Introduction

The CROWN module in BehavePlus is based on models developed by Van Wagner (1977, 1993), Rothermel (1991), Thomas (1963), and Byram (1959). Outputs are listed on tabs labeled **Spread Outputs** (e.g., rate of spread, transition to crown fire) and **Intensity Outputs** (e.g., flame length, fireline intensity). This lesson addresses Intensity Outputs.

The Intensity Outputs tab contains the output variables: Crown Fireline Intensity, Crown Flame Length, and Canopy Heat per Unit Area. Power of the Fire and Power of the Wind are also calculated, with indication as to whether the fire might be wind-driven or plume-dominated (Rothermel 1991). Given the many influencing factors and unknowns in crown fire behavior, these values encourage a person to consider the possibility of an extreme fire behavior under low wind conditions.

Objectives

1. Understand how crown fireline intensity and flame length are modeled in BehavePlus.
2. Create a worksheet that produces a CROWN run to evaluate crown fire intensity and flame length.
3. Understand power of the fire, power of the wind, and their relationship to wind-driven and plume-dominated fire.
4. Correctly interpret BehavePlus CROWN module runs.

Where This Lesson Fits In

This is an optional lesson in the Modeling Unit. Lessons in the Modeling Unit cover capabilities, limitations and assumptions, and sensitivity of the various models in BehavePlus. It is assumed that the trainee has skill with program operation.

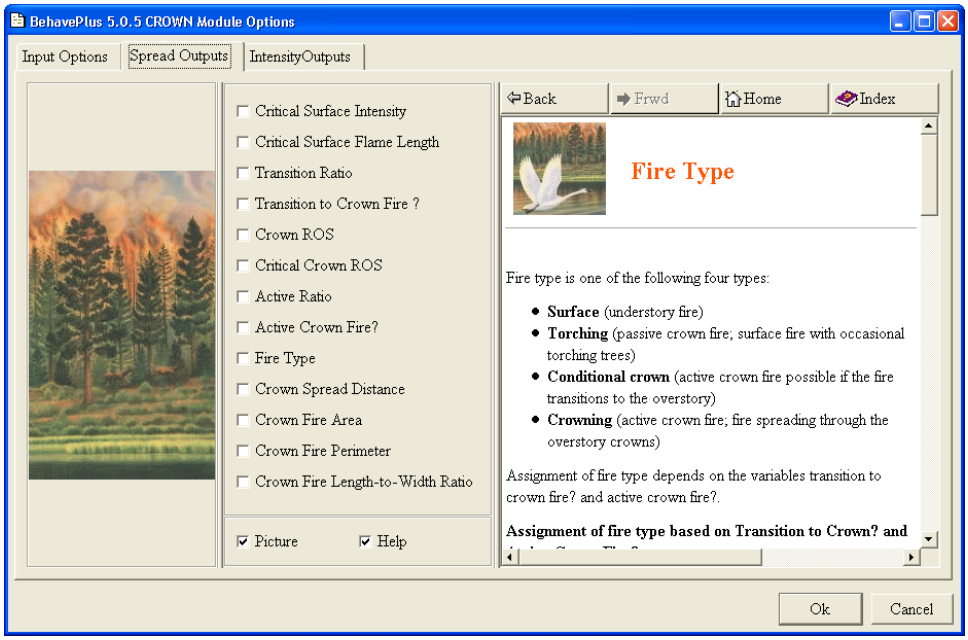
The **Surface Fire Spread and Intensity** lesson should be done before this lesson.

There are two lessons associated with crown fire modeling in BehavePlus. The associated **Crown Fire Spread** lesson covers crown fire spread rate, area, perimeter, and fire type (surface, torching, crowning, or conditional crown).

CROWN Spread Outputs Tab

Let's begin by reviewing the crown fire **Spread Outputs** tab.

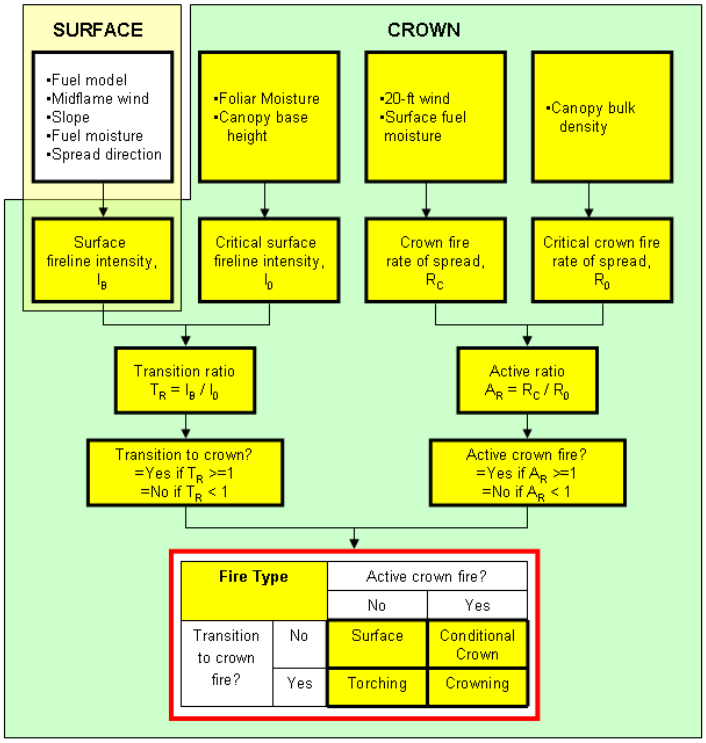
- Open the **BasicStart.bpw** worksheet
- Open the **Module Selection** window.
- Remove the check mark by SURFACE.
- Check CROWN.
- Click on **CROWN > Options…**.
- Click on the **Spread Outputs** tab (The program will default to this tab), and view the variables available on **Spread Outputs** tab.
- Clear the checkmarks by all variables.



A flowchart of the relationship among the first nine variables (Critical Surface Intensity through Fire Type) can be found by scrolling down in the **Help** window for any of the variables.

- Hover over Fire Type, and scroll towards the bottom of the **Help** window.

The following chart appears. Boxes in yellow represent the calculations necessary to calculate the requested output. In this case, Fire Type is the ratio of the Transition to Crown Fire? variable to the Active Crown Fire? variable. Each of the inputs necessary to calculate those two variables are, therefore, also needed to calculate Fire Type.



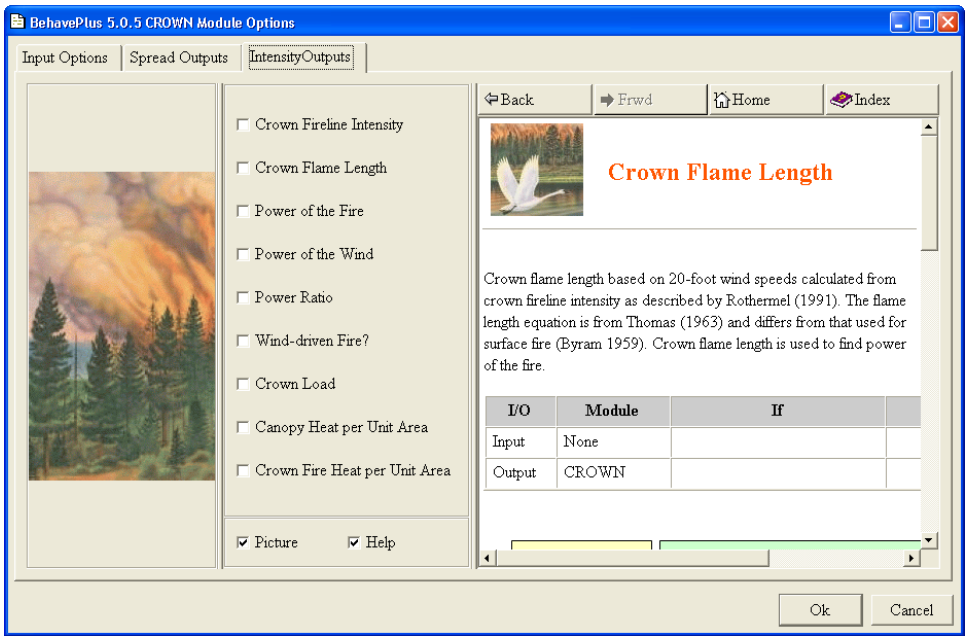
- Do not close the **CROWN Module Options** window; you will continue using it in the next section.

More information on CROWN output variables that can be selected on the CROWN Spread Outputs tab, including Fire Type, are covered in the Modeling lesson entitled **Crown Fire Spread**.

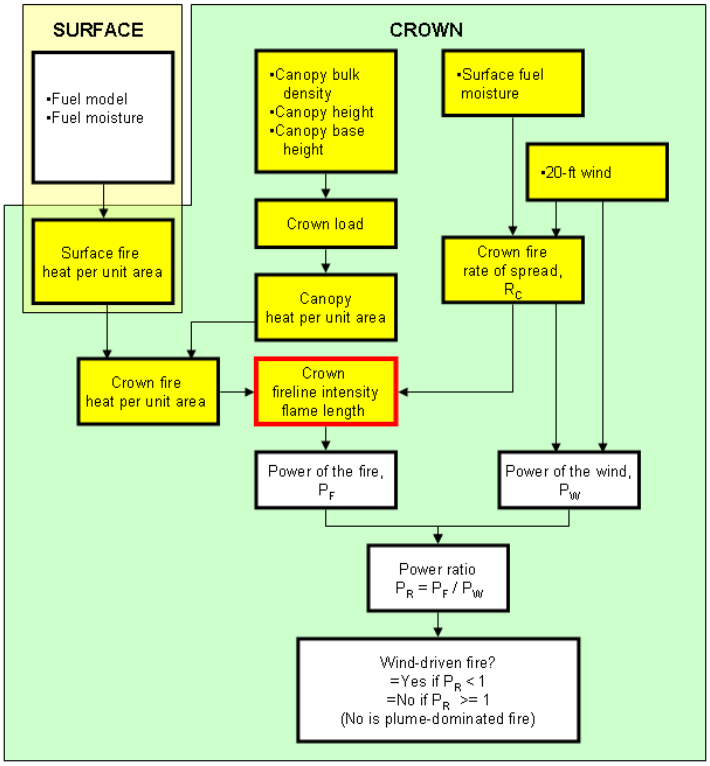
CROWN Intensity Outputs Tab

This lesson covers those CROWN Module output variables that can be selected on the **Intensity Outputs** tab.

- Click on the **Intensity Outputs** tab.



- Hover over the Crown Flame Length variable to activate the context-sensitive **Help** window.
- Scroll down in the **Help** window to see a flowchart of all of the variables on the **Intensity Outputs** tab.



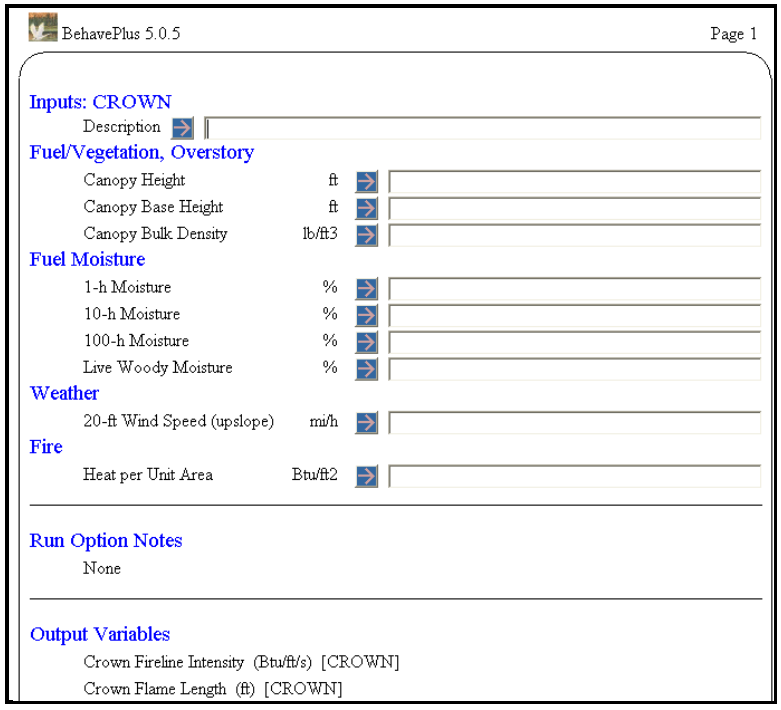
Crown Flame Length is dependent upon the Crown Fire Heat per Unit Area and the Crown Fire Rate of Spread.

