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Fuel Characteristic Classification System Version 3.0: Technical Documentation

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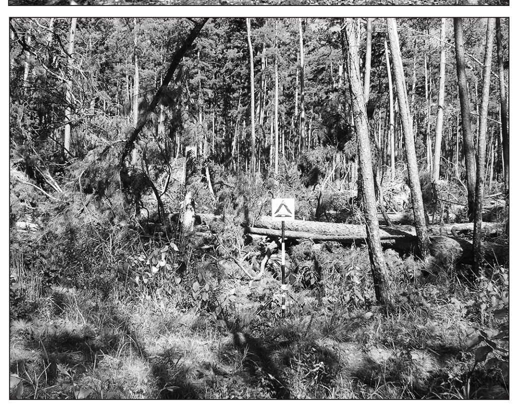

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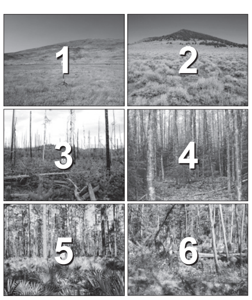

Cover photographs:
Fuelbeds are structurally complex and vary widely in their physical attributes and potential fire behavior. These grassland, shrubland, and forest examples illustrate a diversity of vegetation and fuels: (1) grassland in southeastern Oregon, (2) sagebrush shrubland in southeastern Oregon, (3) young lodgepole pine forest in Wyoming, (4) birch and aspen forest in Alaska, (5) longleaf pine forest plantation in Florida, and (6) shortleaf and loblolly pine forest in Texas, 1 month after a hurricane. All photos by Robert Vihnanek, Fire and Environmental Research Applications Team, Pacific Wildland Fire Sciences Laboratory, Pacific Northwest Research Station.

Abstract

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The Fuel Characteristic Classification System (FCCS) is a software module that records wildland fuel characteristics and calculates potential fire behavior and hazard potentials based on input environmental variables. The FCCS 3.0 is housed within the Integrated Fuels Treatment Decision Support System (Joint Fire Science Program 2012). It can also be run from command line as a stand-alone calculator. The flexible design of FCCS allows users to represent the structural complexity and diversity of fuels created through natural processes (e.g., forest succession and disturbance) and management activities (e.g., forest harvesting and fuels reduction). Each fuelbed is organized into six strata, including canopy, shrubs, herbaceous vegetation, woody fuels, litter-lichen-moss, and ground fuels. Strata are further divided into categories and subcategories. Fuelbeds representing common fuel types throughout much of North America are available in the FCCS reference library. Users may select an FCCS fuelbed to represent their specific project or customize a fuelbed to reflect actual site conditions. The FCCS reports the following results: (1) fuel characteristics by fuelbed, stratum, category, and subcategory; (2) surface fire behavior (i.e., reaction intensity, rate of spread, and flame length); and (3) FCCS fire potential ratings of surface fire behavior, crown fire behavior, and available fuels. With its large fuels data set and ability to represent a wide variety of fuel conditions, the FCCS has numerous applications, from small-scale fuel reduction projects to large-scale emissions and carbon assessments. This report provides technical documentation of the required inputs and computations in the FCCS.

Keywords: Fuel characteristics, fire behavior, fire modeling, carbon, biomass.

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Introduction

The Fuel Characteristic Classification System (FCCS) provides fire and fuel managers with a consistent and effective way to characterize and classify wildland fuels. The FCCS can be used to query and record fuelbed information and to generate numerical inputs to fire behavior, fire effects, and dynamic vegetation models.

Characterizing fuels and assessing their fire hazard has always been important to fire and fuel managers. These topics are becoming increasingly important to other specialists, including ecologists, air quality and smoke managers, land use planners, global change scientists, and carbon modelers. With its large data set and ability to represent a wide variety of fuel conditions, the FCCS has numerous applications, from small-scale fuel reduction projects to large-scale emissions and carbon assessments. Sample applications include:

- **Fuel reduction projects**—FCCS can be used as a planning tool to target which fuels should be removed to effectively reduce fire hazard. It can also be used as a reporting tool to summarize pre- and postburn fuel characteristics and fire hazard potential.
- **Emissions inventories**—Air quality specialists may run FCCS to calculate fuel loading to be used as inputs to emissions and smoke production software packages such as Consume (USDA FS 2012a) or BlueSky (Larkin et al. 2009).
- **Regional assessments**—FCCS fuelbeds and outputs can be used to map fuel loading, carbon stores, or fire hazard. Because fuelbeds have no inherent scale, FCCS outputs can be easily mapped in a geographic information system (GIS) by assigning polygons or raster cells with a unique fuelbed identification number. The FCCS makes point-based calculations of fuel characteristics and potential fire behavior and does not simulate fire spread across landscapes.
- **Carbon accounting**—FCCS can be used to compile carbon stores before and after disturbance and to predict carbon flux from fires.

FCCS defines a fuelbed as the inherent physical characteristics of fuels that contribute to fire behavior and effects (Riccardi et al. 2007a). A fuelbed can represent any scale considered to be mostly uniform. For example, a 10,000-ac western sagebrush ecosystem may be adequately represented by a single fuelbed, whereas a 100-ac tropical rain forest may require several fuelbeds to capture the variability of vegetation and other fuels. Because FCCS fuelbeds are not scale dependent, they are easily mapped, and calculated results can readily be incorporated into geospatial analyses. The FCCS describes fuelbeds in six strata, including canopy, shrubs, herbaceous vegetation (herb), woody fuels, litter-lichen-moss (LLM), and ground fuels. Each stratum is further divided into one or more categories and subcategories to represent the complexity of wildland and managed fuels (fig. 1).

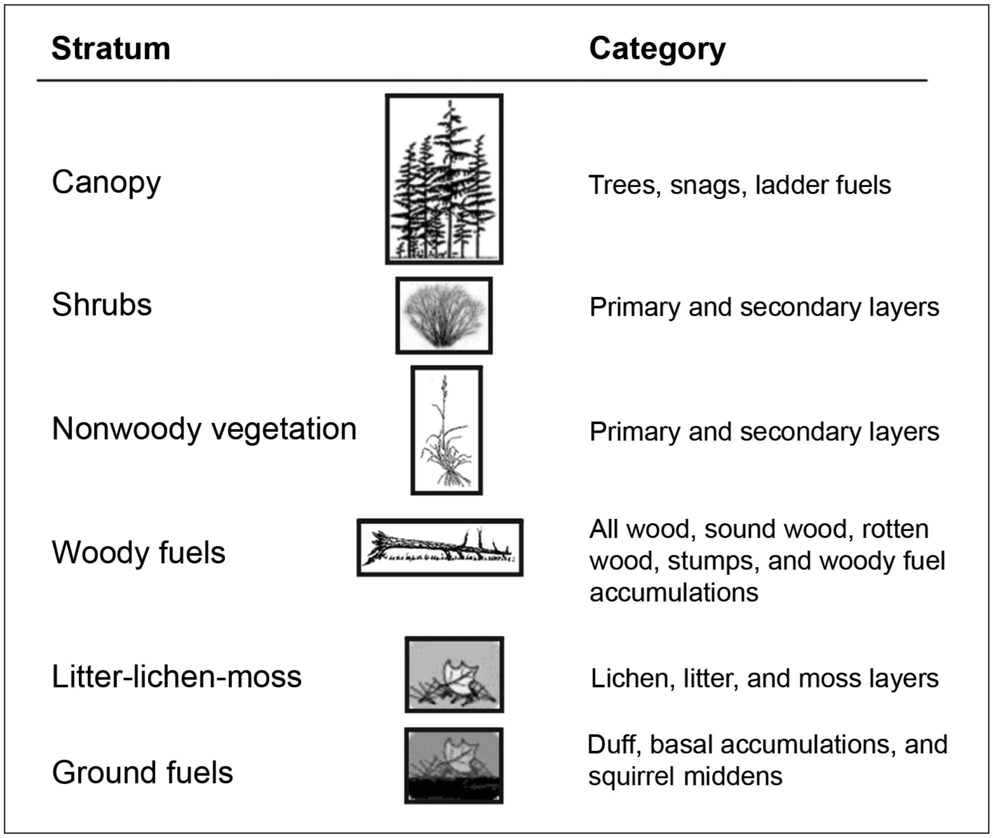

Figure 1—Fuelbed strata and categories in the Fuel Characteristic Classification System.

FCCS summarizes and calculates fuel characteristics for each fuelbed stratum, category, and subcategory. The characteristics include percentage of cover, depth (in feet or inches), total fuel loading in tons per acre (tons/ac), live fuel loading (tons/ac), dead fuel loading (tons/ac), fuel area index (analogous to leaf area index) square foot per square foot (ft^2/ft^2), packing ratio, tree density (number/ac), tree height to live crown (ft), and tree diameter at breast height (dbh).

Based on fuel characteristics and input environmental variables, FCCS predicts surface fire behavior including reaction intensity in British thermal units per square foot per minute ($Btu/ft^2/min$), rate of spread (ft/min), and flame length (ft). The FCCS also calculates a set of FCCS fire potentials including surface fire behavior potential, crown fire potential, and available fuel potential. The FCCS fire potentials are indexed values, scaled between 0 and 9, and are based on default environmental conditions. They provide a flexible means of expressing any fuelbed as a function of its potential to produce fire behavior or effects. Their intent is to provide an approach to quantifying fuels that is easy to communicate among fuels specialists and across a diversity of fuel types.

This report provides an updated and more complete documentation of the scientific basis for the FCCS than is available in the previously published literature. A series of seven peer-reviewed manuscripts were published in a special issue of the *Canadian Journal of Forest Research* (Berg 2007) and supported the first release of FCCS software. Ottmar et al. (2007) provided a history and overview of the system. Riccardi et al. (2007a, 2007b) described the development of FCCS fuelbeds and calculation of fuelbed characteristics. Sandberg et al. (2007a) detailed the conceptual basis and calculation of FCCS fire potentials. A new formulation of the Rothermel (1972) surface fire spread model was introduced by Sandberg et al. (2007b). Schaaf et al. (2007) introduced a new conceptual approach to crown fire potential modeling, building on concept introduced in Sandberg et al. (2007b). Finally, McKenzie et al. (2007) showed how FCCS fuelbeds have been mapped at large spatial scales across forested landscapes.

This documentation reflects changes and additions to the capabilities of the FCCS software gained through the experience of working with many users in training sessions and on-the-ground applications of the system. Because the FCCS is a substantial departure from traditional fuel inventory and modeling concepts, extensive input was elicited from scientists and resource managers in North America during development and testing. User feedback in the past few years has guided significant upgrade of the science and software behind FCCS and contributed to further changes detailed in this report.

The FCCS was recently recoded to be better integrated with Consume (Prichard et al. 2007) and the Fire Emissions Production Simulator (FEPS) (Anderson et al. 2004). A batch version of the FCCS version 3.0 is available for download at http://www.fs.fed.us/pnw/fera. FCCS can also be used within the Interagency Fuels Treatment Decision Support System (Joint Fire Science Program 2012) and will be also available for use within an integrated user interface that is currently under development for FCCS, Consume and FEPS and will be available for download at http://www.fs.fed.us/pnw/fera in early 2014.

The FCCS supports both English and metric inputs and outputs, but actual calculations are in the English measurement system. This documentation was developed in part to provide future developers and users of the FCCS with a specification of all calculations within the system. To avoid conversion errors between this documentation and the programming code, we retained English units throughout this report.

The FCCS scientific documentation is organized into the following sections:

- Inferred variables used in FCCS calculations.
- Calculation of fuelbed characteristics.
- Surface fire behavior calculations, including updates since Sandberg et al. (2007b).
- Crosswalk to stylized fuel models (Anderson 1982, Scott and Burgan 2005).
- Crown fire behavior potentials, including updates since Schaaf et al. (2007).
- Available fuel potentials.

Equations are numbered and referenced. For complex equations with several component terms, the source equation is listed in parentheses after the component term name (e.g., propagating flux ratio in rate of spread, eq. 26). A comprehensive list of variable names and associated symbols is included in the appendix. Wherever possible, we used common published symbology for variables.

Unless otherwise noted, subscript references in the following equations are assigned to fuelbed divisions as follows:

i = species or type,
j = category or subcategory,
k = stratum, and
m = layer (e.g., surface fuels and low surface fuels).

Inferred Variables

The FCCS inferred variables are internal data sets used to calculate physical characteristics of wildland fuels. Inferred variables are used in association with a plant species or type designation (e.g., litter type or duff derivation) (tables 1 and 2). They include fuel chemistry, heat content, particle density, and bulk density values and currently cannot be modified by users. Nomenclature for many of the inferred variables were derived in the development of the Rothermel fire spread model (Rothermel 1972, Scott and Burgan 2005) and the Van Wagner crown fire model (Scott and Reinhardt 2001, Van Wagner 1977). Their values are based on published and unpublished data where available or where a convention has been established by widespread use in other models such as BEHAVE (Andrews et. al. 2003). Defaults were estimated when no data were available. The FCCS inferred variables by species database can be downloaded at USDA FS (2012d).

Table 1—Inferred variables invoked by type used in the canopy, shrub, woody, litter-lichen-moss, and ground fuels strata

Stratum-category	Type, arrangement, or subcategory	Inferred variables: Particle density of foliage or rotten wood (ρ_f or ρ_r[a])	Low fuel heat content (h)	Fuel area index (FAI)	Surface-area-to-volume ratio (σ)	Packing ratio (β)	Bulk density (ρ_b)
		Pounds per cubic foot	*British thermal units per pound*	*Square foot per square foot*	*Square foot per cubic foot*		*Pounds per cubic foot*
Canopy:[b]							
	Arboreal lichen	25.00	8,000	0.26	—	2.00×10^{-6}	—
	Dead branches	18.72[a]	8,000	0.06	—	3.00×10^{-4}	—
	Climbing ferns/ other epiphytes	25.00	8,000	0.18	—	2.00×10^{-6}	—
	Stringy or fuzzy bark	18.72[a]	8,000	0.12	—	6.00×10^{-6}	—
	Vines-lianas	25.00	8,000	0.18	—	1.40×10^{-5}	—
	Leaning snags	18.72[a]	8,000	0.07	—	1.83×10^{-4}	—
	Tree regeneration	25.00	8,000	13.8	—	1.33×10^{-4}	—
Shrub:[c]		25.00	8,000	—	2,500	—	—
Woody:[d]							
	0 to 0.25 inches	—	—	—	500	—	—
	>0.25 to 1 inch	—	—	—	109	—	—
	>1 to 3 inches	—	—	—	30	—	—
	>3 to 9 inches	—	—	—	8	—	—
	>9 to 20 inches	—	—	—	4	—	—
	>20 inches	—	—	—	2	—	—
Litter-lichen-moss:							
Litter—							
Short needle pine		25.00	8,000	—	2000	—	1.65
Long needle pine	Normal	25.00	8,000	—	1500	—	1.65
	Fluffy	25.00	8,000	—	1500	—	1.65
	Perched	25.00	8,000	—	1500	—	1.65
Other conifer		25.00	8,000	—	2000	—	1.65
Deciduous hardwood	Normal	25.00	8,000	—	2500	—	0.83
	Fluffy	25.00	8,000	—	2500	—	0.83
	Perched	25.00	8,000	—	2500	—	0.83
Evergreen hardwood	Normal	25.00	8,000	—	2500	—	0.83
	Fluffy	25.00	8,000	—	2500	—	0.83
	Perched	25.00	8,000	—	2500	—	0.83
Palm frond		25.00	8,000	—	2500	—	0.17
Grass		25.00	8,000	—	3500	—	0.28
Lichen		25.00	6,000		1500		0.28
Moss	Sphagnum	25.00	6,000	—	1000	—	0.83
	Other moss	25.00	6,000	—	2000	—	0.83
Ground fuels:							
Upper duff—	Dead litter and moss	25.00	8,000	—	2000	—	4.41
	Fibric peat	25.00	8,000	—	2000	—	4.41
Lower duff—	Humus or muck	25.00	8,000	—	500	—	9.92
	Humic peat	25.00	8,000	—	500	—	12.12

Table 1—Inferred variables invoked by type used in the canopy, shrub, woody, litter-lichen-moss, and ground fuels strata (continued)

		Inferred variables					
Stratum-category	**Type, arrangement, or subcategory**	**Particle density of foliage or rotten wood (ρ_f or ρ_r[a])**	**Low fuel heat content (h)**	**Fuel area index (FAI)**	**Surface-area -to-volume ratio (σ)**	**Packing ratio (β)**	**Bulk density (ρ_b)**
		Pounds per cubic foot	*British thermal units per pound*	*Square foot per square foot*	*Square foot per cubic foot*		*Pounds per cubic foot*
Squirrel middens		25.00	8,000	—	100	—	2.75
Basal accumulations	Bark slough	25.00	8,000	—	500	—	2.75
	Branches	25.00	8,000	—	2,000	—	2.75
	Broadleaf deciduous	25.00	8,000	—	1,500	—	1.71
	Broadleaf evergreen	25.00	8,000	—	1,500	—	1.71
	Grass	25.00	8,000	—	1,500	—	1.27
	Needle litter	25.00	8,000	—	1,500	—	1.65
	Palm fronds	25.00	8,000	—	1,500	—	1.27

[a] Fluffy is defined as fresh uncompacted litter, and perched is a litter layer dominated by litter perched on herbaceous or woody fuels.

[b] Including needle drape.

[c] Including ladder fuels.

[d] Sound and rotten.

Table 2—Additional inferred variables by litter, lichen, and moss types and arrangements

Type	**Arrangement**	**Maximum loading that would consume in the flaming stage of combustion (MaxFlameWL)**	**Maximum fuel area index value (maxFAI)**	**Relative packing ratio (β')**	**Reaction efficiency (ηβ')**
		Pounds per acre	*Square foot per square foot*		
Litter type—					
Short needle pine		2,900	4.44	8.03	0.18
Long needle pine	Normal	5,800	6.66	6.35	.27
	Fluffy	6,000	6.89	4.38	.49
	Perched	7,500	6.89	1.64	.95
Other conifer		2,900	4.44	8.03	.18
Deciduous hardwood	Normal	3,100	5.93	10.31	.11
	Fluffy	4,000	7.65	6.65	.30
	Perched	5,000	7.65	1.66	.95
Evergreen hardwood	Normal	3,100	5.93	10.31	.11
	Fluffy	4,000	7.65	6.65	.30
	Perched	5,000	7.65	1.66	.95
Palm frond		2,000	4.59	7.65	.23
Grass		667	2.12	10.07	.15
Moss type—					
Sphagnum		1,740	1.33	4.55	.40
Other moss		5,800	8.88	8.03	.18
Ground lichen		5,800	6.66	6.35	.27

Inferred Variables by Species

Bulk density (ρ_b; lb/ft^3)—

Tree and shrub canopy bulk density data are taken from published sources such as the Natural Fuels Photo Series (Ottmar et al. 2004), Anderson (1969), and expert opinion of the authors.

Crown packing ratio (β; dimensionless)—

Packing ratio (β) of tree crowns by species; defined as the fraction of crown volume occupied by fuel including needles and fine branches.

Crown shape factor (CSF; dimensionless)—

A geometrical adjustment factor used to differentiate crown shapes of coniferous and broadleaf trees in volume and loading calculations.

Flammability index (η_F; dimensionless)—

The flammability index allows for the designation of species with special properties with respect to fire. The flammability index is assigned by species based on information from the Fire Effects Information System (USDA FS 2012c), available literature, and expert opinion. Flammable species are those that have extractives (e.g., terpenes, fats, waxes, and oils, particularly terpenoid hydrocarbons and lipids, which provide a ready source of combustible volatiles. High heat of combustion, volatility, and lower limits of flammability are associated with flammable species (Pyne et al. 1996). Neutral species do not contribute to reaction intensity.

Foliage particle density (ρ_f; lb/ft^3)—

Taken from standard sources (e.g., Hoadley 1991, Wenger 1984). A default value of 25.0 lb/ft^3 is used when values are not available.

Low fuel heat content (h; Btu/lb)—

Heat of a material produced by combustion (Byram 1959).

Rotten wood particle density (ρ_r; lb/ft^3)—

Taken from standard sources (e.g., Hoadley 1991, Wenger 1984). A default value of 18.7 lb/ft^3 is used when values are not available.

Sound wood particle density (ρ_b; lb/ft^3)—

Taken from standard sources (e.g., Hoadley 1991, Wenger 1984). A default value of 25.0 lb/ft^3 is used when values are not available.

Surface-area-to-volume ratio (σ; ft^2/ft^3)—

The amount of surface area per unit volume of fuels (Fons 1946).

Inferred Variables by Type (i.e., Litter Type)

Bulk density (ρ_b; lb/ft^3)—
Based on expert opinion (Ottmar et al. 2007).

Fuel area index (FAI; ft^2/ft^2)—
A dimensionless measure of cover and the total fuel surface area per unit ground area. It is analogous to a two-sided leaf area index, which is often used in agricultural and ecological research. FAI is calculated for each species in FCCS but is inferred for type designations.

Low fuel heat content (h; Btu/lb)—
Heat of a material produced by combustion.

MaxFAI (dimensionless)—
Maximum fuel area index by LLM type (Ottmar 2005).

MaxFlameW$_L$ (lb/ft^3)—
Maximum flame-available loading by LLM type.

Packing ratio (β; dimensionless)—
A measure of fuelbed compactness; the fraction of the fuel array volume occupied by fuel. Packing ratio is calculated for each species in FCCS but is inferred by type.

Particle density (ρ; lb/ft^3)—
Taken from standard sources (Hoadley 1991, Wenger 1984).

