FOFEM 6.7

FIRST ORDER FIRE EFFECTS MODEL

USER GUIDE

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FIRE AND AVIATION MANAGEMENT
ROCKY MOUNTAIN RESEARCH STATION
FIRE MODELING INSTITUTE

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Cover artwork courtesy of Courtney Couch-Johnson

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Introduction

FOFEM - A First Order Fire Effects Model - is a computer program that was developed to meet needs of resource managers, planners, and analysts in predicting and planning for fire effects.

Quantitative predictions of fire effects are needed for planning prescribed fires that best accomplish resource needs, for impact assessment, and for long-range planning and policy development. We have developed the computer program FOFEM to meet this information need.

Much fire effects research has been conducted, but the results of this research have tended to be empirical, and thus limited in applicability to situations similar to those under which the research was conducted. Additionally, fire effects research results have not previously been assembled in a common format that is easily accessed and used, but rather have been scattered in a variety of journals and publications.

In developing FOFEM, we have searched the fire effects literature for predictive algorithms useful to managers. These algorithms have been screened to evaluate their predictions over a range of conditions. We also determined the conditions under which each is best suited to use by examining the documentation of these algorithms. Thus, a major internal component of FOFEM is a decision key that selects the best available algorithm for the conditions specified by a user.

In addition to selecting appropriate algorithms for users, we have also attempted to make these algorithms simple to apply; this has been done by incorporating the algorithms into an easy-to-use computer program. Realistic default values, documented in detail in this guide, have been provided for many inputs, minimizing the data required. These defaults were derived from a variety of research studies. Any of these default values can be overridden by the user, allowing the use of this program at different levels of resolution and knowledge.

We anticipate that FOFEM will be useful in a variety of situations. Examples include: setting acceptable upper and lower fuel moistures for conducting prescribed burns; determining the number of acres that may be burned on a given day without exceeding particulate emission limits; assessing effects of wildfire; developing timber salvage guidelines following wildfire; and comparing expected outcomes of alternative actions.

Significant version changes are provided in the Updates section.

Overview

First order fire effects are those that concern the direct or indirect or immediate consequences of fire. First order fire effects form an important basis for prediction secondary effects such as tree regeneration plant succession, and changes in site productivity, but these long-term effects generally involve interaction with many variables (for example, weather, animal use, insects, and disease) and are not predicted by this program. Currently, FOFEM provides quantitative fire effects information for tree mortality, fuel consumption mineral soil exposure, smoke and soil heating.

FOFEM is national in scope. It uses four geographical regions: Pacific West, Interior West, North East, and South East. Forest cover types provide an additional level of resolution within each region. Geographic regions and cover types are used both as part of the algorithm selection key, and also as a key to default input values.

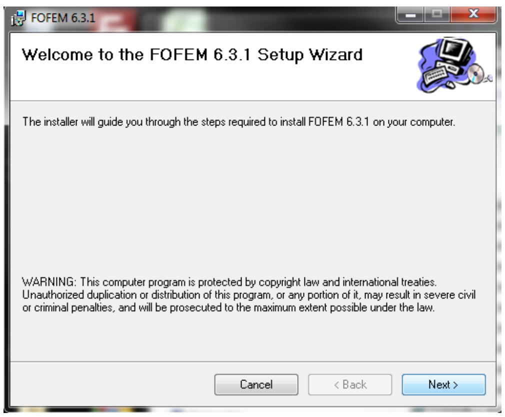
System Requirements

FOFEM6 will run on PCs running Windows 7, 8 or 10.

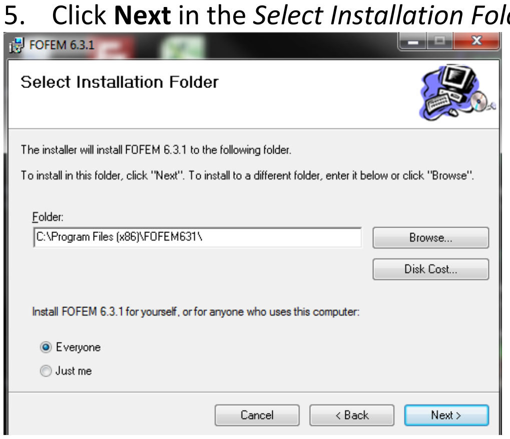
Installation

The FOFEM installation package can be downloaded from the Science Applications page on the Missoula Fire Sciences Lab website: www.firelab.org.

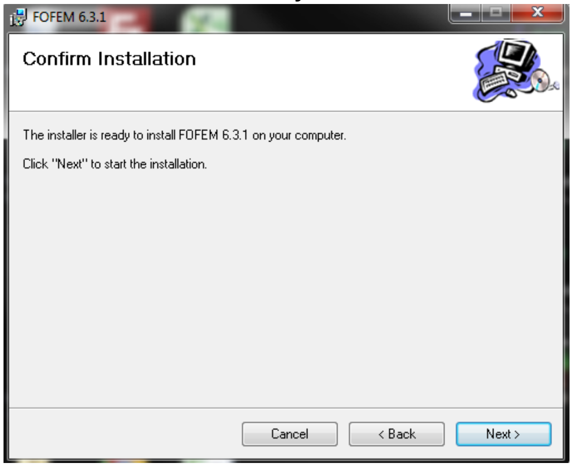
1. Download the installer package to a folder of your choice and unzip the contents of the file.
2. In Windows Explorer or My Computer navigate to the folder of unzipped FOFEM installation files. Double-click *Setup.exe*.
3. Click **Next** in the *Setup Wizard* window.
4.



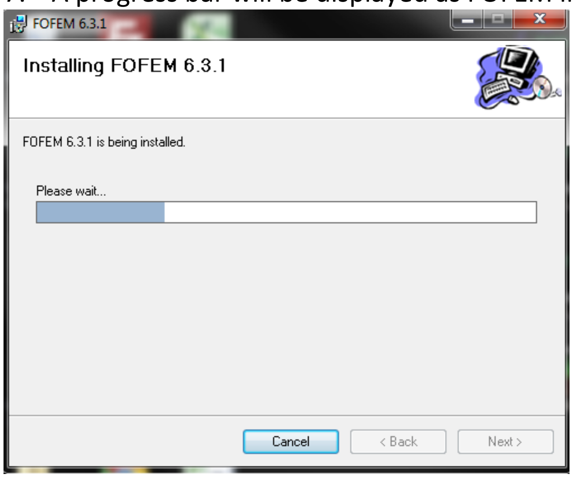
5. Click **Next** in the *Select Installation Folder* window.



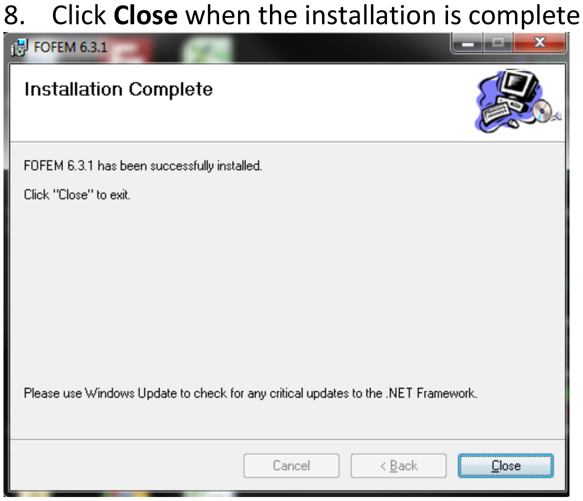
6. Click **Next** in the *Confirm Installation* window.



7. A progress bar will be displayed as FOFEM in being installed.



8. Click **Close** when the installation is complete.



Files will be placed in two folders:

C:\Program Files\FOFEM6.5 – program executable files

C:\Users\Username\AppData\Local\FOFEM6.5 – reference files and user files.

These files are added to the user folder when FOFEM is run the first time:

- *fofem.ini* – Initialization file.
- *CLB-FOFEM_Path.bat* – Batch file to set the path to the FOFEM install folder. Used when running FOFEM from the command line.
- *CLB-FOFEM-Run.bat* – Example DOS batch file. Used when running FOFEM from the command line.
- *FOF_SPP.CSV* – Links to species codes, mortality equations, bark thickness equations, region and crown coefficient. Space delimited.
- *FOF_NVCS.CSV* – Default fuel loading for NVCS types. Comma delimited.
- *FOF_FCCS.CSV* - Default fuel loading for FCCS fuelbeds. Comma delimited.
- *FOF_FLM.CSV* - Default fuel loading for FLM classes. Comma delimited.
- *FOF_SAF.CSV* - Default fuel loading for SAF/SRM types. Comma delimited.
- *fofem.prj* – Project file of saved settings.
- *Emission_Factors.csv* – Emissions factors. Comma delimited.
- *FFI_FOFEM_Sample.Tre* – Example FFI export file that includes tree data for mortality simulations.
- *FFI_Sample_Sample.FFI* - Example FFI export file that includes fuels data for consumption, emissions and soil heating simulations.

A good place to get started is Getting Started.

Features

- Graphics: Graphs are available for each of the major fire effects categories: tree mortality, fuel consumption, smoke, and soil heating. The graphs can be viewed in their respective graph windows and also be saved to file, printed or copied into the system clipboard.
- Reports: reports are available for fuel consumption, emissions, soil heating and tree mortality.
- Files: FOFEM provides a variety of options for saving data to files; include graphs, reports and other calculated outputs.
- Fuel Types: FOFEM provides default fuel loadings for SAF/SRM cover types; NVCS cover types and FCCS, FLM types and FFI data.
- Batch Processing: Multiple plots can be processed using input text files. See Batch Processing

  NOTE: FOFEM can also be used to run batch files from the system command line circumventing the GUI completely.

Modeling Approach

In developing the decision key to select algorithms, we were guided not only by the conditions under which an algorithm was developed, but also by a need to develop a model without sharp discontinuities or inconsistencies. This made algorithm selections, in some cases, a judgment call and it also led to the exclusion of some algorithms that may have performed well but in very restricted situations, or that require inputs not easily available to managers. Details about algorithms and their sources are documented in the Scientific Content sections of this guide.

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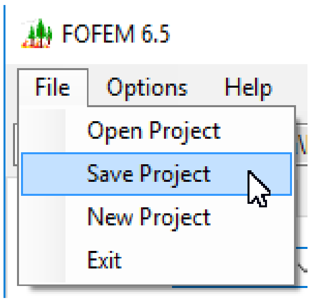
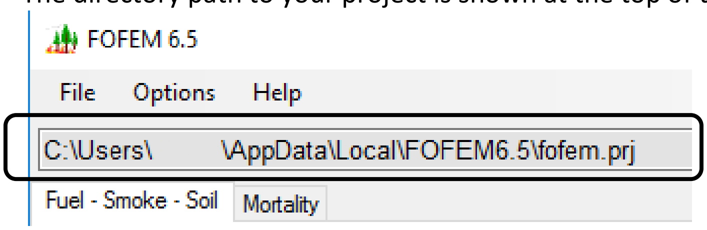
We would like to thank Tara Keyser and Mike Battaglia for their help with this version of FOFEM. We add them to the list of previous FOFEM contributors: Larry Gangi, Jeff Jones, Jim Reardon, Sharon Hood Tom Waldrop, Jim Brown, Wendel Hann, Dan Jimenez, Scott Mincemoyer, Kevin Ryan, Melanie Miller, Gaylon Campbell, Roger Hungerford, and Deb Tirmenstein. Courtney Couch provided the artwork used on the FOFEM splash screen.

Getting Started

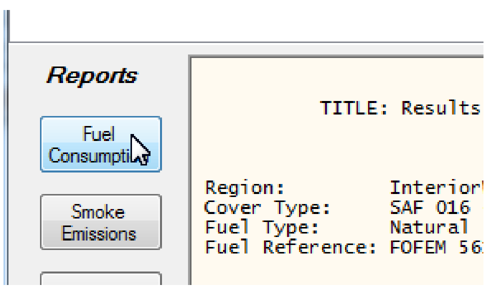
When you start FOFEM for the first time it will open using the default project file (with a PRJ extension), which is stored in your user folder *(C:\Users*username*\AppData\Local\FOFEM6.5*). You can choose a different project folder by selecting **File>Save Project** and navigating to a different directory. At any time during a FOFEM session you can save all of your settings to a file by selecting **File>Save Project**. Any number of project files can be saved.



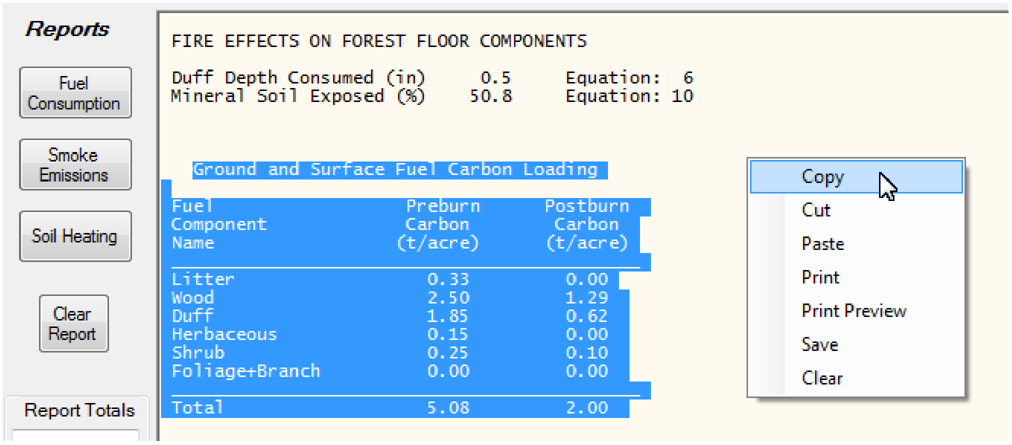
The directory path to your project is shown at the top of the FOFEM user interface.



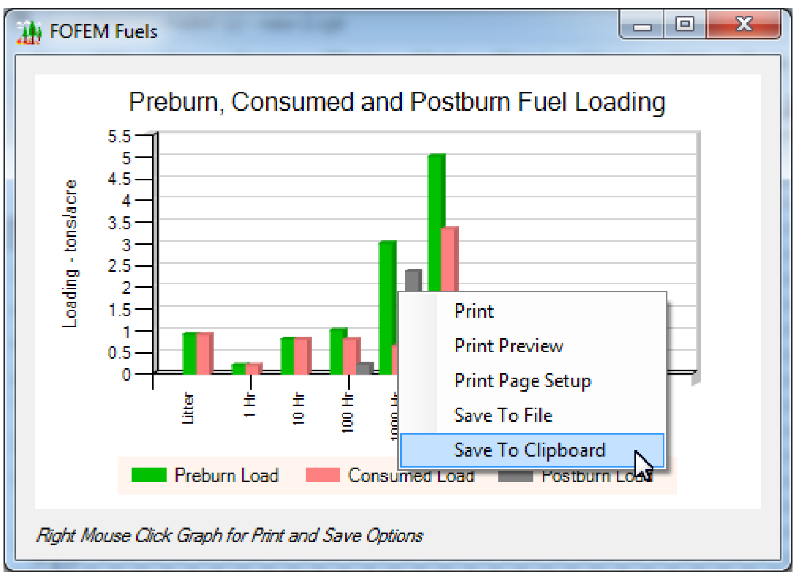
To create a report or graph make the desired settings for cover type, fuel moisture, etc. then click the desired button located on the right or left side of the user interface.



Report text can be moved into electronic documents using Copy/Paste commands. To copy report text, highlight the desired text, right-click in the report window and select **Copy**. Then open your document and use the paste command to move the selected text. You can also print reports.



Graphs can also be copied or printed using right-click commands.



Setting a Work Folder

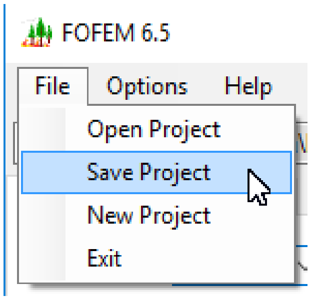
Your work folder is the folder that contains your active project file. When you start FOFEM your work folder using the last project file you were working with. The work folder path and project file name are always shown at the top of the user interface. The suggested work folder path is: *C:\Users*\username*\AppData\Local\FOFEM6.5*.

There are two ways to set your work folder, under the main menu option Project:

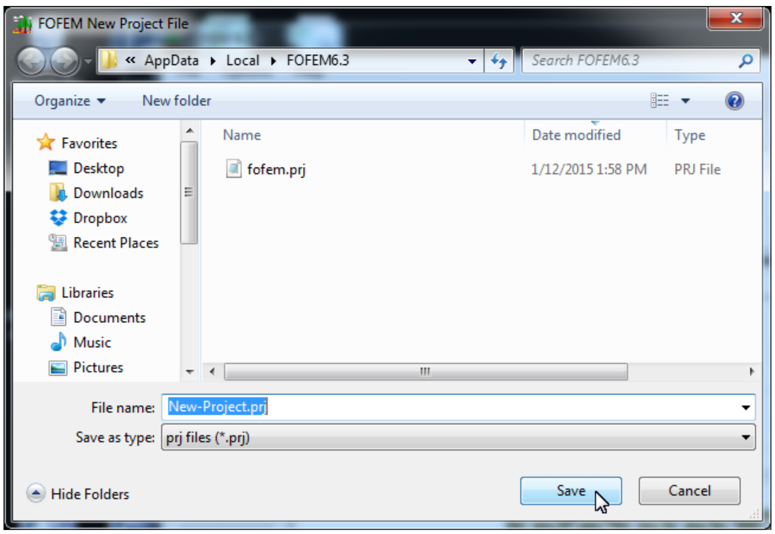
1. **Open Project** - opens a project file
2. **New Project** - creates a new project file

If you move to a different folder when doing one of the above you will change your work folder.

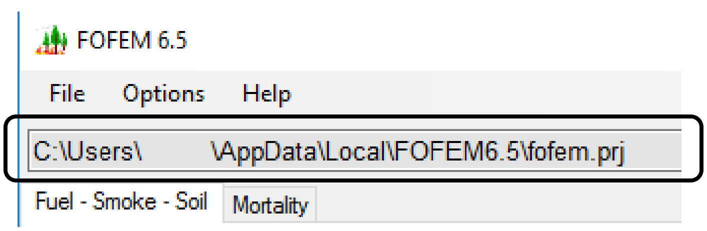
Select **File>New Project** from the main menu.



Select a project name and directory for your new project and click **Save**.



The project name and file path will be displayed at the top of the user interface.

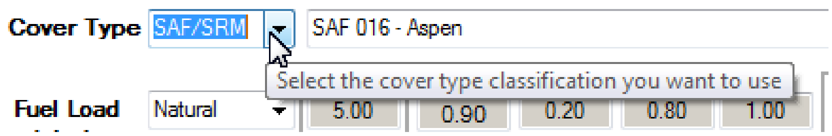


General Rule

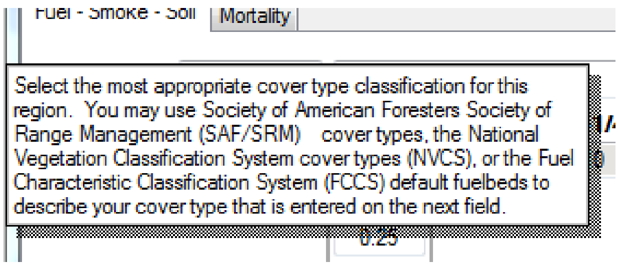
You should always check all of your screen settings before creating any report or graph. Whenever you make a change to a screen setting it can affect other screen settings or values, for example changing *Moisture* regime effects percent moisture for four fuel components. Some user entered values may also change or remain the same as other settings are changed and adjusted. This document attempts to explain the rules, but the easiest rule to remember is the one mentioned above – always review all of your screen settings before you create a reports or graphs.

Getting Help

FOFEM has a variety of ways for you to get help. Most of the controls on the main window have a small Tool Tip textbox that will appear when you move and hold the cursor over them.



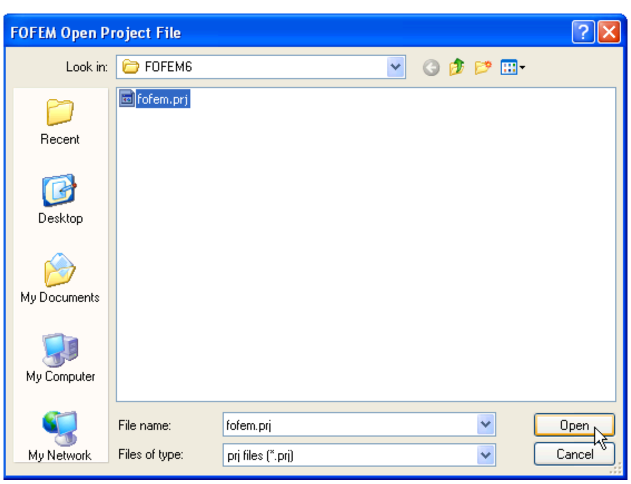
The F1 function key can also be used to give you more detailed help. Mouse click in the field next to the label you are interested in (for example, in the *Cover Type* field.), hit the F1 key and a small dialog box will pop up with the help text in it.



This document is the third source of help. Aside from just explaining how to use FOFEM it contains other content such as modeling approach, scientific content, and references.

Open & Save File Window

Whenever you save or open a file in FOFEM you'll be using a window like the one shown below, the only difference being the title and the file type(s). The example shown below is for opening a project file, which uses the file PRJ extension. The window allows you to navigate to folders, create folders, etc., it also selectively shows you particular files types.

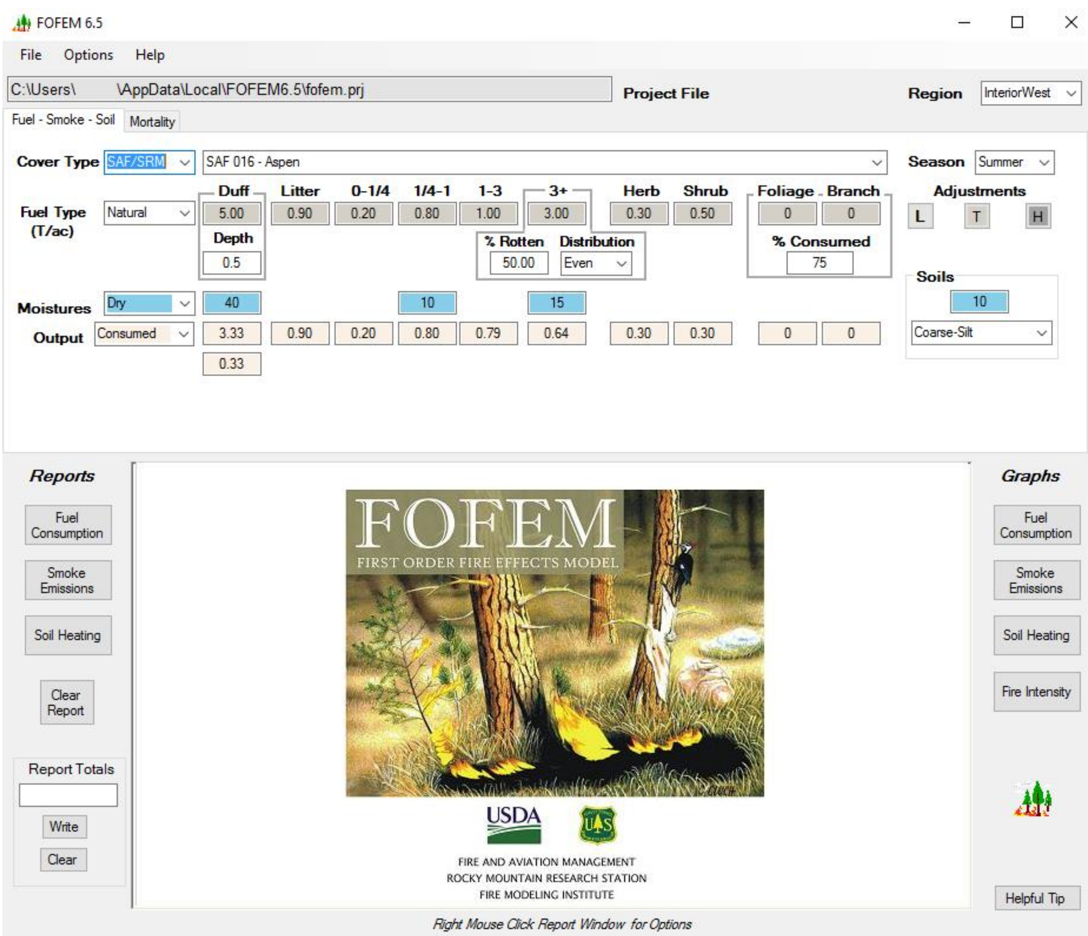


Main FOFEM Window

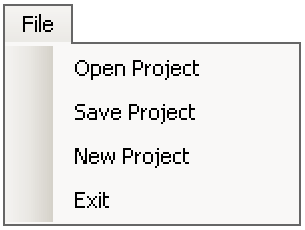
Main Window

The FOFEM window has three sections:

1. The upper section contains the main menu and FOFEM header dropdown list. See Main Menu - File, Main Menu – Options, and FOFEM Header
2. The middle section contains the Fuel-Smoke-Soil Tab and Mortality Tab. Click on the tab for the model you wish to run, the screen shot below has the former tab selected.
3. The bottom section contains buttons for creating reports and graphs, and a large text area where the reports are placed. Graphs are opened in a separate window and can be copied, saved or printed.



Main Menu - File



A project file is a snapshot of all the FOFEM screen settings captured directly from the screen and saved to a file. This is done by using the **Save Project** menu item. By saving your settings in a project file you can restore them at any time by using the **Open Project** menu item. Any number of project files can be saved. Your active (current) project file is always shown in the **Project File** field. The folder that contains you active project file is you Work folder. The Work folder is your default folder for opening and saving files.

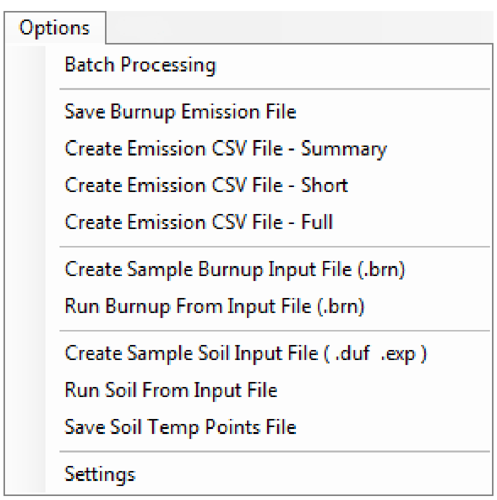
Open Project: Open a project file. The Work folder will get set to the folder where the project file is located. If you go to a different folder to open a project file, it will become your new Work folder and it will be shown in the Project File field.

Save Project: Save will only save your screen settings to a project file, it will not change your Work folder setting. However you can save project files to any folder you choose.

New Project: Save the screen setting to a project file and in addition place the project file's folder and name in the Project File field

Exit: Exit FOFEM. Make sure you save any of you work of project file before you exit.

Main Menu – Options



Batch Processing: Run FOFEM models using input files with multiple plots. See Batch Processing for details.

Save Burnup Emission File: The Burnup model in FOFEM can produce a smoke emissions file, which can be exported to a spreadsheet for graphing. The file is a text file and shows emissions across time. See Sample Burnup Output Files

Create Emissions CSV File – Summary: This comma delimited file includes emissions and the emission factors for flaming/short-term smoldering, coarse wood residual smoldering component, duff residual smoldering component and total emissions for 204 smoke components. Units shown in parenthesis can be changed on the Settings window.

Label	Description
Emis-Code	Emissions component code
Name	Name of emissions component
STFS-Emis	Short-term flaming and smoldering emissions (lbs/ac, T/ac or g/m^2)
CWDRSC-Emis	Coarse woody debris residual smoldering component emissions (lbs/ac, T/ac or g/m^2)
DuffRSC-Emis	Duff residual smoldering component emissions (lbs/ac, T/ac or g/m^2)
Total-Emis	Total emissions (lbs/ac, T/ac or g/m^2)
STFS-EF	Emissions factor used to calculate STFS emissions (lbs/T or g/kg)
CWDRSC-EF	Emissions factor used to calculate coarse woody debris residual smoldering component emissions (lbs/T or g/kg)
DuffRSC-EF	Emissions factor used to calculate duff residual smoldering component emissions (lbs/T or g/kg)

Create Emissions CSV File – Short: The file includes information reported at every time step. Units shown in parenthesis can be changed on the Settings window.

