United States Department of Agriculture

MCFire Model Technical Description

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Forest Service

Pacific Northwest Research Station

General Technical Report PNW-GTR-926

August 2016

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Cover photo by Tom Iraci.

Abstract

Conklin, David R.; Lenihan, James M.; Bachelet, Dominique; Neilson, Ronald P.; Kim, John B. 2016. MCFire model technical description. Gen. Tech. Rep. PNW-GTR-926. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 75 p.

MCFire is a computer program that simulates the occurrence and effects of wildfire on natural vegetation, as a submodel within the MC1 dynamic global vegetation model. This report is a technical description of the algorithms and parameter values used in MCFire, intended to encapsulate its design and features a higher level that is more conceptual than the level provided by the computer source code, so that programmers and users can better understand its features and limitations. Two primary sources of the MCFire algorithms are the National Fire-Danger Rating System and CONSUME 3.0. MC1 reads elevation, soil data, and climate data; simulates vegetation biochemistry and biogeography; and invokes MCFire to simulate fire and its effects. Unlike MC1, which runs on a monthly time step, MCFire simulates fire on a daily time step. MC1 and MCFire are typically run on a grid of independent cells, with neither model designed to simulate interaction among cells. MCFire estimates daily fire weather from monthly weather variables; calculates fuel load and moisture; determines the occurrence of fire; estimates fire behavior, including rate of spread, energy release, fireline intensity, crown scorching and area burned; and estimates fire effects on grass and tree mortality, biomass consumption, emissions, and black carbon production.

Keywords: dynamic global vegetation model, fire, MC1, MCFire, modeling, wildfire.

Preface

This report is a technical description of MCFire, a submodel within the MAPSS-CENTURY (MC1) dynamic global vegetation model (Brachelet 2001a). MCFire was developed by the Mapped Atmosphere-Plant-Soil System Team, at the U.S. Forest Service Pacific Northwest (PNW) Research Station. The development of MCFire was led by James M. Lenihan, a PNW research ecologist, and the first draft of this report was composed by David R. Conklin, who worked with the Mapped Atmosphere-Plant-Soil System Team first as a programmer and later as a Ph.D. student at Oregon State University. It was originally written to facilitate the porting of MCFire logic from MC1 into other dynamic global vegetation models. Many years have elapsed since this draft was composed and reviewed, and in those years all the original authors have left the team and the PNW Station. MC1 and MCFire, however, continue to be used by an active community of professionals; and, although code development by MC1 users continues, much of MCFire logic remains unchanged. Furthermore, as of this writing, no publication has yet described the detailed structure of the MCFire algorithms for its users and students. For these reasons, we are publishing this report after a long hiatus.

An important change was made to MCFire since the original draft of this report was written: in 2005, the fire occurrence algorithm was revised to use the fine-fuel moisture code and build-up indices from the Canadian Forest Fire Weather Index System (Van Wagner 1987) instead of relying on Palmer Drought Severity Index (Palmer 1965), the 1,000-hour fuel moisture content (Fosberg et al. 1981), and fine-fuel flammability (Cohen and Deeming 1985). The new fire occurrence algorithm is described in appendix 3.

Recently, MC1, including MCFire, was rewritten in C++ to improve its computational efficiency. The new version is called MC2. MCFire within MC2 retains the same algorithms as MCFire in MC1. The source code for both MC1 and MC2, including MCFire, is available from the PNW Station or from an Oregon State University code repository website.[1]

[1] On file with: Forestry Sciences Laboratory, 3200 SW Jefferson Way, Corvallis, OR 97730.

Contents

Section 1. Introduction

MCFire is a computer program that simulates the occurrence and effects of wildfire on natural vegetation (Lenihan et al. 1998) as a submodel within the MAPSS-CENTURY (MC1) dynamic global vegetation model (Daly et al. 2000). A hybrid of MAPSS biogeography model (Neilson 1995) and Century Soil Organic Matter Model (Parton et al. 1987), MC1 simulates plant functional types, ecosystem fluxes of carbon, nitrogen, water, and fire disturbance. It has been documented extensively (Aber et al. 2001; Bachelet et al. 2001a, 2001b, 2003, 2004, 2005; Daly et al. 2000; Lenihan et al. 2003). MC1 is implemented on spatial data grids of varying resolutions (ranging from 0.5 degree to 2.5 minutes) depending on the resolution of the climatic input data. MC1 is run separately for each grid cell with no exchange of information among cells. MC1 reads climate data at a monthly time step and executes interacting modules that simulate biogeography, biogeochemistry, and fire disturbance (fig. 1).

