FIRE EFFECTS TRADEOFF MODEL

# FETM

# FETM 4 Technical Documentation

## A Landscape-Scale Planning Model for Air Quality Specialists and Fire Managers

Prepared by Air Sciences, Inc.

with assistance from TW Environmental, Inc.

February 2003

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# 1 Introduction and Overview

## 1.1 Introduction

This document contains the technical description of the Fire Effects Tradeoff Model, Version 4 (hereafter referred to as *FETM 4*). This technical documentation includes a description of the architecture, equations, assumptions, and principal components and processes used in FETM 4. A sensitivity analysis, along with recommendations on the appropriate uses of the model, is also included in this document.

A companion Users Guide has also been prepared and is available from USDA Forest Service, Pacific Northwest Region, Attn: Jim Russell, Regional Air Program Manager.

## 1.2 Overview of the Model

The Fire Effects Tradeoff Model is a stochastic, dynamic, non-spatial computer simulation model. It is designed to simulate the tradeoffs between wildland fire and various fuel treatment alternatives at the landscape level over long periods of time (up to 300 years) and under diverse environmental conditions, natural fire regimes, and management policies. FETM 4 provides the user with several measures of the potential tradeoffs between alternatives, including: annual acres burned, annual pollutant emissions (up to six pollutants may be evaluated at one time), and the present net value of costs and benefits of wildland fire versus that of all fuel treatments combined. FETM 4 has nationwide application and can be used by any federal, state, or private organization.

At its core, FETM 4 is a vegetation dynamics model that simulates changes in vegetation composition over time in response to various human-caused and natural disturbances. A wide variety of disturbances may be accounted for in the model, including: timber harvesting and other forms of fuel removal (e.g., firewood collection), mechanical fuel treatments, prescribed fire, wildland fire, windthrow, insects, disease, and, in the absence of disturbance, natural succession. A key feature of FETM 4 that distinguishes it from other vegetation dynamics models is its linkage between vegetation composition (fuel loading) and wildland fire behavior and effects. For example, an increase in the proportion of highly flammable vegetation classes in an area will produce a concomitant increase in the number of acres burned annually by wildland fire. Over time, the increased number of wildland fire acres burned (a form of *natural* fuel treatment) will, in combination with other management actions, reduce the proportion of highly flammable vegetation classes across the landscape and eventually lead to a reduction in the number of annual wildland fire acres . This cyclic pattern in the number of wildland fire acres over time is evident in the output from FETM 4.

The amount of wildland fire and other fuel treatments required to “tip the scales” in favor of lower average flammability (and lower numbers of annual wildland fire acres ) depends on the magnitude of the fuel treatments (outflow) versus the rate of recruitment into the more flammable vegetation classes (inflow) resulting from a combination of natural disturbances (e.g., insects, disease, and windthrow), management activities (e.g., timber harvesting), and natural succession.

FETM 4 is non-spatial, meaning that while it can predict the overall outcome of a treatment (for example, prescribed fire) within a specific Analysis Area, it cannot predict where specific impacts may occur. For example, within a particular stand type (e.g., immature mixed conifer), FETM 4 can predict the number of acres of the stand that will be affected by wildland fire, but cannot predict where within the stand those effects will occur or if they will be contiguous or dispersed.

Because it is a dynamic model, FETM 4 can predict changes in landscape composition over time. The model then uses the changes in landscape composition to predict air quality emissions during a planned or unplanned fire event, to estimate costs associated with controlled or uncontrolled burns, and to track treated acres, among other factors.

FETM 4 is also a stochastic model, meaning that it includes one or more random variables. Currently, the random variables include wildland fire frequency by fire weather class, and wildland fire size for the fires that fall outside the range of recent historic data for the Analysis Area.

## 1.3 The FETM Modeling Process

FETM 4 is a model that requires input data from several disciplines. For this reason, the model is best applied by a team of specialists with expertise in various aspects of the modeling process (i.e., Silviculture, fire behavior, fire ecology, land management planning, and air quality, to mention just a few). One person who is familiar with the structure of FETM 4 should be assigned the task of coordinating the modeling analysis.

The FETM 4 modeling process can be described as a series of five steps as described below.

### 1.3.1 Selecting an Analysis Area

The modeling process begins by identifying a geographic area of interest, referred to in FETM 4 as an *Analysis Area*. An Analysis Area may be an entire administrative unit (e.g., a National Forest, BLM Area, National Wildlife Refuge, or private ownership), any single part of an administrative unit, or any combination of administrative units, or parts of administrative units *as long as those units or parts of units are contiguous*. The *modeling objectives* usually dictate the appropriate geographic scale.

### 1.3.2 Stratifying the Analysis Area by FCCs

Once the Analysis Area has been identified, it may be stratified into a series of user-defined vegetation and fuel-loading classes called Fuel Characteristic Classes (FCCs). Each FCC is a unique description of the total fuel bed, which begins at mineral soil and ends at the top of the tallest shrubs or trees occupying each site (Greenough, 2001). In FETM 4, FCCs are described in terms of four qualitative attributes—predominant vegetation, age class, loading class, and activity class; quantitatively in terms of a host of physical parameters relating to fuel loading of dead-and-down woody fuels by size class, duff loading, fuel bed depth, fuel moisture content; and stand characteristics including the height to the base of the live crown, foliage and one-hour fuel loading, stand density, average stand diameter, total stand height, and many more. Because of their different characteristics, each FCC has potentially different fire behavior (e.g., fire spread rate), disturbance effects, fuel consumption, and emissions.

The process of stratifying the area into FCCs is one of the more challenging aspects of FETM 4, primarily because it is entirely at the users discretion how best to characterize the Analysis Area. There is no limit on the number of FCCs that may be used; the user may select a few or several hundred. In general, the greater the number of FCCs that are selected, the greater is the resolution in defining disturbance effects and (presumably) the greater the accuracy of the modeling analysis. However, the decision to use many FCCs comes at a considerable price in terms of the difficulty in obtaining the required inputs, and the time it takes to enter the data and to run the model. In practice, an Analysis Area of approximately a million acres in size should be adequately characterized with fewer than 200 FCCs.

### 1.3.3 Defining Disturbance Types and Effects

Once the Analysis Area has been stratified into FCCs, the types and effects of disturbances may be characterized. The effects of various management-related and natural disturbances on vegetation composition and fuel loading are simulated in FETM 4 using a system of *schedules* and *effects matrices*. The schedules define the magnitude of the disturbance (i.e., the number of acres that are affected annually), and the effects matrices (sometimes referred to as *transition* matrices) define the direction of change following the disturbance.

Form-based schedules are used to assign the magnitude of disturbance from selected management activities, such as timber harvesting, mechanical fuel treatments, and prescribed fire. Schedules are also used to define the magnitude of disturbance from some natural causes such as insects, disease, and windthrow. Each FCC must be scheduled separately. If no acres are entered in the schedule for an FCC, it means that no disturbance is expected for that FCC. The effects matrices are populated with fractional numbers that determine the number of acres transferred from the *parent* FCC to one or more *sibling* FCCs following a disturbance. FETM 4 contains one matrix for each disturbance type except fire, which uses three separate disturbance matrices (one for each of three fire intensity classes: low, moderate, and high). Each column in the matrix represents a different parent FCC; each row represents a different sibling FCC.

In FETM 4, the effects of a disturbance are always manifested as a transfer in the number of acres from one FCC to one or more FCCs following the disturbance. For example, the effect of a moderate-intensity wildland fire in an overstocked, immature Ponderosa Pine FCC might be to transfer 50 percent of the parent FCC acres to bare ground, and 30 percent to an immature Ponderosa Pine FCC with a lower stand density and lower total surface fuel loading. In this example, 20 percent would remain in the parent FCC; that is, 20 percent of the area is assumed to be insufficiently affected by moderate-intensity wildland fire to cause a change in FCC.

### 1.3.4 Defining the Relationship Between the Fire Spread Rate and Expected Wildland Fire Size

Wildland fire is treated as a random (stochastic) event whose size varies according to the fire weather conditions and the vegetation composition within the Analysis Area. The largest fires are expected to occur under high or extreme fire weather conditions, when the fire rate of spread is the greatest. Smaller fires are expected under low or moderate fire weather conditions, when the expected spread rates are lower.

The accuracy of the fire size simulation in FETM 4 depends on a reasonable characterization of the relationship between the expected fire size and the fire rate of spread in each of the four fuel categories: timber litter, slash, grass, and brush. To build these relationships, an experienced fire planner or fire behavior analyst is needed to evaluate the fire rates of spread required to achieve a set of fixed—or breakpoint—fire sizes: 0.25 acre, 10 acres, 100 acres, 300 acres, and 1,000 acres. A fire behavior analyst is also needed to survey the recent historical record and to extract representative wind-driven wildland fires whose size and active spread time is known, and can be used to assess potential fire sizes under more extreme weather conditions.

A separate but related task in FETM 4 is to characterize each of the four National Fire Danger Rating System (NFDRS) fire weather classes in terms of ranges of computed spread components. The median spread component for each fire weather class is used to determine the expected fire size in that fire weather class.

### 1.3.5 Defining Scenarios and Running the Model

Prior to running the model, the user must define a *scenario* (or *run scenario*). A scenario consists of a set of FCCs with initial acreage estimates for each, a set of schedules and disturbance types, a set of effects matrices (one for each disturbance type, plus three for fire), and other user options such as the pollutant species to model, the number of years in the simulation, and the number of iterations over which the results are to be averaged.

The number of iterations to be included in the scenario is an important consideration. FETM 4 may be run with a single iteration or over multiple iterations that are arithmetically averaged prior to the reporting of results. This flexibility enables the user to view the episodic pattern of wildland fire (single iteration) or the expected outcome that would result from multiple iterations. The average of multiple runs of FETM 4 is recommended in order to provide an adequate sampling of the consequences of wildland fire in combination with various fuel treatments designed to achieve certain resource objectives or to mitigate the hazard of wildland fire.

FETM 4 produces numerous text output files that are stored in scenario-specific folders under the main program directory (see Appendix B for a listing of the file names and contents). The data in these files may be imported into the model for graphing and reporting purposes. The users guide provides much more information on importing the data to produce reports and graphs.

## 1.4 Development History

The development of FETM began in early 1993 under the direction of the Region 6 Prescribed Fire/Wildfire Working Group. A study plan summarizing the modeling approach was completed in July 1993 (USDA Forest Service, 1993), and programming began shortly thereafter. Version 1.0 of FETM was completed in late 1995 and tested immediately on a 1.2-million-acre study area located in the Grande Ronde River Basin in northeastern Oregon. A technical document summarizing the development and initial application of the FETM model in the Grande Ronde River Basin was completed in February 1996 (Schaaf et al., 1996).

FETM Version 1.0 was programmed in an interpreted language, S-Plus. Subsequent funding from the Forest Service allowed the model to be enhanced with improved fire sizing algorithms (FETM Version 2.0; December 1996), and to be brought into a Visual Basic programming environment linked to Microsoft Access database files and FORTRAN 99 subroutines (FETM Version 3.4; April 1998). A users guide for FETM Version 3.4 was produced in April 1998 (CH2M Hill, 1998).

In late 1998, the USDA Forest Service received funding from the Joint Fire Science Program to continue development of FETM. Work on FETM Version 4 began in August 1999. The new model was completed in June 2001, culminating in the release of FETM 4, Version 4.2. Preparation of this technical documentation, and a companion users guide, are two of the task items required in the 1998 FSP funding proposal.

# 2 Objectives

This chapter summarizes the FETM 4 development and application objectives. The development objectives are those that guided the construction of FETM 4. The application objectives are those that describe the intended uses of FETM 4.

## 2.1 Development Objectives

The development objectives for FETM 4, as defined in our proposal to the Joint Fire Science Program (Snell and Schaaf, 1998), are listed below. They range from Task 1, Develop a Prototype Model, to Task 5, Prepare a Technical Paper for Journal Publication. This technical document specifically addresses Task 4, Document and Provide Literature Support. But other task items are also discussed in this technical document, and they are marked with an asterisk (*). The remaining task items, while they may contain valuable enhancements to the model, do not have sufficient technical details associated with them to warrant a discussion here.

### 2.1.1 Phase I Model Development

Task Objectives

1. Prepare a prototype FETM Version 4, incorporating any required revisions to the wildfire size and fire distribution algorithms. The prototype model would be used in the field test of candidate vegetation dynamics models being proposed by the Riverside Fire Laboratory.
2. Develop the full FETM Version 4 model, incorporating all the modifications listed in the "Materials and Methods" section of the proposal, including the following tasks:
    a. Modify computation of final fire size as function of fire rate of spread. *
    b. Evaluate algorithms used to compute landscape-scale fire size. *
    c. Add capability to assess economic effects of fuels treatment. *
    d. Integrate CONSUME 2.1 algorithm to compute fuel consumption and emissions.
    e. Compute emission rates for a variety of chemical constituents found in wildland fire smoke.
    f. Display and print audience-specific reports and graphs.
    g. Compute crown mass by size component. *
    h. Simulate disturbance effects by insects, disease, and biomass utilization. *
    i. Integrate latest NFDRCALC dynamic link library. *

j. Integrate capability to use regional or sub-regional data templates.

k. Integrate capability to view changes in fuel loading over time.

l. Modify transition matrices to include disturbance "effects" only. *

m. Integrate capability to allow users to enter treatment acres in schedule format. *

n. Add capability to model changes in management policies over time.

o. Combine wildland fire and prescribed fire effects into single effects matrix. *

p. Add comprehensive HELP screens.

q. Add process pathway diagram as help screen.

r. Add capability to cross-reference FCCs to other vegetation and coordination classes.

s. Populate fuel loading in FCC data table from derivative fuel model data table.

t. Distribute PCHA model with FETM.

### 2.1.2 Phase II Sensitivity Testing

Task Objectives

3. Test the sensitivity of model outputs to key model inputs, algorithms, and relationships.
4. Document and provide literature support for the component algorithms used in FETM Version 4.2.
5. Prepare a technical paper supporting the core framework of FETM Version 4.2 for publication in a national or international peer-reviewed scientific journal.

All of these task items have been completed with the sole exception of Task 2(t), Distribute PCHA model with FETM, and Task 5, Preparation of Technical Paper for Journal Publication. Task 2(t) was not completed because the technical review committee guiding the development of FETM 4 thought it unnecessary. The reason is that the PCHA model is readily available from the fire applications website, so instead the development team simply requested that the website address be listed in the FETM 4 Users Guide. The peer-reviewed paper will be prepared and submitted at a later date.

## 2.2 Application Objective

FETM 4 has been designed to meet the needs of land management planners, fire planners, air quality specialists, and other resource specialists seeking a model to quantitatively assess the long-term consequences of alternative land management practices. Specifically, the model may be used to:

- Support fire planning and budgeting decisions by demonstrating the long-term costs and benefits of alternative fuel treatment and fire suppression programs.
- Identify the economic and environmental effects and tradeoffs of fuel treatment alternatives and wildland fire.
- Assess the long-term impacts of human-caused and natural disturbances on ecosystems, including the long-term changes in vegetation composition, fuel loading, and wildland fire effects.
- Assist fuel specialists in identifying specific vegetation types to target for fuel reduction.

The outputs from FETM 4 that provide this capability include: annual fuel treatment acres (planned and accomplished), annual wildland fire acres by fire intensity level, annual vegetation composition (i.e., number of acres within the Analysis Area by FCC), annual pollutant emissions for up to seven different pollutant species, expected wildland fire size in each of the four National Fire Danger Rating System fire weather classes, and annual costs and benefits of wildland fire versus various fuel treatment alternatives.

# 3 FETM 4 Architecture

This chapter summarizes the linked algorithms that are used to perform the dynamic calculations in FETM 4. These calculations utilize *secondary model inputs*, which are computed in FETM 4 on the basis of the *primary model inputs* provided by the user (see Chapter 6, Glossary of Terms). The chapter that follows (Chapter 4) summarizes the component processes in FETM 4 that generate the secondary model inputs.

The calculation "engine" of FETM 4 consists of the following nested algorithms (Figure 3-1):

- Landscape Composition Algorithm
- Wildland Fire Acreage Algorithm
- Wildland Fire Emissions Algorithm
- Prescribed Fire Emissions Algorithm

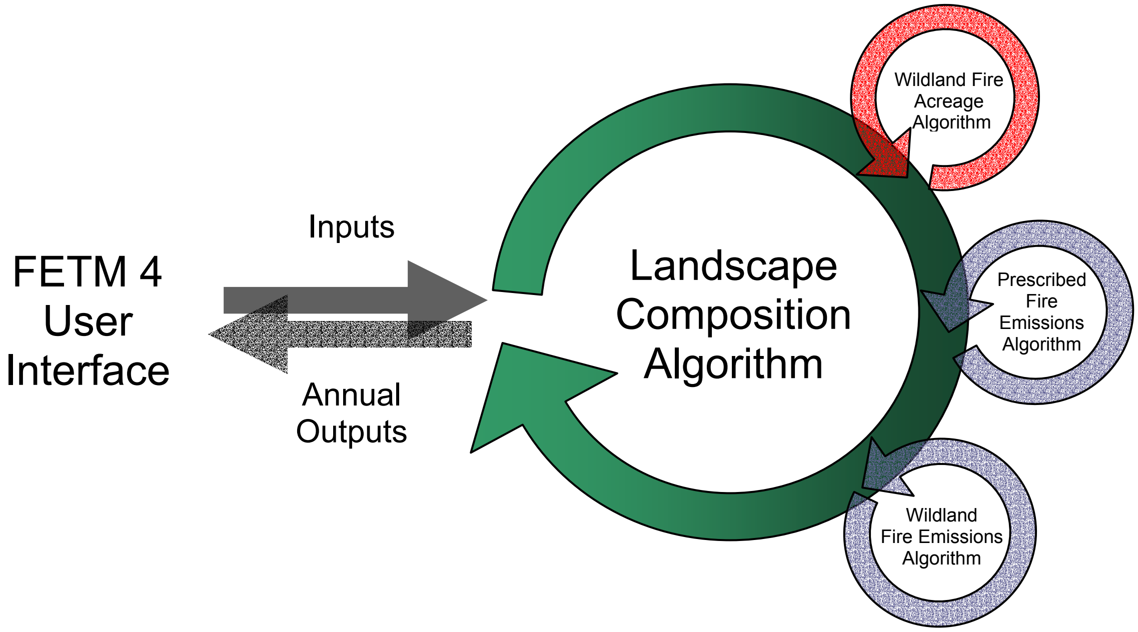

**Figure 3-1. Nested Dynamic Algorithms in FETM 4**

The Landscape Composition Algorithm is the principal dynamic algorithm in FETM 4. It tracks the change in the landscape composition over time in response to all natural disturbances (e.g., wildland fire, insects, disease, and windthrow) and all management-related disturbances (e.g., timber harvesting, mechanical treatments, and prescribed fire). It also accounts for the effects of natural succession over time on areas that are unaffected by disturbance. Because of their complexity, some of the effects—for example, wildland fire acres, wildland fire emissions, and prescribed fire emissions—are calculated in separate subroutines that are called from the main program.

The Wildland Fire Acreage Algorithm computes the annual wildland fire frequency and annual wildland fire acres in four different National Fire Danger Rating System (NFDRS; Deeming et al., 1977; Cohen and Deeming, 1985) fire weather classes. FETM 4 includes four NFDRS weather classes: low, moderate, high, and extreme.

The Wildland Fire Emissions Algorithm computes annual wildland fire emissions given the predicted number of fires per year, number of acres burned per fire, fuel consumption per acre, and the emissions per acre in each of the four NFDRS weather classes.

The Prescribed Fire Emissions Algorithm computes annual prescribed fire emissions given the scheduled (and available) number of acres burned per year, and the per-acre fuel consumption and emissions for the FCC-specific NFDRS fire weather classes prescribed by the user.

Each of these component algorithms is described below.

The dynamical engine FETM 4 is programmed in the FORTRAN 90 language and compiled using the Lahey FORTRAN 90 compiler. A map and description of the major subroutines used in FETM 4 are included in Appendix A.

## 3.1 Landscape Composition Algorithm

### 3.1.1 Description

At the core of the dynamic calculations in FETM 4 is the landscape composition algorithm which tracks annual changes in the landscape composition within the user-defined Analysis Area. In FETM 4, the landscape composition is characterized in terms of the number of acres in one or more unique *fuel characteristic classes* (FCCs) defined by the user. The fuel classification system, from which the FCCs are derived, is a comprehensive system for classifying fuel beds on the basis of general fuel bed information (including cover type, structure, and other attributes), physiognomic variables (growth habit, surface area to volume ratios), and gradient variables (canopy physical characteristics such as height and density, woody fuel loading, and other factors)(Cushon et al., 2000). Physiognomic and gradient variables are described for each of the six different fuel bed strata extending from the mineral soil surface to the top of the canopy (ground fuel, moss/lichen/litter, woody fuel, low vegetation, shrub, canopy), and for two to four fuel bed categories within each stratum (total of 16 fuel bed categories).

In FETM 4, a set of FCCs should be defined and chosen to represent discrete points (vegetation growth stages) along the continuum of change—both spatial and temporal—that characterizes the vegetated environment. For example, the continuum of change from bare ground to late successional Ponderosa Pine might be represented by a single FCC at each of the following vegetation growth stages: bare ground, seedlings and saplings, pole stand, early mature stand, and late mature stand. Ideally, additional FCCs would be added to each vegetation growth stage in order to represent the expected result of natural and human-caused disturbances. For example, the "early mature" FCC might be expanded into two FCCs: "early mature-low stand density," and "early mature-high stand density." Natural succession would annually move acres from the low stand density FCC to the high stand density FCC. Wildland fire, on the other hand, might be expected to produce limited overstory mortality and move acres from the high stand density FCC back to the low stand density FCC. Or, as in the case of a stand replacement fire, the disturbed area might move entirely back to bare ground.

FETM 4 defines FCCs in a slightly different manner than that used in the FCC classification system described in Cushon et al. (2000). The primary reason for this is that the FCC concept began as an offshoot of the early development of FETM, and FETM 4 has retained the original style of defining FCCs. In time, and as the FCC classification system is refined and brought into common use, FETM will be modified to use their style of classification. In FETM 4, FCCs are currently defined on the basis of several qualitative attributes, including: vegetation type, stand age or structural class, loading class, and management activity class. FCCs are further defined on the basis of numerous physical attributes of the surface and elevated fuel bed, including: surface loading of "live" fuels (tons per acre), surface loading of dead-and-down woody fuels by size class, crown fuel loading by size class, and numerous other attributes required to compute the crown fuel loading such as species, crown class, diameter, height, density, crown bulk density, foliar moisture content, and height to the base of the live crown.

There is no limit on the number of FCCs that may be defined and used in FETM 4. However, the time involved in parameterizing and running the model is greatly affected by the number of FCCs chosen. The goal of modeling should be to select the fewest number of FCCs possible to characterize the composition of the Analysis Area over time. Most Analysis Areas can be adequately characterized with fewer than 200 FCCs.

In the model as in nature, the distribution of FCC acres within an Analysis Area changes over time as a result of growth and succession, as well as from natural and human-caused disturbances such as timber harvesting, mechanical fuel treatments (e.g., crushing), disease and insect mortality, and fire. In the absence of disturbance, stands are expected to develop in an uninterrupted, stepwise manner toward an endpoint that perpetuates itself; that is, to progress in structure toward a climax state (Clements, 1936). In FETM 4, growth and succession effects are represented by a transfer in acres from one FCC to one or more FCCs, each FCC representing a different vegetation growth stage. This change in vegetation growth stage may be accompanied by a change in surface fuel loading or by a change in stand composition, or both. The overall flammability and potential for large wildland fires within the Analysis Area may also be affected by a change in vegetation growth stage, depending on the direction and magnitude of the change in fuel bed characteristics. In the forested ecosystems of the western United States, the progression is typically from low surface fuel loading/low elevated fuel loading (relatively low large-fire potential) early in succession to high surface fuel loading/high elevated loading (relatively high large-fire potential) midway through succession, to moderate surface loading/high elevated loading (moderate large-fire potential) late in succession. But this is entirely dependent on the vegetation types and fire weather that dominates each geographic area.

Because FETM 4 deals with discrete vegetation growth stages, the rate of change from one stage to the next depends on the difference in the median age. A linear rate of change is assumed between successive stages.

With disturbance, particularly wildland fire disturbance, the changes across vegetation states may take multiple pathways, creating a mosaic of landscape patterns. The effects of harvesting practices or fire might be to maintain a structure state in a park-like condition or set it back to an earlier successional state, depending on the assumptions made about known species and vegetative community response to different disturbance regimes. The number of acres affected by disturbance each year are defined by the user and stored in disturbance-specific "schedules." The direction of change following each disturbance are also defined by the user and stored in disturbance-specific "effects matrices." In the schedules, the user defines the number of acres that will be affected each year by FCC. The effects matrices are used to redistribute the disturbed acres identified in the schedules. Each effects matrix is made up of **n** x **n** elements ("coefficients"), which specify the fraction of each disturbed acre that are transferred from one FCC to another as a result of the disturbance. Here, **n** is the number of FCCs used to characterize the Analysis Area.