Crown Fireline Intensity and Flame Length

We will do a simple model run and then discuss the inputs and the intermediate calculations involved in the calculation of Crown Fireline Intensity and Crown Flame Length shown in the flowchart above. Yellow highlights in the flowchart indicate the values that are used in the calculations.

- On the **Intensity Outputs** tab, select only Crown Fireline Intensity and Crown Flame Length as output variables.
- Click **Ok** twice.

The resulting Worksheet will look like the following.



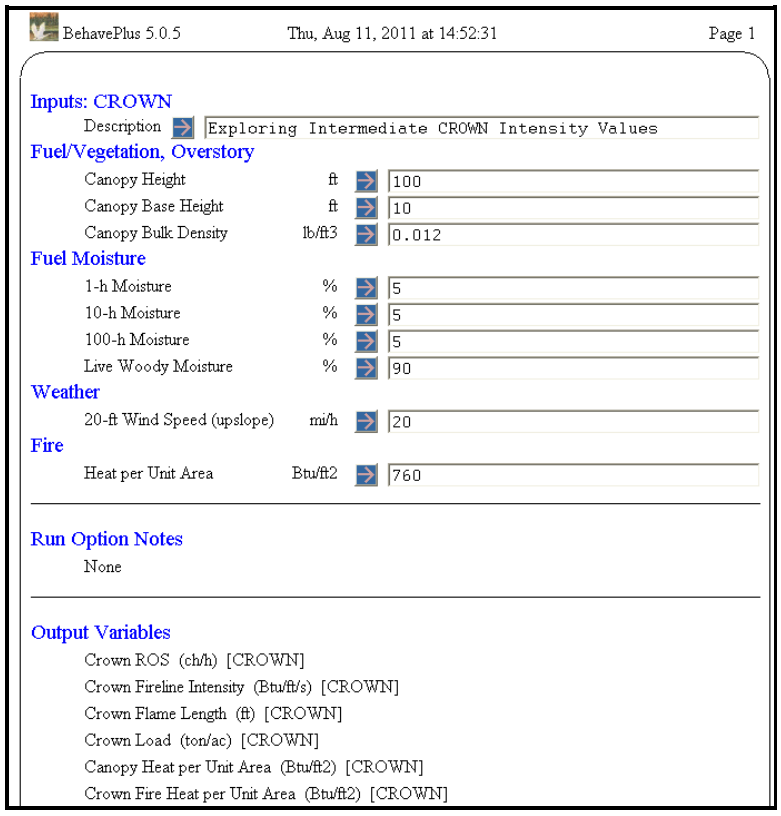
Only those variables required to calculate Crown Flame Length and Crown Fireline Intensity are requested on the Worksheet.

Now, let's select some intermediate variables. Since the additional output variables are intermediate values, the input lines on the Worksheet don't change.

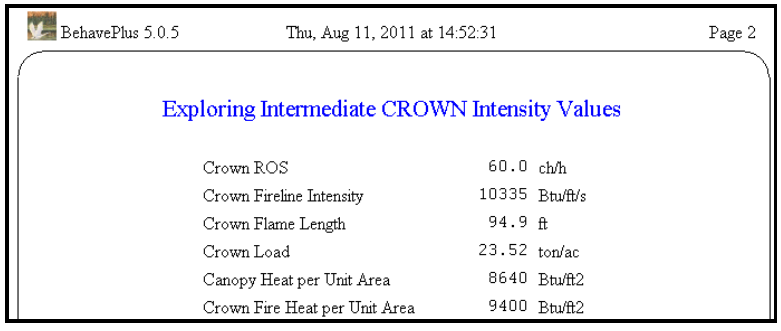
- Go to the **Module Selection > CROWN > Options… > Spread Outputs** tab.
- Select Crown ROS (Rate of Spread).
- Click on the **Intensity Outputs** tab.

- In addition to those variables selected previously, select Crown Load, Canopy Heat per Unit Area, and Crown Fire Heat per Unit Area.
- Click **Ok** twice.

- Enter values on the Worksheet as shown.



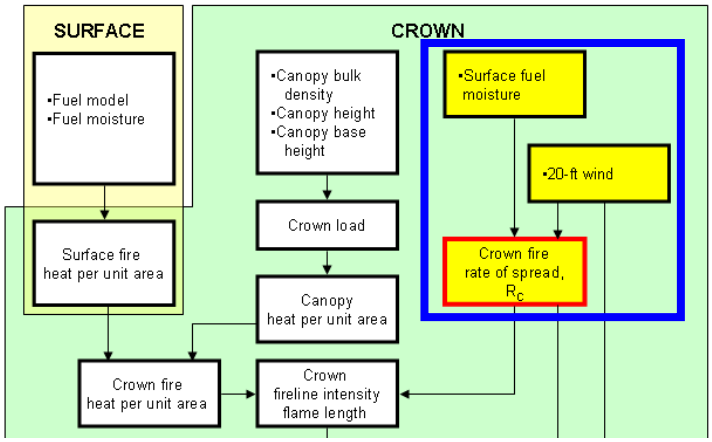
- **Calculate** the Run.



Crown Fire Rate of Spread

Let's examine the various intermediate values in more detail. The only values used to calculate crown fire rate of spread (Crown ROS) are surface fuel moisture values and 20-ft Wind Speed. The model used for the calculation of Crown ROS is covered in the **Crown Fire Spread** lesson. As a review, Crown ROS is based on a correlation

developed by Rothermel (1991) between calculated surface fire rate of spread and seven wind-driven crown fires observed in the Northern Rockies. The correlation is based on surface fuel moisture values and the 20-ft wind speed. This model was designed to predict the spread of a crown fire for several hours over long distances with variable fuel and slope conditions. Think about the fuel and terrain changes over this temporal and spatial range.



Let's examine Crown ROS again. Remember, Crown ROS is dependent on surface fuel moisture, so those values are entered into the Worksheet. We will use the same Worksheet for the next several examples.

- Open a new **BasicStart.bpw** Worksheet.
- In **Module Selection**, unselect SURFACE and select CROWN.
- In **CROWN > Options…**, select only Crown ROS on the **Spread Outputs** tab.
- Enter values on the Worksheet as shown below, using a range of wind speeds.

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Inputs: CROWN

Description		CROWN Module: Crown Rate of Spread
Fuel Moisture		
1-h Moisture	%	5
10-h Moisture	%	6
100-h Moisture	%	7
Live Woody Moisture	%	90
Weather		
20-ft Wind Speed (upslope)	mi/h	10, 15, 20, 25, 30

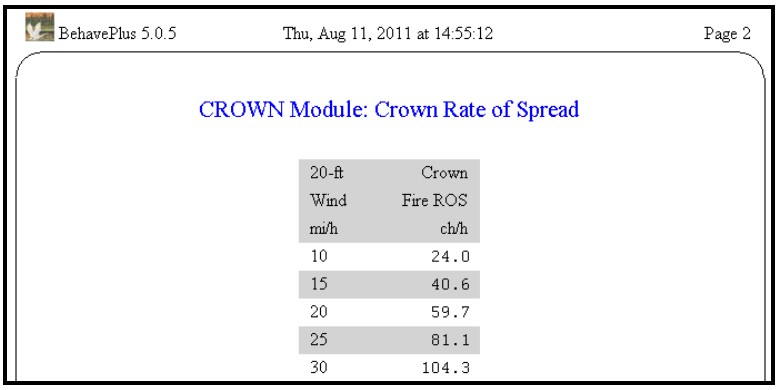
Run Option Notes

None

Output Variables

Crown ROS (ch/h) [CROWN]

- **Calculate** the Run.
- Click **Ok** to accept the default outputs.



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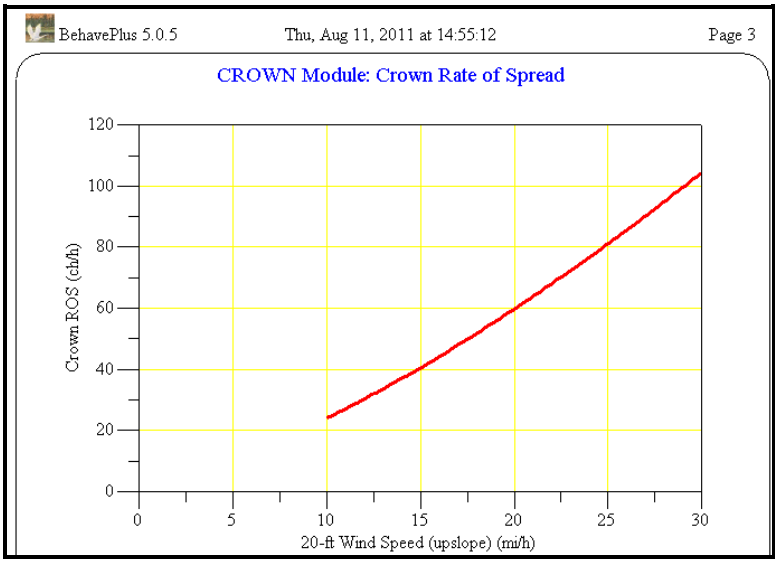
CROWN Module: Crown Rate of Spread

20-ft Wind mi/h	Crown Fire ROS ch/h
10	24.0
15	40.6
20	59.7
25	81.1
30	104.3



From this example, you can see that the Crown ROS is very sensitive to the input wind speed. Remember, this 20-ft Wind Speed value is for the sustained winds, and doesn't account for gusts. If gusts are expected in the area, you may want to look at higher wind speed values as well to see the short-term impact of a gust.

Crown Fireline Intensity

Crown Fireline Intensity is computed in BehavePlus using the same equation that Byram (1959) developed for surface fireline intensity; however, input variables now incorporate crown fire metrics.

$I_B = R_c H_A$ Equation 1

$H_A = hw$ Equation 2

where:

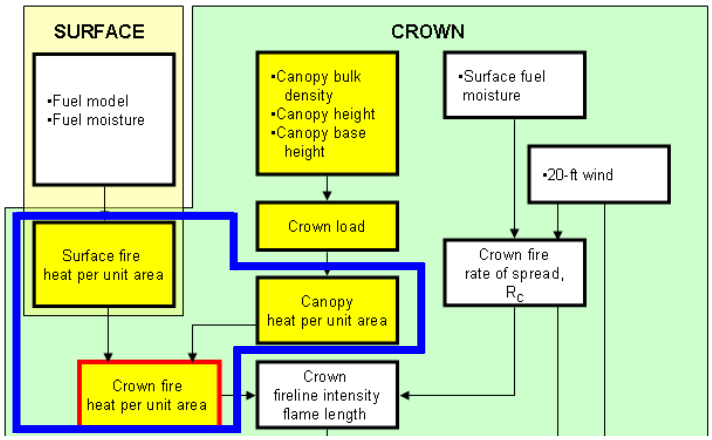
I_B = Fireline intensity, Btu/ft · s
R_c = Average fire rate of spread, ft/s
H_A = Heat per unit area, Btu/ft^2

h = Heat of combustion or heat content of fuels, Btu/lb
w = Weight of available surface and canopy fuels (needle biomass) at the fire front, lb/ft^2

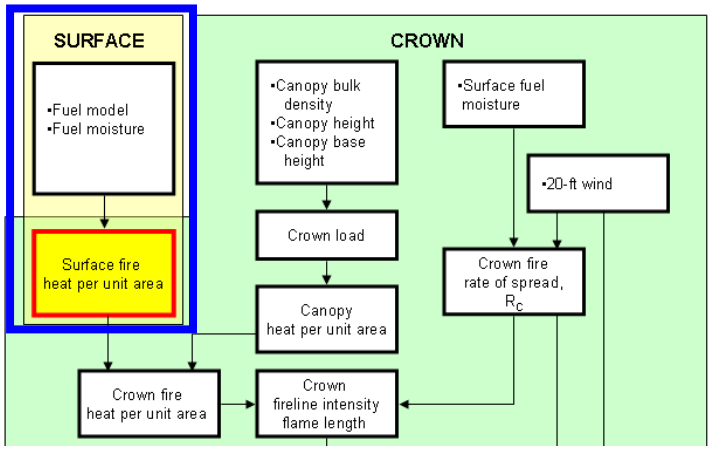
Let's explore these equations more thoroughly. The R_c (average crown fire rate of spread; Crown ROS) is obtained as described in the previous section.

