Introduction

Crown scorch height is calculated in the SCORCH module and tree mortality is calculated in MORTALITY. The modules can be used independently to gain an understanding of the mathematical models or to use observed rather than calculated flame length or scorch height. More commonly SURFACE, SCORCH, and MORTALITY are selected and linked, with flame length calculated in SURFACE and used to calculate scorch height in SCORCH, which is used to calculate tree mortality in MORTALITY.

Objectives

1. Calculate scorch height from surface fire.
2. Compare the role of wind in flame length calculation and in flame tilt as it affects scorch height.
3. Describe the calculation of tree mortality from crown scorch.
4. Demonstrate tree mortality calculations.
5. Discuss the role of bark thickness.
6. Discuss the updates to Version 5.0.

Where This Lesson Fits In

This is a lesson in the Modeling Unit. It is assumed that the trainee has completed the four lessons in the Introduction Unit and has basic BehavePlus operation skills.

The **Surface Fire Spread and Intensity** lesson should be done before this lesson.

Introduction

Crown scorch is calculated in the SCORCH module and tree mortality in the MORTALITY module. SCORCH returns a value of Scorch Height, used indirectly as a predictor variable in some mortality equations. MORTALITY uses probability to predict if a tree will die during a fire. These modules run similar algorithms to both FOFEM and FFE-FVS. The calculations can be either done independently or linked together with output from one module being used as input to the other. In this lesson we will do both. It can help understanding of a module if it is used independently; however, models are more often linked for application.

The SCORCH module predicts tree Scorch Height, which is the height above the ground that the temperature in a convection column reaches lethal temperature to kill live crown foliage. This temperature is assumed to be 140 degrees Fahrenheit (60 degrees Celsius). It is calculated using a model developed by Van Wagner (1973). He measured 13 experimental outdoor fires to calculate Scorch Height that varies with the 2/3 power of fireline intensity. Wind speed and Air Temperature were added to the Van Wagner's equations and are inputs to the SCORCH module. Byram (1959) related Flame Length to Fireline Intensity, so surface fire intensity can be entered as either Flame Length or Fireline Intensity. This module defaults to Flame Length.

Probability of Mortality is the likelihood that a tree will be killed by a fire. The equation used to calculate Probability of Mortality depends on the Mortality Tree Species. There are 12 mortality equations, which variously include Bark Thickness, Tree Crown Length Scorched and/or Tree Crown Volume Scorched. BehavePlus version 5.0 includes an update to the mortality equations for 10 species based on work by Hood et al. 2008.

We'll start by evaluating the SCORCH module.

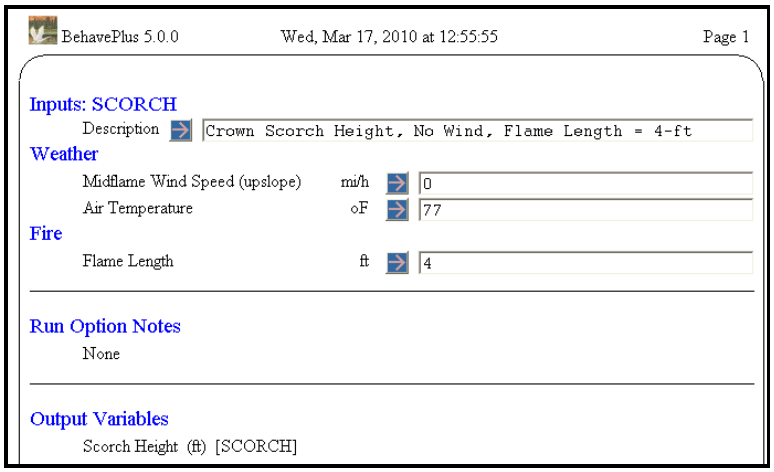
Crown Scorch Height (SCORCH) Module

We start by examining the scorch height model by selecting only SCORCH.

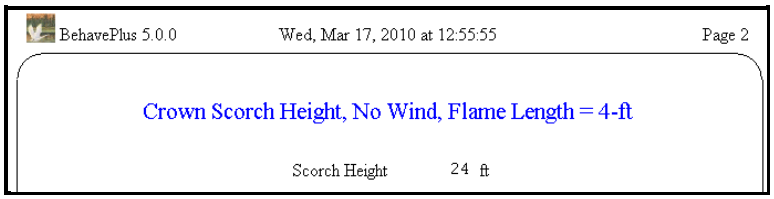
- Open the **BasicStart.bpw** Worksheet.
- Go to **Configure > Module selection**.
- Unselect SURFACE.
- Select SCORCH.

SCORCH defaults to using Flame Length as a measure of fire intensity (the necessary input for Van Wagner's scorch equation discussed in the Introduction).

- Press **Ok**.
- Enter the **Weather** and **Fire** inputs as shown below.



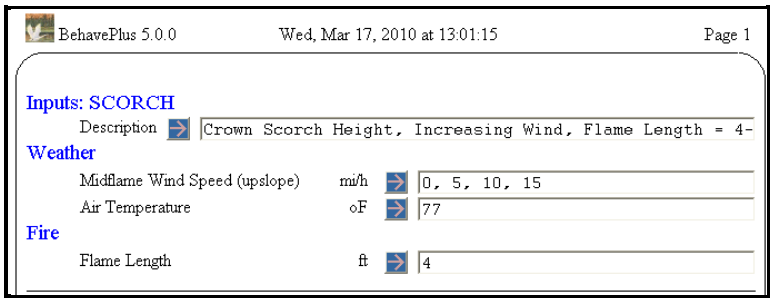
- **Calculate** the Run.
- Click **Ok**.

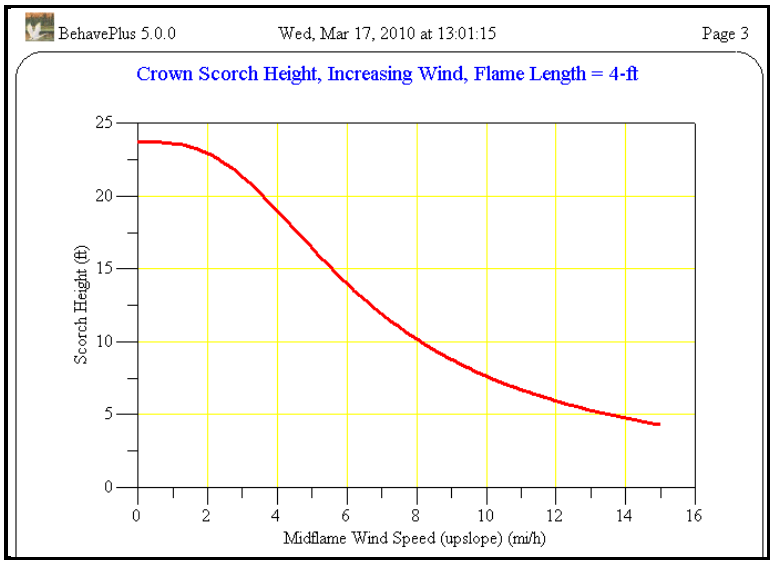


A Scorch Height of 24 feet is predicted with the input conditions.

