FuelCalc 1.0

Reference Guide

9/30/2008

FuelCalc 1.0 is a software package that calculates initial fuel quantities, simulates a variety of fuel treatment scenarios, and then calculates potential fire behavior. All calculations are done at the plot level, with summaries to a stratum (stand). Development of FuelCalc 1.0 was funded by the Joint Fire Sciences Program.

Contents

1. Introduction to FuelCalc 1.0

Ground, surface, piled and canopy fuel characteristics are essential inputs to computer models of fire behavior and fire effects. FuelCalc is a computer application for (1) calculating ground, surface, piled, and canopy fuel characteristics from existing standard fuel inventory methods, (2) simulating the effects of various fuel treatments on those fuel characteristics, and (3) calculating potential fire behavior and fire effects outputs.

The basic application of FuelCalc is at the individual-plot level, with summaries to the stand level (or any other stratum classification as defined within FuelCalc, such as administrative unit or vegetation type). FuelCalc can work with any number of plots and strata, limited only by computer processing time and data storage space. FuelCalc does not geospatially analyze its data, but is being considered for inclusion in the ArcFuels geospatial fuel analysis system and the geospatial fuel treatment analysis taught by the National Interagency Fuel Technology Transfer Team (NIFTT).

FuelCalc has a diverse user group. Primary users are local- and regional-level fuel management specialists who are design and analyze fuel management projects. Fuel management specialists use FuelCalc to calculate ground, surface, piled, and canopy fuel characteristics, simulate the effects of various fuel treatments on fuel characteristics and fire behavior in support of fuel management planning and implementation, then use that information to inform a decision regarding whether, where and how to treat a fuelbed.

FuelCalc has significant functional overlap with the Fire and Fuels Extension to the Forest Vegetation simulator (FFE-FVS). FuelCalc will not perform temporal simulation of fuel dynamics related to vegetation growth, as is done in FFE-FVS. Instead, FuelCalc focuses on improving the simulation of fuel treatments. (Improvements are primarily in the user-interface, not the ability to simulate specific treatments.)

FuelCalc 1.0 replaces a prototype version of FuelCalc. The prototype version had limited distribution and focused on estimating canopy characteristics from a treelist. Characterization of other fuel strata, simulation of the effects fuel treatment, and simulation of fire behavior potential were not included in the prototype version.

FuelCalc is intended to be in continuous development with input from its users. New fuel and fire behavior modeling methods can be added in future versions as need dictates and as funding allows. New functions or features can also be added as users recommend them.

1.1 History of FuelCalc

In 2001, a National Park Service project funded by the Joint Fire Science Program funded the creation of a project-specific spreadsheet—called FuelCalc.xls—that calculated surface fuel load (from both planar intercept and Burgan-Rothermel inventory methods), created custom fuel models, and calculated surface and crown fire potential indices for each of 700 sample points in the database. This project-specific tool was not distributed to the fire management community.

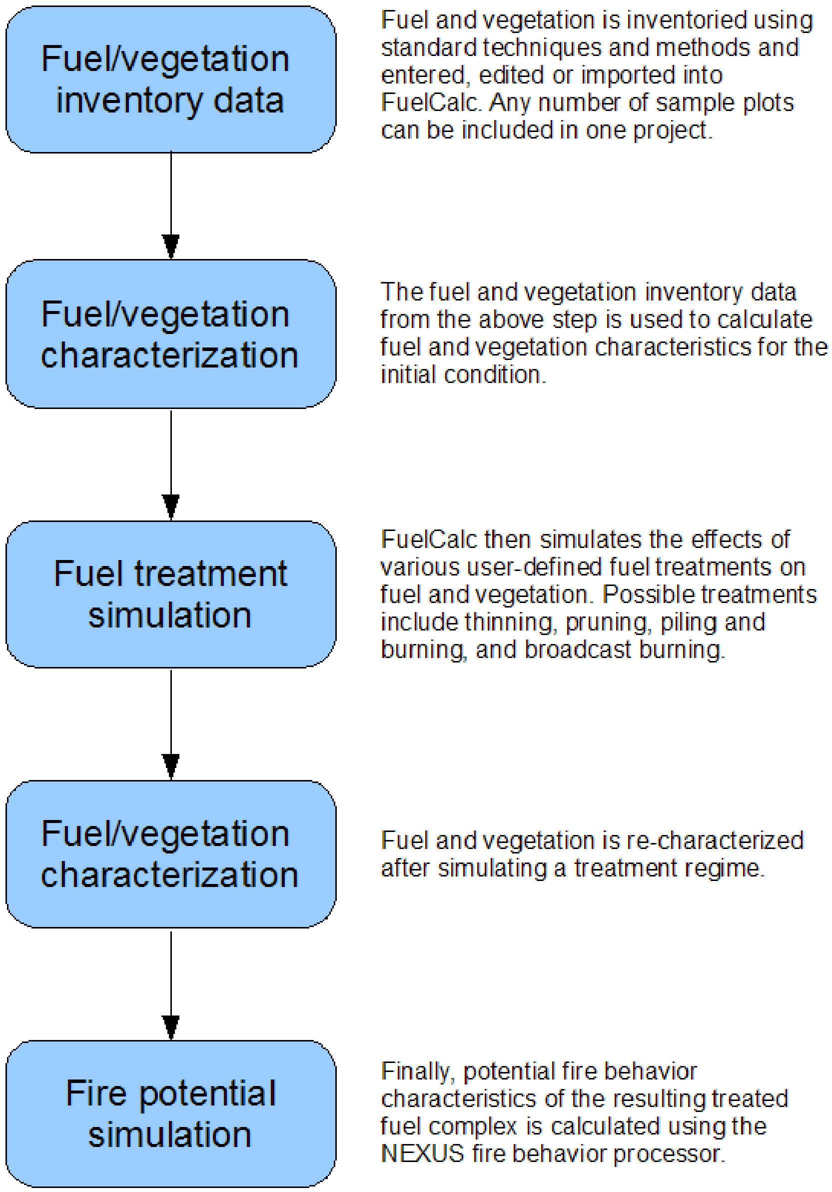
Because no standard tool exists to reduce planar intercept data to fuel load, individual fuel managers have created custom tools, usually in spreadsheets, to do just that. Duncan Lutes, now at the Missoula Fire Sciences Lab, maintained such a tool, which he also called FuelCalc.

Elizabeth Reinhardt at the Missoula Fire Sciences Lab created a prototype canopy fuel quantification tool called FuelCalc. This prototype implemented the same canopy fuel quantification method used in the Fire and Fuels Extension to the Forest Vegetation Simulator (FFE-FVS), but was much simpler to use if temporal simulation of fuel dynamics is not needed. Reinhardt's prototype FuelCalc was used by the LANDFIRE fuel staff to quantify canopy characteristics and used in their efforts to create nationwide maps of canopy characteristics for fire behavior modeling.

The JFSP has funded the development of a full-version of FuelCalc 1.0. FuelCalc 1.0 has the canopy fuel quantification of Reinhardt's FuelCalc, the planar intercept calculations of Lutes' FuelCalc, and the fire modeling functionality of Scott's FuelCalc. In addition, this FuelCalc 1.0 also simulates the effects of certain fuel treatments on fuel and potential fire behavior.

1.2 Overview of FuelCalc process

The following chart illustrates the fuel calculation and simulation process used in FuelCalc.



1.3 Units of Measure

FuelCalc is flexible in the choice of units of measure for each input or output quantity. Each input or output quantity has a so-called "native" unit of measure—the units of measure used internally by FuelCalc to store and process data. In most cases, a FuelCalc native unit is some form of metric unit, but does not necessarily follow the more strict SI units. FuelCalc maintains a list of allowable units of measure for each input and output quantity, and stores the conversion factor between the allowable units and the native units. Data in all FuelCalc files are stored in FuelCalc's native units, but can be displayed and edited in any of the allowable units at any time. All data editing or entering is assumed to be in the current display units, so be sure to set the display units to the units of your data *before* entering or editing the data—any data previously entered are converted when switching display units.

Additional allowable units and conversion factors can be added to FuelCalc as needed. The native and allowable optional units for each input or output quantity used in FuelCalc are shown in Appendix B.

1.4 Organization of data

A FuelCalc project consists of fuel inventory data, tree inventory data, and model settings describing fuel treatments and calculation options for one or more sample points (plots). Basic FuelCalc data is organized by sample point. FuelCalc accommodates a variety of sampling designs and methods. Digital photos of each sample point can be stored in a FuelCalc project for visual reference.

The following two sections describe what information FuelCalc needs about the sample points and about the strata in a FuelCalc project.

1.4.1 Sample point (plot)

FuelCalc requires basic information about each sample point: slope steepness, aspect, elevation, and location (latitude/longitude). The latitude/longitude information is currently not used directly in FuelCalc, but is recorded so that it can be supplied to a geospatial tool such as ArcFuels. Aspect and slope steepness are used (in conjunction with other factors specified separately) to estimate fine dead fuel moisture content for use in simulating potential fire behavior. Slope steepness is used with other inputs in simulating potential fire behavior. Elevation is not currently used in FuelCalc, but later versions may use this input to further refine the fine dead fuel moisture content estimate.

Sample-point Input	Native units
Slope Steepness	percent
Aspect	degrees
Elevation	meters
Latitude	degrees
Longitude	degrees

1.4.2 Stratum

Assigning sample points to a stratum is an optional feature of FuelCalc. If desired, each sample point in a FuelCalc project can be assigned to a user-defined stratum for later summary. A stratum can be a geographic extent (stand, forest, state or region, for example) or other classification (forest type, ownership, etc.). Only one stratum level (with any number of classes) is allowed in FuelCalc—a more complex data analysis can be conducted outside of FuelCalc. Regardless of how the stratum designation is used in FuelCalc, each sample point must belong to exactly one and only one stratum.

1.5 Species management

The biomass equations necessary for estimating canopy fuel characteristics are available for a relatively small fraction of the tree species recognized by vegetation ecologists. Also, the accepted scientific name and code for many tree species have changed over the years. To resolve these issues FuelCalc uses a step-wise approach to managing species, similar to that of the FFI fire monitoring software.

FuelCalc recognizes 2018 unique tree species. Of those, only 160 are needle-leaf coniferous species that by default FuelCalc considers to contribute to available canopy fuel; the remaining 1858 species are broad-leaf species that normally do not contribute to available canopy fuel. Nonetheless, FuelCalc recognizes all 2018 tree species so that broadleaf species can be included in calculations of canopy fuel characteristics if desired. Because the scientific names or codes used to identify a particular species may have changed over the years, FuelCalc also recognizes 2897 outdated tree species codes. Each of these outdated codes is mapped by FuelCalc to the currently accepted code for the species.

At the beginning of a FuelCalc project, the user selects which individual species of this whole list to include in the FuelCalc project. For each species identified for inclusion in the project, the user sets certain characteristics that FuelCalc will apply to all trees of that species. An example of such information is shown in the table below.

scientific name	NRCS code	FuelCalc display name	Include As Canopy Fuel	species retention priority	Biomass Equation Set
pinus ponderosa	PIPOP	PP	YES	1.0	26
pseudotsuga menziezii	PSMEM	Doug-fir	YES	0.8	6
populus tremuloides	POTR5	Aspen	NO	0.5	40
larix occidentalis	LAOC	Western larch	YES	1.0	17

First, the display name to use in the FuelCalc data-entry interface is set. The default display name is the standard NRCS symbol for that species. This can be changed to a locally used species code, the common name for that species, or any other designator that the user will be familiar with.

Next, the user specifies whether to include biomass for each species should be included as available canopy fuel—that is, whether its foliage and fine twigs contribute to crown fire initiation and spread. The default value for this field is “yes” for all 160 needle-leaf coniferous species and “no” for all 1858 broad-leaf species. These defaults can be changed for any species selected for inclusion in a FuelCalc project.

Next, the user specifies a relative retention priority for each species in the project. This factor is used on combination with other tree characteristics and fuel treatment settings to give each tree at a plot a relative priority for retaining that tree after a thinning. (Priority for removal is 1 minus the retention priority.) By default, each species' retention priority is set to 1.0, meaning that species will not play any factor in the ordering of trees for retention. A lower value for retention priority means that—all other things equal—that species will have a lower priority to be retained. The value of the species retention priority should be coordinated with other fuel treatment retention priority factors, discussed in a later section.

Next, the user selects which of FuelCalc’s available biomass equation sets to use for each species included in the project. The available biomass equation sets is limited, and can only be expanded by the FuelCalc developers as additional equations become available. Selecting the biomass equation set selects a suite of equations or models to use for a given species. Any given equation set may be used for more than one species.

FuelCalc 1.0 has 55 equation sets to choose from, shown below.