The heat of combustion (h) and available fuel (w) are combined to produce a Crown Fire Heat per Unit Area (H_A; Equation 2). As shown in the flowchart below, Heat per Unit Area (HPUA) is calculated separately for the surface fire (Surface Fire HPUA) and the contribution of the crown fuel (Canopy HPUA), such that

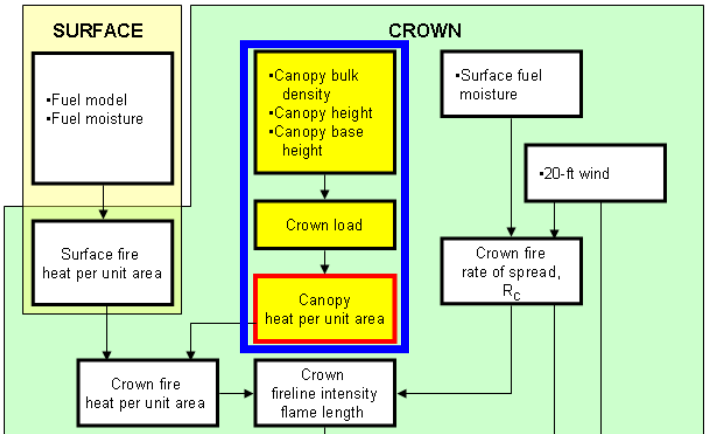
$$H_{A,crown} = H_{A,surface} + H_{A,canopy} \qquad \text{Equation 3}$$



If the SURFACE and CROWN modules are linked (in other words, BOTH are selected in the **Module Selection** window), Surface Fire HPUA is calculated in the SURFACE module, using an appropriate fuel model (for the surface fuels) and associated fuel moistures. This is reflected in the flowchart below by the yellow box titled SURFACE. If only the CROWN module is selected, the surface fire HPUA must be entered directly on the Worksheet.



Canopy Heat per Unit Area is assumed to be produced by consumption of conifer needles. Using Equation 2, Canopy HPUA is derived from Crown Load and the heat content of fuels (assumed to be 8000 Btu/lb for conifer needles).



Crown Load is the amount of conifer needles in the canopy. It is estimated from Canopy Bulk Density and the *difference* between the Canopy Height, and Canopy Base Height.

$w_{cr} = CBD \times (HT - CBH)$ Equation 4

where:

w_{cr} = Crown load, lb/ft^2
CBD = Canopy bulk density, lb/ft^3
HT = Canopy height, ft
CBH = Canopy base height, ft

We'll examine the sensitivity of the Crown Load model to various inputs of Canopy Bulk Density and Canopy Base Height. You may remember from the lesson on crown fire spread that canopy base height helps determine if a fire can transition to a crown fire, while canopy bulk density helps determine if an active crown fire can be sustained. When looking at the intensity of the crown fire, we must consider that we *already have an active crown fire*. The variables are used to estimate how fast and how hot the fire is burning. This will ultimately help us determine if the crown fire is likely to be plume-dominated or wind-driven.

Unfortunately, these two variables are difficult to measure. In fact, there are no standard methods for measuring the major crown fuel properties of canopy bulk density and canopy base height. Average values likely do not describe the conditions that determine crown fire behavior. Looking at ranges of values will help us understand the sensitivity of the model to these inputs.

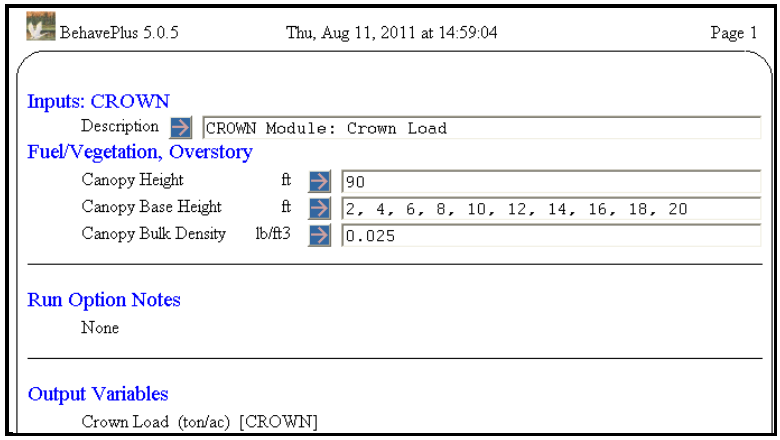
- On the Worksheet you just used, go to **Module Selection > CROWN > Options… >**
- On the **Spread Outputs** tab, unselect Crown ROS.
- On the **Intensity Outputs** tab, select Crown Load.

- Click **Ok** twice.

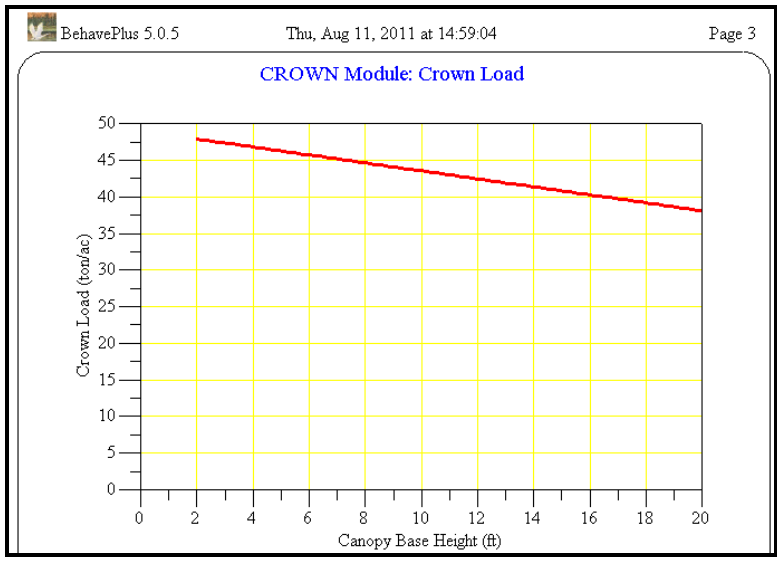
There are only three values needed to calculate the Crown Load (how much easily ignitable fuel (mainly conifer needles)) exists in the canopy.

First, we'll look at the Canopy Base Height.

- Enter values on the Worksheet as shown below.



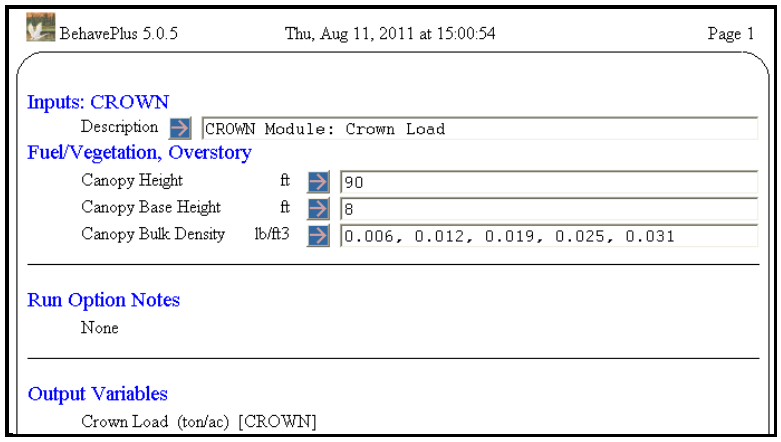
- **Calculate** the Run.
- Click **Ok** to accept the default outputs.
- Look at the graph for Crown Load vs. Canopy Base Height.



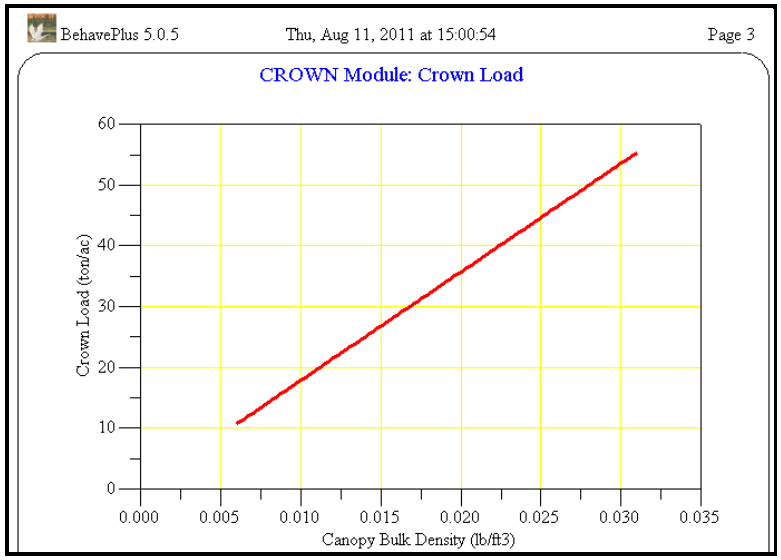
The Crown Load doesn't vary much with Canopy Base Height (less than 10 ton/ac). So, while an accurate estimate of Canopy Base Height is critical to getting the transition to crown fire correct, it is less important for estimating Crown Load. You may wish to try other values of Canopy Bulk Density to see if the sensitivity of Crown Load to Canopy Base Height changes.

Now, we'll look at the Canopy Bulk Density.

- Return to the Worksheet and enter values as shown below.
- For Canopy Bulk Density, select the **Guide** button.
- In the **Input Guide** window, select **Choices**.
- Select all of the values, and click **Ok**.



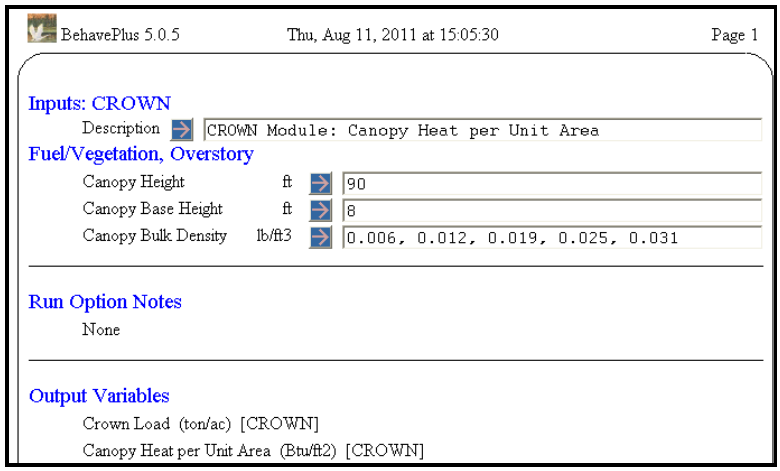
- **Calculate** the Run.
- Click **Ok** to accept the default outputs.
- Look at the graph for Crown Load vs. Canopy Bulk Density.