Particle volume (PV; ft^3/ac)—
The volume of space filled by fuel particles. Whereas bulk volume is the volume of fuels and the interstitial airspace between fuels (e.g., volume of a tree crown), particle volume only considers the space containing fuel particles. It is calculated as dry weight biomass (lb/ac) divided by particle density (lb/ft^3).

Relative packing ratio (β; dimensionless)—
The ratio of actual fuel packing ratio to optimum packing ratio. This can also be calculated as the ratio of optimum depth to actual depth.

Surface-area-to-volume ratio (σ; ft^2/ft^3)—
The amount of surface area per unit volume of fuels (Fons 1946).

Calculation of Fuelbed Characteristics

FCCS organizes fuels into six horizontal fuelbed strata including canopy, shrubs, herb, woody fuels, LLM, and ground fuels (fig. 1). Strata are further divided into categories and subcategories (table 3). The fuelbed categories and subcategories have common combustion characteristics. For example, the canopy stratum includes three categories: trees, snags, and ladder fuels. The tree category is divided into three subcategories: overstory, midstory, and understory trees.

- Canopy stratum: includes trees, snags, and ladder fuels.
- Shrub stratum: primary and secondary shrub layers.
- Herb stratum: herb (i.e., grasses, sedges, rushes and forbs) in primary and secondary layers.
- Woody fuels stratum: includes all downed and dead wood, sound wood, rotten wood, and stumps.

Table 3—User-input FCCS fuelbed variables used in the calculation of physical characteristics and properties of wildland fuels

Strata, category, and subcategory	Variables
Canopy:	
Total canopy—	Percentage cover[a]
Trees—	Percentage cover[a,c]
Overstory, midstory, understory	Height (ft)[a,c] Height to live crown (ft)[a,c] Density (number of stems/ac)[a,c] Diameter at breast height (in)[c] Species and relative cover (percentage)[a,c]
Snags—	
Class 1 snags with foliage	Height (ft)[a,c] Height to snag crown base (ft)[a] Density (number of stems/ac)[a,c] Diameter at breast height (in)[c] Species and relative cover (percentage)[a,c]
Subcategory: class 1 (without foliage), class 2, class 3	Height (ft)[c] Diameter (in)[c] Density (number of stems/ac)[c] Species and relative cover (percentage)[c]
Ladder fuels—	
Type: arboreal lichens and mosses, climbing ferns and other epiphytes, dead branches, leaning snags, stringy or fuzzy bark, tree regeneration, and vines-liana	Minimum height (ft) Maximum height (ft) Is there vertical continuity sufficient to carry fire between the canopy and lower strata?[a]
Shrubs:	
Primary layer, secondary layer	Percentage cover[a,b,c] Height (ft)[a,b,c] Percentage live[a,b] Loading (tons/ac)[a,b,c]— optional Species and relative cover (percentage)[a,b,c]
Needle drape	Is needle drape on shrubs sufficient to affect fire behavior?[a]

Table 3—User-input FCCS fuelbed variables used in the calculation of physical characteristics and properties of wildland fuels (continued)

Strata, category, and subcategory	Variables
Herbs:	
Primary layer, secondary layer	Percentage cover[a,b]
	Height (ft)[a,b]
	Percentage live[a]
	Loading (tons/ac)[a,b,c]
	Species and relative cover (percentage)[a,b]
Woody fuels:	
All woody—	Total cover (percentage)[a,b]
	Depth (ft)[a,b]
Sound wood—	Species and relative cover (percentage)[a,b]
0 to 0.25 in	Loading (tons/ac)[a,b,c]
>0.25 to 1 in	Loading (tons/ac)[a,b,c]
>1 to 3 in	Loading (tons/ac)[a,b,c]
>3 to 9 in	Loading (tons/ac)[a,b,c]
>9 to 10 in	Loading (tons/ac)[a,b,c]
>20 in	Loading (tons/ac)[a,b,c]
Rotten wood—	Species and relative cover (percentage)[a,b]
>3 to 9 in	Loading (tons/ac)[a,b,c]
>9 to 10 in	Loading (tons/ac)[a,b,c]
>20 in	Loading (tons/ac)[a,b,c]
Stumps—	Species and relative cover (percentage)[c]
Sound, rotten, lightered/pitchy	Height (ft)[c]
	Diameter (in)[c]
	Density (number per acre)[c]
Piles—	Loading (tons/acre)[c]
Litter-lichen-moss:	
Litter—	Litter arrangement (fluffy, normal, perched)[a,b,c]
Type: Short needle pine, long needle pine,	Litter type and relative cover (percentage)[a,b,c]
other conifer, broadleaf deciduous,	Depth (in)[a,b,c]
broadleaf evergreen, palm frond, grass	Percentage of cover (%)[a,b,c]
	Loading (tons/ac)[a,b,c] —optional
Lichen—	Depth (in)[a,b,c]
	Percentage of cover (%)[a,b,c]
	Loading (tons/ac)[a,b,c] —optional
Moss—	Depth (in)[a,b,c]
Type: spaghnum, other moss	Percentage of cover (%)[a,b,c]
	Loading (tons/ac)[a,b,c] —optional
Ground fuels:	
Upper duff—	Depth (in)[c]
Derivation: dead litter and moss; fibric peat	Percentage cover (%)[c]
	Loading (tons/ac)[c] —optional
Lower duff—	Depth (in)[c]
Derivation: humus or muck; humic peat	Percentage of cover (%)[c]
	Loading (tons/ac)[c] —optional
Basal accumulations—	Depth (in)[c]
Derivation: bark slough, branches, broadleaf	Radius (ft)[c]
deciduous, broadleaf evergreen, grass,	Percentage of trees affected (%)[c]
needle litter, palm fronds	Loading (tons/ac)[c] —optional
Squirrel middens—	Depth (in)[c]
	Radius (ft)[c]
	Density (number per acre)[c]
	Loading (tons/ac)[c] —optional

Superscripts *a*, *b*, and *c* indicate variables important to crown fire potentials, surface fire behavior algorithms, and carbon accounting, respectively.

- Litter-lichen-moss stratum: litter, lichen, and moss layers.
- Ground fuels stratum: includes duff, basal accumulations, and squirrel middens.

The FCCS fuel characteristics calculator provides summaries of fuelbed inputs, such as percentage cover and fuelbed depth, and calculates additional fuel characteristics such as live and dead fuel loading, FAI, and packing ratio by stratum, category, and subcategory. Inputs specific to individual categories or strata are also summarized (e.g., tree density, dbh, and height to live crown in the canopy stratum).

Weighted Average of Inferred Variables

Inferred variables, including surface-area-to-volume ratio, flammability index, and particle density, are often summarized by category and stratum to be used in surface and crown fire behavior calculations.

Weighted average by species loading (Y_k; dimensionless)—
Calculated for each inferred variable:

$$y_k = \sum_{j=1} y_j = \sum_{i=1} y_i \frac{w_i}{w_j} \tag{1}$$

where
y = inferred variable,
k = subscript reference to stratum,
j = subscript reference to category or subcategory,
i = subscript reference to species,
w_i = loading by species (tons/ac), and
w_j = total loading by category or subcategory (tons/ac).

Generalized equations for FAI, packing ratio, depth, and fuel loading are detailed in the following sections.

Fuel area index (FAI; dimensionless)—
To assimilate the heterogeneous fuel structures represented by FCCS fuelbeds, FCCS calculates the total fuel surface area for all size classes of fuels including live foliar biomass. The FAI is the total fuel surface area per unit ground area (ft^2/ft^2). Analogous to a two-sided leaf area index, FAI is used to calculate the FCCS fire potentials (Riccardi et al. 2007b). In each stratum, category, and subcategory, FCCS calculates live fuel FAI, dead fuel FAI, FAI of very fine (flash) fuels, and total FAI.

Fuel area index is calculated by species or type (i.e., litter type) and then summarized by category, subcategory, and stratum:

$$FAI_k = \sum_{j=1} FAI_j = \sum_{i=1} \frac{w_i \sigma_i}{\rho_i} \tag{2}$$

where

k = subscript reference to stratum,

j = subscript reference to subcategory or category,

i = subscript reference to species or type,

w_i = loading by species or type (lb/ft^2),

σ_i = surface-area-to-volume ratio inferred by species or type (ft^2/ft^3) (tables 1 and 2), and

ρ_i = particle density inferred by species or type (lb/ft^3) (tables 1 and 2).

Packing ratio (β; dimensionless)—

The proportion of fuelbed stratum volume occupied by fuel particles (Rothermel 1972) and is an important factor in predicting fire behavior. At low packing ratios (or bulk fuel densities), fire intensity is limited by excessive heat loss. At high packing ratios, lack of oxygen limits fuel combustion. Packing ratio (β; dimensionless) is calculated by species or type and is summed by category and stratum.

$$\beta_k = \sum_{j=1} \beta_j = \sum_{i=1} \frac{w_i}{\rho_i \delta_k} \tag{3}$$

where

k = subscript reference to stratum,

j = subscript reference to subcategory or category,

i = subscript reference to species or type,

w_i = loading by species (lb/ft^2),

ρ_i = particle density inferred by species or type (lb/ft^3) (tables 1 and 2), and

δ_k = stratum depth (ft).

Depth (δ; ft)—

A basic measure of the vertical structure of a fuelbed stratum, category, or subcategory. Based on common usage, the term height (ft) is used as an input in canopy, shrub, and herb strata, whereas depth (in) is used for woody fuels, LLM, and ground fuels strata. The woody fuels stratum contains downed and dead woody fuels, stumps, and tree cones. For consistency, FCCS considers only the depth of fine woody fuels (<3 in in diameter) in the woody fuels stratum. Depth of each stratum or category is calculated as:

$$\delta_k = \text{Height}_{\text{Top}} - \text{Height}_{\text{Bottom}} \tag{4}$$

where
k = subscript reference to stratum,
$Height_{Top}$ = top height of a fuel stratum or category (ft), and
$Height_{Bottom}$ = bottom height of fuel stratum or category (ft).

For canopy tree subcategory layers, depth is calculated as the distance between input values of height to live crown and tree height. For surface fuels (shrubs, herb, woody fuels, andLLM depth is equal to the input height or depth of each fuel category or subcategory. For ground fuels, depth is equal to the input depth of each ground fuel category.

Fuel loading (w; tons/ac)—
The dry weight biomass of fuels, which is important in many FCCS calculations including FAI, packing ratio, total carbon, surface fire behavior, crown fire potentials, and available fuel potentials. Loading calculations are handled differently in each stratum and category as detailed below:

Canopy stratum—Canopy stratum loading is the sum of all trees, snags, and ladder fuels and only includes the foliage and fine branch (<1.5 in) loading of tree crowns.

Tree crown loading **($w_{TreeCrown\ j}$; tons/ac)**—Calculated by species and summed by tree subcategory (i.e., overstory, midstory, and understory):

$$w_{TreeCrown.\ j} = 0.0005 \sum_{i=1} (ACV\ CrownBD)_i \tag{5}$$

where
j = subscript reference to tree subcategory (overstory, midstory, understory),
0.0005 = conversion factor (tons/lb),
i = subscript reference by tree species,
ACV_i = bulk crown volume (ft^3/ac) adjusted for species relative cover and crown shape factor (eq. 5a), and
$CrownBD_i$ = crown bulk density inferred by species (lb/ft^3).

Adjusted crown volume **(ACV_{Tree}; ft^3/ac)**—The calculated volume of tree crowns by species:

$$ACV_{Tree\ i} = Y_{Tree\ j} \left(\frac{RelCov_i}{100}\right) CSF_i \tag{5a}$$

where
i = subscript reference to tree species,
j = subscript reference to tree subcategory (overstory, midstory, understory),
$Y_{Tree\ j}$ = bulk crown volume (ft^3/ac) of each tree subcategory, calculated in equation (5b),

$RelCov_i$ = percentage of total cover by tree species, and
CSF_i = crown shape factor (conifer or broadleaf) inferred by tree species.

***Bulk crown volume* ($Y_{Tree\ j}$; ft^3/ac)**—The total volume of each tree subcategory, including interstitial spaces between tree crowns. It is calculated as:

$$Y_{Tree\ j} = 43560 \left(\frac{\theta_j}{100}\right)(\text{Height} - \text{HLC})_j \tag{5b}$$

where
j = subscript reference to tree subcategory (overstory, midstory, understory),
θ_j = percentage cover of each tree subcategory (%),
$Height_j$ = height of each tree subcategory (ft),
HLC_j = height to live crown of each tree subcategory (ft), and
43560 = square feet per acre.

***Total aboveground tree loading* (w_{Tree}; tons/ac)**—Total aboveground tree loading is calculated for each tree subcategory by using the equations in table 4. Equations numbers are assigned to each tree species in the FCCS inferred variables database. The equations yield aboveground biomass in kilograms per tree and are converted to tons per acre with a conversion factor to tons and input tree density.

$$w_j = 0.0011\ AB_j\ Density_j \tag{6}$$

where
j = subscript reference to tree subcategory (overstory, midstory, understory),
0.0011 = conversion of kilograms to tons,
AB_j = calculated aboveground biomass (kilograms) (table 4), and
$Density_j$ = input tree density by tree subcategory (number/ac).

***Class 1 snags with foliage loading* (canopy stratum) ($w_{SnagC1F}$; tons/ac)**—Crown loading for class 1 snags with foliage is calculated similarly to that of tree crown loading:

$$w_{SnagC1F} = 0.0005 \sum_{i=1} (\text{ACV CrownBD})_i \tag{7}$$

where
i = subscript reference to species,
0.0005 = conversion factor to tons (tons/lb),
ACV_i = bulk crown volume (ft^3/ac) adjusted species relative cover and crown shape factor (eq. 7a), and
$CrownBD_i$ = crown bulk density inferred by species (lb/ft^3).

Table 4—Total aboveground biomass equations by major tree species groups[a]

Equation number	Species group	A	B	C	Equation form	Range of diameter at breast height	Reference
						Centimeters	
1	Aspen/alder/cottonwood/willow	-2.2094	2.3867		$kg = e^{[A+B\ln(dbh)]}$	1–70	Jenkins et al. (2003)
2	Soft maple/birch	-1.9123	2.3651		$kg = e^{[A+B\ln(dbh)]}$	1–66	Jenkins et al. (2003)
3	Mixed hardwood	-2.48	2.4835		$kg = e^{[A+B\ln(dbh)]}$	1–56	Jenkins et al. (2003)
4	Hard maple/oak/hickory/beech	-2.0127	2.4342		$kg = e^{[A+B\ln(dbh)]}$	1–73	Jenkins et al. (2003)
5	Cedar/larch	-2.0336	2.2592		$kg = e^{[A+B\ln(dbh)]}$	1–250	Jenkins et al. (2003)
6	Douglas-fir	-2.2304	2.4435		$kg = e^{[A+B\ln(dbh)]}$	1–210	Jenkins et al. (2003)
7	True fir/hemlock	-2.5384	2.4814		$kg = e^{[A+B\ln(dbh)]}$	1–230	Jenkins et al. (2003)
8	Pine	-2.5356	2.4349		$kg = e^{[A+B\ln(dbh)]}$	1–180	Jenkins et al. (2003)
9	Spruce	-2.0773	2.3323		$kg = e^{[A+B\ln(dbh)]}$	1–250	Jenkins et al. (2003)
10	Juniper/oak/mesquite	-0.7152	1.7029		$kg = e^{[A+B\ln(dbh)]}$	1–78	Jenkins et al. (2003)
11	Cactus	.001	3.2327		$kg = A\ dbh^{B}$	n/a	Sampaio and Silva (2005)
12	Palm	24.559	4.921	1.017	$kg = A + (B\ Height) + (C\ Height^2)$	0.2–14.5	Penman et al. (2003)

[a] Equations are in metric units, and input tree diameter must be converted from inches to centimeters. An equation number is assigned to each tree species in the Fuel Characteristic Classification System inferred variables database.

Adjusted crown volume **($ACV_{SnagC1F}$; ft^3/ac)**—Calculated as:

$$ACV_{SnagC1F} = Y_{SnagC1F}\left(\frac{RelCov_i}{100}\right)CSF_i \qquad (7a)$$

where

i = subscript reference to class 1 snag species,

$Y_{SnagC1F}$ = bulk crown volume (ft^3/ac) of class 1 snags with foliage, as calculated in equation 7b,

$RelCov_i$ = percentage of total class 1 foliage snag cover by tree species, and

CSF_i = crown shape factor (conifer or broadleaf) by tree species.

Bulk crown volume **($Y_{SnagC1F}$; ft^3/ac)**—Calculated as:

$$Y_{SnagC1F} = 43560\left(\frac{\theta_{SnagC1F}}{100}\right)(Height - HCB)_{SnagC1F} \qquad (7b)$$

where

43560 = conversion factor (ft^2/ac),

$\theta_{SnagC1F}$ = input percentage cover of class 1 snags with foliage (percentage),

$Height_{SnagC1F}$ = input height of class 1 snag category (ft), and

$HCB_{SnagC1F}$ = input height to crown base of class 1 snags with foliage (ft).

Snag wood loading **(canopy stratum) ($w_{SnagWood}$; tons/ac)**—Snag wood loading is calculated by species and then summed by snag subcategory (i.e., class 1, class 2, and class 3 snags).

$$W_{SnagWood\ j} = 0.0005 \sum_{i=1} 0.25\left(\text{Diameter}_j\right)^2 \pi\ \text{Height}_j\ \text{Density}_j\ \rho_i \left(\frac{\text{RelCov}_i}{100}\right) \quad (8)$$

where

j = subscript reference to snag subcategory,

i = subscript reference to species,

0.0005 = conversion factor to tons (tons/lb),

0.25 = constant in volume equation for a cylinder,

Diameter_j = diameter at breast height of snag subcategory (ft),

π = pi,

Height_j = height of snag subcategory (ft),

Density_j = stems per acre of snag subcategory,

ρ_i (wood particle density) = particle density inferred by species and snag category (i.e., a sound wood density is applied to class 1 snags and rotten wood density is applied to class 2 and 3 snags) (lb/ft^3) (table 1), and

RelCov_i = percentage of total snag subcategory cover by species.

Ladder fuels loading **(canopy stratum) (w_{Ladder}; tons/ac)**—Ladder fuels loading is inferred by ladder fuel type (i.e., arboreal lichens and moss, climbing ferns and other epiphytes, dead branches, leaning snags, profuse epicormic sprouting, stringy or fuzzy bark, tree regeneration, and vines-liana) (table 1).

Shrub loading **(w_{Shrub}; tons/ac)**—Total aboveground shrub loading can be either input or calculated in FCCS. The FCCS calculates primary and secondary layer shrub loading based on input percentage cover and height by species (table 5). Shrub stratum loading is the sum of the primary and secondary layer loadings (w_j).

$$w_{Shrub} = \sum_{j=1}^{2} w_j = \sum_{i=1} (A+B)_i \theta_j\ \text{Height}_j N_i \quad (9)$$

where

j = subscript reference to primary and secondary shrub categories,

i = subscript reference to shrub species,

w_j = primary and secondary shrub loading,

A = equation coefficient by species (table 5),

B = equation coefficient by species (table 5),

θ_j = input percentage cover by primary or secondary category,

Height_j = input height of primary or secondary category (ft) (used only in eqs. 26 through 29), and

N = conversion factor to tons/ac.

***Shrub crown loading* ($w_{ShrubCrown}$; tons/ac)**—FCCS estimates the proportion of crown loading by species (table 5) and uses a calculated shrub crown loading in surface fire behavior and crown fire potential calculations.

$$w_{ShrubCrown} = w_{Shrub} PercentCrown \qquad (9a)$$

where

w_{Shrub} = total aboveground shrub stratum loading, and

PercentCrown = conversion from total aboveground biomass to crown loading of foliage and small branches.

Table 5—Biomass equations used in Fuel Characteristic Classification System to calculate shrub loading (w; tons/ac)

BioEqID[a]	Source species	A	B	X1[b]	X2	N[c]	Percentage[d]	Reference
1	*Diervilla lonicera*	0.8601	0.3238	θj		0.0248	35	Ohmann et al. (1981)
2	*Ledum groenlandicum*	3.341	.0001	θj		0.0248	50	Ohmann et al. (1981)
3	*Lonicera canadensis*	0.9266	.2727	θj		0.0248	35	Ohmann et al. (1981)
4	*Rosa* spp. (Minnesota)	0.7867	.3964	θj		0.0248	35	Ohmann et al. (1981)
5	*Rubus parviflorus*	0.7885	.2508	θj		0.0248	60	Ohmann et al. (1981)
6	*Rubus pubescens*	1.6346	.0214	θj		0.0248	35	Ohmann et al. (1981)
7	*Vaccinium angustifolium*	1.2458	.1496	θj		0.0248	60	Ohmann et al. (1981)
8	*Vaccinium myrtilloides*	0.9340	.3747	θj		0.0248	35	Ohmann et al. (1981)
9	*Rubus spectabilis*	14.4183	12.561	θj		0.0045	45	Alaback (1986)
10	*Vaccinium alaskense*	-7.2200	17.307	θj		0.0045	35	Alaback (1986)
11	*Gaultheria shallon*	11.6990	3.5180	θj		0.0045	60	Alaback (1986)
12	*Mahonia nervosa*	14.2180	1.9840	θj		0.0045	50	Gholz et al. (1979)
13	*Ephedra torreyana*	0	627.00	θj/100		0.0045	50	Gholz et al. (1979)
14	*Flourensia cernua*	0	1425.0	θj/100		0.0045	50	Smith and Ludwig (1976)
15	*Larrea tridentata*	0	1504.0	$(θj/100)^2$		0.0045	35	Smith and Ludwig (1976)
16	*Prosopis glandulosa*	0	287.00	$(θj/100)^2$		0.0045	50	Smith and Ludwig (1976)
17	*Yucca elata*	0	1435.0	θj/100		0.0135	100	Smith and Ludwig (1976)
18	*Arctostaphylos patula*	0	.1410	θj		1	50	Martin et al. (1981)
19	*Ceanothus velutinus*	0	.1080	θj		1	50	Martin et al. (1981)
20	*Purshia tridentata*	0	.0500	θj		1	35	Martin et al. (1981)
21	*Artemisia tridentata*	0	230.586	θj		0.0005	35	Ottmar et al. (2000)
22	*Ceanothus chaparral*	0	.3720	θj		1	50	Ottmar et al. (1998)
23	*Adenostoma fasciculatum*	0	.1700	θj		1	40	Ottmar et al. (1998)
24	*Arctostaphylos uva-ursi*	0	.0022	θj		1	50	Alexander (1978)
25	*Yucca elata (brevifolia)*	0	1435.0	$(θj/100)^2$		0.0135	100	Smith and Ludwig (1976)
26	Juniper shrubs	0	.1000	$(θj/100)^2$	$Height_j/2$	1	65	Ottmar et al. (2000)
27	Broadleaf deciduous shrubs	0	2000.0	θj/100	$Height_j$	0.0005	40	Ottmar et al. (2002)
28	Broadleaf evergreen shrubs	0	3000.0	θj/100	$Height_j$	0.0005	50	Ottmar et al. (1998)
29	Pocosin shrubs	0	4000.0	θj/100	$Height_j$	0.0005	65	Ottmar and Vihnanek (2000)

[a] BioEqID is an inferred variable assigned by species.
[b] θ = input percent cover by primary and secondary shrub layer.
[c] N is a conversion factor .
[d] Percentage of aboveground biomass that is from the crown. This includes shrub foliage and small branches.