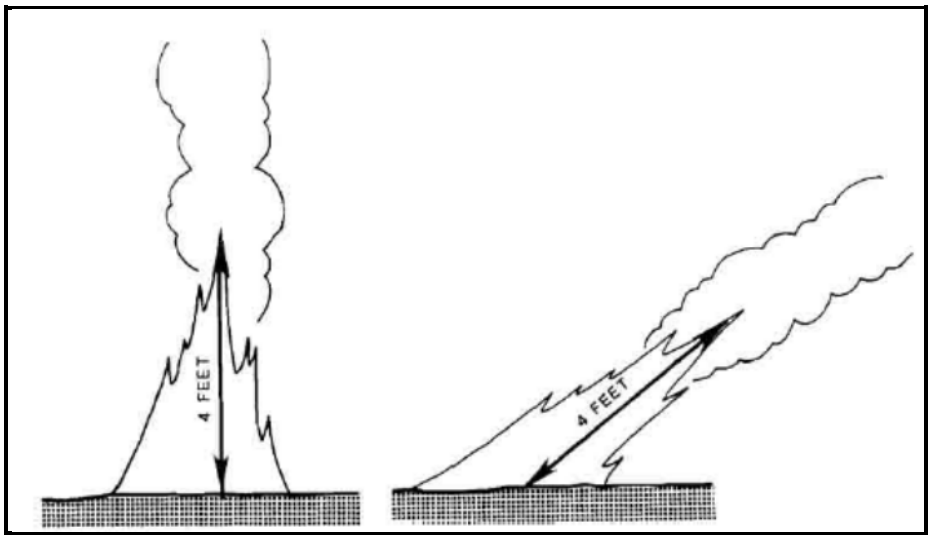
SCORCH and Increasing Wind

Theoretically, if Flame Length were held constant, wind would cause the flame to tilt or flatten resulting in lower Scorch Heights (Van Wagner 1973) and Scorch Height would follow a relationship as shown in the graph below. The relationship below occurs if several fires have similar Flame Lengths of 4 feet, but different Midflame Wind Speeds.





However, in realistic fire situations on a single heading fire, wind causes Flame Lengths to increase due to increasing surface fire behavior and the result is higher Scorch Heights. We'll address a more realistic scenario of the relationship of wind, flame length, and scorch in a later section.



Above are two separate fires, both with 4 ft Flame Lengths (Andrews et al. 1989). If the wind speed is zero, then the flame is nearly vertical. As wind increases above zero, the flame tilts, and Scorch Height decreases. This relationship is NOT to be confused for evaluating a single fire with increasing winds. For a single fire, increasing Midflame Wind Speed would increase surface fire behavior resulting in increasing Flame Lengths and greater Scorch Height.

SCORCH, SURFACE and Increasing Wind

Van Wagner's (1973) Scorch Height equation related fire intensity to Scorch Heights using an Air Temperature of 77° F and zero wind. These parameters are held constant in the First Order Fire Effects Model (FOFEM v 5.7), but they can be changed in BehavePlus.

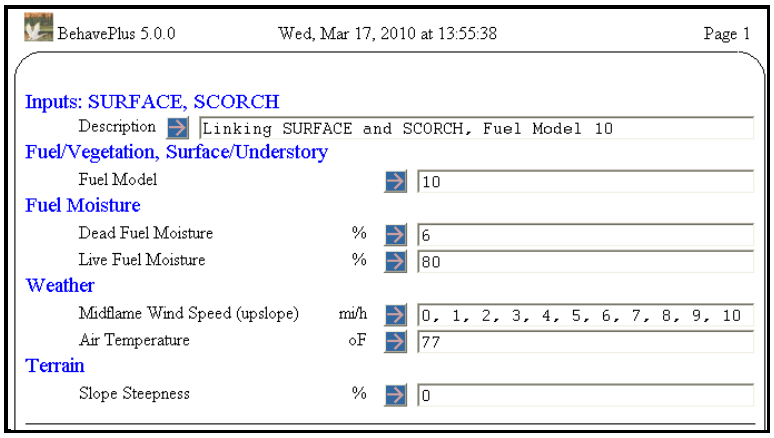
By linking the SURFACE and SCORCH modules, Flame Length can be predicted using the SURFACE module and used to calculate Scorch Height in SCORCH.

We'll run a simulation whereby surface fire behavior outputs are produced using the SURFACE module, and then Scorch Height is predicted using those fire behavior outputs. Both of the output variables Fireline Intensity and Flame Length from the SURFACE module can be used to predict Scorch Height. We'll use Flame Length for this simulation.

- Open the **BasicStart.bpw** worksheet.
- Go to **Configure > Module selection** and select SURFACE.
- To simplify the input screen, go to **Options…**, select the **Fuel & Moisture** tab and select **Moisture is entered by dead and live category**.
- Select the **Basic Outputs** tab and make Flame Length as the only output.
- Click **Ok**.

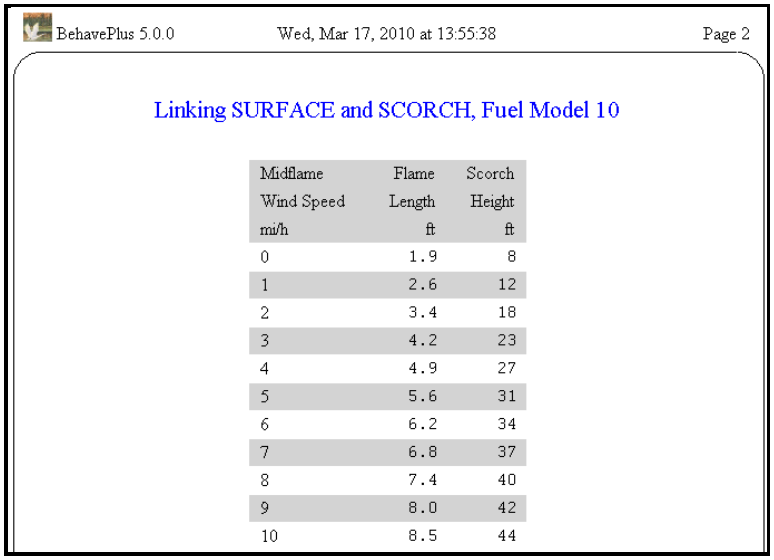
- Select SCORCH, and open **SCORCH > Options…**.
- Click on the **Output Variable** tab and make sure Scorch Height is selected.
- Click on the **Input Options** and select **Surface fire intensity is entered as flame length**.
- Click **Ok**.

- Make sure both SURFACE and SCORCH are selected.
- Click **Ok**.
- Enter **Fuel/Vegetation**, **Fuel Moisture**, **Weather** and **Terrain** input as shown below.