Label	Description
Time	Time since fire initiation at end of time step (seconds)
Fire-Intensity	Reaction intensity (kW/m^2)
Flame-Con	Emissions from consumed fuels assigned flaming and short-term smoldering emission factors during the time step; includes litter, 1Hr, 10Hr, 100Hr, herb, shrub, foliage, branch and, when intensity >15 kW/m^2, coarse wood (1kHr). (lbs/ac, T/ac or kg/m^2)
Coarse-Con	Emissions from consumed coarse wood (1kHr) during the time step when intensity <15 kW/m^2. (lbs/ac, T/ac or kg/m^2)
Duff-Con	Emissions from consumed duff during the time step. (lbs/ac, T/ac or kg/m^2)
Litter-Fuel	Litter fuel load at beginning of time step. (lbs/ac, T/ac or kg/m^2)
Litter-Con	Litter load consumed during time step. (lbs/ac, T/ac or kg/m^2)
1Hr-Fuel	1Hr fuel load at beginning of time step. (lbs/ac, T/ac or kg/m^2)
1Hr-Con	1Hr load consumed during time step. (lbs/ac, T/ac or kg/m^2)
10Hr-Fuel	10Hr fuel load at beginning of time step. (lbs/ac, T/ac or kg/m^2)
10Hr-Con	10Hr load consumed during time step. (lsb/ac, T/ac or kg/m^2)
100Hr-Fuel	100Hr fuel load at beginning of time step. (lbs/ac, T/ac or kg/m^2)
100Hr-Con	100Hr load consumed during time step. (lbs/ac, T/ac or kg/m^2)
1kHr-Fuel	>3” (1000Hr) fuel load at beginning of time step. (lbs/ac, T/ac or kg/m^2)
1kHr-Con	>3” (1000Hr) load consumed during time step. (lbs/ac, T/ac or kg/m^2)
CO2	Carbon dioxide emitted during time step. (lbs/ac, T/ac or g/m^2)
CO	Carbon monoxide emitted during time step. (lbs/ac, T/ac or g/m^2)
CH4	Methane emitted during time step. (lbs/ac, T/ac or g/m^2)
NOx as NO	Nitrogen oxide emitted during time step. (lbs/ac, T/ac or g/m^2)
SO2	Sulfur dioxide emitted during time step. (lbs/ac, T/ac or g/m^2)

PM2.5	Particulate matter less than 2.5 micrometers emitted during time step. (lbs/ac, T/ac or g/m^2)
PM10	Particulate matter less than 10 micrometers emitted during time step. (lbs/ac, T/ac or g/m^2)

Create Emissions CSV File – Full: Same information as the *CSV – Short* file but includes an additional 197 smoke components.

Create Sample Burnup Input File: See notes above for menu item Run Burnup from Input File. See Sample Burnup Input File

Run Burnup from Input File: This option lets you run Burnup from an input text file to create two output files. Output files show predicted fuel consumption and smoke emissions. You can create a sample input file by using the Create Sample Burnup Input File menu item below. For more details see Running Burnup from an input File

Create Sample Soil Input Files: Create sample files to run the soil heating model from a soil input file. If there is no duff the sample file will have an *.exp* extension and will run the no-duff soil heating model. The file will include the duff heating efficiency set on the Settings menu. If duff load is greater than zero the example file will have a *.duf* extension and will run the duff soil heating model. The file will include the woody fuels and litter heat efficiency, and herb and shrub heat efficiency set on the Settings menu. See Scientific Content–Soil Heating for more details.

Run Soil from Input File: This option lets you create a soil heating graph using a text file as input. You can create sample input files for templates using the *Create Sample Soil Input Files* menu item below. The samples files contain comments to explain the file contents. See Scientific Content–Soil Heating for more details.

Save Soil Temp Points File: Creates a text file containing a table of temperature. This file can be used with other graphing software. Before using this option you will need to create a soil graph. For more details see Output Graphing File.

Settings: This window allows you to change units for emissions and change other simulation settings. These settings are not saved in the project file.

NOTE: If non-default settings are desired they must be set every time FOFEM Is opened.

Emissions Output Unit – Set units in the Smoke Emissions report. Available units are *lbs/ac* (default), *Tons/acre* or *g/m^2*

Duff Heat Production Source – Set heat content of burning duff.

Production Source	Heat of combustion (Mj/kg)	Note
PeatLow	15	Default. Used in previous versions of FOFEM
PeatHigh	20	
DuffLow	25	
DuffHigh	30	

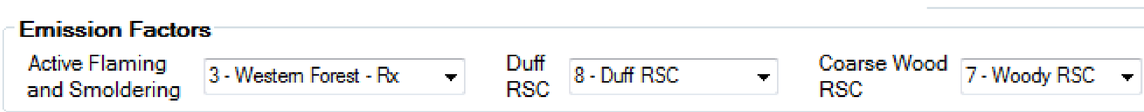
Values based on: *Frandsen, W.H. 1991. Heat evolved from Smoldering Peat. Int. J. Wildland Fire l(3): 197-204*

Heat Efficiency – The proportion of heat intensity that is directed to the soil for determining soil heating. The components are *Duff*, *W/L* (woody fuels and litter) and *H/S* (herb and shrub). Default values provided next to each field are the values used in previous versions of FOFEM.

Emissions Factors – Select the Default or the Expanded Emissions Factors.

Default emission factors are described in the Scientific Content–Smoke Emissions–Default Emission Factors

When the *Expanded* emission factors radio button is selected, fields for setting the emission factors are added to the user interface.



Additionally, FOFEM will make two changes to the way emissions are estimated:

1) Emission factors used for calculating emissions are read from the *Emission_Factors.csv* file found here: *C:\Users\...\AppData\Local\FOFEM6.5*. The *Emission_Factors.csv* file includes emissions factors for over 200 smoke components (compared to seven smoke components in the default emission logic).

2) FOFEM will use different logic for estimating emissions. Most fuels are assumed to be consumed early in the fire with emissions from the flaming and smoldering phases of combustion entrained in the plume. Post frontal consumption of duff and large woody material are consumed in the smoldering phase of combustion.

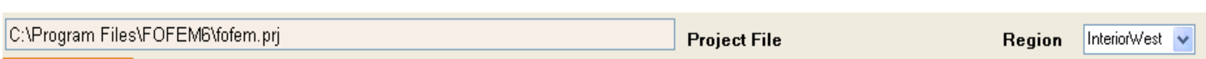
See the Scientific Content–Smoke Emissions–Expanded Emission Factors section for more information.

FOFEM Header

Project File

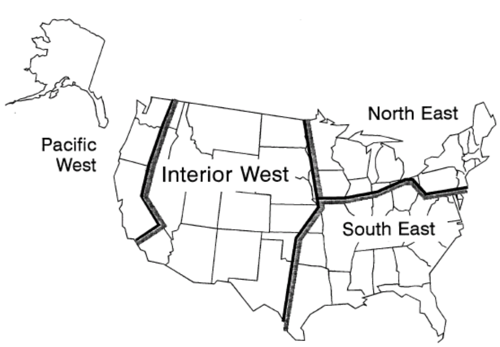
The Project window displays the active (current) project file.

The window also lets you know what your Work folder is by showing the full folder path.



Region

The region you select will determine the availability of cover types and tree species, and which consumption and mortality equations are used.



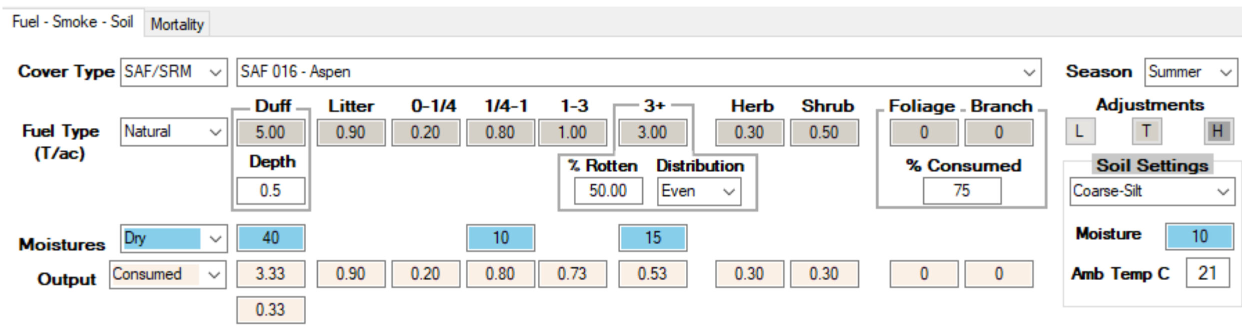
Select a region that is appropriate for you project.

1. Interior West
2. Pacific West
3. North East
4. South East

Fuel-Smoke-Soil Tab

This tab located on the main FOFEM window contains all of the inputs needed to calculate fuel consumption, smoke/emissions and soil heating outputs.

Interface



Cover Type: The smaller dropdown list field contains the Cover Type Classification and the larger dropdown list field contains the fuelbed code and name.

NOTE: Only cover types that are relevant to the Region you have selected will be loaded.

Season: For setting the of the burn: Spring, Summer, Fall, Winter. The selection of some FOFEM model equation is dependent on the season selection. See Decision Dependency.

Fuel Type: The dropdown list on the left let you set the whether the fuels were Natural or Slash. The selection modifies of the fuel loading of the fuel components to the right. Depending on the cover classification you have selected, not all cover types will have adjustments. See Cover Type Classification.

Duff, Litter, 0-1/4, … Branch: These are the individual fuel loadings for the cover type you have selected are placed in this row of textboxes. Right-clicking a fuel cell displays options for setting the individual fuel loading value: Light, Typical, Heavy, User. The background color of the cell will change based on the setting.

Adjustments: Clicking these buttons will adjust fuel loadings for all fuel components. The number of buttons shown is dependent upon the selected cover classification. The single letter on each button indicates the adjustment - **L**ight, **T**ypical and **H**eavy

Depth: Duff depth. When selecting a 'User' value for duff load duff depth is initially set to duff load *0.10.

% Rotten: The amount of 3+ inch fuel that is rotten.

Distribution: 3+ inch log loading distribution, see the Distribution table.

% Consumed: The percent of Foliage and Branch fuels that you want to be consumed will be based on this percentage.

*NOTE: The entered percent is directly applied to the foliage, but only 50 percent is applied to branch. That is ….for decimal percentage N, then Consumed foliage = foliage load * N, Consumed Branch = branch load * (N * 0.50)*

Moistures: Default moisture regimes are available in the dropdown: Wet, Moderate, Dry, Very Dry. The values are user editable by highlighting the value in the textbox and typing in a new value. Fuel moistures values are gravimetric fuel moisture. See Moisture Regime.

NOTE: When duff moisture is set to 10% (lowest valid moisture) all duff will be consumed regardless of what FOFEM's assigned duff equation predicts. This is helpful when doing soil simulations in that it will allow the heat from all burning material to reach the soil.

NOTE: The Burnup model simulates consumption of woody fuels. In Burnup, litter and 0 – ¼ inch (1-hr) fuel moisture is 2% lower than the ¼ – 1 inch (10-hr) moisture. 1 – 3 inch (100-hr) fuel moisture is 2% higher than the ¼ – 1 inch (10-hr) moisture.

Output: Select the calculated values you want shown in the textboxes at the right: Consumed, Post, Consumed %. This setting does not affect the reports or graphs.

Soil Moist / Type: this setting modifies heat transfer through the soil and can be set to these soil families: Loamy Skeletal, Fine-Silt, Fine, Coarse-Silt, Coarse-Loamy. Soil moisture is user editable by highlighting the value in the textbox and typing in a new value. Soil moisture in volumetric soil moisture. If you aren't interesting in soil heating outputs then these settings are not used for simulating consumption or emissions.

Amb Temp C: Ambient air temperature in degrees Celsius. The value is only used in soil simulations.

Cover Type Classification

Set this box according to the cover type classifications you want to use.

You have five choices.

1. SAF/SRM – Society of American Foresters/Society for Range Management
2. NVCS – National Vegetation Classification System
3. FCCS – Fuel Characteristic Classification System
4. FLM – Fuel Loading Models
5. FFI – Data file exported from FFI

Selecting FCCS or FLM cover type will cause the low (L) and high (H) fuel load adjustment buttons to disappear because these classes do not have adjustment codes associated with them.

NOTE: FCCS coarse woody fuel loadings are stored (see fof_fccs.csv file), in six size and decay classes (sound and rotten; 3–9 in., 9–20 in., and >20 in). When the Cover Type classification is set to FCCS FOFEM shows one total 3+ loading on the user interface along with a calculated rotten percentage and a "Fixed' log load distribution but when fuel consumption is calculated the individual size classes are used behind the scenes. If you do choose to change an FCCS fuel load, percent rotten or log load distribution, FOFEM will use the percent rotten and log load distributing as shown on the screen.

NOTE: The list of FCCS fuelbeds and associated component fuel loads was current as of 5/2016. For more information about FCCS see http://www.fs.fed.us/pnw/fera/fccs/.

NOTE: For more information about FLMs see:

Lutes, DC; Keane, RE; Caratti, JF. (2009). A surface fuel classification for estimating fire effects. International Journal of Wildland Fire 18: 802-814

Sikkink, Pamela G.; Lutes, Duncan C.; Keane, Robert E. 2009. Field guide for identifying fuel loading models. Gen. Tech. Rep. RMRS-GTR-225. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 33 p.

Outputs

The bottom half of the Fuel – Smoke – Soil window is where you produce reports and graphs.

To create a **Report** click any one of the buttons on the left and a report will be placed in the Report window. Each time a button is clicked a new report is added to the end of the report, scroll down in the text window to see it. You can right-click to *Copy*, *Cut*, *Paste*, *Print*, *Save* or *Clear*.

Reports

Fuel Consumption Report

The top section of this report shows the input settings that you have selected for Region, Cover Type, etc. The next section of the report shows each fuel components. For the 3+ inch fuel loading each individual size class is shown as well as total, the size classes are broken up according the Log Distribution setting you selected on the main window. If you adjusted any of the fuel loadings you will see the characters “u”, “+”, or “-“ to designate the type of adjustment as noted at the bottom of the report.

Equation Reference Numbers are described in the Scientific Content section for the applicable fuel component.

TITLE: Results of FOFEM model execution on date: 10/1/2012

FUEL CONSUMPTION CALCULATIONS

Region: PacificWest
Cover Type: SRM 210 - Bitterbrush
Fuel Type: Natural
Fuel Reference: PMS-830

FUEL CONSUMPTION TABLE

Fuel Component Name	Preburn Load (t/acre)	Consumed Load (t/acre)	Postburn Load (t/acre)	Percent Reduced (%)	Equation Reference Number	Moist. (%)
Litter	0.60 u	0.60	0.00	100.0	999	
Wood (0-1/4 inch)	0.15 +	0.15	0.00	100.0	999	
Wood (1/4-1 inch)	0.06	0.06	0.00	100.0	999	10.0
Wood (1-3 inch)	3.00 u	2.29	0.71	76.5	999	
Wood (3+ inch) Sound	3.50 u	0.49	3.01	14.0	999	15.0
3->6	0.88	0.28	0.59	32.4		
6->9	0.88	0.12	0.76	13.6		
9->20	0.88	0.06	0.81	7.2		
20->	0.88	0.03	0.85	2.9		
Wood (3+ inch) Rotten	3.50 u	0.94	2.56	26.8	999	15.0
3->6	0.88	0.46	0.42	52.5		
6->9	0.88	0.26	0.61	30.1		
9->20	0.88	0.15	0.73	17.1		
20->	0.88	0.07	0.81	7.6		
Duff	1.00 u	0.67	0.33	66.7	2	40.0
Herbaceous	0.44	0.44	0.00	100.0	22	
Shrubs	1.25 -	1.00	0.25	80.0	231	
Crown foliage	2.00 u	1.50	0.50	75.0	37	
Crown branchwood	1.00 u	0.38	0.63	37.5	38	
Total Fuels	16.50	8.52	7.98	51.6		

'u' Preburn Load is User adjusted
'+' Preburn Load is Heavy/Abundant
'-' Preburn Load is Light/Sparse

The bottom section of the report contains the fire effects on the forest floor and carbon loadings.

FIRE EFFECTS ON FOREST FLOOR
Mineral Soil Exposed (%) 50.8 Equation: 10

Ground and Surface Fuel Carbon Loading

Fuel Component Name	Preburn Carbon (T/ac)	Postburn Carbon (T/ac)
Litter	0.44	0.00
Wood	5.30	1.38
Duff	9.25	3.08
Herbaceous	0.08	0.00
Shrub	0.13	0.05
Foliage+Branch	5.60	2.00
Total	20.80	6.52

Smoke Emission Report

Emission amounts for each component are shown for flaming and smoldering. Units can be set on the Settings menu. See the Scientific Content – Smoke Emissions sections for more information about emissions production in the two modeled phases. Additionally, consumption by phase and burnout time for fuels simulated in Burnup are report in the bottom two tables.

```
          TITLE: Results of FOFEM model execution on date: 7/25/2018

                   FUEL EMISSIONS CALCULATIONS

Region:         NorthEast
Cover Type:     SAF 001 - Jack Pine
Fuel Type:      Natural
Fuel Reference: FOFEM 121


                      Emissions   -- lb/ac
                     flaming      smoldering       total
--------------------------------------------------------------
   CO 2              218778         21726         240504
   CO                   802          5338           6140
   CH 4                  98           243            341
   NOX                  394             0            394
   SO2                  123            18            141
   PM 2.5               320           401            721
   PM 10                378           473            851
--------------------------------------------------------------

                                   Consumption      Duration
                                      T/ac     hour:min:sec
flaming & short term smoldering:      61.51        00:17:45
            residual smoldering:       8.84        02:23:45
                         Total:       70.35

                             Burnout Time
                       Component   hour:min:sec  total seconds
                        Litter       00:01:00         60
                        1 Hour       00:01:15         75
                        10 Hour      00:04:45        285
                        100 Hour     00:26:15       1575
                        1000 Hour    02:23:30       8610
                        Duff         00:19:45       1185
```

Soil Heating Report

If selecting the Massman soil model option, you will be prompted to run the Massman model which can take a few minutes. You must run a Massman graph each time you create a Massman soil report. See the Scientific Content – Soil Heating section for more information about the Campbell and Massman soil models.

Soil Layer Maximum Temperature: the table shows the maximum temperatures that were reached at each layer.

```
                        Soil Heat Report

Region:          InteriorWest
Cover Type:      SAF 213 - Grand Fir
Fuel Type:       Natural
Fuel Reference: FOFEM 071
Duff Depth.....: Pre-Fire:   3.56 cm.,  Post-Fire:   0.73 cm.

                     Soil Layer Maximum Temperature

Depth (cm)    0    1    2    3    4    5    6    7    8    9   10   11   12   13
Temp (C)    223  173  129   99   73   68   63   57   52   46   40   33   27   21
Time (min)  165  176  209  221  223  227  238  248  257  265  272  277  280    1

Max Depth Having 60 degrees: 6
Max Depth Having 275 degrees: - None -
```

Depth: Layers are in one-centimeter increments starting with the surface being 0

Temp: The maximum temperature (Celsius) that the layer reached

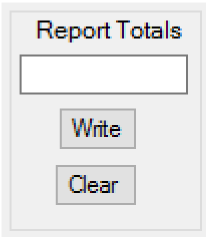
Time: How many minutes it took to reach the layer's maximum temperature

NOTE: The number 1 means that no heat from the fire reached the layer as shown at the 13 cm layer.

Max Depth Having 60/275 degrees: The deepest layers to reach 60 and 275 degrees. This example shows that the deepest layer to reach 60 degrees was 7 cm. This example also shows that there were no layers reaching 275 degrees, including the surface, so the word "None" is shown.

Report Totals

This option allows you to report results from multiple FOFEM simulations in a summary table format. To create a summary report type a simulation name in the textbox and click one of the report buttons. Add successive reports by entering a new name and clicking the report button again. When you have completed all the simulations you want to compare click the **Write** button and the results will be placed into the report. Hit the **Clear** button to clear all of the stored totals.



Summary reports provide a quick way to compare simulation results at various prescriptions. The example summary report below shows totals taken from two smoke emissions reports (because emissions are closely tied to consumption a fuel consumption summary report is included with the emissions summary report).

Report Totals:

Fuel Consumption Summary - (T/ac)

Id	Litter	Wood 0->1/4	Wood 1/4->1	Wood 1->3	Wood 3+	Duff	Herb	Shrub	Crown Folge	Crown Brnch
VeryDry	1.20	0.56	0.75	2.30	4.64	18.80	0.15	0.15	1.20	6.00
Dry	1.20	0.56	0.75	2.30	4.23	16.67	0.15	0.15	1.20	6.00

Report Totals:

Smoke Emission Summary (lb/ac)

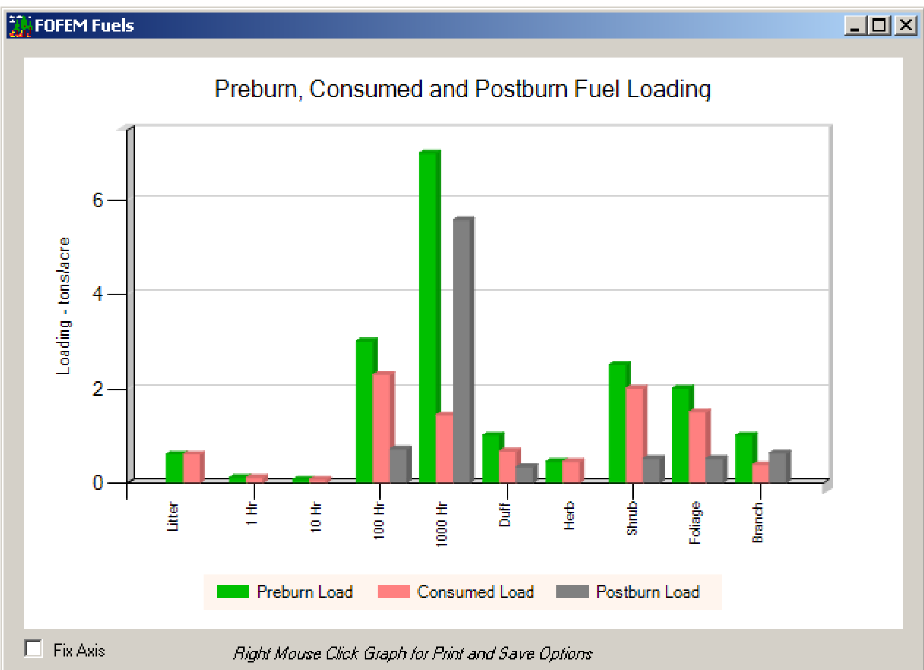
Id	PM10	PM2.5	CH4	CO	CO2	NOX	SO2
VeryDry	1465.3	1241.8	739.6	16015.1	98174.8	60.3	71.5
Dry	1331.2	1128.1	670.6	14502.8	91907.5	60.1	66.4

The example was created by running two emissions reports and naming each based on the moisture regime setting selected. The first report was named “VeryDry” and the second emissions report was named “Dry”. The summary report was produced by clicking the **Write** button.

Graphs

To create a **Graph** click the buttons on the right side and a window will pop up with the graph. You can leave the graph windows open and watch them change as you modify your inputs on the main window.

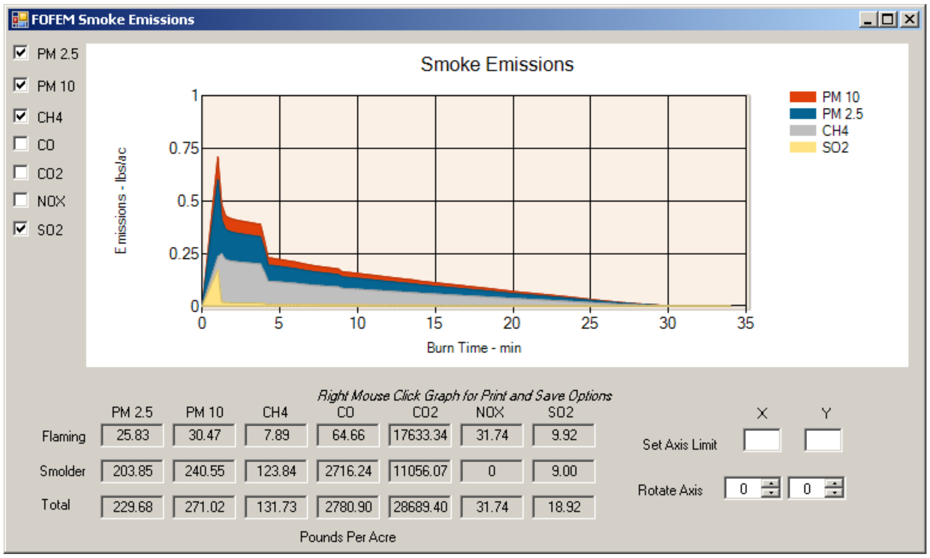
Fuel Consumption Graph



The graph shows the pre-burn load, the amount consumed and the post-burn load amount.

Fix Axis: The graph will readjust the Y axis whenever you change an input on the main window. You can prevent this from occurring by clicking this checkbox. This can be handy if you are trying to compare outputs. Clicking the box will freeze the scale of the Y axis. Uncheck the box and the FOFEM will set the axis automatically.

Smoke Emissions Graph



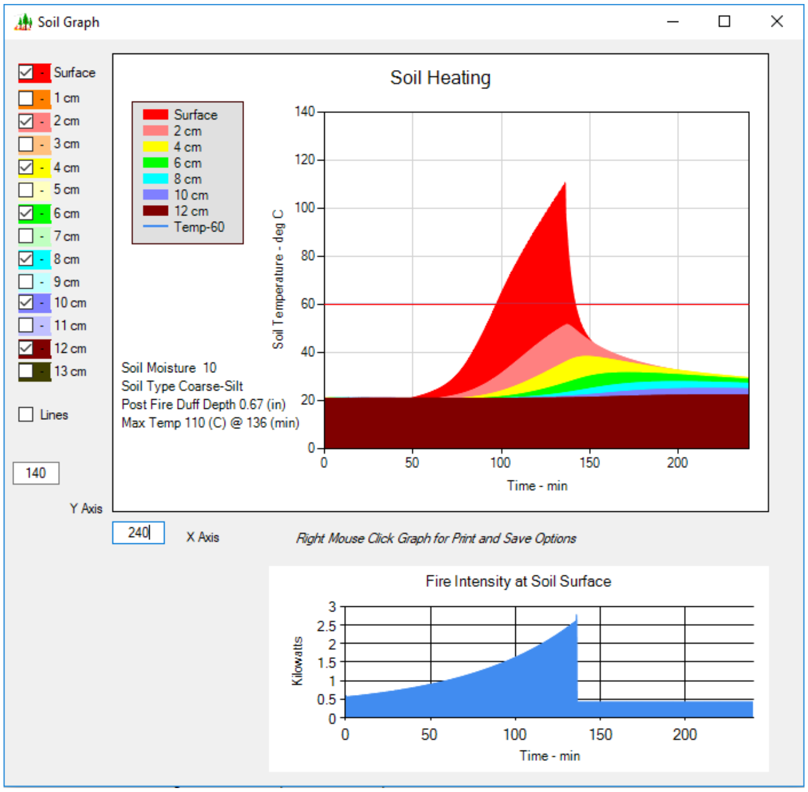
The graph displays the rate which components are being emitted. By selecting the checkboxes on the left you can show one or more of the emission components.

Set Axis Limit: To limit the X or Y axis, enter a number in the textbox and hit the return key. If no values are entered FOFEM will automatically set them

Rotate Axis: The graph can also be rotated on either or both axis using the up/down boxes.

Soil Heating Graph

Campbell Model



Right-click the window to *Save* or *Print*.

Soil Temperature graph: The top graph shows soil temperatures (C) for each selected layer (cm) over time (min.).

Fire Intensity graph: The intensity graph at the bottom displays intensity (kW/m^2) at the soil surface over time (min.). This is the proportion of the total reaction intensity used by the soil heating models. When there is duff present the intensity comes entirely from the burning duff. When duff is present the intensity comes entirely from the burning duff. When there is no duff then graphed intensity is a proportion of the total woody fuel, litter, herb and shrub combustion intensity. Settings for these values can be changed on the **Settings** page. See Duff Heat Production Source and Heat Efficiency.

Soil Depth: Soil temperature at the selected depths will be included on the graph.

Post Fire Duff Depth: Specifies the amount of duff depth that is remaining after a simulated fire.

Max Temp xx @ min xx: The maximum temperature and the time in minutes that it was reached. This number represents the layer closest to the surface that is selected (checked) in the layer checkboxes.

