9	94	3.6	91	3.6	1.0	Yes	4.0	59.7	0.1	No	Torching
2	2	101	3.8	91	3.6	1.1	Yes	5.4	59.7	0.1	No	Torching
3	2.2	109	3.9	91	3.6	1.2	Yes	7.1	59.7	0.1	No	Torching
4	2.3	118	4	91	3.6	1.3	Yes	9.1	59.7	0.2	No	Torching
5	2.5	127	4.2	91	3.6	1.4	Yes	11.4	59.7	0.2	No	Torching
6	2.7	136	4.3	91	3.6	1.5	Yes	13.9	59.7	0.2	No	Torching
7	2.9	146	4.5	91	3.6	1.6	Yes	16.5	59.7	0.3	No	Torching
8	3.1	156	4.6	91	3.6	1.7	Yes	19.3	59.7	0.3	No	Torching
9	3.3	166	4.7	91	3.6	1.8	Yes	22.3	59.7	0.4	No	Torching
10	3.5	176	4.9	91	3.6	1.9	Yes	25.4	59.7	0.4	No	Torching
11	3.7	186	5	91	3.6	2.0	Yes	28.7	59.7	0.5	No	Torching
12	3.9	197	5.1	91	3.6	2.2	Yes	32.0	59.7	0.5	No	Torching
13	4.1	208	5.2	91	3.6	2.3	Yes	35.5	59.7	0.6	No	Torching
14	4.3	218	5.4	91	3.6	2.4	Yes	39.2	59.7	0.7	No	Torching
15	4.5	229	5.5	91	3.6	2.5	Yes	42.9	59.7	0.7	No	Torching
16	4.7	241	5.6	91	3.6	2.6	Yes	46.8	59.7	0.8	No	Torching
17	5	252	5.7	91	3.6	2.8	Yes	50.7	59.7	0.9	No	Torching
18	5.2	263	5.8	91	3.6	2.9	Yes	54.8	59.7	0.9	No	Torching
19	5.4	275	6	91	3.6	3.0	Yes	58.9	59.7	1.0	No	Torching
20	5.6	286	6.1	91	3.6	3.1	Yes	63.2	59.7	1.1	Yes	Crowning
21	5.9	298	6.2	91	3.6	3.3	Yes	67.5	59.7	1.1	Yes	Crowning
22	6.1	310	6.3	91	3.6	3.4	Yes	71.9	59.7	1.2	Yes	Crowning
23	6.3	322	6.4	91	3.6	3.5	Yes	76.4	59.7	1.3	Yes	Crowning
24	6.6	334	6.5	91	3.6	3.7	Yes	81.1	59.7	1.4	Yes	Crowning
25	6.8	346	6.6	91	3.6	3.8	Yes	85.7	59.7	1.4	Yes	Crowning
26	7.1	358	6.7	91	3.6	3.9	Yes	90.5	59.7	1.5	Yes	Crowning
27	7.3	370	6.8	91	3.6	4.1	Yes	95.4	59.7	1.6	Yes	Crowning
28	7.5	382	6.9	91	3.6	4.2	Yes	100.3	59.7	1.7	Yes	Crowning
29	7.8	395	7	91	3.6	4.3	Yes	105.3	59.7	1.8	Yes	Crowning
30	8	407	7.1	91	3.6	4.5	Yes	110.4	59.7	1.9	Yes	Crowning
31	8.3	420	7.2	91	3.6	4.6	Yes	115.5	59.7	1.9	Yes	Crowning
32	8.5	432	7.3	91	3.6	4.7	Yes	120.7	59.7	2.0	Yes	Crowning
33	8.8	445	7.4	91	3.6	4.9	Yes	126.0	59.7	2.1	Yes	Crowning
34	9	458	7.5	91	3.6	5.0	Yes	131.4	59.7	2.2	Yes	Crowning
35	9.3	471	7.6	91	3.6	5.2	Yes	136.8	59.7	2.3	Yes	Crowning
36	9.5	483	7.7	91	3.6	5.3	Yes	142.3	59.7	2.4	Yes	Crowning
37	9.8	496	7.8	91	3.6	5.5	Yes	147.9	59.7	2.5	Yes	Crowning
38	10	509	7.9	91	3.6	5.6	Yes	153.5	59.7	2.6	Yes	Crowning
39	10.3	522	8	91	3.6	5.7	Yes	159.2	59.7	2.7	Yes	Crowning
40	10.6	536	8.1	91	3.6	5.9	Yes	165.0	59.7	2.8	Yes	Crowning
41	10.8	549	8.2	91	3.6	6.0	Yes	170.8	59.7	2.9	Yes	Crowning
42	11.1	562	8.3	91	3.6	6.2	Yes	176.7	59.7	3.0	Yes	Crowning
43	11.3	575	8.4	91	3.6	6.3	Yes	182.6	59.7	3.1	Yes	Crowning
44	11.6	589	8.5	91	3.6	6.5	Yes	188.6	59.7	3.2	Yes	Crowning
45	11.9	602	8.5	91	3.6	6.6	Yes	194.7	59.7	3.3	Yes	Crowning
46	12.1	615	8.6	91	3.6	6.8	Yes	200.8	59.7	3.4	Yes	Crowning
47	12.4	629	8.7	91	3.6	6.9	Yes	207.0	59.7	3.5	Yes	Crowning
48	12.7	642	8.8	91	3.6	7.1	Yes	213.2	59.7	3.6	Yes	Crowning
49	12.9	656	8.9	91	3.6	7.2	Yes	219.5	59.7	3.7	Yes	Crowning
50	13.2	670	9	91	3.6	7.4	Yes	225.8	59.7	3.8	Yes	Crowning