The coefficients in the effects matrices are constant over time. The number of disturbed acres may vary from year to year, but the disturbance effects (direction of change) are always the same.

Historically, in fire-prone ecosystems large wildland fires have been the single greatest contributor to change in the acreage distribution from year to year. For this reason, previous investigations have focused on largest "escaped" fires, which are fires that escape initial attack and grow to sizes greater than 1,000 acres based on modeling using the National Fire Management Analysis System (NFMAS). Escaped fires are usually associated with high or extreme fire weather conditions. However, in many fire-dominated ecosystems of the western United States, the majority of the annual wildland fire acres occur under moderate fire weather. FETM 4 tracks the number of acres burned in each of the four NFDRS fire weather classes. The greater the acreage consumed by wildland fires, the greater the shift in the acreage distribution from high-flammability fuels to low-flammability fuels. On the other hand, the greater the number of acres in the more flammable classes that are treated to reduce fuel loading (by prescribed fire or other means), the lower the total acreage consumed by wildland fire. This is due to a direct link between fuel loading and fire spread.

The time scale in FETM is fixed in *years*. The simulation period may extend from one year to any number of years, but except in rare circumstances, should be 100 years or less. The landscape composition reflects the conditions that exist at the end of the year.

### 3.1.2 General Equations

The equation describing this general, non-spatial acreage distribution algorithm *for a single disturbance matrix* **M**, followed by natural succession **S**, is:

$$\tilde{a}_t = \mathbf{S}\left\{\left(\tilde{a}_{t-1} + \left(\tilde{s}_t - \mathbf{M}\,\tilde{s}_t\right)\right) + \tilde{w}_t\right\} \tag{3-1}$$

where $\tilde{a}_t$ is the vector of FCC acres in year t, $\tilde{s}_t$ is the vector of acres scheduled for treatment by **M**, and $\tilde{w}_t$ is a net-change vector that accounts for random fire events in year t. The tilda mark (~) is used to indicate a vector arrayed by FCC.

Generalized to account for up to eight disturbance types, equation (3-1) becomes:

$$\tilde{a}_t = \mathbf{S}\left\{\left(\tilde{a}_{t-1} + \sum_{r=1}^{8} \tilde{s}_{t,r}\left(\mathbf{I} - \mathbf{M_r}\right)\right) + \tilde{w}_t\right\} \tag{3-2}$$

where r is the index of disturbance types, and I is the identity matrix. $M_1$ through $M_4$ are user-defined management activities, $M_5$ is prescribed fire, and $M_6$ through $M_8$ are user-defined insect or disease disturbance types.

Up to seven different *levels* of prescribed fire activity may be run in FETM at one time. By *level*, we mean some arbitrary multiple of the total acreage scheduled for prescribed fire treatment each year—10 or 150 percent of the schedule acres, for example—in "targeted" FCCs. Thus, equation (3-2) may be expanded to its most general form:

$$\tilde{a}_{t,p} = \mathbf{S}\left\{\left(\tilde{a}_{t-1,p} + \sum_{r=1}^{8} \tilde{s}_{t,r,p}\left(\mathbf{I} - \mathbf{M_r}\right)\right) + \tilde{w}_{t,p}\right\} \tag{3-3}$$

where p is the prescribed fire treatment level. Note that only in the case of prescribed fire does the vector of (scheduled) disturbed acres, $\tilde{s}_{t,r,p}$, vary with the prescribed fire treatment level, p.

Equation 3-2 also highlights the hierarchy of matrix operations that are contained in FETM. The scheduled disturbances ($\mathbf{M_1}$ through $\mathbf{M_8}$) can all be combined to produce a modified acreage distribution vector in the current year. This vector is then modified to account for the effects of wildland fire in the current year, $\tilde{w}_{t,p}$, and this vector is then multiplied by the natural succession transition matrix, **S**, to yield the final acreage distribution vector in the current year, $\tilde{a}_{t,p}$.

Equation 3-3 does not include the wildland fire effects transition matrix. Instead, the wildland fire effects transition matrix, **W**, is used to derive the wildland fire acreage net-change vector, $\tilde{w}_{t,p}$. The methodology used to compute the wildland fire net change vector is described in Chapter 3.2, Wildland Fire Acreage Algorithm.

Development of the 10 transition matrices (**$\mathbf{M_1}$** through **$\mathbf{M_8}$**, wildland fire, and natural succession), as well as the initial acreage distribution vector ($\tilde{a}_{t,p}$), is described in the Users Guide, Define Disturbance Effects.

## 3.2 Wildland Fire Acreage Algorithm

### 3.2.1 Description

When wildland fires occur in an ecosystem, the predominant fuel category, fuel loading, structure, and flammability all change as the vegetation structure and composition changes. In FETM, these changes are represented as step changes in the acreage distribution vector [$\tilde{a}_{t-1,p}$ in Equation (3-3)]. The magnitude and direction of these shifts depends on the number, size, and intensity (ecological effects) of the fires. FETM simulates these factors based on Analysis Area-specific fuel loading and structure data, historical fire frequencies, and fire weather conditions.

The number of wildland fire acres each year is the product of the expected wildland fire size (area-weighted potential fire size, in acres) and wildland fire frequency (in number of fires per year), summed over all fire weather classes. The expected wildland fire size is determined by summing the scalar product of two vectors: the potential wildland fire sizes by FCC (assuming that fires are allowed to burn homogeneously within an individual FCC) and the fractional distribution of acreage at the beginning of the simulation time period by FCC. The resultant expected wildland fire size is then "distributed" back onto the ground using the same fractional distribution of acreage by FCC.

The following sections describe the general equation, fire frequency, fire sizes, and fire effects.

### 3.2.2 General Equations

In Equations 3-1 and 3-2, the elements of wildland fire acreage vector, $\tilde{w}_{t,p}$, represents for each FCC the net gain or loss of acres attributable to wildland fires in year t and prescribed fire treatment level p. These same formulas are applied successively for each prescribed-fire treatment level. For a given year t, the net acreage change is a function of the expected acres burned by FCC and the wildland fire effects:

$$\tilde{w}_t = \sum_{\mathbf{i}=1}^{4} (\mathbf{W_i} - \mathbf{I})\,\tilde{F}_{t,i} \qquad (3\text{-}4)$$

where

$\tilde{w}_t$ = column-vector containing net change in acreage (by FCC) attributable to random wildland fire events in year t

**$\mathbf{W_i}$** = n x n wildland fire effects matrix for each weather class i, where n is the number of FCCs

**I** = n x n identity matrix

$\widetilde{F}_{t,i}$ = column-vector of expected FCC acres burned (prior to any consideration of fire effects) in year t and for the $i^{th}$ fire weather class. Note that the vector of expected acres burned varies dramatically from one prescribed fire treatment level to the next.

Equation 3-4 exhibits a coarse negative (behavior dampening) feedback to the prediction of wildland fire size. The initial behavior of the feedback mechanism depends on the relative proportion of the study area occupied by FCCs with low rates of fire spread versus those with high rates of fire spread. If the proportion of the total area occupied by FCCs with high rates of spread is large, then large wildland fires will be produced that will rapidly convert the area to lower flammability, and wildland fire size will subsequently decrease. Conversely, if the proportion occupied by FCCs with relatively low rates of spread is large, then the smaller number of annual acres burned will permit a steady increase in the average fuel loading over time, leading to larger wildland fires. Over time, the relative proportion of acres in high rate-of-spread and low rate-of-spread FCC will fluctuate back and forth (gentle rise, steep decline; similar to that which occurs in nature). The curves should approach, but never quite attain, an equilibrium state given the irregular and infrequent nature of wildland fire.

#### 3.2.2.1 Wildland Fire Effects by Fire Weather Class ($W_i$)

FETM 4 requires the user to enter detailed information on *wildland fire effects* in each of three different fire-intensity-level (FIL)-specific matrices: one for FIL 1 and 2 fires, one for FIL 3 and 4 fires, and one for FIL 5 and 6 fires. Wildland fire effects are the impact of wildland fire on FCCs. These effects are manifested in FETM 4 as a change in the FCC number used to characterize the disturbed area, resulting from a change in FCC surface loading or structure, or a change in the overlying stand characteristics (if present).

Wildland fire effects are most easily differentiated by FIL, which is why FETM 4 requires the user to enter the initial information by FIL. However, all of the internal calculations in FETM 4 are by fire weather class, not by FIL. A process is included in FETM 4 to map the FIL-specific fire effects matrices into fire weather class-specific matrices.

FETM 4 populates four composite fire effects matrices, one for each fire weather class, on the basis of the FIL-specific wildland fire effects matrices that are entered by the user and the FCC-specific Burning Index (BI) values computed by the model. The process for populating the four wildland fire effects matrices is as follows:

1. The NFDRCalc dynamic link library (see Section 4.4.1, Surface Fire Behavior) is used to compute a matrix of BI values by FCC and fire weather class. There are four BI values for each FCC, one for each of the four fire weather classes: low, moderate, high, and extreme.

2. The flame length (in feet) for each FCC and fire weather class is then computed using the formula:

$$\text{Flame Length (feet)} = \frac{\text{BI}}{10} \quad \text{(rounded to nearest integer)} \tag{3-5}$$

3. The flame lengths for each FCC and fire weather class are then mapped into the six fire intensity levels (FILs). The FIL definitions are as follows: FIL 1—0 to 2-foot flame lengths, FIL 2—2 to 4-foot flame lengths, FIL 3—4 to 6-foot flame lengths, FIL 4—6 to 8-foot flame lengths, FIL 5—8 to 12-foot flame lengths, and FIL 6—greater than 12-foot flame lengths. The result is a matrix of FIL values for each FCC and fire weather class.

4. The wildland fire effects matrix for the low fire weather class (*"low" fire effects matrix*) is then populated based on the FIL values computed in Step 3 for the low fire weather class. The FCC number and associated FIL value dictates which of the three input FIL matrices (FIL 1/2, FIL 3/4, or FIL 5/6) and which column in those matrices will be extracted and placed in the resultant "low" fire effects matrix. The FCC number determines the column to be extracted. The FIL number determines which of the three input FIL-specific matrices the column is to be extracted from. For example, if we are populating the fire effects matrix for FCC 50, then the 50th column from one of the three FIL-specific matrices will be extracted and placed in the 50th column of the "low" fire effects matrix. This column of data includes all the information necessary to determine the effect of wildland fire on FCC 50. But from which of the three input matrices will the column be extracted? If the FIL for FCC 50 is either 1 or 2, then the 50th column from the FIL 1/2 input matrix will be extracted and placed in the 50th column of the "low" fire effects matrix. Alternatively, if the FIL for FCC 50 is either 3 or 4, then the 50th column from the FIL 3/4 input matrix will be extracted and placed in the 50th column of the "low" fire effects matrix. And if the FIL for FCC 50 is either 5 or 6, then the 50th column from the FIL 5/6 input matrix will be extracted and placed in the 50th column of the "low" fire effects matrix. This process is repeated for each of the FCCs, from one to the maximum number of FCCs present, until the effects matrix is fully populated.

5. The fire effects matrices for the moderate, high, and extreme fire weather classes are composed using the same process described in Step 4.

The result of Steps 1 through 5 is a set of fully populated wildland fire effects matrices by fire weather class.

#### 3.2.2.2 Expected of Wildland Fire Acres Vector ( $\widetilde{F}_{t,i}$ )

In (3-4), the vector of expected wildland fire acres by FCC, $\widetilde{F}_{t,i}$, is assessed for each year t and fire weather class i:

$$\widetilde{F}_{t,i} = o_{t,i}\left(\widetilde{P}_{t,i}\ \widetilde{f}_t\right) \tag{3-6}$$

where

$o_{t,i}$ = Stochastic fire frequency (number per year) in year t and the ith fire weather class

$\widetilde{P}_{t,i}$ = *Potential* wildland fire size vector in year t and the $i^{th}$ fire weather class

$\widetilde{f}_{t,i}$ = column-vector containing the fractional distribution of FCC acres within the the Analysis Area in year t and for the $i^{th}$ fire weather class

Note that the total wildland fire acres per year may be determined by summing Equation (3-5) across all FCCs and fire weather classes.

By *potential wildland fire size*, $\widetilde{P}_{t,i}$ , we mean the size that would result under an assumed level of suppression efficiency and environmental conditions if a wildland fire was burned uniformly and continuously within a single fuel model for the time period during which fires burned historically. For example, if the largest fires that occurred historically within the Analysis Area burned most of their acres over a five- to seven-day period, then future fires predicted in the model are also assumed to burn over a five- to seven-day period.

In FETM, the potential wildland fire sizes are computed using a composite curve of rate of spread (ROS; x-axis variable) versus final fire size (y-axis variable). The relationships are generated for each of the four fuel categories—grass, slash, brush, and timber litter—using information imported from the Interagency Initial Attack Assessment (IIAA; USDA Forest Service, 2001a) model and from case history for large fires that have escaped initial attack within the study area of interest. This is discussed in greater detail in Chapter 4, FETM 4 Assumptions and Component Processes.

#### 3.2.2.3 Wildland Fire Frequency ($o_{t,i}$)

The number of wildland fires that occur annually in each of the four NFDRS fire weather classes is treated as a stochastic (i.e., random) variable in FETM 4. At the beginning of each year in the simulation, a random number is selected from a uniform probability distribution. This random number is then mapped onto a cumulative Poisson probability distribution (density function) whose shape is determined based on the mean number of fires by fire weather class for the Analysis Area of interest. A Poisson probability distribution is a discrete probability distribution (Ross, 1993), meaning that the outcome of the random variable (k) is uniformly distributed as integers over the interval from [k,k+1]. An important characteristic of the Poisson probability distribution is that the mean of the distribution is equal to its variance over a range of values from [0, ∞].

FETM 4 uses a FORTRAN 90 random seed generator (RANDOM_SEED subroutine) to fix the sequence of numbers used in the random number generator (RANDOM_NUMBER subroutine). The randomly generated numbers are then used to map into the Poisson probability a density function (RPOIS subroutine). The output from this sequence of subroutines is a random number of wildland fires per year in each of the four fire weather classes.

The mean number of fires for each of the distributions is computed from historical fire occurrence data compiled by the user for the Analysis Area of interest, as described in the Users Guide, Define Initial Fire Frequency.

As with all probability models, the adequacy of the Poisson distribution is determined by whether the model provides a reasonable approximation of the actual number of fires that have occurred, or are expected to occur, each year.

#### 3.2.2.4 FCC Percent Area Distribution ($\tilde{f}_t$)

The percentage of area within each FCC is computed at the beginning of each simulation time step as:

$$\tilde{f}_t = f_{t,} \frac{a_{t,j}}{\sum_{j=1}^{N} a_{t,j}} \qquad (3\text{-}7)$$

where $f_t$ is the total area within the Analysis Area in each simulation year, and $a_{t,j}$ is the number of acres within each FCC at the start of each year t. Here, j has replaced the tilda (~) on $\tilde{a}_t$ as an explicit index of FCCs ranging from 1 to N (that is, $a_{t,j} = \tilde{a}_t$).

## 3.3 Wildland Fire Emissions Algorithm

The total annual emissions from wildland fire ($WE^{x}_{t,p}$; in pounds of pollutant emitted per year) are calculated based on the fire type (e.g., wildland fire, prescribed fire) and character (e.g., surface fire, passive crown fire, active crown fire), the number of acres burned, and the pollutant-specific per-acre emissions rate predicted by CONSUME version 2.1 (Ottmar et al., 1992; see also: www.fs.fed.us/pnw/fera/products/consume.html). This is expressed in the following equation:

$$WE^{x}_{t,p} = \sum_{i=1}^{4} F_{t,p,i}\ we^{x}_{i} \qquad (3\text{-}8)$$

where

$WE^{x}_{t,p}$ = Total emissions of pollutant "x" in year t for the pth prescribed fire treatment level

$F_{t,p,i}$ = Wildland fire acres in year t for the pth prescribed fire treatment level and the ith fire weather class

$we^{x}_{i}$ = Per-acre wildland fire emissions of pollutant "x" for the ith fire weather class (in pounds of pollutant emitted per acre burned)

The annual wildland fire acreage vector, $F_{t,p,i}$, was determined as shown in Equation (3-6). The fuel consumption and emission rates were obtained using the CONSUME 2.1 model (see Chapter 4.1, Fuel Consumption).

## 3.4 Prescribed Fire Emissions Algorithm

The total annual emissions from prescribed fire ($PE_{t,p}^{x}$; in pounds of pollutant emitted per year) are calculated based on the prescribed fire type (e.g., piles, activity broadcast burn, natural broadcast burn), the number of acres burned, and the pollutant-specific per-acre emissions rate predicted by CONSUME version 2.1 (Ottmar et al., 1992; see also: www.fs.fed.us/pnw/fera/products/consume.html). This is expressed in the following equation:

$$PE_{t,p}^{x} = P_{t,p}\ pe^{x} \tag{3-9}$$

where

$PE_{t,p}^{x}$ = Total prescribed fire emissions of pollutant "x" in year t for the pth prescribed fire treatment level

$P_{t,p}$ = Prescribed fire acres in year t for the pth prescribed fire treatment level

$pe^{x}$ = Per-acre prescribed fire emissions of pollutant "x" (in pounds of pollutant emitted per acre burned)

The annual prescribed fire acres burned, $P_{t,p}$, is a user input to FETM. The prescribed-fire fuel consumption and pollutant-specific emission rates were obtained using the CONSUME 2.1 model (see Chapter 4.1, Fuel Consumption).

# 4 FETM 4 Assumptions and Component Processes

This chapter describes the component processes and assumptions that are used in FETM 4. Some of these component processes exist in FETM 4 as stand-alone executable files (*.exe extension) or as dynamic link libraries (*.dll extension). Others are embedded in the code of the FETM 4 graphic user interface.

## 4.1 Fuel Consumption and Emissions

In FETM 4, fuel consumption and emissions are calculated using the CONSUME 2.1 Active X component, USFSCAX.DLL. CONSUME 2.1 is the latest version of the CONSUME fuel consumption and smoke emissions model, produced by the Fire and Environmental Research Applications unit of the USDA Forest Service, Pacific Northwest Research Station, Seattle (Ottmar et al., 1992). The current version of the DLL used in FETM 4 is 2.01.0146, dated February 28, 2001.

Fuel consumption and emissions are calculated for each FCC and weather class for three burn types: prescribed fire, surface fire; wildland fire, surface fire; and wildland fire, crown fire. The calculation results are determined from the following CONSUME 2.1 output parameters: Cons Total, EmisCH4, EmisCO, EmisCo2, EmisNMHC, EmisPM10, and EmisPM25. The wildland crown outputs are scaled by the crown fraction burned (computed using Equation (4-3a)) for the associated weather class.

Table 4.1 lists the various inputs and assumptions used by FETM 4 in calling USFSCAX.

## 4.2 Weather Processing

In FETM 4, the four NFDRS fire weather classes described in Chapter 3, FETM 4 Architecture, are defined according to a range of spread component (SC) values that are defined by the user (see Users Guide, Define Weather Class Data). When characterizing the weather classes for a particular Analysis Area, the user assigns the *percentile SC breakpoints* between the low and moderate, moderate and high, and high and extreme weather classes. The 15th, 90th, and 98th percentile SC values are the default breakpoints, however they may be changed to any value.

FETM 4 uses the median SC in each range to represent the fire rate of spread by fire weather class. The weather parameters in each of the fire weather classes—including the 1-hour, 10-hour, 100-hour, and 1,000-hour dead-and-down woody fuel moisture, the live herbaceous and live woody fuel moistures, the 20-foot average wind speed, and the fuel temperature—are computed by taking the algebraic mean value of the subset of days whose computed SC lies in the range of SC values that define each fire weather class. For example, assume that the low fire weather class is defined as the range of SC values from SC 0 through SC 9. The weather data for this fire weather class is determined by taking the algebraic mean for every

## Table 4-1. Assumptions Used in Calling CONSUME 2.1 ActiveX Control

| Consume Value | Prescribed Fire (Surface) | Prescribed Fire (Pile) | Wildland Fire (Surface) | Wildland Fire (Pile) | Wildland Fire (Crown) |
|---|---|---|---|---|---|
| **General Species** | Determined from the vegetation type | Determined from the vegetation type | Determined from the vegetation type | Determined from the vegetation type | Determined from the vegetation type |
| **Snow-Off Date** | 1/1/9999 – Taken by CONSUME to mean "no snow" | 1/1/9999 – Taken by CONSUME to mean "no snow" | 1/1/9999 – Taken by CONSUME to mean "no snow" | 1/1/9999 – Taken by CONSUME to mean "no snow" | 1/1/9999 – Taken by CONSUME to mean "no snow" |
| **Duff Type** | Black (litter type) | Black (litter type) | Black (litter type) | Black (litter type) | Black (litter type) |
| **Unit Size (acres)** | 1 | 1 | 1 | 1 | 1 |
| **Fuel Moisture Method, 1,000-Hr** | NFDR-TH | NFDR-TH | NFDR-TH | NFDR-TH | NFDR-TH |
| **Date of Burn** | 01/01/2001 | 01/01/2001 | 01/01/2001 | 01/01/2001 | 01/01/2001 |
| **Days Since Rain** | 6 | 6 | 45 | 45 | 45 |
| **Fuel Loading, 1-Hr** | 1-hr fuel loading | 0 | 1-hr fuel loading | 0 | 1-hr fuel loading |
| **Fuel Loading, 10-Hr** | 10-hr fuel loading | 0 | 10-hr fuel loading | 0 | 0 |
| **Fuel Loading, 100-Hr** | 100-hr fuel loading | 0 | 100-hr fuel loading | 0 | 0 |
| **Fuel Loading, 1,000-Hr** | 1,000-hr fuel loading | 0 | 1,000-hr fuel loading | 0 | 0 |
| **Fuel Loading, 10,000-Hr** | 10,000-hr fuel loading | 0 | 10,000-hr fuel loading | 0 | 0 |

## Table 4-1 (cont.). Assumptions Used in Calling CONSUME 2.1 ActiveX Control

| Consume Value | Prescribed Fire (Surface) | Prescribed Fire (Pile) | Wildland Fire (Surface) | Wildland Fire (Pile) | Wildland Fire (Crown) |
|---|---|---|---|---|---|
| **Fuel Loading, Over 10,000-Hr** | 10,000-hr+ fuel loading | 0 | 10,000-hr+ fuel loading | 0 | 0 |
| **Fuel Loading, Over 3 Rotten** | 0 | 0 | 0 | 0 | 0 |
| **Duff Depth** | Duff depth | 0 | Duff depth | 0 | 0 |
| **Litter Depth** | 0 | 0 | 0 | 0 | 0 |
| **Forest Floor Depth** | Duff depth | 0 | Duff depth | 0 | 0 |
| **Grass/Herbs** | Live herb loading | 0 | Live herb loading | 0 | Crown foliage loading |
| **Shrubs** | Live wood loading | 0 | Live wood loading | 0 | 0 |
| **Type of Fuel** | If Activity Class is 'Natural', then 'Natural' Else 'Activity – Non Piled' | Activity – Piled | If Activity Class is 'Natural', then 'Natural' Else 'Activity – Non Piled' | Activity – Piled | Activity – Non Piled, Activity – Piled, or Natural based on DFM and activity class |
| **Harvest Date** | If activity class is 'Natural', then 1/1/9999 – no harvest. Else 1/1/2000 | 1/1/2000 | If activity class is 'Natural', then 1/1/9999 – no harvest. Else 1/1/2000 | 1/1/2000 | 1/1/9999 – no harvest |
| **Slope** | Derived from slope class | Not assigned | Derived from slope class | Not assigned | Derived from slope class |

## Table 4-1 (cont.). Assumptions Used in Calling CONSUME 2.1 ActiveX Control

<table>
<tr><th>Consume Value</th><th>Prescribed Fire (Surface)</th><th>Prescribed Fire (Pile)</th><th>Wildland Fire (Surface)</th><th>Wildland Fire (Pile)</th><th>Wildland Fire (Crown)</th></tr>
<tr><td rowspan="2"><b>Ignition Duration (minutes)</b></td><td rowspan="2">180</td><td rowspan="2">180</td><td>Calculated from the spread component and potential fire size associated with the weather class as:</td><td>0</td><td>Calculated from the spread component and potential fire size associated with the weather class as:</td></tr>
<tr><td colspan="3"><b>Ignition Duration</b> (min) = $\frac{\sqrt{\text{Final Fire Size (ac)} * 43{,}560 \left(\text{ft}^2/\text{ac}\right)}}{\text{SC}\ (\text{ft}/\text{min})}$</td></tr>
<tr><td><b>Fuel Moisture, 10-Hr</b></td><td>10-hr surface fuel moisture for the weather class</td><td>10-hr surface fuel moisture for the weather class</td><td>10-hr surface fuel moisture for the weather class</td><td>10-hr surface fuel moisture for the weather class</td><td>10 -hr surface fuel moisture for the weather class</td></tr>
<tr><td><b>Fuel Moisture, 1,000- Hr</b></td><td>1,000-hr surface fuel moisture for the weather class</td><td>1,000-hr surface fuel moisture for the weather class</td><td>1,000-hr surface fuel moisture for the weather class</td><td>1,000-hr surface fuel moisture for the weather class</td><td>1,000-hr surface fuel moisture for the weather class</td></tr>
<tr><td><b>Fuel Moisture, Duff</b></td><td>If fuel type is ‘Natural, then 1,000-hr fuel moisture * 4. Else 0.</td><td>0</td><td>If fuel type is ‘Natural, then 1,000-hr fuel moisture * 4. Else 0.</td><td>1,000-hr fuel moisture * 4</td><td>1,000-hr fuel moisture * 4</td></tr>
<tr><td><b>Wind Speed (mph)</b></td><td>20-foot wind speed for the weather class</td><td>20-foot wind speed for the weather class</td><td>20-foot wind speed for the weather class</td><td>20-foot wind speed for the weather class</td><td>20-foot wind speed for the weather class</td></tr>
<tr><td><b>Pile Information</b></td><td></td><td>From pile definition associated with FCC</td><td></td><td>From pile definition associated with FCC</td><td></td></tr>
</table>

day in the fire season whose computed SC lies between SC 0 and SC 9 (inclusive).