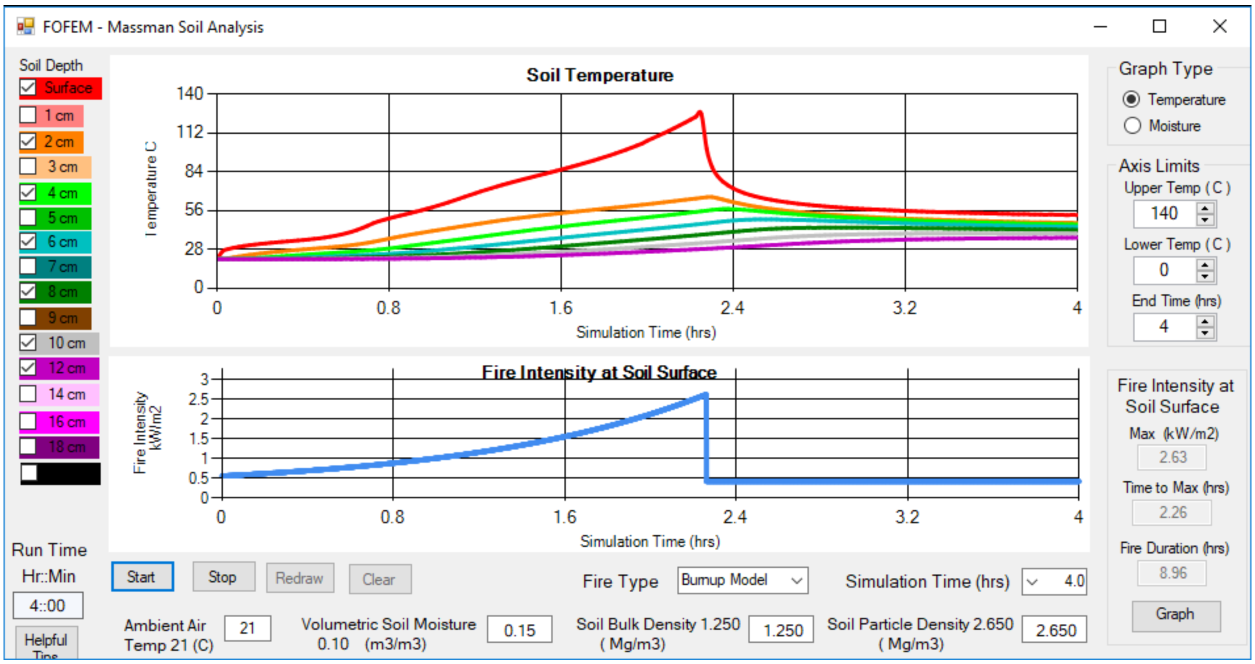
Lines: Selecting this checkbox will show the graph in line form.

Y Axis, X Axis: Used to limit the axis enter a number and hit the return key, otherwise FOFEM will automatically set them.

NOTE: When doing soil heating simulations, you should be aware that the amount of duff consumed is an important factor and that some duff reduction equations may never allow *complete combustion of duff. However, FOFEM allows you to force duff consumption of 100 percent – please see [notes related to moisture and duff](#).*

Massman Model

Set **Soil Depths**, **Simulation Time**, **End Time**, **Fire Type**, etc. as desired and click *Start*. At the end of the **Simulation Time** a window will display the simulation time and path where the soil temperature and soil moisture files have been saved. Click *Stop* to stop the simulation at any time. The soil temperature and soil moisture files will only include information to the time the simulation was stopped, not to the time shown in the **Simulation Time** field. The Massman soil report will also only include the information up to the time the simulation was stopped.



Soil Temperature graph: The top graph shows soil temperatures (C) for each selected layer (cm) over time (hrs.).

Fire Intensity graph: The intensity graph at the bottom displays intensity (kW/m^2) at the soil surface over time (hrs). This is the proportion of the total reaction intensity used by the soil heating models. When duff is present the intensity comes entirely from the burning duff. When there is no duff then graphed intensity is a proportion of the total woody fuel, litter, herb and shrub combustion intensity. Settings for these values can be changed on the **Settings** page. See [Duff Heat Production Source](#) and [Heat Efficiency](#).

Soil Depth: Soil temperature or moisture at the selected depths will be included on the graph.

NOTE: The model runs slower as more depths are added to the graph.

Graph Type: Display either soil temperature or soil moisture graph. Either graph can be displayed during or after completing a simulation by clicking the desired radio button.

Axis Limits: Set the range of temperatures to be shown on the graph (y-axis). During a simulation or after it is complete, the axis limits can be changed. Click the *Redraw* button to update the graph. The simulation will not be re-run.

End Time (hrs): Set the length of time (x-axis) on the graph. Soil temperature and moisture are modeled at 3-second intervals but plotted in 15-minute timesteps. During a simulation or after it is complete, the **End Time** can be changed. Click the *Redraw* button to update the graph. The simulation will not be re-run.

Ambient Air Temp (*C*): Ambient air temperature. Default is 21 degrees C.

Soil Bulk Density (ρ_b): The mass of a soil sample (g, kg, Mg) divided by the volume of the sample (cm^3 or m^3). Typical values for soil bulk density range from 0.8 g/cm^3 (Mg/m^3) to 1.8 g/cm^3 (Mg/m^3).

Soil Particle Density (ρ_p): The density of a typical inorganic soil particle (e.g., grain of sand, rock, etc). Most soils have a particle density of 2.65 g/cm^3 (Mg/m^3).

Volumetric Soil Moisture (ϑ): The volume of liquid water contained within any given sample divided by the total volume of that sample (m^3/m^3). ϑ is related to the soil water content *w* (kg/kg) by the ratio of the density of liquid water, ρ_l (1 g/m^3 or 1 Mg/m^3), to the soil bulk density or $\vartheta = w(\rho_l/\rho_b)$.

Fire Intensity at the Soil Surface (kW/m^2): The amount of energy associated with a fire that impinges on the soil surface. In the case of a flame front this is usually a small fraction (5-10%) of the total radiant energy released by a fire. In the case of a smoldering fire it is likely to be a much greater percentage of the fire's total radiant energy. With the present model this fire intensity at the soil surface can be thought of as the total amount of energy that is responsible for heating the soil surface and throughout the soil profile, evaporating any soil moisture, and creating any atmospheric convective currents that carry heat away from the soil surface. When **Fire Type** is set to the *Burnup Model* and there is duff the graph displays the proportion of intensity from the burning duff. When there is no duff present then intensity is simulated as a proportion of the total woody fuel, litter, herb and shrub combustion intensity. Settings for the proportion of intensity on the soil surface can be changed on the **Settings** page. See Duff Heat Production Source and Heat Efficiency.

Max (kW/m^2): The peak Fire Intensity at the Soil Surface. Any short intense fire can create a maximum in excess of 50 kW/m^2, whereas long duration, smoldering fires are likely to have a maximum between about 2 and 5 kW/m^2.

Time to Max (hrs): The time delay expressed in hours between when the fire begins and when the soil heating reaches is maximum value. For the purposes of running the model it is unnecessary to set the **Time to Max** greater than 4 hours and in most cases 1 hour or less should be adequate.

Fire Duration (hrs): The length of time that the fire heats the soil surface. For slash pile burns this could be as long as 100 hours. Most other fires are likely to be much shorter than this.

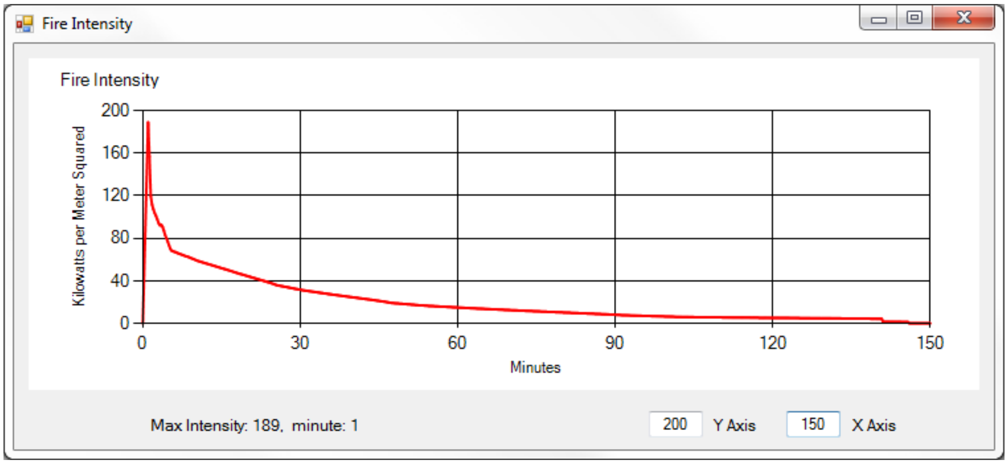
Simulation Time (hrs): The modeled run time. For example, the user could set up a run with a fire duration of 50 hours, but only run the model for the first 12 hours of the fire (**Simulation Time** = 12 hrs).

Fire Type allows the user to select from four fire types: *Wild Fire, Prescribed Burn, Pile Burn, and Burnup Model*. For the first three types, the default settings are different for **Fire Intensity at the Soil Surface**, **Max**, **Time to Max**, **Fire Duration** and **Simulation Time**. For these three types of fires the mathematical shape of the curve that describes the **Fire Intensity at the Soil Surface** is predefined. The Burnup Model setting calculates and outputs the **Fire Intensity at the Soil Surface** based on the user inputs to the FOFEM Model. This FOFEM Model output is then used to drive the soil heating model.

*NOTE: When **Fire Type** is set to* Burnup Model *the values in **Max**, **Time to Max** and **Fire Duration** are automatically set and cannot be changed.*

Fire Intensity Graph

This graph shows the reaction intensity of all the consumed components over time. This is different than Fire Intensity at Soil Surface shown in the soil heating graphs.



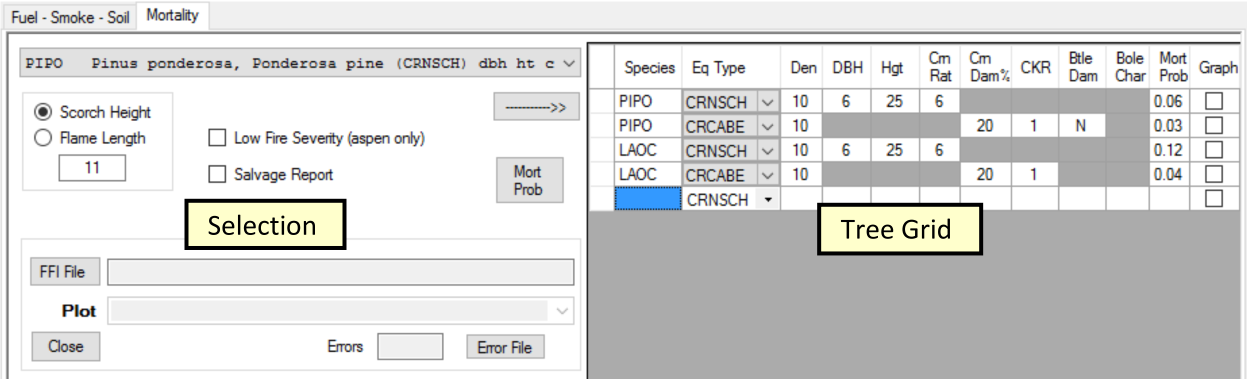
X Axis, Y Axis: to limit the axis enter a number and hit the return key, otherwise FOFEM will automatically set them.

Mortality Tab

In predicting stand mortality, FOFEM assumes a continuous fire. If a burn is very discontinuous or patchy, and the user can estimate the proportion of the area burned, then the per-acre estimates of tree mortality computed by FOFEM can be adjusted by multiplying them by the proportion burned.

Interface

The **Mortality** tab is located on the main window next to the **Fuel – Smoke – Soil** tab. The interface is divided into the selection pane on the left and the tree grid on the right.



Selection Pane

Species dropdown: The dropdown includes all species associated with the currently selected Region that have mortality equations in FOFEM. Each row includes the species code, scientific name, common name, mortality equation code and required inputs. There may be more than one species option based on the number of valid mortality equations. For example, there are two options for white fir shown below; one for the *Crown Scorch* mortality equation and one for *Crown-Cambium-Beetle* equation type (variables at the right are required).

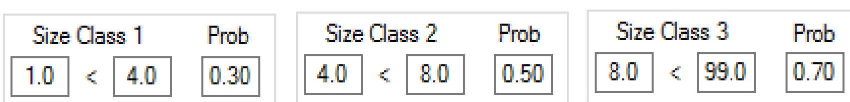
```
ABCO   Abies concolor, White fir      (CRNSCH) dbh ht cr
ABCO   Abies concolor, White fir      (CRCABE) dbh len ckr btl
```

To add a species code into the Species field in the tree grid, select a species code in the dropdown and the click the arrow. Be sure to select the option with the desired mortality equation. If you know the species code you can type it in the Species column in the tree grid.

Scorch Height / Flame Height: FOFEM does not calculate flame height so it must be entered before making a simulation. Select the appropriate radio button and enter a value in the box (feet).

Low Severity (aspen only): Check this box when simulating low fire severity and aspen mortality. This option will select a different equation for estimating aspen mortality than when unchecked

Salvage Report: This report is used to create a table of live and dead trees by size class regardless of species. Check the box to set up to three diameter classes for calculating pre- and post-fire tree density. All trees with calculated probability of mortality less than the probability of mortality cutoff for the class are “Killed”.



NOTE: The DBH field is required if the record is to be included in the Salvage Report even if DBH is not required for the selected mortality equation type (e.g., CRCABE)

Mort Prob: Click this button to calculate the mortality probability for each record and report it in the *Mort Prob* column in the tree grid.

FFI File: Click this button to navigate to select a tree file exported from the FFI software.

Errors: When a FFI tree is selected the box will report the number of errors found in the file.

Error File: Click this button to view a list of errors found in the FFI tree file.

Example error file:

The file provides the path to the error file, the plot record where the error was noted (concatenated plot name, monitoring status and monitoring status order) and the errors found. Missing values not needed to make mortality calculations will not lead to an error.

```
File Location: C:\Users\    \AppData\Local\FOFEM6.5\WillisPk-Err.txt
Some missing numeric values may be shown as '-1'
Row number represents file record within selected plot

>>----> Plot: WillisPk001-ReMeasure2-2, Row: 4, Spe: PSME, Den: 10.0, Dia:-1.0, TreHgt:-1.0,
CrnBas:75.0, TreSta: H, CrnClass: C, CrnRatio: 2, CharHgt: -1.0, CrnScoPer: 0.0,
CrnScoHgt: -1.0, CKR: -1, BtlDam: N, EquaTyp: CRNSCH, FSH: , FS: -1.0, Sev:
Missing DBH
Missing Tree Height
```

Plot: Select the desired plot from the dropdown.

Close: Click this button the clear the FFI tree file selection.

Tree Grid

Species: The species code can be selected from the species drop down in the Selection Pane or typed in the tree grid.

Eq. Type: There are three tree mortality equation types: *CRNSCH*, *CRCABE* and *BOLCHR.* When a mortality equation type is selected the required input cells are colored white in the tree grid. The table below identifies the required fields for each mortality equation type. See the Scientific Content – Calculating Tree Mortality section for more information.

Equation Type	Equation Code	DBH	Hgt	Crn Rat	Crn Dam%	CKR	Btle Dam	Bole Char
Crown Scorch	CRNSCH	X	X	X				
Crown-Cambium-Beetle	CRCABE				X	X	X	
Bole Char	BOLCHR	X						X

NOTE: In previous versions of FOFEM the Crown Scorch *equation type was call* Pre-fire *and* Crown-Cambium-Beetle *equation type was called* Post-fire*.*

Den: Trees per acre.

DBH: Diameter breast height in inches.

Hgt: Total tree height in feet.

Crn Rat: Crown ratio/10. Valid values: 1 – 10

Crn Dam %: Crown damage percent.

CKR: Cambium Kill Rating. Valid values: 0 – 4

Btle Dam: Beetle damage. Valid values: Y, N

Bole Char: Maximum bole char height in feet.

Mort Prob: Mortality probability. FOFEM calculates this value when the **Mort Prob** button is selected.

Graph: Select the checkbox for one or more species to be graphed.

To delete a row from the data grid, highlight the row by clicking the gray area to the left of the Species column then hit the **Delete** key on your keyboard.

If desired, select **File>Save Project** to save your tree grid settings in a project file.

Mortality Report

This report includes: pre- and post-fire stand density and number of trees killed in 2 inch size classes, a table of mortality probabilities for each record in the tree grid, mortality probability for a range of flame lengths, crown scorch and/or bole char heights (depending on equation type) and summary information.

Right-click in the report window to copy, save or print the report

```
~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
 TITLE: Results of FOFEM model execution
 TREE MORTALITY MODULE:
 REGION: InteriorWest
 FLAME LENGTH (FT): 11.00
 Scorch Height: 103.02

 ORIGINAL STAND DENSITY AS INPUT TO FOFEM

 Species              Midpoint Diameter classes (in)
 Code            1     3     5     7     9    11    13    15    17    19
 ______________________________________________________________________
 PIPO            0     0     0    10     0     0     0     0     0     0
 LAOC            0     0     0    10     0     0     0     0     0     0
 PSME            0     0     0    10     0     0     0     0     0     0
```

TOTALS	0	0	0	30	0	0	0	0	0	0

DBH classes (in): 1: 0-<2, 3: 2-<4, 5: 4-<6, ... 39: 38 and over

POSTFIRE STAND DENSITY (TREES/ACRE)

Species Code	Midpoint Diameter classes (in) 1	3	5	7	9	11	13	15	17	19
PIPO	0	0	0	2	0	0	0	0	0	0
LAOC	0	0	0	3	0	0	0	0	0	0
PSME	0	0	0	0	0	0	0	0	0	0
TOTALS	0	0	0	5	0	0	0	0	0	0

DBH classes (in): 1: 0-<2, 3: 2-<4, 5: 4-<6, ... 39: 38 and over

TREES PER ACRE KILLED BY THE FIRE

Species Code	Midpoint Diameter classes (in) 1	3	5	7	9	11	13	15	17	19
PIPO	0	0	0	8	0	0	0	0	0	0
LAOC	0	0	0	7	0	0	0	0	0	0
PSME	0	0	0	10	0	0	0	0	0	0
TOTALS	0	0	0	25	0	0	0	0	0	0

DBH classes (in): 1: 0-<2, 3: 2-<4, 5: 4-<6, ... 39: 38 and over

PROBABILITY OF MORTALITY FOR EACH SPECIES/DIAMETER ENTRY

Species Code	DBH (inch)	Height (feet)	Crn Rat	Mort Prob	Mortality Equation Id	Name
PIPO	6.0	25	6	0.80	19	Ponderosa pine and Jeffery pine
LAOC	6.0	25	6	0.70	14	Western larch
PSME	6.0	25	6	0.98	20	Douglas-fir

AVERAGE MORTALITY PROBS BY FLAME LENGTH BY SPECIES/DIAMETER ENTRY

Species Code	Tree DBH	Flame Length (feet) 2	4	6	8	10	12	14	16	18	20
PIPO	6.0	0.06	0.79	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
LAOC	6.0	0.08	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70
PSME	6.0	0.12	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98
AVERAGES	6.0	0.09	0.82	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83

```
STAND TREE MORTALITY
Total prefire number of trees:    30
Number of trees killed by the fire:    25
Percent mortality:  83
Percent mortality for trees 4+ in DBH:  83
Average tree diameter (DBH) of fire killed trees:    6.0

 Stand Basal Area:   sq/ft   Percent
     Prefire Live:    5.89    100
    Postfire Live:    1.01     17
  Postfire Killed:    4.88     83

  Stand Canopy Cover:    Percent (only species containing height are used)
   Prefire Live:           5
  Postfire Live:           1
         Change:           4
```

Original Stand Density: The pre-fire stand data reported by species and diameter class. An additional table will be included if trees greater than 19 inches are included in the simulation.

Post-fire Stand Density: The post-fire stand data reported by species and diameter class. An additional table will be included if trees greater than 19 inches are included in the simulation.

Trees Killed by Fire: The trees killed by the simulated fire reported by species and diameter class. An additional table will be included if trees greater than 19 inches are included in the simulation.

Probability of Mortality: This table shows the probability of mortality for all the trees included in the simulation, the Mortality Equation ID and Mortality Equation Name used to predict the mortality.

> *NOTE: Not all tree species have species specific mortality equations so review the equations used for the species in your simulation. See* [*Scientific Content – Computing Tree Mortality*] *for more information.*

Average Mortality tables for each equation type**.** The table for crown scorch (CRNSCH) equations displays the probability of mortality at a variety of crown scorch or flame lengths (as set on the

Mortality tab) for the species/DBH combinations entered in the data grid. The table for canopy damage-cambium kill rating-beetle (CRCABE) equations displays the probability of mortality for a variety of crown damage ranges and the table for bole char (BOLCHR) equations displays the probability of mortality for a range of bole char heights.

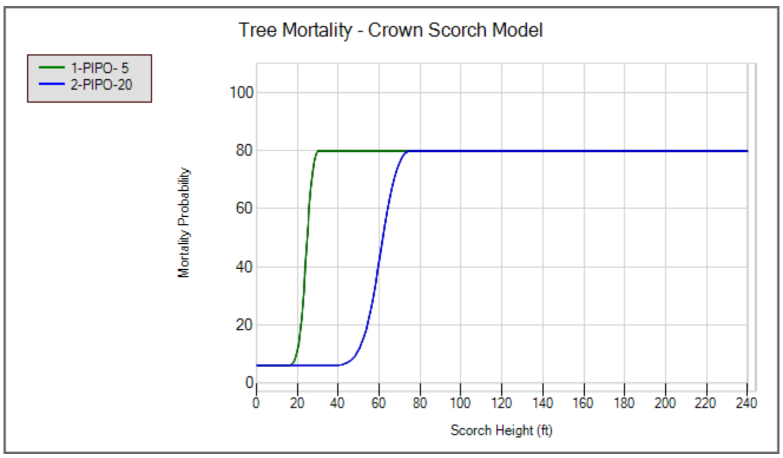
Stand Tree Mortality: Summary information for the simulation. Average diameter of killed trees is the weighted mean diameter (not quadratic mean diameter). Tree height is used in the calculation of **Stand Canopy Cover**. If tree height is missing, the tree record will not be included in cover estimate.

Graphs

The FOFEM mortality graphs display mortality probability over a range of dependent variables. Each of the examples below includes two tree records but the graphs can include as many tree records as desired.

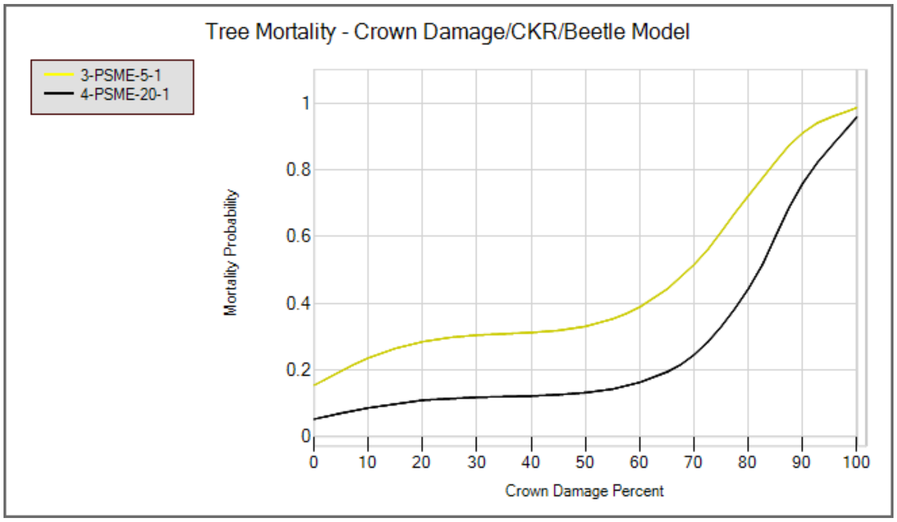
Mortality Graph – Scorch Height - CRNSCH

The mortality graph displays mortality probability for the tree record(s) using the CRNSCH equation where the *Graph* box is checked in the species grid. The legend in the upper left shows the line color, tree grid record number, tree species and DBH for each record that is graphed. The X axis variable is flame length or crown scorch as set by the user on the **Mortality** tab.



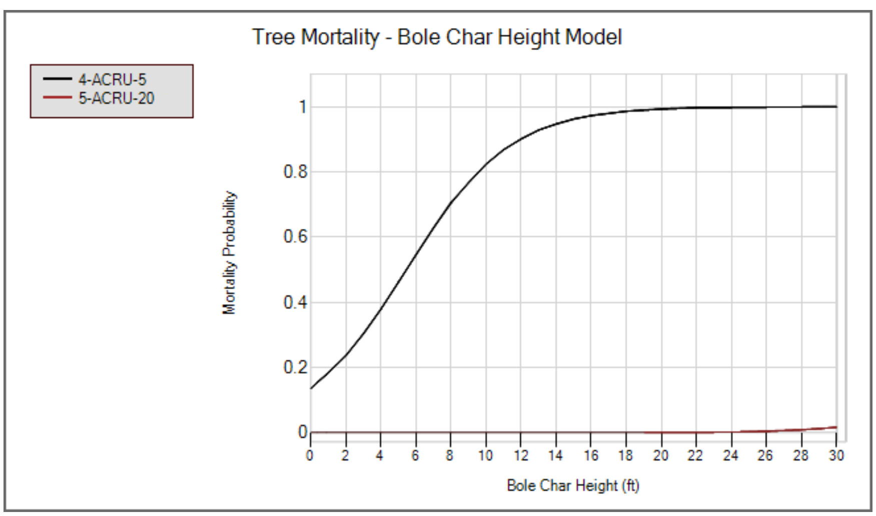
<u>Mortality Graph – Crown Damage - CRCABE</u>

The mortality graph displays mortality probability for the tree record(s) using the CACRBE equation where the *Graph* box is checked in the species grid. The legend in the upper left shows the line color, tree grid record number, tree species, DBH and CKR for each record that is graphed. The X axis variable is crown damage percent.



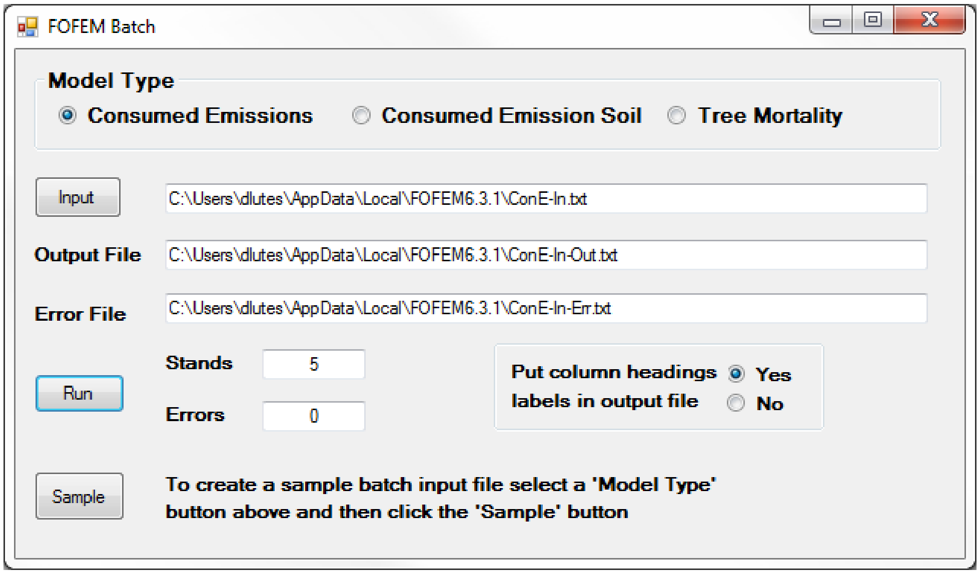
<u>Mortality Graph – Bole Char - BOLCHR</u>

The mortality graph displays mortality probability for the tree record(s) using the BOLCHR equation where the *Graph* box is checked in the species grid. The legend in the upper left shows the line color, tree grid record number, tree species and DBH for each record that is graphed. The X axis variable is bole char height.

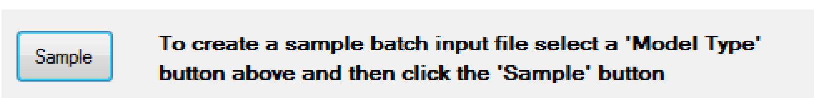


Batch Processing

FOFEM contains a batch mode for processing multiple plots using input files. Batch files can be processed in either one of two ways: 1) Using the user interface or 2) From a system command line prompt. Each procedure is explained below.

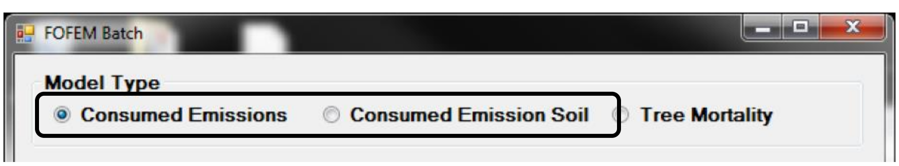


There is a button on the FOFEM Batch dialog box for creating sample batch input files. The sample files are specific to each Model Type and contain comments and column headings to aid you in formatting your own files.



Batch runs using the user interface

1. Open the FOFEM Batch File Dialog Box from the main menu **Options->Batch Processing**
2. Select a **Model Type** by clicking the radio button immediately preceding the model name: *Consumed Emissions*, *Consumed Emission Soil* or *Tree Mortality*.



3. Select a batch input file by clicking the **Input** button.
4. Set the **Output File** name. A default file name will be shown based on the selected input file name, you can use the default path and file name or edit it. The **Error File** name will be generated by the program based on the input file name.
5. Click **Yes** or **No** to put column heading labels into your output file. You have the option of putting a single row of column labels to the top of your output file. The labels are abbreviations for each column of output data and are helpful if you are going to import the data into a spreadsheet or database.

6. To create an additional report with model outputs in the column format check Include *Column Style Report* box.
7. Click **Run** to process.

The number of stands/plots run from the input file will be displayed in the **Stands** field.