Using NEXUS

By default, NEXUS combines surface and crown fire models into an integrated simulation. As in Chapter 8, simply set the Simulation Type to “conifer” (for conifer crown fire), then enter into the worksheet the fire modeling environment variables described in Table 9-1. The inputs should appear as in Figure 9-13 below.



**Figure 9-13** – The inputs pane of the Input/Output tab of NEXUS. Enter a 20-ft wind speed (*OWND*) value of 20 mi/h on this sheet. A range of values can be set on a separate tab.

No further work is required to produce outputs; once a valid set of inputs is present, outputs are automatically generated. Review the results in the Output pane on the right side of the screen (Fig. 9-14).

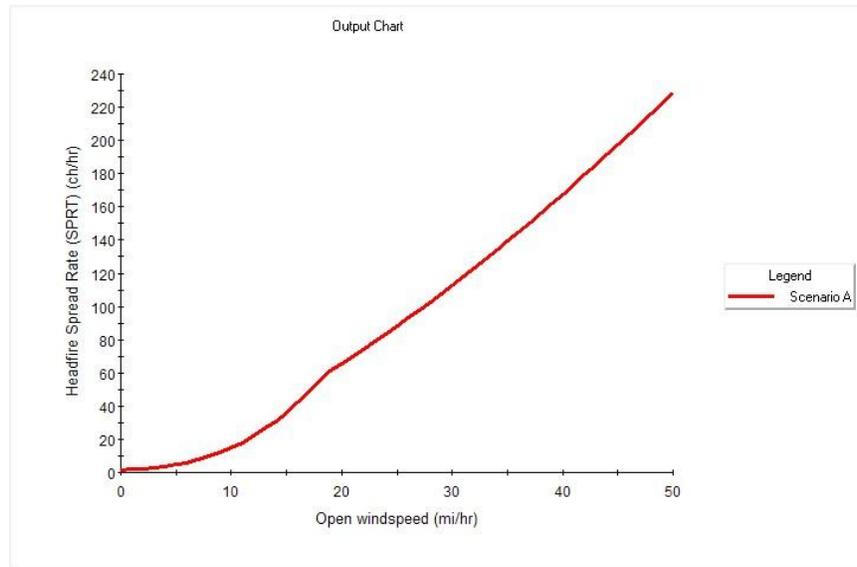
Date:  Analyst:  Run File:

**Output**

Scenario	A	B	C	D	Units
FTYP	active				nominal
CRFB	1				fraction
SPRT	65.54				ch/hr
HRUA	4188				BTU/hr
FLIN	5032				BTU/hr
FIS	4.2				
FLML	58.7				feet
EMFW	8.2				mi/hr
<b>Crown Fire Indices</b>					
TORI	0.7				mi/hr
CRNI	18.6				mi/hr
SURI	18.6				mi/hr
<b>Critical Initiation</b>					
FLNInitiation	92				BTU/hr
FLMInitiation	3.6				feet
SPRTInitiation	1.81				ch/hr
<b>Critical Active</b>					
ACBDactive	0.14				kg/m <sup>3</sup>
SPRTactive	53.65				ch/hr
<b>Cessation</b>					
OWNDcessation	1				mi/hr

**Figure 9-14** – Output pane of the Input/Output tab of NEXUS, listing the whole suite of NEXUS results for the 20-ft wind speed entered in the inputs pane. Use the drop-down buttons to change the output units.

These results are for only the 20-ft wind speed entered into the inputs pane (Fig. 9-13). To see results over a range of wind speeds, as we did in BehavePlus, simply switch to the *Output Table* or *Output Chart* tab and select Open (20-ft) wind speed as the Row Input variable, ranging from 0-50 in steps of 1, and then select the desired output variable and units. In this case, let's look at rate of spread in ch/h, which are the NEXUS defaults. The resulting output chart will appear as in Figure 9-15 below.



**Figure 9-15** – Output chart for final rate of spread (ch/h) over a range of wind speeds from 0 to 50 mi/h. To see these results in tabular form, simply switch to the *Output Table* tab; all settings from the chart are also applied to the table.

Note that because NEXUS integrates the surface and crown fire models, this chart automatically reflects the integration of those models but does not show type of fire. However, the crown fire hazard characteristics chart (Fig. 9-8) displays this same rate of spread result along with the thresholds for initiation and sustained crown fire spread and the Torching and Crowning Indices, which allows visualization of the type of fire.

### Chapter 9 summary

Operational fire behavior modeling systems use separate models of surface and crown fire behavior and then combine them into an integrated simulation. This integration is accomplished using two transition models. One model identifies the conditions under which a surface fire can transition to some kind of crown fire, and the second model determines the type of crown fire: passive or active.

BehavePlus and NEXUS use the same underlying models in nearly identical ways, so their results are almost perfectly consistent. The differences between the two systems are that:

- 1) BehavePlus does not use slope steepness in its estimation of crown fire spread rate, so it takes slightly greater wind speeds to achieve the threshold rate of spread in BehavePlus than it does in NEXUS, and
- 2) BehavePlus does not estimate a final, integrated rate of spread value, whereas NEXUS integrates surface and crown fire rate of spread through the use of a transition function called crown fraction burned.

## Conclusion

This document provided foundational information on wildfire behavior modeling as practiced in the United States. The information presented here is not a substitute for modeling experience gained during an apprenticeship under a master or journey-level fire behavior modeler. However, it does provide the solid foundation upon which to build such experience.

Although only two specific fire behavior modeling systems—NEXUS and BehavePlus—were discussed in detail, the fire modeling principles are applicable to the full range of operational software modeling systems available for use in the United States.

Chapter 1 provided an overview of fire behavior modeling that defined “fire” and “wildfire;” presented two ways of describing the morphology of a wildfire; defined four primary, quantitative wildfire behavior characteristics; and introduced the five major influences on wildfire behavior simulations.

Chapter 2 described how surface fuel is characterized for fire behavior modeling, including an overview of fire behavior fuel models as used in fire behavior modeling systems. The chapter also included a description of the required fuel model parameters, a description of the standard fire behavior fuel models available for use in any fire modeling project, and highlighted the need for and use of custom fuel models in BehavePlus and NEXUS.