Equation set	NRCS code	Common name
1	ALRU2	Red Alder
2	ALRH2	White Alder
3	CHNO	Alaska Cedar
4	CADE27	Incense Cedar
5	THPL	Western Red Cedar
6	PSME	Douglas Fir
7	ABGR	Grand Fir
8	ABPR	Noble Fir
9	ABAM	Pacific Silver Fir
10	ABLA	Subalpine Fir
11	ABCO	White Fir
12	TSME	Mountain Hemlock
13	TSHE	Western Hemlock
14	JUSC2	Rocky Mountain Juniper
15	JUOS	Utah Juniper
16	LALY	Subalpine Larch
17	LAOC	Western Larch
18	ARME	Madrone
19	ACMA3	Bigleaf Maple
20	ACGL	Mountain Maple
21	LIDE3	Tanoak
22	PIAR	Bristlecone Pine
23	PIJE	Jeffrey Pine
24	PIFL2	Limber Pine
25	PICO	Lodgepole Pine
26	PIPO	Ponderosa Pine
27	PIAR5	Ponderosa Pine SW
28	PILA	Sugar Pine
29	PIMO3	Western White Pine
30	PIAL	Whitebark Pine
31	PIED	Colorado Pinyon
32	SEQUO	Coast Redwood
33	SEGI2	Giant Sequoia
34	PIPU	Blue Spruce
35	PIBR	Brewer Spruce
36	PIEN	Engelmann Spruce
37	PISI	Sitka Spruce
38	PIGL	White Spruce
39	TABR2	Pacific Yew
40	POTR5	Quaking Aspen
41	BEPA	Paper Birch
42	BEAL2	Yellow Birch
43	CHTH2	Atlantic White Cedar
44	ABBA	Balsam Fir
45	TSCA	Eastern Hemlock
46	ACRU	Red Maple

47	ACSA3	Sugar Maple
48	QUKE	Calif Black Oak
49	QUMU	Giant Chinkapin Oak
50	QURU	Northern Red Oak
51	PIST	Eastern White Pine
52	PITA	Loblolly Pine
53	PIRI	Pitch Pine
54	PIMA	Black Spruce
55	PIRU	Red Spruce

An equation set is a table of references to parameters or equations for each of the species listed above. The equation set consists of references to:

- A total canopy fuel mass equation
- A foliage mass equation
- A fine twig mass equation
- A vertical distribution equation
- A crown area equation for use in estimating canopy cover
- Proportion equations for 10-, and 100-h timelag size classes
- A bark thickness equation for tree mortality (next version)

That is, when the user enters a species to use in a FuelCalc Project, he chooses which of the 55 equation sets to use to represent the species being entered.

1.6 Entering, importing, and exporting Data

Fuel and vegetation inventory data can be entered directly into FuelCalc using its user-interface, or imported from other data sources, such as FFI (FIREMON and FEAT Integrated).

When entering data, the user specifies what units of measure to use for each quantity being entered. Regardless of the units used for data entry, the data is converted to FuelCalc's native units for storage. The units of measure for display and editing of any data can be changed at any time.

When importing data, FuelCalc reads data fields in the FFI project and maps them to the corresponding field in FuelCalc in the native units. FuelCalc can be updated in the future to accommodate additional data import formats.

Once data has been entered or imported into FuelCalc, it can be edited and supplemented with additional data as necessary.

2. Fuel Quantification Methods in FuelCalc

Fuel quantification is the backbone of FuelCalc—no other fire management application brings together such a wide array of ground, surface and canopy fuel estimation techniques in one place. Additional methods can be implemented in FuelCalc as necessary to support inventory methods actually used in the field. If fuel characteristics are known, those characteristics can be entered directly in FuelCalc, and used in subsequent fuel treatment and fire behavior potential simulations.

The ground, surface and canopy fuel quantification methods employed in FuelCalc are described in the following sections.

2.1 Ground Fuel (GF)

The term “ground fuel” is used loosely in FuelCalc to refer to all fuelbed components whose load (oven-dry mass per unit area) can be estimated as the product of depth and bulk density: duff, leaf litter, lichen, and moss. The inputs for this component are shown in the following table:

Ground fuel input	Native units
Total Duff Depth	cm
Litter Depth	cm
Lichen Depth	cm
Live Moss Depth	cm
Dead Moss Depth	cm
BulkDensityConstantSet	See below

The depth of each component is recorded directly in FuelCalc (multiple measurements are averaged to compute a sample point-level estimate) or imported from another database. In addition, a bulk density constant set (BDCS) is selected for the plot. The Bulk Density Constant Set (BDCS) is described in section 2.1.1 below. The following table illustrates FuelCalc's calculation of these ground fuel components for a single sample point for the default bulk density values for each component.

Ground fuel quantity	default bulk density (kg/m^3)	Depth observation 1 (cm)	Depth Observation 2 (cm)	Depth Observation 3 (cm)	Mean Depth (cm)	Final load estimate (kg/m^2)
Litter	46.4	1.0	3.0	4.5	2.8	1.3
Lichen	46.4	0	0	0	0.0	0.0
Live moss	14.0	0	2.0	n/o	1.0	0.14
Dead moss	23.0	0	0	0	0.0	0.0
Upper duff	45.0	4	8	0	4.0	1.8
Lower duff	110	10	23	0	11	12.1
Total duff	88.1	14	31	0	15	13.2

The table above illustrates the difference between a “zero” and “n/o” (for no observation). The following table lists the outputs generated by this method. The “GF” prefix indicates that these variables come specifically from the ground fuel method rather than direct entry.

Ground Fuel Output	Native units
GF.TotalDuffLoad	kg/m2
GF.LitterLoad	kg/m2
GF.LichenLoad	kg/m2
GF.LiveMossLoad	kg/m2
GF.DeadMossLoad	kg/m2

2.1.1 Bulk Density Constant Set

A bulk density constant set (BDCS) is analogous to an FCS but contains different information. A BDCS lists bulk density values for litter, lichen, live moss, dead moss, and duff. FuelCalc consists of one default BDCS; the user may add any number of additional BDCSs to represent ground fuel whose characteristics differ from those of the default BDCS.

Input Quantity	**Default value (kg/m^3)**
Litter bulk density	46.4
Lichen bulk density	46.4
Live moss bulk density	14.0
Dead moss bulk density	23.0
Duff bulk density	88.1

2.2 Surface Fuel

Surface fuel consists of dead and down woody debris, grass and herbaceous fuel, and shrub fuel. Two methods of inventorying dead and down woody fuel are included in FuelCalc: the planar intercept method (aka Brown's transect) or the Burgan–Rothermel method. Only the Burgan–Rothermel inventory method can be used to inventory the herbaceous and shrub fuel components of surface fuel.

Dead down woody debris is classified by fuel particle diameter into the following standard classes:

Timelag class	Particle diameter	
	mm	in
1-hr	< 6	< 0.25
10-hr	6 - 25	0.25 – 1.0
100-hr	25 - 75	1.0 – 3.0
1000-hr (SizeClass1)	75 - 150	3.0 – 6.0
1000-hr (SizeClass2)	150 - 225	6.0 – 9.0
1000-hr (SizeClass3)	225 - 300	9.0 – 12
1000-hr (SizeClass4)	300 - 500	12 - 20
1000-hr (SizeClass5)	> 500	> 20

Note: The diameter classes in mm are whole-number rough equivalents to the standard classes expressed in inches. The discrepancy between classifications is small enough to ignore.

Dead down woody debris is also classified into the following decay classes:

FuelCalc decay class	description
VS	very sound
MS	mostly sound
S	sound
R	rotten
VR	very Rotten

For purposes of association with particle density (specific gravity), all fuel particles less than 75 mm diameter (3 inches) are assumed to be very sound.

2.2.1 Planar intercept (PI)

FuelCalc allows the use of a planar intercept (PI) inventory method for quantifying the load of dead and down fuel of all size classes. The PI method consists of observations of fuel particle counts or measurements across a plane of known length and inclination, and a selection of fuel constants needed to reduce the raw observations to load. Inputs for the planar intercept method are shown in the following table:

Planar intercept input	Native units
0 - 1/4 plane length	meters
1/4 - 1 plane length	meters
1 - 3 plane length	meters
3+ plane length	meters

Transect Number	count
Slope Steepness	percent
True Azimuth	degrees
number of 0 - 1/4 intercepts	count
number of 1/4 - 1 intercepts	count
number of 1 - 3 intercepts	count
Log Diameter	cm
Decay Class	category
FuelConstantSet	see below

Like the bulk density constant set described for ground fuel above, the fuel constants needed for using the PI method are cataloged in a Fuel Constant Set (FCS). FuelCalc's default FCS values are shown in section 2.2.1.1 below. The user may add additional fuel constant sets as appropriate, and then assign these additional FCSs to individual transects within FuelCalc.

Outputs of the planar intercept method are woody fuel load by timelag class, as shown below.

Planar intercept output	Native units
PI.WoodyLoadOneHr	kg/m^2
PI.WoodyLoadTenHr	kg/m^2
PI.WoodyLoadHndrdHr	kg/m^2
PI.WoodyLoadThousandHr	kg/m^2

In addition, the woody load of fuel particles greater than 75 mm diameter is calculated by sub-class (five of them) and decay class (also five of them). The size and decay classes are described in section 2.2.

2.2.1.1 Fuel Constant Set

In addition to a count of particle intersections by size class (or log diameter measurements), the planar intercept inventory method requires a long list of additional fuel constants inputs for each transect: quadratic mean diameter by size class, a factor to correct for non-horizontal position of fuel particles by size class, and fuel particle specific gravity by size class. Rather than ask the user to enter these 14 inputs for each transect, FuelCalc instead places all 14 constants into a cohesive set, much like a fuel model is a cohesive set of fuel parameters. The user need only select an FCS to specify all 14 constants at once.

FuelCalc includes only one FCS by default; it represents a generic mix of tree species. The user can add any number of fuel constant sets to FuelCalc for use in the planar intercept method. Adding a new FCS is only needed if the default FCS values do not adequately represent the fuel particle characteristics at all sample points in a FuelCalc project. The following table lists the fuel constants of FuelCalc’s default FCS.

Fuel constant	Default value
QMD1 (cm^2)	0.09742
QMD10 (cm^2)	1.865
QMD100 (cm^2)	17.81
NHC1	1.13
NHC10	1.13
NHC100	1.13
SG1	0.48
SG10	0.48
SG100	0.40
SG1000-1	0.40
SG1000-2	0.37
SG1000-3	0.34
SG1000-4	0.31
SG1000-5	0.28

2.2.2 Burgan–Rothermel (BR)

The Burgan–Rothermel (BR) method of surface fuel inventory was published in 1984 and implemented in the FUEL subsystem of the BEHAVE fire behavior prediction system. BehavePlus, the replacement for BEHAVE, does not include that function. Nonetheless, the BR method is a very quick and reasonable way to estimate surface fuel quantity and characteristics, so it has been implemented in FuelCalc 1.0.

The BR inventory method consists of three strata: grass, shrub, and litter fuel strata. The inputs are shown in the following table, and then details are provided in individual sections.

Burgan-Rothermel Input	Native units
Grass Type	category
Grass Class	category
Grass Depth	cm
Grass Cover	percent
Fraction Dead	percent
Shrub Type	category
Shrub Class	category
Shrub Depth	cm
Shrub Cover	percent
Fraction 0-to-1/4 dead	percent
Fraction 1/4-to-1 dead	percent
Fraction 1-3 dead	percent
Fraction Live	percent
Waxy?	category
Litter Source	category
Needle Length	category
Litter Compactness	category
Litter Depth	cm
Litter Cover	percent
Fraction 0-to-1/4 inch	percent
Fraction 1/4-to-1 inch	percent

Fraction 1-3 inch	percent

2.2.2.1 Grass

The BR inventory of grass fuel consists of five inputs: grass type, grass class, grass depth, grass cover and fraction of grass load that is live.

There are four possible grass types. The classification is based on coarseness of the grass stems.

Grass Type
fine grasses
medium-coarse grasses
coarse grasses
very coarse grasses

See Burgan and Rothermel (1984) for a list of species that may be appropriate for each grass type. Grass type is used to determine the surface-area-to-volume ratio of the grass stems, and to determine (in part) the bulk density of grass fuel.

There are six grass classes. Grass class is based on the apparent density of stems. See Burgan and Rothermel for photos illustrating the various grass classes.

Grass Class
very sparse
sparse
moderately sparse
moderately dense
dense
very dense

Grass class is used in combination with grass type to estimate the bulk density of grass fuel at the sample point.

Grass depth is the depth of the grass fuel at the sample plot. The native units for grass depth in FuelCalc are centimeters, but grass depth can be entered, edited or displayed in inches, feet, or meters.

Grass cover is the relative amount of the sample plot that is covered by the grass fuel. Native units for grass cover are percent, but it can also be entered, edited, or displayed as a fraction.

Finally, the fraction of grass load that is live is an estimate of the total grass load at the plot that is living at the time of sampling. Native units are percent, but this can also be expressed as a fraction. For fire modeling, the grass fraction live is not used.