The number of errors encountered in the input field will be displayed in the **Errors** field and the error messages will be placed in the error file.

> *NOTE: You can create a sample input file by selecting a Model Type and then clicking the **Sample** button. The sample file includes comments and notes about inputs and other features you might choose to use.*

The output file is in comma delimited format. The column headers are defined in the Batch Output File section.

Batch - Consumed Emissions and Consumed Emission Soil

Batch Input file – Consumed Emissions and Consumed Emission Soil

Batch input must use a comma delimited format. The *.TXT* extension by default but any extension can be used. Numerical fields can be an integer or a floating point number. Comment lines can be created by placing a "#" in column one. Blank input lines found in the input file will be ignored.

> *NOTE: In FOFEM batch input files lines that are comments begin with a "#" followed by a space and then the comment text. Lines that are switches begin "#", followed immediately by the name of the switch. For example: "*# FOFEM*" is a comment* and *"*#1k-SizeClass*" is a switch.*

No output record will be created for any input record that contains errors. If an unusually large number of error messages occur while you are processing a file you should check the input file format and also make sure that you have selected the proper Model Type for the input file you are using. Model Type is selected at the top of the FOFEM Batch window. The options are: *Consumed Emissions*, *Consumed Emission Soil* and *Tree Mortality*.

Each row of input data represents one plot and will produce one row of output. All columns shown in the Batch File Description table below are numeric unless specified as text.

Batch Input File Description table

For *Consumed Emissions* and *Consumed Emission Soil* Model Types

Column No.	Field Name	Description
1	Plot Id	Text or numeric, this field can be entered with or without delimiting double quote marks unless there are embedded blank characters, which require quotes. To avoid needing quotes, use underscores or hyphens. E.g., *Ridge_1* or *Ridge-1* instead of *"Ridge 1"*.
2	Litter	Litter fuel load (T/ac)
3	1 Hour	Loading of 0 – ¼ in. fuels (T/ac)
4	10 Hour	Loading of the ¼ - 1 in. fuels (T/ac)
5	10 Hour Moisture	Moisture of the 10 hour fuels; range: 3 - 298%
6	100 Hour	Loading of the 1 – 3 in. fuels (T/ac)
7	1000 Hour[1]	Loading of the greater than 3 in. fuels (T/ac)
8	1000 Hour Moisture	Moisture of the 1000 hour fuels; range: 1 - 300%

9	1000 Hour Percent Rotten	Percent of 1000 hour load that is rotten, expresses as a whole number; range 0 - 100%
10	1000 Hour Weight Distribution[2]	Defines how the 1000 hour fuel is distributed into size classes; "Even", "Right", "Left", "End", "Center"
11	Duff	Duff Loading; range 0 - 356.79 T/ac. *NOTE: if duff loading is 0 then duff depth must be 0*
12	Duff Moisture	Duff moisture; range 10 - 197.2%
13	Duff Depth	Duff Depth, inches; range 0 – 999 in. *NOTE: if duff depth is 0 then duff loading must be 0*
14	Duff Moisture Method[3]	The method used to measure duff moisture; "Entire", "Lower", "NFDR", "Adj_NFDR"
15	Herbaceous	Herbaceous fuel load (T/ac)
16	Shrub	Shrub fuel load (T/ac)
17	Crown Foliage	Crown Foliage fuel load (T/ac)
18	Crown Branch	Crown Branch fuel load (T/ac)
19	Percent of Crown Burn	Percent of crown that will burn, expressed as a whole number; range 1 – 100%
20	Region	"InteriorWest", "PacificWest", "NorthEast", "SouthEast"
21	Cover Group	See the Setting Cover Groups section below
22	Season	"Spring", "Summer", "Fall", "Winter"
23	Fuel Category	"Natural", "Piles", "Slash"
24[4]	Soil Family	"Loamy-Skeletal", "Fine-Silt", "Fine", "Coarse-Silt", "Coarse-Loamy" Use "NA" to indicate none available, in which case no soil heating will be calculated for the record
25[4]	Soil Moisture	Soil Moisture; range 0 – 25%

[1] 1000 hour fuels can be entered as a total or as individual size class amounts. See the 1k-SizeClass switch description for more information.

[2] Size class distributions.

Size Class	**3 – 6 in.**	**6 – 9 in.**	**9 – 20 in.**	**20+ in.**
Even	25%	25%	25%	25%
Right	7%	16%	27%	50%
Left	50%	27%	16%	7%
End	35%	15%	15%	35%
Center	15%	35%	35%	15%

[3] If you do not have duff fuel, enter zeros for load and depth, a minimum moisture amount of 10 and "Entire" for Duff Moisture Method. Even when there is no duff fuel the Burnup model still requires duff moisture to work.

[4] Input files running the Soil Model Type require fields 24 & 25.

[5]Moisture Regime defaults are based on western systems:

Regime	**Duff**	**10-hr**	**3+ in**	**Soil**
Wet	130	22	40	25
Moderate	75	16	30	15
Dry	40	10	15	10
Very Dry	20	6	10	5

Setting Cover Groups

FOFEM batch was designed to accommodate a wide variety of users and their data (with/without cover type and various cover type classifications). Accordingly it has been setup to use a cover group code rather than what would be a rather extensive list of cover types from multiple cover type classifications.

Cover Group is used to determine appropriate consumption formulas for herbaceous, shrub and duff fuel loading, in turn fuel consumption is used to compute smoke emission amounts and simulate soil heating.

Type	Short code	Long code
Grass	GG	GrassGroup
Shrub	SG	ShrubGroup
Shrub-Chaparral[1]	SGC	ShrubGroupChaparral
Sagebrush	SB	Sagebrush
Ponderosa pine	PN	Ponderosa
Pocosin	PC	Pocosin
Balsam, Black, Red, White Spruce	BBS	BalBRWSpr
Red, Jack Pine	RJP	RedJacPin
White Pine Hemlock	WPH	WhiPinHem

[1] This group only differs from the shrub group in that it uses the chaparral duff consumption equation (#19).

If you cannot determine a Cover Group use the double quote marks (“”) or leave the field empty to indicate none and consumption will be calculated using the general consumption algorithm.

NOTE: For more details concerning how cover groups are used to determine consumption see *Cover Groups, Decision Dependency, Duff Consumption, Herbaceous Consumption and Shrub Consumption*

Switches

The *Consumed Emissions* and *Consumed Emission Soil* batch input files have the optional switches listed below:

#ConsumptionEquation: This optional switch is used to set the FOFEM equations for:

Litter load consumption
% duff consumption
Duff depth consumption
Mineral soil exposure
Herbaceous load consumption
Shrub load consumption

Using this switch requires you add six equation numbers, separated with commas, at the end of each record, in the order they appear above. Enter equation number -1 to use default equation. Separate equation numbers with commas.

Valid equation numbers are:

Litter: 997, 998, 999
% Duff consumption: 1, 2, 3, 4, 16, 17, 19, 20
Duff depth consumption: 5, 6, 7, 15
MSE: 9, 10, 11, 12, 13, 14, 18, 202
Herb: 22, 221, 222, 223
Shrub: 23, 231, 232, 233, 234, 235, 236

If this switch is not used FOFEM will use default logic to set consumption equations. Equations are described in the Scientific Content-Fuel Consumption section.

#EFG-STFS n, *#EFG-CWDRSC* n, *#EFG-DuffRSC* n: These optional switches are used to set emission factor groups for short-term flaming and smoldering (STFS), CWD residual smoldering component (CWDRSC) and Duff residual smoldering component (DuffRSC).
When using this option all three switches are required.
Refer to Emission_Factors.csv (found here: C:\Users\...AppData\Local\FOFEMx.x) for valid emission factor group numbers.
Example:
#EFG-STFS 3
#EFG-CWDRSC 7
#EFG-DuffRSC 8
If this switch is not used FOFEM will use default logic to set emissions factors.

#Emission-File EmFile: This switch creates an emission file for each plot. The required switch argument ('EmFile') will be used as the prefix for the emissions output files. The files are saved in the same folder as the other output files and will have .emi extensions.

#BurnUpFile Burnup.txt: This switch specifies the name of the Burnup parameter file. Do not specify a path. Place the parameter file in the same folder as the batch input file (e.g., *ConE-In.txt*).

#1k-SizeClass: This switch specifies down woody fuels greater than 3 inches in diameter (1000-hour fuels) are entered in size classes. Replace columns 7 thru 10 described in Batch File Description table with the nine columns in the table below. Then enter Duff in column 16 followed by the remaining data described in the Batch File Description table (i.e., duff, duff moisture, duff depth…).

Column No.	Description
7	3 – <6 in. sound (T/ac)
8	6 – <9 in. sound (T/ac)
9	9 – <20 in. sound (T/ac)
10	20 + in. sound (T/ac)
11	3 – <6 in. rotten (T/ac)
12	6 – <9 in. rotten (T/ac)
13	9 – <20 in. s rotten (T/ac)
14	20 + in. rotten (T/ac)
15	1000 Hour fuel moisture (%)

Batch Output File – Consumed Emissions and Consumed Emission Soil

The file is saved in comma delimited format in the same folder as the input file. One output record is created for each stand.

Column No.	Field name	Description
1	Std	Stand/plot Id from input file
2	LitPre	Pre fire loading (T/ac)
3	LitCon	Consumed loading (T/ac)
4	LittPos	Post fire loading (T/ac)
5	DW1Pre	Pre fire 1-hour loading (T/ac)

6	DW1Con	Consumed 1-hour loading (T/ac)
7	DW1Post	Post fire 1-hour loading (T/ac)
8	DW10Pre	Pre fire 10-hour loading (T/ac)
9	DW10Con	Consumed 10-hour loading (T/ac)
10	DW10Post	Post fire 10-hour loading (T/ac)
11	DW100Pre	Pre fire 100-hour loading (T/ac)
12	DW100Con	Consumed 100-hour loading (T/ac)
13	DW100Post	Post fire loading (T/ac)
14	DW1kSndPre	Pre fire 1000 hour sound loading (T/ac)
15	DW1kSndCon	Consumed 1000 hour sound loading (T/ac)
16	DW1kSndPost	Post fire 1000 hour sound loading (T/ac)
17	DW1kRotPre	Pre fire 1000 hour rotten loading (T/ac)
18	DW1kRotCon	Consumed 1000 hour rotten loading (T/ac)
19	DW1kRotPost	Post fire 1000 hour rotten loading (T/ac)
20	DufPre	Pre fire duff loading (T/ac)
21	DufCon	Consumed duff loading (T/ac)
22	DufPos	Post fire duff loading (T/ac)
23	HerPre	Pre fire herb loading (T/ac)
24	HerCon	Consumed herb loading (T/ac)
25	HerPost	Post fire herb loading (T/ac)
26	ShrPre	Pre fire shrub loading (T/ac)
27	ShrCon	Consumed shrub loading (T/ac)
28	ShrPost	Post fire shrub loading (T/ac)
29	FolPre	Pre fire crown foliage loading (T/ac)
30	FolCon	Consumed crown foliage loading (T/ac)
31	FolPost	Post fire crown foliage loading (T/ac)
32	BraPre	Pre fire crown branch loading (T/ac)
33	BraCon	Consumed crown branch loading (T/ac)
34	BraPost	Post fire crown branch loading (T/ac)
35	MSEPer	Post fire mineral soil exposed (%)
36	DufDepPre	Pre fire duff depth (in.)
37	DufDepCon	Consumed duff depth (in.)
38	DufDepPost	Post fire duff depth (in.)
39	PM10F	PM_{10} flaming emissions (lb/ac)
40	PM10S	PM_{10} smoldering emissions (lb/ac)
41	PM25F	$PM_{2.5}$ flaming emissions (lb/ac)
42	PM25S	$PM_{2.5}$ smoldering emissions (lb/ac)
43	CH4F	CH_4 flaming emissions (lb/ac)
44	CH4S	CH_4 smoldering emissions (lb/ac)
45	COF	CO flaming emissions (lb/ac)
46	COS	CO smoldering emissions (lb/ac)
47	CO2F	CO_2 flaming emissions (lb/ac)
48	CO2S	CO_2 smoldering emissions (lb/ac)
49	NOXF	NO_x flaming emissions (lb/ac)
50	NOXS	NO_x smoldering emissions (lb/ac)
51	SO2F	SO_2 flaming emissions (lb/ac)

52	SO2S	SO_2 smoldering emissions (lb/ac)
53	FlaDur	Total flame time (seconds)
54	SmoDur	Total smoldering time (seconds)
55	FlaCon	Total flame consumed amount (T/ac)
56	SmoCon	Total flame consumed amount (T/ac)
57[1]	Lay0	Layer 0 maximum temperature at soil surface (C)
58[1]	Lay2	Layer 2 maximum temperature at 2 cm (C)
59[1]	Lay4	Layer 4 maximum temperature at 4 cm(C)
60[1]	Lay6	Layer 6 maximum temperature at 6 cm (C)
61[1]	Lay60d	Deepest layer reaching 60 degrees C (cm) "-1" means no layer reached that temperature
62[1]	Lay275d	Deepest layer reaching 275 degrees C (cm) "-1" means no layer reached that temperature

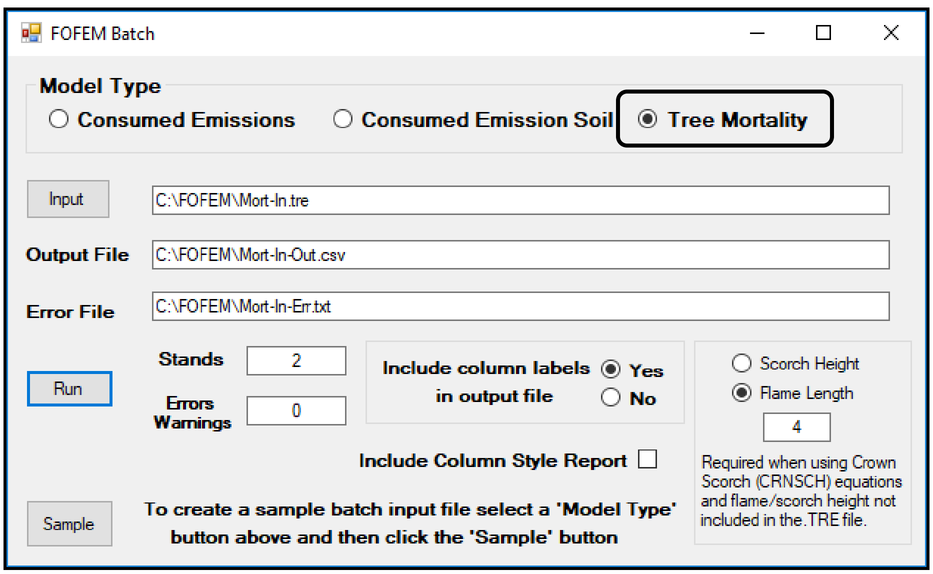
[1] When Model Type = *Consumed Emission Soil* these additional columns of output will be added.

Batch - Tree Mortality

<u>Batch Input File – Tree Mortality</u>

The input file must use a comma delimited format. The *.TRE* extension is used by default but any extension is allowed. Numerical fields can be entered as integer or floating point numbers. Text fields with embedded spaces must by enclosed in double quotes. Comment lines can be inserted by placing a "#" in column 1, blank lines are also allowed.

Any input records containing errors will not be included in mortality predictions for the stand.



If records using the Crown Scorch (CRNSCH) equation types are included in the input file then *Flame Height* or *Scorch Length* settings may be included in the input file for each of those records. If the *Flame Height* or *Scorch Height* settings are missing in the input file then the settings on the batch window will be used (lower right corner of the screen).

Click the **Sample** button to create sample batch input files. The sample files contain comments, column headings and example tree records to help you format your own files.

<u>Batch Files – Tree Mortality</u>

Batch Input File Description table
For *Tree Mortality* Model Types

Column No.	Field Name	Description	Require for Equation Type
1	Plot ID	Text or numeric, this field can be entered with or without delimiting double quote marks unless there are embedded blank characters, which require quotes. To avoid needing quotes, use underscores or hyphens. E.g., *Ridge_1* or *Ridge-1* instead of *“Ridge 1”.*	All
2	Monitoring Status	FFI Monitoring Status	Not Required
3	Monitoring Status order Number	FFI Monitoring Status Order Number	Not Required
4	Tree Species	NRCS tree species code. See the fof_spp.csv file for a complete list of valid codes. The file can be found in the FOFEM install directory, be careful not alter file in any way.	All
5	Tree Expansion Factor	Stand Density (Trees per acre)	All
6	Diameter	Diameter Breast Height (in.)	CRNSCH, BOLCHR
7	Tree Height	Tree Height (ft)	CRNSCH
8	Crown base Height	Live crown base height	CRNSCH
9	Tree Status	Live (L), Healthy (H), Unhealthy (U), Sick (S), Dead (D)	Not required. Records where Tree Status is coded “D” are ignored
10	Crown Class	Dominant (D), Codominant (C), Intermediate (I), Suppressed (S), Open grown (O), Emergent (E)	Not required
11	Crown Ratio	Crown Ratio; range 1 – 100[1]	CRNSCH
12	Char Height	Maximum bole char height (ft)	BOLCHR
13	Crown Damage Percent	Crown scorch or crown kill percent	CRCABE
14	Crown Scorch Height	Crown scorch height	Not Required
15	Cambium Kill Rating	Cambium condition at ground line in four quadrants of tree bole (0 – 4)	CRCABE
16	Beetle damage	Evidence of beetle damage (Y, N)	CRCABE
17	Equation Type	Mortality equation type (CRNSCH, CRCABE, BOLCHR)	All
18	Flame Length or Scorch Height[2]	You can enter a flame length or a scorch height (ft)	CRNSCH

19	Col 1 Identifier[2]	Text. Enter “F” to specify you are using Flame Length in Column 7 or “S” for scorch height.	CRNSCH
20	Fire Severity	Text, "Low" for low or leave blank ""	CRNSCH

[1] Note this is different than the on the FOFEM user interface where crown ratio is 1 – 10

[2] If these values are missing FOFEM will use the fields on the FOFEM Batch window. If running FOFEM from the DOS command line, fields 18 and 19 are required in the input file.

Switches

The *Tree Mortality* batch input files have an option switch from creating a salvage report. The salvage report includes a row for each record (instead of a row for each stand, as in the Tree Mortality output file) and is useful for showing which trees FOFEM predicts will survive and those that will be killed by a simulated fire.

#SalDia-1, SalDia-2, SalDia-3: These optional switches are used to define one to three DBH classes and mortality cutoff for creating a report of potential salvage. The classes are not species dependent. The mortality cutoff is the probability of mortality that must be exceeded for the report to label the tree killed. The switch format is:

SalDia-*n* *Sm DBH* *Lg DBH* *Cutoff* ; where

n is *1, 2 or 3.* Up to three classes can be defined. Classes cannot overlap.

Sm DBH is the smallest diameter (in.) in the class (inclusive)

Lg DBH is the largest diameter in the class (exclusive)

Cutoff is the calculated probability of mortality that must be exceeded for the tree to be declared killed.

Example class are provided in the *Tree Mortality* sample input file.

Batch Output File –Tree Mortality

The file is saved in comma delimited format in the same folder as the input file. One output record is created for each stand.

Column No.	Field Name	Description
1	PlotID	Stand/plot Id from input file (if the file was created in FFI then the PlotID also includes the assigned monitoring status and monitoring status order number.
2	Density Prefire	Total number of pre-fire trees (trees/acre)
3	Density Postfire	Total number of post fire trees (trees/acre)
4	Density Killed	Total number of trees killed (trees/acre)
5	BAPre	Total basal area of pre-fire trees (ft^2)
6	BAPost	Total basal area post fire (ft^2)
7	BAKld	Total basal area of the killed trees (ft^2)
8	CanCovPrefire	Total crown cover of pre-fire trees (%)
9	CanCoverPostfire	Total crown cover of post fire trees (%)

10	CanCovDiff	Total crown cover change (%)
11	DBHKldAvg	Arithmetic mean DBH of killed trees (in.)
12	MortAvg4	Average percent mortality for trees where DBH $\geq$4 inches (%)
13	MortAvg	Average percent morality for all trees (%)

Batch Output File –Tree Mortality Salvage Report

The file is saved in comma delimited format in the same folder as the input file. One output record is created for each input record.

Column No.	**Field Name**	**Description**
1	PlotID	Stand/plot Id from input file (if the file was created in FFI then the PlotID also includes the assigned monitoring status and monitoring status order number.
2	Species Code	Symbol for the species being modeled
3	DBH	Diameter Breast Height (in.)
4	Height	Tree height (ft)
5	Crn Rat	Crown ratio (0 – 10)
6	Crn Dam%	Crown volume damage (%)
7	CKR	Cambium kill rating (0 -4)
8	Btle Dam	Beetle damage (Y, N)
9	Bole Char	Height of bole char (ft)
10	Mort Prob	Probability of mortality calculated in FOFEM for the record
11	Cut Off	Probability of mortality that must be exceeded for the tree to be labeled killed in report
12	Status (Live/Dead)	If *Mort Prob* for the record is greater than the *Cutoff* then the trees in the record are assumed to have been killed (*K*), otherwise they survived the fire (*L*)

Batch Burnup Parameter File

This file allows you to set specific input parameters for the Burnup model that FOFEM uses to simulate consumption of woody fuels. The parameters in this file will be used instead of the default parameters used in FOFEM.

The text in the example below can be cut and paste into a text file as the basis for your Burnup Batch Parameter File.

> *NOTE: In FOFEM batch input files lines that are comments begin with a "#" followed by a space and then the comment text. Lines that are switches begin "#", followed immediately by the name of the switch. For example:* # FOFEM example file *is a comment.* #MAX_TIMES *is a switch.*

Example Batch Parameter File

```
# Sample Burnup input Parameter File
# This file is used in conjunction with the Batch input
# file command switch #BurnUpFile
#
# Maximum number iterations burnup does, default 3000
# Valid 1 -> 100000
#MAX_TIMES 3000
#
# Intensity of the igniting surface fire,
# kW/m2 sq m, 40.0 -> 1.0e5, burnup var – fi, default 50.0
#INTENSITY 50.0
#
# Residence time of the ignition surface fire, seconds
# Default = 60.0, FOFEM's burnup input file uses 30.0
# Burnup var = ti,   limits 10.0 -> 200.0
#IG_TIME 60
#
# Windspeed at top of fuelbed meters/second
# Burnup var = u, default 0, limits 0.0 -> 5.0,
#WINDSPEED 0.0
#
# Fuel depth, meters,
# Burnup var = d, default 0.3, limits 0.1 -> 5.0
#DEPTH  0.3
#
# Ambient air temperature, degrees Celsius
# Burnup var = tamb, default 27,
# If ( tamb-273 < tam1 || tamb-273 > tam2)
# const double tam1 = -40.0,  tam2 = 40.0;
#AMBIENT_TEMP  27.0
#
# Fire environment minimum dimension parameter
# Default 1.83
#R0  1.83
#
# Fire environment increment temp parameter
# Default 0.40
#DR  0.4
#
# Time step for integration of burning rates.
# TIMESTEP * MAX_TIMES gives max simulation period default 15
#TIMESTEP 15
#
# Sigma - Surface area to volume ratio
#SURat_Lit          8200.0
#SURat_DW1          1480.0
#SURat_DW10          394.0
#SURat_DW100         105.0
#SURat_DWk_3_6        39.4
#SURat_DWk_6_9        21.9
#SURat_DWk_9_20       12.7
#SURat_DWk_20         5.91
```

Batch runs using the system command line prompt

The FOFEM6 batch command line option was designed to allow the program to be run in situations where a user interface is not relevant or not allowed by the system or application that it is running under. All of the program's output, including errors, will be written to text files (the program will attempt to pop up a Windows dialog box if it detects any command line program arguments). A sample input file can be created in the FOFEM Batch window as described in the previous section of the user guide.

When running FOFEM in a command window (DOS window) you need to set a system *PATH* variable in order for the system to find the FOFEM executable in its installation folder. Setting the Path variable will allow you to run FOFEM in batch mode from any directory (e.g., your working directory: *C:\Users...FOFEM6.7*).

Running *Path-FOFEM.bat* file – found in the *C:\Users …FOFEM6.5* folder - will automatically set the *Path* variable. To run the file, simply double-click on the filename in Windows Explorer or My Computer.

Optionally, you can open a command window and type the *Path* variable at the prompt:

set path=%path%;C:\Program Files (x86)\FOFEMFolder

where FOFEMFolder is the name of your FOFEM installation folder in the *C:\Programs Files (x86)* folder (e.g., *FOFEM6.7*).

At the command prompt type *FOF_GUI ?* to display the DOS options for running FOFEM.

NOTE: The Emissions_Factors.csv *file must be in the same folder as the* Infile.

1. Open a command window and at the command prompt enter the string to run FOFEM using the following syntax:

   > FOF_GUI C | S | M infile outfile runfile errorfile [H]

   Select one of the following as the first argument:

   C = Consumed/Emissions model

   S = Consumed/Emissions/Soil model

   M = Mortality model

   Set input and output file names:

   Infile = standard batch input file for the selected model type to be run

   NOTE: Only the infile *is an input file, the other three files are created when the program is run.*

   outfile = batch output file created by program, contains calculation values

   runfile = upon completion this file is created and contains number plots processed, number of errors, and file names

   errorfile = any error or warning messages

   H = is an optional argument, when present column heading labels will be placed in the *outfile*

2. When program is complete, you should check the error file to see if any errors were encountered, the run file also contains the number of errors.

Example FOFEM Command Line Text

In the example DOS commands below the first command sets the *Path* variable, the second sets the directory where the input file is saved and the third runs FOFEM using a Consumed/Emissions input file (identified by the *C* argument). When running a simulation that calculates emissions, FOFEM will need access to the file of emission factors: *Emission_Factors.csv*. This file is part of the FOFEM install package. It is suggested to put *Emission_Factors.csv* and the input files are in the same directory when running FOFEM from the command line. In the example, the input file is named *ConE-In.txt*, the output files that are created when FOFEM runs are *ConE-out.txt*, *ConE-run.txt and ConE-err.txt*. The *H* option is used to add headers in the ConE-Out.txt file. After FOFEM executes the output files can be open with a text editor.

```
C:\>set path=%path%;C:\program files (x86)\fofem6.7
C:\>cd c:\users\...\appdata\local\fofem6.7
C:\>fof_gui C ConE-in.txt ConE-Out.txt ConE-run.txt ConE-Err.txt H
```

Scientific Content – Soil Heating

The soil heating component is a product of many years of work by several different researchers. The models are intended to give a view of soil heating based on point-based surface fuel and soil conditions. However, fire practitioners and researchers understand that fire is non-uniform and often erratic in behavior. As a consequence of this variability, it is difficult to attempt to predict soil heating on a unit scale when in reality most fire patterns are mosaic. We strongly encourage the user to experiment with a variety of model input values in order to best predict and understand varying fire regimes. For example, run a number of simulations of various sampled fuelbeds and assume the simulated effects are distributed spatially with the same frequency as the distribution of the fuelbeds.

Campbell Soil Heating Model

The degree and depth of mineral soil heating over time is simulated using a model developed at the Rocky Mountain Research Station Fire Sciences Laboratory in a joint effort with Dr. Gaylon S. Campbell and staff at Washington State University. This model assumes that soil temperature gradients in the horizontal direction are small compared to those in the vertical direction and the model predicts the downward heat flow into the soil using a one-dimensional model. This model has broad applicability due to its ability to predict soil temperature depth profiles over a wide range of soil moistures, densities and mineralogy.

Before the Campbell soil heating model is initiated the FOFEM model uses two alternative approaches to simulate the amount of heat delivered to the soil surface. The *non-duff model* assumes radiant heating (simulated in the Burnup model) from the flaming combustion of the woody, litter, herbaceous and shrub fuelbed components heats the soil surface. Alternatively, the *duff model* assumes radiant and conductive heat from only the burning duff/organic soil horizons heats the soil surface.

The energy at the soil surface resulting from surface fires (non-duff model) is often of moderate to high intensity but of short duration. In contrast to flaming combustion, smoldering (duff model) is commonly characterized by lower energy intensities and longer durations. After ignition, the continued smoldering of the duff/organic soil horizons is no longer dependent on the surface fire environment but is a function of soil moisture, mineral content and bulk density. Total heat at the soil surface is often greater than resulting from surface fires because of the long duration and relatively close proximity of the smoldering combustion front and the mineral soil surface (Neary et al, 2005).

In FOFEM, the transfer of heat from the surface into and within the mineral soil is accomplished using the 1-dimensional Campbell model and is a function of soil moisture and soil properties. The soil heating model is more sensitive to the amount and the duration of heat released during burning and the soil moisture content and is less sensitive to other characteristics such as soil family type or texture.

The soil heating component of FOFEM has been designed in a way that makes it easy for the user to change key variables like duff depth, moisture content, and soil family directly on the user interface. There is also an option for the user to run the soil heating model from input files changing more specific inputs to the soil heating model.