Chapter 3 described five forest canopy characteristics as used in fire behavior simulations and included methods for estimating them.

Chapter 4 was dedicated to fuel moisture content inputs to fire behavior modeling systems. It includes sections on dead fuel moisture content, live herbaceous moisture content and its use in dynamic fuel modeling, live woody fuel moisture content, and foliar moisture content.

Chapter 5 described the slope characteristics—steepness and aspect—that directly or indirectly affect fire behavior simulations.

Chapter 6 described wind characteristics, including wind speed time-averaging period, reference height above the ground, and the different ways to specify wind direction in fire behavior modeling systems.

Chapter 7 described the simulation of surface fire behavior characteristics with Rothermel’s (1972) spread model. The structure of the spread model and factors affecting rate of spread were described, as well as how fire modeling software estimates fireline intensity using Rothermel’s spread model.

Chapter 8 described the development and application of Rothermel’s (1991) model of long-range average and near-maximum crown fire spread rate. The chapter also addressed factors affecting how spotting from crowning wildfires contributes to overall wildfire growth.

Chapter 9 described the general process for integrating surface and crown fire models, including a discussion of the conditions required for crown fire initiation and sustained

active crown fire spread. Two indices of the potential for crown fire initiation and two for sustained crown fire spread were described.

By itself, mastery of the information presented in this document does not necessarily qualify the reader to use fire behavior modeling software. It does, however, provide the foundation necessary for eventually mastering any of the operational models currently used in the United States.

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## Appendix B: Unit Conversions

A	B	C	
<b>Rate of spread</b>			<h3 style="text-align: center;">INSTRUCTIONS</h3> <p style="text-align: center;"><b>To convert from A to C</b></p> <p>Multiply by the factor in column B that is associated with the “to” units in column C.</p> <p>Example: to convert from a rate of spread of 12 m/min to ch/h, multiply by 2.9826:</p> $12 \text{ m/min} * 2.9826 = 35.8 \text{ ch/h}$ <p style="text-align: center;"><b>To convert from C to A</b></p> <p>Divide by the factor in column B that is associated with the “from” units in column C.</p> <p>Example: to convert from a rate of spread of 2.4 mi/h to m/min, divide by 0.037282:</p> $2.4 \text{ mi/h} / 0.037282 = 64.4 \text{ m/min}$ <p style="text-align: center;"><b>To convert from C to C</b></p> <p>First, divide by the factor in column B that is associated with the “from” units in column C, then multiply by the factor in column B that is associated with the “to” units in column C.</p> <p>Example: to convert from a rate of spread of 40 ch/h to mi/h, divide by 2.9826 then multiply by 0.037282:</p> $40 \text{ ch/h} / 2.9826 * 0.037282 = 0.5 \text{ mi/h}$
m/min	3.2808	ft/min	
	2.9826	ch/h	
	0.06	km/h	
	0.037282	mi/h	
<b>Wind speed</b>			
km/h	54.681	ft/min	
	0.91134	ft/s	
	0.62137	mi/h	
	0.27778	m/s	
<b>Length, width, height</b>			
m	100	cm	
	39.370	in	
	3.2808	ft	
<b>Fuelbed depth</b>			
cm	0.39370	in	
	0.032808	ft	
	0.01	m	
<b>Fireline intensity</b>			
kW/m	0.28909	BTU/(ft-s)	
	1	kJ/(m-s)	
<b>Fuel particle heat content</b>			
kJ/kg	0.001	MJ/kg	
	0.43027	BTU/lb	
<b>Fuel load</b>			
kg/m <sup>2</sup>	4.4609	ton/ac	
	0.20482	lb/ft <sup>2</sup>	
	10	tonne/ha	
	10	Mg/ha	
<b>Bulk density</b>			
kg/m <sup>3</sup>	1.3597	ton/(ac-ft)	
	0.062428	lb/ft <sup>3</sup>	
<b>Basal area</b>			
m <sup>2</sup> /ha	4.3560	ft <sup>2</sup> /ac	
<b>Heat per unit area</b>			
kJ/m <sup>2</sup>	0.088114	BTU/ft <sup>2</sup>	
<b>Area</b>			
m <sup>2</sup>	10.764	ft <sup>2</sup>	
	0.0002471	ac	
	0.0001	ha	
<b>Surface-area-to-volume ratio</b>			
cm <sup>2</sup> /cm <sup>3</sup>	30.480	ft <sup>2</sup> /ft <sup>3</sup>	
	100	m <sup>2</sup> /m <sup>3</sup>	