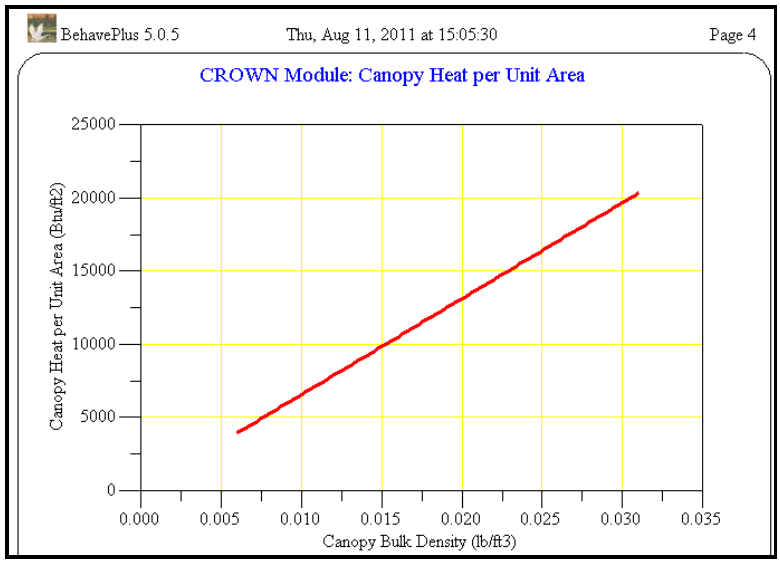
Crown Load is very sensitive to the Canopy Bulk Density. We'll talk more about how to estimate Canopy Bulk Density later in the lesson. However, you will want to be aware of the sensitivity of the model to ensure the best available values are used. You should also consider using a range of reasonable values.

Now that we've calculated a Crown Load, we can calculate the Canopy Heat per Unit Area. Since Crown Load is the only input into Canopy HPUA, Worksheet inputs do not change. And, Canopy HPUA will be sensitive to the same variables as Crown Load.

- Return to the Worksheet you've been using.
- On the **Module Selection > CROWN > Options… > Intensity Outputs** tab, select both Crown Load and Canopy Heat per Unit Area
- Use the values from the Run we just created, with the same range of Canopy Bulk Density values (see Worksheet below).

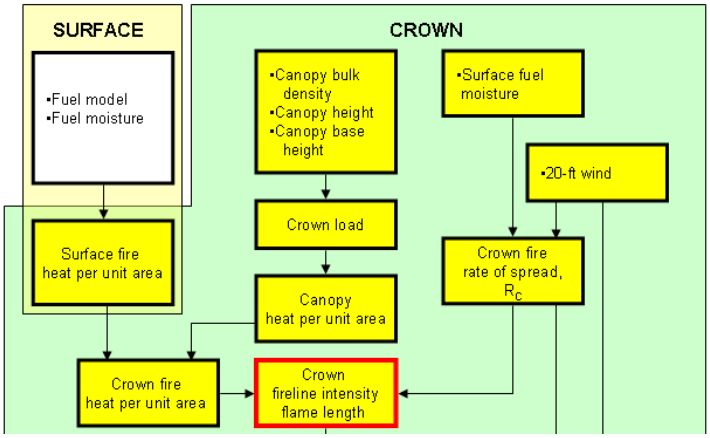


- **Calculate** the Run.
- Click **Ok** to accept the default outputs.
- Look at the graph for Canopy Heat per Unit Area vs. Canopy Bulk Density.



Wow, the Canopy Heat per Unit Area is extremely sensitive to the Canopy Bulk Density. This is apparently a critical value that we will want to try and "get right."

As mentioned previously, Canopy Heat per Unit Area and surface fire Heat per Unit Area are then summed to produce Crown Fire Heat per Unit Area (Equation 3). Remember, Crown Fire Heat per Unit Area is a direct input into the Crown Fireline Intensity.



In this example, we look at the heat per unit area values. As mentioned previously, the surface fire Heat per Unit Area can be either calculated using the SURFACE module or defined on the Worksheet. We will assume a surface fire Heat per Unit Area of 760 Btu/ft^2.

- On the Worksheet you just used, go to **Module Selection > CROWN > Options…**.
- On the **Intensity Outputs** tab, change your selection to
  - Canopy Heat per Unit Area and
  - Crown Fire Heat per Unit Area.
- Click **Ok** twice.
- Enter values on the Worksheet as shown below, including the Heat per Unit Area.

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Inputs: CROWN

Description		CROWN Module: Heat per Unit Area
Fuel/Vegetation, Overstory		
Canopy Height	ft	90
Canopy Base Height	ft	8
Canopy Bulk Density	lb/ft3	0.025
Fire		
Heat per Unit Area	Btu/ft2	760

Run Option Notes

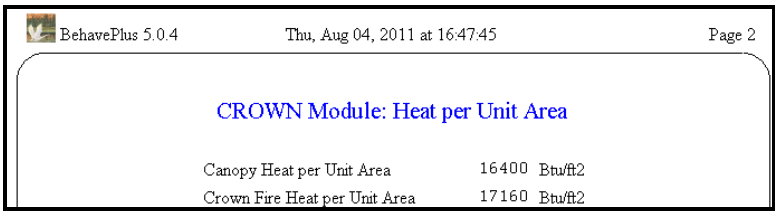
None

Output Variables

Canopy Heat per Unit Area (Btu/ft2) [CROWN]

Crown Fire Heat per Unit Area (Btu/ft2) [CROWN]

- **Calculate** the Run.



The Crown Fire Heat per Unit Area is the sum of the Canopy Heat per Unit Area (16400 Btu/ft^2) and the surface fire Heat per Unit Area (input as 760 Btu/ft^2).

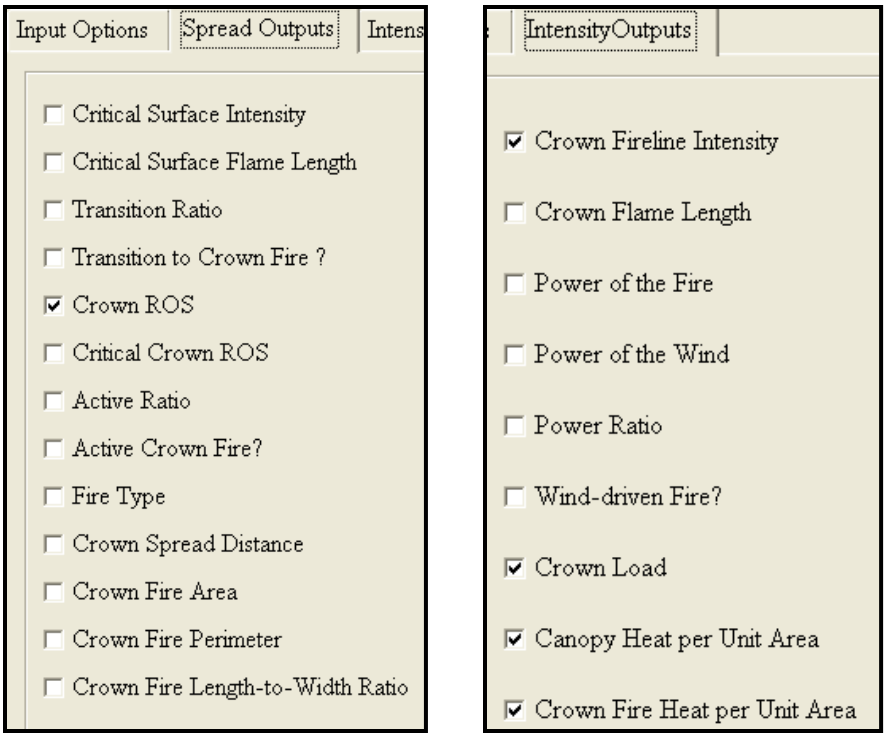
Even though we only used one value in the above example, remember that all variables are sensitive to the same things as their inputs. Since Canopy Heat per Unit Area is sensitive to Canopy Bulk Density, Crown Fire Heat per Unit Area are, too. You can test this out for yourself.

Now, we have everything we need to calculate Fireline Intensity, which we will do in the next section. It is based on Crown Fire Rate of Spread (R_c) and Crown Fire Heat per Unit Area ($H_{A,\ crown}$), providing all of the necessary inputs for Equation 1.

Calculating Crown Fireline Intensity using the CROWN Module

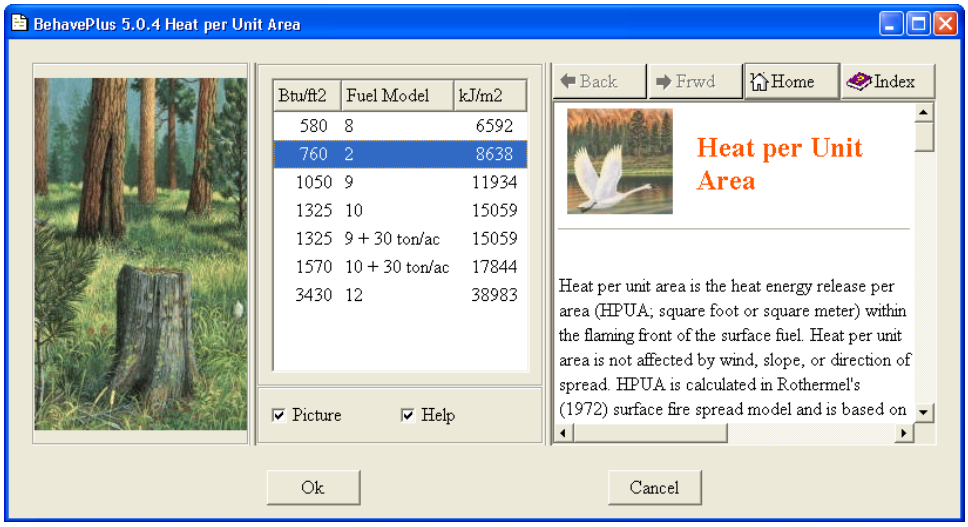
In this example, we'll use outputs using from the CROWN module to produce estimates of Crown Fireline Intensity. Those intermediates necessary for the computation of Crown Fireline Intensity will be selected as outputs as well.

- Open a new **BasicStart.bpw** Worksheet.
- Go to **Configure > Module selection**.
- Deselect **SURFACE** and select **CROWN**.
- Click on **CROWN > Options…**.
- Go to the **Spread Outputs** tab and select only Crown ROS.
- Go to the **Intensity Outputs** tab and select the following outputs:
  - Crown Fireline Intensity,
  - Crown Load,
  - Canopy Heat per Unit Area, and
  - Crown Fire Heat per Unit Area.