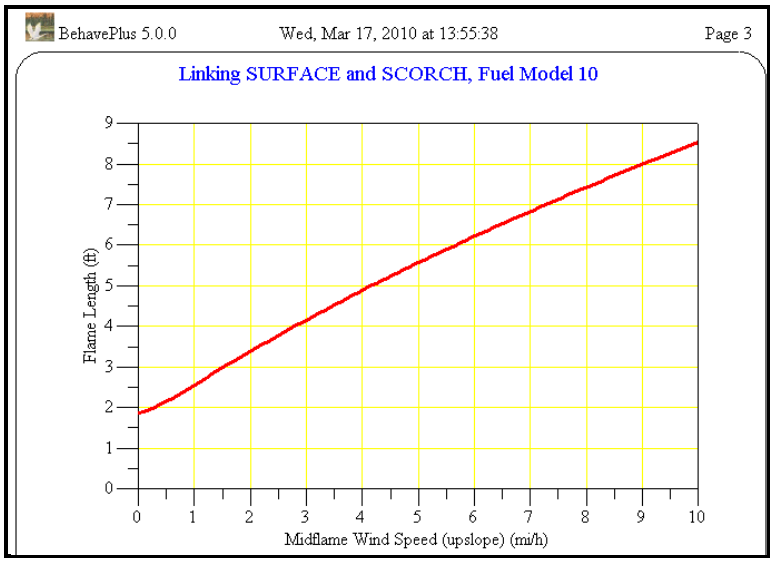


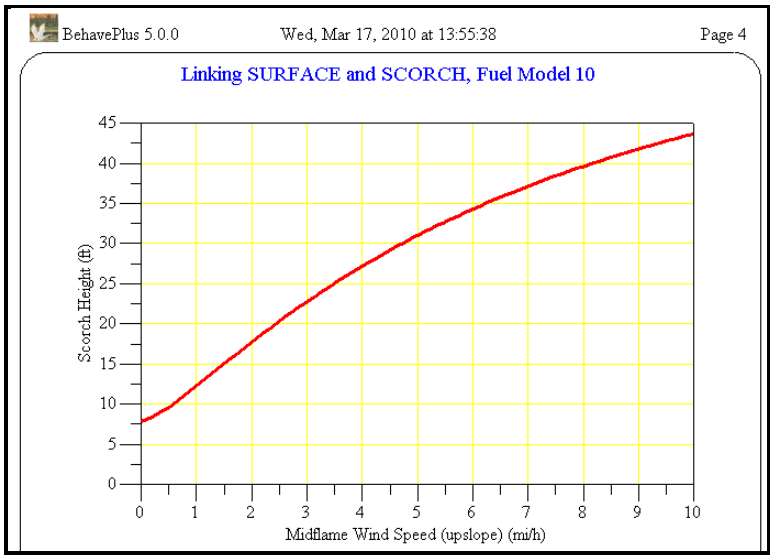
Note: Midflame Wind Speed is represented by a range of wind speeds from 0 to 10 mi/h with 0% Slope.

- **Calculate** the Run.
- Click **Ok**.



Midflame Wind Speed mi/h	Flame Length ft	Scorch Height ft
0	1.9	8
1	2.6	12
2	3.4	18
3	4.2	23
4	4.9	27
5	5.6	31
6	6.2	34
7	6.8	37
8	7.4	40
9	8.0	42
10	8.5	44





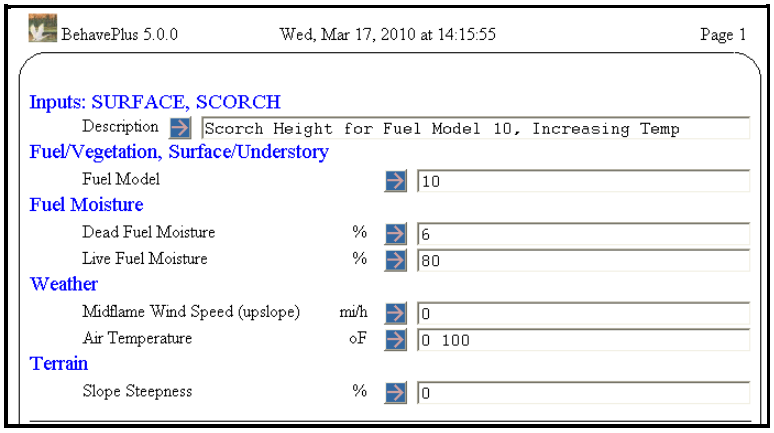
As Midflame Wind Speed increases from 0 to 10 mi/h, Scorch Height increases from 9 to 50 feet for Fuel Model 10. The corresponding increase in Scorch Height with wind is due to the corresponding increase in Flame Length (from 1.9 to 8.5 feet). An increase in wind resulted in an increase in surface fire behavior outputs such as Flame Length and Fireline Intensity, which resulted in higher Scorch Heights.

Tabular output showing both Flame Length and Scorch Height are shown because we selected Flame Length as an output in the SURFACE module. It was not necessary to select Flame Length or Fireline Intensity as **Basic Outputs** in the SURFACE module to compute Scorch Height; however, you will need to select the SURFACE module itself, even if no outputs are reported. If SURFACE is not selected, you will be required to input Flame Length or Fireline Intensity directly to compute Scorch Height.

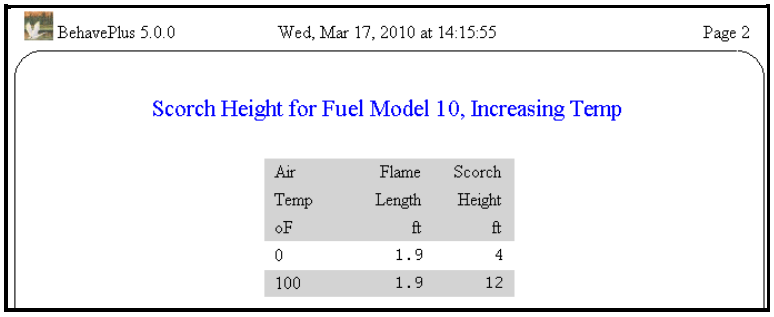
SCORCH and variable temperature

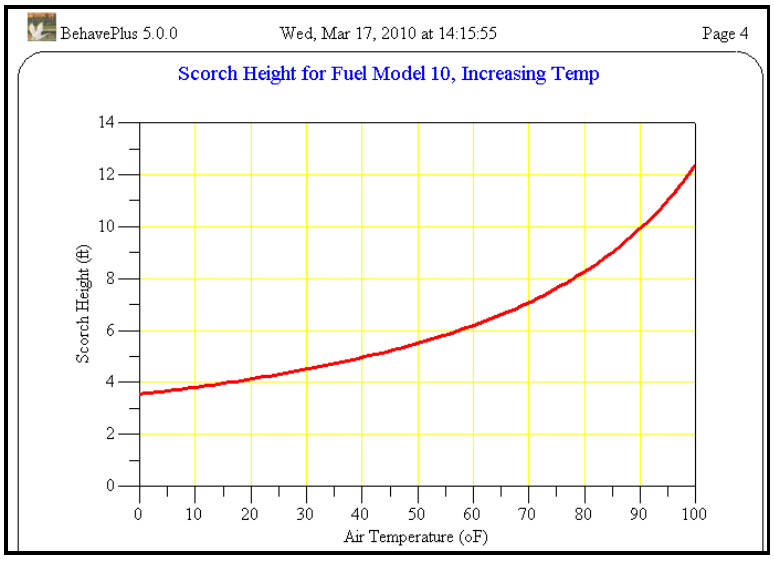
The previous scenario demonstrated how Flame Lengths and Scorch Heights change with Midflame Wind Speed. We'll do the same with increasing Air Temperature.

- Continue using the Worksheet above.
- Change the Midflame Wind Speed and Air Temperature as below.



- **Calculate** the Run.
- Click **Ok**.





Scorch Height increases with associated increases in Air Temperature. This occurs even as Flame Length stays constant, because Flame Length is not dependent on Air Temperature and does not directly change with increasing temperature. Scorch Height increases more dramatically as wind speed increases as compared to temperature.

FOFEM and BehavePlus

Both FOFEM and BehavePlus compute Scorch Height and Probability of Mortality using the same equations. FOFEM, however, holds Air Temperature constant at 77°F and wind constant at 0 mi/h. BehavePlus allows the user to change these variables, which markedly affects Scorch Height, as shown in the scenarios in this lesson.