Herb loading **(w_{Herb}; tons/ac)**—Required input variable by primary and secondary layer.

Sound and rotten woody fuel loading **(woody fuels stratum) (w_j; tons/ac)**—Required input variables by diameter size class.

Stump loading **(woody fuels stratum) (w_{Stumpj}; tons/ac)**—Calculated for each subcategory (i.e., sound, rotten or lightered/pitchy).

$$w_{Stump\,j} = 0.0005 \sum_{i=1} 0.25 \left(\frac{Diameter_j}{12}\right)^2 \pi\ Height_j Density_j \rho_i \tag{10}$$

where

j = subscript reference to stump subcategory,

i = subscript reference to species,

0.0005 = conversion factor to tons (ton/lb),

0.25 = constant in calculation of the volume of a cylinder,

$Diameter_j$ = input diameter of each stump subcategory (in),

12 = conversion factor from inches to feet,

$Height_j$ = input height of each stump subcategory (ft),

$Density_j$ = stems per acre by stump subcategory, and

ρ_i = wood particle density based on stump species (lb/ft^3).

Sound wood particle densities (ρ_s) by species are used for sound stumps, and rotten wood particle densities (ρ_r) are used for rotten and lightered/pitchy stumps.

Tree cone loading **(woody fuels stratum) (w_j; tons/ac)**—Required input variable.

Pile loading **(w_{Pile}; tons/ac)**—Total pile loading is calculated in the Pile Calculator (USDA FS 2012e) and can be entered in FCCS fuelbeds and used in available fuel potential and total carbon calculations.

Litter-lichen-moss stratum loading **(w_{LLM}; tons/ac)**—Stratum loading is the sum of LLM loading, which are calculated separately, based upon input depth, percentage cover, and inferred bulk density (table 1):

$$w_{LLM} = \sum_{j=1}^{3} w_j = \sum_{i=1} \frac{43560}{2000}\ \rho_{b_i} \delta_j\ \theta_j \tag{11}$$

where

j = subscript reference to LLM;

i = subscript reference to type (i.e., litter type or moss type);

43560 = conversion factor (ft^2/ac);

2000 = conversion factor (lb/ton);

ρ_{b_i} = bulk density by lichen, moss, or litter type (lb/ft^3) (table 1);
δ_j = depth of LLM (ft). Litter depth is weighted by the relative cover of each litter type (i.e., longleaf pine, shortleaf pine); and
θ_j = percentage cover of LLM.

***Ground fuels loading* ($w_{GroundFuels}$; tons/ac)**—The sum of all ground fuel types, including duff (upper and lower duff), squirrel middens, and basal accumulations.

***Duff loading* (ground fuels stratum) (w_{Duff}; tons/ac)**—The sum of upper and lower duff loading, which are calculated based on inferred bulk density by duff derivation (table 1) as well as input depth and percentage cover of each duff layer.

$$w_j = \frac{43560}{2000}\ \rho_{b_j}\delta_j\,\theta_j \tag{12}$$

where
j = subscript reference to duff subcategory (i.e., upper or lower duff layer),
43560 = conversion factor (ft^2/ac),
2000 = conversion factor (lb/ton),
ρ_{b_j} = bulk density by duff derivation of upper (lb/ft^3) (table 1),
δ_j = input depth of the duff subcategory weighted by its relative cover (ft), and
θ_j = percentage cover of the duff layer.

***Basal accumulation loading* (ground fuels stratum) (w_{BA}; tons/ac)**—Estimated based on input dimensions and inferred bulk density by basal accumulation derivation (e.g., bark slough or needle litter). The input radius of basal accumulations is measured from the edge of the tree to the outside edge of the basal accumulation. Bulk volume is estimated as a paraboloid shape minus a cylindrical volume of the tree bole. The FCCS assumes that only overstory trees have basal accumulations.

$$w_{BA} = Y_{BA}\ \mathrm{Density}_{BA}\,\frac{\rho_{b\ BA}}{2000} \tag{13}$$

where
$Y_{BA\ j}$ (ft^3/ac) = estimated basal accumulation volume, calculated as the difference between the gross volume of a parabaloid minus the cylindrical volume of the tree bole (eq. 13a);
$\mathrm{Density}_{BA}$ (number/ac) = calculated as the product of overstory tree density and input percentage affected of basal accumulations divided by 100;
$\rho_{b\ BA}$ = inferred bulk density of basal accumulations (lb/ft^3) (table 1); and
2000 = conversion factor (lb/ton).

Basal accumulation volume **($Y_{BA.j}$; ft^3/ac)**—Calculated as:

$$Y_{BA\ W\bar{J}} = \left[\left(\frac{\pi\ Depth_{BA}\ Width_{BA}^{2}}{8}\right) - \left(\pi\left(\frac{Diameter_{Overstory}}{2}\right)^{2} Depth_{BA}\right)\right] Density_{Overstory} \quad (13a)$$

where

$Depth_{BA}$ (ft) = input basal accumulation depth converted to feet,

$Width_{BA}$ (ft) = calculated as the sum of the basal accumulation and tree diameters,

$Diameter_{Overstory}$ (ft) = input overstory tree diameter,

$Depth_{BA}$ (ft) = input basal accumulation depth converted to feet, and

$Density_{Overstory}$ (number/ac) = input overstory density.

Squirrel midden loading **(ground fuels stratum) (w_{SM}; tons/ac)**—Estimated based on input dimensions and an inferred bulk density (table 1).

$$w_{SM} = Y_{SM}\ Density_{SM} \frac{\rho_{b\ SM}}{2000} \quad (14)$$

where

Y_{SM} (ft^3/ac) = estimated squirrel midden volume, calculated as the volume of a parabaloid (eq. 14a);

$Density_{SM}$ (number/ac) = input density of squirrel middens;

$\rho_{b\ SM}$ = inferred bulk density of squirrel middens (lb/ft^3) (table 1); and

2000 = conversion factor (lb/ton).

Squirrel midden volume **(Y_{SM}; ft^3/ac)**—Calculated as:

$$Y_{SM} = \frac{\pi\ Depth_{SM}\ Width_{SM}{}^{2} Density}{8} \quad (14a)$$

where

Depth (ft) = input squirrel midden depth converted to ft,

Width (ft) = calculated as $2Radius_{SM}$, and

Density (middens/acre) = input number of squirrel middens per acre.

Live versus dead loading **(w; tons/ac)**—After total fuel loading is calculated, live and dead loadings are based on designation of live or dead by an inferred internal variable (table 6) or input variable (percentage live) in the shrub and herb strata.

Table 6—Inferred live and dead designations

Fuel category	Live	Dead
Trees	X	
Snags		X
Ladder fuels—		
Arboreal lichen	X	
Dead branches		X
Climbing ferns/other epiphytes	X	
Stringy or fuzzy bark	X	
Vines-liana	X	
Leaning snags		X
Tree regeneration	X	
Shrubs	X	
Herb	X	
Woody fuels		X
Litter-lichen-moss—		
Litter		X
Lichen	X	
Moss	X	
Ground fuels		X

Total carbon (C; tons/ac)—Estimated to be between 48 and 52 percent of plant biomass (Eggleston et al. 2006, McGroddy et al. 2004). The FCCS reports total carbon by stratum, category, and subcategory by using conversion factors listed in table 7.

$$C_j = \text{PropC}\ w_j \tag{15}$$

where

PropC = proportion of dry weight biomass that is carbon, and

w_j = loading by stratum, category, and subcategory (ton/acre).

Table 7—Proportion of carbon by fuelbed category and subcategory

Stratum	Category/subcategory	Proportion of dry weight biomass that is carbon (PropC)
Canopy	Trees	
	Overstory (total)	0.5
	Midstory (total)	.5
	Understory (total)	.5
	Snags	
	Class 1 foliage (crown only)	.5
	Class 1 wood	.5
	Class 2 wood	.4
	Class 3 wood	.4
	Ladder fuels	.5
Shrubs	Primary and secondary layers	.5
	Needle drape	.5

Table 7—Proportion of carbon by fuelbed category and subcategory (continued)

Stratum	Category/subcategory	Proportion of dry weight biomass that is carbon (PropC)
Herb	Primary and secondary layers	.5
Woody fuels	Sound wood (all size classes)	.5
	Rotten wood (all size classes)	.4
	Stumps	
	Sound	.5
	Rotten	.4
	Lightered	.5
	Woody fuel accumulations	.5
Litter, lichen, and moss	Litter, lichen, and moss	.5
Ground fuels	Duff (upper and lower layers)	.4
	Basal accumulations	.5
	Squirrel middens	.5

Surface Fire Behavior

The FCCS surface fire behavior calculator predicts surface fire reaction intensity (Btu/ft^2/min), rate of spread (ft/min), and flame length (ft) based on fuelbed characteristics and a user-specified moisture scenario, midflame windspeed, and slope gradient. Sandberg et al. (2007b) present a spread model formulation based on Rothermel (1972) with logical improvements and corrected analytical interpretations of data reported by Frandsen (1973) and Wilson (1990). In this section, we have expanded the documentation to better inform users and developers. We also present changes made to the model since 2007 as a result of field testing and expert-user feedback on model performance.

The reformulated Rothermel model in the FCCS inherits many of the same assumptions as the original Rothermel (1972) fire spread model (table 8). Predictions are made based on the assumption of a steady-state head fire and model spread in the flaming front, which is dominated by fine dead and live fuels. The main difference in the FCCS model is its modification to allow for heterogeneous surface fuel inputs (Sandberg 2007a). Heat source and heat sink terms of the FCCS rate of spread equation are calculated by surface fuel stratum (shrubs, herbs, woody fuels, and the LLM stratum) and summed. Because FCCS allows for heterogeneous surface fuels, it does not rely on stylized fire behavior fuel models and can more realistically represent actual surface fuel characteristics. This change shifts the potential applications from one of strictly modeling surface fire behavior to allowing predictions of both fire behavior and effects (e.g., fuel consumption and emissions) using the same inputs. It also allows for objective comparison of predicted fire behavior in realistic fuelbeds, such as comparison in treated versus untreated

Table 8—Comparison of the original Rothermel (1972) and Fuel Characteristic Classification System (FCCS) (2007) fire spread models

Basis of comparison	Rothermel (1972)	FCCS (2007)
Assumptions	Steady state head fire	Same
	Flaming front (fine fuels)	Same
	Uniform fuel moisture, wind, slope	Same
	Homogenous surface fuels (fuel model)	Heterogeneous surface fuels (four strata)
Objective	Support fire management operations in standard fuels under changing environmental conditions (i.e., weather and topography)	Compare fire behavior between varying fuelbed characteristics and changing environmental conditions
Applications	Surface fire behavior modeling	Surface fire behavior modeling
		Fire effects modeling
		Fuel treatment assessment
		Habitat assessments
Fuel characteristics crosswalk	Stylized fuel models	Measured fuel characteristics
	Fuel models cannot be crosswalked to realistic fuels	Crosswalk from fuelbeds to fuel models (original 13 and standard 40)

fuels. Fuelbeds in FCCS can be quite complex and reflect changes in fuel characteristics from vegetation succession over time, natural disturbances, and active management such as forest harvesting and prescribed burning (Ottmar et al. 2007).

Several weaknesses remain in the physical theory underlying the modified spread model in FCCS. For example, we are limited by the reliance on empirical data to estimate the propagating flux ratio as a single term, rather than the more appropriate treatment of flux as a set of dependent variables that consider convective, radiative, and brand transfer modes individually. Although the FCCS model now resolves the fire behavior contribution of heterogeneous mixtures of fuelbed categories within strata and mixtures of strata within surface layers, it remains weak in the ability to predict the interaction of fires in multiple layers such as dependent crown fires or surface fires driven by the contribution of litter. Finally, we are confident that FCCS manages the influence of live fuel moisture on surface more logically than earlier models, but we still base predictions on our hypotheses of live moisture dynamics rather than solid scientific evidence.

Table 9 presents an overview of the surface fire behavior equations in FCCS and how they differ from the Rothermel (1972) spread model. With few exceptions, the main difference between the FCCS (2007) modeling approach and the Rothermel (1972) model is the treatment of more complex fuelbeds with four surface fuel strata. The LLM stratum is generally much more densely packed and constitutes a different combustion environment than other surface fuels (shrubs, herb, and woody fuels). For this reason, the LLM stratum is often treated separately from the other surface fuels.

Table 9—Comparison of equation forms in Rothermel (1972) and Fuel Characteristic Classification System (FCCS) (2007)

Type of equation	Rothermel equation	Fuel Characteristic Classification System
Rate of spread (R) (equation 25)	$$R = \frac{I_R \xi (1 + \varphi_w + \varphi_k)}{\rho_b \varepsilon Qig}$$ where I_R = surface reaction intensity (British thermal unit [BTU]/ft^2/min), ξ = propagating flux ratio, φ_w = wind coefficient, φ_s = slope coefficient, ρ_b = oven dry particle density (lb/ft^3), ε = effective heating number, and Qig = heat of preignition (BTU/lb).	$$R = \max(R_{Surf}, R_{LLM}) \text{ Where } R = \frac{I_R \xi (1 + \varphi_w + \varphi_s)}{q}$$ where m = subscript reference to rate of spread calculated for all surface fuels (R_{Surf}) and the litter, lichen, and moss (LLM) stratum (R_{LLM}); I_R = surface reaction intensity (BTU/ft^2/min), calculated individually for the LLM stratum and summed for the other strata (shrub, herb, woody fuels); ξ = propagating flux ratio calculated by stratum; φ_w = wind coefficient; φ_s = slope coefficient; and q = surface heat sink, individually calculated for each stratum and then summed.
Surface fire reaction intensity (I_R) (equation 16)	$$I_R = \Gamma' w_n h\, \eta_M \eta_K$$ where Γ' = optimum reaction velocity, calculated as the product of maximum reaction velocity and reaction efficiency; w_n = net fuel loading (ovendry fuel loading w_o divided by 1 + ST (total mineral content); h = fuel particle low heat content (BTU/lb); η_M = moisture damping coefficient, and η_K = mineral damping coefficient (calculated from fuel particle mineral content).	$$I_R = \sum_{k=1}^{4} \left[\left(\eta_{\beta'}\right)^A \Gamma' w_o h\, \eta_M\, \eta_K \eta_F \right]_k$$ where k = subscript reference to surface fuel stratum; $\left(\eta_{\beta'}\right)^A$ = reaction efficiency, used to modify reaction velocity as in Rothermel but expressed explicitly here; Γ' = maximum reaction velocity; w_o = oven dry fuel loading. The FCCS does not adjust for mineral content, but the difference is slight (5 percent). h = fuel particle low heat content (BTU/lb), η_M = moisture damping coefficient of live and dead fuels, η_K = mineral damping coefficient (constant = 0.42), and η_F = flammability index assigned by species and LLM type (2 = flammable, 1 = neutral).
Reaction efficiency $\left(\eta_{\beta'}\right)^A$ (equation 17)	Embedded within the optimum reaction velocity term and expressed as: $$\left(\eta_{\beta'}\right)^A = \max \left(\frac{\beta}{\beta_{op}}\right)^A e^{\left[A\left(1-\frac{\beta}{\beta_{op}}\right)\right]}$$ where A = Rothermel's A is an exponential term that lessens the influence of relative packing ratio on reaction efficiency in very fine fuels and is calculated as $$A = \frac{1}{(4.774\sigma^{0.1} - 7.27)}$$ $\frac{\beta}{\beta_{op}}$ = relative packing ratio, calculated as the ratio of packing ratio to optimum packing ratio.	Reaction efficiency is calculated in the FCCS as: $$\left(\eta_{\beta'}\right)^A = \left(\beta' e^{1-\beta'}\right)^A$$ where A = Rothermel's A, $A_i = 133\sigma_k^{-0.7913}$ and β' = relative packing ratio, calculated as the ratio of optimum depth and average depth of surface fuels (effective depth). This is a comparable calculation of relative packing ratio to Rothermel but uses depth instead of packing ratio.

Table 9—Comparison of equation forms in Rothermel (1972) and Fuel Characteristic Classification System (2007) (continued)

Type of equation	Rothermel equation	Fuel Characteristic Classification System
Propagating flux ratio (ξ) (equation 28)	$\xi = (192 + 0.2595\sigma)^{-1}\, e^{[(0.792 + 0.681\sigma^{0.5})(\beta + 0.1)}$ where β = packing ratio.	$\xi = (0.03 + 2.5\beta_{\varepsilon})$ This new equation form represents a recalculation of Rothermel's (1972) propagating flux ratio and regresses empirical data on effective packing ratio (β_{ε}) calculated as the ratio of the reactive fuel volume to fuel depth (Sandberg et al. 2007b).
Wind coefficient (φ_w) (equation 30)	$\varphi_w = CU^B\left(\frac{\beta}{\beta_{op}}\right)^{-E}$ where $C = 747e^{-0.133\sigma^{0.55}}$ $B = 0.02526\sigma^{0.54}$ $E = 0.715e^{-3.59\sigma\, 10^4}$	$\varphi_{w_m} = 8.8\left(\frac{1}{\beta'^{E}_{m}}\right)\left(\frac{U}{BMU}\right)^B$ where 8.8 = windspeed multiplication constant (see Sandberg et al. 2007 for details), $\frac{U}{U_{BMU}}$ = ratio of input windspeed to benchmark 4 mph windspeed, B = 1.2 (intermediate of published values (Sandberg et al. 2007), β' = relative packing ratio, $E = 0.55 - 0.2\ \frac{(FAI_{Surf} - FAI_{Woody})}{FAI_{Surf}}$, and m = subscript reference to all surface fuels and the LLM stratum.
Slope coefficient (φ_S) (equation 31)	$\varphi_S = 5.275\beta^{-0.3}\tan(Slope)^2$ where β = fuelbed packing ratio, and Slope = input slope (°)	$\varphi_{S_i} = 5.275\left(\frac{Slope}{100}\right)^2 \beta_m^{-0.3}$ where β = packing ratio, m = subscript reference to all surface fuels and the LLM stratum, and Slope = input slope (percent).
Heat sink (q) (equation 32)	Heat sink denominator term, expressed as $\rho_b \varepsilon Q_{ig}$ where ρ_b = ovendry particle density (lb/ft^3), ε = effective heating number, and Q_{ig} = heat of preignition (Btu/lb).	$q_{Surf} = \sum_{m=1}^{2} \eta_{\beta'_m}\left(\frac{RV\ PD\ Qig}{MinEff\delta}\right)_m$ where m = subscript reference to shrub, herb, woody fuels, and LLM strata; $\eta_{\beta'}$ = reaction efficiency (dimensionless) (equation 18); RV_i = the reactive volume of each fuel stratum (ft^3/ft^2) (equation 21a); PD_i = particle density summarized by stratum (lb/ft^3); Qig_i = heat of ignition by stratum (Btu/lb) (equation 34a, 34b); and $MinEff\delta_i$ = area-weighted average depth of each surface fuel stratum (equation 31), capped at a 1 ft maximum in order not to reduce the calculated heat sink in deep (i.e., greater than 1 ft) stratum.