The BR grass inventory produces five outputs: grass bulk density, total grass load, dead grass load, live grass load, and surface-area-to-volume (SAV) ratio.

Grass bulk density is estimated as a function of grass class and grass type according to the following table. These values were not expressly described in Burgan and Rothermel (1984) or in the FUEL subsystem of BEHAVE. Instead, we determined that the method used these values by working backward from the FUEL outputs.

Bulk Density (kg/m^3)		Grass Type			
		fine	Medium-coarse	coarse	Very coarse
Grass Class	Very sparse	0.0799	0.0799	0.4086	0.4086
	sparse	0.2372	0.2372	0.5657	0.5657
	Moderately sparse	0.4086	0.5657	0.7354	0.7354
	Moderately dense	0.5657	0.9193	0.9193	0.9193
	Dense	0.7354	1.2257	1.2257	1.2257
	Very dense	0.9193	1.4708	1.4708	1.4708

Total grass load is the product of grass bulk density (from table above), grass depth, and grass cover. Live grass load is the product of total grass load and the fraction grass load that is live. Dead grass load is the total grass load minus the live grass load.

Grass SAV ratio is a function of the grass type, as shown in the table below.

grass type	SAV ratio (m^{-1})
1	9842
2	7382
3	4921
4	4921

Burgan-Rothermel grass component outputs are shown in the following table:

Grass output	Native units
BR.GrassBulkDensity	kg/m^3
BR.GrassLoadDead	kg/m^2
BR.GrassLoadLive	kg/m^2
BR.GrassLoadTotal	kg/m^2
BR.GrassSAV	1/m

2.2.2.2 Shrub

The BR inventory of shrub fuel consists of nine inputs: shrub type, shrub class, shrub depth, shrub cover and fraction of total shrub load that is in three dead fuel size classes and one live fuel class, and a binary variable indicating whether or not the shrub is contains volatile waxes.

There are five shrub types; the classification is based on the nature of the stems and leaves of the shrubs at the sample point.

Shrub Type
fine stems, thin leaves
medium stems, thin leaves
medium stems, thick leaves

very dense, fine stems and leaves
thick stems and leaves

See Burgan and Rothermel (1984) for a list of species that may be appropriate for each shrub type. Grass type is used to determine the surface-area-to-volume ratio of the shrub stems and leaves, and to determine (in part) the bulk density of shrub fuel.

There are six shrub classes. Shrub class is based on the apparent density of stems. See Burgan and Rothermel for photos illustrating the various grass classes.

Shrub Class
very sparse
sparse
moderately sparse
moderately dense
dense
very dense

Shrub class is used in combination with shrub type to estimate the bulk density of shrub fuel at the sample point.

Shrub depth is the depth of the shrub fuel stratum at the sample plot. The native units for shrub depth in FuelCalc are centimeters, but shrub depth can be entered, edited or displayed in inches, feet, or meters.

Shrub cover is the relative amount of the sample plot that is covered by the shrub fuel. Native units for shrub cover are percent, but it can also be entered, edited, or displayed as a fraction.

Finally, the fraction of total shrub load that is allocated to various live and dead size classes is used to estimate the shrub load in those classes. Native units are percent, but this can also be expressed as a fraction.

The BR shrub inventory produces nine outputs: shrub bulk density, total shrub load, live shrub load, dead shrub load in three size classes, shrub stem and shrub leaf SAV ratios, and the shrub live heat content.

Shrub bulk density is estimated as a function of shrub class and shrub type according to the following table. These values were not expressly described in Burgan and Rothermel (1984) or in the FUEL subsystem of BEHAVE. Instead, we determined that the method used these values by working backward from the FUEL outputs.

Shrub Bulk Density (kg/m^3)		Shrub Type				
		Fine stems, thin leaves	Medium stems, thin leaves	Medium stems, thick leaves	Very dense, fine stems and leaves	Thick stems and leaves
Shrub Class	Very sparse	0.1843	0.1843	0.1843	1.4708	3.6770
	Sparse	0.3677	0.5529	0.5529	2.9416	5.6570
	Moderately sparse	0.5529	0.7354	0.7354	4.3259	7.3541

	Moderately dense	0.7354	1.0976	1.0976	6.6855	9.1926
	Dense	1.4708	1.8385	1.8385	9.1926	10.5058
	Very dense	2.9416	3.3428	3.3428	10.5058	14.7082

Total shrub load is the product of shrub bulk density (from table above), shrub depth, and shrub cover. Live shrub load is the product of total shrub load and the fraction shrub load that is live. Dead shrub load by size class is the product of total shrub load and the specified fractions of the total load in three size classes.

Shrub stem and foliage SAV ratios are a function of the shrub type, as shown in the table below.

Shrub type	**SAV ratio (m^{-1})**	
	foliage	**stems**
Fine stems, thin leaves	8366	9842
Medium stems, thin leaves	6275	7382
Medium stems, thick leaves	4880	5741
Very dense, fine stems and leaves	4880	5741
Thick stems and leaves	4880	5741

Finally, the heat content applied to the live fuel component of the shrubs at the sample point depends on whether they are waxy.

Heat Content (kJ/kg)	
Waxy	20685
Not waxy	18361

The Burgan-Rothermel shrub component outputs are as follows:

Shrub component output	**Native units**
BR.ShrubBulkDensity	kg/m^3
BR.ShrubLoadOneHr	kg/m^2
BR.ShrubLoadTenHr	kg/m^2
BR.ShrubLoadHndrdHr	kg/m^2
BR.ShrubLoadLive	kg/m^2
BR.ShrubLoadTotal	kg/m^2
BR.ShrubFoliageSAV	1/m
BR.ShrubStemSAV	1/m
BR.ShrubLiveSAV	1/m
BR.ShrubLiveHeatContent	kJ/kg

2.2.2.3 Litter

The BR inventory of litter fuel consists of eight inputs: litter compactness, litter source, litter needle length, litter depth, litter cover, and the fraction of total litter load in each of three size classes

There are three levels of litter compactness: loose, normal, and compact. Litter source can be conifer, hardwood, or both. Needle length can be long, short, or both. Litter depth is the depth of the fuel layer that includes fallen foliage as well as dead and down twigs and branches less than 3 inches in diameter. Litter cover is the relative amount of the sample area covered by litter. The fraction of total litter load is a ocular estimate of the distribution of the total litter load in the three standard dead fuel size classes: 0–6 mm, 6–25 cm, and 25–75 mm. The sum of these percentages must add to 100.

The BR litter inventory method produces six outputs: litter bulk density, total litter load, dead and down load by size class, and SAV ratio of the finest size class.

Litter bulk density is a function of the litter source, compactness, and needle length, as shown in the table below.

Litter Bulk Density (kg/m^3)		Litter compactness		
Litter source	**Needle length**	**loose**	**normal**	**compact**
conifer	**Long**	15.9872	19.8759	27.2374
	Short	45.9631	45.9631	61.2841
	Both	23.7229	27.2374	36.7705
Hardwood	**Long**	15.9872	19.8759	27.2374
	Short	15.9872	19.8759	27.2374
	Both	15.9872	19.8759	27.2374
both	**Long**	15.9872	19.8759	27.2374
	Short	22.2851	28.2850	36.7705
	Both	18.3852	22.9815	30.6421

Total litter load is the product of litter bulk density (from the above table) and litter depth. Dead-and-down load by size class is the product of the total litter load and the specified fraction of that load for each of the three size classes. The SAV ratio of the finest size class (1-h timelag class) is held constant in FuelCalc at 6562 m^{-1}.

Burgan-Rothermel litter component outputs are as follows:

Burgan-Rothermel litter outputs	Native units
BR.WoodyBulkDensity	kg/m^3
BR.WoodyLoadOneHr	kg/m^2
BR.WoodyLoadTenHr	kg/m^2
BR.WoodyLoadHndrdHr	kg/m^2
BR.WoodyOneHrSAV	1/m

2.3 Piled Fuel (PL)

Hardy's (1996) method of inventorying piled fuel (PL) is included in FuelCalc 1.0. The PL method consists of steps for determining the fuel mass and pile area of an individual pile. Individual-pile inputs are as follows:

Pile Inputs	Native units
Expansion Factor	1/ha
Pile Shape	category
Length 1	meters
Width 1	meters
Height 1	meters
Length 2	meters
Width 2	meters
Height 2	meters
Packing Ratio	dimensionless
Proportion Species 1	percent
Density Species 1	kg/m3
Density Species 2	kg/m3

2.3.1 Individual pile calculations

2.3.1.1 Gross pile volume

The gross volume of an individual pile is a function of the shape and size of the pile. FuelCalc recognizes nine different shapes, shown in the table below with the dimensions required for each shape. There are two half-frustum of cone shapes, depending on whether the width or height of the pile is known. See Hardy (1996) for drawings of the different shapes and their required measurements.

		Required pile dimensions					
shape code	name of shape	l	w	h	l	w	h
1	section of sphere (w, h)		•	•			
2	half-section of sphere (h only)			•			
3	paraboloids (w, h)		•	•			
4	half-cylinder (l, w, h)	•	•	•			
5	half-frustum of cone (l, w, w)	•	•			•	
6	half-frustum of cone (l, h, h)	•		•			•
7	cone with round ends (l, w, w)	•	•			•	
8	half-ellipsoid (l, w, h)	•	•	•			
9	irregular solid (l, l, w, w, h, h)	•	•	•	•	•	•

For any individual pile with specified shape code and its associated pile dimsnsions, FuelCalc calculates the gross volume of the pile according to the equations in Hardy (1996). The gross pile volume includes the air spaces as well as the solid fuel pieces in the pile.

2.3.1.2 Net pile volume

Net pile volume is the volume of solid fuel in the pile. It is calculated as the product of gross pile volume and the packing ratio of the pile. The higher the packing ratio, the more solid fuel there is for a given gross volume. Packing ratio of piled fuel varies from 0.10 to 0.25 for a densely packed pile. Use the following table as a guideline for estimating pile packing ratio.

Pile packing ratio	description
0.10 to 0.15	Piles with species content dominated by ponderosa pine with mean diameters of the large woody fuel of less than 10 inches.
0.15 to 0.20	Piles dominated by short-needled conifers.
0.20 to 0.25	Highly compacted, clean piles with larger logs (diameters greater than 10 inches), especially those built with a crane or loader.

2.3.1.3 Pile mass

The oven-dry mass of an individual pile is the product of net pile volume (see section 2.3.1.2 above) and the density of the wood particles it contains. FuelCalc allows the user to choose two different wood density values (and the relative proportion of each species) for an individual pile, and then computes the weighted-average wood density. That weighted-average wood density is multiplied by the net pile volume to estimate the mass of wood in the pile.

Use the following table of wood density values (adapted from Hardy 1996) as a guide to determining wood density.

Species	Oven-dry wood density (kg/m^3)
Rotten wood (any species)	300
Western redcedar (*Thuja plicata*)	311
Black cottonwood (*Populus trichocarpa*)	311
Quaking aspen (*Populus tremuloides*)	351
True fir (*Abies procera*)	370
Red alder (*Alnus rubra*)	370
Sitka spruce (*Picea sitchensis*)	370
Ponderosa pine (*Pinus ponderosa*)	380
Lodgepole pine (*Pinus contorta*)	380
Western hemlock (*Tsuga heterophylla*)	420
Bigleaf maple (*Acer macrophyllum*)	441
Vine maple (*Acer circinatum*)	441
Douglas-fir (*Pseudotsuga menziesii*)	450
Western larch (*larix occidentalis*)	481
Tanoak (*Lithocarpus densiflora*)	580

2.3.1.4 Pile area

The ground area covered by each pile is calculated according to the pile shape and dimensions.

2.3.1.5 Pile load

The load of each pile is calculated as the oven-dry mass (section 2.3.1.3) divided by the pile area (2.3.1.4). This represents the mass per unit area of the pile itself, not the plot average.

2.3.2 Plot-level pile calculations

The previous section described calculations for individual piles in a plot. This section describes how those individual-plot calculations are compiled into plot-level summaries. Summarizing pile-level calculations to the plot level requires the assignment of an expansion factor for each pile. The pile expansion factor is similar to a tree expansion factor in a treelist; it indicates the number of piles per unit area to be represented by the pile. For a fixed size sample area, pile expansion factor is the inverse of the sample area size. For example, if the pile was measured as part of a complete census of piles in a whole unit, then the pile expansion factor for every pile in the inventory is the inverse of the unit size (ha). For example, if a pile is measured on a 5-ha unit, then the pile expansion factor is 0.2 ha^{-1} (1 / 5 = 0.2). If a pile was measured as part of 1-ha sample plot, then the pile expansion factor is 1 ha^{-1}.