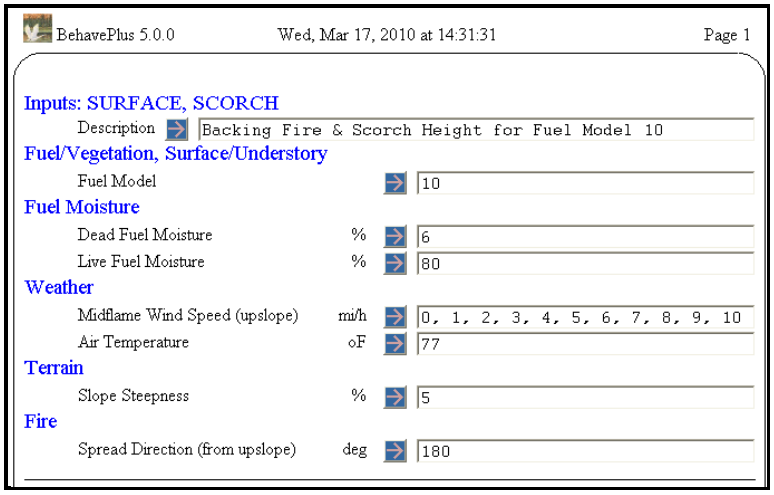
SCORCH and backing fire

As wind increases, heading fire behavior usually increases, but the situation may be different for a backing fire. While most fire behavior prediction models are created and used best when predicting heading fires, BehavePlus has options to predict backing fire behavior. This may be pertinent when evaluating possible fire effects for planning an ignition pattern for a prescribed fire or burnout.

- If a backing fire is planned, what is the possible range of Scorch Heights when Midflame Wind Speed ranges from 0 to 10 mi/h?

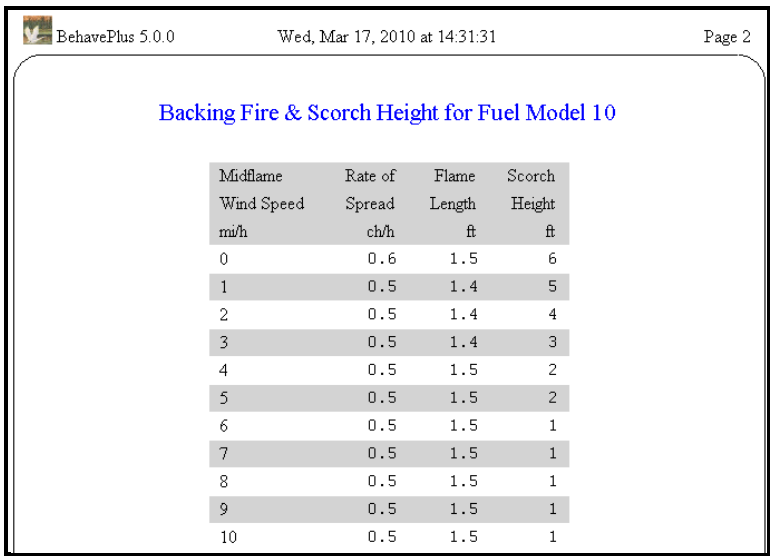
- Continue with the worksheet above.
- Go to **Configure > Module selection > SURFACE > Options...**.
- Select the **Directions** tab and choose **Surface fire spread direction is in directions specified on the worksheet**.
- Add the output variable Surface Rate of Spread.
- Press **Ok**.

- Enter input as shown below. Midflame Wind Speed ranges from "0" to "10" mi/h. Slope is "5%." A value of "180" degrees from upslope represents the backing fire spread direction. Change the Air Temperature to "77°F".



An important assumption with wind and slope when linking SCORCH and SURFACE needs to be addressed. *Midflame* Wind Speed is used in the Scorch Height calculation in SCORCH. *Effective* Wind Speed is used in the calculation of Flame Length in SURFACE. Effective Wind Speed is the combined effect of slope and wind.

The Scorch Height model was developed for flat ground and should be used on slopes with care. If SCORCH is used when the percentage of slope is greater than zero, the slope is essentially ignored except in the effect that it has on the Flame Length calculations in SURFACE. SCORCH uses Midflame Wind Speed as if the fire were on flat ground.

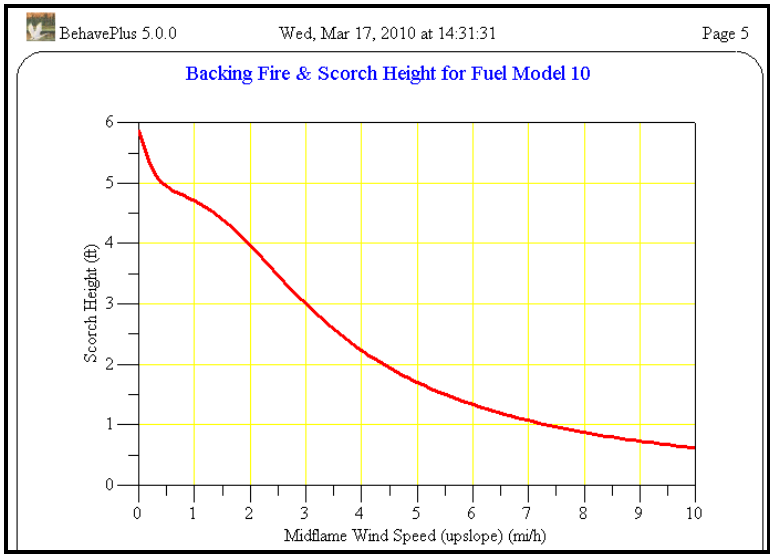


Midflame Wind Speed mi/h	Rate of Spread ch/h	Flame Length ft	Scorch Height ft
0	0.6	1.5	6
1	0.5	1.4	5
2	0.5	1.4	4
3	0.5	1.4	3
4	0.5	1.5	2
5	0.5	1.5	2
6	0.5	1.5	1
7	0.5	1.5	1
8	0.5	1.5	1
9	0.5	1.5	1
10	0.5	1.5	1

Slope was set at 5% for this example. If slope had been set to 0%, at 0 mi/h Midflame Wind Speed, the only difference would be an increase in Flame Length (1.9 feet) and

Scorch Height (8 feet). At zero Midflame Wind Speed, slope is used to calculate Effective Wind Speed, which is then used to compute Flame Length and consequently Scorch Height. As soon as the Midflame Wind Speed exceeds 1 mi/h, a 5% slope becomes negligent in the calculation of Effective Wind Speed and does not make a difference in Scorch Height for backing fires.

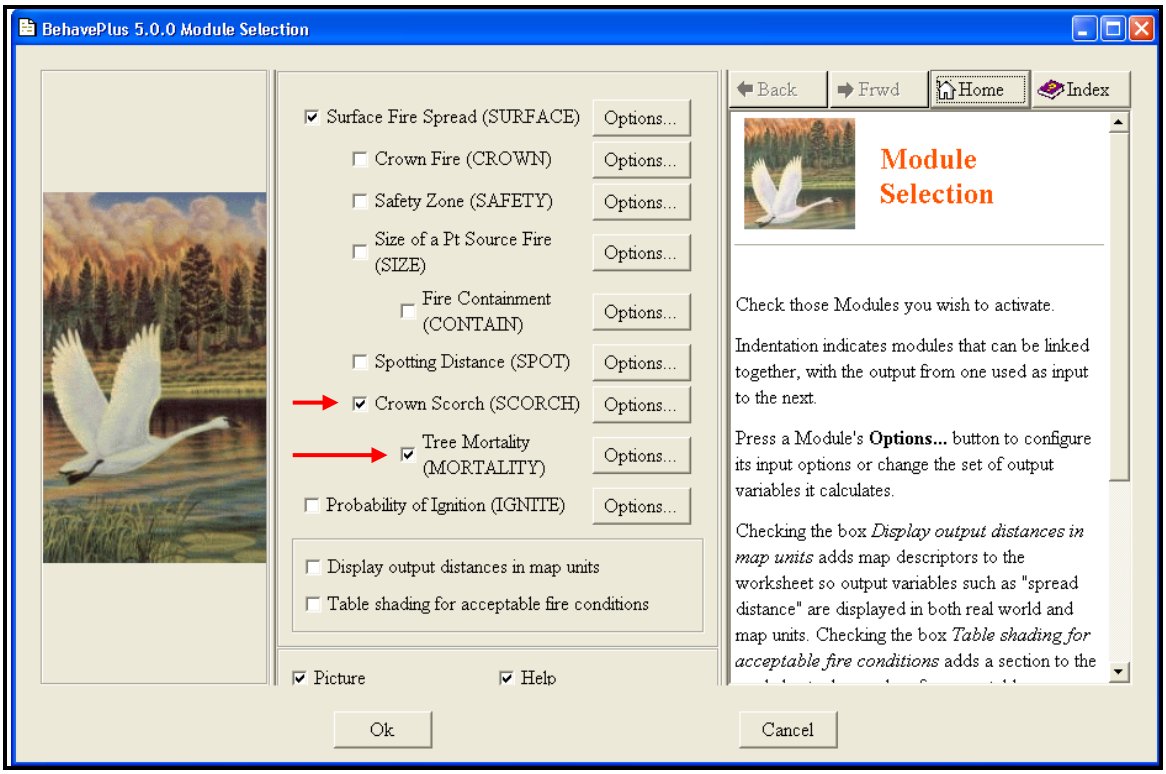
The answer to our initial question is that Scorch Heights will range from 1 to 5 feet for Midflame Wind Speeds of 1 – 10 mi/h for a backing fire ignition pattern.