Reaction Intensity

Reaction intensity (I_R; Btu/ft^2/min)—
The heat release rate per unit area of the surface fire flaming front (Rothermel 1972). In FCCS, it is calculated as the sum of component reaction intensities for each stratum including shrubs, herbaceous vegetation, woody fuels, and LLM. The LLM stratum differs from other surface fuels in its fuel packing ratio and configuration, and its potential reaction intensity is calculated somewhat differently from that of other surface fuel strata. Reaction intensity is calculated as the sum of component reaction intensities ($I_{R\ Comp}$) by surface fuel stratum:

$$I_R = \sum_{k=1}^{4} I_{R\ Comp_k} \tag{16}$$

$$I_{R\ Comp_k} = \sum_{k=1}^{3} \left[\left(\eta_{\beta'}\right)^A \Gamma'_{max}\, w_o\, h\, \eta_M \eta_K \eta_F \right]_k + \left[\left(\eta_{\beta'}\right)^A \Gamma'_{max}\, w_o\, h\, \eta_M \eta_K \eta_F \right]_{LLM}$$

where

k = subscript reference to a single fuelbed stratum (shrubs, herbs, and woody fuels);

$I_{R\ Comp_k}$ = component reaction intensity by stratum;

$\eta\beta'$ = total reaction efficiency of other surface fuels (shrubs, herbs, and woody fuels) or LLM (dimensionless) (eq. 17);

A = Rothermel’s A; exponent that reduces the influence of relative packing ratio on reaction efficiency in very fine fuels (eq. 21);

Γ'_{max} = maximum reaction velocity that would exist at optimum fuelbed depth with no fuel moisture or mineral content (1/min) (eq. 22);

w_o = flame-available loading of each surface fuel stratum (lb/ft$_2$); includes shrub crowns, herbs, flame-available LLM, and a proportion of small woody fuels including all 1-hr fuels, 25 percent of 10-hr fuels, and 12.5 percent of 100-hr fuels and is equivalent to wn in Rothermel (1972) in that it is net of silica content and represents the material available for flaming combustion;

h = low fuel heat content of each surface fuel stratum (Btu/lb) (eq. 23);

η_M = moisture damping coefficient, which reduces reaction velocity (dimensionless) (eq. 24);

η_K = mineral damping coefficient, which reduces reaction velocity (0.42, dimensionless) and corresponds to a conventional value for silica-free ash content of 1 percent established by Rothermel (1972);

η_F= flammability index,[1] weighted by species loading by stratum (eq. 1) (dimensionless); and

LLM = subscript reference to the LLM stratum.

Reaction efficiency ($\eta\beta'$; dimensionless)—
Reaction efficiency is calculated as a proportional value between 0 and 1 and represents the damping effect of inefficiently packed fuels in the reaction intensity equation (eq. 16). As fuels approach an optimum packing ratio, reaction efficiency approaches 1. All components within a stratum are assumed to burn within a single flame envelope and have one reaction efficiency. Strata within a fuel layer (i.e., all surface fuels and low surface fuels) are assumed to burn with one reaction efficiency. For example, because shrubs rarely burn without lower surface fuels, the reaction efficiency of the all surface fuels layer includes shrubs, herbs, and woody fuels. Low surface fuels may carry flames without involving shrubs, so are assumed to burn with a single reaction efficiency determined by the combined characteristics of only the herb and woody fuels strata. Reaction efficiency is calculated separately for the LLM stratum and is weighted by LLM type (table 2). It is calculated as follows for all surface and lower surface fuel layers:

$$\eta_{\beta'_m} = \left(\beta'_m e^{1-\beta'_m}\right) \tag{17}$$

where

m = subscript reference to all surface fuels (includes shrubs, herbs, and woody fuels), and lower surface fuels (herbs and woody fuels), and

β'_m = relative packing ratio (dimensionless) (eq. 18).

***Relative packing ratio* (β'_m; dimensionless)**—The ratio of optimum depth to actual depth (β'_m, dimensionless), used in calculating reaction efficiency (eq. 17):

$$\beta'_m = \left(\frac{\delta_{opt}}{Eff\delta}\right)_m \tag{18}$$

where

m = subscript reference to upper surface fuels (includes shrubs, herbs, and woody fuels) and lower surface fuels (herbs and woody fuels only),

$\delta_{opt\ m}$ = optimum depth (ft) determines the depth that creates an optimum air to fuel ratio (eq. 19), and

$Eff\delta_m$ = effective depth of surface fuel layer (ft) (eq. 20).

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[1] Flammability index is a multiplier based on expert opinion applied to species that burn with more intensity than most, generally resulting from differences in fuel chemistry or live fuel dynamics. Flammable species = 2, neutral species = 1 (dimensionless).

***Optimum depth* (δ_{opt}; ft)**—The depth at which fuels are optimally packed for maximum reaction velocity:

$$\delta_{opt_m} = PV_m + OptAirVol_m \tag{19}$$

where
m = subscript reference to upper surface fuels (shrubs, herbs, and woody fuels) and lower surface fuels (herbs and woody fuels only),
PV_m = volume of particles in a square foot area (ft^3/ft^2 = ft) (eq. 19a), and
$OptAirVol_m$ = optimum air volume of surface fuels and low surface fuels (ft^3/ft^2 = ft) (eq. 19b).

***Particle volume* (PV; ft^3/ft^2)**—The volume of particles in a square foot area, calculated for upper surface fuels (including shrubs, herbs, and woody fuels), and lower surface fuels (herbs and woody fuels only).

$$PV_m = (BV_{Woody}\ \beta_{Woody}) + \sum_{k=1}^{2} PV_k \tag{19a}$$

where
m = subscript reference to upper surface fuels and lower surface fuels,
BV_{Woody} = bulk volume of the woody fuel stratum (ft^3/ft^2),
β_{Woody} = packing ratio of the woody fuel stratum (dimensionless) (eq. 3),
k = subscript reference to shrub stratum and herb stratum, and
PV_k = particle volume of the shrub stratum and herb, calculated as dry weight biomass (lb/ft^2) divided by particle density for each stratum (lb/ft^3).

***Optimum air volume* ($OptAirVol_m$; ft^3/ft^2)**—The volume of air space between fuel particles that would result in maximum reaction intensity.

$$OptAirVol_m = \sum_{k=1} 45RV_k \tag{19b}$$

where
m = subscript reference to upper surface fuels and lower surface fuels;
k = subscript reference to shrubs, herbs, and woody fuels for upper surface fuels and herbaceous and woody fuels only for lower surface fuels;
45 = is the optimum air to volume ratio of fuel particles (Sandberg et al. 2007b);
and RV_k = the reactive volume of each fuel stratum, calculated as flame-available loading divided by particle density (ft^3/ft^2) for each stratum (eq. 19c).

Reactive volume **(RV_k; ft^3/ft^2)**—The volume of fuel in each stratum that would be involved in flaming combustion and used in calculating optimum air volume (eq. 19b). Reactive volume of LLM fuels is capped at maximum reactive volume, which is calculated as MaxFlameLoading (inferred) divided by LLM particle density (lb/ft^2).

$$RV_k = \sum_{k=1} \frac{w_{FlameAvailable\,k}}{25} \tag{19c}$$

where

k = subscript reference to shrubs, herbs, woody fuels, and LLM strata;

$w_{FlameAvailable}$ = loading available for flaming combustion, defined as: total shrub loading, total herbaceous loading, a portion of woody fuel loading (100 percent 1-hr, 25 percent 10-hr, and 12.5 percent 100-hr woody timelag classes), and total LLM loading (lb/ft^2) ; and

25 = default particle density (lb/ft^3).

This definition of RV, based on $w_{FlameAvailable}$, is different than the “shell volume” introduced by Sandberg et al. (2007a), which in turn differs from the “surface area” approach inherent in Rothermel (1972). The latest definition recognizes that energy from the combustion of a woody fuel shell thicker than the pyrolysis thickness at ignition is available to feed flame intensity and spread.

Effective depth of upper and lower surface fuels **($Eff\delta_m$; ft)**—Used in calculating relative packing ratio (eq. 18) and calculated as the depth (ft) of upper and lower surface fuel layers, weighted by reactive volume and percentage cover.

$$Eff\delta_m = \sum_{k=1} \frac{(RV\ \delta\ CovRatio)_k}{RV_k} \tag{20}$$

where

m = subscript reference to upper surface fuels (shrubs, herbs, and woody fuels) or low surface fuels (herbs and woody fuels only),

k = subscript reference to surface fuel stratum,

RV_k = the reactive volume of each fuel stratum, calculated as flame-available loading divided by particle density (ft^3/ft^2) (eq. 19c),

δ_k = input depth of each surface stratum (ft), and

$CovRatio_k$ = cover of each stratum divided by 100.

***Rothermel's A* (A; dimensionless)**—Modifies reaction efficiency in equation (16) to account for the lower sensitivity of reaction efficiency to relative packing ratio in flash fuels (or thermally thin fuels). It is set to 1.0 for woody fuels and LLM strata. For shrub crowns and herbaceous fuels, it is calculated as:

$$A_k = 133\sigma_k^{-0.7913} \tag{21}$$

where

k = subscript reference to surface fuel stratum (shrubs, herbs, woody fuels, and LLM),

133 = empirical constant (Rothermel 1972),

σ_k = surface-area-to-volume ratio by stratum (ft^2/ft^3), and

-0.7913 = empirical constant (Rothermel 1972).

***Maximum reaction velocity* (maxΓ'; per minute)**—The reaction velocity that would exist at optimum fuelbed depth with no fuel moisture or mineral content; used in calculating reaction intensity (eq. 16). Reaction velocity is the ratio of the reaction zone efficiency to unit time (Rothermel 1972). Maximum reaction velocity of woody fuels and LLM strata are 9.495/min and 15/min, respectively. Maximum reaction velocity is calculated for shrubs and herbs as:

$$\max\Gamma_k = 9.495\left(\frac{\sigma_k}{\sigma_{Woody}}\right) \tag{22}$$

where

9.495 = maximum reaction velocity of typical woody fuels (Rothermel 1972),

k = subscript reference to shrub and herb strata,

σ_k = surface-area-to-volume ratio of shrubs and herbs (ft^2/ft^3). Shrub σ is calculated as the average of the $\sigma_{Foliage}$ and σ_{Woody}, and

σ_{Woody} = surface-area-to-volume ratio typical of small woody fuels (488 ft^2/ft^3).

Equation 22 is a significant departure from the calculation of the Rothermel (1972) maximum reaction velocity, which was a curvilinear fit of empirical data that in effect reached a maximum value near 16/min for extremely fine fuels (thermally thin or flash fuels). This revised equation is benchmarked to Rothermel's data when the surface-area-to-volume ratio is 488/ft representative of small woody fuels but extrapolated by using an inverse function that allows maximum reaction velocity to exceed 16/min for thermally thin fuels. This equation is also a departure from the value used by Sandberg et al. (2007b).

***Heat content* (h; Btu/lb)**—The low fuel heat content of each surface fuel stratum used in calculation of reaction intensity (eq. 16). Heat content is adjusted for live foliar moisture content in shrub and herb strata. Woody fuel heat content is assumed to be 8000 Btu/lb, and LLM heat content is inferred by type and weighted by loading of each LLM type (e.g., litter type, moss type or lichen) (table 2).

$$h_k = h - FM_k V \tag{23}$$

where

k = subscript reference to shrub and herb strata,

h = default low fuel heat content (8000 Btu/lb),

FM_k = input foliar moisture content (percentage) for shrub and herb strata. Fuel moisture is expressed as percentage multiplied by 100 in this equation (e.g., 90 rather than 0.9), and

V = latent heat of vaporization (11.16 Btu/lb).

***Moisture damping coefficient* (η_M; dimensionless)**—The moisture damping coefficient reduces reaction velocity in equation (16) and is calculated as the weighted average of live and dead fuels for each stratum by the following regression equation:

$$\eta_{M_k} = \left[\eta_{Live}\left(1 - Prop_{Dead}\right)\right]_k + \left[\eta_{Dead} Prop_{Dead}\right]_k \tag{24}$$

$$\eta_j = \left[1 - 2.59\left(\frac{FM_j}{Mx_j}\right)\right] + \left[5.11\left(\frac{FM_j}{Mx_j}\right)^2\right] - \left[3.52\left(\frac{FM_j}{Mx_j}\right)^3\right]$$

where

k = subscript reference to surface fuel stratum (i.e., shrub, herb, woody fuels, LLM),

j = subscript reference to live or dead fuels in each stratum,

η_{Live} = live moisture damping coefficient (dimensionless),

η_{Dead} = dead moisture damping coefficient (dimensionless),

$Prop_{Dead_k}$ = ratio of dead loading to total loading (dimensionless),

FM_j = percentage fuel moisture by dry weight of live fuels (live shrubs, live herbs) and dead fuels (woody fuels, LLM).

Dead shrubs and herbs are assumed to have the same fuel moistures as small (<3 in diameter) woody fuels, and

Mx_j = moisture content of extinction for live shrubs, live herbs, dead woody fuels and LLM.

Rate of Spread

Surface fire rate of spread (R; ft/min)—
Calculated as the ratio of heat source (defined as the surface fire energy propagated to unburned fuels) to surface fuel heat sink (defined as the energy required to preheat surface fuels). Owing to the difference in packing ratio between the LLM stratum and other surface fuels, litter-dominated fuelbeds may have substantially different rates of spread than other fuelbeds. For this reason, R is calculated separately for the LLM stratum. Surface rate of spread is calculated as the maximum of the rate of spread of all surface fuels (including shrubs, herbs, woody fuels, and LLM) and that of RLLM. Rate of spread is also capped at a maximum based on input windspeed and slope.

$$R = \min(\text{WindSlopeCap}, R_{Max}) \tag{25}$$

where
WindSlopeCap = maximum rate of spread based on input windspeed and slope (ft/min) (eq. 26) and
R_{Max} = maximum rate of spread (ft/min) (eq. 27).

WindSlopeCap (ft/min)—
Calculated as the maximum possible rate of spread based on input windspeed and slope and limits the final rate of spread (eq. 25).

$$\text{WindSlopeCap} = 88\ U(1 + \varphi_S) \tag{26}$$

where
88 = conversion factor from mph to ft/min,
U = input midflame windspeed (mph), and
φ_S = slope coefficient (eq. 31).

Maximum rate of spread (R_{Max}; ft/min)—
Calculated as the maximum of surface fuel and LLM rates of spread and used in equation (25).

$$R_{Max} = \max(R_{Surf}, R_{LLM}) \tag{27}$$

$$R_m = \frac{I_{R_m}\xi_m\left(1 + \varphi_W + \varphi_S\right)_m}{q_{Surf\,m}}$$

where
m = subscript reference to surface fuels (R_{Surf}) and the LLM stratum (R_{LLM}),
I_{R_m} = reaction intensity of all surface fuels and component I_R for the LLM stratum (Btu/ft^2/min) (eq. 16),

ξ_m = propagating flux ratio, the proportion of I_R transferred to unburned fuels (dimensionless) (eq. 28),
$(1+\varphi_W+\varphi_S)_m$ = acceleration of the rate of spread owing to windspeed (φ_W, eq. 30) and slope (φ_S, eq. 31) (dimensionless), and
$q_{Surf\,m}$ = heat sink term of all surface fuels and the LLM stratum (Btu/ft^3) (eq. 32).

Propagating flux ratio **(ξ_{Surf}; dimensionless)**—A regression equation that estimates the proportion of the reaction intensity that contributes to the forward rate of spread (eq. 27). The FCCS equation (Sandberg et al. 2007b) is a slight departure from Rothermel (1972) because we assume that the efficiency of heat transfer to the unburned reactive fuels is directly proportional to the bulk density of those fuels. The new equation was recalculated by regressing empirical data from Rothermel (1972) on effective packing ratio, defined here as the ratio of reactive volume to depth.

$$\xi_{Surf} = 0.03 + 2.5 \min\left(0.06, \frac{\sum_{k=1}^{4} RV_k}{\delta_{SurfHeatSink}}\right) \tag{28}$$

where
0.03 = y-intercept of the regression equation for the propagating flux ratio (dimensionless),
2.5 = slope of the regression equation for the propagating flux ratio (percentage),
min = minimum expression,
0.06 = maximum value allowed, which limits propagating flux ratio to ≤ 0.18 (dimensionless),
k = subscript reference to each surface fuel stratum,
RV_k = reactive volume of each surface fuel stratum (ft^3/ft^2) (eq. 19c), and
$\delta_{SurfHeatSink}$ = depth of surface fuel heat sink (ft) (eq. 29).

Propagating flux ratio for the LLM stratum (ξ_{LLM}; dimensionless)—
Calculated as:

$$\xi_{LLM} = 0.03 + 2.5\min\left(0.06, \frac{RV_{LLM}}{Depth_{LLM}}\right) \tag{28a}$$

where
RV_{LLM} = reaction volume of the LLM stratum (eq. 19c), and
$Depth_{LLM}$ = total depth of the LLM stratum (ft).

Depth of surface heat sink ($\delta_{SurfHeatSink}$; ft)—
Area-weighted average depth of each surface fuel stratum used in calculating propagating flux ratio (eq. 28). Calculated as the sum of each stratum depth (ft) multiplied by percentage cover, such that:

$$\delta_{SurfHeatSink} = \sum_{k=1}^{4} \delta_k \, CovRatio_k \tag{29}$$

where
k = subscript reference to shrub, herb, woody fuels, and LLM strata;
δ_k = depth of each surface stratum (ft) (eq. 4); and
$CovRatio_k$ = input percentage cover (percentage) by stratum divided by 100 (dimensionless).

Wind coefficient (φ_W; dimensionless)—
Wind and slope coefficients (eq. 31) modify the heat source term of the rate of spread equation (eq. 27). Owing to differences in fuel characteristics and boundary conditions between the LLM stratum and other surface fuel strata, a wind coefficient is calculated separately for the LLM stratum. The wind coefficient term in the rate of spread equation (eq. 25) is a weighted average of the LLM and surface wind coefficients using the relative contribution of LLM and other strata to reaction intensity.

$$\varphi_w = \left(1 - \frac{I_{R.LLM}}{I_R}\right) \varphi_{w_{Surf}} + \left(\frac{I_{R.LLM}}{I_R} \varphi_{w_{LLM}}\right) \tag{30}$$

$$\varphi_{w_m} = 8.8 \left(\frac{1}{\beta'^{E}_{m}}\right) \left(\frac{U}{BMU}\right)^B$$

where
$I_{R.LLM}$ = component reaction intensity of the LLM stratum (eq. 16),
I_R = surface fire reaction intensity (eq. 16),
$\varphi_{w_{Surf}}$) = surface fuel wind coefficient,
$\varphi_{w_{LLM}}$ = LLM wind coefficient,
m = subscript reference to surface fuels or LLM stratum,

$8.8 = \frac{1}{\varphi_w}$ when $\beta'^E = \frac{U}{BMU} = 1$

β'_m = relative packing ratio of surface fuels or LLM (dimensionless) (eq. 18),
E = exponential term representing a mild effect of large fuels in reducing the accelerating effect of wind on fire spread by attenuating the wind flow within the fuelbed (eq. 30a); this term is assumed to be the same for the LLM stratum as calculated for all surface fuels,

U = input midflame windspeed (ft/min),
BMU = benchmark midflame windspeed constant = 352 ft/min, and
B = exponential response of wind coefficient to windspeed. A null value would indicate no response, and unity would indicate a linear response. Rothermel (1972) allows B to vary from 0.5 to 2.0. Beer (1993) recommends 1.0. The FCCS (Sandberg et al. 2007b) uses a constant value of 1.2 (dimensionless).

Exponential flash term (E; dimensionless)—
FAI-weighted value of surface fuels used in the wind coefficient calculation (eq. 30). Assumed to be 0.35 for all flash fuels (i.e. σ >714/ft) and 0.55 for all thermally thick woody fuels (i.e., σ <714/ft) (dimensionless),

$$E = 0.55 - 0.2\,\frac{\left(FAI_{Surf} - FAI_{Woody}\right)}{FAI_{Surf}} \qquad (30a)$$

where
0.55 = y intercept of regression equation (dimensionless);
0.2 = slope term of regression equation (dimensionless);
FAI_{Surf} = sum of shrub, herb, and woody fuels FAI (dimensionless) (eq. 2), and
FAI_{Woody} = FAI of woody fuels (dimensionless).

Slope coefficient (φ_S; dimensionless)—
Wind and slope coefficients modify the heat source term of the rate of spread equation (eq. 25). Owing to differences in fuel characteristics and boundary conditions between the LLM stratum and other surface fuel strata, a slope coefficient is calculated separately for the LLM stratum. The slope coefficient term in the rate of spread equation is a weighted average of the LLM and surface wind coefficients using the relative contribution of LLM and other strata to reaction intensity.

$$\varphi_S = \left[\left(1 - \frac{I_{R.LLM}}{I_R}\right)\varphi_{S_{Surf}}\right] + \left[\left(\frac{I_{R.LLM}}{I_R}\right)\varphi_{S_{LLM}}\right] \qquad (31)$$

$$\varphi_{S_m} = 5.275\left(\frac{Slope}{100}\right)^2 \beta_m^{-0.3}$$

where
$I_{R.LLM}$ = component reaction intensity of the LLM stratum (eq. 16),
I_R = surface fire reaction intensity (eq. 16),
$\varphi_{S_{Surf}}$ = surface fuel slope coefficient,
$\varphi_{S_{LLM}}$ = LLM slope coefficient,
m = subscript reference to surface fuels or LLM stratum,

5.275 = Rothermel's (1972) empirically derived minimum slope coefficient, i.e., fire spread rate at 100 percent slope as a multiple of no-slope spread rate in extremely densely packed fuelbeds,
Slope/100 = input slope (percentage) divided by 100,
β_m = packing ratio of LLM and all other surface fuels (calculated as the sum of shrub, herb, and woody packing ratios) (dimensionless), and
-0.3 = exponential constant derived by Rothermel (1972) to represent observations of the effect of fuelbed packing ratio on the influence of slope on fire spread.

Heat sink (q_{Surf}; Btu/ft^3)—
The heat sink term of the rate of spread equation (eq. 25) is calculated for each surface fuel stratum and then summed. This calculation is slightly different in its representation of the effect of fuelbed depth than the calculation described by Sandberg et al. (2007b). First, the calculated heat sink required for ignition is now reduced by the reaction-efficiency term. Second, the effective depth of each stratum included in the heat sink term is limited to 1 ft based on an assumption that it is seldom necessary to preheat more than 1 ft of depth within a stratum to achieve ignition of the stratum. Both corrections are applied to avoid unrealistic predictions of fire behavior in very dense or very tall fuelbeds.

$$q_{Surf} = \sum_{k=1}^{4} \eta_{\beta'_m} \left(\frac{RV\ PD\ Qig}{\delta_{SurfHeatSink}}\right)_k \tag{32}$$

where
k = subscript reference to shrub, herbs, woody fuels, and LLM strata;
m = subscript reference to reaction efficiency of all surface fuels (applicable to the shrub stratum), low surface fuels (applicable to herbs and woody strata), and the LLM stratum ($\eta_{\beta'_m}$, eq. 17);
RV_k = the reactive volume of each fuel stratum (ft^3/ft^2) (eq. 19c);
PD_k = particle density summarized by stratum (lb/ft^3);
Qig_k = heat of ignition by stratum (Btu/lb) (eq. 32a,b); and
$\delta_{SurfHeatSink}$ = depth of surface fuel heat sink (ft) (eq. 29).