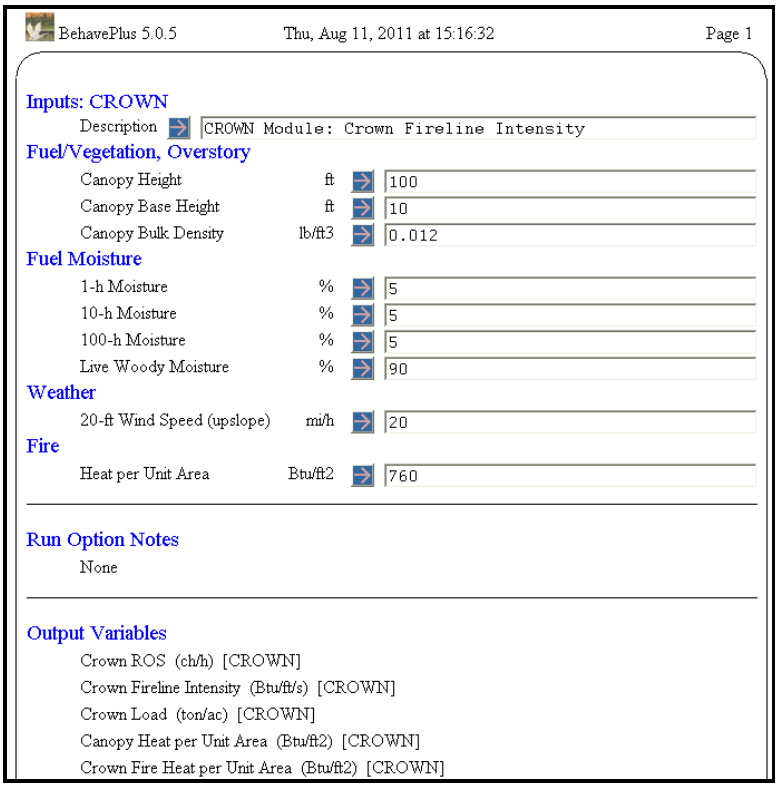
- Enter values on the Worksheet.
- For Heat per Unit Area, click the **Guide** button ( ).
- On the Input Guide window select **Choices**.

The following options are available.



- Select Fuel Model 2 to represent surface Heat per Unit Area values. (These values are based on the Burnout model and will be explained later.)

- Enter remaining values as shown on the Worksheet below.



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Inputs: CROWN

Description		CROWN Module: Crown Fireline Intensity
Fuel/Vegetation, Overstory		
Canopy Height	ft	100
Canopy Base Height	ft	10
Canopy Bulk Density	lb/ft3	0.012
Fuel Moisture		
1-h Moisture	%	5
10-h Moisture	%	5
100-h Moisture	%	5
Live Woody Moisture	%	90
Weather		
20-ft Wind Speed (upslope)	mi/h	20
Fire		
Heat per Unit Area	Btu/ft2	760

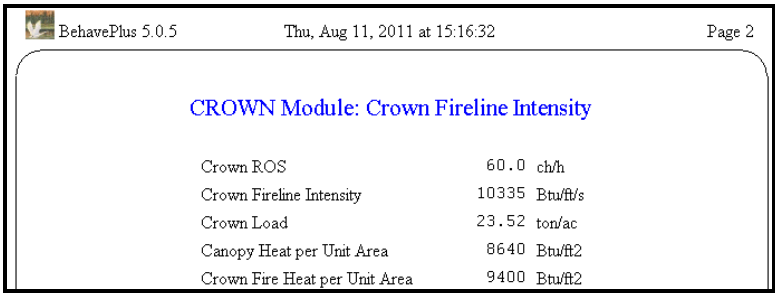
Run Option Notes

None

Output Variables

Crown ROS (ch/h) [CROWN]
Crown Fireline Intensity (Btu/ft/s) [CROWN]
Crown Load (ton/ac) [CROWN]
Canopy Heat per Unit Area (Btu/ft2) [CROWN]
Crown Fire Heat per Unit Area (Btu/ft2) [CROWN]

- **Calculate** this Run.



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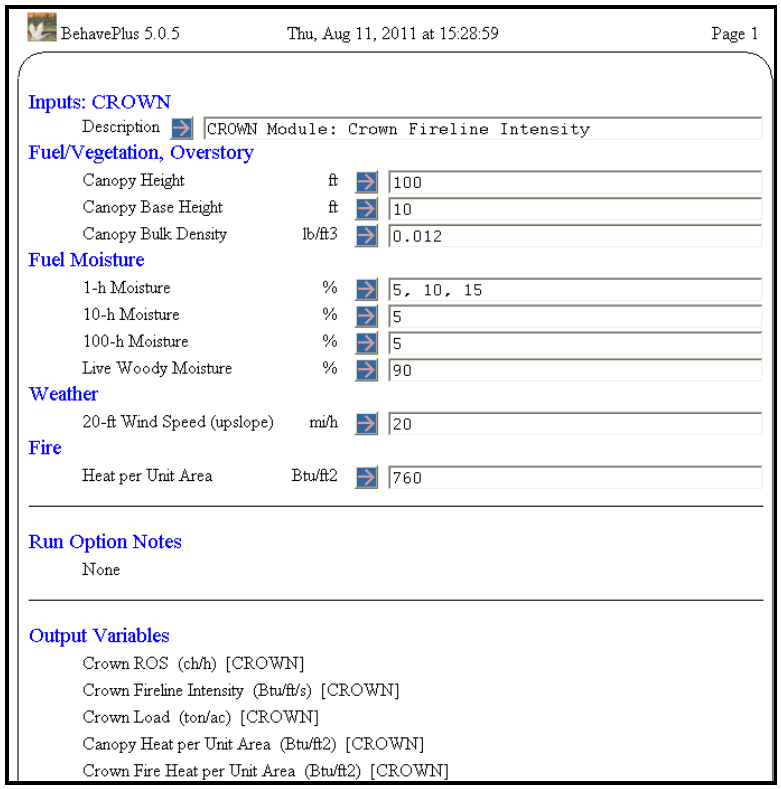
CROWN Module: Crown Fireline Intensity

Crown ROS	60.0	ch/h
Crown Fireline Intensity	10335	Btu/ft/s
Crown Load	23.52	ton/ac
Canopy Heat per Unit Area	8640	Btu/ft2
Crown Fire Heat per Unit Area	9400	Btu/ft2

We did not use the SURFACE module in this scenario, only the CROWN module. Consequently, outputs **must** be interpreted as if crown fire behavior is occurring.

Finally, let's see which variables are affected by 1-h moisture. Before we do a Run, look back at the flow chart (Hint: Check the **Guide** button by Canopy Bulk Density and scroll down in the **Help** window to the second flow chart.). Which variables do you expect to change if you change the surface fuel moisture? To stay the same?

- Return to the Worksheet and change the 1-h Moisture as shown below.



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Inputs: CROWN

Description		CROWN Module: Crown Fireline Intensity
Fuel/Vegetation, Overstory		
Canopy Height	ft	100
Canopy Base Height	ft	10
Canopy Bulk Density	lb/ft3	0.012
Fuel Moisture		
1-h Moisture	%	5, 10, 15
10-h Moisture	%	5
100-h Moisture	%	5
Live Woody Moisture	%	90
Weather		
20-ft Wind Speed (upslope)	mi/h	20
Fire		
Heat per Unit Area	Btu/ft2	760

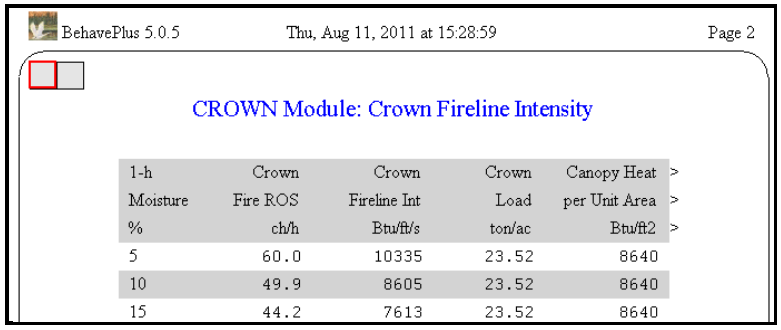
Run Option Notes

None

Output Variables

Crown ROS (ch/h) [CROWN]
Crown Fireline Intensity (Btu/ft/s) [CROWN]
Crown Load (ton/ac) [CROWN]
Canopy Heat per Unit Area (Btu/ft2) [CROWN]
Crown Fire Heat per Unit Area (Btu/ft2) [CROWN]

- **Calculate** this Run.
- Click **Ok** to accept the default outputs.



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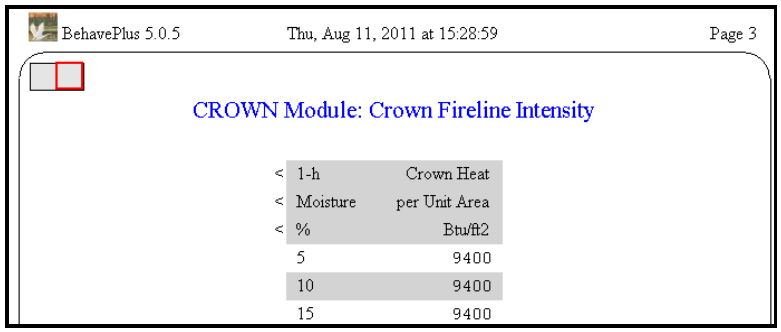
CROWN Module: Crown Fireline Intensity

1-h Moisture %	Crown Fire ROS ch/h	Crown Fireline Int Btu/ft/s	Crown Load ton/ac	Canopy Heat per Unit Area Btu/ft2
5	60.0	10335	23.52	8640
10	49.9	8605	23.52	8640
15	44.2	7613	23.52	8640



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CROWN Module: Crown Fireline Intensity

1-h Moisture %	Crown Heat per Unit Area Btu/ft2
5	9400
10	9400
15	9400

The Crown ROS and Crown Fireline Intensity are both affected by the 1-h Moisture.

Crown Flame Length

Crown Flame Length is based on the 20-ft Wind Speed used to calculate Crown Fireline Intensity (Rothermel 1991). The flame length equation for crown fire is taken from Thomas (1963) and differs from that used for surface fire (Byram 1959). Byram's equation, used to estimate surface fire flame length, was not used because it underpredicts crown fire flame lengths. Thomas' (1963) flame length equation, based on convection theory, is:

$$F_T = 0.2 \times I_B^{2/3} \qquad \text{Equation 5}$$

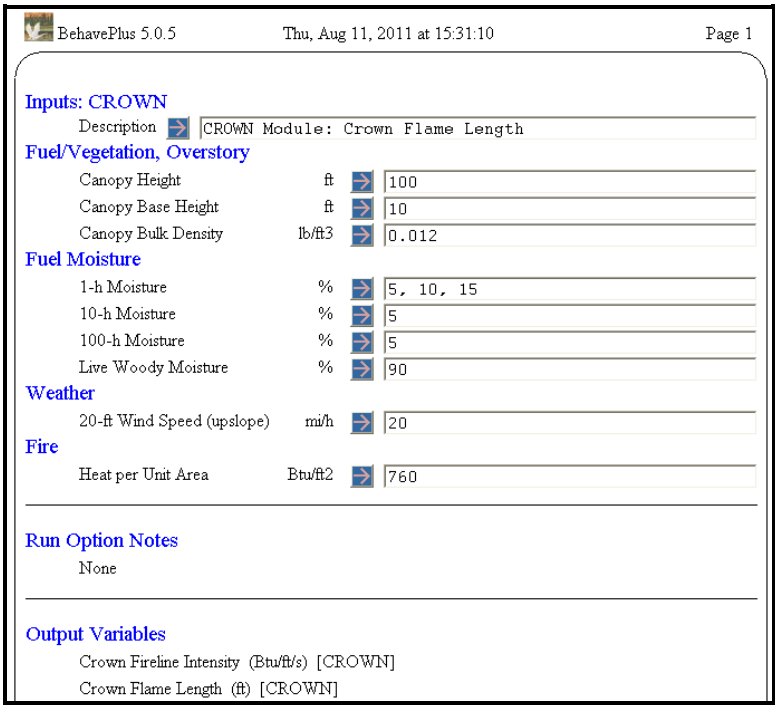
where

F_T = Crown Flame Length, ft
I_B = Crown Fireline Intensity, Btu/ft · s

Thomas' model was found to correlate well with observed crown fire flame lengths except for low-intensity crown fires.

- On the Worksheet you just used, go to **Module Selection > CROWN > Options…**.
- On the **Spread Outputs** tab, uncheck Crown ROS.
  - On the **Intensity Outputs** tab, change your selection to Crown Fireline Intensity and Crown Flame Length
- Click **Ok** twice.