Both tabular and graphical output show that for backing fire, Scorch Height decreases with increasing Midflame Wind Speed. This occurs because upslope wind will not increase backing fire behavior as it would for a heading fire. Flame Length stays essentially constant at approximately 1.5 feet (see table on p. 10) as Midflame Wind Speed increases from 0 to 10 mi/h. Increasing wind will tilt or flatten the flame, resulting in lower Scorch Heights.

SURFACE, SCORCH and MORTALITY

The SURFACE, SCORCH and MORTALITY modules will be linked for this next example. The indents in the **Module Selection** window indicate that modules can be linked, with outputs from one module becoming inputs to another module.



When SURFACE, SCORCH, and MORTALITY are selected, the Flame Length calculated in SURFACE is used in the calculation of Scorch Height in SCORCH, which is used in turn to calculate tree mortality (Probability of Mortality) in MORTALITY. However, MORTALITY can also be used as an independent module, with user input of Scorch Height.

Tree Mortality

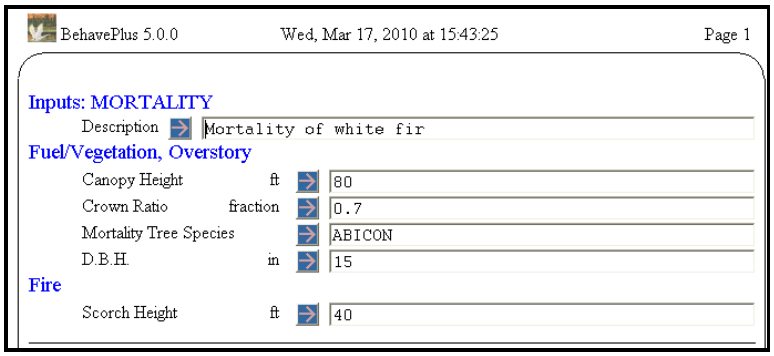
Probability of Mortality is the likelihood that a tree will be killed by a fire. The equation used to calculate Probability of Mortality depends on Mortality Tree Species. There are 12 mortality equations, which variously include Bark Thickness, Tree Crown Length Scorched, DBH, and/or Tree Crown Volume Scorched. Other influencing factors are not included in the models.

Probability of Mortality can be interpreted in two ways: (1) it is the probability of an individual tree dying or (2) it can be multiplied by the number of trees on a site to estimate the number of trees per area that will die. Probability of Aspen Mortality is calculated by a different model and is available by selecting the western aspen special case fuel model in SURFACE (see the **Special Case Fuel Model – Western Aspen Lesson** for more details).

MORTALITY

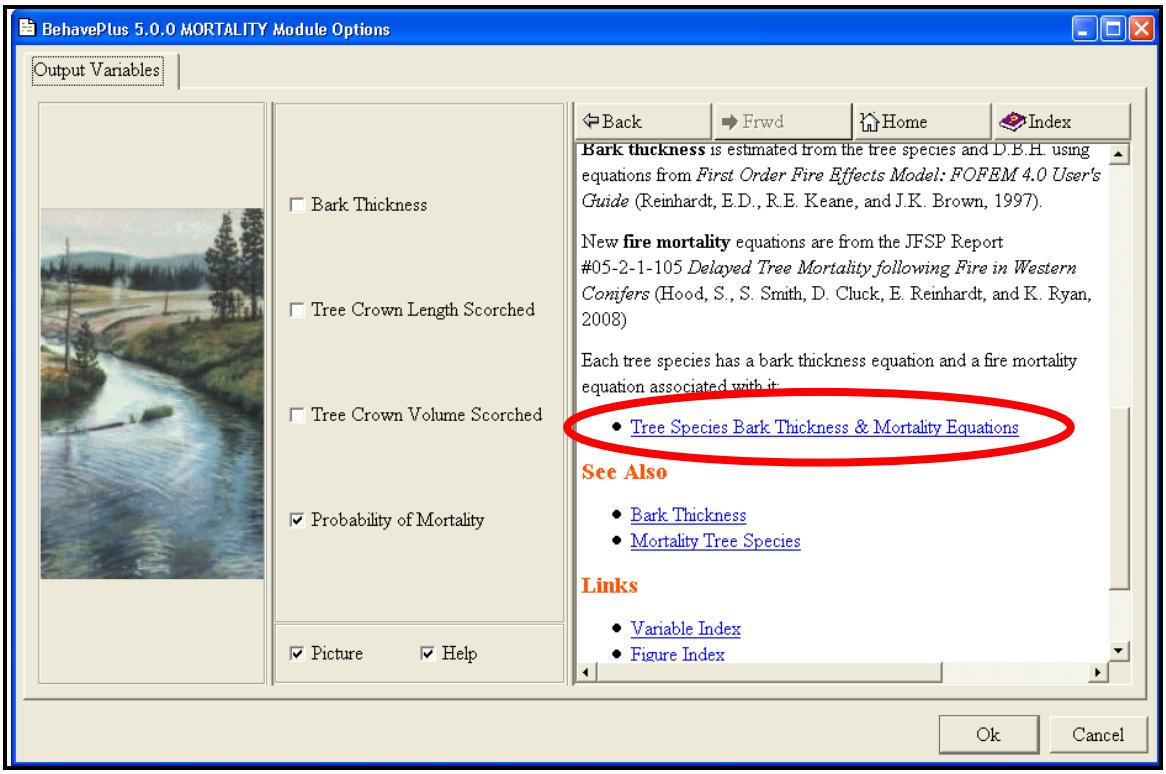
The first scenario will use the MORTALITY module by itself.

- Go to **Module selection > MORTALITY > Options...**.
- Select the **Output Variable** Probability of Mortality.
- Make sure MORTALITY is the only module selected.
- Press **Ok**.
- Enter **Fuel/Vegetation** and **Fire** input as shown below.