Plot-level piled fuel outputs are shown in the following table:

Piled fuel outputs	Native units
PL.FractionGroundAreaPileCovered	percent
PL.PileLoadWherePiled	kg/m^2
PL.PileLoadWholePlot	kg/m^2

2.3.2.1 Total pile cover

Pile cover is the fraction of the total sample area that is covered by a pile. Total pile cover is the sum-product of pile expansion factor (2.3.2) and individual pile area (2.3.1.4) for each pile. That result is divided by 100 to express the total pile cover as a percentage.

2.3.2.2 Total pile load (whole plot)

Total pile load is the sum-product of individual pile mass (2.3.1.3) and pile expansion factor (2.3.2). Total pile load represents the average load in piles over the whole sample area. The load of piles would be much greater underneath the actual piles.

2.3.2.3 Pile load where piled

This is the mean fuel load where the piles exist, calculated as the total pile load divided by the total pile cover (as a fraction).

2.4 Canopy Fuel (CF)

This section describes the stepwise procedure for calculating canopy bulk density (CBD), canopy base height (CBH), stand height (SH) and canopy fuel load (CFL). Estimating the available crown fuel mass for an individual tree (*ACM*) is the most basic step of the procedure; *ACM* is used to estimate each of the four canopy fuel characteristics. Basic inputs for the canopy fuel calculations are a treelist. Components of the FuelCalc treelist are shown in the table below.

Treelist input	Native units
species	NRCS code
expansion factor	1/ha
diameter	cm
crown base height	meters
height	meters
status	category
crown class	category
snag code	category
biomass adjustment	dimensionless
removal	dimensionless
comment	

Species is the NRCS species code for the tree record in a tree list. The list of currently accepted NRCS codes is kept internally in FuelCalc. See the description of species management in section 1.5 for more details on how to specify species in FuelCalc.

Expansion factor is the number of trees per hectare that a tree record represents. If the tree was sampled on a fixed-area plot, then expansion factor is the inverse of plot size (in hectares). For example, if a tree in a tree record was measured on a plot exactly 1000 m2 in size(0.1 ha), then the expansion factor is 1/0.1 = 10 trees per ha.

Diameter is the outside-bark tree stem diameter at breast height.

Crown base height is the vertical distance from the ground to the lowest height above the ground that an individual tree contains enough available fuel to propagate fire vertically through its crown. This definition includes any ladder fuel like needle drape or moss associated with the tree.

Height is the vertical distance from the ground to the tip of the tree stem.

Status refers to the health of the tree stem in the treelist. The following table lists the four possible tree health status categories. This variable is used to prioritize trees for removal during a thinning.

code	Tree status
H	healthy
U	unhealthy
S	sick
D	dead

Crown class refers to crown position of each tree. Crown class is used to adjust the estimated biomass for each tree, and to prioritize trees for removal.

code	Crown class
O	open-grown
E	emergent
D	dominant
C	co-dominant
I	intermediate
S	suppressed

Snag code is categorical description of the status of a dead tree. Live trees should be coded 0. Snag code is used to determine the branch biomass associated with each dead tree. Trees with snag code of 1a will contribute to available canopy fuel; all others do not.

code	description
0	live tree
1a	Recently dead; red or brown foliage attached
1b	Recently dead; foliage fallen; fine twigs attached
2	Few limbs; minor bark sloughing
3	limb stubs only; significant; bark sloughing
4	few or no limb stubs; broken top; some rot
5	no limb stubs; broken top; rotten

Biomass adjustment is an optional multiplier on a tree's estimated biomass. This adjustment is made in addition to any adjustments based on crown position. The purpose of this adjustment is to allow biomass adjustment for factors other than crown position, such as disease.

Finally, the Removal variable is used to indicate what fraction of the tree record to remove during a free thinning. It is analogous to cutting efficiency. If the removal variable is 0.75 for a tree record, then the expansion factor for a tree is reduced to 25 percent of its original value.

Canopy fuel outputs are shown in the following table:

Canopy fuel outputs	Native units
CF.CanopyBaseHeight	meters
CF.StandHeight	meters
CF.CanopyBulkDensity	kg/m^3
CF.CanopyFuelLoad	kg/m^2

2.4.1 Adjusted total mass of an individual tree crown

Estimation of adjusted total crown mass (*ATCM*) of an individual tree is the most basic step in the process of estimating canopy fuel and related characteristics; it is estimated by first estimating total crown mass (*TCM*) then adjusting that estimate as necessary. *TCM* is calculated from allometric equations that relate the mass of a tree's foliage and branchwood to its dimensions (primarily height and diameter). Each equation pertains to a particular species. In common practice, the equation for one species is often used for other species with similar branch and foliage characteristics. This practice is necessary because equations are available for a small fraction of the species for which these estimates must be made.

A variety of equations may be available for a given species, each with different independent variables. Some equations include crown ratio (*CR*) as an independent variable while others do not. In order to simulate the effects of tree manipulation like mechanical pruning or crown scorch, it is important that the *TCM* equation include *CR* or a surrogate variable. If an equation that uses *CR* is not available, then we add a term that simply adjusts the predicted *TCM* by the ratio *CR*/*CR*', where *CR*' is a "standard" crown ratio for the equation. The *TCM* for trees with greater crown ratio than the standard is increased; *TCM* is decreased for trees with crown ratio less than the standard.

Equations may also apply only to a particular crown class (i.e., dominant, co-dominant, etc.). For example, Brown (1978) published separate equations for intermediate trees and for dominant and co-dominant trees. If an equation for dominant and co-dominant trees must be used for sub-dominant classes, it may be necessary to adjust *TCM* to account for the lower biomass of sub-dominant trees. This adjustment is currently handled by species-specific crown class adjustment factors (*CCAF*) for each crown class. Note that sub-dominant trees often have lower crown ratios than dominant trees, and *CR* is accounted for separately, either in the TCM equation or with the surrogate described above. Therefore, the CCAFs should not take into account the fact that sub-dominant trees generally have lower *CR*s, just that the density of foliage and fine branchwood is lower on sub-dominant trees. The default *CCAF*s used in FuelCalc are listed as part of the equation set, but can be edited for each individual species.

2.4.2 Proportion of TCM in different size classes

The process described above provides an adjusted estimate of the total crown mass, in all size classes, and vertically distributes it along the length of a crown. It is necessary to also know how that fuel is divided into separate size classes in order to estimate available crown mass (*ACM*), and for estimating activity fuel load following crown scorch, pruning, or thinning.

The mass of any individual size class is simply the product of *ATCM* and the proportion associated with the size class as predicted with Brown's equations.

2.4.3 Available adjusted crown fuel mass for an individual tree

The available adjusted crown fuel mass of an individual tree (ACM_{avail}) is the adjusted mass of its foliage and some fraction of its fine branchwood. For coarse-branched species like ponderosa pine, even the finest branchwood is simply too large to burn in the short duration of a crowning fire; only the foliage contributes to ACM_{avail}. For species with relatively fine branches, like Douglas-fir, some fraction of the branchwood may contribute to crown fire behavior in addition to the foliage. The amount of the fine branchwood suggested to include as available varies. Brown suggested that roughly half of the 0 – 6 mm branchwood is available during a crown fire. Scott and Reinhardt (2005) included all of the 0 – 6 mm dead branchwood and all of the 0 – 3 mm live branchwood as available. Even for those species that contain branchwood in such small diameters, foliage mass is commonly many times greater than available branchwood mass. For that reason, some authors have opted to include only foliage as available fuel, and ignored any potential contribution of fine branchwood. However, a destructively sampled dataset indicates that not including any branchwood as available would reduce the estimated canopy bulk density by 20 – 30% in stands dominated by fine-branched species (Scott and Reinhardt 2005). Although it is not known what fraction of branchwood is best to use here, we have opted to use half of the 0 – 6 mm class because the mass of 0 – 3 mm branches is not commonly known.

2.4.4 Canopy fuel load

The plot-level available canopy fuel load (CFL_{plot}) is the sum-product of available adjusted crown fuel mass and tree expansion factor for every tree in a treelist.

2.4.5 Vertical distribution of canopy mass within a tree crown

Previous canopy fuel profiles were created in FuelCalc by assuming that the fuel mass for an individual tree was uniformly distributed along the vertical length of its crown. Gray and others (2006) developed species-specific equations for predicting the distribution of canopy fuel along the length of a tree crown based on a dataset of destructively measured trees. These equations are available for only a small number of species. For species for which an equation is not available, we can either assign an equation we do have, or simply assume the default uniform vertical distribution.

Estimation of *CBD* is not strongly affected by the shape of the vertical distribution, but *CBH* and activity fuel mass is sensitive to the distribution shape, especially when determining the effects of crown scorch or pruning activities.

The following process is used to vertically distribute crown mass within an individual tree crown. The equations were constructed to distribute ACM_{avail}, but we assume they also apply to the distribution of *ACM* of all other size classes as well.

2.4.6 Canopy Bulk Density

FuelCalc estimates an effective plot-level CBD as the maximum 3-m average CBD_m that occurs in the profile.

2.4.7 Canopy base height (CBH) and stand height (SH)

FuelCalc estimates plot-level canopy base height (*CBH*) as the lowest height above the ground at which CBD_m >= 0.012 kg/m^3. This threshold-*CBD* method works well in most situations, but fails completely in others. For example, a plot with low *CBD* (due to thinning, for example, or one in a naturally open stand) may not exceed the threshold at any height, even though it is possible that every tree has a crown that extends to the ground. We addressed this issue in FuelCalc by reducing the threshold to 10 percent of the maximum CBD value for CBD less than 0.12 kg/m3. In other words, when plot-level CBD is greater than 0.12 kg.m3 the normal threshold of 0.012 kg/m3 is used; when CBD is less than 0.12 the threshold is 0.1 times the CBD value. This approach ensures that there is always a CBH value returned.

2.4.8 Canopy cover

Canopy cover is used to estimate the amount of shading and, in some fire behavior applications, wind adjustment factor. FuelCalc estimates canopy cover following the model used in FFE-FVS…

2.5 Fuel Summary

FuelCalc provides several options for inventorying or specifying each individual component of a plot-level ground and surface fuel profile. The following table lists the individual components of a ground and surface fuel profile. (Canopy fuel profile is calculated separately.) Where the user provides enough data to estimate a certain quantity from more than one method, the user-defined preference order determines which estimate to include in the summary. For example, the user may provide inventory data that can be used to estimate duff load—duff depth and bulk density—but also directly enter duff load from a photo guide or other source. The preference order determines which of those duff load estimates to use in the summary.

input variable	native units
TotalDuffLoad	kg/m2
LitterLoad	kg/m2
LichenLoad	kg/m2
TotalMossLoad	kg/m2
GrassLoadTotal	kg/m2
ShrubLoadLive	kg/m2
WoodyLoadOneHr	kg/m2
WoodyLoadTenHr	kg/m2
WoodyLoadHndrdHr	kg/m2
WoodyLoadThousandHr	kg/m2
PileLoadWholePlot	kg/m2
FM.WoodyOneHrSAV	1/m
FM.GrassSAV	1/m
FM.ShrubLiveSAV	1/m
FM.FuelBedDepth	cm

Total duff load, litter load, lichen load and moss load can come from either the ground fuel inventory (GF) or from direct entry (DE).

Grass load and shrub load can come from the Burgan-Rothermel (BR) inventory method or from direct entry.

WoodyLoadOneHr is the load of dead and down woody fuel particles in the 1-h timelag class (0-6 mm diameter). WoodyLoadTenHr and WoodyLoadHndrdHr are the load in the 10- and 100-hr timelag classes. These quantities can come from the Planar-Intercept (PI) method, Burgan-Rothermel, or direct entry.

WoodyLoadThousandHr is the load of fuel particles greater than 75 mm diameter. This estimate can come from the Planar-intercept method or from direct entry. Also, the load in the 1000-hr timelag class can be broken down into the five different coarse-woody-fuel size classes and five different decay classes.

PileLoadWholePlot is the total mass of fuel in piles divided by the area where the piles are found. The load of piled fuel is much greater in the small area under the piles themselves. This quantity can come from a piled fuel inventory (PL) or from direct entry.

FM.WoodyOneHrSAV , FM.GrassSAV and FM.ShrubLiveSAVare the surface-area-to-volume ratios to use in a fire behavior fuel model. These quantities can come from either the Burgan-Rothermel inventory method, from direct entry, or from a default value.

FM.FuelBedDepth is the depth of the surface fuelbed to use in a fire behavior fuel model. This quantity can come from the Burgan-Rothermel Inventory, from direct entry, or from a calculation based on live and dead fuel loads.

3. Fuel Treatment Simulation

In addition to calculating existing ground, surface and canopy fuel characteristics, FuelCalc also simulates the effects of fuel treatment on those same characteristics. This section describes the process used to define and simulate fuel treatments in FuelCalc.