Massman Soil Model

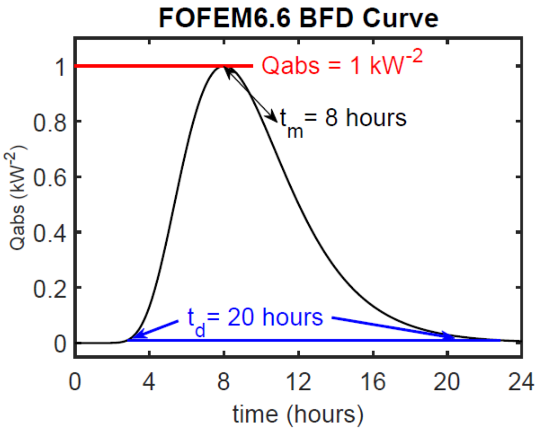
Introduction and Model Description

Virtually all extant models used to simultaneously simulate heat and moisture transport in soils are "equilibrium" models. That is, they model the water vapor within a soil pore as a variable that is completely determined by the temperature of the soil surrounding the pore and the soil water potential of the liquid water held on the soil surfaces bounding that pore. Under normal ambient conditions and daily cycles of soil heating and cooling this equilibrium assumption appears valid and has led to significant insights into the coupling between soil heat flow and the associated evaporation, condensation, and transport of soil moisture. But under conditions of extreme heating, sufficient to completely vaporize all liquid water within a soil pore, then the equilibrium assumption must fail because, although moisture vapor can still exist within the pore space (possibly as super-heated steam), the pore is too hot and too dry for liquid water to occur there. Because of this decoupling of the liquid and vapor phases within the soil, the non-equilibrium approach inherently represents the fundamental physical processes of evaporation and condensation of soil moisture better than the equilibrium approach does. Therefore, a non-equilibrium model is more appropriate when describing soil heat and moisture flow during fires than an equilibrium model. The heat-moisture-vapor (HMV) model (Massman 2015) is the first non-equilibrium model developed exclusively for simulating soil heating and moisture transport during fires.

Because the HMV-model specifically decouples pore water vapor from the pore liquid water, the model has three model variables -- soil temperature, soil water potential, and soil water vapor -- rather than the two that characterize equilibrium models: soil temperature and soil water potential. The HMV-model model also includes several supporting relationships that describe the soil thermal conductivity, the soil water retention curve, hydraulic conductivity functions for water transport, and the non-equilibrium evaporative source term all as functions of these three variables. When the boundary conditions and soil physical properties are included, the number of input parameters to this model is about 35. Not surprisingly, this additional complexity of the non-equilibrium approach comes at a computational cost, i.e., it runs significantly slower than the Campbell soil heating model (an equilibrium model) (Campbell et al. 1995). But the benefit of the non-equilibrium approach is that the HMV-model produces more realistic (and quantitatively better) simulations of soil temperature and moisture dynamics during and after a fire than does the equilibrium model (Robichaud et al. 2018).

Surface heating function, fire type, and boundary conditions

The forcing function that drives a model also determines the type and mathematical shape of the solution (simulation). In the case of the FOFEM soil heating modules this forcing function is encoded in the boundary conditions at the soil surface as determined from the surface heating function. For the Campbell soil heating module only the Burnup model can be used as input to drive soil heating. But, for the HMV-model the soil surface forcing can be taken either from the Burnup or input directly by the user (without first running Burnup) using one of the three different fire types: wild fire, prescribed burn, or pile burn. In these latter three cases, the surface heating function is modeled after the BFD curve (Barnett 2002), an example of which is shown in the figure below.



Q_{abs} = **Max**
t_d = **Fire Duration**
t_m = **Time to Max**

There are three parameters that define the BFD curve as implemented in the HMV-model: (1) **Max** [kW/m^2] = the maximum value of the heating rate, (2) **Time to Max** [hr] = the time at which the fire reaches it maximum value, and (3) **Fire Duration** [hr] = the duration of the fire. Default values for each of these three parameters are provided on the Massman graph window, but they can be changed if desired. Regardless of the type of fire being simulated, it is usually unnecessary to choose **Time to Max** longer than 4 hours or so from t (time) = 0 when the simulated fire is initiated. **Fire Duration**, can vary from 1 hour to as much as 120 hrs. The default values for **Max** are chosen empirically, such that shorter burns (**Fire Duration** ~1 to 5 hours or so) will burn more rapidly and, thus, more intensely than a longer burn (**Fire Duration** ~10 to 100 hours). Therefore, assuming more or less similar fuel loadings for shorter and longer burns, a higher value for **Max** is associated with shorter burns than for longer burns. For example, observations of pile burns suggest that they can heat the soil for several hours or even several days. Therefore, for relatively longer pile burns (**Fire Duration** ~40 to 120 hours) **Max** never exceeded 20 kW/m^2 for any simulation. But relatively shorter pile burns (**Fire Duration** ~2 to 30 hours) would sometimes be associated with **Max** as high as 50 kW/m^2. Nonetheless, it needs to be emphasized that the relationship between **Fire Type**, **Max**, and **Fire Duration**, as codified in the default values displayed on the Massman graph window, is more intuitive than absolute. In addition to fuel loading, these model parameters should also depend on fuel type, fuel moisture, and ambient temperature and humidity. The HMV-model is set up for the user to input other values than the defaults to aid the user in finding the best set of model input parameters for the desired application. Otherwise, it is not possible to know *a priori* what the optimal input parameters for any given fire or burn scenario might be.

<u>Soil parameters</u>

The key input parameters for the soil are the **Soil Particle Density** and the **Soil Bulk Density**. The default values for these are 2.65 Mg/m^3 for the particle density and about 1.25 Mg/cm^3 for the bulk density. In general, particle density and bulk density do not vary excessive across soil types. For example, particle density varies between about 2.50 and 2.85 Mg/cm^3 almost universally and about 80% of all western US soils have a bulk density between about 1.0 and 1.85 Mg/cm^3 with a median value between 1.25 and 1.35 Mg/cm^3. It is important to emphasize that these default values have been tested fairly extensively with the HMV-model and that almost any combination of these two input parameters will produce very credible simulations for soil temperature and moisture for almost all western US soils. But because the model is sensitive to the exact numerical values for particle and bulk density, using any known values is preferred and so the HMV-model does allow the user to input values other than the default.

Assumptions for the duff soil heating model

The duff model simulates soil heating resulting from the transfer of heat from the duff smoldering combustion zone into the mineral soil. The total energy reaching the mineral soil surface is a function of the heat energy content of the duff soil material, moisture content and the duration of smoldering and is the product of duff consumed (kg/m^2) and the energy content of duff fuels). Duff consumption is calculated using the appropriate duff consumption equation based on the selected region, fuel/vegetation type and duff moisture. Duff moisture can be directly input or the user may choose one of the fuel moisture regimes from the FOFEM interface (very dry to wet).

FOFEM uses duff load consumed and duff moisture in the logic provided by Albini (1994) to determine the intensity of consuming duff at each time step assuming heat from burning peat = 20 MJ/kg (Frandsen 1987):

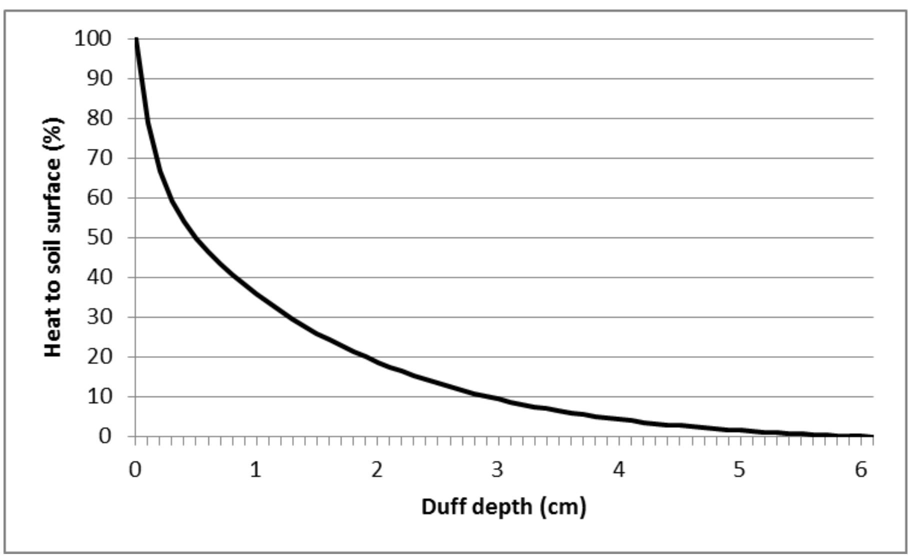
$$I_d = (7.5x10^{-4}) – (2.7x10^{-4}R_M);$$

where I_d is the intensity of the burning duff (kg/s/m^2) and R_M is the gravimetric soil moisture (Frandsen 1991b). In FOFEM, duff burning rate is not influenced by wind or burning surface fuels.

It is commonly observed that not all heat from smoldering is directed downward into the soil. The amount of heat from smoldering transferred to the soil is dependent on a several factors. During smoldering the remaining unburned duff between the combustion zone and the soil surface acts as an efficient insulator. The proportion of heat directed to the soil surface is calculated with the equation:

$$H = -1.6996 + (32.7652 * EXP(-7.4601*D_d)) + (68.9349 * EXP(-0.6077*D_d))$$

Where H is the percent of total heat of combustion that is directed to the soil surface, D_d is duff depth measured in cm. This equation does not account for soil moisture which is a variable that may significantly influence the conductivity of heat in duff.



Duff smoldering is commonly observed many hours after flaming combustion has ended. The long duration of smoldering is a major factoring influencing heat transfer into the soil and subsequent fire effects. FOFEM predicts the duration of smoldering as a function of duff thickness, moisture and mineral content (Frandsen 1991).

Assumptions for non-duff soil heating model

When no duff/ or organic soil horizon is present then soil heating is driven by the radiant energy from flaming combustion of litter, woody fuels, herbs and shrubs. Burning duration of litter and woody fuels is determined in Burnup. Herb and shrub fuels burn at a rate of 10 t/ac/min. The non-duff model assumes only a portion of the consumption intensity is delivered to the soil surface. These values were developed after comparing simulated outputs to results from field data.

Component	Proportion of intensity directed to soil surface
Woody debris and litter	15%
Herbaceous and shrubs	10%

Running Soil Heating from Main Menu

NOTE: This option is available for the Campbell Model only

The soil heating component of FOFEM gives the option to run the Duff or Non-Duff model from a soil heating input file.

From the main FOFEM menu:

- **Options > Create Sample Soil Input File.** This selection creates a soil heating input file for the "duff" or the "non-duff" input files.
- **Options > Run Soil from an Input File**. This selection will run an existing soil heat input file. The input file extensions are; *.exp* and *.duf* for the non-duff and duff models, respectively

The simplest method to produce an input file is to use the *Create Sample Soil Input File (.exp, .duf)* option from the menu. Some input values in the data files result from the user selections on the FOFEM interface. This file can then be edited to make the desired changes.

Duff Model Input File Input File Description

Section 1

This section may be used to document user changes to the input file.

- **# -** The line starting with a pound sign (#) followed by a space is a comment. You can enter an entire line(s) as a comment as long as you start it with a pound sign in column one.

Section 2

This section defines the duff fuel parameters.

- **Duff weight (Tons/Acre)** is the preburn duff loading. Default values are used for the selected fuel types or the user may enter other values.
- **Duff depth (inches)** is the duff layer thickness. Default values are used for the selected fuel types of the user can enter other values.
- **Duff consumed (%)** is the percent duff consumed 0 -100% (integer values). Consumption is estimated from the default fuel type duff consumption equation or the user may enter other values.

- **Duff moisture content (%)** is the gravimetric moisture content (%) and is typically obtained by oven drying. Moisture values vary from 10% or less for extremely dry conditions to 75% to 130% for wet conditions. Values of 10% or less will result in 100% duff consumption for all fuel types.

Section 3

This section defines the various soil properties. Soil bulk density, soil particle density and thermal conductivity are determined from the soil family type. Two parameters of most immediate interest to users are:

- **Soil starting water content (g/cm^3) -** is the volumetric soil moisture content. It can be estimated as function of bulk density (g/cm^3) and the mass of water (g)
- **Soil starting temperature (C^0)-** The temperature of mineral soil at the start of the soil heating simulation is assumed to be uniform throughout the depth profile used for predictions.

Other parameters in this section have been determined by laboratory work. These default values for each soil family type should not be modified.

Section 4

This section of the input file begins with the word 'layers' on a single line starting column 1.

Each of the values on this line represents a depth (centimeters) that the model will predict temperature at. Note: the user must specify 13 depths.

<u>Example Duff soil input file</u>

Section 1

```
# Duff Model - Example Inputs File
# Use this file type when duff is present
# Lines that start with a # are comments.
# Warning: extreme or missing values in this file can
# cause unexpected results.
# These inputs represent the current GUI settings.
# However if no duff is present a fictitious amount will be used.
# And the soil type = Coarse-Silt
```

Section 2

```
Duff-Model
duff-weight              5.0   pre-burn weight - (T/ac)
duff-depth              0.50   duff depth - (in)
duff-consumed           66.7   percent consumed, whole integer 0 -> 100
duff-moisture           40.0   very dry 20, dry 40, moderate 75, wet 130
```

Section 3

```
bulk-density            1230000   soil bulk density - (g/m3)
particle-density        2350000   soil particle density - (g/m3)
extrap-water            0.16   extrapolated water cont. at -1 (J/kg)
thermal-conduct         2.53   thermal conductivity of mineral fraction
Vries-shape             0.103   de Vries shape factor
water-content           0.218   water content for liquid recirculation
cop-power               3.43   power for recirculation function
time-step               10      time step - (sec)
start-water             0.10   starting soil water content, Wet 0.25, Mod 0.15, Dry 10, V-
Dry 5,  m3/m3
start-temp              21.0   starting soil temperature (C)
efficiency-duff         100  percent of Duff fire intensity applied to soil surface
```

Section 4

```
# Specifiy exactly 13 depths (cm)
layers   1 2 3 4 5 6 7 8 9 10 11 12 13
```

Non-Duff Model Input File Description

Section 1

This section can be used to document changes to the input file.

- **# -** The line starting with a pound sign (#) followed by a space is a comment. You can enter an entire line(s) as a comment as long as you start it with a pound sign in column one.

Section 2

This section defines the various soil properties. Soil bulk density, soil particle density and thermal conductivity are determined from the soil family type. In this section, two parameters of interest to most users are:

- **Soil starting water content (g/cm^3) -** is volumetric mineral soil moisture. It can be estimated as function of bulk density (g/cm^3) and the mass of water (g). It is assumed to be uniform throughout the soil depths at the beginning of the heating simulation.

- **Soil starting temperature (C^0) -** The mineral soil is assumed to be at a uniform temperature throughout the depth profile used for temperature predictions.

Other parameters in this section have been determined by laboratory work and at this time the default values for each soil family type should be used. (See tables 1 -3 for soil parameters)

Section 3

This section of the input file begins with the word ‘layers’ on a single line starting column 1.

Each of the values on this line represents a depth (centimeters) that the model will predict temperature at. Note: the user must specify 13 depths.

Section 4

This section defines the proportion of radiant energy generated by flaming combustion of the surface fuels that is transferred to the soil.

- **Efficiency WL and Efficiency HS (%)** - The user can define the percent of heat transferred downward into the bare soil by the Wood/Litter and Herb/shrub loads. In general, estimates of the energy reaching the soil surface from flaming combustion range from 5 to 25 %.

- **FI- interval (sec) -** The user may modify the duration of surface heating by changing the ‘fi-interval’ value.

Section 5

- **Fire intensity (kW/m^2) -** Values in the two columns of this section are fire intensity estimates. The estimates are calculated in FOFEM from the Wood/Litter and Herb/Shrub loadings of the selected fuel type. These estimates are modified by the WL and HS efficiency values before they are input into the model.

Example Non-duff soil input file

```
Section 1
# Zero Duff Model - Example Input File
# Use this file type when there is an absence of duff
# Lines that start with a # are comments.
# Warning: extreme or missing values in this file can
# cause unexpected results.
# These inputs represent the current GUI settings.
# Fire intensity is simulated using GUI settings.
# Soil characteristics represent Coarse-Silt
```

Section 2

```
NonDuff-Model
bulk-density          1230000   soil bulk density - (g/m3)
particle-density      2350000   soil particle density - (g/m3)
extrap-water          0.16   extrapolated water cont. at -1 (J/kg)
thermal-conduct       2.53   thermal conductivity of mineral fraction
Vries-shape           0.103   de Vries shape factor
water-content         0.218   water content for liquid recirculation
cop-power             3.43   power for recirculation function
time-step             10      time step - (sec)
start-water           0.10   starting soil water content, Wet 0.25, Mod 0.15, Dry 0.10, V-Dry
0.05,  m3/m3
start-temp            21.0   starting soil temperature (C)
```

Section 3

```
# Specifiy exactly 13 depths - (cm)
layers   1  2  3 4  5  6  7  8  9  10  11  12  13

# Specify fire intensity (Kw/m2) for Wood/Liter and Herb/Shrub
efficiency-WL    15    percent of Wood and Liter fire intensity applied to soil surface
efficiency-HS    10    percent of Herbaceous and Shrub fire intensity applied to soil surface
fi-interval       15    time between fire intensity values listed in arrays below - (sec)
```

Section 4

```
# Fire intensity (kW/m2) arrays for Wood/Liter and Herb/Shurb
# specify total fire intensity (above efficiency percents will be applied to these values)
# values must start on the line immediately after 'fire-intensity'
fire-intensity
    22     10
    43     21
    65     31
    86     42
    35      0
    26      0
    23      0
    21      0
    19      0
    18      0
    17      0
    17      0
    16      0
    15      0
    14      0
```

Soil Family Description

- **Loamy-Skeletal**: Rock fragments make up 35% or more by volume; enough fine earth to fill interstices larger than 1 mm; the fraction finer than 2 mm is loamy as defined for the loamy particle-size class.

- **Fine-Silty:** By weight, <15% of the particles are fine sand (diameter 0.25-0.1 mm) or coarser, including fragments up to 7.5 cm in diameter; 18 – 34% clay in the fine-earth fraction.

- **Fine:** A clayey particle-size class that has 35 – 59% clay in the fine-earth fraction.
- **Coarse-Silty**: By weight, <15% of the particles are fine sand (diameter 0.25-0.1 mm) or coarser, including fragments up to 7.5 cm in diameter; <18% clay in the fine-earth fraction.
- **Coarse-Loamy**: By weight, 15% or more of the particles are fine sand (diameter 0.25-0.1 mm) or coarser, including fragments up to 7.5 cm in diameter; <18% clay in the fine-earth fraction.

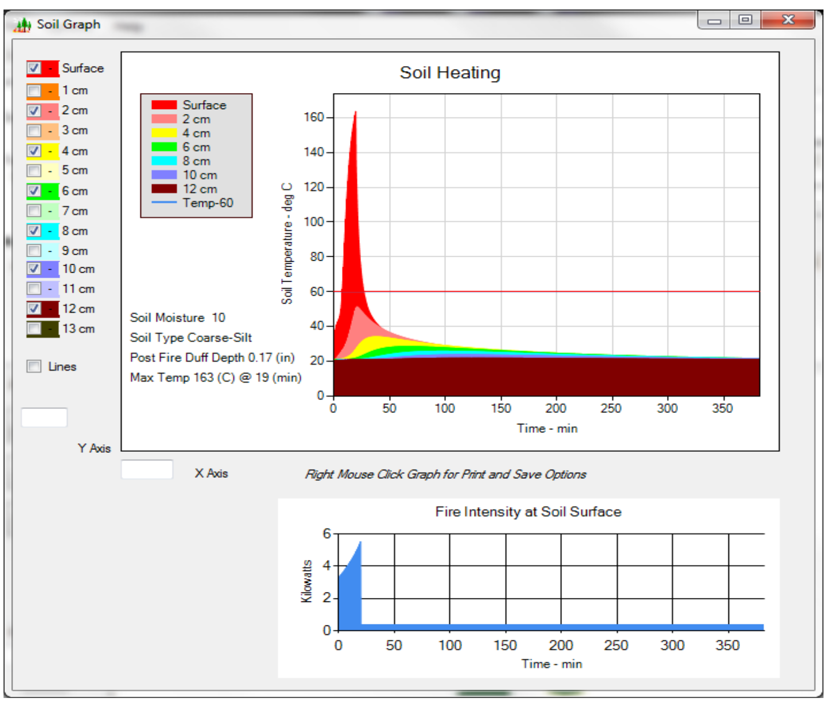
Descriptions of soil types used in the development of the soil heating model (Campbell, et al. 1995)

Soil Name	Soil Family Type	Soil Class	Location
Quincy sand	Sand	Mixed mesic Xeric Torripsamment	Hanford, WA
Boldercreek	Loamy-skeletal	Mixed frigid Typic vitrandept	Wallace, ID
Palouse B	Fine-silty	Mixed mesic Pachic Ultic Haploxeroll	Whitman Co. WA
Volkmar	Silt loam	Aeric Cryaquept	Delta, AK

Soil Simulation Outputs

The results of each soil heating simulation will be output in graphical form.

The graphical format plots temperature in Celsius (C) verses time in minutes and allows for scaling adjustments along the x and y-axis. The graph displays temperature at each depth and highlights temperatures that exceed 60 degrees C; this temperature is typically considered the lethal tissue temperature for living organisms. The graphical output also includes the starting soil moisture, soil type, post fire duff depth and maximum temperature reached at the soil surface. Intensity is shown in the bottom graph. Right-click either graph to save or print the image.



Output Graphing File

FOFEM can create an output text file that can be used as input for other graphing programs, for example Excel or SPSS. To save the soil points to a file select **Options > Save Soil Temp Points File**.

Below is a small part of an output file. The grid of values that represents the current graph displayed in the FOFEM graph window. Accordingly, you must create a soil graph before you attempt to save the points to a file.

Time	Surface	1-cm	2-cm	3-cm	4-cm	5-cm	6-cm	7-cm	8-cm
min.	cm								
0.3	31.4	21.6	21.0	21.0	21.0	21.0	21.0	21.0	21.0
0.7	34.3	22.3	21.0	21.0	21.0	21.0	21.0	21.0	21.0
1.0	36.4	23.0	21.0	21.0	21.0	21.0	21.0	21.0	21.0
1.3	37.9	23.9	21.0	21.0	21.0	21.0	21.0	21.0	21.0
…	…	…	…	…	…	…	…	…	…

Column 1 is decimal minutes since ignition, column 2 is the temperature (C) of surface layer at the specified time, column 3 is the temperate at 1 cm depth and subsequent columns show soil temperature at the specified depth. The temperature of 21ºC represents the ambient temperature that is used in this example.

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Robichaud, PR, WJ Massman, AS Bova, A Girona-Garcia, and M Lesiecki. 2018. The Next Generation Soil Heating Model. FINAL REPORT for JFSP PROJECT ID: 15-1-05-11.

Scientific Content - Computing Bark Thickness

FOFEM bark thickness equations are from the equations and sources listed in the Forest Vegetation Simulator with modifications made using descriptions in: North American Trees by R.J. Preston, Jr.; A Natural History of Western Trees and A Natural History of Trees of Eastern and Central North America by D. C. Peattie and The Audubon Society Field Guide to North American Trees, Western and Eastern regions by E. L. Little. In the FOFEM model, spruce spp. mortality is constrained to be at least 80 percent, thus the FOFEM bark thickness equations for the spruces are the least researched.

Single bark thickness (SBT) is assumed to have a linear relationship to diameter breast height (DBH), both measured in inches, in the form SBT=v(DBH); where v is a species specific bark thickness coefficient from table 1. Species specific bark thickness indices can be found in the "Brk" column of the FOF_SPP.CSV file typically located in: *C:\Users*\username*\AppData\Local\FOFEM6.5.*

FOFEM bark thickness indices and coefficients.

Bark thickness index FOF_SPP.CSV	**Bark thickness coefficient**	**Bark thickness index FOF_SPP. DAT**	**Bark thickness coefficient**
1	0.019	21	0.042
2	0.022	22	0.043
3	0.024	23	0.044
4	0.025	24	0.045
5	0.026	25	0.046
6	0.027	26	0.047
7	0.028	27	0.048
8	0.029	28	0.049
9	0.03	29	0.05
10	0.031	30	0.052
11	0.032	31	0.055
12	0.033	32	0.057
13	0.034	33	0.059
14	0.035	34	0.06
15	0.036	35	0.062
16	0.037	36	0.063
17	0.038	37	0.068
18	0.039	38	0.072
19	0.04	39	0.081
20	0.041	100	[1]

[1]*Longleaf SBT = 0.435 + (0.031 * DBH)* *(SBT and DBH measured in cm)*

Source: Wang, GG; Wangen, S; Reinhardt, E; Waldrop, TA, Outcalt, KW; Walker, JL; Brockway, DG; Haywood, JD; Hiers, JK. 2007. Modify FOFEM for use in the Coastal Plain Region of the Southeastern US. JFSP Program Report: 05-4-3-06. Available at: http://www.firescience.gov/projects/05-4-3-06/project/05-4-3-06_final_report.pdf.

Scientific Content - Computing Tree Mortality

Estimating Tree Mortality – Crown Scorch (CRNSCH)

These equations were called "pre-fire" equations in previous version of FOFEM. Tree mortality is estimated using bark thickness and percent crown volume scorched as independent variables. This assumption, while extremely simplistic, allows mortality to be simulated for trees as long as bark thickness (estimated using species-DBH relationships), tree height, crown ratio and scorch height are known. The CRNSCH models all predict tree mortality occurring within 3 years of the fire.

Either crown scorch height or flame length may be used in FOFEM to predict tree mortality. If flame length is entered, scorch height is computed using Van Wagner's (1973) scorch height model, assuming a temperature of 77 degrees F and a midflame wind speed of 0 mph. These values seem conservative for many situations since computed scorch height varies little with temperature between 40 and 80 degrees F, and wind speeds between 0 and 10 mph. These ranges encompass many prescribed fire situations. At higher wind speeds typical of many wildfires, computed scorch heights actually decrease for a given flame length, so predicted scorch height and consequently, tree mortality will be over predicted. Entering scorch height directly allows the user to bypass these assumptions. Van Wagner's scorch height model was developed from stands of red pine on flat ground; it can be expected to perform poorly on steep slopes, at ridge tops, and in stands with large openings in the canopy. Again, using scorch height as a predictive variable, instead of flame length, allows the user to avoid errors in predicting scorch height. This may be an especially good option when predicting effects of fire after the fact – in this case scorch height can be observed directly in the field.

The data from which the tree mortality algorithm was developed was limited to western conifers greater than 5 inches DBH under burned with prescribed fire. The predictions should apply reasonably well to wildfires. Some post fire insect damage is implicitly included in these predictions, as trees damaged by insects after burning were not excluded from the data. Major post fire insect attacks are not modeled however. Root damage is not explicitly modeled, although it may be correlated with cambial damage in many cases.

The mean, standard error, median, and range of crown scorch and DBH by species of trees used to develop some of the crown scorch mortality models are listed below.

Species	No. of trees	Type[1]	Crown Scorch %			DBH (cm)		
			Mean ±SE	Md	Range	Mean ±SE	Md	Range
Lodgepole pine	2196	V	19 ± 0.7	0	0-100	20.8 ± 0.1	19.6	10.2-56.4
Whitebark pine	148	V	24 ± 2.9	2	0-100	22.9 ± 0.6	22.5	12.4-58.9
Engelmann spruce	223	V	30 ± 2.2	20	0-100	33.2 ± 1.1	30.2	12.7-85.1
Red fir	209	L	42 ± 1.8	46	0-89	42.1 ± 1.2	38.9	15.2-104.6
Subalpine fir	947	V	65 ± 1.3	85	0-100	19.4 ± 0.2	17.5	10.2-75.2
White fir	2304	L	67 ± 0.5	74	0-100	59.2 ± 0.4	56.9	15.2-152.7
Incense cedar	783	L	40 ± 1.1	38	0-98	51.6 ± 0.9	43.7	25.4-166.4
Yellow pine[2]	7309	V	58 ± 0.4	70	0-100	41.8 ± 0.3	35.1	6.3-178.1
Douglas-fir	1539	V	34 ± 0.9	20	0-100	33.7 ± 0.4	30.5	10.2-105.4
Western larch	461	V	26 ± 1.7	5	0-100	38.1 ± 0.6	38.1	10.2-98.8
Sugar pine	719	L	40 ± 1.1	41	0-98	73.3 ± 1.0	70.4	25.6-188.0

[1] L = crown length; V = crown volume

[2] Includes ponderosa and Jeffrey pine

Mortality Equations - CRNSCH

NOTES:

Total Crown Length = tree height * (crown ratio/10)

NOTE: The FOFEM interface expects crown ratio, in integer values, from 1 to 10. When reading input files FOFEM expects crown ratio in integer values from 1 to 100 and the denominator in this equation is 100.

Crown Length Scorched = scorch height – (tree height – total crown length)

NOTE: If result is negative, crown length scorched = 0. If crown length scorched is greater than total crown length then crown length scorched = total crown length.

% Crown Volume Scorched = 100 * (crown length scorched * (2.0 * total crown length – crown length scorched)) / total crown length ^2

Based on Peterson, D.L. and Ryan, K.C. 1986. Modeling Postfire Conifer Mortality for Long-range Planning. Environmental Management. 10(6) 797-808.