## 4.3 Crown Mass

For FCCs with an existing overstory of trees, the tree crown biomass by fuel size class is estimated using the Crown Mass dynamic link library (DLL). The Crown Mass DLL, produced for FETM 4 by Fire Program Solutions and Acacia Services (www.fireps.com), is licensed for unlimited use inside of FETM 4. For any use outside of FETM 4, a special license is required from the developers. The Crown Mass DLL uses debris prediction equations found in the scientific literature to estimate the total loading (mass) of foliage and 1-hour, 10-hour, 100-hour, and 1,000-hour branch wood. Relevant publications include: Brown (1978), Brown et al. (1977), Snell et al. (1980), Snell and Anholt (1981), Snell and Little (1983), and Snell and Max (1985). The version of the DLL found in FETM 4 (Crown Mass version 1.1.0.33, modified June 26, 2000, 7:47:10 AM) contains debris prediction equations for 33 western tree species.

The canopy fuel loading available for crowning (CFAC) is based on the foliage mass and the 1-hour time lag dead fuel mass. Current assumptions (Reinhardt et al., 2000) are that the foliage mass and 50 percent of the 1-hour time lag dead fuel mass contribute to the flaming portion of a crown fire. However, the assumption of 50 percent may be changed in FETM 4 prior to running the Crown Mass DLL.

In addition to computing the total crown loading, the Crown Mass DLL returns other information required to assess the crown fire potential (see Chapter 4.4.2, Crown Fire Behavior), such as the canopy base height and the maximum crown bulk density (Reinhardt et al., 2000; Van Wagner, 1993, 1977).

The canopy base height (CBH) required for crown-fire initiation is based on the minimum height above the ground (nearest one foot) at which the threshold crown bulk density (CBD) required for vertical propagation of fire is achieved. The default minimum CBD in FETM is 100 pounds of CFLC per acre-foot, or 0.0023 pounds of CFLC per cubic foot based on work by Sando and Wick (1972). This program default may be changed in FETM 4 prior to running the Crown Mass DLL.

The Crown Mass DLL accepts tree list data entered by the user in forms constructed in FETM 4. Guidance on entering data into FETM 4 is provided in the FETM 4 Users Guide.

## 4.4 Fire Behavior

### 4.4.1 Surface Fire Behavior

Expected surface fire behavior is generated in FETM 4 using the version of the NFDRCalc dynamic link library that is included in the FireFamily Plus Version 2.0 modeling system (USDA Forest Service, 2000). The NFDRCalc dynamic link library contains the equation set used to compute the National Fire Danger Rating System parameters. Fire behavior is assessed in FETM 4 using the following parameters:

- Rate of spread (chains per hour)
- Fireline intensity (BTU per foot per second)
- Spread component (feet per minute)
- Energy release component (dimensionless)
- Burning index (dimensionless)
- Ignition component (dimensionless)

These fire behavior parameters are computed using the NFDRCalc dynamic link library upon returning to FETM 4 from the Historic Analysis-Initial Attack (HAIA) model, a component of FETM 4 (see Users Guide, Initiate HAIA). The NFDRCalc dynamic link library is executed once for each of the *derivative NFDRS fuel models* selected by the user inside of HAIA, but only if the weather-based outputs have been computed first by HAIA. A total of 284 derivative fuel models are available within HAIA and FETM, the same set of derivative fuel models included in the current version of the FORBS model (USDA Forest Service, 1999). Fire behavior for FCCs is obtained by mapping each of the FCCs to one of the 284 derivative NFDRS fuel models. The 284 derivative fuel models and their characteristics are listed in Appendix B, Table B-1, Fuel Model Parameters for the FETM 4 Fuel Model Set.

## 4.4.2 Crown Fire Behavior

### 4.4.2.1 Crown Fire Initiation

For tree crowns to ignite, the intensity of the surface fire, $I_{surface}$, must be greater than the critical fire line intensity required to ignite the tree crowns, $I_{critical}$. $I_{surface}$ is computed in FETM 4 using the same algorithm as the one used in the FireFamily Plus. $I_{critical}$ is a function of the crown base height (CBH, in feet) and the crown foliar moisture content, M (in percent) (Van Wagner, 1977, 1993; summarized in Alexander, 1988):

$$I_{critical} = \left(0.003096 \cdot CBH\left(197.50 + 11.186 \cdot M\right)\right)^{1.5} \tag{4-1}$$

where $I_{surface}$ and $I_{critical}$ are both in units of BTU per foot of fire front per second.

The crown base height is computed in FETM 4 using the Crown Mass dynamic link library (see Chapter 4.3, Crown Mass). The foliar moisture content (in percent) is a user entry in FETM 4 (see Users Guide, Manage Fuel Characteristic Class Data).

### 4.4.2.2 Crown Fire Propagation

For an active crown fire, the crown fire rate of spread ($ROS_{crown}$; chains per hour) must be greater than the rate for active crowning (RAC)(Van Wagner, 1977, 1993; summarized in Alexander, 1988). $ROS_{crown}$ is computed using the equation:

$$ROS_{crown} = ROS_{surface} + CFB \cdot \left(ROS_{max\ crown} - ROS_{surface}\right) \tag{4-2}$$

where

$ROS_{surface}$ = Surface rate of spread (chains per hour)
CFB = Crown fraction burned (dimensionless)
$ROS_{max\ crown}$ = Maximum crown rate of spread (chains per hour)

$ROS_{surface}$ is computed using the NFDRCalc dynamic link library (see Chapter 4.4.1, Surface Fire Behavior).

CFB (dimensionless) is computed using the following relationship:

$$CFB = 1 - e^{-0.238\ x} \tag{4-3a}$$

where

$$x = \frac{\left(I_{surface} - I_{critical}\right) ROS_{surface}}{I_{surface}} \tag{4-3b}$$

$ROS_{max\ crown}$ is computed as:

$$ROS_{max\ crown} = 3.34 \cdot ROS_{FBPS\ FM10} \tag{4-4}$$

where $ROS_{FBPS\ FM10}$ is the rate of spread in a standard Fire Behavior Prediction System fuel model 10 in an unshaded condition and with a mid-flame wind speed calculated from the 20-foot wind speed and a wind speed adjustment factor of 0.5. The 20-foot wind speed is an Analysis Area-, FCC-, and NFDRS fire weather class-specific value.

The Rate for Active Crowning (RAC; chains per hour) is computed using the equation:

$$RAC = \frac{0.55861}{CBD_{max}} \tag{4-5}$$

Where $CBD_{max}$ is the maximum crown bulk density (pounds of crown foliage and small branch wood per cubic foot) in any single, one-foot-thick layer within the tree crown. $CBD_{max}$ is computed in FETM 4 using the Crown Mass dynamic link library described in Chapter 4.3, Crown Mass.

## 4.5 Fire Type

### 4.5.1 Fire Types Considered

Three types of fires are computed in FETM 4, each with differing implications in terms of the expected fire size and total emissions (see Chapter 4.5.3, Effect of Fire Type on Fire Size and Emissions). The three fire types computed by FETM 4 are:

- Surface fire
- Passive crown fire (also called "dependent" crown fires by Van Wagner, 1977)
- Active crown fire

A fourth fire type—independent crown fire—is considered very uncommon and short-lived (Van Wagner, 1993) and therefore not considered in FETM 4.

## 4.5.2 Fire Type Selection Algorithms

### 4.5.2.1 Surface Fire

A *surface fire* is expected when $I_{surface} < I_{critical}$.

$I_{surface}$ is computed in FETM 4 using the same algorithm as that used in the FireFamily Plus. $I_{critical}$ is computed using Equation (4-1).

### 4.5.2.2 Passive Crown Fire

A *passive crown fire* is expected when $I_{surface} \geq I_{critical}$ but $ROS_{crown} < RAC$.

$I_{surface}$ and $I_{critical}$ are computed as explained above. $ROS_{crown}$ is computed using Equation (4-2). RAC is computed using Equation (4-5).

### 4.5.2.3 Active Crown Fire

An *active crown fire* is expected when $I_{surface} \geq I_{critical}$ and $ROS_{crown} \geq RAC$.

$I_{surface}$, $I_{critical}$, $ROS_{crown}$, and RAC are all computed as explained above.

## 4.5.3 Effect of Fire Type on Wildland Fire Size and Emissions

With surface fires, the expected fire size is determined from the surface rate of fire spread. And pollutant emissions result from the consumption of surface fuels only (including brush and other "live" fuels but not tree crowns).

With passive crown fires, the expected fire size is similarly determined from the surface rate of spread. Pollutant emissions, on the other hand, result from the consumption of surface fuels, intermediate live fuels, *and* tree crowns. The fraction of the tree crowns that are burned and produce emissions is determined using Equation 4-3a.

With active crown fires, the expected fire size is determined based on the crown rate of spread, which is scaled by the CFB between the surface rate of spread and the maximum crown rate of spread. As in the case of passive crown fires, pollutant emissions result from the consumption of surface fuels, intermediate live fuels, and tree crowns. The fraction of the tree crowns that are burned is generally greater than for passive crown fires (determined by Equation 4-3a), and so the total emissions are greater for active crown fires than for passive crown fires.

Crown fire emissions, even those produced by active crown fires, are usually only a small fraction of the total emissions generated from wildland fires.

## 4.6 Expected Wildland Fire Size

In FETM 4, the expected wildland fire size is determined by multiplying the expected number of fires per year by the area-weighted *potential fire size* (see Chapter 6, Glossary). This operation is illustrated in Equation (3-6). The potential fire size vector is calculated from a set of predictive equations developed for each of the four major fuel categories: namely, timber-litter, slash, grass, and brush. These predictive equations, which show the dependent variable, potential fire size (in acres) as some function of the wildland fire rate of spread (in chains/hour), are developed independently for each fuel category because each possesses distinctly different patterns of fire behavior due to differences in flame lengths and difficulty of suppression. The predictive equations are the product of a nonlinear least-squares regression curve-fit of the data points (see Chapter 4.5.2, Curve-Fitting Algorithm). The predictive equations (actually a composite of two unmatched curve fits) allow the user to estimate the wildland fire size for any fire rate of spread.

The predictive equations vary considerably from one Analysis Area to another depending on the mix of vegetation types and fuel loadings, the efficiency of the suppression organization, and other factors that influence wildland fire size such as terrain and characteristic weather conditions.

The predictive equations for each fuel category and fire weather class are mapped to each FCC based on the derivative fuel model assigned to each FCC.

### 4.6.1 Data Points Used to Construct Relationship Between Wildland Fire Size and Rate of Spread

In FETM 4, the composite relationship between the potential fire size and wildland fire ROS is constructed using data from three sources:

- HAIA-generated (or user-entered) breakpoint rates of spread (BROS) for “controlled” wildland fires less than 1,000 acres.
- Empirical data for “escaped” wildland fires greater than 1,000 acres in size.
- Random selection of wildland fire size for wildland fires whose FETM-predicted size is larger than the largest wildland fire found in the recent historical record (referred to as the “historical maximum wildland fire size”).

The data points populating each of these three regions of the composite relationship are discussed below.

#### 4.6.1.1 HAIA-Generated BROS for Controlled Wildland Fires Less Than 1,000 Acres in Size

The construction of the composite final fire size versus ROS curve begins with the calculation of *breakpoint rates of spread (BROS) for controlled fires* less than 1,000 acres in size occurring in five different fire size classes: A (0 to less than ¼ acre in size), B (¼ acre to less than 10 acres in size), C (10 acres to less than 100 acres in size), D (100 acres to less than 300 acres in size), and E (300 acres to less than 1,000 acres in size). BROS are defined as the fire spread rates (measured in chains per hours) that occur at the "breakpoints" between the fire size classes; that is, the spread rates required to achieve fires that are ¼, 10, 100, 300, and 1,000 acres in size given the suppression organization and other Analysis Area-specific factors that influence fire growth.

The BROS values may be computed using HAIA (see users guide) or input directly by the user. The HAIA module permits new BROS values to be computed inside FETM 4 (or the user may simply use the BROS imported from the IIAA database files) to reflect changes in the weather station prioritization, suppression organization, season start/end dates, or other changes that would produce differences in the suppression effectiveness. Modifications may also be made to reflect the lack of fire protection resources available during multiple-fire occurrence episodes, particularly if those episodes account for a large percentage of the total fire occurrence in the Analysis Area of interest.

#### 4.6.1.2 Empirical Data for Escaped Wildland Fires Greater Than 1,000 Acres in Size

Another major data source for generating the composite ROS versus potential fire size curves is empirical data for recent wildland fires that have escaped initial attack; that is, "escaped" wildland fires greater than roughly 1,000 acres in size.

To characterize these fires, the user is required to input information on at least three wind-driven fires that exhibit the characteristic elliptical fire growth pattern. Required fields include: fire name, final fire size (acres), and the total time of active fire spread (hours). The effective spread rate of the fire was then calculated using a modified form of Anderson's double-elliptical fire growth model (USDA Forest Service, 1990):

$$\mathrm{ROS} = \sqrt{\frac{\mathrm{A}}{\mathrm{K\,T}^2}} \tag{4-6}$$

where

A = final fire size (acres)
K = area factor (acres/chain$^2$) |
ROS = fire spread rate (chains/hour)
T = time of active fire spread (hours)

Table 4-2 presents the area factors (K) as a function of the 20-foot wind speed (mph) up to a maximum wind speed of 15 mph.

#### 4.6.1.3 Wildland Fires Sizes Greater Than the Historical Maximum Wildland Fire Size

For individual FCCs whose FETM-predicted wildland fire size is greater than the maximum historical wildland fire size for the appropriate fuel category, FETM 4 randomly selects a new wildland fire size from a uniform probability distribution ranging from, at the low end, the upper-bound of escaped wildland fire sizes (or 1,000 acres, which ever is larger) to, at the upper end, some arbitrary user-defined maximum potential fire size. The maximum potential wildland fire size in a fuel category—timber litter, slash, grass, and brush—represents the largest possible fire that could occur if it was allowed to burn uniformly and continuously within any single fuel model comprising the fuel category. Different maximum potential fire sizes are expected for each of the four fuel categories.

**Table 4-2. Area Factors for Elliptical Fire Growth Model**

| 20-Foot Wind Speed (mph) | Area Factor, K (acres/chain2) |
|---|---|
| 1 | 0.115 |
| 2 | 0.100 |
| 3 | 0.085 |
| 4 | 0.070 |
| 5 | 0.060 |
| 6 | 0.054 |
| 7 | 0.047 |
| 8 | 0.042 |
| 9 | 0.038 |
| 10 | 0.032 |
| 11 | 0.029 |
| 12 | 0.026 |
| 13 | 0.022 |
| 14 | 0.019 |
| 15 | 0.018 |

Source: USDA Forest Service (1990)

### 4.6.2 Fitting Curves to Wildland Fire Size and ROS Data Points

FETM 4 allows the user to fit a set of curves to the controlled wildland fire size data and the escaped wildland fire data described above in Chapter 4.5.1. Curves are fit to each of these two data sets independently, with an unregulated “matching region” between the curves. The only condition that FETM 4 imposes is that the predicted size of escaped fires cannot be less than the escaped fire threshold of 1,000 acres. Care should be taken in ensuring that the matching region between the two curves is appropriate, particularly if different data points are used to define the composite fire size versus ROS relationship between alternative Analysis Areas or scenarios.

#### 4.6.2.1 Functional Forms Used to Fit Curves

Three functional curve forms are provided in FETM 4 for fitting a curve to the controlled wildland fire sizes:

- Linear with a zero y-intercept
- Power function
- Second-order polynomial with a zero y-intercept

These three forms were selected because: (1) they are expected to fit the range of BROS values that typically occur in vegetated environments, (2) they are all monotonically increasing (i.e., mathematical expression that means "continuously increasing y values with increasing x values"), and (3) they produce lines that pass through the origin.

Eight functional forms were chosen to fit the escaped wildland fire data:

- Linear
- Linear with y-intercept=0
- Power function
- Double-quadratic function
- Second-order polynomial
- Second-order polynomial with y-intercept=0
- Exponential function
- Power function; 10 raised to power of a 3rd-order polynomial ("default" curve fit used in FETM 1.0)

These functional forms were selected to provide flexibility in fitting curves to escaped wildland fire size data.

#### 4.6.2.2 Non-Linear Curve Fitting Algorithm

The curve-fitting algorithm employed in FETM 4 is based on the *Levenberg-Marquardt method* (also called the *Marquardt method*; Press et al., 1992), which has become the standard in nonlinear least squares curve-fitting routines. This method attempts to minimize the non-dimensional statistic $\chi^2$ (chi-squared) of a fit between a set of data points with individual standard deviations and a nonlinear function (one of those listed above) that is dependent on one or more coefficients. The routine iterates until there is a reduction in the $\chi^2$ statistic from one step to the next that is less than a tolerance of $1 \times 10^6$.

The curves and their predictive equations are unique to each Analysis Area and vary greatly with the particular data used to populate the graphs. Care must be taken to accurately represent the pattern of wildland fire growth and suppression effectiveness in the area of interest.

## 4.7 Economic Analysis

In FETM 4, the Present Net Value (PNV; i.e., discounted benefits less discounted costs) is used as the primary measure of economic efficiency for use in comparing different scenarios or alternatives. The PNV calculation in FETM 4 includes the following economic components:

- Monetary cost of fire suppression
- Monetary cost of fuel treatment
- Monetary cost (or benefit) of wildland fire measured in terms of a decrease (or increase) in the value of timber and range resources (referred to as *Monetary Net Value Change*, or *Monetary NVC*)

Non-monetary cost (or benefit) of wildland fire is measured in terms of a decrease (or increase) in the value of other non-timber and non-range resources, including: water use, water storage, fish (warm/cold streams), fish (anadromous/sport), fish (commercial), wildlife (big game), wildlife (other), recreation (dispersed/developed), recreation (wilderness), and improvements (referred to as *Non-Monetary NVC*).

The PNV calculation is summarized as follows:

$$\mathrm{PNV}^{x} = \sum_{i=1}^{I} \left[ \frac{\mathrm{FSC}_i + \mathrm{FTC}_i + \mathrm{NVC}(\mathrm{monetary})_i^{x} + \mathrm{NVC}(\mathrm{nonmonetary})_i^{x}}{(1+r)^{i}} \right] \tag{4-7}$$

where

$\mathrm{PNV}^{x}$ = Present net value of all future costs and benefits (dollars) for fire type x, where x is either wildland fire or prescribed fire

$\mathrm{FSC}_i$ = Fire suppression costs at the end of future year i (dollars) (wildland fire only)

$\mathrm{FTC}_i$ = Fuel treatment costs at the end of future year i (dollars) (user-specified management activities and prescribed fire only)

$\mathrm{NVC}(\mathrm{monetary})_i^{x}$ = Net value change of all monetary resources at the end of future year i (dollars) for fire type x, where x is either prescribed fire or wildland fire

$\mathrm{NVC}(\mathrm{nonmonetary})_i^{x}$ = Net value change of all non-monetary resources at the end of future year i (dollars) for fire type x, where x is either prescribed fire or wildland fire

$i$ = Year index

$r$ = Real discount rate (fraction)

$I$ = Total number of years in simulation (years)

The PNV is the discounted value in the starting year, referred to as the *monetary target year*, of the FETM 4 simulation.

For applications of FETM 4 on land administered by the USDA Forest Service, the discount rate is 4 percent in real or constant dollars as prescribed by forest planning regulations in the Forest Service Handbook (FSH 1909.17). For evaluations on other lands, a 4-percent real discount rate is also recommended for evaluations of long-term investments and operations in land and resource management.

The components of the PNV calculation are described in more detail below.

### 4.7.1 Wildland Fire Suppression Costs

Wildland fire suppression costs (i.e., $FSC_i$ in Equation 4-7) are calculated on the basis of the following components (both IIAA terms):

- Average acre cost (AAC) *by fire size class*
- Unit mission cost (UMC) *by fire size class*

The AAC is the average per-acre cost of fire suppression. For fires that are controlled during initial attack (that is, fire sizes less than 1,000 acres), the AAC is the total emergency fire suppression cost for the fire minus the UMC for the fire, and minus the cost for personnel, equipment, and supplies that is paid for within the (non-emergency) fire program budget. For fires that escape initial attack (that is, grow to a size greater than 1,000 acres), the AAC is the total emergency fire suppression cost of the fire.

The UMC are costs incurred by a particular type of unit each time it is dispatched to a fire that is eventually controlled during the initial attack phase of suppression. For IIAA users, these costs are normally charged to emergency fire suppression funds and do not include preparedness funds.

The equation summarizing the calculation of the fire suppression costs is as follows:

$$\mathrm{FSC_i} = \sum_{m=1}^{6} \sum_{j=1}^{4} \left(\text{Number of Fires}\right)_{i,j,m} \left(\text{Per Fire AAC} + \text{Per Fire UMC}\right)_m \tag{4-8}$$

where

i = Simulation year
j = Fire weather class index [range: 1 to 4]
m = Fire size class [range: 1 to 6 (Size Classes A through F)]

In FETM 4, the per-fire AAC and UMC values by fire size class may be obtained in one of two ways: (1) by importing the relevant AAC and UMC values from the IIAA database file using HAIA, or (2) by directly entering the fire suppression costs by fire size class on the appropriate form in FETM 4.

If HAIA is used, the AAC and UMC values are imported from the IIAA model, and area-weighted average AAC and UMC values are computed on the basis of the fraction of the total Analysis Area found within each *representative location* (an IIAA term). This area weighting is facilitated by a user entry in HAIA specifying the percentage of each representative location found within the Analysis Area.

HAIA was modified to compute the UMC values by fire size class, a departure from the methodology used in the IIAA model.

### 4.7.2 Fuel Treatment Costs

The fuel treatment costs (i.e., $FTC_i$ in Equation 4-7) are computed based on user-provided fuel treatment cost per acre by treatment activity and by FCC. Fuel treatment activities include (total of five to consider):

- Management Activity 1 (user-specified)
- Management Activity 2 (user-specified)
- Management Activity 3 (user-specified)
- Management Activity 4 (user-specified)
- Prescribed Fire

The fuel treatment costs are calculated as follows:

$$FTC_i = \sum_{k=1}^{K} (\text{Acres Treated})_{i,k}^{y} (\text{Per Acre Fuel Treatment Cost})^{y} \tag{4-9}$$

where

i = Year index
k = FCC index [range: 1 to K]
y = Treatment type (list includes user-specified management activities 1 though 4 and prescribed fire)

The user in the scheduling forms in FETM 4 enters the per-acre fuel treatment costs.

### 4.7.3 Net Value Change Calculation

Net Value Change (NVC) is defined as the algebraic sum of the economic effects—whether positive and negative—of wildland fire. A negative NVC represents an economic loss or cost. A positive NVC represents an economic gain or benefit.

NVC is dependent on the number of acres burned and the fire intensity level. The greater the number of acres burned and the greater the fire intensity, the greater (that is, the more *negative*) is the NVC. NVC is computed for both monetary resources (timber and range resources) and non-monetary resources (others listed in the introductory paragraph to Chapter 4.6, Economic Analysis).