The values on the Worksheet should not change since all of these values are needed to calculate the Crown Fireline Intensity – the only input into Crown Flame Length.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Inputs: CROWN

Description		CROWN Module: Crown Flame Length
Fuel/Vegetation, Overstory		
Canopy Height	ft	100
Canopy Base Height	ft	10
Canopy Bulk Density	lb/ft3	0.012
Fuel Moisture		
1-h Moisture	%	5, 10, 15
10-h Moisture	%	5
100-h Moisture	%	5
Live Woody Moisture	%	90
Weather		
20-ft Wind Speed (upslope)	mi/h	20
Fire		
Heat per Unit Area	Btu/ft2	760

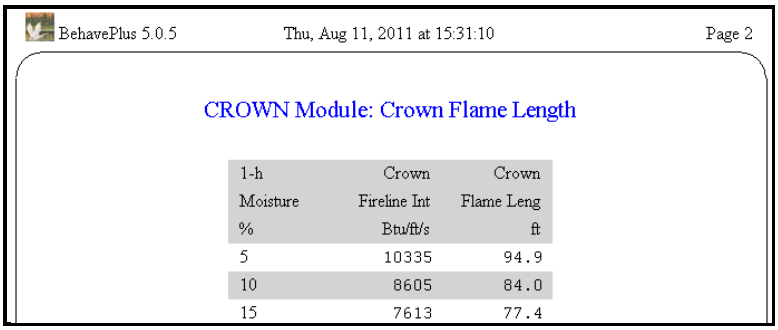
Run Option Notes

None

Output Variables

Crown Fireline Intensity (Btu/ft/s) [CROWN]
Crown Flame Length (ft) [CROWN]

- **Calculate** the Run.



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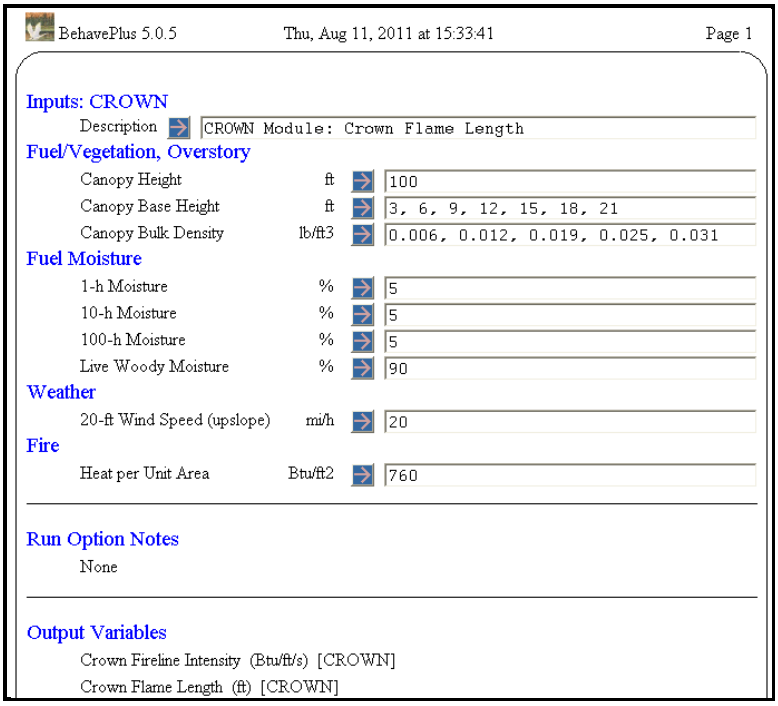
CROWN Module: Crown Flame Length

1-h Moisture %	Crown Fireline Int Btu/ft/s	Crown Flame Leng ft
5	10335	94.9
10	8605	84.0
15	7613	77.4

For a Crown Fireline Intensity of 10,300 Btu/ft/s, Crown Flame Length is approximately 95 ft. Higher 1-h fuel moisture values result in lower Crown Fireline Intensities, and therefore, lower Crown Flame Lengths.

Let's check the sensitivity of Crown Flame Length to Canopy Bulk Density and Canopy Base Height.

- Return to the Worksheet and change the values as shown below.
  - Canopy Base Height ranges from 3 to 21 in steps of 3.
  - For Canopy Bulk Density, click on the **Guide** button, and then the **Choices** button. Select all values.
- Your outputs should be Crown Fireline Intensity and Crown Flame Length.



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Inputs: CROWN

Description		CROWN Module: Crown Flame Length
Fuel/Vegetation, Overstory		
Canopy Height	ft	100
Canopy Base Height	ft	3, 6, 9, 12, 15, 18, 21
Canopy Bulk Density	lb/ft3	0.006, 0.012, 0.019, 0.025, 0.031
Fuel Moisture		
1-h Moisture	%	5
10-h Moisture	%	5
100-h Moisture	%	5
Live Woody Moisture	%	90
Weather		
20-ft Wind Speed (upslope)	mi/h	20
Fire		
Heat per Unit Area	Btu/ft2	760

Run Option Notes

None

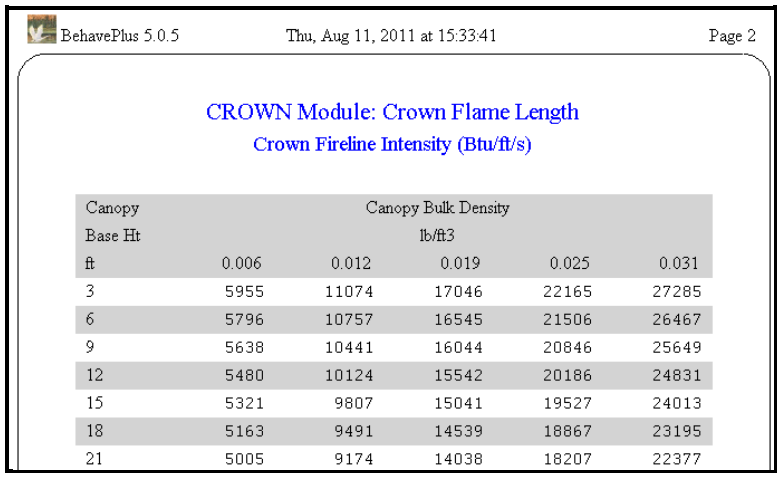
Output Variables

Crown Fireline Intensity (Btu/ft/s) [CROWN]

Crown Flame Length (ft) [CROWN]

- **Calculate** this Run.

- Select the following in the **Calculate Results** window.
  - **Select the Table Row Variable** is **Canopy Base Height**. (This puts the table on one page.)
  - **Select the X-Axis Variable** is **Canopy Bulk Density**.
- Click **Ok**.



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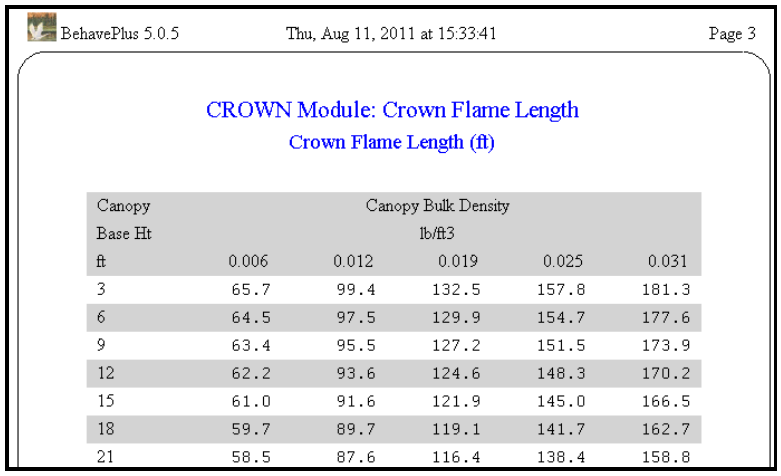
CROWN Module: Crown Flame Length

Crown Fireline Intensity (Btu/ft/s)

Canopy Base Ht	Canopy Bulk Density lb/ft3				
ft	0.006	0.012	0.019	0.025	0.031
3	5955	11074	17046	22165	27285
6	5796	10757	16545	21506	26467
9	5638	10441	16044	20846	25649
12	5480	10124	15542	20186	24831
15	5321	9807	15041	19527	24013
18	5163	9491	14539	18867	23195
21	5005	9174	14038	18207	22377



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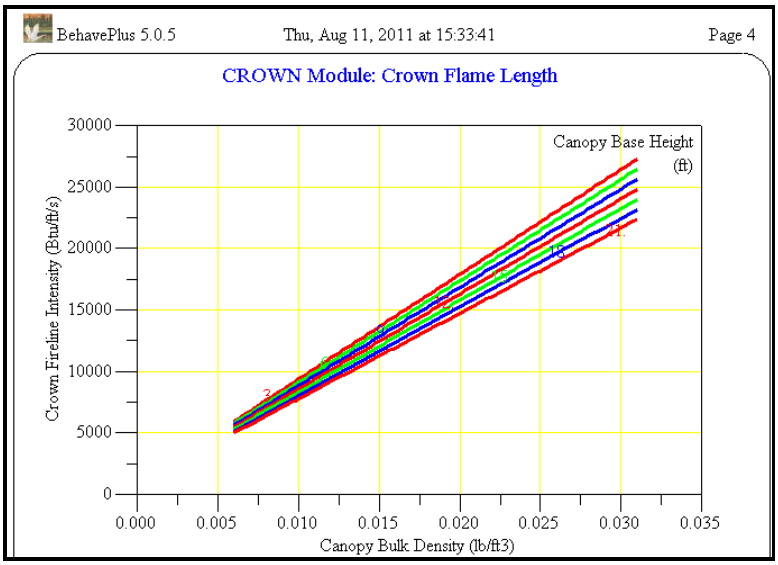
CROWN Module: Crown Flame Length

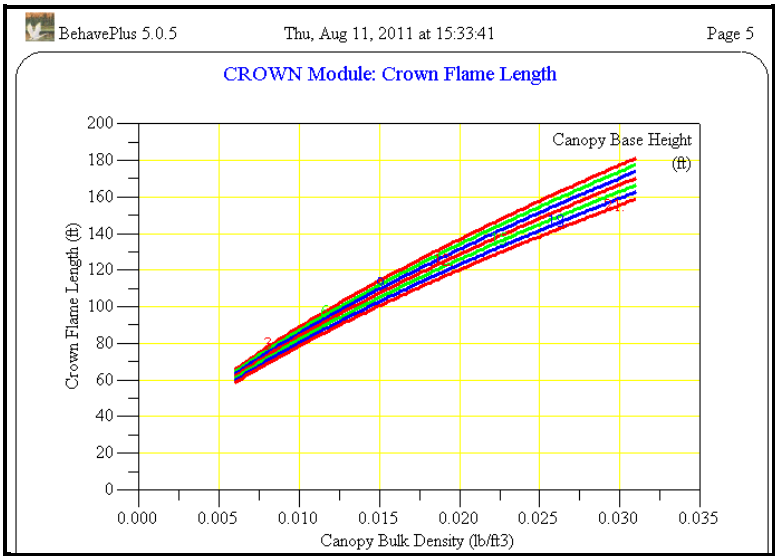
Crown Flame Length (ft)

Canopy Base Ht	Canopy Bulk Density lb/ft3				
ft	0.006	0.012	0.019	0.025	0.031
3	65.7	99.4	132.5	157.8	181.3
6	64.5	97.5	129.9	154.7	177.6
9	63.4	95.5	127.2	151.5	173.9
12	62.2	93.6	124.6	148.3	170.2
15	61.0	91.6	121.9	145.0	166.5
18	59.7	89.7	119.1	141.7	162.7
21	58.5	87.6	116.4	138.4	158.8

The table shows that Crown Flame Length is affected by both variables. As Canopy Base Height increases, the Crown Flame Length decreases. And, as Canopy Bulk Density increases, Crown Flame length also increases.