% Crown Length Scorched = 100 * (crown length scorched/total crown length)

Equation 1:

Used when other equations are not specified. P_m = probability of mortality, BT=bark thickness (in), CS= crown volume scorched (%)

If DBH> 1” then $P_m = 1/[1+\exp(-1.941+(6.316*(1.0-\exp(-BT)))-0.000535*CS^2))]$

If DBH < 1” and Crown Height/Length Scorched > 50% then $P_m = 1$

If DBH < 1” and Ht < 3’ then $P_m = 1$

Else $P_m = 1/[1+\exp(-1.941+(6.316*(1.0-\exp(-BT)))-0.000535*CS^2))]$

Source: *Ryan, K.C. and Amman, G.D. 1994. Interactions between fire-injured trees and insects in the Greater Yellowstone Area. pp. 259-271 in: DG Despain (ed) Plants and their Environments: Proceedings of the First Biennial Scientific Conference on the Greater Yellowstone Ecosystem.*

Equation 3:

Spruces other than Engelmann

Same as Equation 1 but constrains mortality to at least 80%

Source: Anecdotal evidence

Equation 4:

Quaking Aspen. CH=char height (in.) (CH= Flame height/1.8), DBH (in.)

If Fire Severity = “Low” then

$$P_m = 1/[1+\exp((0.251*(DBH*2.54)-(0.07*CH*2.54*12)-4.407)]$$

If Fire Severity <> “Low” then

$$P_m = 1/[1+\exp((0.0858*DBH*2.54)-(0.118*CH*2.54*12)-2.157)]$$

Source: *Brown, J. K.; DeByle, N. V. 1987. Fire damage, mortality, and suckering in aspen. Canadian Journal of Forest Research. 17: 1100-1109*.

Equation 5:
Longleaf pine: BT=bark thickness (cm); SCH=proportion of crown volume scorched (0-10).
BT=0.435+(0.031*DBH(cm))
If SCH= 0 then P_m=0
If SCH>0 then P_m=1/(1+e^0.169+(5.136*BT)+(14.492*BT^2)-(0.348*SCH^2))
Cutoff for mortality is 0.3 rather than 0.5.
Source: *Wang, GG; Wangen, S; Reinhardt, E; Waldrop, TA, Outcalt, KW; Walker, JL; Brockway, DG; Haywood, JD; Hiers, JK. 2007. Modify FOFEM for use in the Coastal Plain Region of the Southeastern US. JFSP Program Report: 05-4-3-06. Available at: http://www.firescience.gov/projects/05-4-3-06/project/05-4-3-06_final_report.pdf*

This equation was one of 14 equations developed by Wang and others for predicting probability of longleaf mortality from low severity prescribed fire in the Southeastern Plains, Middle Atlantic Coastal Plains and Southern Coastal Plain in the southeastern U.S. Some of the other longleaf mortality equations included in Wang and others JFSP report have better predictive power but require input of relative humidity, an input not currently available in FOFEM. While not the optimal selection the equation from Wang, et al. that FOFEM uses in this version performs better than the equation used in previous version of FOFEM and was selected because it could be easily included incorporated in FOFEM. When FOFEM is updated to allow more complex inputs for predicting tree mortality and/or new longleaf pine mortality equations are developed FOFEM will be updated according.

Equation 10:
White fir: CLS=Crown length scorched (%)

$$P_m = 1/\left[1 + \exp\left(-\left(-3.5083 + (CLS * 0.0956) - (CLS^2 * 0.00184) + (CLS^3 * 0.000017)\right)\right)\right]$$

Source: *Hood, S.M.; Lutes, D.C. 2017. Predicting post-fire tree mortality for 12 western US conifers using the First-Order Fire Effects Model (FOFEM). Fire Ecology 13:66-84.*

Equation 11:
Subalpine fir and grand fir: CVS = crown volume scorched (%)

$$P_m = 1/\left[1 + \exp\left(-\left(-1.6950 + (CVS * 0.2071) - (CVS^2 * 0.0047) + (CVS^3 * 0.000035)\right)\right)\right]$$

Source: *Hood, S.M.; Lutes, D.C. 2017. Predicting post-fire tree mortality for 12 western US conifers using the First-Order Fire Effects Model (FOFEM). Fire Ecology 13:66-84.*

Equation 12:
Incense cedar: CLS = crown length scorched (%)

$$P_m = 1/\left[1 + \exp\left(-\left(-4.2466 + (CLS^3 * 0.000007172)\right)\right)\right]$$

Source: *Hood, S.M.; Lutes, D.C. 2017. Predicting post-fire tree mortality for 12 western US conifers using the First-Order Fire Effects Model (FOFEM). Fire Ecology 13:66-84.*

Equation 14:
Western larch: CVS = crown volume scorched (%), dbh = diameter breast height (cm)

$$P_m = 1/\left[1 + \exp\left(-\left(-1.6594 + (CVS * 0.0327) - (dbh * 0.0489)\right)\right)\right]$$

Source: *Hood, S.M.; Lutes, D.C. 2017. Predicting post-fire tree mortality for 12 western US conifers using the First-Order Fire Effects Model (FOFEM). Fire Ecology 13:66-84.*

Equation 15:
Engelmann spruce: CVS = crown volume scorched (%)
$$P_m = 1/[1 + \exp(-(0.0845 + (CVS * 0.0445)))]$$
Source: *Hood, S.M.; Lutes, D.C.. 2017. Predicting post-fire tree mortality for 12 western US conifers using the First-Order Fire Effects Model (FOFEM). Fire Ecology 13:66-84.*

Equation 16
Red fir: CLS = crown length scorched (%)
$$P_m = 1/\left[1 + \exp\left(-\left(-2.3085 + (CLS^3 * 0.000004059)\right)\right)\right]$$
Source: *Hood, S.M.; Lutes, D.C. 2017. Predicting post-fire tree mortality for 12 western US conifers using the First-Order Fire Effects Model (FOFEM). Fire Ecology 13:66-84.*

Equation 17:
Whitebark pine and lodgepole pine: CVS = crown volume scorched (%)
$$P_m = 1/\left[1 + \exp\left(-\left(-0.3268 + (CVS * 0.1387) - (CVS^2 * 0.0033) + (CVS^3 * 0.000025) - (dbh * 0.0266)\right)\right)\right]$$
Source: *Hood, S.M.; Lutes, D.C. 2017. Predicting post-fire tree mortality for 12 western US conifers using the First-Order Fire Effects Model (FOFEM). Fire Ecology 13:66-84.*

Equation 18:
Sugar pine: CLS = crown length scorched (%)
$$P_m = 1/\left[1 + \exp\left(-\left(-2.0588 + (CLS^2 * 0.000814)\right)\right)\right]$$
Source: *Hood, S.M.; Lutes, D.C. 2017. Predicting post-fire tree mortality for 12 western US conifers using the First-Order Fire Effects Model (FOFEM). Fire Ecology 13:66-84.*

Equation 19:
Ponderosa/Jeffrey pine: CVS = crown volume scorched (%)
$$P_m = 1/\left[1 + \exp\left(-\left(-2.7103 + (CVS^3 * 0.000004093)\right)\right)\right]$$
Source: *Hood, S.M.; Lutes, D.C. 2017. Predicting post-fire tree mortality for 12 western US conifers using the First-Order Fire Effects Model (FOFEM). Fire Ecology 13:66-84.*

Equation 20:
Douglas-fir: CVS = crown volume scorched (%)
$$P_m = 1/\left[1 + \exp\left(-\left(-2.0346 + (CVS * 0.0906) - (CVS^2 * 0.0022) + (CVS^3 * 0.000019)\right)\right)\right]$$
Source: *Hood, S.M.; Lutes, D.C. 2017. Predicting post-fire tree mortality for 12 western US conifers using the First-Order Fire Effects Model (FOFEM). Fire Ecology 13:66-84.*

Equation 21:
Black Hills ponderosa pine: DBH (cm)
(1) Seedlings (Height <1.37 m (4.5 ft)): flame length (cm), height (cm)
P_m *= 1/(1 + EXP(-(2.714 + (4.08 * flame length) + (-3.63 * height))))*

(2) Saplings (Height >1.37 m (4.5 ft) and DBH <10.2 cm (4 in.)): flame length (m), height (m)
P_m *= 1/(1 + EXP(-(-0.7661 + (2.7981 * flame length) + (-1.2487 * height))))*

(3) Other trees (DBH >10.2 cm (4 in.)): DBH (cm), CLS = live crown length scorched (%)
P_m *= 1/(1 + EXP(-(1.104 + (DBH * -0.156) + (0.013* CLS) + (0.001 * DBH * CLS))))*
Where;
CLS = ((max height of crown length scorched – canopy base height)/(tree height – canopy base height)) *100

Black Hills PIPO Eq.1 - Seedlings: *Battaglia, M.; Smith, F.W.; Sheppard, W.D. 2009. Predicting Mortality of ponderosa pine regeneration after prescribed fire in the Black Hill, South Dakota, USA. Int'l. Jour. Wildland Fire. 18; 176-190*

Battaglia, M.; Smith, F.W.; Sheppard, W.D. 2008. Can prescribed fire be used to maintain fuel treatment effectiveness over time in Black Hills ponderosa pine forests? For. Ecol. And Mgt. 256: 2029-2038

Used published Eq. 2 (table 5) from the IJWF paper (same as Eq. 1 in the For. Ecol. Mgt. paper). Used this equation because independent variables are in FOFEM data. NOTE: Email from Battaglia Aug. 5, 2016 clarifying the sign of the intercept term.

NOTE: Set DBH to 0.1 when using this equation

Black Hills PIPO Eq.2 - Saplings: *Battaglia, M.; Smith, F.W.; Sheppard, W.D. 2009. Predicting Mortality of ponderosa pine regeneration after prescribed fire in the Black Hill, South Dakota, USA. Int'l. Jour. Wildland Fire. 18; 176-190*

Battaglia, M.; Smith, F.W.; Sheppard, W.D. 2008. Can prescribed fire be used to maintain fuel treatment effectiveness over time in Black Hills ponderosa pine forests? For. Ecol. And Mgt. 256: 2029-2038

Used published Eq. 4 (Table 6) from the IJWF paper (same as Eq. 3 in For. Ecol. And Mgt. paper). Picked the DBH limit of 4 in. based on range of saplings described in Table 3 in the IJWF paper. Used this equation because independent variables are in FOFEM data.

Black Hills PIPO Eq. 3 - >4 in. DBH: *Keyser, T.L.; Smith, F.W.;Lentile, L.B.; Sheppard, W.D. 2006. Modeling postifire mortality of ponderosa pine following a mixed-severity wildfire in the Black Hill: The role of tree morphology and direct fire effects. For. Sci. 52(5): 530-539*

Used published Eq. 2 (table 1) because it has the highest H-L and ROC of the equations that used independent variables available in FOFEM.

Estimating Tree Mortality – Crown Damage-Cambium Kill Rating-Beetle Attack (CRCABE)

These equation were called "post-fire" equations in previous versions of FOFEM. Tree mortality using the CRCABE mortality equation type is computed using algorithms presented in Hood and Lutes 2017. The CRCABE mortality models are generally more accurate than the CRNSCH equation type; however, assessing cambium kill rating and presence of bark beetle damage require specific training, which may limit application of the equation type. The CRCABE models all predict tree mortality occurring within 3 years of the fire.

The models were developed using these potential variables: DBH, crown damage percent, cambium kill rating (CKR), and bark beetle attacks.

> Crown damage: a value from 0 to 100 based on percent total crown length scorched, percent total crown volume scorched or percent total crown volume killed (bud kill).
>
> DBH: diameter at breast height in inches.
>
> CKR: Cambium Kill Rating. A value from 0 to 4, obtained by sampling a small section of the cambium at ground line at four evenly spaced locations around the tree. CKR is the number of dead cambium samples.
>
> Bark beetles: presence/absence of bark beetle attack signs such as boring dust and pitch tubes. This variable is not required for all species.

For the vast majority of tree species, the percentage crown needle scorch and crown bud kill are equal. Therefore, the term crown scorch has been used throughout FOFEM to indicate the level of post-fire crown injury. The two exceptions in the post-fire injury species list are ponderosa pine and Jeffrey, which have both crown needle scorch and crown bud kill equations in FOFEM. The kill model is more accurate than the scorch model because it reflects the true crown injury level and ability of the tree to recover its crown over time. However, one cannot assess crown kill until the first bud break after the fire. If post-fire tree mortality must be assessed before bud-break, the crown scorch model can be used. In the species selection dropdown list in FOFEM the Jeffery pine and ponderosa pine equations that use crown kill to predict mortality use a species code followed with a K (e.g., PIPOK and PIJEK). The equations that use crown scorch do not include a K (e.g., PIPO and PIJE).

The mean, standard error, median, and range of crown scorch and DBH by species of trees used to develop Crown Damage-CKR-Beetle mortality models are shown below.

Species	No. of trees	Type[1]	Crown Scorch %			DBH (cm)		
			Mean ±SE	Md	Range	Mean ±SE	Md	Range
Lodgepole pine	2038	V	19 ± 0.7	0	0-100	20.8 ± 0.1	19.6	10.2-56.4
Whitebark pine	148	V	24 ± 2.9	2	0-100	22.9 ± 0.6	22.5	12.4-58.9
Engelmann spruce	223	V	30 ± 2.2	20	0-100	33.2 ± 1.1	30.2	12.7-85.1
Red fir	209	L	42 ± 1.8	46	0-89	42.1 ± 1.2	38.9	15.2-104.6
Subalpine fir	947	V	65 ± 1.3	85	0-100	19.4 ± 0.2	17.5	10.2-75.2
White fir	2304	L	67 ± 0.5	74	0-100	59.2 ± 0.4	56.9	15.2-152.7
Incense cedar	783	L	40 ± 1.1	38	0-98	51.6 ± 0.9	43.7	25.4-166.4
Yellow pine[2]	4115	V	62 ± 0.6	80	0-100	47.1 ± 0.4	40.1	9.7-178.1
Douglas-fir	1409	V	33 ± 0.9	20	0-100	33.2 ± 0.5	30.0	10.2-105.4
Western larch	389	V	15 ± 1.3	0	0-100	38.8 ± 0.7	39.4	10.2-98.8
Sugar pine	719	L	40 ± 1.1	41	0-98	73.3 ± 1.0	70.4	25.6-188.0

[1] L = crown length; V = crown volume [2] Includes ponderosa and Jeffrey pine

Mortality Equations – CRCABE

Equation WF:
White fir post-fire: CKR = Cambium Kill Rating, CLS = crown length scorched (%), beetles = ambrosia beetle (attacked value = 1; unattacked value = -1), DBH (cm)

$$P_m = 1/\left[1+\exp\left(-\left(-3.5964+(CLS^3*0.00000628)+(CKR*0.3019)+(DBH*0.019)+(beetles*0.5209)\right)\right)\right]$$

Source: *Hood S, Lutes D. 2017. Predicting post-fire tree mortality for 12 western US conifers using the First-Order Fire Effects Model (FOFEM). Fire Ecology 13:66-84.*

Equation SF:
Subalpine fir and grand fir post-fire: CKR = Cambium Kill Rating, CVS = crown volume scorched (%)

$$P_m = 1/\left[1+\exp\left(-\left(-2.6036+(CVS^3*0.000004587)+(CKR*1.3554)\right)\right)\right]$$

Source: *Hood S, Lutes D. 2017. Predicting post-fire tree mortality for 12 western US conifers using the First-Order Fire Effects Model (FOFEM). Fire Ecology 13:66-84.*

Equation IC:
Incense cedar post-fire: CKR = Cambium Kill Rating, CLS = crown length scorched (%)

$$P_m = 1/\left[1+\exp\left(-\left(-5.6465+(CLS^3*0.000007274)+(CKR*0.5428)\right)\right)\right]$$

Source: *Hood S, Lutes D. 2017. Predicting post-fire tree mortality for 12 western US conifers using the First-Order Fire Effects Model (FOFEM). Fire Ecology 13:66-84.*

Equation WL:
Western larch post-fire: CKR = Cambium Kill Rating, CVS = crown volume scorched (%)

$$P_m = 1/\left[1+\exp\left(-\left(-3.8458+(CVS^2*0.0004)+(CKR*0.6266)\right)\right)\right]$$

Source: *Hood S, Lutes D. 2017. Predicting post-fire tree mortality for 12 western US conifers using the First-Order Fire Effects Model (FOFEM). Fire Ecology 13:66-84.*

Equation WP:
Whitebark pine and lodgepole pine post-fire: CKR = Cambium Kill Rating, CVS = crown volume scorched (%), DBH (cm)

$$P_m = 1/\left[1+\exp\left(-\left(-1.4059+(CVS^3*0.000004459)+(CKR^2*0.2843)-(DBH*0.0485)\right)\right)\right]$$

Source: *Hood S, Lutes D. 2017. Predicting post-fire tree mortality for 12 western US conifers using the First-Order Fire Effects Model (FOFEM). Fire Ecology 13:66-84.*

Equation ES:
Engelmann spruce post-fire: CKR = Cambium Kill Rating, CVS = crown volume scorched (%)

$$P_m = 1/\left[1+\exp\left(-\left(-2.9791+(CVS*0.0405)+(CKR*1.1596)\right)\right)\right]$$

Source: *Hood S, Lutes D. 2017. Predicting post-fire tree mortality for 12 western US conifers using the First-Order Fire Effects Model (FOFEM). Fire Ecology 13:66-84.*

Equation SP:
Sugar pine post-fire: CKR = Cambium Kill Rating, CLS = crown length scorched (%), beetles = Red turpentine beetle and/or Mountain pine beetle (attacked value = 1; unattacked value = -1)

$$P_m = 1/\left[1+\exp\left(-\left(-2.7598+(CLS^2*0.000642)+(CKR^3*0.0386)+(beetles*0.8485)\right)\right)\right]$$

Source: *Hood S, Lutes D. 2017. Predicting post-fire tree mortality for 12 western US conifers using the First-Order Fire Effects Model (FOFEM). Fire Ecology 13:66-84.*

Equation RF:
Red fir post-fire: CKR = Cambium Kill Rating, CLS = crown length scorched (%)

$$P_m = 1/\left[1+\exp\left(-\left(-4.7515+(CLS^3*0.000005989)+(CKR*1.0668)\right)\right)\right]$$

Source: *Hood S, Lutes D. 2017. Predicting post-fire tree mortality for 12 western US conifers using the First-Order Fire Effects Model (FOFEM). Fire Ecology 13:66-84.*

Equation DF:
Douglas-fir post-fire: CKR = Cambium Kill Rating, CVS = crown volume scorched (%), beetles = Douglas-fir beetle (attacked value = 1; unattacked value =0) , DBH (cm)

$$P_m = 1/\left[1+\exp\left(-\left(\begin{array}{l}-1.8912+(CVS*0.07)-(CVS^2*0.0019)+(CVS^3*0.000018)+(CKR*0.5840)\\-(DBH*0.031)-(beetles*0.7959)+(DBH*beetles*0.0492)\end{array}\right)\right)\right]$$

Source: *Hood S, Lutes D. 2017. Predicting post-fire tree mortality for 12 western US conifers using the First-Order Fire Effects Model (FOFEM). Fire Ecology 13:66-84.*

Equation PP:
Ponderosa pine and Jeffrey pine (scorch) post-fire: CKR = Cambium Kill Rating, CVS = crown volume scorched (%), beetles = mountain pine beetle, red turpentine beetle, or ips beetle (attacked value = 1; unattacked value =0)

$$P_m = 1/\left[1+\exp\left(-\left(-4.1914+(CVS^2*0.000376)+(CKR*0.5130)+(beetles*1.5873)\right)\right)\right]$$

Source: *Hood S, Lutes D. 2017. Predicting post-fire tree mortality for 12 western US conifers using the First-Order Fire Effects Model (FOFEM). Fire Ecology 13:66-84.*

Equation PK:
Ponderosa pine and Jeffrey pine (kill) post-fire: CKR = Cambium Kill Rating, CVK = crown volume killed (%)
beetles = mountain pine beetle, red turpentine beetle, or ips beetle (attacked value = 1; unattacked value =0)

$$P_m = 1/\left[1+\exp\left(-\left(-3.5729+(CVK^2*0.000567)+(CKR*0.4573)+(beetles*1.6075)\right)\right)\right]$$

Source: *Hood S, Lutes D. 2017. Predicting post-fire tree mortality for 12 western US conifers using the First-Order Fire Effects Model (FOFEM). Fire Ecology 13:66-84.*

Estimating Tree Mortality - Bole Char (BOLCHR)

Tree mortality using the BOLCHR mortality equation type is computed using algorithms presented in Keyser et al. 2018.

Data were collected two years after, typically, late dormant season prescribed fire on 210 plots in 13 National Parks in the Southern U.S. The models predict the probability of mortality using species, DBH and bole char height. Char height was measured from the ground to the highest point of bole char regardless of slop position. Total tree height and base of live crown were not measured and recorded so they could not be included in the analysis. Tree recorded as dead included those with top-kill (main bole killed but potentially sprouting) as the result of the fire. Goodness-of-fit varied with poorest fit generally associated with fire tolerant species and best fit with fire sensitive species.

Values represent the median ± s.d. (minimum, maximum). Asterisks (*) indicate a significant difference between trees recorded as live and dead 2 years following prescribed fire according to Wilcoxon Rank Sum Test. *DBH*, diameter at breast height (cm); *CHAR*, maximum bole char height (m); *Burn units*, Percentage of all burn units (n=91) containing a given species; *Plots*, percentage of all plots (n=210) containing a given species.

Species	Number of trees	DBH (cm)	CHAR (m)	Burn units	Plots
Acer rubrum	610	16.4 ± 9.0* (2.5, 70.0)	0.1 ± 0.5 (0.0, 3.5)	58	43
Cornus florida	134	5.3 ± 5.3* (2.5, 23.9)	0.2 ± 0.3* (0.0, 2.0)	25	15
Nyssa sylvatica	330	10.0 ± 10.9* (2.5, 66.8)	0.5 ± 0.8* (0.0, 5.3)	51	38
Oxydendrum arboreum	344	15.3 ± 7.8* (2.5, 40.0)	0.2 ± 1.0* (0.0, 7.0)	36	31
Quercus alba	626	25.6 ± 13.5* (2.5, 84.4)	0.2 ± 0.8* (0.0, 6.5)	66	45
Quercus coccinea	601	29.7 ± 12.8* (2.5, 82.2)	0.5 ± 0.8* (0.0, 10.0)	66	53
Quercus marilandica	188	18.3 ± 7.5* (2.9, 45.2)	0.3 ± 0.9* (0.0, 4.8)	26	16
Quercus montana	830	25.8 ± 13.0* (2.7, 97.0)	0.3 ± 1.0* (0.0, 7.0)	45	37
Quercus velutina	459	26.8 ± 14.2* (2.7, 76.3)	0.4 ± 0.9* (0.0, 12.0)	64	44
Sassafras albidum	73	4.3 ± 4.3 (2.5, 25.4)	0.4 ± 0.6* (0.0, 2.9)	13	9

Mortality Equations - BOLCHR

Equation 100:
Red maple: DBH = Diameter breast height (cm), CHAR = Maximum bole char height (m)

$$P_m = 1/[1 + Exp(-(2.3017 + (-0.3267 * DBH) + (1.1137 * CHAR))]$$

Source: *Keyser, T.L.; McDaniel, V.L.; Klein, R.N.; Drees, D.G; Burton, J.A.; Forder, M.M. 2018. Short-term stem mortality of 10 deciduous broadleaved species following prescribed burning in upland forests of the Southern US. International Journal of Wildland Fire. 27: 42-51.*

Equation 101:
Flowering dogwood: DBH = Diameter breast height (cm), CHAR = Maximum bole char height (m)

$$P_m = 1/[1 + Exp(-(-0.8727 + (-0.1814 * DBH) + (4.1947 * CHAR))]$$

Source: *Keyser, T.L.; McDaniel, V.L.; Klein, R.N.; Drees, D.G; Burton, J.A.; Forder, M.M. 2018. Short-term stem mortality of 10 deciduous broadleaved species following prescribed burning in upland forests of the Southern US. International Journal of Wildland Fire. 27: 42-51.*

Equation 102:
Blackgum: DBH = Diameter breast height (cm), CHAR = Maximum bole char height (m)

$$P_m = 1/[1 + Exp(-(2.7899 + (-0.5511 * DBH) + (1.2888 * CHAR))]$$

Source: *Keyser, T.L.; McDaniel, V.L.; Klein, R.N.; Drees, D.G; Burton, J.A.; Forder, M.M. 2018. Short-term stem mortality of 10 deciduous broadleaved species following prescribed burning in upland forests of the Southern US. International Journal of Wildland Fire. 27: 42-51.*

Equation 103:
Sourwood: DBH = Diameter breast height (cm), CHAR = Maximum bole char height (m)

$$P_m = 1/[1 + Exp(-(1.9438 + (-0.4602 * DBH) + (1.6352 * CHAR))]$$

Source: *Keyser, T.L.; McDaniel, V.L.; Klein, R.N.; Drees, D.G; Burton, J.A.; Forder, M.M. 2018. Short-term stem mortality of 10 deciduous broadleaved species following prescribed burning in upland forests of the Southern US. International Journal of Wildland Fire. 27: 42-51.*

Equation 104:
White oak: DBH = Diameter breast height (cm), CHAR = Maximum bole char height (m)

$$P_m = 1/[1 + Exp(-(-1.8137 + (-0.0603 * DBH) + (0.8666 * CHAR))]$$

Source: *Keyser, T.L.; McDaniel, V.L.; Klein, R.N.; Drees, D.G; Burton, J.A.; Forder, M.M. 2018. Short-term stem mortality of 10 deciduous broadleaved species following prescribed burning in upland forests of the Southern US. International Journal of Wildland Fire. 27: 42-51.*

Equation 105:
Scarlet oak: DBH = Diameter breast height (cm), CHAR = Maximum bole char height (m)

$$P_m = 1/[1 + Exp(-(-1.6262 + (-0.0339 * DBH) + (0.6901 * CHAR))]$$

Source: *Keyser, T.L.; McDaniel, V.L.; Klein, R.N.; Drees, D.G; Burton, J.A.; Forder, M.M. 2018. Short-term stem mortality of 10 deciduous broadleaved species following prescribed burning in upland forests of the Southern US. International Journal of Wildland Fire. 27: 42-51.*

Equation 106:
Blackjack oak: DBH = Diameter breast height (cm), CHAR = Maximum bole char height (m)

$$P_m = 1/[1 + Exp(-(0.3714 + (-0.1005 * DBH) + (1.5577 * CHAR))]$$

Source: *Keyser, T.L.; McDaniel, V.L.; Klein, R.N.; Drees, D.G; Burton, J.A.; Forder, M.M. 2018. Short-term stem mortality of 10 deciduous broadleaved species following prescribed burning in upland forests of the Southern US. International Journal of Wildland Fire. 27: 42-51.*

Equation 107:
Chestnut oak: DBH = Diameter breast height (cm), CHAR = Maximum bole char height (m)

$$P_m = 1/[1 + Exp(-(-1.4416 + (-0.1469 * DBH) + (1.3159 * CHAR))]$$

Source: *Keyser, T.L.; McDaniel, V.L.; Klein, R.N.; Drees, D.G; Burton, J.A.; Forder, M.M. 2018. Short-term stem mortality of 10 deciduous broadleaved species following prescribed burning in upland forests of the Southern US. International Journal of Wildland Fire. 27: 42-51.*

Equation 108:
Black oak: DBH = Diameter breast height (cm), CHAR = Maximum bole char height (m)

$$P_m = 1/[1 + Exp(-(0.1122 + (-0.1287 * DBH) + (1.2612 * CHAR))]$$

Source: *Keyser, T.L.; McDaniel, V.L.; Klein, R.N.; Drees, D.G; Burton, J.A.; Forder, M.M. 2018. Short-term stem mortality of 10 deciduous broadleaved species following prescribed burning in upland forests of the Southern US. International Journal of Wildland Fire. 27: 42-51.*

Equation 109:
Sassafras: DBH = Diameter breast height (cm), CHAR = Maximum bole char height (m)

$$P_m = 1/[1 + Exp(-(1.6779 + (-1.0299 * DBH) + (10.2855 * CHAR))]$$

Source: *Keyser, T.L.; McDaniel, V.L.; Klein, R.N.; Drees, D.G; Burton, J.A.; Forder, M.M. 2018. Short-term stem mortality of 10 deciduous broadleaved species following prescribed burning in upland forests of the Southern US. International Journal of Wildland Fire. 27: 42-51.*

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Canopy Cover

Canopy Cover is calculated using crown width equations, which are then converted to crown area. The equations use species specific coefficients (see table below). Once crown cover is calculated for individual trees and then accumulated for the tree list, an overlap correction factor is applied.

Equation for trees over 4.5 feet:

$CW = A * D^B$
where;
CW = Crown Width (ft)
A = A Coefficient
D = Diameter (in.)
B = B Coefficient

NOTE: Tree records without DBH will not be included in the cover calculations.