Heat of ignition (Qig_k; Btu/lb)—
Heat of pre-ignition, the amount of heat required to ignite 1 lb of fuel. Used in the heat sink calculation (eq. 32) and calculated by stratum, heat of ignition is calculated as a weighted average of live and dead fuels in shrubs and herb:

$$Qig_k = \left[Qig_{Live}\left(1 - Prop_{Dead}\right)\right]_k + \left[Qig_{Dead}Prop_{Dead}\right]_k \tag{32a}$$

where
k = subscript reference to each surface fuel stratum,
Qig_{Live} = live fuel heat of ignition (Btu/lb),
$Prop_{Dead}$ = proportion of dead fuel loading to total fuel loading, and
Qig_{Dead} = dead fuel heat of ignition (Btu/lb).

Component heat of ignition (Qig_j; Btu/lb)—
Individually calculated for live shrubs, live herbs, and woody fuels. Dead shrubs, dead herbaceous vegetation, and the LLM stratum are assumed to have the same heat of ignition as woody fuels:

$$Qig_j = 250 + \left(V\,FM_j\right) \qquad (32b)$$

where
j = subscript reference to live shrubs, live herb, and woody fuels,
250 = heat of preignition of dry cellulose (Btu/lb),
V = latent heat of vaporization (11.16 Btu/lb), and
FM_j = fuel moisture content (percentage).

Flame Length

Flame length (FL; ft)—
Defined as the distance between the flame tip and the midpoint of the flame depth at the base of the flame (Albini 1976, Byram 1959). In the FCCS, flame length is calculated as the product of reaction intensity and rate of spread:

$$FL = 0.45(I_R\ R\ t_R)^{0.46} \qquad (33)$$

where
0.45 = constant of proportionality (Byram 1959),
I_R = surface reaction intensity (Btu/ft^2/min) (eq. 16),
R = rate of spread (ft/min) (eq. 25),
t_R = flame residence time (min) (eq. 34), and
0.46 = constant (Fons 1946).

***Flame residence time* (t_R; min)**—Defined as the time fuels contribute to propagating flux and is estimated as:

$$t_R = 192\,\frac{\sum_{k=1}^{4}(I_R\ RT)_k}{I_R} \qquad (34)$$

where
192 = unit conversion based on the commonly used assumption that woody fuels consume at rate of 8 min/in, as limited by thermal diffusivity (Anderson 1969),
k = subscript reference to shrubs, herb, woody fuels, and LLM strata,
I_{R_k} = contribution to reaction intensity of each fuelbed stratum (Btu/ft$_2$/min) (eq. 16), and

RT_k = reaction thickness of each stratum (ft) (eq. 35).

Reaction thickness (RT; ft)—
Reaction thickness, used to estimate flame residence time (eq. 34), is the approximate thickness of a fuel element shell that contributes to reaction intensity. Reaction thickness is estimated to be 0.0028 ft in thermally-thick fuel elements (Sandberg et. al. 2007b) based on data from Frandsen (1973). When the diameter of a fuel element is less than twice the reaction thickness, the entire fuel element contributes to reaction intensity, and reaction thickness is simply the radius (or one-half the thickness) of the fuel element.

$$RT_k = \min\left(0.0028, \frac{2}{\sigma_k}\right) \tag{35}$$

where
k = subscript reference to shrubs, herbs, woody fuels, and LLM strata,
0.0028 = assumed maximum reaction thickness (ft),
$2/\sigma$ = radius (or one-half the thickness) of the fuel element, and
σ_k = surface-area-to-volume ratio (ft^2/ft^3). Shrub surface-area-to-volume ratio is adjusted as the average between inferred shrub and woody surface-area-to-volume ratio to represent woody portions and foliar portions of shrub components.

Fuel Model Crosswalks

As part of each fuelbed calculation, FCCS provides a static crosswalk to one of the 13 original fire behavior prediction system (FBPS) fuel models (Anderson 1982) and one of the 40 standard fire behavior fuel models (Scott and Burgan 2005). The crosswalk is invalid under any other environmental scenario and is generally not appropriate for simulating fire spread across landscapes, as in FARSITE (Finney 1998). Fuel model crosswalks may be used in FlamMap (Finney 2006) as long as input wind, slope, and fuel moistures remain the same as in the original FCCS prediction.

A crosswalk to one of the original 13 FBPS fuel models is first calculated based on vegetation type grouping and closest match to predicted rate of spread (ft/min) and flame length (ft). Predicted values of R and FL of the original fuel models were calculated in BEHAVE v3.0 using a D2L2 moisture scenario (Andrews et al. 2003) and 4 mph midflame windspeed and 0 percent slope inputs, and they were then compared to the same values calculated for fuelbeds in FCCS 2.2. The suggested crosswalk to the standard 40 fuel models is only a recommendation because there are multiple standard models that may have predicted fire behavior similar to any FCCS fuelbed.

FBPS Fuel Models

Fire behavior predictions are first grouped into three main categories based on the ratio of rate of spread (R) and flame length (FL).

- Forest: ratio <3:1 (i.e., R = 3 FL)
- Brush and timber slash or litter: 3:1 ≤ ratio <6:1
- Grass: ratio ≥ 6:1

Fuelbeds are then assigned a fuel model based on their predicted FL or R, or both (table 10). Fuel model 7 is never selected because it is basically identical to fuel model 6 but with a different moisture content of extinction.

Table 10—Fuel model crosswalk to the original 13 fire behavior fuel models

Fuelbed type (based on ratio rate of spread/ flame length [R:FL])	Fuel model(s)	Flame length grouping
Forest (ratio <3:1)	8	FL < 2 ft
	9	2 ft ≤ FL < 4 ft (2–4 ft)
	10	4 ft ≤ FL < 6 ft (4–6 ft)
	12	6 ft ≤ FL < 8 ft (6–8 ft)
	13	FL ≥ 8 ft (> 8 ft)
Brush and timber slash or litter (3:1 ≥ ratio <6:1)	4	FL ≥ 14 ft (> 14 ft)
	5	6 ft ≤ FL < 14 ft (6-14 ft)
	6 (or 7)[a]	2 ft ≤ FL < 6 ft and R ≥ 12 ft/min (2–6 ft)
	11	2 ft ≤ FL < 4 ft and R < 12 ft/min (2–4 ft)
	8	FL < 2 ft
Grass (ratio ≥ 6:1)	1	36 ft/min ≤ R < 84 ft/min (36–84 ft/min)
	2	R < 36 ft
	3	R ≥ 84 ft/min

[a] Suggested fuel model crosswalks do not include fuel model 7, but this fuel model could be selected in place of fuel model 6 in shrub fuels with particularly high moisture contents of extinction.

Standard Fuel Models

The FCCS crosswalk to standard fuel models follows the procedure outlined by Scott and Burgan (2005). The first step is to crosswalk to one of the 13 original models as outlined above (table 10). The second step is to calculate the departure of predicted R and FL between FCCS fuelbed calculations and fuel models used in BehavePlus (Andrews et al. 2003) estimates at D2L2 and 4 mph windspeed. The FCCS calculates a ratio value of each fuelbed's predicted FL and R to FBPS fuel model benchmarks (table 11). It then makes a crosswalk assignment to one of the 40 standard fuel models (table 12). In many cases, FCCS selects one of several close matches. Users are encouraged to consider alternative matches by comparing FCCS and BehavePlus outputs that may provide better coincidence of fire behaviors over the range of expected fuel and weather conditions.

Table 11—Adjective assignment of the percentage difference between predicted rate of spread (R) and flame length (FL) values and benchmark values

Adjective class to be used in the table 12 look up table	Ratio range[a]
Low	<0.50
Slightly lower	0.50 to <0.85
Comparable	0.85 to <1.15
Slightly higher	1.15 to <1.50
Higher	1.50 to <2.00
Much higher	2.00 to <3.00
High	> 3.00

[a] Ratio values are calculated as the ratio of predicted R or FL to benchmark values. A ratio value of 1 indicates an exact match.

$$\text{FuelModel}_{FL} = \text{closest match} = 1.0 \approx \frac{FL_{FCCS}}{FL_{FuelModel_i}} \tag{36}$$

$$\text{FuelModel}_{R} = \text{closest match} = 1.0 \approx \frac{R_{FCCS}}{R_{FuelModel_i}} \tag{37}$$

where

FL_{FCCS} = predicted FCCS flame length (ft),

$FL_{FuelModel}$ = benchmark FBPS flame length (ft),

R_{FCCS} = predicted FCCS rate of spread (ft/min), and

$R_{FuelModel}$ = benchmark FBPS flame length (ft/min).

Table 12—Crosswalk matrix from original Fire Behavior Prediction System (FBPS) fuel model assignment to standard fuel models

Original FBPS fuel model[a]	Ratio of FCCS rate of spread to benchmark rate of spread[b]	Ratio of FCCS flame length to benchmark flame length						
		Low	Slightly lower	Comparable	Slightly higher	Higher	Much higher	High
		Standard fuel model code[c]						
1—Short grass (1 ft)	Low	GR1	GR1	GR1	GR4	GR7	GR9	GR9
	Slightly lower	GR1	GR1	GR2	GR4	GR7	GR9	GR9
	Comparable	GR1	GR2	GR2	GR4	GR7	GR9	GR9
	Slightly higher	GR1	GR2	GR2	GR5	GR8	GR9	GR9
	Higher	GR1	GR2	GR3	GR5	GR8	GR9	GR9
	Much higher	GR2	GR3	GR3	GR6	GR9	GR9	GR9
	High	GR2	GR3	GR3	GR6	GR9	GR9	GR9
2—Timber (grass and understory)	Low	GS1	GR1	GR3	GR3	GR4	GR5	GR8
	Slightly lower	GS1	GR1	GR3	GR4	GR4	GR5	GR8
	Comparable	GS1	GR2	GR3	GR4	GR4	GR5	GR8
	Slightly higher	GS2	GR2	GR3	GR4	GR4	GR5	GR8
	Higher	GS2	GR3	GR3	GR4	GR5	GR6	GR9
	Much higher	GR3	GR3	GR3	GR4	GR5	GR7	GR9
	High	GR3	GR3	GR3	GR4	GR5	GR7	GR9

Table 12—Crosswalk matrix from original fire behavior prediction system (FBPS) fuel model assignment to standard fuel models (continued)

Original FBPS fuel model[a]	Ratio of FCCS rate of spread to benchmark rate of spread[b]	Ratio of FCCS flame length to benchmark flame length: Low	Slightly lower	Comparable	Slightly higher	Higher	Much higher	High
		Standard fuel model code[c]						
3—Tall grass (2.5 ft)	Low	GR3	GR4	GR5	GR7	GR8	GR9	GR9
	Slightly lower	GR4	GR4	GR6	GR7	GR8	GR9	GR9
	Comparable	GR4	GR4	GR6	GR7	GR8	GR9	GR9
	Slightly higher	GR4	GR4	GR6	GR7	GR8	GR9	GR9
	Higher	GR4	GR4	GR6	GR8	GR8	GR9	GR9
	Much higher	GR4	GR4	GR6	GR8	GR9	GR9	GR9
	High	GR4	GR4	GR6	GR8	GR9	GR9	GR9
4—Chaparral	Low	SH5	SH6	SH6	SH6	SH6	SH6	SH6
	Slightly lower	SH5	GR8	SH6	SH6	SH6	SH6	SH6
	Comparable	SH6	GR8	GR8	GR8	GR8	SH9	SH9
	Slightly higher	SH7	SH7	GR8	GR8	GR8	GR8	GR8
	Higher	SH8	SH8	GR8	GR8	GR8	GR8	GR9
	Much higher	GR8	GR8	GR8	GR8	GR8	GR9	GR9
	High	GR8	GR8	GR8	GR8	GR9	GR9	GR9
5—Brush	Low	SH1	GR1	TU5	TU5	SH7	SH7	SH7
	Slightly lower	SH1	GR1	TU5	TU5	SH7	SH7	SH7
	Comparable	SH1	GS2	TU5	TU5	SH7	SH7	SH7
	Slightly higher	SH1	GS2	TU5	TU5	SH7	SH7	SH7
	Higher	SH1	GS2	TU5	TU5	SH7	SH7	SH7
	Much higher	SH2	GS2	TU5	SH5	SH5	SH5	SH5
	High	SH2	GS2	TU5	GR8	GR8	GR8	SH5
6—Dormant brush, hardwood slash	Low	SH2	SH2	SH4	SH4	SH6	SH6	SH6
	Slightly lower	SH2	SH2	SH4	SH4	SH6	SH6	SH6
	Comparable	SH2	SH2	SH4	SH4	SH6	SH6	SH9
	Slightly higher	SH2	SH2	SH4	SH4	SH6	SH9	SH9
	Higher	SH2	SH4	SH4	SH6	SH6	SH9	SH5
	Much higher	SH2	SH4	SH4	SH6	SH5	SH5	SH5
	High	SH2	SH4	SH4	SH5	SH5	SH5	GR8
7—Southern rough	Low	SH3	SH3	SH4	SH4	SH7	SH9	SH9
	Slightly lower	SH3	SH3	SH4	SH4	SH7	SH9	SH9
	Comparable	SH3	SH3	SH4	SH4	SH7	SH9	SH9
	Slightly higher	SH3	SH3	SH4	SH4	SH7	SH9	SH9
	Higher	SH3	SH3	SH4	SH4	SH7	SH9	SH5
	Much higher	SH3	SH4	SH4	SH7	SH7	SH5	SH5
	High	SH3	SH4	SH4	SH7	SH9	SH5	GR8
8—Closed timber litter	Low	TL1	TL3	TL3	TL3	TL7	TL8	TL8
	Slightly lower	TL1	TL3	TL3	TL4	TL7	TL8	TL8
	Comparable	TL1	TL3	TL3	TL4	TL7	TL8	TL8
	Slightly higher	TL1	TL3	TL3	TL4	TL7	TL8	TL8
	Higher	TL1	TL3	TL3	TL4	TU1	TL6	TL8
	Much higher	TL3	TL3	TL3	TL4	TL5	TL6	TL8
	High	TL3	TL3	TL4	TL4	TL5	TL6	TL8

Table 12—Crosswalk matrix from original fire behavior prediction system (FBPS) fuel model assignment to standard fuel models (continued)

	Ratio of FCCS rate of spread to benchmark rate of spread[b]	Ratio of FCCS flame length to benchmark flame length						
Original FBPS fuel model[a]		Low	Slightly lower	Comparable	Slightly higher	Higher	Much higher	High
		Standard fuel model code[c]						
9—Hardwood (long-needle pine) litter	Low	TL2	TL3	TL5	TL8	TL9	TL9	TL9
	Slightly lower	TL3	TL3	TL6	TL8	TL9	TL9	TL9
	Comparable	TL3	TL3	TL6	TL8	TL9	TL9	TL9
	Slightly higher	TL3	TL3	TL6	TU2	TL9	TL9	TL9
	Higher	GR1	GR1	TL6	TU2	TU4	SH6	SH8
	Much higher	GR1	GR1	GR1	TU2	SH6	SH8	SH8
	High	GR1	GR1	GR1	GR2	SH6	SH8	SH8
10—Timber (litter and understory)	Low	TU1	TU1	TU2	TU5	TU5	TU5	TU5
	Slightly lower	TU1	TU1	TU2	TU5	TU5	TU5	TU5
	Comparable	TU1	TU2	TU2	TU5	TU5	TU5	TU5
	Slightly higher	TU1	TU2	TU4	TU5	TU5	TU5	TU5
	Higher	TU1	TU2	TU4	TU3	TU3	TU3	TU3
	Much higher	TU1	TU2	TU4	TU3	TU3	TU3	TU3
	High	TU2	TU2	TU4	TU3	TU3	TU3	TU3
11—Light slash	Low	TL5	TL5	SB1	SB1	SB2	SB2	SB2
	Slightly lower	TL5	TL5	SB1	SB1	SB2	SB2	SB2
	Comparable	TL5	TL5	SB1	SB1	SB2	SB2	SB2
	Slightly higher	TL5	TL5	SB1	SB1	SB2	SB2	SB2
	Higher	TL5	TL5	SB1	SB1	SB2	SB2	SB2
	Much higher	TL5	SB1	SB1	SB2	SB2	SB2	SB2
	High	TL5	SB1	SB2	SB2	SB2	SB2	SB2
12—Medium slash	Low	SB1	SB2	SB3	SB3	SB3	SB3	SB3
	Slightly lower	SB1	SB2	SB3	SB3	SB3	SB3	SB3
	Comparable	SB1	SB2	SB3	SB3	SB3	SB3	SB3
	Slightly higher	SB1	SB2	SB3	SB3	SB3	SB3	SB3
	Higher	SB2	SB2	SB3	SB3	SB3	SB3	SB3
	Much higher	SB2	SB2	SB3	SB3	SB3	SB3	SB3
	High	SB2	SB3	SB3	SB3	SB3	SB3	SB3
13—Heavy slash	Low	SB2	SB2	SB3	SB3	SB3	SB4	SB4
	Slightly lower	SB2	SB2	SB3	SB3	SB3	SB4	SB4
	Comparable	SB2	SB2	SB3	SB3	SB3	SB4	SB4
	Slightly higher	SB2	SB2	SB3	SB3	SB3	SB4	SB4
	Higher	SB2	SB2	SB3	SB3	SB3	SB4	SB4
	Much higher	SB2	SB2	SB3	SB3	SB3	SB4	SB4
	High	SB2	SB3	SB3	SB3	SB4	SB4	SB4

Note: FCCS = Fuel Characteristic Classification System.
[a] Anderson (1982).
[b] Scott and Burgan (2005).
[c] Adjective classes are defined in table 11.

FCCS Fire Potentials

The FCCS fire potentials are a set of relative values that rate the intrinsic properties of a wildland fuelbed, including its potential for surface fire behavior, crown fire behavior, and available fuel for consumption under a benchmark set of windspeed and fuel moisture conditions (90 percent foliar moisture of shrubs; 60 percent foliar moisture of herbaceous fuels; 6 percent fuel moisture of 1-hr, 7 percent fuel moisture of 10-hr, and 8 percent fuel moisture of 100-hr woody fuels; no slope, 4 mph windspeed) (Sandberg et al. 2007a). They are intended for use in mapping fire hazard, categorizing fuelbeds on the basis of predicted fire behavior, and communicating degree of fire hazard. They can also be used in conjunction with known environmental conditions to predict fire behavior and effects (i.e., scaled downward to reflect fuel moisture conditions, or scaled upward to represent windspeed or slope). The FCCS potentials calculator reports nine FCCS fire potentials for each fuelbed arranged into three summary FCCS fire potentials (fig. 2).

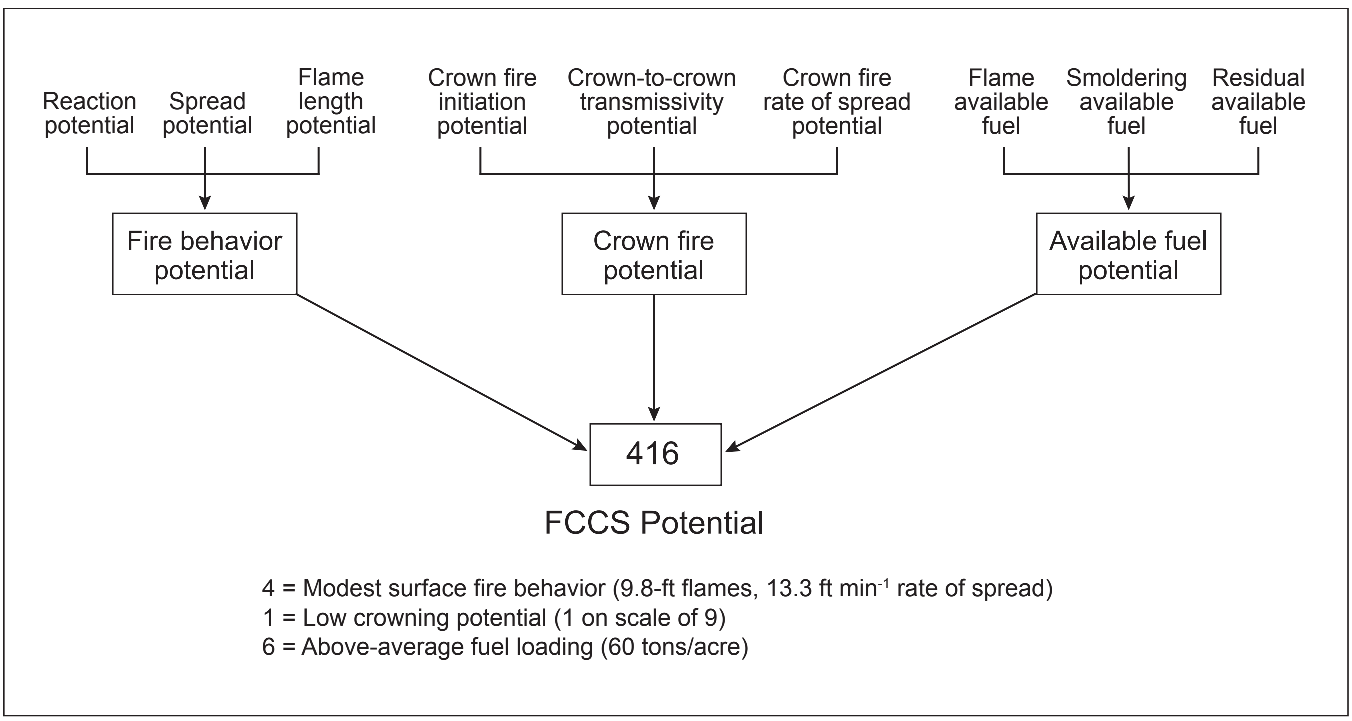

Figure 2—Diagram of Fuel Characteristic Classification System (FCCS) potential.