### 4.7.3.1 Net Value Change for Monetary Resources

The NVC of monetary resources in year i (i.e., $\text{NVC (monetary)}_i^x$ in Equation (4-7)) is computed as follows:

$$\text{NVC (monetary)}_i^x = \sum_{j=1}^{4}\sum_{k=1}^{K}\sum_{l=1}^{6}\Big[\big(\text{Acres Burned}\big)_{i,j,k,l}^x\big(\text{Per-Acre Monetary NVC}\big)_{k,l}\Big] \tag{4-10}$$

where

i = Simulation year
j = Fire weather class index [range: 1 to 4]
k = FCC index [range: 1 to K]
l = Fire intensity level (FIL) index [range: 1 to 6]
x = Fire type (prescribed fire or wildland fire)

The array of wildland fire acres by year, fire weather class, FCC, and FIL is obtained from FETM 4. The per-acre NVC for timber and range resources is obtained from one of two sources: (1) by importing the per-acre NVC values for timber and range resources from the Interagency Initial Attack Assessment (IIAA) model using the HAIA component of FETM 4 (in reality, FETM 4 imports the timber and range tables from IIAA, and the user maps each FCC to one of the immature timber tables, one of the mature timber tables, and one of the range tables), or (2) by assigning user-defined per-acre NVC values for each FCC, bypassing the IIAA-derived NVC values.

### 4.7.3.2 Net Value Change for Non-Monetary Resources

The NVC of non-monetary resources in year i (i.e., $\text{NVC (nonmonetary)}_i^x$ in Equation (4-7)) is computed as follows:

$$\text{NVC (nonmonetary)}_i^x = \sum_{j=1}^{4}\sum_{l=1}^{6}\Big[\big(\text{Acres Burned}\big)_{i,j,l}^x\big(\text{Per-Acre Monetary NVC}\big)_{l}\Big] \tag{4-11}$$

where

i = Simulation years
j = Fire weather class index [range: 1 to 4]
l = Fire intensity level (FIL) index [range: 1 to 6]
x = Fire type (prescribed fire or wildland fire)

Note that the per-acre non-monetary NVC values are independent of FCCs. They vary only with fire intensity level. The per-acre NVC for non-timber and non-range resources are obtained from one of two sources: (1) by importing the NVC values from the IIAA model using the HAIA component of FETM 4, or (2) by assigning user-defined per-acre NVC values by FIL, bypassing the IIAA-derived values.

# 5 Sensitivity Analysis

Sensitivity analysis is an important aspect of simulation model development. Simulation models abstract from reality by introducing simplifying assumptions about the processes—whether physical, chemical, or ecological—that are being modeled. While these assumptions are necessary to make the model building tractable, they have varying implications for the quality of the model output. Through the process of sensitivity analysis, model builders can identify which of the model component algorithms, parameters, and relationships have the greatest impact on the model outputs. Data inputs that are found to significantly affect model outputs can provide model users with valuable information on where to concentrate their efforts in gathering quality input data. These input parameters may also become candidates for additional research and modeling effort to ensure that key components are properly represented in the model.

## 5.1 Venue for Sensitivity Testing

The venue chosen for the FETM 4 sensitivity analysis is a 233,922-acre portion (referred to as the Central North Analysis Area) of the 1,096,000-acre Boundary Waters Canoe Area Wilderness (BWCAW) in northern Minnesota. The North Central Analysis Area was one of five Analysis Areas included as part of a study using FETM 4 to assess the long-term consequences of alternative fuel treatment programs versus the No Action alternative in an area severely damaged by a windstorm. On July 4, 1999, a severe windstorm passed through the area, toppling trees on approximately 367,000 acres within the BWCAW and on an additional 108,000 acres adjacent to the BWCAW. The USDA Forest Service Superior National Forest used FETM 4 to evaluate several fuel treatment alternatives designed to mitigate the hazard of large wildland fires by treating dead-and-down woody fuels within the wilderness (USDA Forest Service, 2001b). The Central North area was chosen for this sensitivity analysis because of the high degree of care taken in preparing the data used in the BWCAW modeling analysis.

A team of scientists from the University of Minnesota, the Superior National Forest, and several consulting firms characterized the post-blowdown vegetation and fuels within the North Central Analysis Area. The study area was stratified into 198 different FCCs based on stand exam and post-blowdown survey information provided by the Superior National Forest. Overstory stands were identified on 188 of the 198 FCCs. Only 10 of the FCCs were assumed to have no overlying stand.

Thirty-three percent of the area is occupied by non-combustible FCCs (either water or rock). It should be noted that FETM 4 allocates fire to all FCCs that are included—regardless of combustibility—based on the observation that reported fire sizes include all acres within the control area boundary, whether blackened or not. If the fire size data is for blackened acres only, then the non-combustible FCCs should be excluded from the Analysis Area description.

Based on the last 10 years of occurrence data from the Superior National Forest, an average of 61 fires per year are reported within the BWCAW. In the North Central Area, an average of 7 fires per year are reported. Of these, 3.75 fires per year are expected to occur under low fire weather conditions, 3 fires per year are expected to occur under moderate fire weather conditions, 0.2 fires per year (i.e., one fire every five years) are expected to occur under high fire weather conditions, and 0.5 fires per year (i.e., one fire every two years) are expected to occur under extreme fire weather conditions.

The No Action alternative for the North Central Analysis Area (named BW07 in the BWCAW study) was used for this sensitivity analysis; that is, no prescribed fire treatments were included in the analysis. The only fuel treatment that occurs in the result of wildland fire, and to a lesser degree, natural succession to less flammable vegetation classes.

## 5.2 Sensitivity Tests Performed

Table 5.1 summarizes the sensitivity tests applied to the FETM 4 model. The results summarized below are the means and standard deviations of model results from 10 individual runs, each run consisting of (unless other noted) 200 independent iterations (simulations).

## 5.3 Sensitivity Test Results

The results of the sensitivity testing of FETM 4 are summarized in the sections and tables that follow.

### 5.3.1 Effect of Increasing the Number of Iterations in a Single Run Over Which Model Results Are Averaged

Table 5-2a and 5-2b present the results of a test to evaluate the effect of increasing the number of model iterations on the mean and variability in the wildland fire acres and emissions over time. This test is designed to show how the mean and variability of 10 independent model runs change as the number of iterations is increased from 30 to 500.

The results show that increasing the number of model iterations had little or no effect on the mean wildfire acres burned in the 1st and 3rd decades, but had a major effect on the variability in the results for the 10 independent model runs. The mean wildfire acres in the 1st decade (that is, the mean for the 10 independent model runs, with a different number of iterations within each run) ranged from a low of 127,071 ± 508 acres (95 percent confidence interval) at 200 iterations to a high of 128,916 ± 1,162 acres at 50 iterations. This is a difference of less than 1.5 percent between the low and high mean values. There is a significant difference between these two sample means at the 95 percent confidence level, but not for any of the other sample means.

The number of model iterations had a much greater effect on the standard deviation. The greater the number of iterations, the lower was the variation among the 10 independent sample means. The standard deviation decreased monotonically with an increasing number

## Table 5-1. Summary of Sensitivity Tests Performed Using FETM 4

| Sensitivity Test Description | Value or Assumption Tested | Number of Runs [1] | Measure of Effect |
|---|---|---|---|
| A. Effect of Increasing the Number of Iterations in a Single Run Over Which Model Results Are Averaged | 1. 30 Iterations per Run<br>2. 50 Iterations per Run<br>3. 100 Iterations per Run<br>4. 200 Iterations per Run<br>5. 500 Iterations per Run | 10<br>10<br>10<br>10<br>10 | • Cumulative Wildland Fire Acres in 1st and 3rd decades (mean, SDEV, percent change, RSD)<br>• Cumulative $PM_{10}$ Emissions in 1st and 3rd decades (mean, SDEV, percent change, RSD) |
| B. Effect of Increasing the Proportion of Analysis Area Occupied by Non-Combustible FCCs | 1. 0% of Area in Non-Combustible FCCs<br>2. 10% of Area in Non-Combustible FCCs<br>3. 20% of Area in Non-Combustible FCCs<br>4. 30% of Area in Non-Combustible FCCs<br>5. 33% of Area in Non-Combustible FCCs | 10<br>10<br>10<br>10<br>10 | • Same as above |
| C. Effect of Ignoring the Presence of Stands (Limits the Opportunity for Active Crown Fire Rates of Spread and Active and Passive Crown Fire Emissions) | 1. Use Original Stand Assignments in BWCAW Analysis ("Stands")<br>2. All FCCs Characterized Using Surface Fuels Only ("No Stands") | 10<br>10 | • Same as above |
| D. Effect of Changing the Historical Fire Sizes for All Fuel Categories | 1. Original Historical Escaped Fire Sizes<br>2. Double the Size of Historical Escaped Fires | 10<br>10 | • Same as above |

### Table 5-1 (cont.). Summary of Sensitivity Tests Performed Using FETM 4

| Sensitivity Test Description | Values Tested | Number of Runs [1] | Measure of Effect |
|---|---|---|---|
| E. Effect of Changing the Breakpoint Spread Component for the Moderate Fire Weather Class | 1. Original Breakpoint for Moderate Fire Weather Class Set at 90th Percentile SC for all Derivative Fuel Models | 10 | • Same as above |
| | 2. Breakpoint for Moderate Fire Weather Class Reset to 50th Percentile Spread Component for Derivative Fuel Models | 10 | |
| F. Effect of Increasing the Maximum Expected Fire Size in Each Fuel Category | 1. 78,000 Acres Maximum in All Fuel Categories (Original) | 10 | • Same as above |
| | 2. 200,000 Acres Maximum in All Fuel Categories | 10 | |
| | 3. 500,000 Acres Maximum in All Fuel Categories | 10 | |

[1] Number of independent runs over which results are averaged and compared. Each run contains 200 iterations unless otherwise noted.

## Table 5-2a. FETM 4 Sensitivity Test Results:

## Effect of Increasing the Number of Model Iterations on Decade-Total Wildland Fire Acres[1]

| | | Decade 1 | | | | Decade 3 | | | |
|---|---|---|---|---|---|---|---|---|---|
| Number | Number of Model Iterations | Total Wildfire Acres (acres) | Percent Change (percent) | SDEV Wildfire Acres (acres) | RSD (percent) | Total Wildfire Acres (acres) | Percent Change (percent) | SDEV Wildfire Acres (acres) | RSD (percent) |
| 1A | 30 | 127,242 | 0 | 2,059 | 1.6 | 23,452 | 0 | 924 | 3.9 |
| 2A | 50 | 128,916 | 1.3 | 1,875 | 1.5 | 23,337 | -0.5 | 561 | 2.4 |
| 3A | 100 | 127,793 | 0.4 | 1,322 | 1.0 | 23,483 | 0.1 | 313 | 1.3 |
| 4A | 200 | 127,071 | -0.1 | 820 | 0.6 | 23,273 | -0.8 | 264 | 1.1 |
| 5A | 500 | 127,340 | 0.1 | 414 | 0.3 | 23,517 | 0.3 | 315 | 1.3 |

[1]Run with total of 157,194 combustible acres, 6 non-combustible acres.

## Table 5-2b. FETM 4 Sensitivity Test Results:

## Effect of Increasing the Number of Model Iterations on Decade-Total $PM_{10}$ Emissions

| | | Decade 1 | | | | Decade 3 | | | |
|---|---|---|---|---|---|---|---|---|---|
| Number | Number of Model Iterations | Total $PM_{10}$ Emissions (tons) | Percent Change (percent) | SDEV $PM_{10}$ Emissions (tons) | RSD (percent) | Total $PM_{10}$ Emissions (tons) | Percent Change (percent) | SDEV $PM_{10}$ Emissions (tons) | RSD (percent) |
| 1A | 30 | 11,436 | 0 | 194 | 1.7 | 2,157 | 0 | 87 | 4.0 |
| 2A | 50 | 11,579 | 1.3 | 156 | 1.3 | 2,133 | -1.1 | 57 | 2.7 |
| 3A | 100 | 11,483 | 0.4 | 112 | 1.0 | 2,153 | -0.2 | 33 | 1.5 |
| 4A | 200 | 11,413 | -0.2 | 68 | 0.6 | 2,127 | -1.4 | 26 | 1.2 |
| 5A | 500 | 11,443 | 0.1 | 35 | 0.3 | 2,159 | 0.1 | 30 | 1.4 |

of model iterations, from a high of 2,059 acres at 30 iterations to a low of 414 acres at 500 iterations.

The *relative standard deviation* (RSD; defined as the standard deviation divided by the mean and multiplied by 100) behaved in the same manner as the standard deviation. The RSD decreases monotonically from a high of 1.5 percent at 30 iterations to a low of 0.3 percent at 500 iterations.

The pattern of $PM_{10}$ emissions mirrored the pattern of wildfire acres burned. As expected, the greater the number of wildfire acres burned, the greater the $PM_{10}$ emissions.

### 5.3.2 Effect of Increasing the Proportion of the Analysis Area Occupied by Non-Combustible FCCs

Table 5-2c and 5-2d summarize the results of a series of sensitivity tests used to assess the effect of increasing the proportion of acres within the Analysis Area that are occupied by non-combustible FCCs on the decade-total wildfire acres burned and $PM_{10}$ emissions. The values in these tables represent the arithmetic average of the 10 independent sample means comprising 200 iterations of the model.

FETM 4 allocates wildland fire acres to each FCC in proportion to each FCC's fraction of the total acres within the Analysis Area, without regard to its combustibility. For example, if an FCC defined as "water" occupies 50 percent of an Analysis Area, then 50 percent of predicted wildland fire acres would be distributed to that FCC. But because the FCC "water" contains no fuel loading, it produces no fuel consumption or emissions. The rationale for distributing fire in this way is that, historically, the acreage reported for wildland fires includes all land uses and types within its perimeter, whether combustible or not. This includes lakes, streams, roads, and rock. In reporting wildland fire acres, however, FETM adjusts the totals to remove acres that are distributed to non-combustible FCCs. In other words, FETM reports "blackened" wildland fire acres only. Even though FETM removes these acres from the total reported wildland fire acres, the presence of non-combustible FCCs *may* have an effect on the total number of wildland fire acres generated by the model.

The results show that the mean number of wildland fire acres in either the 1st or 3rd decades is expected to decrease as the number of non-combustible acres within the analysis

## Table 5-2c. FETM 4 Sensitivity Test Results: Effect of Increasing the Proportion of the Analysis Area Occupied by Non-Combustible FCCs on Decade-Total Wildland Fire Acres[1]

| | | Decade 1 | | | | Decade 3 | | | |
|---|---|---|---|---|---|---|---|---|---|
| Number | Percent of Area Non-Combustible (percent) | Total Wildfire Acres (acres) | Percent Change (percent) | SDEV Wildfire Acres (acres) | RSD (percent) | Total Wildfire Acres (acres) | Percent Change (percent) | SDEV Wildfire Acres (acres) | RSD (percent) |
| 1B | 0 | 102,667 | 0 | 1,125 | 1.1 | 22,051 | 0 | 570 | 2.6 |
| 2B | 10 | 101,616 | -1.0 | 963 | 0.9 | 20,952 | -5.0 | 284 | 1.4 |
| 3B | 20 | 100,717 | -1.9 | 974 | 1.0 | 19,910 | -9.7 | 301 | 1.5 |
| 4B | 30 | 99,849 | -2.8 | 1,517 | 1.5 | 18,970 | -14 | 319 | 1.7 |
| 5B | 33 | 100,104 | -2.5 | 808 | 0.8 | 18,643 | -16 | 233 | 1.2 |

[1]Run with total of 233,916 combustible acres, and from 6 to 76,734 non-combustible acres.

## Table 5-2d. FETM 4 Sensitivity Test Results: Effect of Increasing the Proportion of the Analysis Area Occupied by Non-Combustible FCCs on Decade-Total $PM_{10}$ Emissions

| | | Decade 1 | | | | Decade 3 | | | |
|---|---|---|---|---|---|---|---|---|---|
| Number | Percent of Area Non-Combustible (percent) | Total $PM_{10}$ Emissions (tons) | Percent Change (percent) | SDEV $PM_{10}$ Emissions (tons) | RSD (percent) | Total $PM_{10}$ Emissions (tons) | Percent Change (percent) | SDEV $PM_{10}$ Emissions (tons) | RSD (percent) |
| 1B | 0 | 6,550 | 0 | 68 | 1.0 | 1,498 | 0 | 40 | 2.7 |
| 2B | 10 | 6,483 | -1.0 | 59 | 0.9 | 1,425 | -4.9 | 22 | 1.5 |
| 3B | 20 | 6,427 | -1.9 | 63 | 1.0 | 1,355 | -9.6 | 22 | 1.6 |
| 4B | 30 | 6,368 | -2.8 | 91 | 1.4 | 1,292 | -14 | 23 | 1.8 |
| 5B | 33 | 6,386 | -2.5 | 52 | 0.8 | 1,270 | -15 | 18 | 1.4 |

area increases. Increasing the proportion of non-combustible acres within the Analysis Area from zero percent to 10 percent of the total area (23,932 non-combustible acres) resulted in a less-than-1-percent decrease in mean wildfire acres in the 1st decade, and a less-than-5-percent decrease in mean wildfire acres in the 3rd decade. Additionally, an increase of the proportion of non-combustible acres within the Analysis Area from zero percent to 30 percent of the total area (70,176 non-combustible acres) resulted in a less-than-3-percent decrease in wildfire acres in the 1st decade and a 14-percent decrease in the wildfire acres in the 3rd decade. These results indicate that the model is low to moderately sensitive to changes in the proportion of the analysis occupied by non-combustible FCCs.

In this test, the pattern of $PM_{10}$ emissions mirrors that of wildland fire acres.

### 5.3.3 Effect of Ignoring the Presence of Stands

Tables 5-2e and 5-2f summarize the results of sensitivity testing to determine the effect of ignoring the presence of standing trees within the Analysis Area; that is, determining the effects of fire on the basis of the surface fuel bed only. The values in these tables represent the arithmetic mean and standard deviation of the outcomes of 10 independent model runs (at 200 iterations each) for two scenarios: (1) including stand effects and (2) excluding stand effects (i.e., ignoring presence of standing trees). This test illustrates the influence of standing trees on the wildland fire acres and $PM_{10}$ emissions over time.

Ignoring the presence of standing trees had little or no effect on the mean number of wildfire acres burned in the 1st and 3rd decades. The mean number of wildland fire acres in the 1st decade increased from 127,071 ± 508 acres (including stand effects; 95 percent confidence interval) to 127,203 ± 591 acres (excluding stand effects)—a difference of 132 acres, or 0.1 percent. Although there was a small increase in the number of wildfire acres burned, the difference is not statistically significant at the 95 percent confidence level.

Ignoring the presence of standing trees, however, significantly reduces emissions. Table 5-2f shows that $PM_{10}$ emissions in the first decade are expected to decrease from 11,413 ± 42 tons (with stands) to 10,074 ± 44 tons (without stands)—a difference of 1,339 tons, or 12 percent. The difference between the two sample means is significant at the 95 percent confidence level. This reduction in emissions is the direct result of ignoring consumption and emissions from tree crowns.

## Table 5-2e. FETM 4 Sensitivity Test Results:
## Effect of Ignoring the Presence of Standing Trees on Decade-Total Wildland Fire Acres[1]

| | | Decade 1 | | | | Decade 3 | | | |
|---|---|---|---|---|---|---|---|---|---|
| Number | Treatment | Total Wildfire Acres (acres) | Percent Change (percent) | SDEV Wildfire Acres (acres) | RSD (percent) | Total Wildfire Acres (acres) | Percent Change (percent) | SDEV Wildfire Acres (acres) | RSD (percent) |
| 1C | With Stands | 127,071 | 0 | 820 | 0.65 | 23,273 | 0 | 264 | 1.1 |
| 2C | Without Stands | 127,203 | 0.1 | 954 | 0.75 | 23,261 | -0.05 | 565 | 2.4 |

[1] Run with total of 157,194 combustible acres, 6 non-combustible acres.

## Table 5-2f. FETM 4 Sensitivity Test Results:
## Effect of Ignoring the Presence of Standing Trees on Decade-Total $PM_{10}$ Emissions

| | | Decade 1 | | | | Decade 3 | | | |
|---|---|---|---|---|---|---|---|---|---|
| Number | Treatment | Total $PM_{10}$ Emissions (tons) | Percent Change (percent) | SDEV $PM_{10}$ Emissions (tons) | RSD (percent) | Total $PM_{10}$ Emissions (tons) | Percent Change (percent) | SDEV $PM_{10}$ Emissions (tons) | RSD (percent) |
| 1C | With Stands | 11,413 | 0 | 68 | 0.60 | 2,127 | 0 | 26 | 1.2 |
| 2C | Without Stands | 10,074 | -12 | 71 | 0.70 | 1,807 | -15 | 43 | 2.4 |

### 5.3.4 Effect of Changing the Historical Fire Sizes

Tables 5-2g and 5-2h summarize the results of a test to determine the effect of doubling the historical fire sizes within the Analysis Area on the decade-total wildfire acres and emissions over time. FETM 4 uses information on large fires that have occurred historically within the Analysis Area to generate composite final fire size versus rate of spread curves in each of four fuel categories (timber litter, slash, grass, and brush). The larger the historical fire sizes, the greater the number of wildfire acres predicted by FETM 4 within the Analysis Area. Anything that affects the shape of the curves will have some effect on wildfire acres burned and emissions.

The values in these tables represent the arithmetic mean and standard deviation of the outcomes of 10 independent model runs (at 200 iterations each) for the original (historical) fire sizes and for the alternative case of a doubling of the historical fire sizes.

Doubling the historical fire sizes resulted in a 17-percent increase in the wildfire acres burned in the 1st decade, from 127,071 ± 508 acres (95 percent confidence interval) using the historical fire sizes to 149,125 ± 661 acres using the doubled wildfire sizes. The difference between the two is significant at the 95 percent confidence level.

The increase in wildfire acres was less dramatic in the 3rd decade: a doubling of the historical fire sizes resulted in a 7-percent increase in wildfire acres. The decline in the rate of increase in wildfire acres produced by a doubling of the historical wildfire sizes is attributed to the fuel treatment effect of large wildfires. The greater the number of wildfire acres burned, the greater is the area-average reduction in residue loadings and the smaller are the sizes of future wildfires.

Doubling the historical fire sizes produced a similar effect on $PM_{10}$ emissions. The $PM_{10}$ emissions increased roughly 15 percent, from 11,413 ± 42 tons (95 percent confidence interval) under the original scenario to 13,140 ± 52 tons under the alternative scenario. The difference between the two means is also significant at the 95 percent confidence level.

## Table 5-2g. FETM 4 Sensitivity Test Results:

## Effect of Changing the Historical Fire Sizes on Decade-Total Wildland Fire Acres[1]

| | | Decade 1 | | | | Decade 3 | | | |
|---|---|---|---|---|---|---|---|---|---|
| Number | Treatment | Total Wildfire Acres (acres) | Percent Change (percent) | SDEV Wildfire Acres (acres) | RSD (percent) | Total Wildfire Acres (acres) | Percent Change (percent) | SDEV Wildfire Acres (acres) | RSD (percent) |
| 1D | 1x Historical Fire Sizes | 127,071 | 0 | 820 | 0.65 | 23,273 | 0 | 264 | 1.1 |
| 2D | 2x Historical Fire Sizes | 149,125 | 17 | 1,067 | 0.72 | 24,968 | 7.3 | 370 | 1.5 |

[1] Run with total of 157,194 combustible acres, 6 non-combustible acres.

## Table 5-2h. FETM 4 Sensitivity Test Results:

## Effect of Changing the Historical Fire Sizes on Decade-Total $PM_{10}$ Emissions

| | | Decade 1 | | | | Decade 3 | | | |
|---|---|---|---|---|---|---|---|---|---|
| Number | Treatment | Total $PM_{10}$ Emissions (tons) | Percent Change (percent) | SDEV $PM_{10}$ Emissions (tons) | RSD (percent) | Total $PM_{10}$ Emissions (tons) | Percent Change (percent) | SDEV $PM_{10}$ Emissions (tons) | RSD (percent) |
| 1D | 1x Historical Fire Sizes | 11,413 | 0 | 68 | 0.60 | 2,127 | 0 | 26 | 1.2 |
| 2D | 2x Historical Fire Sizes | 13,140 | 15 | 84 | 0.64 | 2,237 | 5.2 | 38 | 1.7 |

### 5.3.5 Effect of Changing the Breakpoint Spread Component for the Moderate Fire Weather Class

Tables 5-2i and 5-2j summarize the results of a test to determine the effect of changing the breakpoint spread component (SC) used to characterize the moderate fire weather class. In this test, the breakpoint SC was changed from the 90th percentile SC to the 50th percentile SC for all derivative fuel models. This change is expected to enlarge the range of weather conditions included in the moderate fire weather class (thereby moderating its fire behavior) and to restrict the range of weather conditions included in the high fire weather class (thereby increasing its fire behavior). Because most of the fire starts in the Boundary Waters Analysis Area occur in the moderate fire weather class, this change is expected to reduce the decade-total wildfire acres and emissions.

Changing the breakpoint SC used to characterize the moderate fire weather class had a marked effect on the wildfire acres burned and emissions over time. The number of wildfire acres in the 1st decade decreased 44 percent from 127,071 ± 508 acres using the 90th percentile SC as the breakpoint to 70,893 ± 741 acres using the 50th percentile SC as the breakpoint. The difference between the two means is highly significant at the 95 percent confidence level.

The decrease in the wildfire acres is even more dramatic in the 3rd decade: -48 percent.