## Appendix C: Overview of Fuel and Fire Behavior Modeling Systems

A wide variety of fuel and fire behavior modeling systems is available for use in fire management planning or wildfire incident management applications. Although there is considerable overlap in functionality between many of the modeling systems, each has unique features that make it useful for these purposes. This appendix is a summary of the modeling capabilities of a few of the commonly used systems. A website reference is provided for each software system.

### Fuel modeling systems

Three fuel modeling software systems are mentioned in this Introduction to Fire Behavior Modeling guide: FFE-FVS, FuelCalc, and FMAPlus®. FFE-FVS and FuelCalc are government-produced systems available free of charge; FMAPlus® is commercial software available for purchase from its developer.

#### FFE-FVS

The Fire and Fuel Extension to the Forest Vegetation Simulator (FFE-FVS; Reinhardt and Crookston 2003)) is a comprehensive fuel dynamics simulation system that runs on the long-established Forest Vegetation Simulator, making it the only fuel modeling system capable of simulating long-term fuel dynamics—the growth, accumulation, and decay of forest fuel.

*Temporal extent:* current condition, short-term changes (due to treatments and disturbance), long-term changes (decades)

*Geospatial extent:* point/plot

*Fuel modeling:* Calculates current canopy fuel characteristics and surface fuel model; simulates the effects of a variety of fuel treatments (thinning, burning) and natural disturbances (wildfire, insects) on surface and canopy fuel characteristics; simulates growth and mortality of forest vegetation and its effect on surface and canopy fuel characteristics.

*Fire modeling:* Calculates basic potential fire behavior characteristics, and crown fire hazard indices are calculated using the Scott and Reinhardt (2001) wildfire simulation approach.

*Basic inputs:* treelist, fuel loads by class and component

*Website:* <http://www.fs.fed.us/fmssc/fvs/description/ffe-fvs.shtml>

#### FuelCalc

FuelCalc is a surface and canopy fuel characteristics calculation engine available as a desktop application. FuelCalc is still in development. Even when completed, it will have few functions not available in FFE-FVS. Its primary advantage over FFE-FVS will be ease of use.

*Temporal extent:* current condition, short-term changes (due to treatments and disturbance)

*Geospatial extent:* point/plot

*Fuel modeling:* Calculates current canopy fuel characteristics and surface fuel model; simulates the effects of a variety of fuel treatments (thinning, burning) and natural disturbance (wildfire) on surface and canopy fuel characteristics.

*Fire modeling:* none in current release.

*Basic inputs:* treelist, fuel loads by class and component

*Website:* <http://www.fs.fed.us/fmi/downloads/fuelcalc.html>

### **FMAPlus®**

FMAPlus® Version 3 is a suite of programs for use by resource managers to inventory and estimate surface and canopy fuel loading and to predict surface and canopy fire behavior and resulting fire effects.

*Temporal extent:* current condition, short-term changes (due to treatments)

*Geospatial extent:* point/plot

*Fuel modeling:* Calculates current canopy fuel; simulates the effects of thinning on canopy fuel characteristics.

*Fire modeling:* Basic potential fire behavior characteristics and crown fire hazard indices are calculated using either the Finney (1998) or the Scott and Reinhardt (2001) wildfire simulation approach.