The FCCS fire potentials are organized in three categories:

Surface fire behavior summary potential (SFP; dimensionless)—
Surface fire behavior potential is calculated as the maximum of the FL and R potentials, scaled to values of 0 to 9 (dimensionless). The three components of FBP are:

- ***Reaction potential*** **(RP) (eq. 39)**—Represents the reaction intensity (energy release per unit area per unit time) under dry fuel conditions, scaled to an index value.
- ***Spread potential*** **(SP) (eq. 40)**—Is proportional to the R (distance per unit time at benchmark environmental conditions) in surface fuels.
- ***Flame length potential*** **(FP) (eq. 41)—**Provides a measure of predicted FL (in feet, at benchmark environmental conditions) proportional to fireline intensity or FL.

Crown fire summary potential (CFP; dimensionless)—
Crown fire summary potential derives from application of the FCCS crown fire model described by Schaaf et al. (2007), which uses concepts and algorithms from Van Wagner (1977), Alexander (1988), Scott and Reinhardt (2001), and Sandberg et al. (2007b). Crown fire potential is scaled from 0 to 9 (dimensionless) and is calculated as three subpotentials:

- ***Crown fire initiation*** **(IC; dimensionless)**—Is the ratio of surface fireline intensity to critical fireline intensity (eq. 43). Represents the likelihood that a surface fire will propagate into a crown fire.
- ***Crown-to-crown transmissivity*** **(TC; dimensionless)**—Represents the potential for fire to carry through a forest canopy (eq. 49).
- ***Crown fire rate of spread*** **(RC; dimensionless)**—Is a relative index of crown fire spreading potential (eq. 54).

Available fuel summary potential (AFP; dimensionless)—
Available fuel potential estimates the mass of fuel present within the outside shell of layers of canopy, surface, and ground fuel elements that are potentially combustible under dry conditions in the flaming, smoldering, and residual smoldering phases of combustion. The summary index and subpotentials are expressed in units of 10 tons/ac. The summary index is confined to 0 to 9, but subpotentials can exceed 9 to represent actual available loading values. Depths of woody fuel shell (½ in, 2 in, and 4 in) involved in each combustion phase were estimated from fuel consumption models within Consume (Prichard et al. 2007).

- ***Flame available fuel*** **(FA; 10 tons/ac)**—Is the sum of mass within ½ in of the surface of the fuel element available for the flaming stage of combustion. This variable is the sum of three subcomponents:

    - ***Flame-reactive surface available fuel* (FAR)**—Is the mass of fuel consumed in the flaming front of a spreading surface fire. FAR contributes to forward energy transfer and is the mass of thermally thin fuel elements plus a thin skin of larger fuel elements with a thickness that represents the depth of the pyrolysis zone. The surface fuel includes shrub crowns, herb, woody fuels, and LLM strata.
    - ***Flame-available postreactive surface fuels* (FAP)**—Is the remainder of flame-available surface fuel after the passage of the flaming front. This variable represents the flaming consumption that occurs behind the flaming front and does not contribute to FL or propagating flux.
    - ***Flame-available canopy fuel* (FAC)**—I s the mass of tree canopy and fine twigs.
- ***Smoldering available fuel* (SA; 10 tons/ac)**—Is the sum of mass between ½ and 2 in of a fuel surface.
- ***Residual available fuel* (RA; 10 tons/ac)**—Is the sum of mass between 2 and 4 in of a fuel surface.

Surface Fire Potentials

FCCS calculates the summary surface fire behavior summary potential (SFP) as the maximum of the spread potential and FL potential, scaled to values of 0 to 9. This summary potential value does not include reaction potential. The surface fire behavior potential is calculated as:

$$SFP = \min[9, \max(SP, FP)] \tag{38}$$

where
SP = spread potential (eq. 39) and
FP = flame length potential (eq. 40).

Spread potential (SP; dimensionless)—
Spread potential is proportional to the R (ft/min) in surface fuels at benchmark environmental conditions. Rate of spread is a function of reaction intensity, propagating energy flux, and heat sink provided by unburned fuels in advance of the spreading flame.

$$SP = \min\left[9, \left(N_{SP} R\right)\right] \tag{39}$$

where
N_{SP} = scaling factor = $2\sqrt{R}$) (dimensionless) and
R = surface rate of spread (ft/min) (eq. 25).

Flame length potential (FP; dimensionless)—

Flame length potential is a scaled measure of predicted FL (ft) at benchmark environmental conditions.

$$FP = N_{FP} FL \tag{40}$$

where

N_{FP} = scaling factor = $2\sqrt{FL}$), and

FL = flame length (ft) (eq. 33).

Reaction potential (RP; dimensionless)—

Reaction potential represents reaction intensity, expressed as energy release per unit area and time at benchmark environmental conditions, and is a function of volume of fuels per unit of ground surface, depth of the surface fuelbed strata, heat of combustion, damping coefficients due to moisture and mineral content, and a scaling factor. Although RP is included as a subpotential, it is not used in the calculation of the surface fire behavior summary potential. Reaction potential is the reaction intensity (Btu/ft^2/min) times a scaling factor.

$$RP = N_{RP}(I_R) \tag{41}$$

where

N_{RP} = reaction potential scaling factor = $0.08\sqrt{I_R}$) (dimensionless) and

I_R = reaction intensity (Btu/ft^2/min) (eq. 16).

Crown Fire Potentials

The FCCS crown fire potentials (CFP) include crown fire initiation, crown-to-crown transmissivity, and crown fire rate of spread. They are calculated within the FCCS CFP calculator. The FCCS CFP build on predictions in FCCS 2.2 that incorporate equations published by Schaaf et al. (2007). The FCCS crown fire modeling framework is theoretical and would require further scientific development and verification to provide actual predictions of crown fire intensity and RP. The FCCS currently ranks the relative potential for crown fire initiation and spread on as indexed values between 0 and 9 under default windspeed and fuel moisture conditions (Sandberg et al. 2007a). Crown fire initiation and spread depends on a widely varying combination of fuels, weather, and topographic conditions (Cruz et al. 2006, Cruz and Alexander 2010). Important predictors of crown fire initiation and spread include surface fire intensity, canopy closure, crown density, presence of ladder fuels, and crown base height (Schaaf et al. 2007).

Crown fire summary potential (CFP; dimensionless)—

The crown fire summary potential scales the three subpotentials to an index value between 0 and 9. It places more emphasis on crown fire initiation and rate of spread than crown-to-crown transmissivity (Schaaf et al. 2007).

$$\mathrm{CFP} = 0.4286\left(\mathrm{IC} + \frac{\mathrm{TC}}{3} + \mathrm{RC}\right) \tag{42}$$

where

0.4286 = scaling factor to limit CFP between 0 and 9 (dimensionless),

IC = crown fire initiation potential (dimensionless) (eq. 43),

TC = crown-to-crown transmissivity potential (dimensionless) (eq. 49), and

RC = crown fire rate of spread potential (dimensionless) (eq. 53).

Crown fire initiation potential (IC; dimensionless)—

The FCCS crown fire initiation potential represents the likelihood of a surface fire torching into single or multiple trees. If there are no flammable species in the overstory or understory, crown fire initiation is assumed to be zero.

$$\begin{gathered}\text{If } \mathrm{FAI}_{\mathrm{FlammUC}} = 0\text{, then IC} = 0\\ \text{Else, IC} = \min\left[9,\ \left(4\left(\mathrm{IC_q}^{0.2}\right)\right)\right]\end{gathered} \tag{43}$$

where

$\mathrm{FAI}_{\mathrm{FlammUC}}$ = FAI (eq. 2) of flammable upper canopy subcategories, including overstory and midstory trees and class 1 snags with-foliage. Flammable species are defined as those that contribute energy to the fire. Neutral species, including many broadleaf deciduous trees, are assumed to not contribute to the flammable canopy,

9 = maximum allowable value for IC index,

4 = scaling factor (dimensionless),

$\mathrm{IC_q}$ = crown fire initiation quotient (dimensionless), and

0.2 = scaling factor (dimensionless).

Crown fire initiation quotient ($\mathbf{IC_q}$; dimensionless)—

Ratio of surface fireline intensity to critical fireline intensity.

$$\mathrm{IC_q} = \frac{\mathrm{I_S}}{\mathrm{I'}} \tag{44}$$

where

$\mathrm{I_S}$ = surface fireline intensity (Btu/ft^2/min) (eq. 45) and

I' = critical fireline intensity (Btu/ft^2/min) (eq. 46).

***Surface fireline intensity* (I_S; Btu/ft/sec)**—Numerator term in the crown fire initiation quotient (eq. 44). Surface fireline intensity is the product of surface reaction intensity, flame residence time, and R:

$$I_S = I_R \, t_R \frac{R}{60} \tag{45}$$

where
I_R = surface reaction intensity (Btu/ft^2/min) (eq. 16),
t_R = flame residence time (min) (eq. 34),
R = surface fire R (ft/min) (eq. 25), and
60 = unit conversion (s/min).

***Critical fireline intensity* (I'; Btu/ft/sec)**—Denominator term in the crown fire initiation quotient (eq. 44). Critical fireline intensity is the intensity required for a surface fire to transition into a crown fire (Scott and Reinhardt 2001).

$$I' = \frac{\left(FM_{CAdj} \;\; Gap_{Canopy}\right)^{\frac{3}{2}}}{1718.2} \tag{46}$$

where
FM_{CAdj} = adjusted canopy fuel moisture (percentage) (eq. 47),
Gap_{Canopy} = canopy gap (ft) (eq. 48),
3/2 = assumed power-law vertical rate of temperature decrease in convective plume (Schaaf et al. 2007) (dimensionless), and
1718.2 = unit conversion (kJ/m/sec to BTU/ft/sec).

***Adjusted canopy fuel moisture* (FM_{CAdj}; percentage)**—Used in the critical fireline intensity equation (eq. 46) and calculated as:

$$FM_{CAdj} = 460 + \left(25.9 \frac{FM_C}{100}\right) \tag{47}$$

where
460 = empirical constant in Van Wagner’s (1977) adjustment of energy required for canopy ignition (dimensionless),
25.9 = empirical slope of Van Wagner’s (1977) adjustment of energy required for canopy ignition (dimensionless), and
FM_C = input canopy fuel moisture (default = 90 percent).

Canopy gap **(Gap_{Canopy}; ft)**—Used in the critical fireline intensity equation (eq. 46), canopy gap is a function of the gap between surface and canopy fuels and an assigned ladder fuel rating (table 13). Individual gap terms are calculated for the upper canopy (overstory and midstory trees) and understory trees. A decision rule is employed to determine whether canopy gap equals the overstory gap or understory gap term, such that:

$$\text{If } Gap_{Intermediate} < \left(2.5\,\frac{FAI_{Understory}}{3\pi}\right)\text{, then } Gap_{Canopy} = \max\left[1, \min\left(Gap_{UC}, Gap_{Understory}\right)\right] \quad (48)$$

$$\text{Else } Gap_{Canopy} = Gap_{UC}$$

where

$Gap_{Intermediate}$ = intermediate gap term (ft) (eq. 48a),

2.5 = hypothetical threshold of the vertical gap to FAI ratio that determines whether the understory acts as an effective ladder fuel to the overstory,

$FAI_{Understory}$ = Fuel area index of understory trees (dimensionless) (eq. 2),

Gap_{UC} = upper canopy gap term (ft) (eq. 48), and

$Gap_{Understory}$ = understory tree gap term (ft) (eq. 48b).

Intermediate gap term **($Gap_{Intermediate}$; ft)**—Estimated as the difference between the height to live crown of overstory and midstory trees and the maximum height of understory trees, shrubs or the effective surface depth.

$$Gap_{Intermediate} = \min\left[0, \left(\frac{HLC_{UC} - \max\left(Height_{Understory}, \delta_{Shrub}, Eff\,\delta_{surf}\right)}{LadderFuelRating + 1}\right)\right] \quad (48a)$$

where

HLC_{UC} = minimum height to live crown of overstory and midstory trees and height to crown base of class 1 snags with foliage (ft),

$Height_{Understory}$ = height of understory trees (ft),

δ_{Shrub} = depth of shrub stratum (ft),

$Eff\delta_{Surf}$ = effective depth of surface fuels (ft) (eq. 20), and

LadderFuelRating = inferred by ladder fuel type (dimensionless) (table 13).

Individual canopy gap terms **(Gap_m; ft)**—Upper canopy and understory gap terms are calculated by tree subcategory:

$$Gap_m = \min\left[0, \left(\frac{HLC_{min} - \max\left(\delta_{Shrub}, Eff\,\delta_{surf}\right)}{LadderFuelRating + 1}\right)\right] \quad (48b)$$

where

m = subscript reference to upper canopy and understory trees,

HLC_{min} = minimum height to live crown of overstory, midstory trees, and height to crown base of Class 1 snags for the upper canopy; input height to live crown for the understory (ft),

δ_{Shrub} = depth of shrub stratum (ft),

$Eff\delta_{Surf}$ = effective depth of surface fuels (ft) (eq. 20), and

LadderFuelRating = inferred by ladder fuel type (dimensionless) (table 13).

Table 13—Ladder fuel rating by type

	Rating	
Type	**Box unchecked**[a]	**Box checked**
Arboreal lichen	1	3
Dead branches	0	2
Climbing ferns/other epiphytes	0	2
Stringy or fuzzy bark	1	3
Vines-liana	0	2
Leaning snags	0	2
Tree regeneration	1	3

[a] If the "Is there vertical continuity between the canopy and lower strata?" box is checked, ladder fuel rating are rated higher than if there is no vertical continuity between surface and crown fuels.

Crown-to-crown transmissivity potential (TC; dimensionless)—
Crown-to-crown transmissivity is an index of the relative likelihood of a crown fire to spread horizontally through the canopy. If the fuel area index of the flammable canopy is less than a threshold FAI, transmissivity is assumed to be zero. Otherwise, it is a function of canopy cover and windspeed. Windspeed is included here as a placeholder for future versions where input windspeed may modify CFPs.

$$TC = \left\{ \begin{array}{c} \text{If } FAI_{UC} < \dfrac{TFAI}{3\pi}, \text{ then } TC = 0 \\ \text{Else } TC = \min[9,(10TC_q)] \end{array} \right\} \quad (49)$$

where

FAI_{UC} = fuel area index (eq. 2) of the flammable upper canopy subcategories, including overstory and midstory trees and class 1 snags with foliage (dimensionless),

TFAI = threshold FAI value (eq. 50),

3π = hypothesized lowest threshold TFAI that will support crown-to-crown fire spread (dimensionless),

10 = scaling factor (dimensionless), and

TC_q = efficiency of crown-to-crown heat transfer as a proportion of efficiency when canopy cover is 100 percent (eq. 51).

Threshold FAI **(TFAI; dimensionless)**—Used to determine whether crown-to-crown transmissivity (eq. 49) is zero or is equal to the TC quotient (eq. 51).

$$TFAI = Ae^{-0.0019U} \tag{50}$$

where

A = 2.6296 if $\sigma_{UC} \leq$ 2,000 (ft^2/ft^3) and 3.2868 if σ_{UC} >2,000 (ft^2/ft^3),

σ_{UC} = surface-area-to-volume ratio of upper canopy (overstory trees, midstory trees, and class 1 snags with foliage),

-0.0019 = coefficient describing the reduction in threshold FAI at higher windspeeds after Schaaf et al. (2007), and

U = input midflame windspeed converted to ft/min.

TC_q **(dimensionless)**—Used in calculating transmissivity potential (eq. 48). TC_q estimates the efficiency of crown-to-crown heat transfer as a proportion of maximum efficiency at 100 percent canopy cover.

$$TC_q = \frac{\max\left[0,(Cov_C WAF - 40)^{0.3}\right]}{(100WAF - 40)^{0.3}} \tag{51}$$

where

Cov_C = input total canopy cover (percentage),

WAF = canopy windspeed adjustment factor, set to 1 for the benchmark windspeed of 4 mph (ft/min) (eq. 52),

40 = threshold canopy cover to initiate dependent crown spread (percentage), and

0.3 = coefficient describing the assumed effect of crown cover on transmissivity at benchmark windspeed.

Canopy windspeed adjustment factor **(WAF; dimensionless)**—The canopy windspeed adjustment factor increases or decreases effective canopy cover depending on whether input midflame windspeeds are higher or lower than the benchmark windspeed. Currently, this value is set to 1 because a default windspeed of 4 mph is used. It is calculated as a function of input windspeed, vertical stack velocity, and benchmark windspeed, such that:

$$WAF = \frac{U/\sqrt{U^2+VS^2}}{BMU/\sqrt{BMU^2+VS^2}} \tag{52}$$

where

U = input windspeed (352 ft/min),

VS = vertical stack velocity (900 ft/min), and

BMU = benchmark midflame windspeed (352 ft/min).

Crown fire rate of spread potential (RC; dimensionless)—
Index of the crown fire R. With little available empirical data, crown fire behavior is difficult to model, and actual Rs currently are not possible to predict. The potential index is calculated as:

$$RC = \min\left[9, \left(2.5R_C^{\frac{1}{e}}\right)\right] \tag{53}$$

where
2.5 = scaling factor and
R_C = crown fire R ratio (eq. 54).

***Crown fire rate of spread* (R$_C$; dimensionless)**—The ratio of canopy heat source to canopy heat sink:

$$R_C = \frac{HeatSource_C}{HeatSink_C} = \frac{(I_R + I_{R\,C})\ \xi_C WAF}{q_C} \tag{54}$$

where
I_R = surface fire reaction intensity (Btu/ft^2/min) (eq. 16),
$I_{R\,C}$ = crown fire reaction intensity (Btu/ft^2/min) (eq. 55),
ξ_C = canopy propagating flux ratio (dimensionless) (eq. 58),
WAF = canopy windspeed adjustment factor, set to 1 for the 4 mph benchmark windspeed (dimensionless) (eq. 52), and
q_C = canopy heat sink (Btu/ft^3) (eq. 59).

***Crown fire reaction intensity* (I$_{R.C}$; Btu/ft^2/min)**—Analogous to surface fire reaction intensity (eq. 16) and is calculated as:

$$I_{RC} = \eta_{\beta'_{UC}} \sum_{j=4}^{4} \max\Gamma'\ \eta_K\ W_{oj}\ h_{Adj} \tag{55}$$

where
j = subscript reference to overstory trees, midstory trees, understory trees, and class 1 snags with foliage,
$\eta_{\beta'\,UC}$ = upper canopy reaction efficiency (dimensionless) (eq. 56),
$\max\Gamma'$ = maximum reaction velocity of canopy fuels (15/min),
η_K = mineral damping coefficient, which reduces reaction velocity (0.42; dimensionless),
$W_{o\,j}$ = Fuel loading of flammable trees (overstory, midstory, and understory) and class 1 snags with foliage (lb/ft^2), and
$h_{Adj\,j}$ = Low fuel canopy heat content adjusted for fuel moisture content (Btu/lb) (eq. 57). Because only one crown fuel moisture is input, this value will always be the same for all tree layers.

Reaction efficiency, upper canopy **($\eta_{\beta' UC}$; dimensionless)**—Modifies crown fire reaction intensity (eq. 55). Reaction efficiency represents the damping effect of inefficiently packed fuels in the upper canopy.

$$\eta_{\beta'_{UC}} = \beta'_{UC} e^{1-\beta'_{UC}} \tag{56}$$

where

β'_{UC} = relative packing ratio (dimensionless) (eq. 56a).

Relative packing ratio, upper canopy **(β'_{UC}; dimensionless)**—Calculated as the ratio of optimum depth to mean depth of the upper canopy. This is equivalent to the proportion of canopy space that is occupied relative to the optimum packing ratio.

$$\beta'_{UC} = \frac{\delta_{opt\ UC}}{\delta_{UC}} \tag{56a}$$

where

$\delta_{opt\ UC}$ = optimum depth of the upper canopy (ft) (eq. 56b) and

δ_{UC} = depth of the upper canopy, calculated as the maximum height minus the minimum height to live crown of the overstory, midstory tree layers, and class 1 snags with foliage (ft).

Optimum depth, upper canopy **($\delta_{opt.UC}$; ft)**—The canopy depth that would result in the maximum reaction velocity, assuming that canopy fuels behave similarly to surface fuels and have the same optimum air volume (eq. 19b).

$$\delta_{opt\ UC} = [0.4FAI_{UC}] + \left[\beta_C \left(\frac{ACV_{UC}}{43{,}560}\right)\right] \tag{56b}$$

where

0.4 = optimum spacing between canopy fuels (ft),

FAI_{UC} = fuel area index of the flammable upper canopy layers (defined eq. 43),

β_C = packing ratio of the upper canopy stratum, including overstory and midstory trees and class 1 snags with foliage (eq. 3),

ACV_{UC} = bulk crown volume of overstory and midstory tree layers and class 1 snags with foliage, adjusted for species relative cover and crown shape factor (ft^3/ac) (eq. 5a), and

43,560 = conversion factor to ft (ft^2/ac).