A similar pattern was observed with $PM_{10}$ emissions. The total $PM_{10}$ emissions decreased 42 percent from 11,413 ± 42 tons (95 percent confidence interval) using the 90th percentile SC to 6,631 ± 69 tons using the 50th percentile SC. The difference between the two means is highly significant at the 95 percent confidence level.

## Table 5-2i. FETM 4 Sensitivity Test Results: Effect of Changing the Breakpoint Spread Component for the Moderate Fire Weather Class on Decade-Total Wildland Fire Acres[1]

| | | Decade 1 | | | | Decade 3 | | | |
|---|---|---|---|---|---|---|---|---|---|
| Number | Treatment | Total Wildfire Acres (acres) | Percent Change (percent) | SDEV Wildfire Acres (acres) | RSD (percent) | Total Wildfire Acres (acres) | Percent Change (percent) | SDEV Wildfire Acres (acres) | RSD (percent) |
| 1E | Breakpoint Set at 90th-Percentile SC | 127,071 | 0 | 820 | 0.65 | 23,273 | 0 | 264 | 1.1 |
| 2E | Breakpoint Set at 50th-Percentile SC | 70,893 | -44 | 1,195 | 1.7 | 12,047 | -48 | 235 | 2.0 |

[1] Run with total of 157,194 combustible acres, 6 non-combustible acres.

## Table 5-2j. FETM 4 Sensitivity Test Results: Effect of Changing the Breakpoint Spread Component for the Moderate Fire Weather Class on Decade-Total $PM_{10}$ Emissions

| | | Decade 1 | | | | Decade 3 | | | |
|---|---|---|---|---|---|---|---|---|---|
| Number | Treatment | Total $PM_{10}$ Emissions (tons) | Percent Change (percent) | SDEV $PM_{10}$ Emissions (tons) | RSD (percent) | Total $PM_{10}$ Emissions (tons) | Percent Change (percent) | SDEV $PM_{10}$ Emissions (tons) | RSD (percent) |
| 1E | Breakpoint Set at 90th-Percentile SC | 11,413 | 0 | 68 | 0.60 | 2,127 | 0 | 26 | 1.2 |
| 2E | Breakpoint Set at 50th-Percentile SC | 6,631 | -42 | 111 | 1.7 | 1,203 | -43 | 26 | 2.2 |

### 5.3.6 Effect of Increasing the Maximum Potential Fire Size for All Fuel Categories

Table 5-2k summarizes the results of a test to determine the effect of increasing the maximum potential fire size for all fuel categories in FETM 4 from 78,000 acres to either 200,000 or 500,000 acres. In FETM 4, the maximum potential fire size is used only when the fire size predicted by FETM 4 exceeds the maximum historical size entered by the user. When that occurs, FETM 4 selects the fire size from a uniform probability distribution within the range of the maximum *historical* fire size (lower bound) and the maximum *potential* fire size (upper bound). Otherwise, the maximum potential fire size is not used.

The effect of increasing the maximum potential fire size will depend on the proportion of wildfire acres that are generated by random selection. If a large proportion of the total wildfire acres are generated randomly, then the effect of the change will be more pronounced than if a small proportion of the total wildfire acres are generated randomly.

This test shows that increasing the maximum potential fire size from 78,000 acres to either 200,000 acres or 500,000 acres had no discernible effect on the decade-total wildfire acres burned or emissions. With the maximum potential fire size set at 78,000 acres, a total of 127,071 ± 508 acres (95 percent confidence level) were burned in the 1st decade, and 23,273 ± 163 acres in the 3rd decade. With the maximum potential fire size set at 200,000 acres, a total of 127,791 ± 695 acres (95 percent confidence level) were burned in the 1st decade, and 23,336 ± 255 acres in the 3rd decade. With the maximum potential fire size set at 500,000 acres, a total of 126,783 ± 961 acres (95 percent confidence level) were burned in the 1st decade, and 23,419 ± 208 acres in the 3rd decade. No significant difference was found between any of the sample mean at the 95 percent confidence level.

A similar pattern was observed with $PM_{10}$ emissions in the 1st and 3rd decades.

## Table 5-2k. FETM 4 Sensitivity Test Results:
## Effect of Increasing the Maximum Potential Fire Size for All Fuel Categories on Decade-Total Wildland Fire Acres[1]

| | | Decade 1 | | | | Decade 3 | | | |
|---|---|---|---|---|---|---|---|---|---|
| Number | Treatment (Maximum Potential Fire Size) | Total Wildfire Acres (acres) | Percent Change (percent) | SDEV Wildfire Acres (acres) | RSD (percent) | Total Wildfire Acres (acres) | Percent Change (percent) | SDEV Wildfire Acres (acres) | RSD (percent) |
| 1F | 78,000 | 127,071 | 0 | 820 | 0.7 | 23,273 | 0 | 264 | 1.1 |
| 2F | 200,000 | 127,791 | 0.6 | 1,121 | 0.9 | 23,336 | 0.3 | 412 | 1.8 |
| 3F | 500,000 | 126,783 | -0.2 | 1,551 | 1.2 | 23,419 | 0.6 | 386 | 1.6 |

[1]Run with total of 157,194 combustible acres, 6 non-combustible acres.

### 5.3.7 Discussion

The sensitivity test results are presented in Table 5.3. In general, changes in the input variables resulted in one of three effects:

- A change in the mean wildfire acres over time
- A change in the mean $PM_{10}$ emissions over time
- A change in the variability in the mean wildfire acres or the mean $PM_{10}$ emissions among the 10 independent sample runs

Most of the variables tested had either a low or moderate sensitivity to changes in the input values. That is, a change in the input value produced much less than a corresponding change in the output values, measured in terms of one of the three categories listed above. For example, a 50 percent change in the input value produced far less than a 50 percent change in the mean wildfire acres, mean $PM_{10}$ emissions, or variability of acres or emissions. And a 100 percent change in the input value produced far less than a 100 percent change in the values of the output category.

A few of the input variables that were tested were found to be highly sensitive to changes in the input values. Two of the most sensitive variables were: ignoring the presence of standing trees and changing the breakpoint spread components used to characterize weather classes (in this test, only the breakpoint for the moderate weather class was adjusted). In the case of the former, we found that ignoring the presence of standing trees had an insignificant effect on wildfire acres (most of the acres were generated by either surface fires or passive crown fires), but a significant effect on $PM_{10}$ emissions. The resulting decrease in $PM_{10}$ emissions (12 percent in this case) is attributable to ignoring the $PM_{10}$ emissions that occur from the consumption of crown foliage and fine branch wood.

Of the six variables tested, the one that is considered the most sensitive to changes is the breakpoint SC used to characterize the moderate fire weather class. In our testing, a change in the breakpoint SC from the 90th percentile SC to the 50th percentile SC resulted in a 44-percent reduction in wildfire acres and emissions in the 1st decade, and a 48-percent reduction in the acreage and emissions in the 3rd decade. In light of these results, the user is cautioned to spend a reasonable amount of time refining, and justifying, the breakpoint SC values that are used to characterize all of the NFDRS fire weather classes, but particularly those in which the majority of fires occur.

It should also be noted that these test results are merely a reflection of the sensitivity of the model given the inputs and assumptions for the Boundary Waters CAW Analysis Area. A different Analysis Area, perhaps with a different vegetative composition or natural fire regime, might produce dramatically different results than those shown here. Variables that were not found to be sensitive here might be highly sensitive to change under different circumstances. For example, if the majority of wildfire acres predicted by the model exceeded the historical large fire sizes (perhaps as a result of exceptional buildup of surface or elevated residue loading), then changes in the maximum potential fire size would produce highly significant changes in the wildfire acres burned and emissions.

These results should not be used to justify spending a less-than-adequate amount of time in parameterizing variables with low or moderate sensitivity. All of the variables are important, even those listed as having low sensitivity. The model outputs are ultimately a reflection of the combined accuracy (or inaccuracy) of all the input values, so all of the values should be estimated with care. The model is extra-sensitive to some variables, however, and it is these variables that should receive additional time in refinement.

### Table 5-3. Summary of FETM 4 Sensitivity Test Results

| | | Assessment of Sensitivity | | |
|---|---|---|---|---|
| **Test Number** | **Description** | **Wildfire Acres** | **$PM_{10}$ Emissions** | **Variability** |
| 1 | Effect of Increasing the Number of Model Iterations | Low | Low | Moderate |
| 2 | Effect of Increasing the Proportion of the Analysis Area Occupied by Non-Combustible FCCs | Moderate | Moderate | Low |
| 3 | Effect of Ignoring the Presence of Standing Trees | Low | **High** | Low |
| 4 | Effect of Changing the Historical Fire Sizes | Moderate[1] | Moderate[1] | Moderate |
| 5 | Effect of Changing the Breakpoint Spread Component for the Moderate Fire Weather Class | **High**[2] | **High**[2] | Moderate |
| 6 | Effect of Increasing the Maximum Potential Fire Size | Low | Low | Moderate |

[1] Effect produced by a doubling in the historical fire size

[2] Effect produced by decreasing the breakpoint from the 90th percentile SC to 50th percentile SC

# 6 Acronyms and Glossary

Following is a listing of acronyms and terms used in FETM 4, along with their definitions:

| Term | Description |
|---|---|
| **Active Crown Fire** | Crown fire whose rate of spread is linked to the presence of an intense surface fire. Associated with “pulsing” spread, where a crown fire initially spreads ahead of the surface fire front but then weakens due to a lack of reinforcing surface fire heat. After the surface fire catches up to the now-weakened crown fire front, a new “pulsing” crown fire spread is initiated. |
| **Analysis Area** | The geographic area of interest within FETM 4, comprising all or part of one or more administrative units of any combination of federal, state, and private ownerships. |
| **BROS** | See “Breakpoint Rates of Spread” |
| **Breakpoint Rates of Spread (BROS)** | Rate of spread of fires (measured in chains per hours) at the “breakpoints” that divide the fire size classes (that is, the rate of spread that occurs at fire sizes of ¼, 10, 100, 300, and 1,000 acres) |
| **Dependent Crown Fire** | Synonymous with “Passive Crown Fire” |
| **Dynamic** | A modeling term meaning “includes time as a dimension.” That is, model results are generated over time. |
| **Fire Intensity Level (FIL)** | An expression of fire line intensity. Based on the typical flame length of a fire and used to reflect differences in difficulty of suppression. FILs are classified as follows: FIL 1=0-2 foot flame lengths; FIL 2=2-4 foot flame lengths; FIL 3=4-6 foot flame lengths; FIL 4=6-8 foot flame lengths; FIL 5=8-12 foot flame lengths; and FIL 6=12+ foot flame lengths. |
| **Fire Management Zone (FMZ)** | The basic geographic area for the analysis within the planning unit represented by a single set of fire behavior characteristics that are based on fuels, topography, and local weather regime. |
| **HAIA** | Historical Analysis-Initial Attack (HAIA) model; a component (dynamic link library) in FETM 4. |
| **IIAA** | Interagency Initial Attack Assessment (IIAA) model. The current version of a PC-based model designed to perform initial attack simulation to support the analysis of the effects of candidate fire programs. A companion to the PC Historic Analysis (PCHA) model, which together comprise the National Fire Management Analysis System (NFMAS) |

| Term | Description |
|---|---|
| **Independent Crown Fire** | Crown fire that propagates through the tree crowns without support from an intense surface fire. Van Wagner (1993) suggests that independent crown fires are very uncommon and short-lived. FETM 4 does not account for this type of wildland fire. |
| **Mechanical Fuel Treatment** | Fuel treatment accomplished through mechanical or chemical means to reduce fire hazard of wildland fire. |
| **Net Value Change (NVC)** | The measure of the net change in the positive and negative economic impacts of a fire on planned resource outputs. |
| **PCHA** | PC Historic Analysis (PCHA) model; a companion to the Interagency Initial Attack Assessment (IIAA) model, which together comprise the National Fire Management Analysis System (NFMAS) |
| **Passive Crown Fire** | Crown fire whose rate of spread is dependent on the surface rate of spread. Small scale, usually consuming single trees or small groups of trees and brush. Synonymous with “dependent” crown fire. Also referred to as “torching.” |
| **Potential Fire Sizes** | Hypothetical size that a wildland fire would attain if allowed to burn uniformly and continuously within a single fuel model. |
| **Prescribed Fire** | Any fire ignited by management actions to meet specific objectives. |
| **Primary Input** | Value input (or flag set) by the user. Contrasted with: Secondary Input. |
| **Real Discount Rate** | The interest rate, over and above the rate of inflation, at which future values are discounted to present values. |
| **Representative Location (RL)** | A term used to designate a portion of an FMZ represented by a unique set of data relating to the planned typical dispatch of preparedness forces (kind, amount, attack time), potential NVC, and escaped fire potential. An RL is the basis Analysis Area and represents a defined fire occurrence rate. One RL may represent an entire FMZ if conditions are reasonably uniform. An RL and its descriptors reflect average conditions over the area as a whole. |
| **Secondary Input** | Value calculated by FETM user interface algorithm(s) prior to use in dynamical algorithms. |
| **Stochastic** | ”Involving or containing one or more random variables;” a term used in statistics. |
| **Surface Fire** | Fire that burns only in the surface fuel bed. |
| **Torching** | Synonymous with “Passive Crown Fire” |
| **Wildland Fire** | Any non-structural fire, other than prescribed fire, that occurs in wildlands. Prescribed fire is not considered wildland fire. Wildland fire includes: (1) wildfire (generally considered undesirable), and (2) wildland fire managed for benefits (generally considered desirable). |

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## APPENDIX A

# FETM 4 Subroutine Map

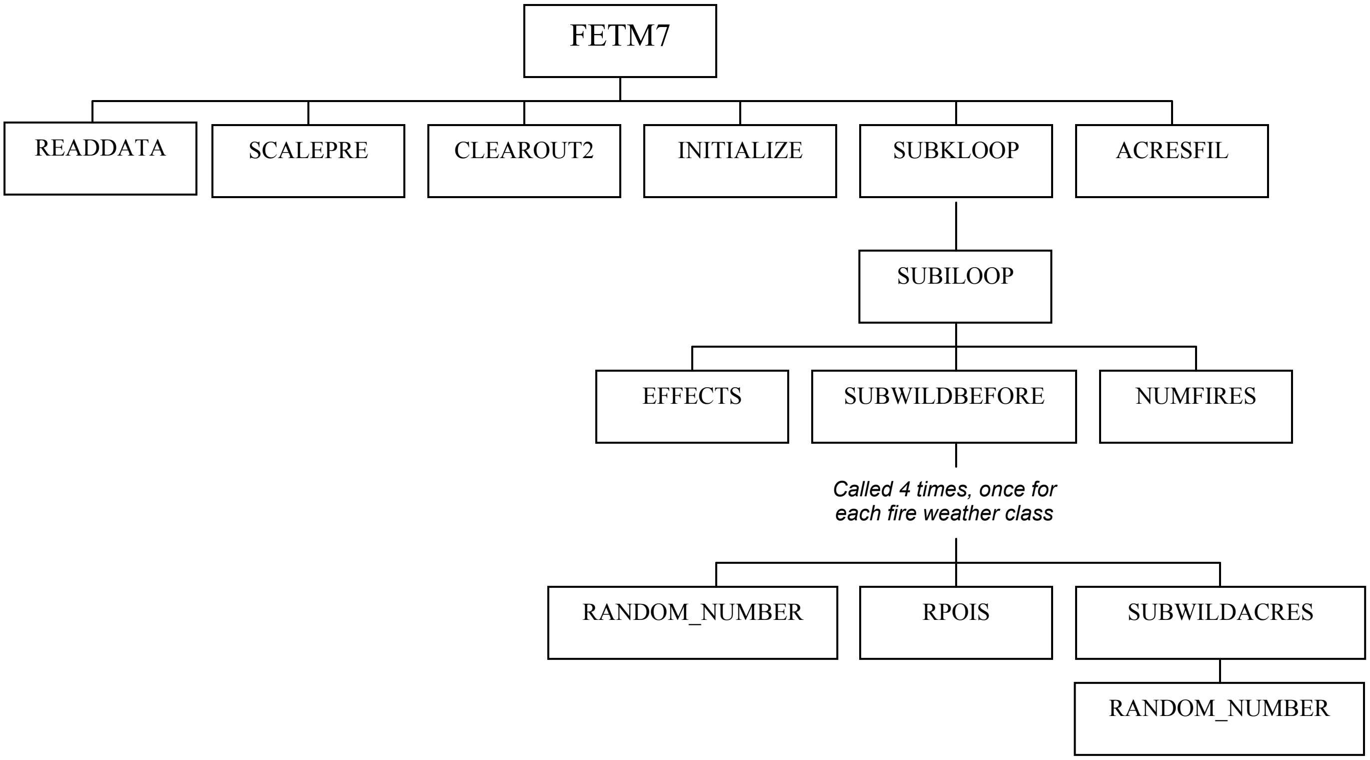

**Figure A-1. Diagram Of FETM 4 Subroutines**

The subroutines named in the above boxes have the following function:

| Subroutine Name | Subroutine Description |
|---|---|
| **READDATA** | Reads the FETM input file (*.inp). |
| **SCALEPRE** | Scales the prescribed fire schedule matrix by a constant for each prescribed fire treatment level, L (up to seven user-specified treatment levels may be run at one time). |
| **CLEAROUT2** | Sets the array tempINR (100,206) to zero, where dimensions are: [number of years in simulation, number of FCCs]. |
| **INITIALIZE** | Clears the following variables:<br>acresFil1, acresFil2, acresFil3, acresFil4, acresFil5, acresFil6, xAcresINR, xAcresINRSq, pacresFil1, pacresFil2, pacresFil3, pacresFil4, pacresFil5, pacresFil6, xManage1AcresINR, xManage2AcresINR, xManage3AcresINR, xManage4AcresINR, xPAcresINR, xRxePM10_I, xRxePM25_I, xRxeHC_I, xRxeCO_I, xRxeCO2_I, xRxeCH4_I , xDisease1AcresINR, xDisease2AcresINR, xDisease3AcresINR, xWildBeforeExINR, xWildBeforeHiINR, xWildBeforeMdINR, xWildBeforeLoINR, xWildBeforeINR, xWildBeforeINRSq, wildBeforeSCL, xWildBeforeI, xWildBeforeISq, xWfEmPM10_I, xWfEmPM25_I, xWfEmHC_I, xWfEmCO_I, xWfEmCO2_I, xWfEmCH4_I, sizeFires, temp |

| Subroutine Name (cont.) | Subroutine Description (cont.) |
|---|---|
| **SUBKLOOP** | Initializes acreage distribution matrix at the beginning of each simulation. Calls SUBILOOP. |
| **ACRESFIL** | Searches the wildland fire acreage array and sums the number of acres in six FIL categories across the four fire weather classes: extreme, high, moderate, and low. The FIL summation is over L loop. The result is a 6 x 7 x 100 array, with dimensions: [number of FIL categories, number of prescribed-fire treatment levels, total number of years in simulation]. Prescribed fire file is a 7 x 100 x 206 array, with dimensions: [level of prescribed-fire treatment, number of years in simulation, number of FCCs]. |
| **SUBILOOP** | Calls the following wildland fire-related subroutines: Effects, SubWildBefore, and NumFires. |
| **EFFECTS** | Apply "effects' matrix and calculate new acreage distribution. |
| **SUBWILDBEFORE** | Computes wildland fire acreage by FCC and fire weather class. |
| **NUMFIRES** | Accumulates number of fires and number of wildland fire acres by fire size class (A though F). |
| **SUBWILDACRES** | Calculates the final fire size in each of the four fire weather classes. Calls random number generator for each FCC whose predicted potential fire size is greater than the historical maximum fire size for its parent fuel category (i.e., timber litter, grass, slash, and brush). Returns "adjusted" potential wildland fire size in range of [upper-limit historical wildland fire size, maximum potential wildland fire size]. |
| **RANDOM_NUMBER** | Returns uniformly distributed pseudo-random numbers in the range of $0 \leq x < 1$. The generator uses an algorithm with a period of approximately $a^{38}$. |
| **RPOIS** | Returns the annual fire frequency by fire weather class by mapping random number onto cumulative Poisson probability distribution. |

### APPENDIX B

# FETM 4 ASCII Output Files

## Directory Structure

The output files from FETM 4 are always stored in a directory with the same name as the scenario name, which is located in "aadata" (Analysis Area data) directory under the directory holding the FETM 4 program files. Generically, these output files are found in:

[FETM 4 program file directory]\aadata\[scenario name]

For example, if the FETM 4 model is installed in c:\models\fetm42, and the scenario is called "test run," then the ASCII output files would be found in:

C:\models\fetm42\aadata\testrun\

If the FETM 4 model is installed in c:\program files\fetm42, and the scenario is called "base case," then the ASCII output files would be found in:

C:\program files\fetm42\aadata\basecase\

## File Names and Descriptions

The names and descriptions of the text output files are described below. All files are space-delimited. They are most easily viewed and used by opening in Microsoft Excel.

| Output File Name | Description of Contents |
|---|---|
| [filename].inp | Input file containing information needed in dynamic calculations (e.g., wildland fire acres and emissions). Maximum of eight characters in filename. |
| acres.csv | File containing FCC acres in each year of simulation. Fields are:<br>• Prescribed fire treatment level: Column 1<br>• Prescribed fire scaling factor: Column 2<br>• FCC number: Column 3<br>• FCC acres by year: Columns 4 through (4 + Maximum Years in Simulation) |
| acerr.csv | File containing standard deviation of FCC acres in each year of simulation (sample population composed of number of iterations assigned by user within the run scenario). Fields are:<br>• Prescribed fire treatment level: Column 1<br>• Prescribed fire scaling factor: Column 2<br>• FCC number: Column 3<br>• FCC acres by year: Columns 4 through (4 + Maximum Years in Simulation) |

| Output File Name (cont.) | Description of Contents (Cont.) |
|---|---|
| fta.csv | File containing fuel treatment acres (actual, not scheduled) by FCC in each year in the simulation. Fields include:<br>• Prescribed fire treatment level: Column 1<br>• Prescribed fire scaling factor: Column 2<br>• Fuel treatment type: Column 3 ("m1" through "m4" are management activities 1-4 and "p" is prescribed fire)<br>• FCC number: Column 4<br>• Fuel treatment acres by year: Columns 5 through (5 + Maximum Years in Simulation) |
| numfire.csv | File containing numbers of wildland fires by fire size class in each year of the simulation. Fields include:<br>• Prescribed fire treatment level: Column 1<br>• Prescribed fire scaling factor: Column 2<br>• Fire size class: Column 3 (A, B, C, D, E, and F fires are: 0-¼ acres,<br>> ¼ to 10 acres, > 10 to 100 acres, >100 to 300 acres, > 300 to 1,000 acres, and > 1,000 acres in size, respectively)<br>• Numbers of wildland fires by year: Columns 4 through (4 + Maximum Years in Simulation) |
| pfa.csv | File containing number of prescribed fire acres (actual, not scheduled) by fire intensity level and FCC in each year in the simulation. Fields include:<br>• Prescribed fire treatment level: Column 1<br>• Prescribed fire scaling factor: Column 2<br>• Fire intensity level (FIL): Column 3 (FIL 1: 0- to 2-foot flame lengths, FIL 2: 2-4 foot flame lengths, FIL 3: 4 -to 6-foot flame lengths, FIL 4: 6- to 8-foot flame lengths, FIL 5: 8- to 12-foot flame lengths, and FIL 6: greater than 12-foot flame lengths)<br>• FCC number: Column 4<br>• Number of prescribed fire acres by year: Columns 5 through (5 + Maximum Years in Simulation) |
| rxe.csv | File containing prescribed fire emissions by pollutant (tons per year) in each year of the simulation. Fields include:<br>• Prescribed fire treatment level: Column 1<br>• Prescribed fire scaling factor: Column 2<br>• Pollutant: Column 3 (named)<br>• Prescribed fire emissions (tons) by year: Columns 4 through (4 + Maximum Years in Simulation) |

| **Output File Name (cont.)** | **Description of Contents (Cont.)** |
|---|---|
| sizea.csv | File containing number of wildland fire acres by fire size class in each year of the simulation. Fields include:<br>• Prescribed fire treatment level: Column 1<br>• Prescribed fire scaling factor: Column 2<br>• Fire size class: Column 3 (A, B, C, D, E, and F fires are: 0-¼ acres, > ¼ to 10 acres, > 10 to 100 acres, >100 to 300 acres, > 300 to 1,000 acres, and > 1,000 acres in size, respectively)<br>• Numbers of wildland fire acres by year: Columns 4 through (4 + Maximum Years in Simulation) |
| wfa.csv | File containing number of wildland fire acres by fire intensity level and FCC in each year in the simulation. Fields include:<br>• Prescribed fire treatment level: Column 1<br>• Prescribed fire scaling factor: Column 2<br>• Fire intensity level (FIL): Column 3 (FIL 1: 0- to 2-foot flame lengths, FIL 2: 2-4 foot flame lengths, FIL 3: 4 -to 6-foot flame lengths, FIL 4: 6- to 8-foot flame lengths, FIL 5: 8- to 12-foot flame lengths, and FIL 6: greater than 12-foot flame lengths)<br>• FCC number: Column 4<br>• Number of wildland fire acres by year: Columns 5 through (5 + Maximum Years in Simulation) |
| wfafcc_rx1.csv | File containing wildland fire acres by FCC and year in the simulation for <u>prescribed fire treatment level 1</u>. Fields include (separated vertically in blocks for extreme, high, moderate, and low fire weather):<br>• FCC number: Column 1<br>• Number of wildland fire acres by year: Columns 2 through (2 + Maximum Years in Simulation) |
| wfafcc_rx2.csv | File containing wildland fire acres by FCC and year in the simulation for <u>prescribed fire treatment level 2</u>. Fields are the same as those described for wfafcc_rx1.csv. |
| wfafcc_rx3.csv | File containing wildland fire acres by FCC and year in the simulation for <u>prescribed fire treatment level 3</u>. Fields are the same as those described for wfafcc_rx1.csv. |
| wfafcc_rx4.csv | File containing wildland fire acres by FCC and year in the simulation for <u>prescribed fire treatment level 4</u>. Fields are the same as those described for wfafcc_rx1.csv. |

| Output File Name (cont.) | Description of Contents (Cont.) |
|---|---|
| wfafcc_rx5.csv | File containing wildland fire acres by FCC and year in the simulation for prescribed fire treatment level 5. Fields are the same as those described for wfafcc_rx1.csv. |
| wfafcc_rx6.csv | File containing wildland fire acres by FCC and year in the simulation for prescribed fire treatment level 6. Fields are the same as those described for wfafcc_rx1.csv. |
| wfafcc_rx7.csv | File containing wildland fire acres by FCC and year in the simulation for prescribed fire treatment level 7. Fields are the same as those described for wfafcc_rx1.csv. |
| wfafwx.csv | File containing wildland fire acres by fire weather class and year in the simulation. Fields include:<br>• Prescribed fire treatment level: Column 1<br>• Prescribed fire scaling factor: Column 2<br>• Fire weather class: Column 3 (Ex: Extreme, Hi: High, Md: Moderate, Lo: Low)<br>• Numbers of wildland fire acres by year: Columns 4 through (4 + Maximum Years in Simulation) |
| wfastat.csv | File containing wildland fire statistics by decade for the period of simulation. Fields include:<br>• Prescribed fire treatment level: Column 1<br>• Prescribed fire scaling factor: Column 2<br>• Statistical parameter: Column 3 ("Mean WF Acres": Mean decade-total wildland fire acres, "Std Dev WF Acres": Standard deviation of decade-total wildland fire acres, "95% CI WF Acres": 95% confidence interval for decade-total wildland fire acres; two-tailed distribution)<br>• Value of statistical parameters by decade: Columns 4 though (4 + Number of Full Decades in the Simulation) |
| wfe.csv | File containing prescribed fire emissions by pollutant (tons per year) in each year of the simulation. Fields include:<br>• Prescribed fire treatment level: Column 1<br>• Prescribed fire scaling factor: Column 2<br>• Pollutant: Column 3 (named)<br>• Wildland fire emissions (tons) by year: Columns 4 through (4 + Maximum Years in Simulation) |

| Output File Name (cont.) | Description of Contents (Cont.) |
|---|---|
| wferr.csv | File containing standard deviation of wildland fire acres in each year of simulation (sample population composed of number of iterations assigned by user within the run scenario). Fields are:<br>• Prescribed fire treatment level: Column 1<br>• Prescribed fire scaling factor: Column 2<br>• FCC number: Column 3<br>• Wildland fire acres by year: Columns 4 through (4 + Maximum Years in Simulation) |