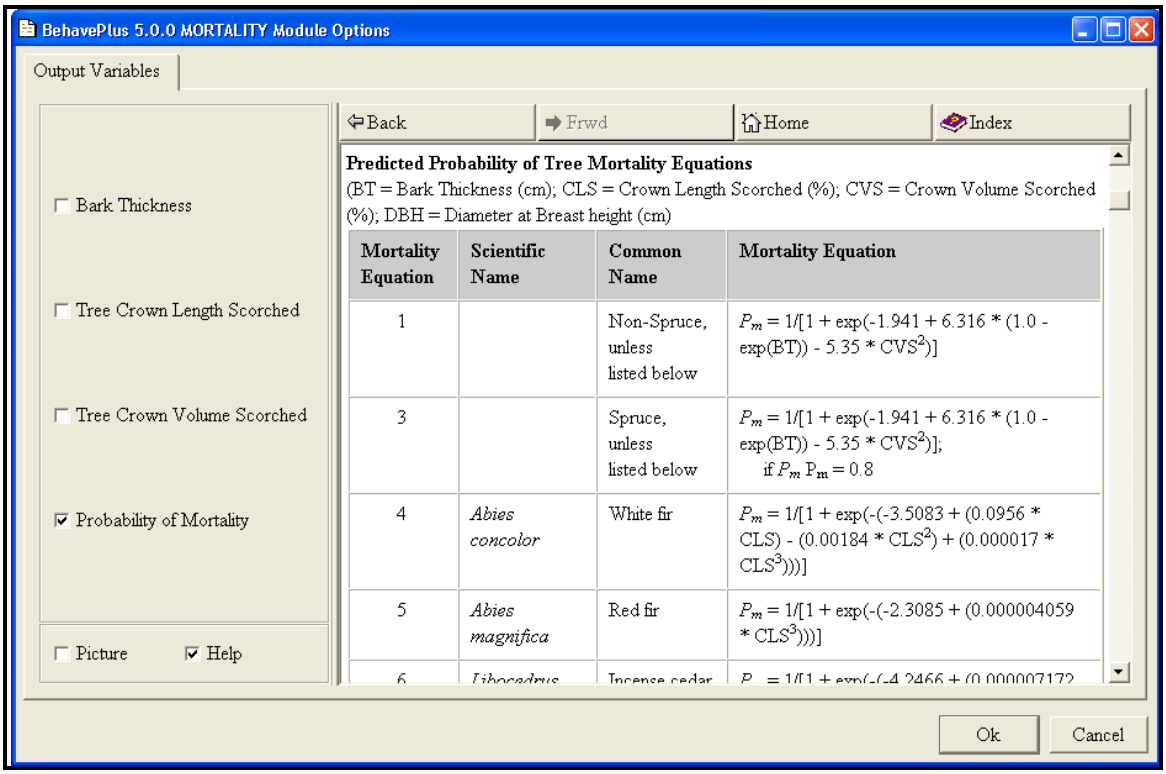


The species chosen was white fir (ABICON or *Abies Concolor*). The BehavePlus Help window indicates that the MORTALITY equation for white fir is specific to this species. To find out more about this equation follow instructions below.

- Click the **Module selection** ( ) toolbar button.
- Click the **Options** button for the MORTALITY module.
- Place cursor over (hover over) Probability of Mortality and look at the **Help** window.
- Scroll down in **Help** and click on **Tree Species Bark Thickness & Mortality Equations**.



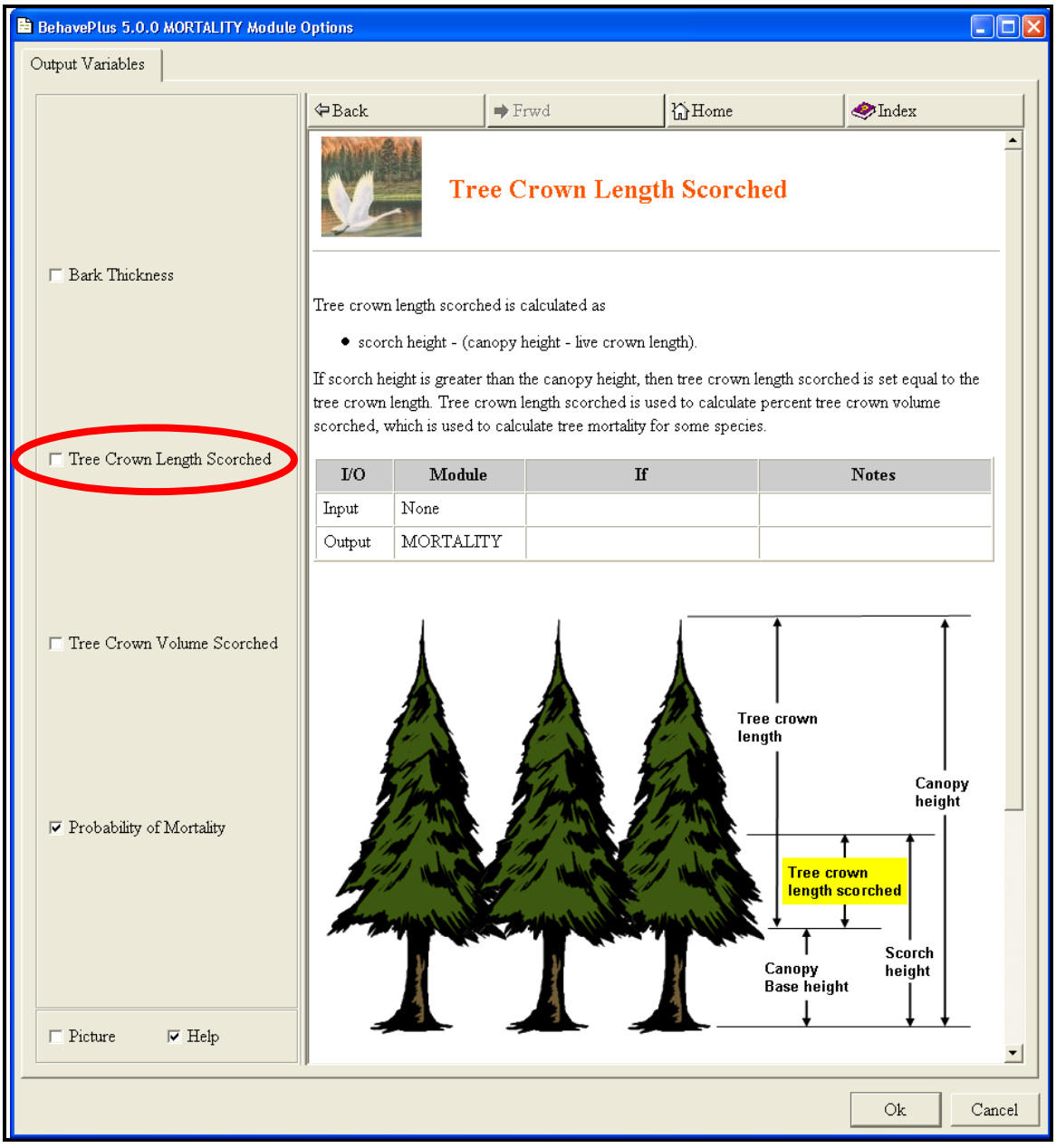
- For more space, remove the picture by clicking next to **Picture**.
- Scroll down the **Help** window again to the Predicted Probability of Tree Mortality Equations table.



It is important to note with the equation for *Abies concolor* (Equation 4) that CLS is the only predictor variable. Consequently, a value for CLS will change the Probability of Mortality for white fir.

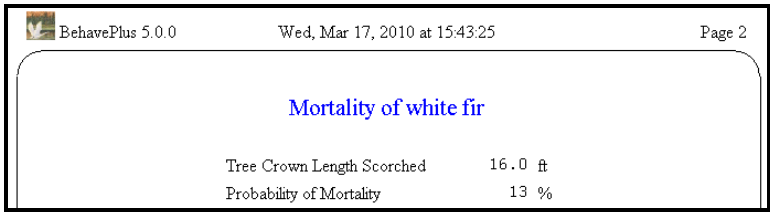
- Look at the top of the table to find the definition for CLS.
  CLS = Crown Length Scorched (%)

- To find out how Crown Length Scorched (CLS) is computed, move your cursor over that variable in the left-hand portion of the window and read the **Help**. Note the figure relating that measurement to other variables.