Low fuel heat content, upper canopy **(h_{Adj}; Btu/lb)**—Contributes to crown fire reaction intensity (eq. 55). Upper canopy heat content is adjusted for each tree subcategory based on input canopy fuel moisture and a constant latent heat of evaporation:

$$h_{Adj_j} = h_j - FM_C V \tag{57}$$

where
h = inferred low fuel heat content of each canopy layer (Btu/lb),
j = subscript reference to overstory, midstory, and understory tree layer subcategory,
FM_C = input tree crown fuel moisture; one input applies to all canopy tree layers (percentage), and
V = latent heat of vaporization (11.16) (Btu/lb).

Canopy propagating flux ratio **(ξ_C; dimensionless)**—Represents the proportion of the canopy reaction intensity that contributes to a crown fire's forward rate of spread (eq. 54).

$$\xi_C = 1 - e^{-\left(\frac{FAI_{UC}}{4\delta_{UC}}\right)} \tag{58}$$

where
FAI_{UC} = fuel area index of flammable upper canopy trees (eq. 43) (dimensionless),
4 = coefficient defining the rate of attenuation of radiant energy from fires in vegetative canopies (Butler et al. 2004), and
δ_{UC} = depth of the upper canopy, calculated as the maximum height minus the minimum height to live crown of the overstory, midstory tree layers, and class 1 snags with foliage (ft).

Canopy heat sink **(q_C; Btu/ft^3)**—Incorporates the component heat sinks of canopy branch wood, canopy foliage, and surface fuels.

$$q_C = q_{CanopyWood} + q_{CanopyFoliage} + q_{Surf} \tag{59}$$

where
$q_{CanopyWood}$ = heat sink of canopy branches (eq. 59a; Btu/ft^3),
$q_{CanopyFoliage}$ = heat sink of canopy foliage (eq. 59a; Btu/ft^3), and
q_{Surf} = heat sink of surface fuels (eq. 32; Btu/ft^3).

Individual heat sink terms **(q_j; Btu/ft^3)**—Canopy heat sink terms that comprise the total canopy heat sink (eq. 59).

$$q_j = \frac{0.5\ FAI_{UC}\ \varsigma_j\ \rho_p\ Qig_C}{\theta_C\ \delta_{UC}} \tag{59a}$$

where

j = subscript reference to canopy branch wood or foliage,

0.5 = division term to divide the upper canopy FAI into two equal components: canopy branch wood and foliage (dimensionless),

FAI_{UC} = fuel area index of the flammable upper canopy layers (eq. 43),

ς_j = ignition thickness of canopy branch wood or foliage, assumed to be equivalent to reaction thickness of herbaceous and woody surface fuels, respectively (eq. 35; ft).

ρ_p = default particle density (25 lb/ft^3),

Qig_C= canopy heat of ignition equaation 959b); Btu/lb),

θ_C = input canopy total percentage cover divided by 100, and

δ_{UC} = depth of the upper canopy, calculated as the maximum height minus the minimum height to live crown of the overstory, midstory tree layers, and class 1 snags with foliage (ft).

Canopy heat of ignition **(Qig_C; Btu/lb)**—The amount of heat required to ignite 1 lb of canopy fuel.

$$Qig_C = 250 + (V\ FM_C) \tag{59b}$$

where

250 = heat of ignition of dry cellulose (Btu/lb),

V = latent heat of vaporization (11.16) (Btu/lb), and

FM_C = input tree crown fuel moisture; one input applies to all canopy tree layers (percentage).

Canopy foliage ignition thickness **($\varsigma_{CFoliage}$; ft)**—Ignition thickness of the canopy foliage is the approximate thickness of a fuel element shell that contributes to the canopy heat sink (eq. 59a).

$$\varsigma_{CFoliage} = \min\left(0.0028, \frac{2}{\sigma_{CFoliage}}\right) \tag{59c}$$

where

0.0028 = assumed maximum ignition thickness (ft),

$2/\sigma$ = radius (or one-half the thickness) of the fuel element, and

$\sigma_{CFoliage}$ = average surface-area-to-volume ratio (ft^2/ft^3) of upper canopy foliage (overstory and midstory trees and class 1 snags with foliage) weighted by loading.

Available Fuel Potentials

Available fuel potentials are calculated in the FCCS AFP Calculator and approximate the combustible biomass under extremely dry moisture conditions in each of three phases of combustion (flaming, smoldering, and residual smoldering). They represent the upper limit of biomass consumption at extreme conditions, so act as an initial step for predicting biomass consumption, emissions, and related fire effects.

Available fuel potential (AFP; 10 tons/ac)—
By default, FCCS calculates AFP as the sum of the three component potentials. Available fuel potentials are scaled by 10 tons/ ac for convenient conversion to actual tons/ac. The AFP summary potential is capped at 9 (90 tons/ac), but no limits are placed on subpotentials so that actual fuel loads are represented. For example, a RA of 13 represents 130 tons/ac of fuel available for residual smoldering combustion.

$$\mathrm{AFP} = \min[9, (\mathrm{FA} + \mathrm{SA} + \mathrm{RA})] \tag{60}$$

where
FA = flame available fuel potential (10 tons/ac) (eq. 61),
SA = smolder available fuel potential (10 tons/ac) (eq. 62), and
RA = residual smolder available fuel potential (10 tons/ac) (eq. 63).

Flame available fuel potential (FA; 10 tons/ac)—
The sum of fuel loadings expected to be consumed in all flaming phases of fire (mass of fuels within ½ in of the surface of the fuel element). Class loadings (class w; tons/ac) are listed in table 14.

$$\mathrm{FA} = N_{FA} \sum_{i=1}^{3} \text{Class w 1, 2, 3} \tag{61}$$

where
N_{FA} = 0.1; scaling factor to confine range of available fuel potential to 0 to 10,
Class w1 = sum of canopy flame available fuel (class C) and reactive surface available fuel (Class R) (tons/ac),
Class w2 = components that may consume a portion in flames (tons/ac), and
Class w3 = components that may consume a shell to a constant depth in flames (tons/ac).

Smolder available fuel potential (SA; 10 tons/ac)—
The sum of fuel loadings expected to be consumed in the smoldering phase of a fire (mass of fuels between ½ and 2 in of a surface). Class loadings (class w; tons/ac) are listed in table 14.

$$SA = N_{SA} \sum_{i=1}^{2} \text{Class w } 4, 5 \qquad (62)$$

where
N_{SA} = 0.1; scaling factor to confine range of available fuel potential to 0-10,
Class w4 = components that may consume a shell to a constant depth in smoldering (tons/ac), and Class w5 = components that may consume a proportion in smoldering (tons/ac).

Table 14—Available fuel potential (AFP) calculations by fuel loading class[a]

Fuel loading class	Definition	Equation/list	Fuel consumed (y_i)[b]	Consumable carbon equation (C)
			Percentage	*Tons/ac*
Class 1	Components that may consume entirely in flames (lb/ft^2)	$W_{\text{Flammable overstory crown}}$	$y1_{\text{Canopy}}$	C = 0.5W (y/100)
		$W_{\text{Ladder fuels}}$	$y1_{\text{Canopy}}$	C = 0.5W (y/100)
		$W_{\text{Flammable understory crown}}$	$y1_{\text{Canopy}}$	C = 0.5W (y/100)
		$W_{\text{Needle drape}}$	$y1_{\text{Canopy}}$	C = 0.5W (y/100)
		$W_{\text{Flammable shrub crown}}$	$y2_{\text{Shrub}}$	C = 0.5W (y/100)
		$W_{\text{Neutral shrub crown}}$	$y2_{\text{Shrub}}$	C = 0.5W (y/100)
		$W_{\text{Live herb}}$	$y3_{\text{Herb}}$	C = 0.5W (y/100)
		$W_{\text{Dead herb}}$	$y4_{\text{1-hr}}$	C = 0.5W (y/100)
		$W_{\text{0–1/4 in sound wood}}$	$y4_{\text{1-hr}}$	C = 0.5W (y/100)
		$W_{\text{1/4–1 in sound wood}}$	$y5_{\text{10-hr}}$	C = 0.5W (y/100)
		$W_{\text{Flame LLM}}$ = min [W_{LLM}, max flame loading]	$y12_{\text{Litter}}$	C = 0.5W (y/100)
Class 2	Components that may consume a proportion in flames (lb/ft^2)	$W_{\text{100-hr < 1/2 in}} = 0.8\ W_{\text{1–3 in sound wood}}$	$y7_{\text{100 hr flame}}$	$C = \frac{0.5W\ (y/100)}{0.8}$
		$W_{\text{Live shrub stems < 3in}} = 0$	$y2_{\text{Shrubs}}$	C = 0.5W (y/100)
		$W_{\text{15\% rotten stump}}$	$y9_{\text{1000-hr}}$	C = 0.5W (y/100)
		$W_{\text{5\% class 2 and 3 snags}}$	$y9_{\text{1000-hr}}$	C = 0.5W (y/100)
		$W_{\text{35\% lightered stump}}$	$y12_{\text{Litter}}$	C = 0.5W (y/100)

Table 14—Available fuel potential (AFP) calculations by fuel loading class[a] (continued)

Fuel loading class	Definition	Equation/list	Fuel consumed (y_i)[b]	Consumable carbon equation (C)
			Percentage	*Tons/ac*
Class 3	Components that may consume a shell to a constant depth in flames (lb/ft^2)	$W_{1000\text{-hr} < ½\text{in}} = 25(FAI_{\text{Sound wood} > 3\text{ in}}{}^{c}/24)$	$y9_{1000\text{-hr flame}}$	$C = 0.5(W_{1000\text{-hr} < 1/2\text{ in}} + W_{1/2\text{ in} < 1000 < 2\text{ in}})$
		$W_{\text{Rotten} < 1\text{ in}} = 18.72(FAI_{\text{Rotten wood}}/12)$	$y5_{10\text{ hr}}$	$C = 0.4W\ (y/100)$
Class 4	Components that may consume a shell to a constant depth in smoldering (lb/ft^2)	$W_{1\text{ in} < \text{Rotten} < 2\text{ in}} = 18.72\text{ lb/ft}^3\ (FAI_{\text{Rotten wood}}/12)$	$y13_{\text{Duff}}$	$C = 0.4W\ (y/100)$
		$W_{\text{Duff} < 4\text{ in depth}}$	$y13_{\text{Duff}}$	$C = 0.4W\ (y/100)$
		$W_{1/2\text{in} < 1000 < 2\text{in}} = 24.96\text{ lb/ft}^3(FAI_{\text{Sound wood} > 3\text{in}}/24)$	$y11_{1000\text{-hr smolder}}$	$C = 0.5\ (W_{1000\text{-hr} < 1/2\text{ in}} + W_{½\text{ in} < 1000 < 2\text{ in}})\ (y/100)$
Class 5	Components that may consume a proportion in smoldering (lb/ft^2)	$W_{\text{Smolder LLM}} = \min(0, W_{\text{LLM}} - W_{\text{Flame LLM}})$	$y12_{\text{Litter}}$	$C = 0.5W\ (y/100)$
		$W_{100\text{-hr} > 1/2\text{ in}} = 0.2W_{1\text{–}3\text{ in Sound wood}}$	$y8_{100\text{ hr smolder}}$	$C = \dfrac{0.5W\ (y/100)}{0.2}$
		$W_{30\%\text{ Jackpot}}$	$y16_{\text{Piles}}$	$C = 0.5W\ (y/100)$
		$W_{30\%\text{ Piles}}$	$y16_{\text{Piles}}$	$C = 0.5W\ (y/100)$
Class 6	Components that may consume totally in residual smoldering (lb/ft^2)	$W_{\text{Squirrel middens}}$	$y14_{\text{residual duff}}$	$C = 0.5W\ (y/100)$
		$W_{\text{Basal accumulation}}$	$y15_{\text{residual rotten}}$	$C = 0.5W\ (y/100)$
Class 7	Components that may consume a proportion in residual smoldering (lb/ft^2)	$W_{20\%\text{ Jackpot}}$	$y15_{\text{residual rotten}}$	$C = 0.4W\ (y/100)$
		$W_{85\%\text{ Rotten stump}}$	$y15_{\text{residual rotten}}$	$C = 0.4W\ (y/100)$
		$W_{90\%\text{ class 2 and 3 snag}}$	$y15_{\text{residual rotten}}$	$C = 0.4W\ (y/100)$
		$W_{65\%\text{ lightered stump}}$	$y15_{\text{residual rotten}}$	$C = 0.4W\ (y/100)$
Class 8	Components that may consume a shell to a constant depth in residual smoldering "C = 0.4W" ("y"/"100") (lb/ft^2)	$W_{1000 > 2\text{ in}} = \max[0, (W_{\text{Sound wood} > 3\text{ in}} - W_{1000\text{-hr} < ½\text{ in}} - W_{1/2\text{ in} < 1000 < 2\text{ in}})]$	$y14_{\text{residual duff}}$	$C = 0.4W\ (y/100)$
		$W_{4\text{ in} < \text{Duff} < 12\text{ in}} = \max[0, (W_{\text{Duff}} - W_{\text{Duff} < 4\text{ in}})$ Maximum allowable value is 128,000 lb/ac	$y14_{\text{residual duff}}$	$C = 0.4W\ (y/100)$
		$W_{\text{Rotten} > 2\text{ in}} = \max[0, (W_{\text{Rotten wood}} - W_{1\text{–}2\text{ in Rotten}} - W_{\text{Rotten} < 1\text{ in}})]$	$y14_{\text{residual duff}}$	$C = 0.4W\ (y/100)$

[a] W = fuel loading (tons/ac), y = predicted fuel consumption (table 15).

[b] See table 15 for percentage of fuel consumed (y) equations.

[c] If depth > 4 in, then $W_{\text{Duff}>4} = \left(\dfrac{4}{\text{Depth}_{\text{Duff}}}\right) W_{\text{Duff}}$.

Residual smolder available fuel potential (RA; 10 tons/ac)—
The sum of fuel loadings expected to be consumed in the residual smoldering or "glowing" phase of a fire (mass of fuels between 2 and 4 in of a surface). Class loadings (class w, tons/ac) are listed in table 14.

$$RA = N_{RA} \sum_{i=1}^{2} \text{Class w 6, 7, 8} \qquad (63)$$

where

N_{RA} = 0.1; scaling factor to confine range of available fuel potential to 0 to 10,
Class w6 = components that may consume totally in residual smoldering (tons/ac),
Class w7 = components that may consume a proportion in residual smoldering (tons/ac), and
Class w8 = components that may consume a shell to a constant depth in residual smoldering (tons/ac).

Table 15—Combustible carbon equations

EquationID	Component	A	B	Ind Var	Benchmark fuel moisture (percent)	Equation form	Percentage consumed at benchmark moisture
y1	Canopy	260	-0.0185	CanopyFM	90	y = A[exp(B*IndVar)]	49
y2	Shrub	-0.731	107	ShrubFM	90	y = A(IndVar + B)	41
y3	Herbaceous	-.891	107	HerbFM	60	y = A(IndVar + B)	54
y4	1-hr	.00025	4	1hrFM	6	y = 100 – [A(IndVarB]	100
y5	10-hr	.160	2	10hrFM	7	y = 100 – [A(IndVarB)]	92
y6	100-hr (total)	-3.330	100	100hrFM	8	y = A(IndVar + B)	73
y7	100-hr (flame)			100hrFM	8	y = total - smolder	59
y8	100-hr (smolder)	.027	30	100hrFM	8	$y = A[(IndVar-B)^2]$	14
y9	1000-hr (total)	-1.800	74.4	1000hrFM	12	y = A(IndVar + B)	53
y10	1000-hr (flame)			1000hrFM	12	y = total - smolder	27
y11	1000-hr (smolder)	.022	41	1000hrFM	12	$y = A[(IndVar-B)^2]$	25
y12	Litter	.356	1.75	10hrFM	7	y = 100 – [A(IndVarB)]	89
y13	Duff	99.2	-.00572	DuffFM	50	y = A[exp(B*IndVar)]	75
y14	Residual duff	-.006	94	DuffFM	50	$y = A[(IndVar^2) + B]$	79
y15	residual rotten	-.000536	98	1000hrFM	150	$y = A[(IndVar^2) + B]$	86
y16	Piles	-.99	94	1000hrFM	12	y = A(IndVar + B)	82
y17	Slash (total)	-3	124	1000hrFM	12	y = A(IndVar + B)	88
y18	Slash (flame)	.036	41	1000hrFM	12	y = total – smolder	58
y19	Slash (smolder)	.036	41	1000hrFM	12	$y = A(IndVar - B)^2$	30

Fuel Consumption and Combustible Carbon

FCCS estimates biomass consumption for each available fuel category, expressed as a percentage of available fuel. The equations are approximate in that they each only include a single fuel moisture as an independent variable, neglecting the influence of fuel loading, fire behavior, wind, and the condition of other categories of fuel (table 15). They are only intended to provide a reasonable midrange estimate of consumption, emissions, carbon yield, and fire effects. For fuelbed-specific and project-specific estimates of fuel consumption, we recommend the use of CONSUME (Prichard et al. 2007) or other more complex algorithms.

Available fuel consumption, $w_{Consumed}$, (tons/ac) is estimated as:

$$w_{Consumed\ j} = 10\sum_{j=1}^{19}(y\ AFP)_j \qquad (64)$$

where

j = subscript reference to fuelbed category,

y_j = fuel consumed (percentage) by fuelbed category, from table 15, and

AFP_j = available fuel per fuelbed category (10 tons/ac).

Combustible carbon (carbon) (tons/ac) is estimated as:

$$C_{carbon} = c_j w_{Consumed} \qquad (65)$$

where

j = subscript reference to fuelbed category,

c_j = carbon mass fraction of biomass (dimensionless), normally assumed to equal 0.5 for all sound or living biomass and equal to 0.4 for all rotten and duff categories (Penman et al. 2003), and

$w_{Consumed\ j}$ = estimated fuel consumption by fuelbed category (tons/ac).

Future Model Development and Validation

To date, the FCCS surface fire behavior predictions have been compared to values obtained in BehavePlus for the 13 and 40 fire behavior fuel models. The FCCS predictions are within the range of fuel model predictions and reflect greater heterogeneity in fuelbed loadings and structure represented in fuelbeds as compared to fuel models (Sandberg et al. 2007a). The FCCS fire behavior predictions have not been validated against published fire behavior or in field-based trials. This is an important next step in model validation. Future development of the FCCS will include validating calculated canopy loading and surface fire behavior predictions with measured fire behavior in wildland fires.

Metric Equivalents

When you know:	Multiply by:	To find:
Inches (in)	2.54	Centimeters (cm)
Feet (ft)	.305	Meters (m)
Acres (ac)	.405	Hectares (ha)
Square feet (ft^2)	.0929	Square meters (m^2)
Cubic feet (ft^3)	.0283	Cubic meters (m^3)
Pounds (lb)	.454	Kilograms (kg)
Pounds per square feet (kg/m^2)	4.88	Kilograms per square meter (lb/ft^2)
Pounds per cubic feet (lb/ft^3)	16.0184	Kilograms per cubic meter (kg/ha)
Pounds per acre (lb/ac)	1.12	Kilograms per hectare (kg/ha)
Number per acre (number/ac)	2.471	Number per hectare (number/ha)
Feet per minute (ft/min)	.305	Meters per minute (m/min)
Miles per hour (mph)	1.609	Kilometers per hour (kph)
British thermal units (Btu)	1,050	Joules (J)
British thermal units per pound (Btu/lb)	2326	Joules per kilogram (J/kg)
British thermal units per square feet per minute ($Btu/ft^2/min$)	189.14	Joules per square meter per second ($J/m^2/s$)

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Appendix—Summary of Equations

Equation number	Variable	Abbreviation/ symbol	Source equation	Unit
1	Weighted average of inferred variables	y_k		
2	Fuel area index	FAI		Dimensionless
3	Packing ratio	β		Dimensionless
4	Depth	δ		ft or inch
5	Loading (tree crowns)	$w_{TreeCrown}$		tons/ac
5a	Adjusted crown volume (trees)	ACV_{Tree}	5	ft^3/ac
5b	Bulk crown volume	Y_{Tree}	5	ft^3/ac
6	Loading (aboveground trees)	w_{Tree}		tons/ac
7	Loading (class 1 snags with foliage crowns)	w_{SnagC1}		tons/ac
7a	Adjusted crown volume (class 1 snags with foliage)	ACV_{SnagC1}	7	ft^3/ac
7b	Bulk crown volume (class 1 snags with foliage)	Y_{SnagC1}	7	ft^3/ac
8	Loading (snag wood)	$w_{SnagWood}$		tons/ac
9	Loading (shrubs)	w_{Shrub}		tons/ac
9a	Loading (shrub crowns)	$w_{ShrubCrowns}$	9	tons/ac
10	Loading (stumps)	w_{Stump}		tons/ac
11	Loading (LLM)	w_{LLM}		tons/ac
12	Loading (duff)	w_{Duff}		tons/ac
13	Loading (basal accumulation)	w_{BA}		tons/ac
13a	Bulk volume (basal accumulation)	Y_{BA}	13	ft^3/ac
14	Loading (squirrel middens)	w_{SM}		tons/ac
14a	Bulk volume (squirrel middens)	Y_{SM}	14	ft^3/ac
15	Total carbon	C		tons/ac
16	Reaction intensity	I_R		$Btu/ft^2/min$
17	Reaction efficiency	$\eta_{\beta'}$	16	Dimensionless
18	Relative packing ratio	β'	17	Dimensionless
19	Optimum depth	δ_{opt}	18	ft
19a	Particle volume	PV	19	ft^3/ft^2
19b	Optimum air volume	OptAirVol	19	ft^3/ft^2
19c	Reactive volume	RV	19b	ft^3/ft^2
20	Effective depth	Effδ	18	ft
21	Rothermel's A	A	16	Dimensionless
22	Maximum reaction velocity	max Γ'	16	1/min
23	Heat content	h	16	Btu/lb
24	Moisture damping coefficient	η_M	16	Btu/lb
25	Rate of spread	R		ft/min
26	Wind/slope cap	WindSlopeCap	25	ft/min
27	Maximum rate of spread	R_{Max}	25	ft/min
28	Propagating flux ratio (surface)	ξ_{Surf}	27	Dimensionless
28a	Propagating flux ratio (LLM)	ξ_{LLM}	27	Dimensionless
29	Depth of surface heat sink	$\delta_{SurfHeatSink}$	28	ft
30	Wind coefficient	φ_W	27	Dimensionless
30a	Exponential flash term	E	30	Dimensionless