Equation for trees under 4.5 feet :

$CW = R * D$
where;
CW = Crown Width (ft)
R = Ratio Coefficient
D = Diameter (in.)

The overlap calculation is:

CovProp = (Cov / 43560)
$PctCov = 100.0 * (1.0 - exp^{CovProp})$
where;

CovProp = Proportion of each acre with crown cover
Cov = total accumulated crown cover (ft^2)
PctCov = percent crown cover adjusted for overlap (ac^{-1})

Coefficients for tree crown widths are based on data from R6 Permanent Plot Grid Inventory.

Eq no.	Scientific Name	Common Name	A Coeff.	B Coeff.	Ratio Coeff.
1	Abies amabilis	Pacific silver fir	3.9723	0.5177	0.473
2	Abies balsamea/concolor lowiana and other	Balsam/white/Sierra white fir and other	3.8166	0.5229	0.452
3	Abies grandis	Grand fir	4.187	0.5341	0.489
4	Abies lasiocarpa	Subalpine fir	3.2348	0.5179	0.385
5	Abies magnifica	Red Fir	3.1146	0.578	0.345
7	Abies procera	Noble Fir	3.0614	0.6276	0.32
8	Callitropsis nootkatensis	Alaska cedar	3.5341	0.5374	0.331
9	Chamaecyparis lawsoniana/ thyoides/Cupressus nootkatensis	Atlantic white/Port Orford cedar/Nootka cypress	4.092	0.4912	0.412
10	Picea spp	Spruce spp	3.6802	0.494	0.412
11	Pinus contorta/banksiana/clausa/ glabra/pungens/resinosa/rigida/ serotina/sylvestris/virginiana	Lodgepole/jack/sand/beach/ spruce/table mountain/red/ pitch/pond/scots/ virginia pine	2.4132	0.6403	0.298

12	Pinus jeffreyi	Jeffrey pine	3.2367	0.6247	0.406
13	Pinus lambertiana	Sugar pine	3.061	0.6201	0.385
14	Pinus monticola/strobus/larix laricina	Western and eastern white pine/tamarack/western larch	3.4447	0.5185	0.476
15	Pinus ponderosa/elliotti/ palustrus/sabiniana/taeda	Ponderosa/slash/shortleaf/ washoe/gray/loblolly pine	2.8541	0.64	0.407
16	Pseudotsuga menziesi	Douglas-fir	4.4215	0.5329	0.517
17	Sequoia gigantea/ sempervirens	Giant sequoia/redwood	4.4215	0.5329	0.517
18	Thuja/juniperus/calocedrus spp	Redcedar/arborvitae/incense-cedar	6.2318	0.4259	0.698
19	Tsuga canadensis/heterophylla	Eastern and western hemlock	5.4864	0.5144	0.533
20	Tsuga mertensiana	Mountain hemlock	2.9372	0.5878	0.253
21	Acer spp	Maple spp	7.5183	0.4461	0.815
22	Alnus rubra	Red alder	7.0806	0.4771	0.73
23	Alnus rhombifolia	White alder	7.0806	0.4771	0.73
24	Betula/celtis spp	Birch/hackberry spp	5.898	0.4841	0.601
25	Castanopsis chrysophylla	Giant chinkapin	2.4922	0.8544	0.14
26	Quaking aspen	Quaking aspen	4.091	0.5907	0.351
27	Populus spp	Cottonwood/poplar spp	7.5183	0.4461	0.815
28	Quercus spp	Oak spp	2.4922	0.8544	0.14
29	Juniperus spp	Juniper spp	4.5859	0.4841	0.468
30	Larix lyallii	Subalpine larch	2.1039	0.6758	0.207
31	Pinus albicaulis/flexilis	Whitebark/limber pine	2.1606	0.6897	0.255
32	Pinus attenuata	Knobcone pine	2.1451	0.7132	0.248
33	Taxus brevifolia	Pacific yew	4.5859	0.4841	0.468
34	Cornus spp	Dogwood spp	2.4922	0.8544	0.14
35	Crataegus spp	Hawthorn spp	4.5859	0.4841	0.468
36	Prunus spp	Cherry spp	4.5859	0.4841	0.468
37	Salix spp	Willow spp	4.5859	0.4841	0.468
39	Other	Other	4.4215	0.5329	0.517

Canopy Cover Equation Citation

Crookston, N.L. and Stage, A.R. 1999. Percent canopy cover and stand structure statistics from the Forest Vegetation Simulator. Gen. Tech. Rep. RMRS-GTR-24. Ogden, UT: U. S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 11 p.

Scientific Content - Fuel Consumption

Default Fuelbeds

Default fuelbeds include loading for fuel components. Fuel loads are based on cover type and on fuel type (natural or slash fuels). The default loads can be adjusted (using the Typical, Light, Heavy adjustment buttons) or replaced with a user value. It is always best to enter fuel loadings directly if you have a good estimate, since fuels vary greatly within cover type.

To provide default fuel loads, an exhaustive search of fuels literature was conducted. The resulting database (Mincemoyer 2002) was added in FOFEM 5.3.

Fuel Consumption

FOFEM predicts the quantity of fuel consumed by prescribed fire or wildfire. Fuel components include duff, litter, 0 - ¼ inch, ¼ - 1 inch, 1 - 3 inch, 3 inch plus dead woody fuels (sound and rotten), herbaceous fuels, shrubs, and canopy fuels affected by crown fire. Mineral soil exposed by fire as a result of duff and litter consumption is also predicted.

One major assumption FOFEM makes in predicting fuel consumption is that the entire area experiences the fire. FOFEM does not predict fire effects for patchy or discontinuous burns. For these situations, results should be weighted by the percent of the area burned.

FOFEM uses the Burnup model to predict consumption of woody fuels. Consumption of other fuels is predicting using a variety of empirical equations and rules of thumb. Previous versions of FOFEM included a number of woody fuel consumption algorithms that were used in different cover types, geographic regions, and fuel types. Although these earlier, empirical algorithms may perform better than Burnup in certain specific circumstances, Burnup is assumed to provide a more logically consistent approach to fuel consumption estimation.

Litter Consumption

In most cases litter consumption is simulated in Burnup.

Equations are selection using a decision process that in part based on region. See Decision Dependency

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Equation 997:
When cover group is flatwood SQRT(Litter Load Consumed) = 0.2871 + (0.9140 * (SQRT(Prefire Litter Load)) – (0.0101 * Litter Moisture Percent)
Loading = Mg ha^{-1}
Source: *Wright, C.S., 2013. Fuel Consumption Models for Pine Flatwoods Fuel Types in the Southeastern United States. South. Journ. Appl. For. 37(3): 148-159.*

Equation 998:
In the Southeast region Litter Load Consumed = Prefire Litter Load * 0.8. The consumed litter load is used as an initial input to Burnup, which simulates 100% litter consumption.
Sources: *Estimate based on personal communication with managers and:*
Reid, A.M.; Robertson, K.M. and Hmielowski, T.L. 2012. Predicting litter and live herb fuel consumption during prescribed fires in native and old-field upland pine communities of southeastern United States. Can. J. For. Res. 42: 1611-1622.

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Prichard, S. J.; Karau, E.C.; Ottmar, R.D.; Kennedy, M.C.; Cronan, J.B.; Wright, C.S.; Keane, R.E. 2014. Evaluation of the CONSUME and FOFEM fuel consumption model in pine and mixed hardwood forests of the eastern United States. Can. J. For. Res. 44: 784-795.

Equation 999:
The consumption of litter is calculated by Burnup. Generally 100% of the litter is consumed.
Sources: *Albini, F.A.; Brown, J.K.; Reinhardt, E.D.; Ottmar, R.D. Calibration of a Large Fuel Burnout Model. International Journal of Wildland Fire 5(3):173-192, 1995. Albini, F.A.; Reinhardt, E.D. Improved Calibration of a Large Fuel Burnout Model. International Journal of Wildland Fire 7(1): 21-28, 1997.*

Duff Consumption

A number of different duff consumption algorithms are incorporated into FOFEM6. Separate predictions are made of percent duff consumption and duff depth consumed. These equations, their sources, and the circumstances under which each is used by FOFEM are summarized below.

Equations are selection using a decision process that in part based on region, fuel category, moisture method and Cover Group . See Decision Dependency

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Equation 1:
Used for predicting percent duff consumption (%DC) from lower duff moisture (LDM) content in the Interior West and Pacific West for activity fuels and natural fuels other than ponderosa pine cover groups.
If LDM <=160% then %DC = 97.1 - 0.519 LDM,
If LDM > 160% the %DC = 13.6,
Source: *Brown, J.K., Marsden, M.M., Ryan, K.C., Reinhardt, E.D. 1985. Predicting duff and woody fuel consumed by prescribed fire in the northern Rocky Mountains. USDA Forest Service Res. Pap. INT-337.*

Equation 2:
Used for predicting percent duff consumption (%DC) from entire or average duff moisture (EDM) content in the Interior West and Pacific West. This equation is also the default equation that FOFEM uses when it cannot find another duff consumption algorithm.
%DC = 83.7 - 0.426 EDM
Source: *Brown, J.K., Marsden, M.M., Ryan, K.C., Reinhardt, E.D. 1985. Predicting duff and woody fuel consumed by prescribed fire in the northern Rocky Mountains. USDA Forest Service Res. Pap. INT-337.*

Equation 3:
Used for predicting percent duff consumption (%DC) from NFDR 1000 hour moisture (NFDTH) content in the Interior West, Pacific West, and North East.
%DC = 114.7 - 4.20 NFDTH
Source: *Brown, J.K., Marsden, M.M., Ryan, K.C., Reinhardt, E.D. 1985. Predicting duff and woody fuel consumed by prescribed fire in the northern Rocky Mountains. USDA Forest Service Res. Pap. INT-337.*

Equation 4:
Used for predicting percent duff consumption (%DC) from lower duff moisture (LDM) content in the Interior West and Pacific West for natural fuels in the ponderosa pine groups.
%DC = 89.9 - 0.55 LDM
Source: *Harrington, M.G. 1987. Predicting reduction of natural fuels by prescribed burning under ponderosa pine in southeastern Arizona. USDA Forest Service Res. Note RM-472.*

Equation 5:
Used for predicting duff depth consumption (DDC) from lower duff moisture (LDM) content in the Interior West and Pacific West (DPRE = pre fire duff depth).
DDC = 1.028 - 0.0089 LDM + 0.417 DPRE
Source: *Brown, J.K., Marsden, M.M., Ryan, K.C., Reinhardt, E.D. 1985. Predicting duff and woody fuel consumed by prescribed fire in the northern Rocky Mountains. USDA Forest Service Res. Pap. INT-337.*

Equation 6:
Used for predicting duff depth consumption (DDC) from entire or average duff moisture (EDM) content in the Interior West and Pacific West (DPRE = pre fire duff depth). This equation is also the default equation that FOFEM uses when it cannot find another duff consumption algorithm.
DDC = 0.8811 - 0.0096 EDM + 0.439 DPRE
Source: *Brown, J.K., Marsden, M.M., Ryan, K.C., Reinhardt, E.D. 1985. Predicting duff and woody fuel consumed by prescribed fire in the northern Rocky Mountains. USDA Forest Service Res. Pap. INT-337.*

Equation 7:
Used for predicting duff depth consumption (DDC) from NFDR 1000 hour moisture (NFDTH) content in the Interior West, Pacific West, and North East (DPRE = pre fire duff depth).
DDC = 1.773 - 0.1051 NFDTH + 0.399 DPRE
Source: *Brown, J.K., Marsden, M.M., Ryan, K.C., Reinhardt, E.D. 1985. Predicting duff and woody fuel consumed by prescribed fire in the northern Rocky Mountains. USDA Forest Service Res. Pap. INT-337.*

Equation 15:
Used for predicting residual duff depth (RD) from average duff moisture (EDM) and preburn duff depth (DPRE). (PINE=1 if cover group is jack pine or 0 if other). This equation was based on data assimilated from many studies and is used where a more site specific equation is lacking.
RD = -0.791 + 0.004 EDM + 0.8 DPRE + 0.56 PINE
Source: *Reinhardt, E.D., Keane, R.E., Brown, J.K., Turner, D.L. 1991. Duff consumption from prescribed fire in the U.S. and Canada: a broadly based empirical approach. Proceedings, 11th Conference on Fire and Forest Meteorology.*

Equation 16:
Used for predicting duff consumption (%DR) in the Southeast except in pocosin cover groups.
PreDL110=litter load+duff load+1-hr load+10-hr load, EDM=entire duff moisture, PreL110=preburn litter load+1-hr+10-hr, DuLittCons=load of litter+duff consumed
DuLittCons = 3.4958 + (0.3833 PreDL110) – (0.0237 EDM) – (5.6075/PreDL110)
If DuLittCons <= PreL110 then %DR = 0
If DuLittCons > PreL110 then %DR = ((DuLittCons – PreL110) / (PreDL110 – PreL110)) * 100%
Source: *Hough, W.A. 1978. Estimating available fuel weight consumed by prescribed fires in the south. USDA Forest Service Res. Pap. SE-187.*

Equation 17:
Piles: FOFEM assumes nominal duff consumption in pile burning (Below the piles). %DR=% duff reduction
%DR = 10%
Source: *Anecdotal evidence*

Equation 19:
Chaparral: FOFEM assumes complete duff consumption in chaparral types. %DR=% duff reduction
%DR = 100%
Source: *Anecdotal evidence*

Equation 20:
Pocosin: Calculates root mat percent biomass consumption (%DR) for deep organic soils in the pocosin cover groups in the southeast US.

NOTE: This equations does not predict consumption of muck soils underlying the root mat.

The root mat and is divided into layers of no more than 4" thickness. Consumption of each layer is calculated separately then summed as the total estimated consumption. Moisture content of layer 1 (MC_{Layer}) is the duff moisture content set on the UI. Moisture content of layers 2, 3, 4, and 5 are 3%, 9%, 18% and 30% greater, respectively, than the moisture content of layer 1. Moisture content of layers 6 and greater are 12% higher than each previous layer. Percent consumption of each layer is calculated using the following logic:

If MC_{Layer} <10 then %DR=100%
If $MC_{Layer} \geq 10$ and MC_{Layer} <30 then %DR = Load * (0.949932 + ((30- MC_{Layer})*0.00251))
If $MC_{Layer} \geq 30$ and MC_{Layer} < 140 then %DR =
Load *(1/(1 + (EXP(-1*(2.033-(0.043* MC_{Layer}) + (0.44*Mineral Content*))))))
If $MC_{Layer} \geq 140$ and MC_{Layer} < 170 then %DR = Load * (0.143441-((MC_{Layer} -140)*0.0049))
If $MC_{Layer} \geq 170$ then %DR=0%

**Mineral content is set to 5%*

Source: *Reardon 2016, per. comm.; Reardon, James; Hungerford, Roger; Ryan, Kevin 2007. Factors affecting sustained smoldering in organic soils from pocosin and pond pine woodland wetlands. International Journal of Wildland Fire. 16: 107-118.*

<u>Mineral Soil Exposure</u>

The amount of mineral soil exposed by a fire is predicted using these equations:

Equation 9:
Used for predicting % mineral soil exposure (MSE) from lower duff moisture (LDM) content in activity fuels in the west.
If LDM <= 135% then MSE = 80.0 - 0.507 LDM,
If LDM > 135% then MSE =23.5 - 0.0914 LDM,
Source: *Brown, J.K., Marsden, M.M., Ryan, K.C., Reinhardt, E.D. 1985. Predicting duff and woody fuel consumed by prescribed fire in the northern Rocky Mountains. USDA Forest Service Res. Pap. INT-337.*

Equation 10:
Used for predicting % mineral soil exposure (MSE) from average duff moisture (EDM) content in the west. This is also the default equation FOFEM uses for predicting mineral soil exposure.
MSE = 167.4 - 31.6 log(EDM)
Source: *Brown, J.K., Marsden, M.M., Ryan, K.C., Reinhardt, E.D. 1985. Predicting duff and woody fuel consumed by prescribed fire in the northern Rocky Mountains. USDA Forest Service Res. Pap. INT-337.*

Equation 11:
Used for predicting % mineral soil exposure (MSE) from NFDR 1000 hour moisture (NFDTH) content in activity fuels in the west.
MSE = 93.3 - 3.55 NFDTH
Source: *Brown, J.K., Marsden, M.M., Ryan, K.C., Reinhardt, E.D. 1985. Predicting duff and woody fuel consumed by prescribed fire in the northern Rocky Mountains. USDA Forest Service Res. Pap. INT-337.*

Equation 12:
Used for % predicting mineral soil exposure (MSE) from NFDR 1000 hour moisture (NFDTH) content in natural fuels in the west.
MSE = 94.3 - 4.96 NFDTH
Source: *Brown, J.K., Marsden, M.M., Ryan, K.C., Reinhardt, E.D. 1985. Predicting duff and woody fuel consumed by prescribed fire in the northern Rocky Mountains. USDA Forest Service Res. Pap. INT-337.*

Equation 13:
Used for % predicting mineral soil exposure (MSE) from lower duff moisture (LDM) content in natural fuels in the west.
MSE = 60.4 - 0.440 LDM
Source: *Brown, J.K., Marsden, M.M., Ryan, K.C., Reinhardt, E.D. 1985. Predicting duff and woody fuel consumed by prescribed fire in the northern Rocky Mountains. USDA Forest Service Res. Pap. INT-337.*

Equation 14:
Used for % predicting mineral soil exposure (MSE) from percent duff reduction (%DR) – a robust equation used when other information is lacking.
MSE = -8.98 + 0.899 %DR
Source: *Brown, J.K., Marsden, M.M., Ryan, K.C., Reinhardt, E.D. 1985. Predicting duff and woody fuel consumed by prescribed fire in the northern Rocky Mountains. USDA Forest Service Res. Pap. INT-337.*

Equation 18:
Piles: FOFEM assumes nominal % mineral soil exposure (MSE) in pile burning (beneath the piles).
MSE = 10%
Source: *Anecdotal evidence*

Equation 202:
Pocosin group: For deep organic soils in the pocosin type, no mineral soil is exposed (MSE).
MSE = 0%
Source: *Hungerford 1996, personal communication*

Herbaceous Consumption

Herbaceous fuels generally are a small component of the total fuel load. However, for completeness, especially in modeling emission production, their consumption is computed by FOFEM. Also see Decision Dependency

---

Equation 22:
All the herbaceous fuels are assumed to burn.
Source: *Anecdotal evidence*

Equation 221:
If the cover group is grass, and the season of burn is spring, only 90% of the herbaceous fuels are consumed.
Source: *Anecdotal evidence*

Equation 222:
For the Southeast region Herb Load Consumed = -0.059 + (0.004 * Litter Fuel Load) + (0.917 * Herb Fuel Load)
Source: *Reid, A.M.; Robertson, K.M. and Hmielowski, T.L. 2012. Predicting litter and live herb fuel consumption during prescribed fires in native and old-field upland pine communities of southeastern United States. Can. J. For. Res. 42: 1611-1622.*

Equation 223:
When cover group is flatwood Herb Load Consumed = Prefire Herb Loading * 0.9944
Loading = Mg ha^{-1}
Source: *Wright, C.S., 2013. Fuel Consumption Models for Pine Flatwoods Fuel Types in the Southeastern United States. South. Journ. Appl. For. 37(3): 148-159*

Shrub Consumption

Shrub consumption is modeled using these equations. Also see Decision Dependency

---

Equation 23:
For cover groups not dominated by shrubs, shrub consumption is set to 60%.
Source: *Anecdotal evidence*

Equation 231:
For cover group not sagebrush but dominated by shrubs, shrub group (except in the southeast), shrub consumption is assumed to be 80%.
Source: *Anecdotal evidence*

Equation 232:
If the cover group is sagebrush and the season is other than fall, shrub consumption is 50%.
Source: *Anecdotal evidence*

Equation 233:
For the southeastern region, for the pocosin cover group, in spring or winter shrub consumption is 90%.
Source: *Anecdotal evidence*

Equation 233:
If the cover group is sagebrush and the season is fall, shrub consumption is 90%.
Source: *Anecdotal evidence*

Equation 234:
Used to predict percent shrub consumption for non-pocosin group in the southeast region.
Percent consumption = (((3.2484 + (0.4322 * preburn litter and duff loading) + (0.6765 * preburn shrub and regeneration loading) – (0.0276* duff moisture) – (5.0796 / preburn litter and duff loading)) – litter and duff consumption) / preburn shrub and regeneration loading) * 100%.
Sources: *Hough, W.A. 1968. Fuel consumption and fire behavior of hazard reduction burns. USDA Forest Service Res. Pap. SE-36. Hough, W.A. 1978. Estimating available fuel weight consumed by prescribed fires in the south. USDA Forest Service Res. Pap. SE-187.*

Equation 235:
For the southeastern region, for the pocosin cover group, in summer or fall shrub consumption 80%.
Source: *Anecdotal evidence*

Equation 236:
When cover group is flatwood: *ln* Shrub Consumed = -0.1889 + (0.9049 * *ln* Prefire Shrub Loading) + (0.0676 * season)
Loading = Mg ha^{-1}. Shrub loading includes saw palmetto. Season = 1 when spring or summer and 0 when fall or winter
Source: *Wright, C.S., 2013. Fuel Consumption Models for Pine Flatwoods Fuel Types in the Southeastern United States. South. J.. Appl. For. 37(3): 148-159.*

Down Woody Fuel Consumption

All down woody fuel consumption is modeled in Burnup

Equation 999:
Estimates of woody fuel consumption derived in Burnup.
Sources: *Albini, F.A.; Brown, J.K.; Reinhardt, E.D.; Ottmar, R.D. Calibration of a Large Fuel Burnout Model. International Journal of Wildland Fire 5(3):173-192, 1995. Albini, F.A.; Reinhardt, E.D. Improved Calibration of a Large Fuel Burnout Model. International Journal of Wildland Fire 7(1): 21-28, 1997.*

Canopy Fuel Consumption

FOFEM does not predict whether a crown fire will occur and canopy fuels will be consumed. It requires the user to estimate the proportion of the stand affected by crown fire. FOFEM simply applies this proportion to the canopy foliage and one-half of the canopy 0-1/4 inch branch wood, so that consumption of these fuels is represented for purposes of estimating smoke production or carbon budget.

Equation 37:
Consumed foliage = (Crown Burn %/100)* Foliage
Source: *Anecdotal evidence*

Equation 38:
Consumed branch wood = (Crown Burn %/100) * Branch * 0.5
Source: *Anecdotal evidence*

Carbon

Carbon loading in the carbon report is calculated using two equations:

1) For down woody material, herbaceous, shrub, branch and foliage loading:
Carbon = loading * 0.50

Source: *Penman, J.; Gytarsky, M.; Hiraishi, T.; Krug, T.; Kruger, D.; Pipatti, L.; Buendia, L.; Miwa, K.; Ngara, T.; Tanabe, K.; Wagner, F., eds. 2003. Good practice guidance for land use, land-use change and forestry. Intergovernmental Panel on Climate Change, Technical Support Unit. Institute for Global Environmental Strategies, Hayama, Kanagawa, Japan. http://www.ipcc-nggip.iges.or.jp*

2) For duff and litter:
Carbon = loading * 0.37

Source: *Smith, James E.; Heath, Linda S. 2002. A model of forest floor carbon mass for United States forest types. Res. Pap. NE-722. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northeastern Research Station. 37 p.*

Moisture Regime

Fuel moisture can be entered directly for duff, 10 hour (1/4-1 inch) woody fuel, and 3+ inch woody fuel. Fuel moisture of 1 hour and 100 fuels are set to 2 percent lower and 2 higher, respectively, of the 10 hour moisture.

Users can also select a moisture regime based on western systems– Wet, Moderate, Dry, Very Dry - to have these moisture contents set by default.

Regime	**Duff**	**10 Hr**	**3+ in.**	**Soil**
Wet	130	22	40	25
Moderate	75	16	30	15
Dry	40	10	15	10
Very Dry	20	6	10	5

For duff moisture, users can enter entire duff moisture content, lower duff moisture content, NFDR 1000 hour index values, or adjusted NFDR 1000 hour values (Ottmar and Sandberg 1983). If you want to set fuel moistures for all woody fuel size classes, or separately for sound and rotten fuels, you can run Burnup from an input file, bypassing the FOFEM user interface. See Running Burnup from an input File

Decision Dependency

This section details the relationship between fuel components and the input variables they depend on to select consumption equations. Not all fuel components base equation selection on input variables (e.g., down woody debris).

Herbaceous Calculations
- Cover Group
- Season

Shrub Calculations
- Cover Group
- Season
- Region

Duff Calculations
- Region
- Cover Group
- Fuel Type
- Moisture Regime

Litter Calculations
- Region

Crown Branch/Foliage, Down Woody Calculations

This fuel components are always calculated using the same equations regardless of Cover Group, Season, etc.

Cover Groups

Cover Group is used to determine consumption formulas for herbaceous, shrub and duff fuel loading, in turn fuel consumption is used to compute smoke emission amounts and simulate soil heating.

The codes are assigned to some but not all cover types, for example cover type SAF 001 Jack Pine is assigned a cover group code of RJP

To see the assigned cover group codes for each cover type you can look in FOFEM's fof_saf.csv, fof_nvcs.csv, fof_flm.csv or fof_fccs.csv files for a reference. The files contain cover type codes as well as fuel loads and equation information for SAF/SFM, NVCS, FLM and FCCS cover classifications. The .csv text files can be found in the FOFEM install directory, you can print them out or view them with a text editor; be careful not to alter them in any way. Each row of the file represents a single cover type with its name contained in the same line. If a cover type belongs to a cover group it will have a short character code in the last data column of the row.

Type	Short code	Long code	Note
Grass	GG	GrassGroup	
Shrub	SG	ShrubGroup	
Shrub-Chaparral	SGC	ShrubGroupChaparral	Same as shrub group except uses chaparral duff consumption equation (#19).
Sagebrush	SB	Sagebrush	

Ponderosa pine	PN	Ponderosa
Pocosin	PC	Pocosin
Balsam, Black, Red, White Spruce	BBS	BalBRWSpr
Red, Jack Pine	RJP	RedJacPin
White Pine Hemlock	WPH	WhiPinHem
Pine Flatwoods	PFL	PinFltwd

For more details concerning how cover groups are used to determine consumption see: Decision Dependency, Duff Consumption, Herbaceous Consumption and Shrub Consumption

Burnup

Burnup is a physical model of heat transfer and burning rate of woody fuel particles as they interact over the duration of a burn. Duff consumption rate is assumed to be constant (Frandsen 1991). Duff consumption amount is computed as described in the Duff Consumption section, depending on cover type and duff moisture. Duff consumption duration is computed from total consumption and consumption rate. At each iteration of the Burnup model, fuel consumption of each woody fuel size class is determined by modeling the heat transfer at intersections with other fuel particles and with the duff. Fire intensity is derived from the combustion of fuels in each time step. The fire is assumed to go out when the overall fire intensity is too low to sustain further combustion. Burnup thus provides estimates of total fuel consumption by size class, and also of consumption rate and fire intensity over time. Burnup outputs are labeled 999 on the FOFEM reports.

For more information see See: *Albini, F.A.; Reinhardt, E.D. (1995) Modeling Ignition and Burning Rate of Large Woody Natural Fuels. International Journal of Wildland Fire 5(2):81-91.*

Running Burnup from an Input File

Burnup can accept as input any number of fuel classes, defined by characteristics including loading, moisture content, surface area to volume ratio, and density. Normally when creating reports and graphs from the FOFEM user interface, Burnup is run using a number of simplified assumptions. For example, only two fuel densities are used, representing sound and rotten wood. However, the full functionality of Burnup is available to users by running Burnup from an input file. If you have a lot of detailed fuel data, you may wish to use this option.

> *NOTE: When using this option you may simulate one plot at a time in Burnup. If you want to simulate multiple plots use the Batch Burnup Parameter File in conjunction with the Burnup switch in the batch input file. See the Batch Processing section for more information. The Batch Burnup Parameter File has a different file format than the format of the Sample Burnup Input File below.*

In order to run Burnup from a file, you must first create that file. You can create a sample input file by using the menu item **Options>Create Burnup Sample Input File**. The sample file will include duff, litter, and woody fuel loading, and associated moistures as set on the user interface. Herb, shrub, foliage and branch material are not included in the sample file. Select **Options>Run Burnup From Input File** to run the Burnup input file you create. Predicted consumption will be saved by default to a file called BurnCons.txt, and emissions data to a file called BurnEmis.txt. These three files are described in more detail below.

Also remember, that whether you edit the sample file or create your own, it must be a text file, so be sure to save it as such no matter what text editor of word processor you use.

The file has two sections. The first section describes simulation parameters and the second section describes the fuel components being simulated.