In FuelCalc, a fuel treatment is an ordered, sequential regime of fuel management actions. The actions that FuelCalc simulates are:

- Thinning
- Pruning
- Piling and burning
- Broadcast burning

When simulating a fuel treatment regime, the above actions are implemented in the order listed. The rare cases where a different order would produce a different result cannot be simulated. Users will be able to simulate any number of user-defined treatments. The following sections describe how the characteristics of each treatment action are described. The initial plot condition (also called pre-treatment or untreated) is simulated by setting all treatment inclusion options to "NO".

The potential effects that the four different treatments could have on fuel or biomass components is shown in the table below.

fuel / biomass component	initial condi-tion	fuel treatment				
		thinning	pruning	piling	pile burning	broadcast burning
duff	X				-	-
litter	X	+	+	-		+ / -
lichen	X					-
moss	X					-
herbaceous	X					-
live woody	X					-
1-hr	X	+	+	-		-
10-hr	X	+	+	-		-
100-hr	X	+	+	-		-
1000-hr (decay class 1)	X	+		-		-
1000-hr (decay class 2)	X			-		-
1000-hr (decay class 3)	X			-		-
1000-hr (decay class 4)	X			-		-
1000-hr (decay class 5)	X			-		-
Piled fuel	X			+	-	
available canopy fuel load	X	-	-			-
standing unavailable branchwood	X	-	-			
standing dead tree boles	X	0 / -				0 / +
Standing live tree boles	X	-				0 / -
forest products		+				
landing pile		+			-	
TOTAL ABOVEGROUND BIOMASS	sum	0	0	0	-	-

Duff is not affected by any treatment component except pile burning, which reduces duff load by burning the duff beneath piles.

Thinning and pruning both add to the litter fuel component, even though the needles are initially still attached to the branches and not necessarily on the ground. Piling reduces litter by adding to piles the needles that are still attached to branches. Broadcast burning initially reduces the litter load, but may also increase litter load as scorched foliage falls to the ground. Lichen, moss, herbaceous, and live woody fuel components are not affected by any treatment except burning, which reduces their loads. The 1-, 10-, and 100-h timelag size class dead and down fuel components are increased by thinning and pruning, but decreased by piling, and broadcast burning. Thinning adds to the 1000-h timelag class fuel load (all of it in decay class 1, very sound). But piling and broadcast burning can then reduce this load. Piling and broadcast burning reduces the load of decay classes 2 – 5 of 1000-h timelag class logs. Nothing adds to the load of these classes because all activity fuel is presumed to be in the very sound class. Piling adds to any existing piled fuel load. Burning the piles subsequently reduces the piled fuel load. Thinning and pruning reduce the available canopy fuel load (foliage and fine branches). Broadcast burning may also reduce available canopy fuel load if crown scorch occurs. Standing unavailable branchwood is all branchwood but the foliage and fine twigs included as available canopy fuel. Thinning and pruning reduce this biomass component. Standing tree boles are the stems of trees at the plot. Thinning reduces this biomass component. Forest products represent the mass per unit plot area that is removed from the area to a processing plant. Only thinning can contribute to this category. Finally, the landing pile is potentially created during a thinning operation.

Now let's look at fuel treatment dynamics from the perspective of treatment component.

Thinning reduces the standing tree boles, available canopy fuel, and standing unavailable branchwood. Those reductions are offset exactly by increases in litter, 1-, 10- 100- and 1000-h timelag dead fuel classes, forest products, and the landing pile.

Pruning reduces available canopy fuel load and standing unavailable branchwood. Those reductions are exactly offset by increases in litter and the 1-, 10- and 100-h timelag classes.

Piling reduces the litter and all dead and down size classes. Those reductions are exactly offset by an increase in the load of piled fuel.

Pile burning reduces the piled fuel and any landing pile created during thinning. The sum of those reductions is the fuel load consumed.

Broadcast burning reduces all ground and surface fuel components, and potentially reduces available canopy fuel load if crown scorch occurs. Broadcast burning may also increase litter and the 1-h timelag class if crown scorch occurs. The net sum of those reductions and increases is the fuel load consumed.

In addition to the effects of fuel treatment on the fuel load and biomass quantities described above, the fuel treatments also affect non-load canopy fuel characteristics, as shown in the table that follows.

fuel / biomass component	initial condi-tion	fuel treatment				
		thinning	pruning	piling	pile burning	broadcast burning
Canopy base height	X	0 / +	0 / +			0 / +
Canopy bulk density	X	0 / -	0 / -			0 / -
Canopy cover	X	-				0 / -

Thinning either increases canopy base height or it leaves it unchanged, depending on the nature of the stand and the intensity of the thinning. For thinning to increase CBH it must remove enough trees that have available biomass low in the stand to raise the height that a critical amount of fuel is reached. High thinning or commercial thinning that leaves small non-commercial trees standing may not change CBH. Likewise, thinning either decreases canopy bulk density or leaves it unchanged, depending on the nature of the stand and the intensity of the thinning. For thinning to decrease CBD is must remove fuel in the most densely packed layers of the canopy. Understory removal may not reduce CBD if the highest CBD is found in the overstory; overstory thinning may not reduce CBD of the highest CBD is found in the understory. Thinning always reduces canopy cover as calculated in FuelCalc.

Pruning does not change canopy cover in FuelCalc, but can have the same effects of CBD and CBH as thinning. Pruning raises CBH as long as the pruning height is greater than the pre-pruning CBH. Pruning can reduce CBD if pruning height approaches the height of maximum bulk density. Because pruning heights are usually limited to low values, pruning generally reduces CBD only if the highest CBD layer is very low to the ground (in the understory layer, for example).

Piling and pile burning are assumed to have no effect on these canopy characteristics. FuelCalc assumes that no trees are scorched or killed when making or burning piles.

Finally, broadcast burning has two direct effects: it scorches trees (similar to pruning) and may kill trees (similar to thinning). Indirectly, these effects can increase CBH, reduce CBD, and reduce canopy cover just as thinning and pruning do. Whether these effects take place depends on the nature of the broadcast burn.

3.1 Thinning

Thinning is the reduction of tree density in a forest stand to meet some objective. In FuelCalc, the density of trees in a stand is quantified by the TreeExpansionFactor for each tree record in a treelist. The TreeExpansionFactor is a numeric value indicating how many trees per unit of stand area (native units are trees per hectare) are represented by a tree record. Thinning in FuelCalc is simulated as the reduction of this TreeExpansionFactor for selected trees in the treelist. To determine which trees will have their TreeExpansionFactor reduced, a RetentionPriority is computed for each tree record.

3.1.1 Retention priority

The RetentionPriority determines the order of removal of the tree records—the tree with the lowest retention priority is removed first. A removed-tree's TreeExpansionFactor will then be reduced by the specified CuttingEfficiency until a target thinning criteria value has been reached, subject to constraints on the minimum and maximum size of tree that may be removed. The CuttingEfficiency is the fraction of a tree record removed during the harvest. The default CuttingEfficiency in FuelCalc is 1.0, meaning that all trees represented by a tree record are removed. The user can specify any value between 0 and 1.0; the CuttingEfficiency is specified for each treatment defined in FuelCalc, and is used for all tree records.

A tree's overall priority for retention is the product of five factors, each of which varies between 0 and 1.0 (with exceptions to flag special conditions, as described below):

- Tree status factor
- Crown class factor
- Crown ratio factor
- Diameter factor
- Species factor

The first four factors are functions of a thinning definition, which allows the user to put more weight on certain factors than. The thinning definition indicates what values to use for each tree based in its status, crown class, crown ratio and diameter. The SpeciesPriority is specified in the ProjectTreeList. The user is responsible for ensuring that these priority factors are set in such a way that orders the trees for removal in a desirable way.

The following sections describe in more detail the different priority factors and how they are combined to an overall RetentionPriority.

Tree status factor

The tree status portion of the priority calculation is a scaling value that indicates the relative retention priority for the four the different tree status categories recognized in FuelCalc:

- Healthy (H)
- Unhealthy (U)
- Sick (S)
- Dead (D)

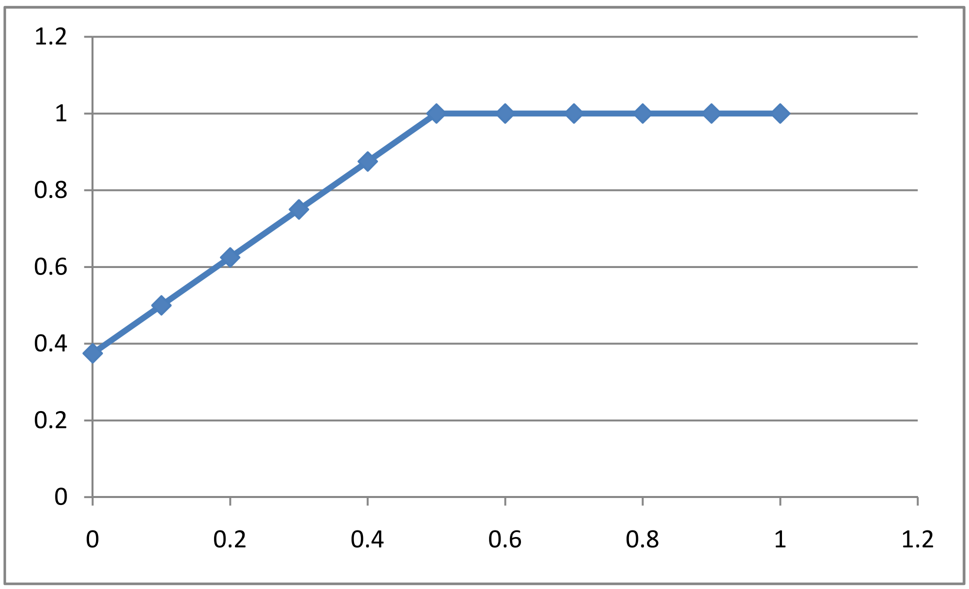
Normal tree status priority values range from 0 to 1, but a special value (9) may also be used. A value of 1 means that a tree of that status is highly desired for retention; a value near 0 means it is highly desired for removal. A value of exactly 0 means that the tree should *always be removed* (provided that it is within the allowable diameter range for cutting). To indicate that a tree should *always be retained*, use a special value of 9. A tree record without a tree status value defaults to a retention value of 1, indicating it is desired for retention. See the Thinning Definition section below for more information about how these values are stored by the user.

Crown class factor

The crown class portion of the RetentionPriority calculation consists of scaling values that indicate the relative retention priority of the different crown classes. Crown class is a categorical variable specified for each tree record as part of the treelist. A thinning type may emphasize retention of certain crown classes over others. These priority values are used to specify which classes are emphasized for retention versus removal. Normal values of crown class priority range from 0 to 1, but a special value (9) may also be used. A value of 1 means that a tree of that status is highly desired for retention; a value near 0 means it is highly desired for removal. A value of 0 means that the tree should *always be removed* (provided that it is within the allowable diameter range for cutting). To indicate that a tree should *always be retained*, use a special crown class priority value of 9. See the Thinning Definition section below for more information about how these values are stored by the user.

Crown ratio factor

Trees with higher crown ratios (CR) are generally more vigorous and therefore are usually a higher priority for retention. However, beyond a certain CR value, increases in crown ratio do not necessarily indicate increased vigor, and therefore do not increase retention priority. This threshold CR value could theoretically vary by species, but in FuelCalc one threshold CR value is used for all species (default = 0.5). All trees with CR >= 0.5 are assigned a retention priority of 1. A tree with a CR of 0.1 is assigned a user-defined priority between 0 and 1 (default = 0.5). Trees with CR between 0.1 and CR of maximum priority are assigned a crown ratio priority that is proportionally scaled between this user-controlled value and 1. The default relationship for low and high thinning is shown below: priority on the Y-axis, crown ratio on the X-axis.