- Select Tree Crown Volume Scorched.
- Click **Ok** twice.
- **Calculate** the Run.
- Click **Ok**.

Tree Crown Length Scorch is computed from Scorch Height and the difference between Canopy Height and live crown length.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Mortality of white fir

Tree Crown Length Scorched	16.0 ft
Probability of Mortality	13 %

This exercise exhibits a basic understanding of the MORTALITY module and the equations that compute probability of mortality.

SURFACE, SCORCH and MORTALITY

Next, we'll link the SURFACE, SCORCH and MORTALITY modules together.

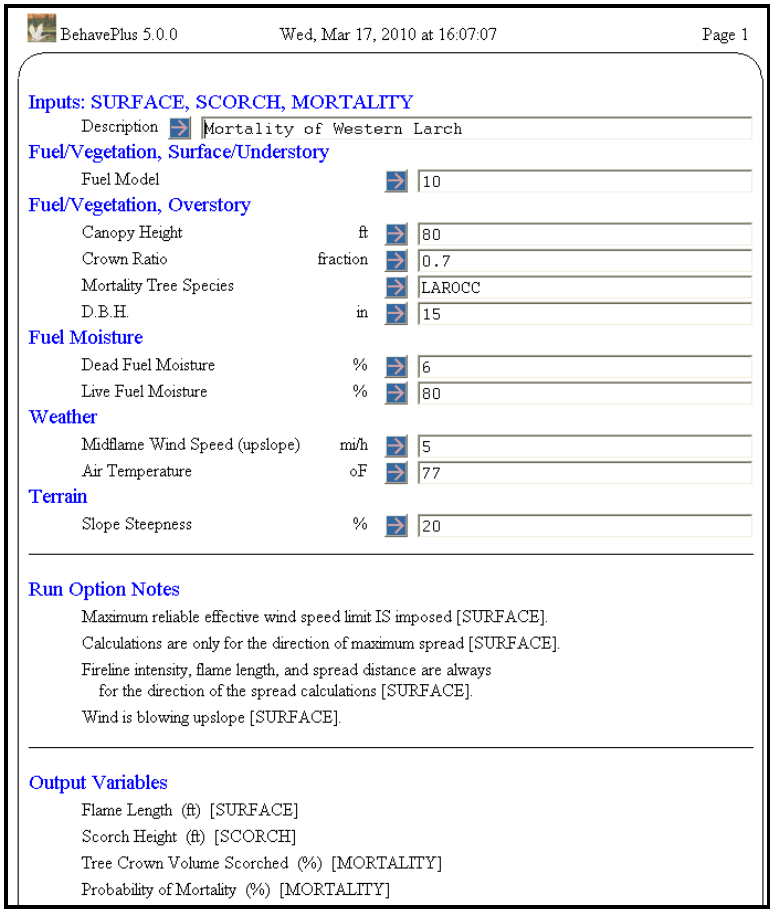
By linking these modules together, we'll first compute fire behavior using the SURFACE module. The Flame Length predicted in the SURFACE module will be used to compute Scorch Height in the SCORCH module. Finally, the predicted Scorch Height will be used to compute the Probability of Tree Mortality in the MORTALITY module.

- Open the **BasicStart.bpw** Worksheet.
- Go to **Configure > Module selection > SURFACE > Options…**.
- Go to the **Basic Outputs** tab and select only Flame Length.
- On the **Fuel & Moisture** tab select **Moisture is entered by dead and live category**.
- Go to the **Directions** tab and make sure **Surface fire spread direction is only in the direction of maximum spread** is selected.
- Press **Ok**.

- Next, select the SCORCH Module. Go to **Options…**.
- Go to the **Inputs Options** tab and select **Surface fire intensity is entered as flame length**.
- Go to the **Output Options** tab and make sure Scorch Height is selected.
- Press **Ok**.

- Finally, select the MORTALITY Module. Go to **Options…**.
- Select Tree Crown Volume Scorched and Probability of Mortality on the **Output Variables** Tab.
- Press **Ok** twice.

- Enter **Fuel/Vegetation (Surface/Understory & Overstory)**, **Fuel Moisture**, **Weather**, and **Terrain** as shown below.



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Inputs: SURFACE, SCORCH, MORTALITY

Description		Mortality of Western Larch
Fuel/Vegetation, Surface/Understory		
Fuel Model		10
Fuel/Vegetation, Overstory		
Canopy Height	ft	80
Crown Ratio	fraction	0.7
Mortality Tree Species		LAROCC
D.B.H.	in	15
Fuel Moisture		
Dead Fuel Moisture	%	6
Live Fuel Moisture	%	80
Weather		
Midflame Wind Speed (upslope)	mi/h	5
Air Temperature	oF	77
Terrain		
Slope Steepness	%	20

Run Option Notes

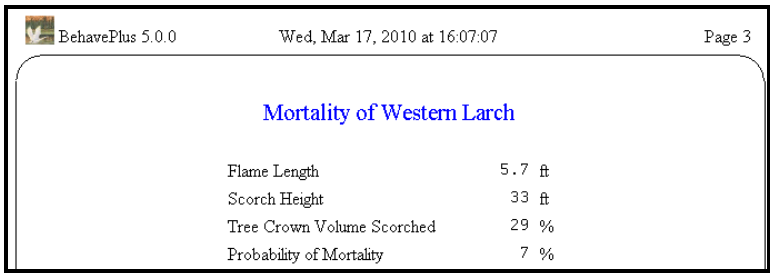
Maximum reliable effective wind speed limit IS imposed [SURFACE].
Calculations are only for the direction of maximum spread [SURFACE].
Fireline intensity, flame length, and spread distance are always for the direction of the spread calculations [SURFACE].
Wind is blowing upslope [SURFACE].

Output Variables

Flame Length (ft) [SURFACE]
Scorch Height (ft) [SCORCH]
Tree Crown Volume Scorched (%) [MORTALITY]
Probability of Mortality (%) [MORTALITY]

Let's quickly review. **Fuel/Vegetation, Surface/Understory**; **Fuel Moisture**; **Weather**; and **Terrain** sections are all required to compute SURFACE fire behavior. The **Fuel/Vegetation, Overstory** section is necessary to compute Scorch Height (SCORCH) and Probability of Mortality (MORTALITY).

- **Calculate** the Run.



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Mortality of Western Larch

Flame Length	5.7 ft
Scorch Height	33 ft
Tree Crown Volume Scorched	29 %
Probability of Mortality	7 %

Given the input conditions, a 5.7 feet Flame Length was predicted in SURFACE. SCORCH used that Flame Length to predict a Scorch Height of 33 feet for this tree.

MORTALITY used that Scorch Height to predict a 7% Probability of Mortality by using 29% Tree Crown Volume Scorched and 15-inch DBH in the mortality equation specific to western larch. See the **Help** window for details on that particular equation, which uses both Tree Crown Volume Scorched and DBH as predictor variables.

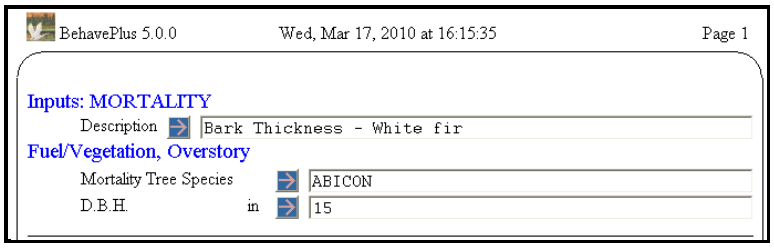
Bark Thickness

Bark Thickness is used to calculate tree mortality for many tree species that do not have a specific mortality equation. Bark thickness is calculated from Mortality Tree Species and DBH using equations from First Order Fire Effects Model: FOFEM 4.0 (Reinhardt and others, 1997). There are 39 separate Bark Thickness equations for a variety of species.