Sample Burnup Input File

```
Max_Times         3000.0
Intensity           50.00   (kW/m2)
Ig_Time             60.00   (sec)
Windspeed            0.00   (m/sec)
Depth                0.30   (m)
Ambient_Temp        27.00   (C)
r0                   1.83
dr                   0.40
Timestep            15.00   (sec)
Duff_Load            1.12   (kg/m2)
Duff_Moist           0.40
1  1    0.20179372  18600.0  0.080  513.0  8200.00 2750.0  0.133 327.0 377.0 0.05
1  2    0.04484305  18600.0  0.080  513.0  1480.00 2750.0  0.133 327.0 377.0 0.05
1  3    0.17937219  18600.0  0.100  513.0   394.00 2750.0  0.133 327.0 377.0 0.05
1  4    0.22421524  18600.0  0.120  513.0   105.00 2750.0  0.133 327.0 377.0 0.05
1  5    0.08408072  18600.0  0.150  513.0    39.40 2750.0  0.133 327.0 377.0 0.05
1  6    0.08408072  18600.0  0.375  224.0    39.40 2750.0  0.133 302.0 377.0 0.05
1  7    0.08408072  18600.0  0.150  513.0    21.90 2750.0  0.133 327.0 377.0 0.05
1  8    0.08408072  18600.0  0.375  224.0    21.90 2750.0  0.133 302.0 377.0 0.05
1  9    0.08408072  18600.0  0.150  513.0    12.70 2750.0  0.133 327.0 377.0 0.05
1 10    0.08408072  18600.0  0.375  224.0    12.70 2750.0  0.133 302.0 377.0 0.05
1 11    0.08408072  18600.0  0.150  513.0     5.91 2750.0  0.133 327.0 377.0 0.05
1 12    0.08408072  18600.0  0.375  224.0     5.91 2750.0  0.133 302.0 377.0 0.05
```

An explanation of simulation parameters in the first section of the input file follows:

Name	Description	Notes
MAX_TIMES	The maximum number of iterations Burnup will compute.	
INTENSITY	Intensity of the igniting surface fire, kW/m^2	
IG_TIME	Residence time of the igniting surface fire, seconds	
WINDSPEED	Wind speed at the top of the fueled, meters/second	
DEPTH	Fueled depth, meters	
AMBIENT_TEMP	Ambient air temperature, degrees C	
R0	Fire environment minimum dimension parameter	
DR	Fire environment increment temperature parameter	
TIMESTEP	Time step for integration of burning rates	(TIMESTEP * MAX_TIMES gives the maximum simulation period
DUFF_LOAD	Duff dry weight loading, kg/m^2	
DUFF_MOIST	Duff moisture content, fraction dry weight	Range 0 to 1

Each subsequent line represents one fuel component. The rows of these lines contain, for that fuel component:

Column No.	Name	Notes	Range (exclusive)
1	Must contain a “1”		
2	Index label		
3	Dry loading	kg/m^2	
4	Heat content	kJ/kg	10000-30000
5	Moisture content	fraction dry load	

6	Oven dry mass density	kg/m^3	200-1000
7	Surface area to volume ratio	m^{-1}	
8	Heat capacity	J/kg K	1000-3000
9	Thermal conductivity	W/m K	0.03-0.25
10	Ignition temperature	C	200-673 27-400
11	Char temperature	C	250-773 6000-500
12	Mineral ash fraction		0-0.10

Sample Burnup Output Files

Consumption

```
Column 1: Fuel component
       2: Preburn  fuel load (kg/m2)
       3: Postburn fuel load (kg/m2)
       4: Time until ignition (sec)
       5: Time until burnout  (sec)
       6: Moisture content   (0->1.0)
       7: Sigma, surface area to volume ratio (per m)
       8: Preburn  fuel load (T/ac)
       9: Postburn fuel load (T/ac)
      10: Preburn  fuel load (lb/ac)
      11: Postburn fuel load (lb/ac)

         1530  Length of fire (sec)

   1    0.20179   0.00000    0 -->    60    0.08  8200.00     0.90000  0.00000   1800      0
   2    0.04484   0.00000    8 -->    90    0.08  1480.00     0.20000  0.00000    400      0
   3    0.17937   0.00000    21 -->   405   0.10   394.00     0.80000  0.00000   1600      0
   4    0.22422   0.04795    40 -->  1455   0.12   105.00     1.00000  0.21386   2000    428
   5    0.08408   0.05614    60 -->  1530   0.15    39.40     0.37500  0.25038    750    501
   6    0.08408   0.03797    28 -->  1530   0.38    39.40     0.37500  0.16935    750    339
   7    0.08408   0.07204    128 --> 1530   0.15    21.90     0.37500  0.32128    750    643
   8    0.08408   0.05785    32 -->  1530   0.38    21.90     0.37500  0.25801    750    516
   9    0.08408   0.07758    143 --> 1530   0.15    12.70     0.37500  0.34599    750    692
  10    0.08408   0.06902    36 -->  1530   0.38    12.70     0.37500  0.30782    750    616
  11    0.08408   0.08135    146 --> 1530   0.15     5.91     0.37500  0.36281    750    726
  12    0.08408   0.07726    40 -->  1530   0.38     5.91     0.37500  0.34457    750    689
```

Emissions

```
Column  1: Time since ignition, seconds
        2: Intensity  (kW/m2)
        3: Emission  PM 2.5   (g/m2)
        4: Emission   PM 10   (g/m2)
        5: Emission     CH4   (g/m2)
        6: Emission     CO2   (g/m2)
        7: Emission      CO   (g/m2)
        8: Emission     NOX   (g/m2)
        9: Emission     SO2   (g/m2)
       10: Flaming Weight      (kg/m2)
       11: Smoldering Weight   (kg/m2)

 60  86.1435  2.5387  2.9957  1.3677  501.2184  27.5695  0.7107  0.3087  0.2221   0.0866
 75  33.7413  0.8659  1.0217  0.5260  46.9617   11.5375  0.0000  0.0382  0.0000   0.0382
 90  25.5121  0.6915  0.8160  0.4201  37.5057   9.2143   0.0000  0.0305  0.0000   0.0305
105  22.3564  0.6478  0.7644  0.3935  35.1341   8.6317   0.0000  0.0286  0.0000   0.0286
120  20.5319  0.6127  0.7230  0.3722  33.2320   8.1644   0.0000  0.0271  0.0000   0.0271
. . .
1530 0.0782   0.0015  0.0018  0.0009   0.0815   0.0200   0.0000  0.0001  0.0000   0.0001
```

NOTE: Emissions are calculated using the expanded emission factors if they have been selected on the user interface otherwise the default emission factors will be used. Emission factor groups are set on the Settings window.

Fuel Consumption Citations

Albini, F.A.; Reinhardt, E.D. Modeling Ignition and Burning Rate of Large Woody Natural Fuels. International Journal of Wildland Fire 5(2):81-91, 1995.

Albini, F.A.; Brown, J.K.; Reinhardt, E.D.; Ottmar, R.D. Calibration of a Large Fuel Burnout Model. International Journal of Wildland Fire 5(3):173-192, 1995.

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Reinhardt, E.D.; Keane, R.E.; Brown, J.K. First Order Fire Effects Model: FOFEM 4.0, User's Guide. General Technical Report INT-GTR-344. 1997.

Reinhardt, E.D., Keane, R.E., Brown, J.K., Turner, D.L. 1991. Duff consumption from prescribed fire in the U.S. and Canada: a broadly based empirical approach. Proceedings, 11th Conference on Fire and Forest Meteorology.

Scientific Content - Smoke Emissions

Smoke Production

The Burnup model was modified to provide separate estimates of flaming and smoldering consumption in each time step for each fuel component by assuming that flaming combustion cannot be sustained below an intensity of about 15 kW/m^2 (Finney 2001).

All litter, herb, shrub, foliage and branch components are assumed to be consumed in the flaming phase. All duff is assumed to burn in the smoldering phase. Emission factors for woody fuels are determined by the intensity calculated in Burnup where <15 kW/m^2 is smoldering and >15 kW/m^2 is flaming. At each Burnup time step the percent of total fuels in the flaming and burning phases of combustion is calculated and the appropriate emission factors are applied to calculate total emissions at each time step.

In the emissions report, total emissions of $PM_{2.5}$, PM_{10}, CH_4, CO, CO_2, NO_X and SO_2 are listed, as well as burn duration. If desired, however, burn intensity and emissions over time can be simulated using the FOFEM menu item **Options>Save Burnup Emission File**. This information is suitable for use in predicting smoke dispersion.

Default Emission Factors

These emission factors are applied to all fuel components.

By distinguishing fuel weight consumed in flaming and smoldering phases of combustion, the Burnup model allows emission factors to be applied separately to the fuel consumed in each phase. Emission factors for particulate and chemical emission species (Ward et al. 1993) are applied to the fuel consumed in flaming and smoldering combustion assuming the values of combustion efficiencies of 0.97 for flaming and 0.67 for smoldering. Thus, the total is combined from the emissions calculated separately from fuel weight consumed in flaming and smoldering.

Pollutant	Flaming Phase		Smoldering Phase	
	Formula	EF (g/kg)	Formula	EF (g/kg)
$PM_{2.5}$	67.4 - (FCE x 66.8)=	2.604	67.4 - (SCE x 66.8)=	22.644
CH_4	42.7 - (FCE x 43.2)=	0.796	42.7 - (SCE x 43.2)=	13.756
CO	961 - (FCE x 984)=	6.520	961 - (SCE x 984)=	301.720
CO_2	FCE x 1833=	1778.01	SCE x 1833=	1228.11
PM_{10}[1]	$PM_{2.5}$ x 1.18=	3.07272	$PM_{2.5}$ x 1.18=	26.71992
NO_x	3.2=	3.2	0=	0
SO^2	1.0=	1.0	1.0=	1.0

[1] Emission factor for PM 10 is computed as 1.18 times emission factor for PM 2.5

NOTE: In the Smoke Emissions report: Flaming Phase = Short Term Flaming and Smoldering *and* Smoldering Phase = Residual Smoldering

Default Emission Citations

Finney, M.A. 2001. FARSITE help documentation.

Hardy, C.C., Burgan, R.E., Ottmar, R.D., Deeming, J.C. 1996. A database for spatial assessments of fire characteristics, fuel profiles, and PM_{10} emissions. Unpublished paper on file at USDA Forest Service, Missoula Fire Sciences Laboratory, Missoula, MT.

Ward, D.E., Peterson, J., Hao, W.M. 1993. An inventory of particulate matter and air toxic emissions from prescribed fires in the USA for 1989. In: Proceedings of the Air and Waste Management Association 1993 annual meeting, Denver, CO. 19 p.

Expanded Emission Factors

When the Expanded emission factors radio button is selected FOFEM will use emission factors in the *Emission_Factors.csv* file. This file contains updated emissions factors presented in Urbanski 2014.

The *Emission_Factors.csv* file includes emissions factors for over 200 smoke components (compared to seven smoke components in the default emissions) from recent research reviews. This table can be updated and/or appended as new emissions factors are identified.

Emission factors for fuels consumed early in the fire are labeled short-term flaming and smoldering and the applicable emission factors are labeled *STFS* in the emission factors file. Emissions for consumed litter, fine woody (1-hr, 10-hr, 100-hr), herb, shrub, foliage and branch fuels are calculated using STFS emission factors. Reaction intensity is calculated in the Burnup model. When intensity is >15 kW/m^2, dead and down woody debris are assumed to be consumed during short-term flaming and smoldering, and emissions are calculated using STFS emission factors. When reaction intensity is <15 kW/m^2 woody fuels are assumed to be consumed in the smoldering phase (post frontal combustion) and emissions are calculated using the coarse woody debris residual smoldering component (*CWDRSC*) emission factors. FOFEM assumes all duff is consumed in the smoldering phase (post frontal combustion). Emission factors for the duff residual smoldering component are labeled *DuffRSC*.

Emissions factor types used to calculate emissions when using the expanded emissions factors.

	Intensity	
Component	**>15 kW/m^2**	**<15 kW/m^2**
Duff	DuffRSC	DuffRSC[1]
Litter	STFS	STFS
Fine Wood	STFS	CWDRSC[2]
Course Wood	STFS	CWDRSC[2]
Herbaceous	STFS	STFS
Shrub	STFS	STFS
Foliage	STFS	STFS
Branch	STFS	STFS

[1] Duff Residual Smoldering Combustion
[2] Coarse Wood Residual Smoldering Combustion (>3" diameter dead and down)

The complete list of expanded emission factors are included in the *Emission_Facotors.csv* file in the FOFEM installation directory. Emissions factors for seven major smoke components simulated in FOFEM are shown in the table below. The first six rows are short-term flaming and smoldering (STFS) emission factors.

Group Number	Cover Type	CO_2	CO	CH_4	NO_X g/kg	NH_3	SO_2	$PM_{2.5}$	PM_{10}
1	Southeastern Forest	1703	76	2.32	1.70	0.14	1.06	12.58	14.8
2	Boreal Forest	1641	95	3.38	1.00	0.79	1.06	21.50	25.4
3	Western Forest-Rx[1]	1598	105	4.86	2.06	1.53	1.06	17.57	20.7
4	Western Forest-WF	1600	135	7.32	2.00	1.50	1.06	23.20	27.4
5	Shrubland	1674	74	3.69	2.18	1.50	0.68	7.06	8.3
6	Grassland	1705	61	1.95	2.18	1.50	0.68	8.51	10.0
7	Coarse Wood RSC[1]	1408	229	13.94	0.00	0.48	0.00	33.00	38.9
8	DuffRSC[1]	1371	257	7.945	0.67	2.67	1.76	35.30	41.6

[1] Default used for data imported from FFI.

FFI data imported for smoke emissions simulation using the expanded emission factors are set to use *Western Forest – Rx* emissions factors by default. Be sure to change the setting if different emissions factors are desired.

If the *Emission_Factors.csv* file is modified FOFEM needs to be closed and reopened for the changes to take effect.

Expanded Emission Citations

Urbanski, S. 2014. Wildland fire emissions, carbon, and climate: Emission factors. Forest Ecology and Management 317 (2014) 51–60.

Appendix A: FFI Export Files - Field Name and Description

Files exported from FFI can be imported into FOFEM. Two file types are exported: one with the fuels information (. FFI extension) and one with the tree information (. TRE extension). These files may also be manually created. Example files are included with the FOFEM installer.

.FFI Files

Table A-1: FFI file field names and descriptions.

.FFI	
Field name	**Description**
PlotId	FFI Macro plot identifier
Monitoring Status	FFI Monitoring status name
Monitoring Status Order	FFI Monitoring status order number (sequentially numbered when there are multiple monitoring statuses for one plot)
TotalDuffLoad[1]	Duff load (t ac^{-1}). From Surface Fuels protocol and/or the Biomass-Fuels protocol
DuffDepth	Duff Depth (in.). From Surface Fuels protocol and/or Biomass-Fuels protocol.
LitterLoad[1]	Litter load (t ac^{-1}). From Surface Fuels protocol and/or the Biomass-Fuels protocol.
LichenLoad[1]	Lichen load (t ac^{-1}). From Surface Fuels – Alaska protocol and/or the Biomass-Fuels protocol.
LiveMossLoad[1]	Live moss load (t ac^{-1}). From Surface Fuels – Alaska protocol and/or the Biomass-Fuels protocol
DeadMossLoad[1]	Dead moss (t ac^{-1}). From Surface Fuels – Alaska protocol and/or the Biomass-Fuels protocol.
OneHour[1]	1-hr (0 - <0.25 in) woody load (t ac^{-1}). From Surface Fuels protocol and/or the Biomass-Fuels protocol and/or Photoload protocol
TenHour[1]	10-hr (0.25 - <1.0 in) woody load (t ac^{-1}). From Surface Fuels protocol and/or the Biomass-Fuels protocol and/or Photoload protocol.
HundredHour[1]	100-hr (1.0 - <3.0 in) woody load (t ac^{-1}). From Surface Fuels protocol and/or the Biomass-Fuels protocol and/or Photoload protocol.
ThousandHourDc1Sz1[1]	Load of 3 - < 6 in. decay class 1 fuels (t ac^{-1}). From Surface Fuels protocol and/or the Biomass-Fuels protocol >3" -9" class[3] and/or Logs-Fixed Area protocol.
ThousandHourDc1Sz2[1]	Load of 6 - < 9 in. decay class 1 fuels (t ac^{-1}). From Surface Fuels protocol and/or the Biomass-Fuels protocol >3" -9" class[4] and/or Logs-Fixed Area protocol.
ThousandHourDc1Sz3[1]	Load of 9 - < 12 in. decay class 1 fuels (t ac^{-1}). From Surface Fuels protocol and/or the Biomass-Fuels protocol >9" -20" class[5] and/or Logs-Fixed Area protocol.

ThousandHourDc1Sz4[1]	Load of 12 - < 20 in. decay class 1 fuels (t ac^{-1}). From Surface Fuels protocol and/or the Biomass-Fuels protocol >9" -20" class[6] and/or Logs-Fixed Area protocol.
ThousandHourDc1Sz5[1]	Load of >= 20 in. decay class 1 fuels (t ac^{-1}). From Surface Fuels protocol and/or the Biomass-Fuels protocol >20" class and/or Logs-Fixed Area protocol.
ThousandHourDc2Sz1[1]	Load of 3 - < 6 in. decay class 2 fuels (t ac^{-1}). From Surface Fuels protocol and/or the Biomass-Fuels protocol >3" -9" class[3] and/or Logs-Fixed Area protocol.
ThousandHourDc2Sz2[1]	Load of 6 - < 9 in. decay class 2 fuels (t ac^{-1}). From Surface Fuels protocol and/or the Biomass-Fuels protocol >3" -9" class[4] and/or Logs-Fixed Area protocol.
ThousandHourDc2Sz3[1]	Load of 9 - < 12 in. decay class 2 fuels (t ac^{-1}). From Surface Fuels protocol and/or the Biomass-Fuels protocol >9" -20" class[5] and/or Logs-Fixed Area protocol.
ThousandHourDc2Sz4[1]	Load of 12 - < 20 in. decay class 2 fuels (t ac^{-1}). From Surface Fuels protocol and/or the Biomass-Fuels protocol >9" -20" class[6] and/or Logs-Fixed Area protocol.
ThousandHourDc2Sz5[1]	Load of >= 20 in. decay class 2 fuels (t ac^{-1}). From Surface Fuels protocol and/or the Biomass-Fuels protocol >20" class and/or Logs-Fixed Area protocol.
ThousandHourDc3Sz1[1]	Load of 3 - < 6 in. decay class 3 fuels (t ac^{-1}). From Surface Fuels protocol and/or the Biomass-Fuels protocol >3" -9" class[3] and/or Logs-Fixed Area protocol.
ThousandHourDc3Sz2[1]	Load of 6 - < 9 in. decay class 3 fuels (t ac^{-1}). From Surface Fuels protocol and/or the Biomass-Fuels protocol >3" -9" class[4] and/or Logs-Fixed Area protocol.
ThousandHourDc3Sz3[v]	Load of 9 - < 12 in. decay class 3 fuels (t ac^{-1}). From Surface Fuels protocol and/or the Biomass-Fuels protocol >9" -20" class[5] and/or Logs-Fixed Area protocol and/or Logs-Fixed Area protocol.
ThousandHourDc3Sz4[1]	Load of 12 - < 20 in. decay class 3 fuels (t ac^{-1}). From Surface Fuels protocol and/or the Biomass-Fuels protocol >9" -20" class[6] and/or Logs-Fixed Area protocol.
ThousandHourDc3Sz5[1]	Load of >= 20 in. decay class 3 fuels (t ac^{-1}). From Surface Fuels protocol and/or the Biomass-Fuels protocol >20" class and/or Logs-Fixed Area protocol.
ThousandHourDc4Sz1[1]	Load of 3 - < 6 in. decay class 4 fuels (t ac^{-1}). From Surface Fuels protocol and/or the Biomass-Fuels protocol >3" -9" class[3] and/or Logs-Fixed Area protocol.
ThousandHourDc4Sz2[1]	Load of 6 - < 9 in. decay class 4 fuels (t ac^{-1}). From Surface Fuels protocol and/or the Biomass-Fuels protocol >3" -9" class[4] and/or Logs-Fixed Area protocol.
ThousandHourDc4Sz3[1]	Load of 9 - < 12 in. decay class 4 fuels (t ac^{-1}). From Surface Fuels protocol and/or the Biomass-Fuels protocol >9" -20" class[5] and/or Logs-Fixed Area protocol.
ThousandHourDc4Sz4[1]	Load of 12 - < 20 in. decay class 4 fuels (t ac^{-1}). From Surface Fuels protocol and/or the Biomass-Fuels protocol >9" -20" class[6] and/or Logs-Fixed Area protocol.
ThousandHourDc4Sz5[1]	Load of >= 20 in. decay class 4 fuels (t ac^{-1}). From Surface Fuels protocol and/or the Biomass-Fuels protocol >20" class and/or Logs-Fixed Area protocol.
ThousandHourDc5Sz1[1]	Load of 3 - < 6 in. decay class 5 fuels (t ac^{-1}). From Surface Fuels protocol and/or the Biomass-Fuels protocol >3" -9" class[3] and/or Logs-Fixed Area protocol.

ThousandHourDc5Sz2[1]	Load of 6 - < 9 in. decay class 5 fuels (t ac^{-1}). From Surface Fuels protocol and/or the Biomass-Fuels protocol >3" -9" class[4] and/or Logs-Fixed Area protocol.
ThousandHourDc5Sz3[1]	Load of 9 - < 12 in. decay class 5 fuels (t ac^{-1}). From Surface Fuels protocol and/or the Biomass-Fuels protocol >9" -20" class[5] and/or Logs-Fixed Area protocol.
ThousandHourDc5Sz4[1]	Load of 12 - < 20 in. decay class 5 fuels (t ac^{-1}). From Surface Fuels protocol and/or the Biomass-Fuels protocol >9" -20" class[6].
ThousandHourDc5Sz5[1]	Load of >= 20 in. decay class 5 fuels (t ac^{-1}). From Surface Fuels protocol and/or the Biomass-Fuels protocol >20" class and/or Logs-Fixed Area protocol.
HerbLoadDead	Dead herb load (t ac^{-1}). From Surface Fuels-Vegetation protocol
HerbLoadLive[1]	Live herb load (t ac^{-1}). From Surface Fuels-Vegetation protocol and/or the Biomass-Fuels protocol and/or Photoload protocol.
ShrubLoadDead	Dead shrub load (t ac^{-1}). From Surface Fuels-Vegetation protocol
ShrubLoadLive[1]	Live shrub load (t ac^{-1}). From Surface Fuels-Vegetation protocol and/or the Biomass-Fuels protocol and/or Photoload protocol.
ShrubLiveSAV	Not used in FOFEM
HerbSAV	Not used in FOFEM
WoodySAVOneHour	Not used in FOFEM
FractionGroundAreaPile Covered	Not used in FOFEM
PileLoadWholePlot	Not used in FOFEM
EmisSTFS[2]	Emission factor group number for short-term flaming and smoldering combustion. See Expanded Emission Factors for more information.
EmisDuffRSC[2]	Emission factor group number for duff residual smoldering combustion. See Expanded Emission Factors for more information.
EmisCWDRSC[2]	Emission factor group number for coarse woody smoldering combustion. See Expanded Emission Factors for more information.

[1] If loading data for the same component exists in more than one protocol, the average of the values will be used in FOFEM.

[2] If you enter data in these fields in the .FFI file, FOFEM will use the data. Set to *0* to use the Default Emissions factors.

[3] 3"–6" class loading = Biomass-Fuels >3"-9"*0.265

[4] 6"–9" class loading = Biomass-Fuels >3"-9"*0.735

[5] 9"–12" class loading = Biomass-Fuels >9"-20"*0.301

[6] 12"–20" class loading = Biomass-Fuels >9"-20"*0.699

.TRE files

Table A-2: TRE file field names and descriptions. Files exported from FFI will include tree data from the Trees-Individuals, Saplings and Seedlings methods but only the Individuals and Sapling data are imported into FOFEM. Not all fields are required for FOFEM mortality simulations. The first row of the file must include the label “PlotID”.

.TRE	
Field name	**Description**
PlotId	FFI Macro plot identifier
Monitoring Status	FFI Monitoring status name
Monitoring Status Order	FFI Monitoring status order number (sequentially numbered when there are multiple monitoring statuses for one plot)
TreeSpecies	Tree species code (NRCS Codes only
TreeExpansionFactor	Representative tree density (trees ac^{-1})
Diameter[1]	Tree DBH or DRC (in.)
TreeHeight	Tree height (ft)
CrownBaseHeight[2]	Live crown base height (ft)
TreeStatus[3]	Tree status (L, H, U, S, D)
CrownClass[4]	Crown class (D, C, I, S)
CrownRatio[5]	Crown ratio (0 - 100)
BoleCharHeight	Bole char height (ft)
CrownScorch%[6]	Crown scorch (%)
ScorchHeight	Scorch height (ft)
CKR	Cambium kill rating (0-4)
BeetleDamage[7]	Beetle damage (Y, N)
EquationType[8]	Equation type (CRNSCH, CRCABE, BOLCHR)
FlHt/ScHt	Flame height/scorch height (ft)
FS	Describes the value in the FlHt/ScHt field. Flame height (F) or scorch height (S).
Severity	Fire severity (L or blank)

[1] If values for both DBH and DRC are entered in FFI, DBH will be used in this file. For trees <4.5’ tall, DBH=0.1” but the records are not imported into FOFEM.

[2] This field is populated with values in the Live Crown Base Height or Live Crown base Height field in the FFI Trees-Individual protocol.

[3] Trees coded D (Dead) are valid but will not be displayed in the tree list in FOFEM.

[4] This field is ignored in FOFEM.

[5] If the Trees – Individuals, Crown Ratio field is null then FOFEM will calculate Crown Ratio using Live Crown Base Height or Crown Fuel Base Height (as selected in FFI); where Crown Ratio = (1 – (Crown Base Height / Tree Height)) * 100. If Crown Base Height and Crown Ratio fields are null the tree record will not be imported into FOFEM.

[6] In the CRCABE equations, this value is set to equal either Crown Length Scorched, Crown Scorch or Crown Kill based on the species and mortality equation.

[7] If the Trees – Individuals, Damage Code 1, 2 or 3 fields equal 10000 or “INSE”, then this field will be set to “Yes”; otherwise, it will be blank.

[8] This value is set based on data in the Trees-Individuals protocol
If the CKR field is not null then “Equation Type” is set to “CRCABE”
If the Char Height field is not null then “Equation Type” is set to “BOLCHR”
Otherwise “Equation Type” is set to “CRNSCH”
See the Equation Type section to see input requirements for the three equation types.

Updates

Version 6.7

1. Added Massman Model for soil heating and moisture simulation

Version 6.6

1. Not released – Test version for Massman Soil model

Version 6.5

1. Added new mortality equations for 10 SE US species (BOLCHR)
2. Updated mortality equation types to pre-and post-fire equations to CRNSCH and CRCABE, respectively.
3. Added new Salvage report in UI and batch
4. Change tree file input format to use FFI .TRE file format.

Version 6.4

1. Added option for using expanded emissions factors and modified emissions logic
2. Added switch in batch option for using expanding emissions factors
3. Added post-fire tree mortality equations to batch option
4. Added switch in batch option for selecting specific consumption equations

Version 6.3.1

1. Updated soil heating logic for duff and non-duff models
2. Updated litter and herb consumption equations, and updated some default fuel loadings for the southeast
3. New pocosin duff consumption equation added
4. FLM fuelbeds updated to match LANDFIRE attribute table
5. Accepts new FFI file imports files that include monitoring status

Version 6.2 Not released

Version 6.1

1. Updated NVCS and SAF default fuel loads for some shortleaf pine – oak and oak types in the southeast.
2. Modified user folder location for better performance on Window 7 and 8 machines.
3. Added ability to input fuels from FFI export files.

Version 6.0

1. Complete redesign of the user interface
2. Improved graphics
3. Mortality tree species codes changed to NVCS codes (FOFEM5 used six character codes)
4. FCCS cover types have been updated and now include foliage and branch fuels.
5. FFI (FEAT/FIREMON/Integrated) tree data can now be imported directly into the Mortality model.
6. The soil simulation model has been refined.
7. Added new tree mortality model for longleaf pine

Version 5.9.1

1. A new batch feature has been added that allows for creating individual emission files, see Batch Processing
2. A second new batch feature is the ability to more precisely set the input parameters of the Burnup consume model. See Batch Burnup Parameter File

Version 5.9

1. Updated the FLM fuel models.
2. Added a Burnup command line option. See Running Burnup from an input File

Version 5.8

1. Program updated to use new revised FCCS fuel loading classes.
2. FLM fuel classes added to program.

Version 5.7

1. Added post-fire injury option to tree mortality window. Updated pre-fire mortality models for several species.

Version 5.6

1. Feature added to allow batch input files to be run from command line

Version 5.5

1. Miscellaneous changes: updates to help text, minor program bug fixes

Version 5.3

1. Batch processing feature added. Multiple plots of input data can be processed to model fuel consumption, smoke emissions, soil heating and tree mortality.
2. Unit Average Combustion Efficiency added to Smoke Emission Report.

Version 5.2

1. Canopy Cover estimates added to the tree mortality report.

Version 5.1

1. Includes additional emissions for NO_X and SO_2.
2. Default moisture settings for moisture regime were changed.
3. Problems with the Mortality Species window for the Windows 2000/XP version were been corrected

Version 5.0

1. Original Release, Windows graphic user interface version enhanced and upgraded from original FOFEM DOS version.