The graphs may help us better interpret our results.





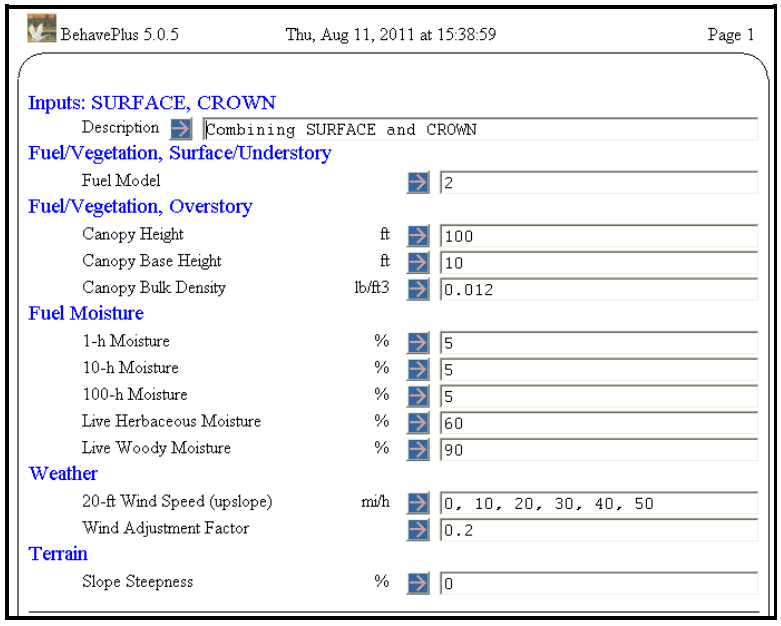
Like Crown Fireline Intensity (top graph above), the Crown Flame Length (bottom graph) is more sensitive to Canopy Bulk Density than to Canopy Base Height. Therefore, while Canopy Bulk Density is difficult to determine, it needs to be as accurate as possible, and you should consider a range of reasonable values in your predictions of Crown Flame Length.

Combining the CROWN & SURFACE Modules

Let's include the SURFACE module in the crown fire behavior modeling and look at the effect of wind speed.

- Open a new **SurfaceCrown.bpw** Worksheet.
- Open the **Module Selection** window; both SURFACE and CROWN are selected.
- Go to **Configure > Module selection > SURFACE > Options…**.

- On the **Wind Speed** tab, verify that **Wind speed is entered as 20-ft wind and Input wind adj factor**.
- On the **Basic Outputs** tab, select Surface Rate of Spread, Heat per Unit Area, Fireline Intensity, and Flame Length.
- Press **Ok** one time.
- Go to **CROWN Options…**.
- On the **Spread Outputs** tab, select only Crown ROS
- On the **Intensity Outputs** tab, select Crown Fireline Intensity and Crown Flame Length.
- Press **Ok** Twice.
- Enter values on the Worksheet as shown below.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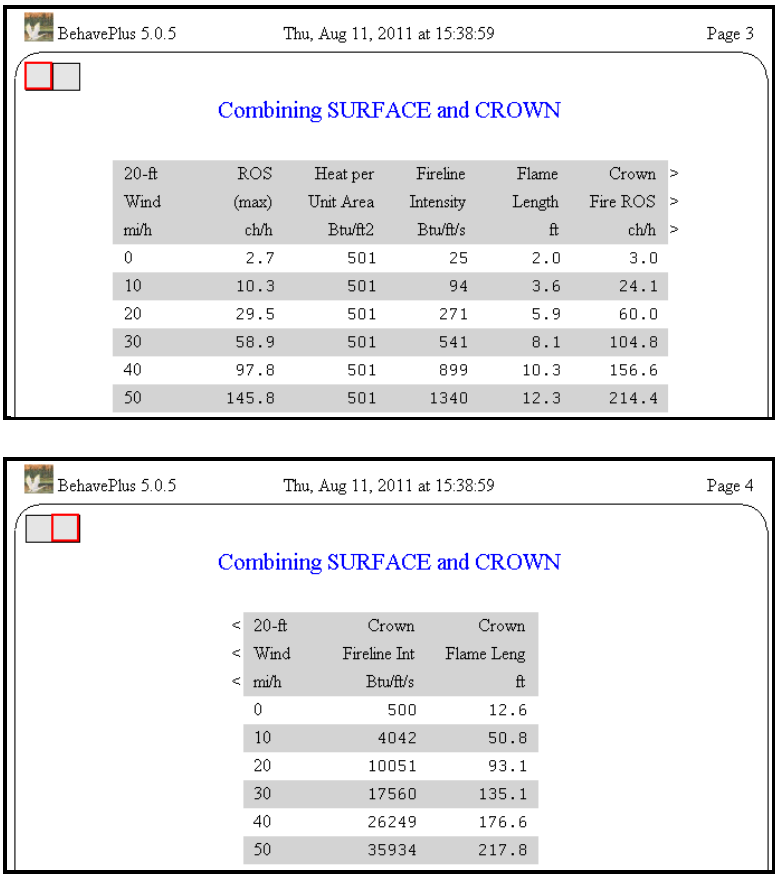
Inputs: SURFACE, CROWN

Description		Combining SURFACE and CROWN
Fuel/Vegetation, Surface/Understory		
Fuel Model		2
Fuel/Vegetation, Overstory		
Canopy Height	ft	100
Canopy Base Height	ft	10
Canopy Bulk Density	lb/ft3	0.012
Fuel Moisture		
1-h Moisture	%	5
10-h Moisture	%	5
100-h Moisture	%	5
Live Herbaceous Moisture	%	60
Live Woody Moisture	%	90
Weather		
20-ft Wind Speed (upslope)	mi/h	0, 10, 20, 30, 40, 50
Wind Adjustment Factor		0.2
Terrain		
Slope Steepness	%	0

- **Calculate** the Run.
- Click **Ok** to accept the default outputs.



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Combining SURFACE and CROWN

20-ft Wind mi/h	ROS (max) ch/h	Heat per Unit Area Btu/ft2	Fireline Intensity Btu/ft/s	Flame Length ft	Crown Fire ROS ch/h
0	2.7	501	25	2.0	3.0
10	10.3	501	94	3.6	24.1
20	29.5	501	271	5.9	60.0
30	58.9	501	541	8.1	104.8
40	97.8	501	899	10.3	156.6
50	145.8	501	1340	12.3	214.4

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Combining SURFACE and CROWN

20-ft Wind mi/h	Crown Fireline Int Btu/ft/s	Crown Flame Leng ft
0	500	12.6
10	4042	50.8
20	10051	93.1
30	17560	135.1
40	26249	176.6
50	35934	217.8

When the SURFACE module is linked to the CROWN module, it is not necessary to enter a surface HPUA value; the SURFACE module will calculate it automatically using the selected Fuel Model and appropriate surface fuel moisture values. In our example, the SURFACE module computes surface HPUA to be 501 Btu/ft^2 for Fuel Model 2 under these conditions.

In the previous two examples, when we used only the CROWN module, we input a surface fire Heat per Unit Area value of 760 Btu/ft^2 based on the value for Fuel Model 2 in the **Choices** list. This list is taken from Rothermel's (1991) crown fire modeling paper, in which he prepared a table of calculated heat per unit area values using the Burnout model (Albini 1976). The Burnout model produces values higher than those calculated by the surface fire spread model used in BehavePlus because it includes the burning of heavy fuels, not just the fine fuels in the flaming front.

Note: SURFACE and CROWN fire behavior outputs such as flame length should be interpreted **as if** that fire type occurs. For instance, given a 20-ft Wind Speed of 10 mi/h, a crown fire would have Flame Lengths approximating 50.8 feet, while a surface fire would have Flame Lengths approximating 3.6 feet. Fire Type is an output feature in the CROWN module and can help to determine if SURFACE or CROWN outputs should be used.

Power of fire and wind

Active crown fires can be either wind- or plume-dominated. Running crown fires or wind-driven fires are dominated by strong winds that drive the fire and can produce spread rates of 80-560 ch/h (1-7 mi/h). Plume-dominated fires, on the other hand, are generally characterized by lower 20-ft Wind Speeds of less than 20 mi/h (Rothermel 1991) and the development of a strong convection column that towers above the fire. Patterns of fire behavior resulting from either wind- or plume-dominated crown fires are different and can affect the safety of individuals on the ground.

Rothermel (1991) provided a method to indicate whether a crown fire might be wind-driven or plume-dominated. It is based on the Crown Fireline Intensity and Crown ROS that we've examined in this lesson so far and uses the variables Power of the Fire and Power of the Wind, which are based on work by Byram (1959) and described by Rothermel (1991).

The Power of the Fire is the rate at which energy is released calculated on a unit area basis, so the units are ft-lb/s/ft^2. This power is the source of energy that produces the convection column.

In contrast, the Power of the Wind is the rate of kinetic energy in the wind field, expressed in the same units as Power of the Fire. Heat energy produced by the fire creates the convection column of the crown fire. As the rising air within the column is subjected to the force of the wind, the column is tipped in the direction the wind is blowing.

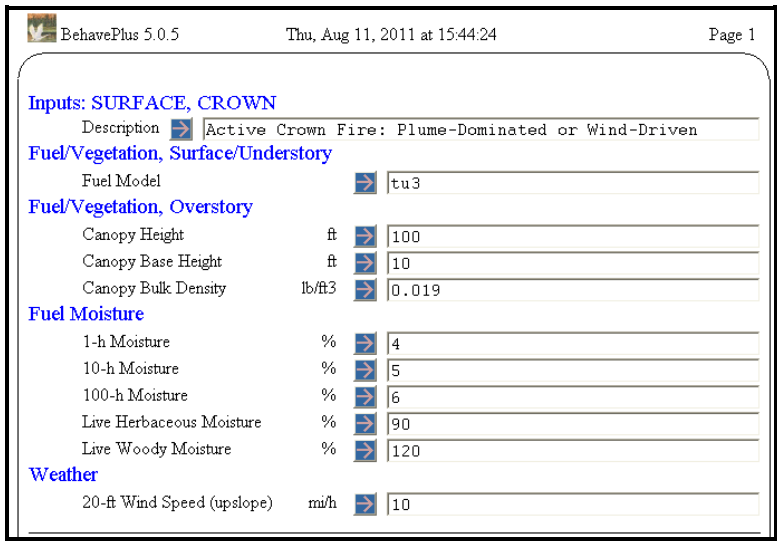
If the Power of the Fire is greater than the Power of the Wind, then the Power Ratio is greater than or equal to 1 ($\geq$1), and the fire-wind system is dominated by the energy of the fire. Such fires may plume-dominated and stand almost vertically. The expected spread rate of a plume-dominated fire is not predicted by the crown rate of spread model in BehavePlus.

If the Power of the Wind is greater than the Power of the Fire, then the Power Ratio is less than 1 (<1), and the fire-wind system is dominated by the energy of the wind. Such fires may be wind-driven. Rothermel (1991) developed a method of estimating the spread rate of a wind-driven crown fire. This is the Crown ROS we examined in the previous lesson on **Crown Fire Spread** and used earlier in this lesson to calculate Crown Fireline Intensity.

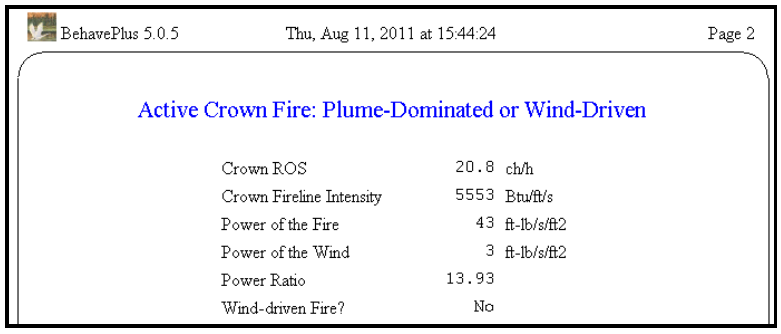
We'll use both the SURFACE and CROWN module to evaluate if a crown fire is plume-dominated or wind-driven.