The calculation to accomplish the above description is as follows:

$$CRpriority = MIN(1, \left(\frac{1 - CRspec}{CRmax - 0.1}\right)(CR - CRmax) + 1)$$

where
CRpriority is the crown ratio priority for a given tree

CRspec is the user-specified crown ratio priority for CR=0.1 (default = 0.5), and
CRmax is the user-specified lowest CR for which CRpriority = 1.0

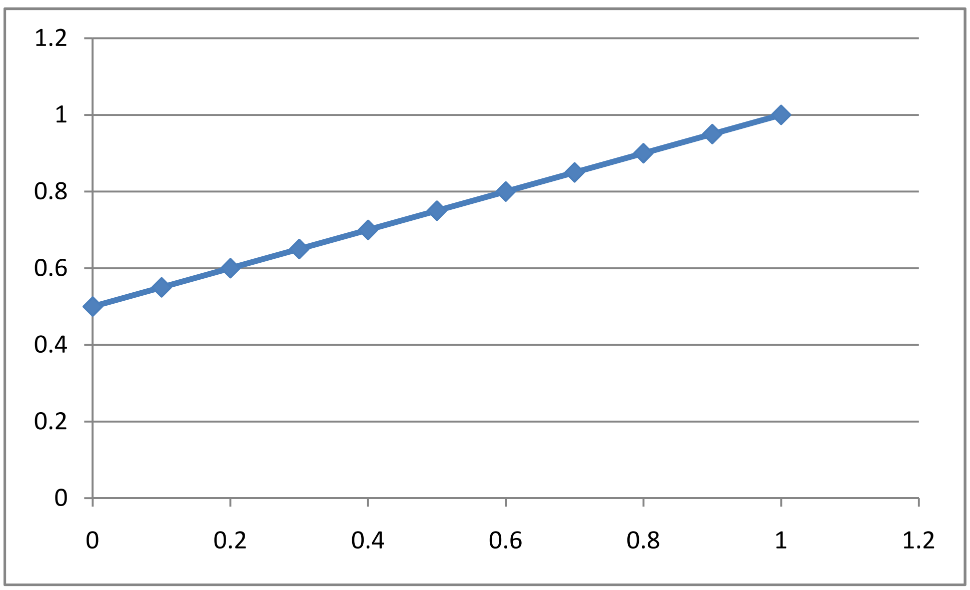
Diameter factor

Tree diameter at breast height can be used to prioritize trees for removal. In FuelCalc this is done by first computing each tree's diameter relative to the largest diameter in the treelist. The result is a fraction between 0 and 1 (a value of 0 is only possible for a DBH = 0 cm). The user separately defines the retention priority of the smallest tree (a number between 0 and 1; default = 0.5). The retention priority of the largest tree is assumed to be 1.0. The final diameter-based retention priority is shown below:

$$DBHpriority = MinDBHpriority * \left(\frac{DBH}{MaxDBH}\right) + MinDBHpriority$$

where
DBHpriority is the diameter priority for a given tree
MinDBHpriority is the retention priority assigned to the smallest tree in the plot
DBH is the subject tree's diameter, and
Max DBH is the diameter of the largest live tree in the plot (that is, tree status not "dead")

The above-described relationship is shown below for a value of MinDBHpriority = 0.5 assigned to the smallest tree. In the chart, the X-axis is the ratio of the subject tree's DBH to the maximum DBH on the plot; the Y-axis is the retention priority.



Species factor

Different thinning prescriptions may emphasize the retention or removal of certain tree species over others. This emphasis is handled by assigning a retention priority to each species. The species priority list depends on the species that are present in any plot's treelist in the project. SpeciesPriority is specified by the user in the ProjectSpeciesList.

Overall retention priority

The overall RetentionPriority for each tree is the simple product of the above five factors. Recall that the TreeStatusPriority and CrownClassPriority values can include, in addition to the normal 0 to 1 range, a special value of 9 to indicate that the tree should always be retained. If either of those two factors is flagged as such, then the sum of the five factors will be greater than 5. The first step in calculating the OverallRetentionPriority is to calculate this sum and assign an OverallRetentionPriority value of -1 to all such cases. All trees whose diameter is less than the MinCutDiameter or greater than the MaxCutDiameter are also not available for harvest and are assigned an OverallRetentionPriority value of -1. For the remaining trees, compute the product of the five individual factors as described above. Those values will all be between 0 and 1. Finally, the treelist should be sorted by this OverallRetentionPriority. Trees not available for harvest (too small, too large, or flagged to always retain) will have a value of -1 and will be at the top of the list. Next will be trees with an OverallRetentionPriority value of 0, which means that at least one of the five factors was 0, indicating the tree should always be harvested. The remaining trees will have values greater than 0 but less than or equal to 1.

Sorting and numbering trees in this way facilitates simulation of tree removal. The trees to always be retained (OverallRetentionPriority = -1) are at the top of the list and can be skipped when selecting trees to remove. Next are the trees to always be removed (OverallRetentionPriority = 0); these can be removed according to the CuttingEfficiency. The remaining trees are ordered by overall priority for retention. They are removed according to the cutting efficiency until the thinning target is reached.

3.1.2 IncludeThinning

A binary (yes/no) variable IncludeThinning is used to specify whether a thinning is to be simulated as part of the fuel treatment. If IncludeThinning = NO then there is no thinning associated with this treatment and we proceed to pruning. If Includethinning = YES then we specify the characteristics of the thinning, as described below.

3.1.3 ThinningDefinition

A thinning definition consists of a set of scaling values that, in combination with SpeciesPriority, permits the calculation of the *retention* priority of each tree in a treelist. (Removal priority is 1 minus the retention priority.) FuelCalc will have four default thinning definitions (Free thinning, Default Low Thinning, Default High Thinning, and Default diameter-limit harvest). The free thinning does not use the same removal priority calculations, but instead uses the FreeThinCuttingEfficiency specified for each tree in the treelist. In addition, the user can create user-defined thinning definitions. The table below illustrates the contents of the Thinning Definitions.

[table here]

3.1.4 CuttingEfficiency

Once the retention priority is calculated for each tree, the order of removal is from lowest priority toward the highest. Cutting efficiency represents what fraction of the tree record is removed. For example, a tree record may represent 25 trees per hectare. A cutting efficiency of 0.75 means that the post-thinning tree record should represent 25 * (1 - 0.75) = 6.25 trees per hectare. The default cutting efficiency is 1, meaning that all trees represented by a particular record are removed.

3.1.5 Diameter limit (minimum)

Regardless of the retention/remove priority as calculated above, the user separately specifies the smallest diameter tree that is to be cut (but not necessarily removed to a landing). The diameter limit is not applied when using the free thinning option.

3.1.6 Diameter limit (maximum)

Likewise, the largest tree that can be cut is also specified. This parameter is useful for simulating a diameter-limit harvest, and for simulating treatments in areas that disallow cutting trees above a certain diameter. The diameter limit is not applied when using the free thinning option.

3.1.7 Thinning criteria (quantity, units, value)

Trees are removed from the treelist according their priority and cutting efficiency, subject to the minimum and maximum diameter constraints, until a user-specified, plot-level thinning criterion is met. The criterion quantity can be: basal area, canopy cover, stand density index, tree density, canopy fuel load, or canopy bulk density. The user specifies which quantity to use, as well as the value (and units). For example, a criterion could be basal area of 100 ft2/ac.

3.1.8 Sub-merchantable tree diameter

The sum-merchantable tree diameter parameter specifies the smallest diameter of tree that is brought to a landing. Trees selected for removal with a diameter between the minimum-diameter limit and the sub-merchantable tree diameters are assumed to be felled but left on the plot.

3.1.9 Merchantable top diameter

The merchantable top diameter parameter specifies the diameter at which the tree top is cut off and left in the plot. Whole-tree harvesting removes the top to the landing, so a value of 0 would be used.

3.1.10 Yardloss

Yardloss refers to the fraction of a tree’s branches and foliage that do not make it to a landing. Factors affecting yardloss include the logging method and whether landing slash is backhauled to the stand.

3.2 Pruning

Pruning is the mechanical removal of the lower branches of trees. FuelCalc uses a very simple approach to simulating pruning. If pruning is included, the only characteristics to specify are the pruning height and the minimum post-pruning CR. All trees are pruned to the specified pruning height, providing that the residual crown ratio after pruning is not less than the specified minimum CR. (This prevents pruning a tree to death.) Therefore, the final pruning height for each tree is MIN(Pruning Height,tree height*minimumCR).

3.2.1 IncludePruning

A binary (yes/no) variable IncludePruning is used to specify whether a thinning is to be simulated as part of the treatment. If IncludePruning = NO then there is no pruning and we proceed to piling and burning. If IncludePruning = YES then we specify the characteristics of the pruning.

3.2.2 PruningHeight

If a pruning is included as part of the treatment, the height of the pruning is specified. All trees in the plot, regardless of their characteristics, are pruned to the specified height.

3.2.3 MinimumResidualCR

The MinimumResidualCR is the smallest post-thinning CR allowed. It is a dimensionless ratio between 0 and 1.0; default = 0.4.

3.3 Piling and burning

Piling and burning is use to simulate either hand-piling or machine piling of fuel in a stand, followed by burning of the piles. This fuel management action does not include piling and burning of landing slash. Piling and burning is simulated simply by specifying the fraction of current fuel load by size class (fine, medium, coarse) that is piled, and the fraction of those size classes consumed.

3.3.1 IncludePileBurning

This binary variable indicates whether piling and burning is to be simulated as part of the treatment.

3.3.2 FractionFuelPiled

Dimensionless ratio indicating what fraction (0-1) of the current woody fuel load is piled. The remainder remains as part of the surface fuel complex. Current fuel load includes activity fuel from thinning or pruning.

3.3.3 FractionFuelConsumed

Dimensionless ratio indicating what fraction (0-1) of the piled fuel is consumed. Default is 0.9; 90 percent of piled fuel consumed when the pile is burned.

3.4 Broadcast Burning

Broadcast burning is the application of prescribed fire to a whole unit, not just to piles or jackpots in a unit. Due to the effects of ignition pattern on fire behavior, FuelCalc does not attempt to simulate the behavior of a prescribed fire. Instead, we ask the user to prescribe a target fire behavior they will attempt to achieve, along with the fuel moisture content and in-stand wind speed at the time of the broadcast burn. FuelCalc will simulate fuel consumption using Albini's Burnup model along with the simulated fuel loads and given fuel moistures. FuelCalc will also simulate the effects of scorch height and tree mortality on the residual fuelbed.

3.4.1 IncludeBroadcastBurn

This binary variable indicates whether broadcast burning is to be simulated as part of the treatment.

3.4.2 BroadcastBurnMoistureContent

The user chooses from four fuel moisture scenarios (very dry, dry, and moderate) and applies those scenarios to all plots in the project.

3.4.3 PrescribedFlameLength

The user specifies the prescribed flame length (ignition pattern is adjusted to achieve the target).

4. Simulating Fire Behavior Potential

FuelCalc simulates potential fire behavior using the calculation engine in NEXUS 2.0. The primary purpose of the potential fire behavior simulations in FuelCalc is to compare the potential of different plots to each other, and to identify changes in fire behavior potential due to simulated fuel treatment.

Fire behavior potential is a function of the three main fire environment components: fuel, weather, and topography. The topography component (aspect and slope steepness) is specified in the plot information portion. Topography does not change with fuel treatment. Weather-related variables include dead fuel moisture content, wind speed and wind direction. Both dead fuel moisture and wind speed are affected by fuel treatment (through canopy cover) and also vary with different topographic conditions that plots may be in. A simple model exists for determining the effect of canopy cover on mid-flame wind speed. That model is already incorporated into the NEXUS calculation engine. However, the effects of topography and canopy cover on dead fuel moisture content are not as simple to simulate. FuelCalc's approach to simulating dead fuel moisture is described in section 4.1 below.

Four basic inputs are required from the user to simulate fire behavior potential in FuelCalc, as shown in the table below:

Display Name	Native units
20-ft wind speed	km/h
spread direction	categorical
wind direction	categorical
WeatherScenario	categorical

20-ft wind speed is the wind speed measured 20 feet (6.1 m) above un-vegetated ground, or above the vegetation, if present. Spread direction is the orientation of the flame front with respect to the heading direction. Four choices are possible:

Spread direction	description
head	heading fire
hank	hanking fire
flank	flanking fire
back	backing fire

The default spread direction is a head fire (a flame front oriented in the direction of maximum spread). Other choices include the hank, flank and rear of a fire. The flame front of a flanking fire is oriented 90 degrees (perpendicular) to the direction of maximum spread; a backing fire is oriented opposite the direction of maximum spread. A hanking fire is where the flame front orientation I between that of the head and flank. Generally, potential fire behavior calculations should be done for the heading or hanking spread direction.

Wind direction is the direction the wind is pushing the fire with respect to (1) true north, or (2) the upslope direction. Wind direction with respect to north is specified as one of the eight cardinal wind directions. Wind direction with respect to slope is specified as one of five classes, as shown in the last five rows of the following table.

Wind direction	description
N	north
NE	northeast

E	east
SE	southeast
S	south
SW	southwest
W	west
NW	northwest
U	upslope
Q-U	quarter-upslope
C-S	cross-slope
Q-D	quarter-downslope
D	downslope

The fire behavior calculations are made with respect to the upslope direction. If a cardinal wind direction is selected, then the aspect of the plot is used to determine the direction with respect to upslope. If a direction with respect to slope is selected, then the aspect of the plot with respect to the cardinal wind direction is not considered.

Finally, a weather scenario is selected for the fire behavior potential simulations. Four stylized weather scenarios are available in FuelCalc.

Weather scenario
very dry
dry
moderate
mild

See section 4.1 for more information in how the weather scenario is used to estimate dead fuel moisture content in FuelCalc.

4.1 Fire modeling inputs

The above section describes the inputs the user specifies in FuelCalc. Those inputs are then used to determine some intermediate input values needed for fire modeling. These intermediate values are shown in the table below.