*Basic inputs:* treelist, fuel loads by class and component

*Website:* <http://www.fireps.com/fmanalyst3/index.htm>

## **Point-level wildfire modeling systems**

Point-level wildfire modeling systems simulate wildfire behavior at a single point on the landscape.

### **BehavePlus**

The BehavePlus fire modeling system is a collection of models that describe fire behavior, fire effects, and the fire environment. BehavePlus produces tables, graphs, and diagrams and can be used for a variety of fire management planning and wildfire incident management applications. BehavePlus is the successor to the BEHAVE fire behavior prediction and fuel modeling system.

*Geospatial extent:* point/plot

*Fire modeling:* Surface and crown fire behavior characteristics are simulated in BehavePlus, but these separate simulations are not fully integrated into a single overall simulation of wildfire behavior in forested environments.

*Basic inputs:* fire environment characteristics at a point: wind characteristics, slope characteristics, surface and canopy fuel characteristics

*Website:* <http://www.firemodels.org/index.php/national-systems/behaveplus>

## **NEXUS**

NEXUS is a crown fire hazard assessment system based on the same fire models used in BehavePlus and the FARSITE family of geospatial fire modeling systems. NEXUS calculates indices of crown fire potential not included in any other modeling system, and also displays dynamic output charts designed to assist the user in understanding how the separate models of surface and crown fire behavior interact.

*Geospatial extent:* point/plot

*Fire modeling:* Surface and crown fire behavior characteristics are fully integrated into a single overall simulation of wildfire behavior characteristics in forested environments.

*Basic inputs:* fire environment characteristics at a point: wind characteristics, slope characteristics, surface and canopy fuel characteristics

*Website:* <http://www.fire.org/nexus/>

## **Nomographs**

Nomographs are a paper-based fire modeling system; no computer is required. Nomographs are available for simulating surface fire spread rate and intensity (Albini 1976, Scott 2007), crown fire spread rate (Rothermel 1991) and the transitions between surface and crown fire (Scott and Reinhardt 2001). Nomographs are useful for simulating fire behavior when a computer-based system is not available. They also visually display fire behavior simulation results over a range of inputs, giving a good indication of the sensitivity of the fire models to their inputs.

*Geospatial extent:* point/plot

*Fire modeling:* Surface fire behavior nomographs simulate surface fire spread rate and intensity. Rothermel's (1991) crown fire nomographs simulate average and maximum crown fire spread rate. Nomographs for crown fire transition indicate the environmental conditions that result in different types of fire.

*Basic inputs:* fire environment characteristics at a point: wind characteristics, slope characteristics, surface and canopy fuel characteristics

*Website:* <http://www.fs.fed.us/fmi/downloads/nomographs.html>

## **Geospatial wildfire modeling systems—the FARSITE family**

A suite of five related geospatial wildfire modeling systems is available for use in the U.S. In this guide, we refer to these systems collectively as the FARSITE family of geospatial fire modeling systems. The two most commonly used systems of the FARSITE family are described in this appendix, the remaining three are advanced applications and are described only in general.

A landscape file (LCP) is a common geospatial data input within the FARSITE family of systems. At a minimum, the LCP contains geospatial data for surface fuel model, slope steepness, aspect, elevation, and canopy cover. In addition, geospatial data regarding canopy base height (CBH) and canopy bulk density (CBD) can also be included in the LCP.

(If not included in the LCP, *CBH* and *CBD* are assumed to be constant across the landscape.

## **FARSITE**

FARSITE (Finney 1998) is a fire growth and behavior simulation system that incorporates models of surface fire, crown fire, point-source fire acceleration, spotting, and dead fuel moisture. FARSITE simulates wildfire growth using Huygens' Principle, treating the fire perimeter as a series of points that spread independently in response to each point's fire environment. FARSITE was built for maximum simulation precision at the expense of processing time. It functions well when simulating the growth and behavior of one fire for up to a few weeks. Fire behavior simulations with FARSITE automatically include an adjustment for the relative spread direction at each perimeter point.