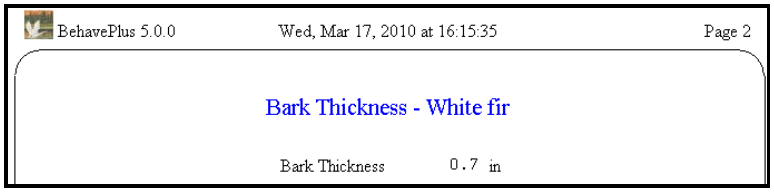
Bark Thickness is an output of the MORTALITY module.

- Open the **BasicStart.bpw** Worksheet.
- Select only the MORTALITY Module. Go to **Options….**.
- Select Bark Thickness and Probability of Mortality on the **Output Variables** tab.
- Press **Ok** twice.

- Enter **Fuel/Vegetation, Overstory** variables as shown below.



This Bark Thickness equation is specific to white fir and uses DBH to compute a Bark Thickness of 0.7 inches.



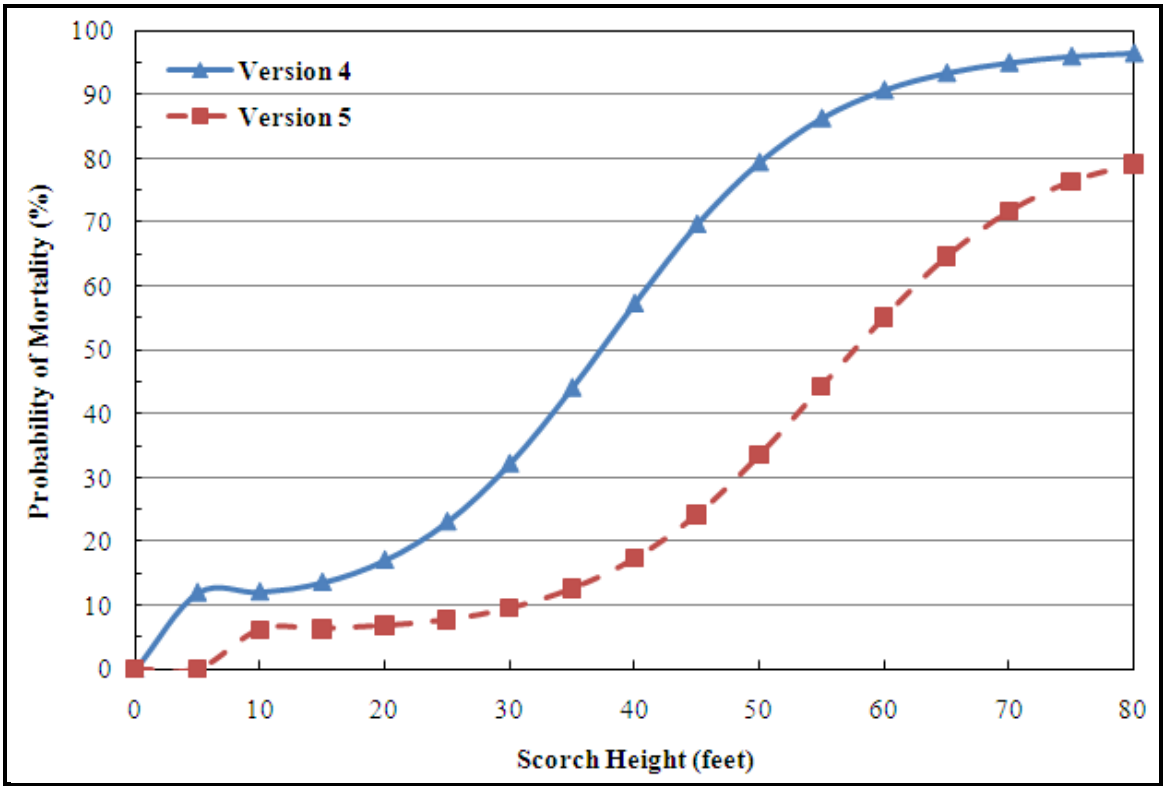
Implications of Model Changes from Version 4.0 to Version 5.0

The tree mortality equations in BehavePlus match those in FOFEM. When the FOFEM models were updated, they were also updated in BehavePlus version 5.0. A user of BehavePlus 4.0 (or of FOFEM before the update) should be aware of differences in mortality predictions.

In BehavePlus version 4.0 (BehavePlus4) there were only two equations for tree mortality: one for spruce and one for all other species. Bark Thickness was calculated from tree species using one of 39 Bark Thickness equations. Probability of Mortality was subsequently calculated from Bark Thickness and Crown Volume Scorched. In version 5.0 (BehavePlus5), 10 species-specific mortality equations were added (Hood and others 2008). Thus, there are a total of 12 mortality equations in BehavePlus5: 10 species-specific equations and two general equations (for all other species, classified as either spruce or non-spruce). In some cases, the resulting difference in Probability of Mortality is large. See the **Help** window for a table of species and equations.

Both BehavePlus4 and BehavePlus5 can be installed on your computer at the same time if you want to perform comparison runs. To make the following comparison, outputs were exported from both versions of BehavePlus (**File>Export Results**); saved as an HTML file; and opened and analyzed in Microsoft® Excel.

This example demonstrates the difference between the old (BehavePlus4) and new (BehavePlus5) calculations for mortality for an 85 feet tall, 15 inch diameter ponderosa pine (PINPON) with 90% Crown Ratio. The difference in mortality is as much as 46% (when Scorch Height is 50 feet). The curves look similar, but the magnitude of mortality is different. Version 4.0 predicts a higher mortality rate with the input parameters compared to version 5.0 for this example.



Scorch Height (feet)	BehavePlus Version 4.0 Probability of Mortality (%)	BehavePlus Version 5.0 Probability of Mortality (%)	Difference (%)
0	0	0	**0**
10	12	6	**6**
20	17	7	**10**
30	32	10	**22**
40	57	17	**40**
50	79	33	**46**
60	91	55	**36**
70	95	72	**23**
80	96	79	**17**

Summary

We calculated crown Scorch Height using only the SCORCH module. Necessary inputs included Air Temperature, Midflame Wind Speed and Flame Length. Once a range of increasing winds was included, a possible misinterpretation of the SCORCH output was addressed: a range of increasing Midflame Wind Speed results in lower Scorch Height, when Flame Length is kept constant. This would only occur on separate fires or possibly on a backing fire. For any given fire, increasing Midflame Wind Speed would increase surface fire behavior resulting in increasing Flame Lengths and greater Scorch Height. This relationship can help a person understand the basis of the Scorch Height model.

We linked the SURFACE and SCORCH modules to produce the Fireline Intensity or Flame Length necessary to compute Scorch Height. A user should be aware that FOFEM, another common fire effects modeling system, uses a constant temperature of 77°F and a constant 0 mi/h Midflame Wind Speed (no wind). BehavePlus allows the effect of both wind speed and temperature to be modeled.

Finally, we linked the SURFACE and SCORCH modules to MORTALITY, demonstrating that Probability of Mortality can be calculated using BehavePlus or directly from field measurements (using only MORTALITY). There are 10 new species-specific Probability of Mortality models, which can be examined in the Help window of BehavePlus. Using BehavePlus versions 4 *and* 5, we examined the impact of the new models on estimates of Probability of Mortality using Ponderosa pine in our example.

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