Intermediate Variable	Native units
MoistureContentOneHr	percent
MoistureContentTenHr	percent
MoistureContentHndrdHr	percent
MoistureContentThousandHr	percent
MoistureContentDuff	percent
WindAdjustmentFactor	dimensionless
MidflameWindSpeed	km/h

The moisture content values are discussed in section 4.1.1 below. WindAdjustmentFactor is the dimensionless ratio of the midflame wind speed to the 20-ft wind speed. WindAdjustmentFactor is calculated in FuelCalc as a function of canopy cover and stand height, both of which are calculated within FuelCalc. Midflame wind speed is therefore calculated as the product of the 20-ft wind speed and the WindAdjustmentFactor.

4.1.1 Dead fuel moisture

Dead fuel moisture content is simulated as a function of four major inputs: weather history (temperature, humidity and precipitation) over prior days and weeks, slope steepness, aspect, and canopy cover. In geospatial fire modeling systems like FARSITE and FlamMap, dead fuel moisture is computed on-the-fly for each discrete element of the landscape based on the exact weather history to that point.

FuelCalc simplifies that approach by limiting the weather history component to just four stylized weather histories that represent very dry, dry, moderate and mild weather. Each stylized weather history consisted of five days of the same daily weather pattern (high and low temperature and humidity).

Stylized weather scenario	Temperature (F) (low/high)	Relative humidity (percent) (high/low)	Precipitation	Sky conditions	Wind speed (km/h)	Wind direction
Very dry	60/90	50/10	none	Clear	13	upslope
Dry	50/80	60/20	none	Clear	13	upslope
Moderate	40/70	70/30	none	Clear	13	upslope
Mild	30/60	80/40	none	Clear	13	upslope

Each of the above weather histories was used to simulate fine dead fuel moisture using FlamMap. The dead fuel moisture content at 3 pm was recorded. The FlamMap "landscape" consisted of a regular arrangement of cells with different canopy covers (from 0 percent to 100 percent in 1 percent increments), slope steepness, and aspect. Elevation was assumed constant. (In FuelCalc, dead fuel moisture is assumed to be the same for plots at different elevations, all other things equal.) Aspect was classified according to the following table (The class value was used in the simulations).

AspectClass				
Aspect		code	description	class value (degrees)
>=	<			
337.5	22.5	N	north	0
22.5	67.5	NE	northeast	45
67.5	112.5	E	east	90
112.5	157.5	SE	southeast	135
157.5	202.5	S	south	180
202.5	247.5	SW	southwest	225
247.5	292.5	W	west	270
292.5	337.5	NW	northwest	315

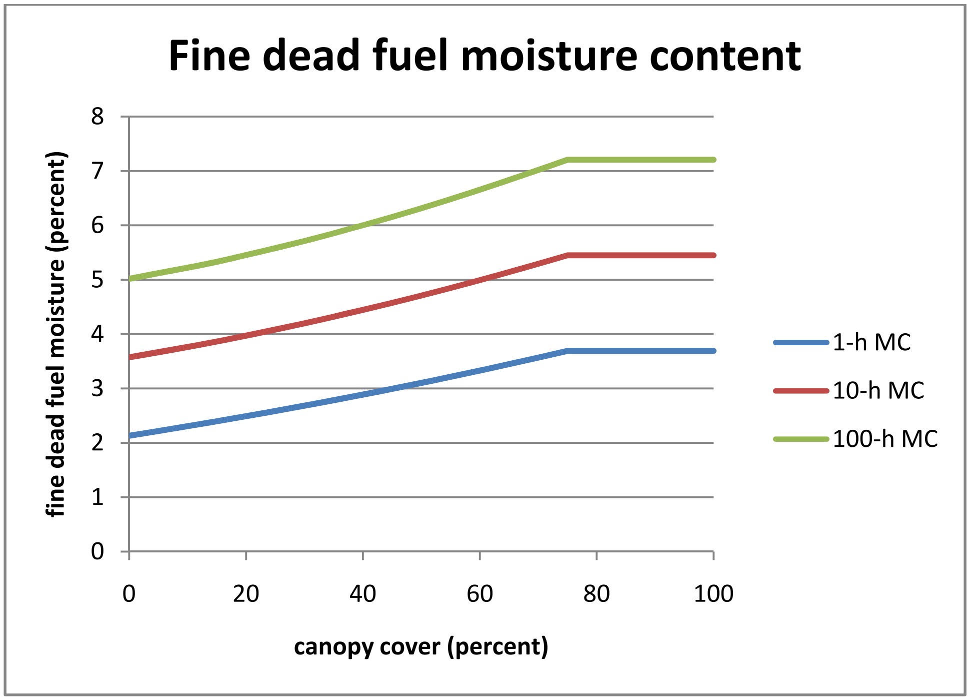
Slope steepness was classified according to the following table (The class value was used in the simulations).

PlotSlopeSteepnessClass				
PlotSlopeSteepness				
>=	<	code	description	class value (percent)
0	5	F	flat	0

5	25	L	low	15
25	55	M	moderate	40
55		S	steep	65

FuelCalc uses the results of those dead fuel moisture simulations to estimate the fine dead fuel moisture for each plot based on the factors above.

The following chart illustrates the simulation results for the very dry weather history on a moderately steep south-facing slope.



FuelCalc assumes a single value for duff and coarse woody debris moisture content for each weather history, regardless of plot or stand characteristics. The moisture content values are shown in the table below.

Weather history	Duff MC (pct)	1000-hr MC (pct)
very dry	15	10
dry	50	15
moderate	125	25
mild	200	50

4.2 Fire modeling outputs

The standard outputs of the fire modeling simulations are shown in the table below.

Fire Behavior Output	Native units
EffectiveMidflameWindSpeed	km/h
TypeOfFire	categorical
RateOfSpread	m/min
FirelineIntensity	kW/m
FlameLength	m
FireIntensityScale	dimensionless
TorchingIndex	km/h
CrowningIndex	km/h
CrownFractionBurned	percent

Effective midflame wind speed is the vector combination of the effects of midflame wind speed and slope steepness, expressed as an equivalent effective midflame wind speed.

Type of fire is a categorical variable indicating whether the simulated fire is expected to be a

- surface fire
- passive or intermittent crown fire
- active or continuous crown fire
- conditional crown fire (either surface fire or continuous crown fire)

Rate of spread is the linear rate of advance of the flame front for the spread direction specified.

Fireline intensity is the rate of heat release per unit length of fire front per unit time. Flame Length is calculated from fireline intensity.

Torching Index is the 20-ft wind speed at which the predicted surface fireline intensity is just enough to ignite the canopy fuel. Crowning Index is the 20-ft wind speed at which the predicted continuous crown fire spread rate is just enough to maintain continuous flame in the canopy.

Finally, crown fraction burned is a transition function calculated to represent the degree of transition from surface fire toward continuous crown fire. This transition function is also used to estimate the fraction of canopy fuel that burns in a crown fire.

4.3 Fuel model parameters

Surface fuel characteristics are fundamental inputs to the Rothermel surface fire spread model used in FuelCalc. FuelCalc allows two approaches for designating fuel model parameters: "modeled" fuel loads, and standard fuel model selection. Modeled fuel loads means using the inventoried or directly entered fuel loads, as modified with fuel treatment, to populate the fuel model parameters. Standard fuel model selection means using the modeled loads to select a standard fire behavior fuel model, then the parameters for the standard model are used in the fire behavior simulation.

4.3.1 Modeled surface fuel loads

The fuel model parameters needed to simulate fire behavior are shown in the table below. Each of these inputs is simulated or cataloged in FuelCalc and can be used directly to simulate fire behavior.

Fuel Model Parameter	Native units
FM.LoadOneHr	kg/m^2
FM.LoadTenHr	kg/m^2
FM.LoadHndrdHr	kg/m^2
FM.LoadHerb	kg/m^2
FM.LoadShrub	kg/m^2
FM.FuelModelType	categorical
FM.WoodyOneHrSAV	1/m
FM.GrassSAV	1/m
FM.ShrubLiveSAV	1/m
FM.FuelBedDepth	cm
FM.DeadHeatContent	kJ/kg
FM.LiveHeatContent	kJ/kg
FM.ExtinctionMoisture	percent

FM.OneHrLoad is the sum of four separate surface fuel components: litter load, lichen load, dead moss load, and woody load of particles less than 6 mm diameter. Each of these components is part of the fuel summary discussed earlier.

FM.TenHrLoad is the load of dead woody fuel particles between 6 and 25 mm diameter.

FM.HndrdHrLoad is the load of dead woody fuel particles between 25 and 75 mm diameter.

FM.LoadHerb is the load of live and dead herbaceous fuel particles.

FM.LoadShrub is the load of shrub foliage and fine twigs (generally less than 6 mm diameter).

FM.FuelModelType is "DYNAMIC" if FMLoadHerb is non-zero, "N/A" otherwise.

FM.GrassSAV is the surface-area-to-volume ratio of the grass and herbaceous fuel component.

FM.ShrubLiveSAV is the surface-area-to-volume ratio of the live shrub component (foliage and fine twigs).

FM.FuelBedDepth is the depth of the surface fuelbed. The total load of all components divided by this fuelbed depth is the bulk density (which itself is proportional to packing ratio). Bulk density and packing ratio are two very important factors affecting predicted spread rate in the Rothermel surface fire spread model. FuelCalc has a rudimentary method for estimating fuelbed depth that may not adequately represent fire behavior. Examine the fire behavior simulation results carefully to see if adjustment to the FuelCalc –estimated fuelbed depth is needed.

FM.DeadFuelHeatContent and FM.LiveFuelHeatContent are the dead and live fuel heat content values. Dead fuel heat content is constant at a default value of 18,593 kJ/kg. Default live fuel heat content is also 18,593 kJ/kg, but can be increased for shrub fuelbeds containing waxy vegetation.

Finally, extinction moisture content is the dead fuel moisture content at which the spread model will predict zero spread rate. Also, the larger the difference between actual dead fuel moisture content and the extinction moisture content, the greater the spread rate. Extinction moisture content is calculated as a function of the bulk density of the fuelbed.

4.3.2 Standard surface fuel model

Using the measured or modeled fuel loads directly in a fire spread model may be problematic, because the model is sensitive to parameters that are difficult to measure or simulate. For that reason, many fire modelers prefer to use a standard fire behavior fuel model rather than the modeled loads directly.

Appendix A shows the method used in FuelCalc to select a standard fire behavior fuel model from measured or calculated fuel characteristics.

5.0 Vegetation characteristics

FuelCalc uses the treelist, as modified by thinning and burning, to estimate several vegetation characteristics.

Vegetation Characteristic	Native units
StemDensity	1/ha
ExceedingStemDensity	1/ha
BasalArea	m2/ha
QuadraticMeanDiameter	cm
StandDensityIndex	1/ha
StandingTotalCubicFootVolume	m3/ha
StandingMerchantableCubicFootVolume	m3/ha
StandingMerchantableBoardFootVolume	MBF/ha
CanopyCover	percent

Stem density is the number of trees of any size per unit horizontal ground area. This number can be very large if the plot has a large number of small trees. Exceeding stem density is the number of trees per unit area that exceed a specified diameter. Basal area is the outside-bark cross-sectional area of live tree stems per unit ground area. Quadratic mean diameter (QMD) is the square root of the arithmetic mean of the squares of the tree diameters on a plot (the root-mean-square diameter). Stand Density Index (SDI) is a measure of stand density that combines stem density and QMD. SDI represents the density of trees expressed as the equivalent number of 25 cm trees per hectare.

The total cubic-foot stem volume per unit area is calculated for each plot, as well as the merchantable cubic-foot and board-foot stem volume. These volume estimates are made using the National Volume Estimator Library.

Finally, canopy cover is the non-overlapping fraction of the vertical projection of tree crowns that covers the plot.

Appendix A – Fuel model selection

Selecting a standard fuel model from fuel load data is a two-step process. The first step is narrowing the range of fuel model choices to a reasonable handful based on fuel type, climate type (extinction moisture content), and which set of fuel models to choose from. Step two is selecting from the narrowed list based on a similarity index of fuelbed characteristics such as fine fuel load, characteristic surface area to volume ratio, packing ratio, and bulk density. These characteristics can be calculated for both the measured/modeled fuel loads and for the standard fuel models.

A1. Narrowing the fuel model choices

For any given fuelbed, three pieces of information are used to narrow the list of fuel model choices: major fire-carrying fuel type, climate type, and fuel model set. A set of rules is used to classify the fuelbed into a major fire-carrying fuel type. Climate type and fuel model set are direct inputs from the user.