- Open a new **BasicStart.bpw** Worksheet.
- Go to **Configure > Module selection**.
- Select both SURFACE and CROWN.
- Go to **SURFACE > Options…**.
- On the **Basic Outputs** tab, de-select all outputs.
- Press **Ok**.

- Go to **CROWN > Options…**.
- On the **Spread Outputs** tab, select Crown ROS.
- On the **Intensity Outputs** tab, select
  - Crown Fireline Intensity,
  - Power of the Fire,
  - Power of the Wind,
  - Power Ratio, and
  - Wind-driven Fire?
- Press **Ok** Twice.
- Enter values on the Worksheet as shown below.



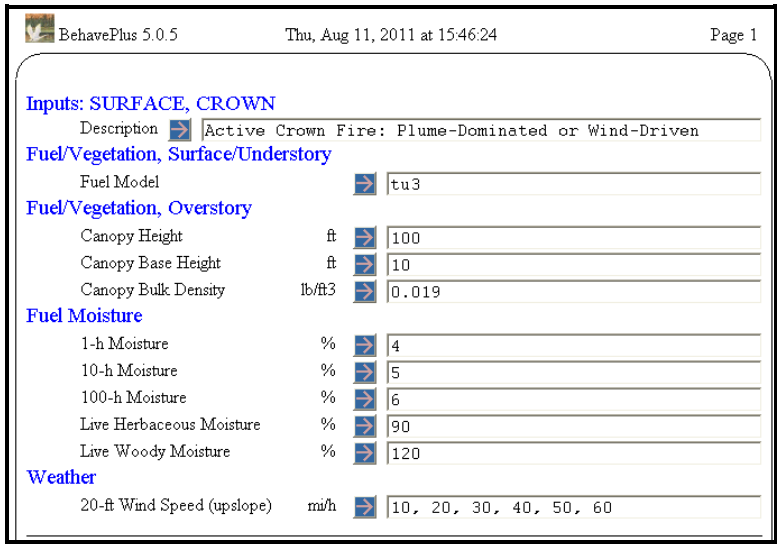
- **Calculate** the Run.



We selected the SURFACE module to compute surface Heat per Unit Area, which is a value necessary for Crown Fireline Intensity. Power of the Fire is a function of that Crown Fireline Intensity. In this example, using fuel model TU3 (timber-understory) with very dry fuel moistures, and a low 20-ft Wind Speed set to 10 mi/h, the Power of the Fire is equal to 43 ft-lb/s/ft^2. Power of the Wind is a function of the 20-ft Wind Speed and Crown Fire Rate of Spread. In this example it is less than the Power of the Fire, at 3 ft-lb /s/ft^2, indicating that the crown fire may be plume-dominated, rather than wind-driven.

Under these conditions, what sustained 20-ft Wind Speed would be required to have a wind-driven crown fire?

We can test this by running a range of wind speed values to see where the outputs change.



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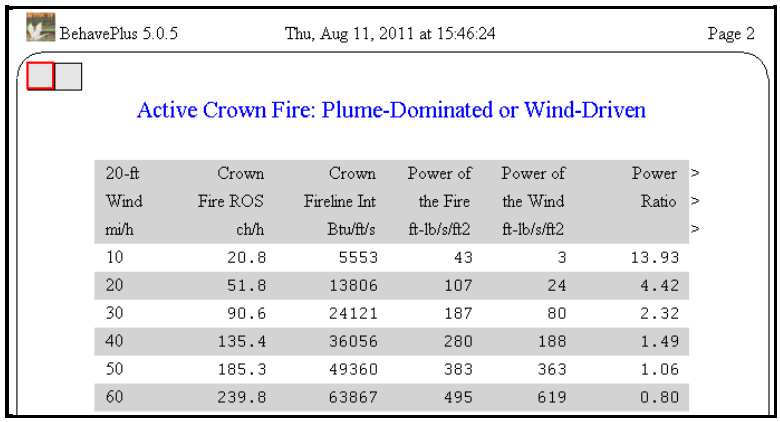
Inputs: SURFACE, CROWN

Description		Active Crown Fire: Plume-Dominated or Wind-Driven
Fuel/Vegetation, Surface/Understory		
Fuel Model		tu3
Fuel/Vegetation, Overstory		
Canopy Height	ft	100
Canopy Base Height	ft	10
Canopy Bulk Density	lb/ft3	0.019
Fuel Moisture		
1-h Moisture	%	4
10-h Moisture	%	5
100-h Moisture	%	6
Live Herbaceous Moisture	%	90
Live Woody Moisture	%	120
Weather		
20-ft Wind Speed (upslope)	mi/h	10, 20, 30, 40, 50, 60



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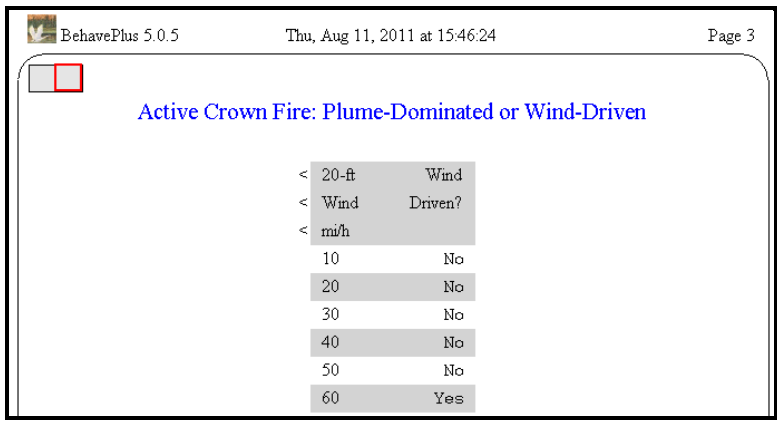
Active Crown Fire: Plume-Dominated or Wind-Driven

20-ft Wind mi/h	Crown Fire ROS ch/h	Crown Fireline Int Btu/ft/s	Power of the Fire ft-lb/s/ft2	Power of the Wind ft-lb/s/ft2	Power Ratio
10	20.8	5553	43	3	13.93
20	51.8	13806	107	24	4.42
30	90.6	24121	187	80	2.32
40	135.4	36056	280	188	1.49
50	185.3	49360	383	363	1.06
60	239.8	63867	495	619	0.80



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Active Crown Fire: Plume-Dominated or Wind-Driven

20-ft Wind mi/h	Wind Driven?
10	No
20	No
30	No
40	No
50	No
60	Yes

Summary

We have evaluated the details of the fire models that comprise Crown Fireline Intensity as well as Power of the Wind and the Power of the Fire. We also ran BehavePlus scenarios to display these outputs. Remember, that crown fire spread modeling is based on observational data for long running crown fires in the Northern Rockies. Use these models but remember the limitations to their application, especially to crown fires that occur for short periods of time or in areas different from the fuels and topography of the northern Rockies. The models for wind-driven and plume-dominated are far from absolute. They just provide an indication of the potential behavior and will encourage the analyst to consider possible crown fire behavior.

References

Albini, F. A. 1976. Computer-based models of wildland fire behavior: a user's manual. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 68 p.

Byram, G. 1959. Combustion of forest fuels. *In* Forest fire control and use. Kenneth P. Davis, ed. McGraw-Hill Book Co., New York. 61-89.

Rothermel, R. C. 1972. A mathematical model for predicting fire spread in wildland fuels. Res. Pap. INT-115. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 40 p.

Rothermel, R. C. 1991. Predicting behavior and size of crown fires in the northern Rocky Mountains. Res. Pap. INT-143. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 46 p.

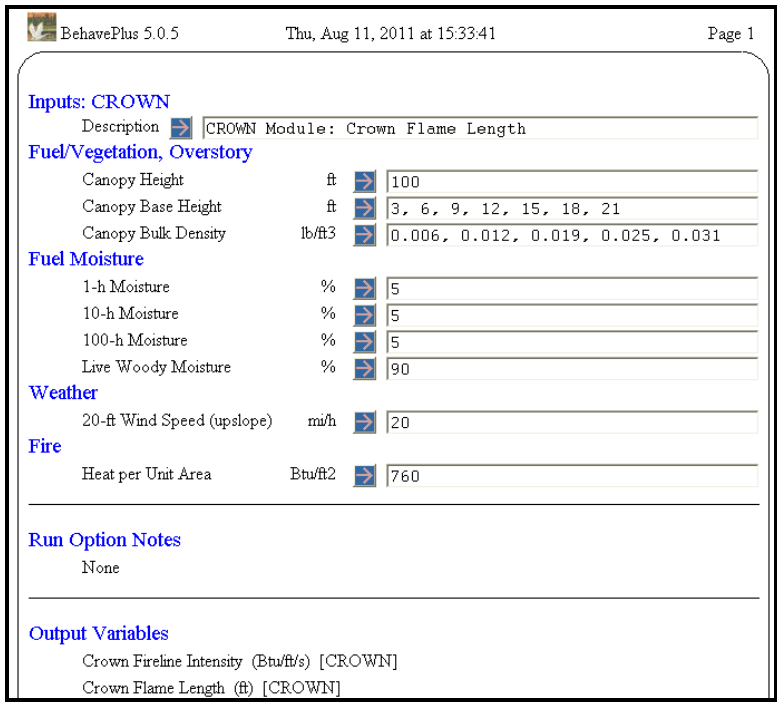
Thomas, P. H. 1963. The size of flames from natural fires. *In* Proceedings, 9th International Symposium on Combustion; 1962; Ithaca, NY: Academic Press: 844-859.

Van Wagner, C. E. 1977. Conditions for the start and spread of crown fire. Canadian Journal of Forest Research. 7:23-34.

Van Wagner, C. E. 1993. Prediction of crown fire behavior in two stands of jack pine. Canadian Journal of Forest Research. 23: 442-449.

Exercises

1. Returning to the Crown Flame Length calculation, which variables is it more sensitive to: Canopy Bulk Density, 1-h Moisture, 20-ft Wind Speed, or Heat per Unit Area? The Worksheet we used on page 20 of the lesson is shown below to get you started. Use your experience to determine typical ranges of values to test the model.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Inputs: CROWN

Description		CROWN Module: Crown Flame Length
Fuel/Vegetation, Overstory		
Canopy Height	ft	100
Canopy Base Height	ft	3, 6, 9, 12, 15, 18, 21
Canopy Bulk Density	lb/ft3	0.006, 0.012, 0.019, 0.025, 0.031
Fuel Moisture		
1-h Moisture	%	5
10-h Moisture	%	5
100-h Moisture	%	5
Live Woody Moisture	%	90
Weather		
20-ft Wind Speed (upslope)	mi/h	20
Fire		
Heat per Unit Area	Btu/ft2	760

Run Option Notes

None

Output Variables

Crown Fireline Intensity (Btu/ft/s) [CROWN]

Crown Flame Length (ft) [CROWN]

2. Given the following conditions, what 20-ft Wind Speed is required to produce a wind-driven crown fire in a mixed Douglas fir/lodgepole pine stand? Calculate the Heat per Unit Area using the SURFACE Module.

   - Fuel Model TU1 (Moderate load conifer litter)
   - Canopy Height = 60 ft
   - Canopy Base Height = 5 ft
   - Canopy Bulk Density = 0.0161 lb/ft^3
   - 1-h Moisture = 5%
   - 10-h Moisture = 6%
   - 100-h Moisture = 7%
   - Live Fuel Moistures = 100% (both Herbaceous and Woody)
   - 20-ft Wind Speed = ???