Equation number	Variable	Abbreviation/ symbol	Source equation	Unit
31	Slope coefficient	φ_S	27	Dimensionless
32	Heat sink	q_{Surf}	27	Btu/ft^3
32a	Heat of ignition	Qig	32	Btu/lb
32b	Heat of ignition by component	Qig_j	32	Btu/lb
33	Flame length	FL		ft
34	Flame residence time	t_R	33	min
35	Reaction thickness	RT	34	ft
36	Flame length fuel model crosswalk	$FuelModel_{FL}$		Dimensionless
37	Rate of spread fuel model crosswalk	$FuelModel_R$		Dimensionless
38	Surface fire behavior potential	SFP		Index (0–9)
39	Reaction potential	RP		Index (0–9)
40	Spread potential	SP		Index (0–9)
41	Flame length potential	FP		Index (0–9)
42	Crown fire summary potential	CFP		Index (0–9)
43	Crown fire initiation potential	ICP		Index (0–9)
44	Crown fire initiation quotient	Ic	43	Dimensionless
45	Surface fireline intensity	Is	44	Btu/ft^2/min
46	Critical fireline intensity	I'	44	Btu/ft^2/min
47	Adjusted canopy fuel moisture	FM_{CAdj}	46	Percentage
48	Canopy gap	Gap_{Canopy}	46	ft
48a	Intermediate gap term	$Gap_{Intermediate}$	48	ft
48b	Individual canopy gap terms	Gap	48	ft
49	Crown-to-crown transmissivity potential	TCP		Index (0–9)
50	Threshold FAI	TFAI	49	Dimensionless
51	Tc quotient	TcQuotient	49	Dimensionless
52	Canopy wind speed adjustment factor	WAF	51	Dimensionless
53	Crown fire rate of spread potential	RCP		Dimensionless
54	Crown fire rate of spread	R_C	53	ft/min
55	Crown fire reaction intensity	$I_{R.C}$	54	Btu/ft^2/min
56	Reaction efficiency, upper canopy	$\eta_{\beta'UC}$	55	Dimensionless
56a	Relative packing ratio, upper canopy	β'_{UC}	56	Dimensionless
56b	Optimum depth, upper canopy	$\delta_{opt.UC}$	56a	ft
57	Low fuel heat content, upper canopy	h_{Adj}	55	Btu/lb
58	Canopy propagating flux ratio	ξ_C	54	Dimensionless
59	Canopy heat sink	q_C	54	Btu/ft^3
59a	Individual canopy heat sink terms	q	59	Btu/ft^3
59b	Canopy heat of ignition	Qig_C	59	Btu/lb
59c	Canopy foliage ignition thickness	$\varsigma_{CFoliage}$	59a	ft
60	Available fuel summary potential	AFP		10 tons/ac
61	Flame available fuel potential	FA	60	10 tons/ac
62	Smolder available fuel potential	SA	60	10 tons/ac
63	Residual smolder available fuel potential	RA	60	10 tons/ac
64	Available fuel consumption	$w_{Consumed}$		tons/ac
65	Combustible carbon	C_{Carbon}		tons/ac

Glossary

Definitions taken directly from the National Wildfire Coordinating Group (2012) glossary of wildland fire terms are noted with an asterisk (*).

Adjusted crown volume—The volume of the overstory and midstory tree crowns and class 1 snag crown foliage that is flammable.

Available fuel potential—The relative value of combustible biomass under oven-dry moisture conditions during the flaming, smoldering, and residual phases of combustion, calculated as a multiple of the total fuel loading of all fuel elements within a set depth from the surface of the fuel component.

Basal accumulation—Needles, twigs, bark pieces, litter, and duff that accumulate and form over time at the base of trees, creating a deeper organic layer than exists in the surrounding area.

Broadleaf—A conventional term applied to trees and shrubs of the flowering plant class Angiospermae, in contrast to the class Gymnospermae, which generally includes needle-leaved and cone-bearing plants.

Broadleaf forest—A forest dominated by deciduous trees with a percentage canopy cover of greater than 60 percent and height exceeding 6 ft.

***Btu (British thermal unit)**—Amount of heat required to raise 1 lb of water 1 °F (from 59.5 to 60.5 °F), measured at standard atmospheric pressure.

Bulk density—The weight per unit volume of wood or foliage that includes the bulk air space between individual pieces of wood or foliage (lb/ft^3).

Canopy cover—The proportion of area covered by a vertical projection of the outermost perimeter of the natural spread of trees, including small openings within the canopy.

Canopy reaction efficiency—The reaction intensity (energy release per unit area per unit time) from the canopy fuels expressed as the ratio to the optimum reaction intensity (<1).

Canopy stratum—The fuel layer in the FCCS that characterizes fuels in the tree, snag, and ladder fuel categories.

Category—Each stratum is divided into at least two categories. For example, the canopy stratum has tree, snag, and ladder fuel categories, and the shrub stratum has a primary and secondary layer. Many categories in FCCS are further divided into subcategories.

Combustion—The process of burning. Fuel combustion consists of three phases in the FCCS: flaming, smoldering and residual smoldering.

Conifer forest—A forest dominated by needle-leaf trees with a percentage canopy cover of greater than 60 percent and height exceeding 6 ft.

Critical fireline intensity—The intensity required for a surface fire to transition into a crown fire (Scott and Reinhardt 2001).

Crown—The part of a tree or woody plant bearing live branches and foliage.

Crown bulk density—The density of the tree crowns including the bulk air space between branches and foliage (lb/ft^3).

***Crown fire**—A fire that advances from top to top of trees or shrubs more or less independent of a surface fire. Crown fires are sometimes classed as running or dependent to distinguish the degree of independence from the surface fire.

Crown fire potential—The three crown fire potentials include crown fire initiation, crown-to-crown transmissivity, and crown fire rate of spread. The FCCS crown fire summary potential scales the three subpotentials to an index value between 0 and 9. It places more emphasis on crown fire initiation and rate of spread than crown-to-crown transmissivity.

Crown packing ratio—Packing ratio (β) of tree crowns by species; defined as the fraction of crown volume occupied by fuel, including needles and fine branches.

Crown shape factor—A geometrical adjustment factor used to differentiate crown shapes of coniferous and broadleaf trees in volume and loading calculations.

Decay class—A class of wood decay from recently killed trees (decay class 1) to highly decomposed wood (decay class 3).

Density—Amount per unit area. For example, the number of trees per acre.

Depth—The vertical extent of a fuel layer. For example, the depth of duff or downed woody fuels.

Diameter at breast height (d.b.h.)—A standard measurement of tree diameter 4.5 feet above the average ground level.

Downed woody fuel—Dead, woody fuel that has fallen on the ground.

Duff—The partially decomposed organic material above mineral soil that lies beneath freshly fallen twigs, needles, and leaves. Sometimes referred to as F (fermentation) and H (humus) layers.

Duff derivation—The parent material from which duff was derived. Examples of the parent material include needles, leaves, moss, bark flakes, or woody debris.

Evergreen—Plants that remain green all year by retaining at least some of their leaves at all times.

FCCS—Fuel characteristic classification system. A catalog of inherent physical properties of wildland fuelbeds and associated calculations of fuel characteristics and fire potentials.

FCCS fire potential—A set of relative values that rate the intrinsic physical capacity of any wildland fuelbed to release energy, spread, crown, consume, and smolder under benchmark dry fuel conditions, 4 mph midflame windspeeds and flat ground. These potentials are calculated from the loading, heat content, bulk density, and characteristic thickness of fuel elements without varying moisture content or environmental conditions.

***Fire behavior**—The manner in which a fire reacts to the influences of fuel, weather, and topography.

Fire behavior fuel model—The formulation of fuelbed inputs into fuel models that allow realistic estimation of fire behavior.

Flame available fuel—Fuel available for consumption during the flaming combustion phase.

***Flame length**—The distance between the flame tip and the midpoint of the flame depth at the base of the flame. An indicator of fire intensity.

Flame length potential—The potential flame length of a fuelbed. Proportional to fireline intensity or flame length.

***Flaming combustion**—Phase of a fire in which the fuel is ignited and consumed by flaming combustion.

***Flash fuels**—Highly combustible fine fuels such as grass, leaves, draped pine needles, fern, tree moss and some kinds of slash, which ignite readily and are consumed rapidly when dry.

Flammability index—An assigned flammability index of 2 for accelerant species that contain volatile compounds that contribute to fire behavior (Pyne et al. 1996) and 1 for neutral species that do not contribute to fire behavior.

Foliar moisture content—Quantity of moisture in live leaves and needles expressed as a percentage of dry weight biomass.

Fuel—combustible material. In wildland fuels, fuel can include any organic material, including live and dead vegetation, litter, and duff.

Fuel area index (FAI)—Total fuel surface area per unit ground area (ft^2/ft^2)

Fuelbed—The inherent physical characteristics of fuels that contribute to fire behavior and effects. The FCCS describes fuelbeds in 6 horizontal layers including canopy, shrubs, herb, woody fuels, litter-lichen-moss, and ground fuels. Each layer, or stratum, is further divided into one or more categories to represent the complexity of wildland and managed fuels. A fuelbed can represent any scale that the user considers to be mostly uniform.

Fuelbed categories—Groupings of fuels within a fuel stratum that share common combustion characteristics. For example, the canopy stratum contains three categories—trees, snags, and ladder fuels. There are 16 fuelbed categories in total.

Fuelbed depth—Average height of surface or canopy fuels contained in the combustion zone of a spreading fire front.

Fuel loading—The dry weight biomass per unit area of combustible material (tons/ac).

Fuel model—A mathematical description of fuels required for the solution of the Rothermel (1972) fire spread model.

Fuel model crosswalk—A static crosswalk to one of the 13 original fire behavior prediction system (FBPS) fuel models (Anderson 1982) and one of the 40 standard fire behavior fuel models (Scott and Burgan 2005) based on the closest match in surface fire rate of spread and flame length.

Fuelbed subcategories—Further grouping of fuels within a fuelbed category with common combustion characteristics. For example, snags are further divided into the following subcategories—class 1 snags with foliage, class 1 snags without foliage, class 2 snags, and class 3 snags.

Gap—A separation in fuel continuity that affects the progression of the flames between fuel elements.

Grass—Member of the family Gramineae and characterized by hollow stems and circular cross sections and bladelike leaves arranged on the culm or stem in two ranks.

Ground fire—A fire that burns low-growing vegetation, litter, and organic material in the soil layer.

Ground fuels stratum—Fuel layer within FCCS that characterizes the duff, squirrel midden, and basal accumulation fuel categories.

Heat content—Heat of a material produced by combustion expressed as the quantity of heat per unit weight of fuel (Btu/lb) (Byram 1959). Also referred to as low-fuel heat content and heat of combustion.

Heat of ignition—Heat of preignition, the amount of heat required to ignite one pound of fuel.

Heat sink—The energy required to preheat surface fuels, influenced by fuel loading and fuel moisture.

Height—Distance from the base to the top of a fuel type. For example, the height of a tree would be the distance from the base of the tree to the top of the tree.

Height to live crown—Distance from the ground surface to the continuous portion of tree crowns, including the branches and foliage.

Herb—A plant that lacks a permanent woody stem and dies back to the ground each year.

Herb stratum—The fuel layer within FCCS that characterizes grasses, sedges, and other herbaceous vegetation.

Inferred variables—Fuelbed characteristics (e.g. surface-area-to-volume ratio, heat of combustion, flammability rating, and particle density) inferred from species or other fuel attributes.

***Ladder fuels**—Fuels that provide vertical continuity between strata, thereby allowing fire to carry from surface fuels into the crowns of trees or shrubs. There are eight ladder fuel types in the FCCS: arboreal lichens and moss, climbing ferns, and other epiphytes, dead branches, profuse epicormic sprouting, stringy or fuzzy bark (e.g., eucalyptus bark), tree regeneration, and vines-lianas.

Layer—Some strata and/or categories and subcategories are divided into layers. The duff category, for example, is divided into upper duff and lower duff layers.

Lichen—A composite plant of algae and fungi. The litter-lichen-moss stratum in FCCS includes ground lichen only.

Lightered stumps—Stumps that contain concentrations of pitch and other resinous volatiles and burn vigorously.

***Litter**—The top layer of forest floor, composed of loose debris of dead sticks, branches, twigs, and recently fallen leaves or needles; little altered in structure by decomposition.

Litter arrangement—The distribution of the litter layer. The FCCS includes three litter arrangement categories including fluffy (recently fallen), normal (litter that has not recently fallen or is not perched on grasses and other herbs), and perched (litter that has fallen mostly on an existing woody fuels or herb layer).

Litter-lichen-moss stratum—The fuel layer within FCCS that characterizes the litter, ground lichen and moss categories.

Live foliar moisture content—Water content of a live fuel (e.g., stems and leaves) expressed as a percentage oven-dry weight of the fuel.

Lower duff layer—The lower half of the duff layer, generally containing most of the humic or highly decayed material. The lower duff layer is denser than the upper duff layer.

***Midflame windspeed**—the average wind from the top of the fuel bed to twice the height of the fuel bed (Andrews 2012).

Midstory—Intermediate and co-dominant trees in the canopy. The FCCS calculator uses the midstory and overstory data in calculating the torching potential.

Mixed forest—A mixed forest is one in which evergreen and deciduous species each generally contribute 25 to 75 percent of total tree cover in both the overstory and midstory tree layers.

Moisture content of extinction—the fuel moisture content at which predicted rate of spread approaches zero.

Moss—A plant in the phylum Bryophyta; usually occurring in a moist habitat.

Moss type—The type of moss (e.g. sphagnum or other moss) that comprises the majority of mosses for a particular fuelbed.

Needle drape—Needles that fall and hang in shrubs or tree branches and provide vertical continuity between the surface fuels and crown fuels in a forested stand, thus contributing to the ease of torching and crowning.

Overstory—Dominant and emergent trees in the canopy. The FCCS uses the midstory and overstory data in calculating the torching potential.

Optimum depth—Used in calculating relative and optimum packing ratios, the canopy depth that would result in the maximum reaction velocity.

Optimum packing ratio—The packing ratio that would occur if fuel particles were optimally spaced (i.e., when the fuel particles each had 0.08 to 0.11 ft of air space from which to draw oxygen). Optimal fuel particle spacing for fine fuels is about 0.08 ft and 0.11 ft for coarse fuels such as wood.

***Packing ratio**—The fraction of a fuel bed occupied by fuels, or the fuel volume divided by bed volume.

Particle density—The density of wood or foliage that does not include the bulk air space between individual pieces of wood or foliage (lb/ft^3).

Particle volume—The volume of space filled by fuel particles. Whereas bulk volume is the volume of fuels and the interstitial airspace between fuels (e.g., volume of a tree crown), particle volume only considers the space containing fuel particles. It is calculated as dry weight biomass (lb/ac) divided by particle density (lb/ft^3).

Percentage cover—The percentage of a surface area covered by a fuelbed category. In FCCS, percentage cover is used to express the relative importance of a fuelbed category within a fuelbed type.

Percentage live—The percentage of a plant or fuel layer (e.g., primary shrubs) that is comprised of live biomass.

Percentage rotten—The percentage of downed, dead woody debris, snags, or duff that is composed of rotten, or partially decayed, material.

Piles—The accumulation of woody debris because of land use activities (e.g., timber harvest, thinning) and natural events (e.g., wind, avalanche, wildfire). The FCCS no longer supports woody fuel accumulations. Pile calculations are handled by the FERA pile calculator.

Primary herb layer—The main layer of vegetation within the herb stratum. Users can determine the primary layer based on a several selection criteria including species, height, mass, etc.

Primary shrub layer—The main layer of vegetation within the shrub fuelbed stratum. Users can determine the primary layer based on several selection criteria including species, height, mass, etc.

Propagating flux ratio—The proportion of the reaction intensity that contributes to the forward rate of spread.

Radius—The length of a line segment between the center and circumference of a log or tree bole.

Rate of spread—The forward rate of spread (distance per unit time) of a surface or crown fire (ft/min).

***Reaction intensity**—Rate of heat release per area of the flaming fire front, expressed as heat energy/area/time (Btu/ft^2/min).

Reaction potential—The reaction intensity of a fuelbed (energy release per unit area per unit time). It is a function of fuel surface area per unit ground surface, depth of the surface fuelbed stratum, heat of combustion, and a scaling factor based on flammability.

Reaction thickness—The approximate thickness of a fuel element shell that contributes to reaction intensity

Reactive volume—The flame-available volume of fuel (ft^3/ft^2) in each stratum that would be involved in flaming combustion and used in calculating optimum air volume.

Relative cover—The relative percentage (0 to 100 percent) of a fixed area covered by a species or fuelbed category.

Relative packing ratio—Proportion of fuelbed space that is occupied relative to the optimum packing ratio (packing ratio/optimum packing ratio).

Residual available fuel—The fuel available for consumption during the residual phase of combustion.

Residual phase—The phase of combustion after the smoldering stage. Sometimes termed the "glowing phase." Residual phase consumption may last for an extended period of time and generally involves woody fuels larger than 2 inches in diameter.

Rotten wood—Partially decomposed wood debris with obvious signs of decay such that the material falls apart when kicked. The three rotten wood diameter classes are 3 to 9 inches, 9 to 20 inches, and >20 inches.

Secondary herb layer—Optional herb layer with a different species composition and/or height than the primary herbaceous layer.

Secondary shrub layer—Optional shrub layer with a different species composition or height than the primary shrub layer.

Shrub—A woody perennial plant differing from a tree by its low stature and by generally producing several basal stems instead of a single bole.

***Slash**—Debris resulting from such natural events as wind, fire, or snow breakage; or such human activities as road construction, logging, pruning, thinning, or brush cutting. It includes logs, chunks, bark, branches, stumps, and broken understory trees or brush.

Smoldering phase—The phase of combustion in which the overall reaction rate of combustion has diminished to a point at which concentrations of combustible gases above the fuel are too low to support a persistent flame envelope. The smoldering phase follows the flaming phase of combustion and is often characterized by large amounts of smoke. The smoldering phase is divided into two phases in FCCS: a smoldering phase representing short-term smoldering and a residual smoldering or "glowing" phase representing long-term smoldering of large wood and duff layers.

Snag—A standing dead tree or part of a dead tree >4.5 feet tall. Snags are classified into four decay class categories—snag class 1 with foliage, snag class 1 without foliage, snag class 2, and snag class 3.

Snag decay class 1 with foliage present—Standing, recently dead trees greater than 4.5 feet tall, predominantly sound with fine and coarse branches, top and foliage intact.

Snag decay class 1 with foliage absent—Standing, recently dead trees greater than 4.5 feet tall, predominantly sound with fine and coarse branches, but with no foliage present.

Snag decay class 2 with branches and bark present—Standing dead trees greater than 4.5 feet tall with coarse branches and bark intact.

Snag decay class 3, rotten and with no branches or bark—Standing dead trees greater than 4.5 feet tall that are predominantly rotten with no bark intact.

Sound wood—Woody debris that has minimal decay. The six sound wood diameter classes in FCCS include 0 to ¼ inch, ¼ to 1 inch, 1 to 3 inches, 3 to 9 inches, 9 to 20 inches, and >20 inches.

Spread potential—The potential for fire to spread in a fuelbed, calculated as a function of reaction potential and the abundance of very fine fuels less than 1 inch in diameter.

Squirrel middens—A mound of cone scales and other cone debris accumulated over time from squirrels extracting seeds. The mounds are composed exclusively of organic matter that can burn for extended periods of time. Squirrel middens are a ground fuel category in FCCS.

Strata/stratum—Vertical layers within the fuelbed that represent unique combustion characteristics. Six strata are recognized—tree, shrubs, herb, woody fuels, litter-lichen-moss, and ground fuels.

Stringy or fuzzy bark—Ladder fuel type and qualitative term as used in the Australian Bushfire Prediction System to account for the role of such bark in many tree species (although few such species are found in the United States and Canada) to act as a ladder fuel or source of firebrand material.

Stump—The remaining part of a tree stem after the trunk is severed.

Subcategory—Categories in the FCCS are often further divided into subcategories. For example, the tree category is divided into overstory, midstory, and understory subcategories.

Surface fire behavior potential—A combination of reaction potential, spread potential, and flame length potential scaled to between 0 and 10.

***Surface-area-to-volume ratio**—the amount of surface area per unit volume of fuels (Fons 1946). The smaller the particle, the more quickly it can become wet, dry out, or become heated to combustion temperature during a fire.

Tree—A tall, perennial woody plant greater than 4.5 feet having a main trunk and branches forming a distinct elevated crown; includes both gymnosperms and angiosperms.

Understory—Tree seedlings and saplings in the canopy layer separated from the overstory and midstory by a gap.

Upper duff layer—The upper half of the duff layer that generally contains a fermentation (F) layer and may contain a portion of the humic (H) layer. The upper duff layer is less dense than the lower duff layer.

Woody fuels stratum—A fuel layer within FCCS that characterizes sound and rotten woody fuels, stumps, and piles.

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