A1.1 Fire-carrying fuel type

FuelCalc method recognizes four of the six fire-carrying fuel types described in Scott and Burgan (2005): grass (GR), grass-shrub (GS), shrub or timber-understory (SH/TU), and timber litter or slash/blowdown (TL/SB). TL and SB fuel types are combined because both consist only of dead fuel. SH and TU fuel types are combined because both consist of a large fraction of dead fuel with a component of live woody or herbaceous fuel. A simple key is used to classify any fuelbed into one of these fuel types. Three fuelbed characteristics must be calculated to use the key:

LiveFraction is the ratio of live fuel load (grass/herbaceous load plus fine live shrub) to the total fine fuel load (which is the live fuel load plus the 1-h timelag class dead fuel load). LiveFraction is used to determine if the fuelbed should be treated as a dead-fuel-only fuel model or as a fuel model that contains live fuel. LiveFraction theoretically varies between 0.0 (for fuelbeds with no live fuel) and 1.0 (for fuelbeds with only live fuel). In practice, fuelbeds normally have some amount of dead fuel, so the LiveFraction normally approaches 1.0 without reaching it.

HerbFraction is the ratio of the herbaceous load to the total fine fuel load. HerbFraction is used to determine if a fuelbed that has previously been determined to have a live fuel component is a grass-dominated fuelbed. Like LiveFraction, HerbFraction theoretically varies between 0.0 (for fuelbeds with no herbaceous fuel) and 1.0 (for fuelbeds with only herbaceous fuel). In practice, even pure-grass fuelbeds normally have some amount of dead fuel (grass litter, for example), so the HerbFraction normally approaches 1.0 without reaching it. A grass dominated fuelbed will have a high HerbFraction.

HerbRatio is the ratio of the herbaceous load to the fine live woody load, which varies between 0.0 and 1.0 for all fuelbeds. If the fuelbed has no live woody load, this ratio should be set to 1.0.

Once the above quantities have been computed, the following selection key identifies the fire carrying fuel type. (In the unlikely event that at fuelbed contains no fine fuel load—just 10- and 100-hr timelag class dead particles—then the fuel type is set to TL/SB.)

A. IF **LiveFraction** <= 0.20 THEN the live fraction is inconsequential and a fuel model that does not include any live fuel will be selected (FuelType = TL/SB)
B. IF **LiveFraction** > 0.20 THEN the live fraction is significant and a fuel model that contains a live herbaceous or live woody component will be selected (continue with a. below)
    a. IF **HerbFraction** >= 0.75 THEN the fuelbed is dominated by herbaceous fuel and a grass-dominated fuel model will be available for selection (FuelType = GR)
    b. IF **HerbFraction** < 0.75 THEN the fuelbed is not dominated by grass/herbaceous fuel (continue with i. below)
        i. IF **HerbRatio** > 2.0 THEN grass/herbaceous component is dominant and fuel type is GR.
        ii. IF **HerbRatio** > 0.25 but <= 2.0 THEN both the grass/herbaceous load is enough to require a GS fuel model, but not enough to indicate a GR model, as above (FuelType = GS)
        iii. IF **HerbRatio** <= 0.25 THEN the grass component is not enough to indicate a GS fuel model, and any SH or TU fuel model may be appropriate (FuelType=SH/TU)

A1.2 Climate Type

Fuel models appropriate for humid and sub-humid climates have higher extinction moisture contents than fuel models for arid and semi-arid climates. Therefore, a different set of fuel models are available for selection in the different climate types (with some overlap). Depending on the application, climate type may be set by the application (by variant in FFE-FVS, for example) or the user will need to indicate the climate type separately (in FuelCalc, for example). Therefore, two climate types are available:

- Arid to semi-arid climates (low extinction moisture content)
- Humid to sum-humid climates (high extinction moisture content)

A1.3 Fuel model set

The last piece of information needed is the fuel model set to use. Two complete sets are available: the original 13 fuel models (Albini 1976, Anderson 1982) and the 40 fuel models (Scott and Burgan 2005). Although those sets were designed to stand alone, some people prefer to draw from among all 53 fuel models. This method allows three choices for fuel model set:

- Original 13
- 40 fuel models
- All 53 fuel models

The table above identifies the standard fuel models appropriate for each of the four fuel types, for both arid climates and for humid climates. The following table

		arid climate fuel models				**humid climate fuel models**			
		GR	**GS**	**SH/TU**	**TL/SB**	**GR**	**GS**	**SH/TU**	**TL/SB**
Original 13 fuel models	1	X	X			X	X		
	2	X	X	X		X	X	X	
	3	X	X			X	X		
	4			X				X	
	5		X	X				X	
	6								
	7			X			X	X	
	8				X				X
	9				X				X
	10			X				X	
	11				X				X
	12				X				X
	13				X				X
New 40 fuel models	GR1	X				X			
	GR2	X	X						
	GR3					X	X		
	GR4	X	X						
	GR5					X	X		
	GR6					X	X		
	GR7	X							
	GR8					X			
	GR9					X			
	GS1		X						
	GS2		X						
	GS3						X		
	GS4						X		
	SH1		X	X			X		
	SH2		X	X					
	SH3						X	X	
	SH4						X	X	

	SH5			X					
	SH6							X	
	SH7			X					
	SH8							X	
	SH9							X	
	TU1			X				X	
	TU2							X	
	TU3							X	
	TU4			X					
	TU5			X					
	TL1				X				X
	TL2				X				X
	TL3				X				X
	TL4				X				X
	TL5				X				X
	TL6				X				X
	TL7				X				X
	TL8				X				X
	TL9				X				X
	SB1				X				X
	SB2				X				X
	SB3				X				X
	SB4				X				X

For example, appropriate fuel models for a grass-dominated fuelbed (GR) in arid climates include fuel models 1, 2, and 3 from the original 13; and GR1, GR2, GR4, and GR7 from the 40 fuel model set. For a grass fuel type in a humid climate, the same original 13 fuel models are available (1, 2, and 3), but the narrowed list from the set of 40 fuel models includes GR1, GR3, GR5, GR6, GR8 and GR9.

Depending on the user's preference, the final narrowed list could include fuel models from 1) only the 13 original fuel models, 2) from only the set of 40 fuel models, or 3) from either set of fuel models.

A2. Selecting a fuel model from the narrowed list

Once the list of potential fuel models has been narrowed from step 1, the next step is to compute a similarity index comparing characteristics of the subject fuelbed to characteristics of each of the fuel models on the narrowed list.

A2.1 Similarity index

The similarity index is the weighted average of three separate fuelbed similarity factors: characteristic surface area to volume ratio (SAV, σ), fuelbed bulk density (ρ), and load (L) of live and dead fuel less than 6 mm (0.25 in.) diameter. Bulk density and SAV are weighted equally; fine fuel load receives twice the weight of SAV and bulk density. Each of these individual factors is the square of the difference between the fuelbed characteristic and the fuel model characteristic, normalized by dividing by the standard deviation of the characteristic across all 53 standard fuel models. The proposed similarity index is therefore defined as follows:

$$Similarity = 0.25 * \left(\frac{\sigma_{fuelbed} - \sigma_{fm}}{409.0}\right)^2 + 0.25 * \left(\frac{\rho_{fuelbed} - \rho_{fm}}{0.4030}\right)^2 + 0.50 * \left(\frac{Wf_{fuelbed} - Wf_{fm}}{3.073}\right)^2$$

where
$\sigma_{fuelbed}$ is the SAV of the subject fuelbed
σ_{fm} is the SAV of the subject standard fuel model
409.0 is the standard deviation of SAV of the 53 standard fuel models
$\rho_{fuelbed}$ is the bulk density of the subject fuelbed
ρ_{fm} is the bulk density of the subject standard fuel model
0.4030 is the standard deviation of the bulk density of the 53 standard fuel models
$Wf_{fuelbed}$ is the fine fuel load of the subject fuelbed
Wf_{fm} is the fine fuel load of the subject standard fuel model
3.073 is the standard deviation of the fine fuel load of the 53 standard fuel models

For each subject fuelbed, the similarity index is computed for each of the standard fuel models on the narrowed list from Step 1.

A2.2 Choosing a standard fuel model

The single best standard fuel model for the subject fuelbed is the one with the lowest similarity index. An index value of 0.0 indicates that all three fuel characteristics of the subject fuelbed exactly match one of the standard fuel models.

Appendix B – Units of Measure

FuelCalc manages units of measure by assigning a native unit of measure to each input and output quantity, and then allowing one or more optional units for each. The conversion factors from the optional units to the native units are stored within FuelCalc. The native and optional units are listed below by category (native units are in bold). In most cases, the native units are some form of metric units. Native units do not necessarily follow SI unit conventions, which are used primarily by scientists.

B1. Units options for generic quantities

Units Option Name	units options
Fuel load	**kg/m2**
	tons/ac
	Mg/ha
	lb/ft2
short distance	**cm**
	in
	m
	ft
medium distance	**meters**
	feet
long distance	**km**
	mi
	meters
	feet
Heat Content	**kJ/kg**
	BTU/lb
relative amount	**percent**
	fraction
SAV ratio	**1/m**
	1/ft
small area	**m2**
	ft2
	ha
	ac
large area	**ha**
	ac
	km2
	mi2
large mass	**Mg**
	ton
	kg
	lb
	[metric] tonne
small mass	**g**
	oz
	kg
	lb
bulk density	**kg/m3**
	lbs/ft3
	ton/ac-ft
diameter	**cm**
	in
expansion factor	**1/ha**
	1/ac
angle	**degrees**
slope	**percent**
	degrees
slow rate	**m/min**
	ch/h

fireline intensity	**kW/m**
	BTU/ft-sec
fire intensity scale	**dimensionless**
fast rate	**km/hr**
	mi/hr
tree density	**1/ha**
	1/ac
cubic tree volume	**m3/ha**
	ft3/ac
board-foot tree volume	**MBF/ha**
	MBF/ac
BasalArea	**m2/ha**
	ft2/ac
StandDensityIndex	dimensionless

Each input or output quantity is assigned to one of these categories for purposes of identifying the native and optional units. Although FuelCalc stores its data in native units, inputs or outputs can be entered, edited or displayed in any allowable units of measure at any time. Additional options for units of measure can be added easily by the FuelCalc developers as end-users make such requests.

B2. Units options for specific input quantities

PROJECT | PLOTS	**units options name**
PlotSlopeUnits	slope
PlotAspectUnits	angle
ElevationUnits	medium distance
LatLongUnits	angle
LatLongUnits	angle
GROUND FUEL	
DuffDepthUnits	short distance
SoilDepthUnits	short distance
LitterDepthUnits	short distance
DuffBulkDensityUnits	bulk density
SoilBulkDensityUnits	bulk density
LitterBulkDensityUnits	bulk density
PLANAR INTERCEPT	
TransectLengthUnits	medium distance
TransectSlopeUnits	slope
TransectAspectUnits	angle
LogDiamUnits	short distance
LogLengthUnits	medium distance
LogDecayUnits	
BURGAN/ROTHERMEL	
BR.DepthUnits	short distance
BR.CoverUnits	relative amount
BR.FractionUnits	relative amount
PILES	
PileExpansionUnits	expansion factor
PileDimensionUnits	medium distance
PileFractionUnits	relative amount
PileBulkDensityUnits	bulk density
TREELIST	
TreeExpansionUnits	expansion factor
TreeDiamUnits	short distance
TreeHeightUnits	medium distance
DIRECT ENTRY	
DE.FuelLoadUnits	load
DE.SAVUnits	SAV
DE.FuelbedDepthUnits	short distance
DE.HeatContentUnits	heat content
DE.PileAreaUnits	small area
DE.PileMassUnits	large mass
DE.FractionUnits	fraction
DE.TreeHeightUnits	medium distance
DE.BulkDensityUnits	bulk density
DE.CoverUnits	fraction

B3. Unit options for specific output quantities

Output quantities	units options name
Output.FuelLoadUnits	load
Output.SAVUnits	SAV
Output.FuelbedDepthUnits	short distance
Output.HeatContentUnits	heat content
Output.PileAreaUnits	small area
Output.PileMassUnits	large mass
Output.FractionUnits	relative amount
Output.TreeHeightUnits	medium distance
Output.BulkDensityUnits	bulk density
Output.MoistureUnits	relative amount
Output.WAFUnits	relative amount
Output.WindSpeedUnits	fast rate
Output.SpreadRateUnits	slow rate
Output.IntensityUnits	fireline intensity
Output.FlameLengthUnits	medium distance
Output.FractionUnits	relative amount
Output.FireIntensityScale	fire intensity scale
Output.TreeDensityUnits	tree density
Output.BasalAreaUnits	basal area
Output.TreeDiamUnits	short distance
Output.CubicVolumeUnits	cubic tree volume
Output.BFVolumeUnits	board-foot tree volume
Output.TreeHeightUnits	medium distance
Output.CoverUnits	relative amount
Output.CFBUnits	relative amount

B3. Unit options for fuel treatment input quantities

Fuel treatment quantities	units options name
MerchDiamUnits	short distance
PruningHeightUnits	medium distance
PrescribedFlameLengthUnits	medium distance
TargetBasalAreaUnits	basalArea
TargetCanopyCoverUnits	relative amount
TargetTreeDensityUnits	tree density
TargetCFLUnits	load
TargetCBDUnits	bulk density