## APPENDIX C

# FETM 4 Fuel Model Parameters

### Table C-1. Fuel Model Parameters for the FETM Fuel Model Set

| Derivative Fuel Model | Parent Fuel Model Name | Loading Class | Shaded/ Unshaded | Wind Reduction Factor | 0-3” D&D Wood Loading | Total D&D Wood Loading | Fuel Bed Depth (feet) | Total Live + D&D Wood Loading | Total Live Loading | Live-Woody Loading | Live-Herb Loading | 1-Hr Fuel Loading | 10-Hr Fuel Loading | 100-Hr Fuel Loading | 1000-Hr Fuel Loading |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| A | Western annual grasses | Medium | Unshaded | 0.36 | 0.20 | 0.20 | 0.80 | 0.50 | 0.30 | 0.00 | 0.30 | 0.20 | 0.00 | 0.00 | 0.00 |
| AH1 | Western annual grasses | High | Shaded | 0.20 | 0.27 | 0.27 | 1.07 | 0.67 | 0.40 | 0.00 | 0.40 | 0.27 | 0.00 | 0.00 | 0.00 |
| AH2 | Western annual grasses | High | Unshaded | 0.50 | 0.27 | 0.27 | 1.07 | 0.67 | 0.40 | 0.00 | 0.40 | 0.27 | 0.00 | 0.00 | 0.00 |
| AL1 | Western annual grasses | Low | Shaded | 0.20 | 0.13 | 0.13 | 0.53 | 0.33 | 0.20 | 0.00 | 0.20 | 0.13 | 0.00 | 0.00 | 0.00 |
| AL2 | Western annual grasses | Low | Unshaded | 0.50 | 0.13 | 0.13 | 0.53 | 0.33 | 0.20 | 0.00 | 0.20 | 0.13 | 0.00 | 0.00 | 0.00 |
| AM1 | Western annual grasses | Medium | Shaded | 0.20 | 0.20 | 0.20 | 0.80 | 0.50 | 0.30 | 0.00 | 0.30 | 0.20 | 0.00 | 0.00 | 0.00 |
| AM2 | Western annual grasses | Medium | Unshaded | 0.50 | 0.20 | 0.20 | 0.80 | 0.50 | 0.30 | 0.00 | 0.30 | 0.20 | 0.00 | 0.00 | 0.00 |
| B | California mixed chaparral | Medium | Unshaded | 0.55 | 8.00 | 8.00 | 4.50 | 19.50 | 11.50 | 11.50 | 0.00 | 3.50 | 4.00 | 0.50 | 0.00 |
| BH1 | California mixed chaparral | High | Unshaded | 0.30 | 10.67 | 10.67 | 6.00 | 25.97 | 15.30 | 15.30 | 0.00 | 4.70 | 5.30 | 0.67 | 0.00 |
| BH2 | California mixed chaparral | High | Unshaded | 0.50 | 10.67 | 10.67 | 6.00 | 25.97 | 15.30 | 15.30 | 0.00 | 4.70 | 5.30 | 0.67 | 0.00 |
| BL1 | California mixed chaparral | Low | Unshaded | 0.30 | 5.37 | 5.37 | 3.02 | 13.08 | 7.71 | 7.71 | 0.00 | 2.35 | 2.68 | 0.34 | 0.00 |
| BL2 | California mixed chaparral | Low | Unshaded | 0.50 | 5.37 | 5.37 | 3.02 | 13.08 | 7.71 | 7.71 | 0.00 | 2.35 | 2.68 | 0.34 | 0.00 |
| BM1 | California mixed chaparral | Medium | Unshaded | 0.30 | 8.00 | 8.00 | 4.50 | 19.50 | 11.50 | 11.50 | 0.00 | 3.50 | 4.00 | 0.50 | 0.00 |
| BM2 | California mixed chaparral | Medium | Unshaded | 0.50 | 8.00 | 8.00 | 4.50 | 19.50 | 11.50 | 11.50 | 0.00 | 3.50 | 4.00 | 0.50 | 0.00 |
| C | Pine grass savanna | Medium | Unshaded | 0.25 | 1.40 | 1.40 | 0.75 | 2.70 | 1.30 | 0.50 | 0.80 | 0.40 | 1.00 | 0.00 | 0.00 |
| CH1 | Pine grass savanna | High | Shaded | 0.20 | 1.86 | 1.86 | 1.00 | 3.60 | 1.74 | 0.67 | 1.07 | 0.53 | 1.33 | 0.00 | 0.00 |
| CH2 | Pine grass savanna | High | Unshaded | 0.40 | 1.86 | 1.86 | 1.00 | 3.60 | 1.74 | 0.67 | 1.07 | 0.53 | 1.33 | 0.00 | 0.00 |
| CL1 | Pine grass savanna | Low | Shaded | 0.20 | 0.94 | 0.94 | 0.50 | 1.80 | 0.86 | 0.33 | 0.53 | 0.27 | 0.67 | 0.00 | 0.00 |
| CL2 | Pine grass savanna | Low | Unshaded | 0.40 | 0.94 | 0.94 | 0.50 | 1.80 | 0.86 | 0.33 | 0.53 | 0.27 | 0.67 | 0.00 | 0.00 |
| CM1 | Pine grass savanna | Medium | Shaded | 0.20 | 1.40 | 1.40 | 0.75 | 2.70 | 1.30 | 0.50 | 0.80 | 0.40 | 1.00 | 0.00 | 0.00 |
| CM2 | Pine grass savanna | Medium | Unshaded | 0.40 | 1.40 | 1.40 | 0.75 | 2.70 | 1.30 | 0.50 | 0.80 | 0.40 | 1.00 | 0.00 | 0.00 |
| D | Southern rough | Medium | Shaded | 0.12 | 3.00 | 3.00 | 2.00 | 6.75 | 3.75 | 3.00 | 0.75 | 2.00 | 1.00 | 0.00 | 0.00 |
| DH1 | Southern rough | High | Shaded | 0.20 | 3.90 | 3.90 | 2.60 | 8.78 | 4.88 | 3.90 | 0.98 | 2.60 | 1.30 | 0.00 | 0.00 |
| DH2 | Southern rough | High | Unshaded | 0.40 | 3.90 | 3.90 | 2.60 | 8.78 | 4.88 | 3.90 | 0.98 | 2.60 | 1.30 | 0.00 | 0.00 |
| DL1 | Southern rough | Low | Shaded | 0.20 | 2.04 | 2.04 | 1.40 | 4.55 | 2.51 | 2.01 | 0.50 | 1.34 | 0.70 | 0.00 | 0.00 |
| DL2 | Southern rough | Low | Unshaded | 0.40 | 2.04 | 2.04 | 1.40 | 4.55 | 2.51 | 2.01 | 0.50 | 1.34 | 0.70 | 0.00 | 0.00 |
| DM1 | Southern rough | Medium | Shaded | 0.20 | 3.00 | 3.00 | 2.00 | 6.75 | 3.75 | 3.00 | 0.75 | 2.00 | 1.00 | 0.00 | 0.00 |
| DM2 | Southern rough | Medium | Unshaded | 0.40 | 3.00 | 3.00 | 2.00 | 6.75 | 3.75 | 3.00 | 0.75 | 2.00 | 1.00 | 0.00 | 0.00 |
| E | Hardwood (winter) | Medium | Unshaded | 0.25 | 2.25 | 2.25 | 0.40 | 3.25 | 1.00 | 0.50 | 0.50 | 1.50 | 0.50 | 0.25 | 0.00 |
| EH1 | Hardwood (winter) | High | Shaded | 0.20 | 3.01 | 3.01 | 0.53 | 4.35 | 1.34 | 0.67 | 0.67 | 2.00 | 0.67 | 0.34 | 0.00 |
| EH2 | Hardwood (winter) | High | Unshaded | 0.30 | 3.01 | 3.01 | 0.53 | 4.35 | 1.34 | 0.67 | 0.67 | 2.00 | 0.67 | 0.34 | 0.00 |
| EL1 | Hardwood (winter) | Low | Shaded | 0.20 | 1.51 | 1.51 | 0.27 | 2.19 | 0.68 | 0.34 | 0.34 | 1.01 | 0.33 | 0.17 | 0.00 |
| EL2 | Hardwood (winter) | Low | Unshaded | 0.30 | 1.51 | 1.51 | 0.27 | 2.19 | 0.68 | 0.34 | 0.34 | 1.01 | 0.33 | 0.17 | 0.00 |
| EM1 | Hardwood (winter) | Medium | Shaded | 0.20 | 2.25 | 2.25 | 0.40 | 3.25 | 1.00 | 0.50 | 0.50 | 1.50 | 0.50 | 0.25 | 0.00 |
| EM2 | Hardwood (winter) | Medium | Unshaded | 0.30 | 2.25 | 2.25 | 0.40 | 3.25 | 1.00 | 0.50 | 0.50 | 1.50 | 0.50 | 0.25 | 0.00 |
| F | Intermediate brush | Medium | Unshaded | 0.42 | 6.00 | 6.00 | 4.50 | 15.00 | 9.00 | 9.00 | 0.00 | 2.50 | 2.00 | 1.50 | 0.00 |
| FH1 | Intermediate brush | High | Unshaded | 0.30 | 7.99 | 7.99 | 6.00 | 19.96 | 11.97 | 11.97 | 0.00 | 3.33 | 2.66 | 2.00 | 0.00 |
| FH2 | Intermediate brush | High | Unshaded | 0.40 | 7.99 | 7.99 | 6.00 | 19.96 | 11.97 | 11.97 | 0.00 | 3.33 | 2.66 | 2.00 | 0.00 |
| FL1 | Intermediate brush | Low | Unshaded | 0.30 | 4.03 | 4.03 | 3.02 | 10.06 | 6.03 | 6.03 | 0.00 | 1.68 | 1.34 | 1.01 | 0.00 |
| FL2 | Intermediate brush | Low | Unshaded | 0.40 | 4.03 | 4.03 | 3.02 | 10.06 | 6.03 | 6.03 | 0.00 | 1.68 | 1.34 | 1.01 | 0.00 |

## Table C-1. Fuel Model Parameters for the FETM Fuel Model Set

| Derivative Fuel Model | Parent Fuel Model Name | Loading Class | Shaded/ Unshaded | Wind Reduction Factor | 0-3” D&D Wood Loading | Total D&D Wood Loading | Fuel Bed Depth (feet) | Total Live + D&D Wood Loading | Total Live Loading | Live-Woody Loading | Live-Herb Loading | 1-Hr Fuel Loading | 10-Hr Fuel Loading | 100-Hr Fuel Loading | 1000-Hr Fuel Loading |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| FM1 | Intermediate brush | Medium | Unshaded | 0.30 | 6.00 | 6.00 | 4.50 | 15.00 | 9.00 | 9.00 | 0.00 | 2.50 | 2.00 | 1.50 | 0.00 |
| FM2 | Intermediate brush | Medium | Unshaded | 0.40 | 6.00 | 6.00 | 4.50 | 15.00 | 9.00 | 9.00 | 0.00 | 2.50 | 2.00 | 1.50 | 0.00 |
| G | Short needle pine (heavy dead) | Medium | Shaded | 0.12 | 9.50 | 21.50 | 1.00 | 22.50 | 1.00 | 0.50 | 0.50 | 2.50 | 2.00 | 5.00 | 12.00 |
| GH1 | Short needle pine (heavy dead) | High | Shaded | 0.20 | 12.67 | 28.67 | 1.33 | 30.01 | 1.34 | 0.67 | 0.67 | 3.33 | 2.67 | 6.67 | 16.00 |
| GH2 | Short needle pine (heavy dead) | High | Unshaded | 0.20 | 12.67 | 28.67 | 1.33 | 30.01 | 1.34 | 0.67 | 0.67 | 3.33 | 2.67 | 6.67 | 16.00 |
| GH3 | Short needle pine (heavy dead) | High | Shaded | 0.30 | 12.67 | 28.67 | 1.33 | 30.01 | 1.34 | 0.67 | 0.67 | 3.33 | 2.67 | 6.67 | 16.00 |
| GH4 | Short needle pine (heavy dead) | High | Unshaded | 0.30 | 12.67 | 28.67 | 1.33 | 30.01 | 1.34 | 0.67 | 0.67 | 3.33 | 2.67 | 6.67 | 16.00 |
| GH5 | Short needle pine (heavy dead) | High | Shaded | 0.40 | 12.67 | 28.67 | 1.33 | 30.01 | 1.34 | 0.67 | 0.67 | 3.33 | 2.67 | 6.67 | 16.00 |
| GH6 | Short needle pine (heavy dead) | High | Unshaded | 0.40 | 12.67 | 28.67 | 1.33 | 30.01 | 1.34 | 0.67 | 0.67 | 3.33 | 2.67 | 6.67 | 16.00 |
| GL1 | Short needle pine (heavy dead) | Low | Shaded | 0.20 | 6.33 | 14.33 | 0.67 | 14.99 | 0.66 | 0.33 | 0.33 | 1.67 | 1.33 | 3.33 | 8.00 |
| GL2 | Short needle pine (heavy dead) | Low | Unshaded | 0.20 | 6.33 | 14.33 | 0.67 | 14.99 | 0.66 | 0.33 | 0.33 | 1.67 | 1.33 | 3.33 | 8.00 |
| GL3 | Short needle pine (heavy dead) | Low | Shaded | 0.30 | 6.33 | 14.33 | 0.67 | 14.99 | 0.66 | 0.33 | 0.33 | 1.67 | 1.33 | 3.33 | 8.00 |
| GL4 | Short needle pine (heavy dead) | Low | Unshaded | 0.30 | 6.33 | 14.33 | 0.67 | 14.99 | 0.66 | 0.33 | 0.33 | 1.67 | 1.33 | 3.33 | 8.00 |
| GL5 | Short needle pine (heavy dead) | Low | Shaded | 0.40 | 6.33 | 14.33 | 0.67 | 14.99 | 0.66 | 0.33 | 0.33 | 1.67 | 1.33 | 3.33 | 8.00 |
| GL6 | Short needle pine (heavy dead) | Low | Unshaded | 0.40 | 6.33 | 14.33 | 0.67 | 14.99 | 0.66 | 0.33 | 0.33 | 1.67 | 1.33 | 3.33 | 8.00 |
| GM1 | Short needle pine (heavy dead) | Medium | Shaded | 0.20 | 9.50 | 21.50 | 1.00 | 22.50 | 1.00 | 0.50 | 0.50 | 2.50 | 2.00 | 5.00 | 12.00 |
| GM2 | Short needle pine (heavy dead) | Medium | Unshaded | 0.20 | 9.50 | 21.50 | 1.00 | 22.50 | 1.00 | 0.50 | 0.50 | 2.50 | 2.00 | 5.00 | 12.00 |
| GM3 | Short needle pine (heavy dead) | Medium | Shaded | 0.30 | 9.50 | 21.50 | 1.00 | 22.50 | 1.00 | 0.50 | 0.50 | 2.50 | 2.00 | 5.00 | 12.00 |
| GM4 | Short needle pine (heavy dead) | Medium | Unshaded | 0.30 | 9.50 | 21.50 | 1.00 | 22.50 | 1.00 | 0.50 | 0.50 | 2.50 | 2.00 | 5.00 | 12.00 |
| GM5 | Short needle pine (heavy dead) | Medium | Shaded | 0.40 | 9.50 | 21.50 | 1.00 | 22.50 | 1.00 | 0.50 | 0.50 | 2.50 | 2.00 | 5.00 | 12.00 |
| GM6 | Short needle pine (heavy dead) | Medium | Unshaded | 0.40 | 9.50 | 21.50 | 1.00 | 22.50 | 1.00 | 0.50 | 0.50 | 2.50 | 2.00 | 5.00 | 12.00 |
| H | Short needle pine (normal dead) | Medium | Shaded | 0.17 | 4.50 | 6.50 | 0.30 | 7.50 | 1.00 | 0.50 | 0.50 | 1.50 | 1.00 | 2.00 | 2.00 |
| HH1 | Short needle pine (normal dead) | High | Shaded | 0.20 | 6.00 | 8.67 | 0.40 | 10.01 | 1.34 | 0.67 | 0.67 | 2.00 | 1.33 | 2.67 | 2.67 |
| HH2 | Short needle pine (normal dead) | High | Unshaded | 0.30 | 6.00 | 8.67 | 0.40 | 10.01 | 1.34 | 0.67 | 0.67 | 2.00 | 1.33 | 2.67 | 2.67 |
| HH3 | Short needle pine (normal dead) | High | Unshaded | 0.40 | 6.00 | 8.67 | 0.40 | 10.01 | 1.34 | 0.67 | 0.67 | 2.00 | 1.33 | 2.67 | 2.67 |
| HL1 | Short needle pine (normal dead) | Low | Shaded | 0.20 | 3.00 | 4.33 | 0.20 | 4.99 | 0.66 | 0.33 | 0.33 | 1.00 | 0.67 | 1.33 | 1.33 |
| HL2 | Short needle pine (normal dead) | Low | Unshaded | 0.30 | 3.00 | 4.33 | 0.20 | 4.99 | 0.66 | 0.33 | 0.33 | 1.00 | 0.67 | 1.33 | 1.33 |
| HL3 | Short needle pine (normal dead) | Low | Unshaded | 0.40 | 3.00 | 4.33 | 0.20 | 4.99 | 0.66 | 0.33 | 0.33 | 1.00 | 0.67 | 1.33 | 1.33 |
| HM1 | Short needle pine (normal dead) | Medium | Shaded | 0.20 | 4.50 | 6.50 | 0.30 | 7.50 | 1.00 | 0.50 | 0.50 | 1.50 | 1.00 | 2.00 | 2.00 |
| HM2 | Short needle pine (normal dead) | Medium | Unshaded | 0.30 | 4.50 | 6.50 | 0.30 | 7.50 | 1.00 | 0.50 | 0.50 | 1.50 | 1.00 | 2.00 | 2.00 |
| HM3 | Short needle pine (normal dead) | Medium | Unshaded | 0.40 | 4.50 | 6.50 | 0.30 | 7.50 | 1.00 | 0.50 | 0.50 | 1.50 | 1.00 | 2.00 | 2.00 |
| I | Heavy logging slash | Medium | Unshaded | 0.46 | 34.00 | 46.00 | 2.00 | 46.00 | 0.00 | 0.00 | 0.00 | 12.00 | 12.00 | 10.00 | 12.00 |
| IA1 | Heavy logging slash | Low- | Shaded | 0.20 | 29.00 | 39.16 | 1.26 | 39.16 | 0.00 | 0.00 | 0.00 | 10.30 | 10.30 | 8.40 | 10.16 |
| IA2 | Heavy logging slash | Low- | Unshaded | 0.30 | 29.00 | 39.16 | 1.26 | 39.16 | 0.00 | 0.00 | 0.00 | 10.30 | 10.30 | 8.40 | 10.16 |
| IA3 | Heavy logging slash | Low- | Unshaded | 0.50 | 29.00 | 39.16 | 1.26 | 39.16 | 0.00 | 0.00 | 0.00 | 10.30 | 10.30 | 8.40 | 10.16 |
| IA4 | Heavy logging slash | Low- | Shaded | 0.20 | 29.00 | 39.16 | 1.80 | 39.16 | 0.00 | 0.00 | 0.00 | 10.30 | 10.30 | 8.40 | 10.16 |
| IA5 | Heavy logging slash | Low- | Unshaded | 0.30 | 29.00 | 39.16 | 1.80 | 39.16 | 0.00 | 0.00 | 0.00 | 10.30 | 10.30 | 8.40 | 10.16 |
| IA6 | Heavy logging slash | Low- | Unshaded | 0.50 | 29.00 | 39.16 | 1.80 | 39.16 | 0.00 | 0.00 | 0.00 | 10.30 | 10.30 | 8.40 | 10.16 |
| IA7 | Heavy logging slash | Low- | Shaded | 0.20 | 29.00 | 39.16 | 2.34 | 39.16 | 0.00 | 0.00 | 0.00 | 10.30 | 10.30 | 8.40 | 10.16 |
| IA8 | Heavy logging slash | Low- | Unshaded | 0.30 | 29.00 | 39.16 | 2.34 | 39.16 | 0.00 | 0.00 | 0.00 | 10.30 | 10.30 | 8.40 | 10.16 |