*Geospatial extent:* landscape

*Fire modeling:* Position of fire perimeter over time; fire behavior characteristics of burned areas within the fire perimeter

*Basic inputs:* LCP file, temporal wind and weather stream

*Website:* <http://www.firemodels.org/index.php/national-systems/farsite>

## **FlamMap Basic**

FlamMap Basic<sup>32</sup> is a geospatial fire behavior characteristics modeling system that computes potential fire behavior characteristics over the full extent of an LCP file. FlamMap produces geospatial data of potential fire behavior characteristics (for example, spread rate, fireline intensity, flame length, and crown fire activity). In addition, FlamMap can produce data describing fire environment conditions (dead fuel moisture, mid-flame wind speeds, and solar irradiance).

FlamMap Basic is not a replacement for FARSITE; there is no temporal component in FlamMap Basic. It uses spatial information on topography and fuels to calculate fire behavior characteristics for a single set of environmental conditions.

Many of the functions of FlamMap Basic are replicated in the Basic Fire Behavior Analysis of the Wildland Fire Decision Support System (WFDSS), an online incident management support and documentation system.

*Geospatial extent:* landscape

*Fire modeling:* fire behavior characteristics, in any specified relative spread direction, across the full extent of an LCP file.

*Basic inputs:* LCP file, wind characteristics, temporal weather stream or constant dead fuel moisture contents

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<sup>32</sup> The FlamMap software has additional modeling capabilities not described in this section, including Minimum Travel Time (MTT) and, in FlamMap version 3, the Treatment Optimization Model (TOM). FlamMap Basic refers to the outputs generated on the "Fire Behavior Outputs" tab of a FlamMap run.

Website: <http://www.firemodels.org/index.php/national-systems/flammap>

### **Advanced systems: FlamMap MTT, FSPro, and FSIM**

Three additional geospatial models in the FARSITE family are used in fire management planning and incident management applications.

*FlamMap MTT* is a module of the FlamMap desktop fire modeling system versions 3 and 5 and is incorporated into WFDSS as Short-term Fire Behavior. MTT—for minimum travel time—was developed as a faster but less precise fire growth algorithm alternative to Huygens' Principle as used in FARSITE. It attains much of its increased speed by assuming that wind speed and fuel moisture are constant over a relatively long time period—one to several burning periods. The MTT module takes advantage of the increased speed to produce simplistic burn likelihood results, as well as intermediate and ancillary outputs such as spread vectors and major travel paths. For more information about FlamMap MTT, visit the FlamMap website listed above for FlamMap Basic.

*FSPro*—for Fire Spread Probability—was initially a desktop application, but is now maintained solely within WFDSS as Long Term Fire Behavior. Like FlamMap MTT, FSPro takes advantage of the relative speed of the MTT algorithm to perform multiple fire growth simulations—typically several thousand—for a period of time from several days to several weeks. Using a Monte Carlo simulation technique, each of the individual fire growth simulations uses different inputs for wind speed, wind direction, fuel moisture, and simulation settings. These inputs are determined by random draw from a distribution determined by historical records. The results of the thousands of simulations are compiled into several products. One product is a histogram showing the distribution of fire size at the end of the time period. Another is a map of the likelihood that each landscape point will be burned by the fire, which is calculated as the number of times a point is burned by individual simulations divided by the total number of simulations performed. FSPro is used only for supporting incident management decisions. For supporting fire management decisions, the related FSIM modeling system is used.

*FSIM*—the Large Fire Simulator—is another step above FSPro in the hierarchy. It uses the same faster MTT algorithm with the same assumptions about constant wind and fuel moisture, but the simulations also include a module to simulate where and when fires ignite across a large landscape, as well as a module to simulate the containment success of large wildfires. Whereas the user sets the time period for an FSPro analysis, FSIM simulates fire start and growth over a whole fire season. Results are similar to those of FSPro: fire size distribution and burn probability. In addition, FSIM computes the mean fireline intensity simulated at each point across the landscape.