## Table C-1. Fuel Model Parameters for the FETM Fuel Model Set

| Derivative Fuel Model | Parent Fuel Model Name | Loading Class | Shaded/ Unshaded | Wind Reduction Factor | 0-3” D&D Wood Loading | Total D&D Wood Loading | Fuel Bed Depth (feet) | Total Live + D&D Wood Loading | Total Live Loading | Live-Woody Loading | Live-Herb Loading | 1-Hr Fuel Loading | 10-Hr Fuel Loading | 100-Hr Fuel Loading | 1000-Hr Fuel Loading |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| IA9 | Heavy logging slash | Low- | Unshaded | 0.50 | 29.00 | 39.16 | 2.34 | 39.16 | 0.00 | 0.00 | 0.00 | 10.30 | 10.30 | 8.40 | 10.16 |
| IH1 | Heavy logging slash | High | Shaded | 0.20 | 37.00 | 49.95 | 1.47 | 49.95 | 0.00 | 0.00 | 0.00 | 13.14 | 13.14 | 10.72 | 12.95 |
| IH2 | Heavy logging slash | High | Unshaded | 0.30 | 37.00 | 49.95 | 1.47 | 49.95 | 0.00 | 0.00 | 0.00 | 13.14 | 13.14 | 10.72 | 12.95 |
| IH3 | Heavy logging slash | High | Unshaded | 0.50 | 37.00 | 49.95 | 1.47 | 49.95 | 0.00 | 0.00 | 0.00 | 13.14 | 13.14 | 10.72 | 12.95 |
| IH4 | Heavy logging slash | High | Shaded | 0.20 | 37.00 | 49.95 | 2.10 | 49.95 | 0.00 | 0.00 | 0.00 | 13.14 | 13.14 | 10.72 | 12.95 |
| IH5 | Heavy logging slash | High | Unshaded | 0.30 | 37.00 | 49.95 | 2.10 | 49.95 | 0.00 | 0.00 | 0.00 | 13.14 | 13.14 | 10.72 | 12.95 |
| IH6 | Heavy logging slash | High | Unshaded | 0.50 | 37.00 | 49.95 | 2.10 | 49.95 | 0.00 | 0.00 | 0.00 | 13.14 | 13.14 | 10.72 | 12.95 |
| IH7 | Heavy logging slash | High | Shaded | 0.20 | 37.00 | 49.95 | 2.73 | 49.95 | 0.00 | 0.00 | 0.00 | 13.14 | 13.14 | 10.72 | 12.95 |
| IH8 | Heavy logging slash | High | Unshaded | 0.30 | 37.00 | 49.95 | 2.73 | 49.95 | 0.00 | 0.00 | 0.00 | 13.14 | 13.14 | 10.72 | 12.95 |
| IH9 | Heavy logging slash | High | Unshaded | 0.50 | 37.00 | 49.95 | 2.73 | 49.95 | 0.00 | 0.00 | 0.00 | 13.14 | 13.14 | 10.72 | 12.95 |
| IL1 | Heavy logging slash | Low | Shaded | 0.20 | 32.00 | 43.16 | 1.33 | 43.16 | 0.00 | 0.00 | 0.00 | 11.36 | 11.36 | 9.28 | 11.16 |
| IL2 | Heavy logging slash | Low | Unshaded | 0.30 | 32.00 | 43.16 | 1.33 | 43.16 | 0.00 | 0.00 | 0.00 | 11.36 | 11.36 | 9.28 | 11.16 |
| IL3 | Heavy logging slash | Low | Unshaded | 0.50 | 32.00 | 43.16 | 1.33 | 43.16 | 0.00 | 0.00 | 0.00 | 11.36 | 11.36 | 9.28 | 11.16 |
| IL4 | Heavy logging slash | Low | Shaded | 0.20 | 32.00 | 43.16 | 1.90 | 43.16 | 0.00 | 0.00 | 0.00 | 11.36 | 11.36 | 9.28 | 11.16 |
| IL5 | Heavy logging slash | Low | Unshaded | 0.30 | 32.00 | 43.16 | 1.90 | 43.16 | 0.00 | 0.00 | 0.00 | 11.36 | 11.36 | 9.28 | 11.16 |
| IL6 | Heavy logging slash | Low | Unshaded | 0.50 | 32.00 | 43.16 | 1.90 | 43.16 | 0.00 | 0.00 | 0.00 | 11.36 | 11.36 | 9.28 | 11.16 |
| IL7 | Heavy logging slash | Low | Shaded | 0.20 | 32.00 | 43.16 | 2.47 | 43.16 | 0.00 | 0.00 | 0.00 | 11.36 | 11.36 | 9.28 | 11.16 |
| IL8 | Heavy logging slash | Low | Unshaded | 0.30 | 32.00 | 43.16 | 2.47 | 43.16 | 0.00 | 0.00 | 0.00 | 11.36 | 11.36 | 9.28 | 11.16 |
| IL9 | Heavy logging slash | Low | Unshaded | 0.50 | 32.00 | 43.16 | 2.47 | 43.16 | 0.00 | 0.00 | 0.00 | 11.36 | 11.36 | 9.28 | 11.16 |
| IM1 | Heavy logging slash | Medium | Shaded | 0.20 | 34.00 | 46.00 | 1.40 | 46.00 | 0.00 | 0.00 | 0.00 | 12.00 | 12.00 | 10.00 | 12.00 |
| IM2 | Heavy logging slash | Medium | Unshaded | 0.30 | 34.00 | 46.00 | 1.40 | 46.00 | 0.00 | 0.00 | 0.00 | 12.00 | 12.00 | 10.00 | 12.00 |
| IM3 | Heavy logging slash | Medium | Unshaded | 0.50 | 34.00 | 46.00 | 1.40 | 46.00 | 0.00 | 0.00 | 0.00 | 12.00 | 12.00 | 10.00 | 12.00 |
| IM4 | Heavy logging slash | Medium | Shaded | 0.20 | 34.00 | 46.00 | 2.00 | 46.00 | 0.00 | 0.00 | 0.00 | 12.00 | 12.00 | 10.00 | 12.00 |
| IM5 | Heavy logging slash | Medium | Unshaded | 0.30 | 34.00 | 46.00 | 2.00 | 46.00 | 0.00 | 0.00 | 0.00 | 12.00 | 12.00 | 10.00 | 12.00 |
| IM6 | Heavy logging slash | Medium | Unshaded | 0.50 | 34.00 | 46.00 | 2.00 | 46.00 | 0.00 | 0.00 | 0.00 | 12.00 | 12.00 | 10.00 | 12.00 |
| IM7 | Heavy logging slash | Medium | Shaded | 0.20 | 34.00 | 46.00 | 2.60 | 46.00 | 0.00 | 0.00 | 0.00 | 12.00 | 12.00 | 10.00 | 12.00 |
| IM8 | Heavy logging slash | Medium | Unshaded | 0.30 | 34.00 | 46.00 | 2.60 | 46.00 | 0.00 | 0.00 | 0.00 | 12.00 | 12.00 | 10.00 | 12.00 |
| IM9 | Heavy logging slash | Medium | Unshaded | 0.50 | 34.00 | 46.00 | 2.60 | 46.00 | 0.00 | 0.00 | 0.00 | 12.00 | 12.00 | 10.00 | 12.00 |
| IY1 | Heavy logging slash | High+ | Shaded | 0.20 | 40.00 | 54.00 | 1.54 | 54.00 | 0.00 | 0.00 | 0.00 | 14.20 | 14.20 | 11.60 | 14.00 |
| IY2 | Heavy logging slash | High+ | Unshaded | 0.30 | 40.00 | 54.00 | 1.54 | 54.00 | 0.00 | 0.00 | 0.00 | 14.20 | 14.20 | 11.60 | 14.00 |
| IY3 | Heavy logging slash | High+ | Unshaded | 0.50 | 40.00 | 54.00 | 1.54 | 54.00 | 0.00 | 0.00 | 0.00 | 14.20 | 14.20 | 11.60 | 14.00 |
| IY4 | Heavy logging slash | High+ | Shaded | 0.20 | 40.00 | 54.00 | 2.20 | 54.00 | 0.00 | 0.00 | 0.00 | 14.20 | 14.20 | 11.60 | 14.00 |
| IY5 | Heavy logging slash | High+ | Unshaded | 0.30 | 40.00 | 54.00 | 2.20 | 54.00 | 0.00 | 0.00 | 0.00 | 14.20 | 14.20 | 11.60 | 14.00 |
| IY6 | Heavy logging slash | High+ | Unshaded | 0.50 | 40.00 | 54.00 | 2.20 | 54.00 | 0.00 | 0.00 | 0.00 | 14.20 | 14.20 | 11.60 | 14.00 |
| IY7 | Heavy logging slash | High+ | Shaded | 0.20 | 40.00 | 54.00 | 2.86 | 54.00 | 0.00 | 0.00 | 0.00 | 14.20 | 14.20 | 11.60 | 14.00 |
| IY8 | Heavy logging slash | High+ | Unshaded | 0.30 | 40.00 | 54.00 | 2.86 | 54.00 | 0.00 | 0.00 | 0.00 | 14.20 | 14.20 | 11.60 | 14.00 |
| IY9 | Heavy logging slash | High+ | Unshaded | 0.50 | 40.00 | 54.00 | 2.86 | 54.00 | 0.00 | 0.00 | 0.00 | 14.20 | 14.20 | 11.60 | 14.00 |
| IZ1 | Heavy logging slash | High++ | Shaded | 0.20 | 45.00 | 60.75 | 1.61 | 60.75 | 0.00 | 0.00 | 0.00 | 15.98 | 15.98 | 13.04 | 15.75 |
| IZ2 | Heavy logging slash | High++ | Unshaded | 0.30 | 45.00 | 60.75 | 1.61 | 60.75 | 0.00 | 0.00 | 0.00 | 15.98 | 15.98 | 13.04 | 15.75 |
| IZ3 | Heavy logging slash | High++ | Unshaded | 0.50 | 45.00 | 60.75 | 1.61 | 60.75 | 0.00 | 0.00 | 0.00 | 15.98 | 15.98 | 13.04 | 15.75 |

### Table C-1. Fuel Model Parameters for the FETM Fuel Model Set

| Derivative Fuel Model | Parent Fuel Model Name | Loading Class | Shaded/ Unshaded | Wind Reduction Factor | 0-3” D&D Wood Loading | Total D&D Wood Loading | Fuel Bed Depth (feet) | Total Live + D&D Wood Loading | Total Live Loading | Live-Woody Loading | Live-Herb Loading | 1-Hr Fuel Loading | 10-Hr Fuel Loading | 100-Hr Fuel Loading | 1000-Hr Fuel Loading |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| IZ4 | Heavy logging slash | High++ | Shaded | 0.20 | 45.00 | 60.75 | 2.30 | 60.75 | 0.00 | 0.00 | 0.00 | 15.98 | 15.98 | 13.04 | 15.75 |
| IZ5 | Heavy logging slash | High++ | Unshaded | 0.30 | 45.00 | 60.75 | 2.30 | 60.75 | 0.00 | 0.00 | 0.00 | 15.98 | 15.98 | 13.04 | 15.75 |
| IZ6 | Heavy logging slash | High++ | Unshaded | 0.50 | 45.00 | 60.75 | 2.30 | 60.75 | 0.00 | 0.00 | 0.00 | 15.98 | 15.98 | 13.04 | 15.75 |
| IZ7 | Heavy logging slash | High++ | Shaded | 0.20 | 45.00 | 60.75 | 2.99 | 60.75 | 0.00 | 0.00 | 0.00 | 15.98 | 15.98 | 13.04 | 15.75 |
| IZ8 | Heavy logging slash | High++ | Unshaded | 0.30 | 45.00 | 60.75 | 2.99 | 60.75 | 0.00 | 0.00 | 0.00 | 15.98 | 15.98 | 13.04 | 15.75 |
| IZ9 | Heavy logging slash | High++ | Unshaded | 0.50 | 45.00 | 60.75 | 2.99 | 60.75 | 0.00 | 0.00 | 0.00 | 15.98 | 15.98 | 13.04 | 15.75 |
| J | Intermediate logging slash | Medium | Unshaded | 0.43 | 20.00 | 25.50 | 1.30 | 25.50 | 0.00 | 0.00 | 0.00 | 7.00 | 7.00 | 6.00 | 5.50 |
| JA1 | Intermediate logging slash | Low- | Shaded | 0.20 | 15.00 | 18.98 | 0.70 | 18.98 | 0.00 | 0.00 | 0.00 | 5.33 | 5.33 | 4.34 | 3.98 |
| JA2 | Intermediate logging slash | Low- | Unshaded | 0.30 | 15.00 | 18.98 | 0.70 | 18.98 | 0.00 | 0.00 | 0.00 | 5.33 | 5.33 | 4.34 | 3.98 |
| JA3 | Intermediate logging slash | Low- | Unshaded | 0.50 | 15.00 | 18.98 | 0.70 | 18.98 | 0.00 | 0.00 | 0.00 | 5.33 | 5.33 | 4.34 | 3.98 |
| JA4 | Intermediate logging slash | Low- | Shaded | 0.20 | 15.00 | 18.98 | 1.00 | 18.98 | 0.00 | 0.00 | 0.00 | 5.33 | 5.33 | 4.34 | 3.98 |
| JA5 | Intermediate logging slash | Low- | Unshaded | 0.30 | 15.00 | 18.98 | 1.00 | 18.98 | 0.00 | 0.00 | 0.00 | 5.33 | 5.33 | 4.34 | 3.98 |
| JA6 | Intermediate logging slash | Low- | Unshaded | 0.50 | 15.00 | 18.98 | 1.00 | 18.98 | 0.00 | 0.00 | 0.00 | 5.33 | 5.33 | 4.34 | 3.98 |
| JA7 | Intermediate logging slash | Low- | Shaded | 0.20 | 15.00 | 18.98 | 1.30 | 18.98 | 0.00 | 0.00 | 0.00 | 5.33 | 5.33 | 4.34 | 3.98 |
| JA8 | Intermediate logging slash | Low- | Unshaded | 0.30 | 15.00 | 18.98 | 1.30 | 18.98 | 0.00 | 0.00 | 0.00 | 5.33 | 5.33 | 4.34 | 3.98 |
| JA9 | Intermediate logging slash | Low- | Unshaded | 0.50 | 15.00 | 18.98 | 1.30 | 18.98 | 0.00 | 0.00 | 0.00 | 5.33 | 5.33 | 4.34 | 3.98 |
| JH1 | Intermediate logging slash | High | Shaded | 0.20 | 23.00 | 29.69 | 0.98 | 29.69 | 0.00 | 0.00 | 0.00 | 8.17 | 8.17 | 6.66 | 6.69 |
| JH2 | Intermediate logging slash | High | Unshaded | 0.30 | 23.00 | 29.69 | 0.98 | 29.69 | 0.00 | 0.00 | 0.00 | 8.17 | 8.17 | 6.66 | 6.69 |
| JH3 | Intermediate logging slash | High | Unshaded | 0.50 | 23.00 | 29.69 | 0.98 | 29.69 | 0.00 | 0.00 | 0.00 | 8.17 | 8.17 | 6.66 | 6.69 |
| JH4 | Intermediate logging slash | High | Shaded | 0.20 | 23.00 | 29.69 | 1.40 | 29.69 | 0.00 | 0.00 | 0.00 | 8.17 | 8.17 | 6.66 | 6.69 |
| JH5 | Intermediate logging slash | High | Unshaded | 0.30 | 23.00 | 29.69 | 1.40 | 29.69 | 0.00 | 0.00 | 0.00 | 8.17 | 8.17 | 6.66 | 6.69 |
| JH6 | Intermediate logging slash | High | Unshaded | 0.50 | 23.00 | 29.69 | 1.40 | 29.69 | 0.00 | 0.00 | 0.00 | 8.17 | 8.17 | 6.66 | 6.69 |
| JH7 | Intermediate logging slash | High | Shaded | 0.20 | 23.00 | 29.69 | 1.82 | 29.69 | 0.00 | 0.00 | 0.00 | 8.17 | 8.17 | 6.66 | 6.69 |
| JH8 | Intermediate logging slash | High | Unshaded | 0.30 | 23.00 | 29.69 | 1.82 | 29.69 | 0.00 | 0.00 | 0.00 | 8.17 | 8.17 | 6.66 | 6.69 |
| JH9 | Intermediate logging slash | High | Unshaded | 0.50 | 23.00 | 29.69 | 1.82 | 29.69 | 0.00 | 0.00 | 0.00 | 8.17 | 8.17 | 6.66 | 6.69 |
| JL1 | Intermediate logging slash | Low | Shaded | 0.20 | 18.00 | 23.02 | 0.84 | 23.02 | 0.00 | 0.00 | 0.00 | 6.39 | 6.39 | 5.22 | 5.02 |
| JL2 | Intermediate logging slash | Low | Unshaded | 0.30 | 18.00 | 23.02 | 0.84 | 23.02 | 0.00 | 0.00 | 0.00 | 6.39 | 6.39 | 5.22 | 5.02 |
| JL3 | Intermediate logging slash | Low | Unshaded | 0.50 | 18.00 | 23.02 | 0.84 | 23.02 | 0.00 | 0.00 | 0.00 | 6.39 | 6.39 | 5.22 | 5.02 |
| JL4 | Intermediate logging slash | Low | Shaded | 0.20 | 18.00 | 23.02 | 1.20 | 23.02 | 0.00 | 0.00 | 0.00 | 6.39 | 6.39 | 5.22 | 5.02 |
| JL5 | Intermediate logging slash | Low | Unshaded | 0.30 | 18.00 | 23.02 | 1.20 | 23.02 | 0.00 | 0.00 | 0.00 | 6.39 | 6.39 | 5.22 | 5.02 |
| JL6 | Intermediate logging slash | Low | Unshaded | 0.50 | 18.00 | 23.02 | 1.20 | 23.02 | 0.00 | 0.00 | 0.00 | 6.39 | 6.39 | 5.22 | 5.02 |
| JL7 | Intermediate logging slash | Low | Shaded | 0.20 | 18.00 | 23.02 | 1.56 | 23.02 | 0.00 | 0.00 | 0.00 | 6.39 | 6.39 | 5.22 | 5.02 |
| JL8 | Intermediate logging slash | Low | Unshaded | 0.30 | 18.00 | 23.02 | 1.56 | 23.02 | 0.00 | 0.00 | 0.00 | 6.39 | 6.39 | 5.22 | 5.02 |
| JL9 | Intermediate logging slash | Low | Unshaded | 0.50 | 18.00 | 23.02 | 1.56 | 23.02 | 0.00 | 0.00 | 0.00 | 6.39 | 6.39 | 5.22 | 5.02 |
| JM1 | Intermediate logging slash | Medium | Shaded | 0.20 | 20.00 | 25.50 | 0.91 | 25.50 | 0.00 | 0.00 | 0.00 | 7.00 | 7.00 | 6.00 | 5.50 |
| JM2 | Intermediate logging slash | Medium | Unshaded | 0.30 | 20.00 | 25.50 | 0.91 | 25.50 | 0.00 | 0.00 | 0.00 | 7.00 | 7.00 | 6.00 | 5.50 |
| JM3 | Intermediate logging slash | Medium | Unshaded | 0.50 | 20.00 | 25.50 | 0.91 | 25.50 | 0.00 | 0.00 | 0.00 | 7.00 | 7.00 | 6.00 | 5.50 |
| JM4 | Intermediate logging slash | Medium | Shaded | 0.20 | 20.00 | 25.50 | 1.30 | 25.50 | 0.00 | 0.00 | 0.00 | 7.00 | 7.00 | 6.00 | 5.50 |
| JM5 | Intermediate logging slash | Medium | Unshaded | 0.30 | 20.00 | 25.50 | 1.30 | 25.50 | 0.00 | 0.00 | 0.00 | 7.00 | 7.00 | 6.00 | 5.50 |
| JM6 | Intermediate logging slash | Medium | Unshaded | 0.50 | 20.00 | 25.50 | 1.30 | 25.50 | 0.00 | 0.00 | 0.00 | 7.00 | 7.00 | 6.00 | 5.50 |

## Table C-1. Fuel Model Parameters for the FETM Fuel Model Set

| Derivative Fuel Model | Parent Fuel Model Name | Loading Class | Shaded/ Unshaded | Wind Reduction Factor | 0-3” D&D Wood Loading | Total D&D Wood Loading | Fuel Bed Depth (feet) | Total Live + D&D Wood Loading | Total Live Loading | Live-Woody Loading | Live-Herb Loading | 1-Hr Fuel Loading | 10-Hr Fuel Loading | 100-Hr Fuel Loading | 1000-Hr Fuel Loading |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| JM7 | Intermediate logging slash | Medium | Shaded | 0.20 | 20.00 | 25.50 | 1.69 | 25.50 | 0.00 | 0.00 | 0.00 | 7.00 | 7.00 | 6.00 | 5.50 |
| JM8 | Intermediate logging slash | Medium | Unshaded | 0.30 | 20.00 | 25.50 | 1.69 | 25.50 | 0.00 | 0.00 | 0.00 | 7.00 | 7.00 | 6.00 | 5.50 |
| JM9 | Intermediate logging slash | Medium | Unshaded | 0.50 | 20.00 | 25.50 | 1.69 | 25.50 | 0.00 | 0.00 | 0.00 | 7.00 | 7.00 | 6.00 | 5.50 |
| JZ1 | Intermediate logging slash | High++ | Shaded | 0.20 | 26.00 | 34.32 | 1.12 | 34.32 | 0.00 | 0.00 | 0.00 | 9.23 | 9.23 | 7.54 | 8.32 |
| JZ2 | Intermediate logging slash | High++ | Unshaded | 0.30 | 26.00 | 34.32 | 1.12 | 34.32 | 0.00 | 0.00 | 0.00 | 9.23 | 9.23 | 7.54 | 8.32 |
| JZ3 | Intermediate logging slash | High++ | Unshaded | 0.50 | 26.00 | 34.32 | 1.12 | 34.32 | 0.00 | 0.00 | 0.00 | 9.23 | 9.23 | 7.54 | 8.32 |
| JZ4 | Intermediate logging slash | High++ | Shaded | 0.20 | 26.00 | 34.32 | 1.60 | 34.32 | 0.00 | 0.00 | 0.00 | 9.23 | 9.23 | 7.54 | 8.32 |
| JZ5 | Intermediate logging slash | High++ | Unshaded | 0.30 | 26.00 | 34.32 | 1.60 | 34.32 | 0.00 | 0.00 | 0.00 | 9.23 | 9.23 | 7.54 | 8.32 |
| JZ6 | Intermediate logging slash | High++ | Unshaded | 0.50 | 26.00 | 34.32 | 1.60 | 34.32 | 0.00 | 0.00 | 0.00 | 9.23 | 9.23 | 7.54 | 8.32 |
| JZ7 | Intermediate logging slash | High++ | Shaded | 0.20 | 26.00 | 34.32 | 2.08 | 34.32 | 0.00 | 0.00 | 0.00 | 9.23 | 9.23 | 7.54 | 8.32 |
| JZ8 | Intermediate logging slash | High++ | Unshaded | 0.30 | 26.00 | 34.32 | 2.08 | 34.32 | 0.00 | 0.00 | 0.00 | 9.23 | 9.23 | 7.54 | 8.32 |
| JZ9 | Intermediate logging slash | High++ | Unshaded | 0.50 | 26.00 | 34.32 | 2.08 | 34.32 | 0.00 | 0.00 | 0.00 | 9.23 | 9.23 | 7.54 | 8.32 |
| K | Light logging slash | Medium | Shaded | 0.36 | 7.00 | 9.50 | 0.60 | 9.50 | 0.00 | 0.00 | 0.00 | 2.50 | 2.50 | 2.00 | 2.50 |
| KA1 | Light logging slash | Low- | Shaded | 0.20 | 2.00 | 2.72 | 0.13 | 2.72 | 0.00 | 0.00 | 0.00 | 0.71 | 0.71 | 0.58 | 0.72 |
| KA2 | Light logging slash | Low- | Unshaded | 0.30 | 2.00 | 2.72 | 0.13 | 2.72 | 0.00 | 0.00 | 0.00 | 0.71 | 0.71 | 0.58 | 0.72 |
| KA3 | Light logging slash | Low- | Unshaded | 0.50 | 2.00 | 2.72 | 0.13 | 2.72 | 0.00 | 0.00 | 0.00 | 0.71 | 0.71 | 0.58 | 0.72 |
| KA4 | Light logging slash | Low- | Shaded | 0.20 | 2.00 | 2.72 | 0.20 | 2.72 | 0.00 | 0.00 | 0.00 | 0.71 | 0.71 | 0.58 | 0.72 |
| KA5 | Light logging slash | Low- | Unshaded | 0.30 | 2.00 | 2.72 | 0.20 | 2.72 | 0.00 | 0.00 | 0.00 | 0.71 | 0.71 | 0.58 | 0.72 |
| KA6 | Light logging slash | Low- | Unshaded | 0.50 | 2.00 | 2.72 | 0.20 | 2.72 | 0.00 | 0.00 | 0.00 | 0.71 | 0.71 | 0.58 | 0.72 |
| KA7 | Light logging slash | Low- | Shaded | 0.20 | 2.00 | 2.72 | 0.26 | 2.72 | 0.00 | 0.00 | 0.00 | 0.71 | 0.71 | 0.58 | 0.72 |
| KA8 | Light logging slash | Low- | Unshaded | 0.30 | 2.00 | 2.72 | 0.26 | 2.72 | 0.00 | 0.00 | 0.00 | 0.71 | 0.71 | 0.58 | 0.72 |
| KA9 | Light logging slash | Low- | Unshaded | 0.50 | 2.00 | 2.72 | 0.26 | 2.72 | 0.00 | 0.00 | 0.00 | 0.71 | 0.71 | 0.58 | 0.72 |
| KH1 | Light logging slash | High | Shaded | 0.20 | 9.50 | 12.95 | 0.56 | 12.95 | 0.00 | 0.00 | 0.00 | 3.37 | 3.37 | 2.76 | 3.45 |
| KH2 | Light logging slash | High | Unshaded | 0.30 | 9.50 | 12.95 | 0.56 | 12.95 | 0.00 | 0.00 | 0.00 | 3.37 | 3.37 | 2.76 | 3.45 |
| KH3 | Light logging slash | High | Unshaded | 0.50 | 9.50 | 12.95 | 0.56 | 12.95 | 0.00 | 0.00 | 0.00 | 3.37 | 3.37 | 2.76 | 3.45 |
| KH4 | Light logging slash | High | Shaded | 0.20 | 9.50 | 12.95 | 0.80 | 12.95 | 0.00 | 0.00 | 0.00 | 3.37 | 3.37 | 2.76 | 3.45 |
| KH5 | Light logging slash | High | Unshaded | 0.30 | 9.50 | 12.95 | 0.80 | 12.95 | 0.00 | 0.00 | 0.00 | 3.37 | 3.37 | 2.76 | 3.45 |
| KH6 | Light logging slash | High | Unshaded | 0.50 | 9.50 | 12.95 | 0.80 | 12.95 | 0.00 | 0.00 | 0.00 | 3.37 | 3.37 | 2.76 | 3.45 |
| KH7 | Light logging slash | High | Shaded | 0.20 | 9.50 | 12.95 | 1.04 | 12.95 | 0.00 | 0.00 | 0.00 | 3.37 | 3.37 | 2.76 | 3.45 |
| KH8 | Light logging slash | High | Unshaded | 0.30 | 9.50 | 12.95 | 1.04 | 12.95 | 0.00 | 0.00 | 0.00 | 3.37 | 3.37 | 2.76 | 3.45 |
| KH9 | Light logging slash | High | Unshaded | 0.50 | 9.50 | 12.95 | 1.04 | 12.95 | 0.00 | 0.00 | 0.00 | 3.37 | 3.37 | 2.76 | 3.45 |
| KL1 | Light logging slash | Low | Shaded | 0.20 | 4.50 | 6.13 | 0.27 | 6.13 | 0.00 | 0.00 | 0.00 | 1.60 | 1.60 | 1.30 | 1.63 |
| KL2 | Light logging slash | Low | Unshaded | 0.30 | 4.50 | 6.13 | 0.27 | 6.13 | 0.00 | 0.00 | 0.00 | 1.60 | 1.60 | 1.30 | 1.63 |
| KL3 | Light logging slash | Low | Unshaded | 0.50 | 4.50 | 6.13 | 0.27 | 6.13 | 0.00 | 0.00 | 0.00 | 1.60 | 1.60 | 1.30 | 1.63 |
| KL4 | Light logging slash | Low | Shaded | 0.20 | 4.50 | 6.13 | 0.40 | 6.13 | 0.00 | 0.00 | 0.00 | 1.60 | 1.60 | 1.30 | 1.63 |
| KL5 | Light logging slash | Low | Unshaded | 0.30 | 4.50 | 6.13 | 0.40 | 6.13 | 0.00 | 0.00 | 0.00 | 1.60 | 1.60 | 1.30 | 1.63 |
| KL6 | Light logging slash | Low | Unshaded | 0.50 | 4.50 | 6.13 | 0.40 | 6.13 | 0.00 | 0.00 | 0.00 | 1.60 | 1.60 | 1.30 | 1.63 |
| KL7 | Light logging slash | Low | Shaded | 0.20 | 4.50 | 6.13 | 0.52 | 6.13 | 0.00 | 0.00 | 0.00 | 1.60 | 1.60 | 1.30 | 1.63 |
| KL8 | Light logging slash | Low | Unshaded | 0.30 | 4.50 | 6.13 | 0.52 | 6.13 | 0.00 | 0.00 | 0.00 | 1.60 | 1.60 | 1.30 | 1.63 |
| KL9 | Light logging slash | Low | Unshaded | 0.50 | 4.50 | 6.13 | 0.52 | 6.13 | 0.00 | 0.00 | 0.00 | 1.60 | 1.60 | 1.30 | 1.63 |

## Table C-1. Fuel Model Parameters for the FETM Fuel Model Set

| Derivative Fuel Model | Parent Fuel Model Name | Loading Class | Shaded/ Unshaded | Wind Reduction Factor | 0-3” D&D Wood Loading | Total D&D Wood Loading | Fuel Bed Depth (feet) | Total Live + D&D Wood Loading | Total Live Loading | Live-Woody Loading | Live-Herb Loading | 1-Hr Fuel Loading | 10-Hr Fuel Loading | 100-Hr Fuel Loading | 1000-Hr Fuel Loading |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| KM1 | Light logging slash | Medium | Shaded | 0.20 | 7.00 | 9.50 | 0.51 | 9.50 | 0.00 | 0.00 | 0.00 | 2.50 | 2.50 | 2.00 | 2.50 |
| KM2 | Light logging slash | Medium | Unshaded | 0.30 | 7.00 | 9.50 | 0.51 | 9.50 | 0.00 | 0.00 | 0.00 | 2.50 | 2.50 | 2.00 | 2.50 |
| KM3 | Light logging slash | Medium | Unshaded | 0.50 | 7.00 | 9.50 | 0.51 | 9.50 | 0.00 | 0.00 | 0.00 | 2.50 | 2.50 | 2.00 | 2.50 |
| KM4 | Light logging slash | Medium | Shaded | 0.20 | 7.00 | 9.50 | 0.60 | 9.50 | 0.00 | 0.00 | 0.00 | 2.50 | 2.50 | 2.00 | 2.50 |
| KM5 | Light logging slash | Medium | Unshaded | 0.30 | 7.00 | 9.50 | 0.60 | 9.50 | 0.00 | 0.00 | 0.00 | 2.50 | 2.50 | 2.00 | 2.50 |
| KM6 | Light logging slash | Medium | Unshaded | 0.50 | 7.00 | 9.50 | 0.60 | 9.50 | 0.00 | 0.00 | 0.00 | 2.50 | 2.50 | 2.00 | 2.50 |
| KM7 | Light logging slash | Medium | Shaded | 0.20 | 7.00 | 9.50 | 0.78 | 9.50 | 0.00 | 0.00 | 0.00 | 2.50 | 2.50 | 2.00 | 2.50 |
| KM8 | Light logging slash | Medium | Unshaded | 0.30 | 7.00 | 9.50 | 0.78 | 9.50 | 0.00 | 0.00 | 0.00 | 2.50 | 2.50 | 2.00 | 2.50 |
| KM9 | Light logging slash | Medium | Unshaded | 0.50 | 7.00 | 9.50 | 0.78 | 9.50 | 0.00 | 0.00 | 0.00 | 2.50 | 2.50 | 2.00 | 2.50 |
| KZ1 | Light logging slash | High++ | Shaded | 0.20 | 12.20 | 16.04 | 0.63 | 16.04 | 0.00 | 0.00 | 0.00 | 4.26 | 4.46 | 3.48 | 3.84 |
| KZ2 | Light logging slash | High++ | Unshaded | 0.30 | 12.20 | 16.04 | 0.63 | 16.04 | 0.00 | 0.00 | 0.00 | 4.26 | 4.46 | 3.48 | 3.84 |
| KZ3 | Light logging slash | High++ | Unshaded | 0.50 | 12.20 | 16.04 | 0.63 | 16.04 | 0.00 | 0.00 | 0.00 | 4.26 | 4.46 | 3.48 | 3.84 |
| KZ4 | Light logging slash | High++ | Shaded | 0.20 | 12.20 | 16.04 | 0.90 | 16.04 | 0.00 | 0.00 | 0.00 | 4.26 | 4.46 | 3.48 | 3.84 |
| KZ5 | Light logging slash | High++ | Unshaded | 0.30 | 12.20 | 16.04 | 0.90 | 16.04 | 0.00 | 0.00 | 0.00 | 4.26 | 4.46 | 3.48 | 3.84 |
| KZ6 | Light logging slash | High++ | Unshaded | 0.50 | 12.20 | 16.04 | 0.90 | 16.04 | 0.00 | 0.00 | 0.00 | 4.26 | 4.46 | 3.48 | 3.84 |
| KZ7 | Light logging slash | High++ | Shaded | 0.20 | 12.20 | 16.04 | 1.17 | 16.04 | 0.00 | 0.00 | 0.00 | 4.26 | 4.46 | 3.48 | 3.84 |
| KZ8 | Light logging slash | High++ | Unshaded | 0.30 | 12.20 | 16.04 | 1.17 | 16.04 | 0.00 | 0.00 | 0.00 | 4.26 | 4.46 | 3.48 | 3.84 |
| KZ9 | Light logging slash | High++ | Unshaded | 0.50 | 12.20 | 16.04 | 1.17 | 16.04 | 0.00 | 0.00 | 0.00 | 4.26 | 4.46 | 3.48 | 3.84 |
| L | Western perennial grass | Medium | Unshaded | 0.44 | 0.25 | 0.25 | 1.00 | 0.75 | 0.50 | 0.00 | 0.50 | 0.25 | 0.00 | 0.00 | 0.00 |
| LH1 | Western perennial grass | High | Shaded | 0.20 | 0.33 | 0.33 | 1.33 | 1.00 | 0.67 | 0.00 | 0.67 | 0.33 | 0.00 | 0.00 | 0.00 |
| LH2 | Western perennial grass | High | Unshaded | 0.50 | 0.33 | 0.33 | 1.33 | 1.00 | 0.67 | 0.00 | 0.67 | 0.33 | 0.00 | 0.00 | 0.00 |
| LL1 | Western perennial grass | Low | Shaded | 0.20 | 0.17 | 0.17 | 0.67 | 0.50 | 0.33 | 0.00 | 0.33 | 0.17 | 0.00 | 0.00 | 0.00 |
| LL2 | Western perennial grass | Low | Unshaded | 0.50 | 0.17 | 0.17 | 0.67 | 0.34 | 0.17 | 0.00 | 0.17 | 0.17 | 0.00 | 0.00 | 0.00 |
| LM1 | Western perennial grass | Medium | Shaded | 0.20 | 0.25 | 0.25 | 1.00 | 0.75 | 0.50 | 0.00 | 0.50 | 0.25 | 0.00 | 0.00 | 0.00 |
| LM2 | Western perennial grass | Medium | Unshaded | 0.50 | 0.25 | 0.25 | 1.00 | 0.75 | 0.50 | 0.00 | 0.50 | 0.25 | 0.00 | 0.00 | 0.00 |
| N | Saw grass | Medium | Unshaded | 0.55 | 3.00 | 3.00 | 3.00 | 5.00 | 2.00 | 2.00 | 0.00 | 1.50 | 1.50 | 0.00 | 0.00 |
| NH1 | Saw grass | High | Shaded | 0.20 | 3.90 | 3.90 | 3.90 | 6.50 | 2.60 | 2.60 | 0.00 | 1.95 | 1.95 | 0.00 | 0.00 |
| NH2 | Saw grass | High | Unshaded | 0.50 | 3.90 | 3.90 | 3.90 | 6.50 | 2.60 | 2.60 | 0.00 | 1.95 | 1.95 | 0.00 | 0.00 |
| NL1 | Saw grass | Low | Shaded | 0.20 | 2.02 | 2.02 | 2.01 | 3.36 | 1.34 | 1.34 | 0.00 | 1.01 | 1.01 | 0.00 | 0.00 |
| NL2 | Saw grass | Low | Unshaded | 0.50 | 2.02 | 2.02 | 2.01 | 3.36 | 1.34 | 1.34 | 0.00 | 1.01 | 1.01 | 0.00 | 0.00 |
| NM1 | Saw grass | Medium | Shaded | 0.20 | 3.00 | 3.00 | 3.00 | 5.00 | 2.00 | 2.00 | 0.00 | 1.50 | 1.50 | 0.00 | 0.00 |
| NM2 | Saw grass | Medium | Unshaded | 0.50 | 3.00 | 3.00 | 3.00 | 5.00 | 2.00 | 2.00 | 0.00 | 1.50 | 1.50 | 0.00 | 0.00 |
| O | High pocosin | Medium | Unshaded | 0.55 | 8.00 | 10.00 | 4.00 | 17.00 | 7.00 | 7.00 | 0.00 | 2.00 | 3.00 | 3.00 | 2.00 |
| OH1 | High pocosin | High | Unshaded | 0.30 | 10.40 | 13.00 | 5.20 | 22.10 | 9.10 | 9.10 | 0.00 | 2.60 | 3.90 | 3.90 | 2.60 |
| OH2 | High pocosin | High | Unshaded | 0.50 | 10.40 | 13.00 | 5.20 | 22.10 | 9.10 | 9.10 | 0.00 | 2.60 | 3.90 | 3.90 | 2.60 |
| OL1 | High pocosin | Low | Unshaded | 0.30 | 5.36 | 6.70 | 2.68 | 11.39 | 4.69 | 4.69 | 0.00 | 1.34 | 2.01 | 2.01 | 1.34 |
| OL2 | High pocosin | Low | Unshaded | 0.50 | 5.36 | 6.70 | 2.68 | 11.39 | 4.69 | 4.69 | 0.00 | 1.34 | 2.01 | 2.01 | 1.34 |
| OM1 | High pocosin | Medium | Unshaded | 0.30 | 8.00 | 10.00 | 4.00 | 17.00 | 7.00 | 7.00 | 0.00 | 2.00 | 3.00 | 3.00 | 2.00 |
| OM2 | High pocosin | Medium | Unshaded | 0.50 | 8.00 | 10.00 | 4.00 | 17.00 | 7.00 | 7.00 | 0.00 | 2.00 | 3.00 | 3.00 | 2.00 |
| P | Southern pine plantation | Medium | Shaded | 0.12 | 2.50 | 2.50 | 0.40 | 3.50 | 1.00 | 0.50 | 0.50 | 1.00 | 1.00 | 0.50 | 0.00 |

## Table C-1. Fuel Model Parameters for the FETM Fuel Model Set

| Derivative Fuel Model | Parent Fuel Model Name | Loading Class | Shaded/ Unshaded | Wind Reduction Factor | 0-3” D&D Wood Loading | Total D&D Wood Loading | Fuel Bed Depth (feet) | Total Live + D&D Wood Loading | Total Live Loading | Live-Woody Loading | Live-Herb Loading | 1-Hr Fuel Loading | 10-Hr Fuel Loading | 100-Hr Fuel Loading | 1000-Hr Fuel Loading |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| PH1 | Southern pine plantation | High | Shaded | 0.20 | 3.25 | 3.25 | 0.52 | 4.55 | 1.30 | 0.65 | 0.65 | 1.30 | 1.30 | 0.65 | 0.00 |
| PH2 | Southern pine plantation | High | Unshaded | 0.40 | 3.25 | 3.25 | 0.52 | 4.55 | 1.30 | 0.65 | 0.65 | 1.30 | 1.30 | 0.65 | 0.00 |
| PL1 | Southern pine plantation | Low | Shaded | 0.20 | 1.68 | 1.68 | 0.27 | 2.36 | 0.68 | 0.34 | 0.34 | 0.67 | 0.67 | 0.34 | 0.00 |
| PL2 | Southern pine plantation | Low | Unshaded | 0.40 | 1.68 | 1.68 | 0.27 | 2.36 | 0.68 | 0.34 | 0.34 | 0.67 | 0.67 | 0.34 | 0.00 |
| PM1 | Southern pine plantation | Medium | Shaded | 0.20 | 2.50 | 2.50 | 0.40 | 3.50 | 1.00 | 0.50 | 0.50 | 1.00 | 1.00 | 0.50 | 0.00 |
| PM2 | Southern pine plantation | Medium | Unshaded | 0.40 | 2.50 | 2.50 | 0.40 | 3.50 | 1.00 | 0.50 | 0.50 | 1.00 | 1.00 | 0.50 | 0.00 |
| Q | Alaskan black spruce | Medium | Unshaded | 0.63 | 6.50 | 7.50 | 3.00 | 12.00 | 4.50 | 4.00 | 0.50 | 2.00 | 2.50 | 2.00 | 1.00 |
| QH1 | Alaskan black spruce | High | Shaded | 0.20 | 8.45 | 9.75 | 3.90 | 15.60 | 5.85 | 5.20 | 0.65 | 2.60 | 3.25 | 2.60 | 1.30 |
| QH2 | Alaskan black spruce | High | Unshaded | 0.40 | 8.45 | 9.75 | 3.90 | 15.60 | 5.85 | 5.20 | 0.65 | 2.60 | 3.25 | 2.60 | 1.30 |
| QL1 | Alaskan black spruce | Low | Shaded | 0.20 | 4.36 | 5.03 | 2.01 | 8.05 | 3.02 | 2.68 | 0.34 | 1.34 | 1.68 | 1.34 | 0.67 |
| QL2 | Alaskan black spruce | Low | Unshaded | 0.40 | 4.36 | 5.03 | 2.01 | 8.05 | 3.02 | 2.68 | 0.34 | 1.34 | 1.68 | 1.34 | 0.67 |
| QM1 | Alaskan black spruce | Medium | Shaded | 0.20 | 6.50 | 7.50 | 3.00 | 12.00 | 4.50 | 4.00 | 0.50 | 2.00 | 2.50 | 2.00 | 1.00 |
| QM2 | Alaskan black spruce | Medium | Unshaded | 0.40 | 6.50 | 7.50 | 3.00 | 12.00 | 4.50 | 4.00 | 0.50 | 2.00 | 2.50 | 2.00 | 1.00 |
| R | Hardwood (summer) | Medium | Shaded | 0.08 | 1.50 | 1.50 | 0.25 | 2.50 | 1.00 | 0.50 | 0.50 | 0.50 | 0.50 | 0.50 | 0.00 |
| RH1 | Hardwood (summer) | High | Shaded | 0.20 | 2.01 | 2.01 | 0.33 | 3.35 | 1.34 | 0.67 | 0.67 | 0.67 | 0.67 | 0.67 | 0.00 |
| RH2 | Hardwood (summer) | High | Unshaded | 0.30 | 2.01 | 2.01 | 0.33 | 3.35 | 1.34 | 0.67 | 0.67 | 0.67 | 0.67 | 0.67 | 0.00 |
| RL1 | Hardwood (summer) | Low | Shaded | 0.20 | 1.02 | 1.02 | 0.17 | 1.70 | 0.68 | 0.34 | 0.34 | 0.34 | 0.34 | 0.34 | 0.00 |
| RL2 | Hardwood (summer) | Low | Unshaded | 0.30 | 1.02 | 1.02 | 0.17 | 1.70 | 0.68 | 0.34 | 0.34 | 0.34 | 0.34 | 0.34 | 0.00 |
| RM1 | Hardwood (summer) | Medium | Shaded | 0.20 | 1.50 | 1.50 | 0.25 | 2.50 | 1.00 | 0.50 | 0.50 | 0.50 | 0.50 | 0.50 | 0.00 |
| RM2 | Hardwood (summer) | Medium | Unshaded | 0.30 | 1.50 | 1.50 | 0.25 | 2.50 | 1.00 | 0.50 | 0.50 | 0.50 | 0.50 | 0.50 | 0.00 |
| S | Tundra | Medium | Unshaded | 0.45 | 1.50 | 2.00 | 0.40 | 3.00 | 1.00 | 0.50 | 0.50 | 0.50 | 0.50 | 0.50 | 0.50 |
| SH1 | Tundra | High | Shaded | 0.20 | 2.01 | 2.68 | 0.53 | 4.02 | 1.34 | 0.67 | 0.67 | 0.67 | 0.67 | 0.67 | 0.67 |
| SH2 | Tundra | High | Unshaded | 0.30 | 2.01 | 2.68 | 0.53 | 4.02 | 1.34 | 0.67 | 0.67 | 0.67 | 0.67 | 0.67 | 0.67 |
| SL1 | Tundra | Low | Shaded | 0.20 | 1.02 | 1.36 | 0.27 | 2.04 | 0.68 | 0.34 | 0.34 | 0.34 | 0.34 | 0.34 | 0.34 |
| SL2 | Tundra | Low | Unshaded | 0.30 | 1.02 | 1.36 | 0.27 | 2.04 | 0.68 | 0.34 | 0.34 | 0.34 | 0.34 | 0.34 | 0.34 |
| SM1 | Tundra | Medium | Shaded | 0.20 | 1.50 | 2.00 | 0.40 | 3.00 | 1.00 | 0.50 | 0.50 | 0.50 | 0.50 | 0.50 | 0.50 |
| SM2 | Tundra | Medium | Unshaded | 0.30 | 1.50 | 2.00 | 0.40 | 3.00 | 1.00 | 0.50 | 0.50 | 0.50 | 0.50 | 0.50 | 0.50 |
| T | Sagebrush-grass | Medium | Unshaded | 0.42 | 1.50 | 1.50 | 1.25 | 4.50 | 3.00 | 2.50 | 0.50 | 1.00 | 0.50 | 0.00 | 0.00 |
| TH1 | Sagebrush-grass | High | Shaded | 0.20 | 2.00 | 2.00 | 1.67 | 6.00 | 4.00 | 3.33 | 0.67 | 1.33 | 0.67 | 0.00 | 0.00 |
| TH2 | Sagebrush-grass | High | Unshaded | 0.30 | 2.00 | 2.00 | 1.67 | 6.00 | 4.00 | 3.33 | 0.67 | 1.33 | 0.67 | 0.00 | 0.00 |
| TH3 | Sagebrush-grass | High | Unshaded | 0.50 | 2.00 | 2.00 | 1.67 | 6.00 | 4.00 | 3.33 | 0.67 | 1.33 | 0.67 | 0.00 | 0.00 |
| TL1 | Sagebrush-grass | Low | Shaded | 0.20 | 1.00 | 1.00 | 0.83 | 3.00 | 2.00 | 1.67 | 0.33 | 0.67 | 0.33 | 0.00 | 0.00 |
| TL2 | Sagebrush-grass | Low | Unshaded | 0.30 | 1.00 | 1.00 | 0.83 | 3.00 | 2.00 | 1.67 | 0.33 | 0.67 | 0.33 | 0.00 | 0.00 |
| TL3 | Sagebrush-grass | Low | Unshaded | 0.50 | 1.00 | 1.00 | 0.83 | 3.00 | 2.00 | 1.67 | 0.33 | 0.67 | 0.33 | 0.00 | 0.00 |
| TM1 | Sagebrush-grass | Medium | Shaded | 0.20 | 1.50 | 1.50 | 1.25 | 4.50 | 3.00 | 2.50 | 0.50 | 1.00 | 0.50 | 0.00 | 0.00 |
| TM2 | Sagebrush-grass | Medium | Unshaded | 0.30 | 1.50 | 1.50 | 1.25 | 4.50 | 3.00 | 2.50 | 0.50 | 1.00 | 0.50 | 0.00 | 0.00 |
| TM3 | Sagebrush-grass | Medium | Unshaded | 0.50 | 1.50 | 1.50 | 1.25 | 4.50 | 3.00 | 2.50 | 0.50 | 1.00 | 0.50 | 0.00 | 0.00 |
| U | Western long-needled conifer | Medium | Shaded | 0.12 | 4.00 | 4.00 | 0.50 | 5.00 | 1.00 | 0.50 | 0.50 | 1.50 | 1.50 | 1.00 | 0.00 |
| UH1 | Western long-needled conifer | High | Shaded | 0.20 | 5.33 | 5.33 | 0.67 | 6.67 | 1.34 | 0.67 | 0.67 | 2.00 | 2.00 | 1.33 | 0.00 |
| UH2 | Western long-needled conifer | High | Unshaded | 0.30 | 5.33 | 5.33 | 0.67 | 6.67 | 1.34 | 0.67 | 0.67 | 2.00 | 2.00 | 1.33 | 0.00 |

### Table C-1. Fuel Model Parameters for the FETM Fuel Model Set

| Derivative Fuel Model | Parent Fuel Model Name | Loading Class | Shaded/ Unshaded | Wind Reduction Factor | 0-3" D&D Wood Loading | Total D&D Wood Loading | Fuel Bed Depth (feet) | Total Live + D&D Wood Loading | Total Live Loading | Live-Woody Loading | Live-Herb Loading | 1-Hr Fuel Loading | 10-Hr Fuel Loading | 100-Hr Fuel Loading | 1000-Hr Fuel Loading |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| UL1 | Western long-needled conifer | Low | Shaded | 0.20 | 2.67 | 2.67 | 0.33 | 3.33 | 0.66 | 0.33 | 0.33 | 1.00 | 1.00 | 0.67 | 0.00 |
| UL2 | Western long-needled conifer | Low | Unshaded | 0.30 | 2.67 | 2.67 | 0.33 | 3.33 | 0.66 | 0.33 | 0.33 | 1.00 | 1.00 | 0.67 | 0.00 |
| UM1 | Western long-needled conifer | Medium | Shaded | 0.20 | 4.00 | 4.00 | 0.50 | 5.00 | 1.00 | 0.50 | 0.50 | 1.50 | 1.50 | 1.00 | 0.00 |
| UM2 | Western long-needled conifer | Medium | Unshaded | 0.30 | 4.00 | 4.00 | 0.50 | 5.00 | 1.00 | 0.50 | 0.50 | 1.50 | 1.50 | 1.00 | 0.00 |