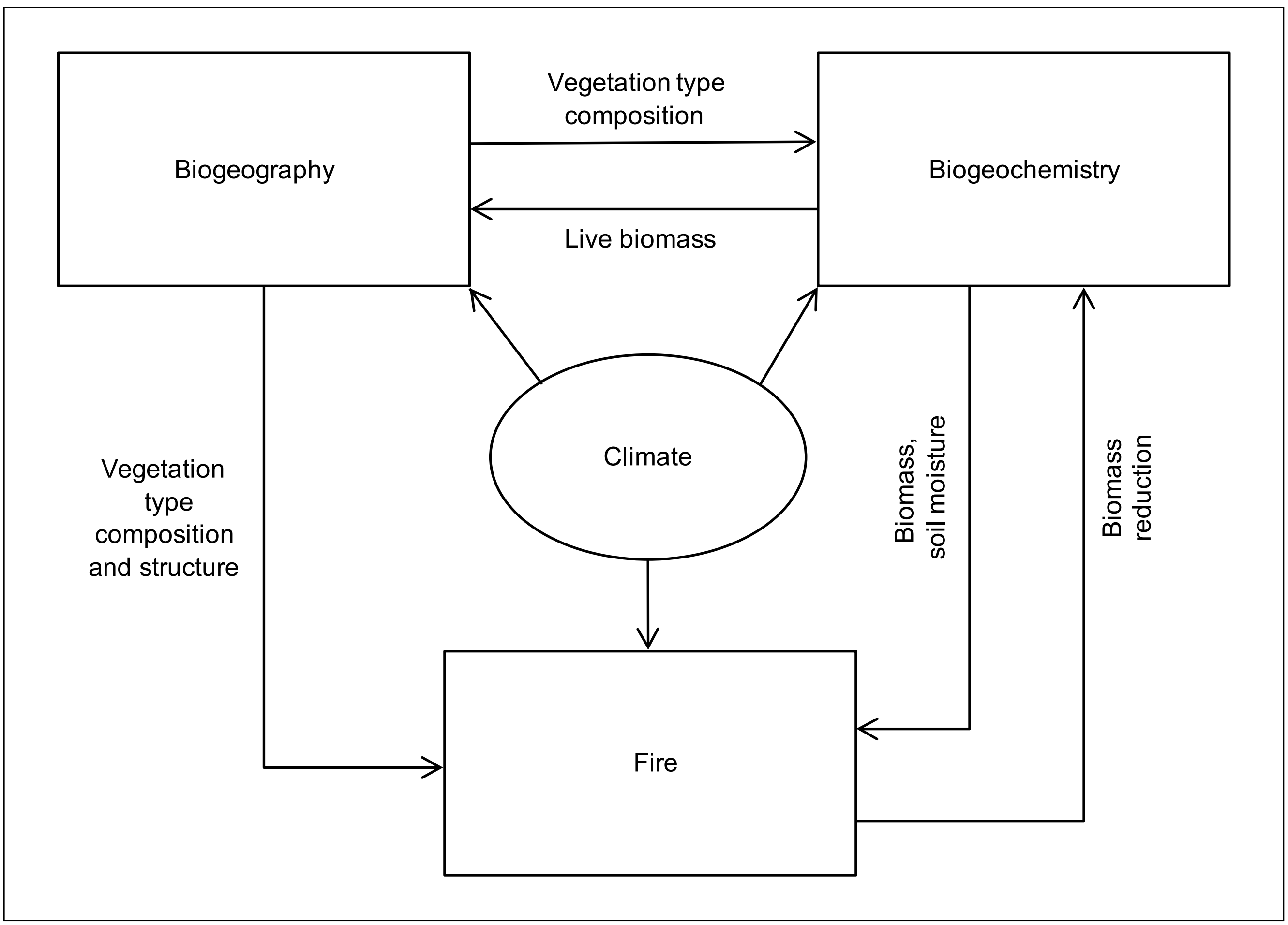

Figure 1—Primary modules in MC1 dynamic global vegetation model.

This report is a technical description of the algorithms and parameter values used in MCFire, intended to encapsulate the MCFire technical design and provide a level of explanation that is more conceptual than the level provided by the computer source code, so that programmers and users can better understand its features and limitations. MCFire is written in C programming language. The two primary sources of equations and parameters used in MCFire are the fire-danger rating system equations developed by the U.S. Forest Service (Cohen and Deeming 1985), and the CONSUME user guide (Prichard et al. 2007).

This report replicates many variables, equations, and parameter values taken from their sources for clarity and completeness. Where appropriate, relevant source code variable names are included in italics to help the reader link the description to the source code. Appendix 1 lists all key variables used by MCFire and appendix 2 documents the source code structure in detail. This report does not include the scientific justifications for MCFire model design developed by Lenihan et al. (1998), or the evaluations of the MCFire model skill by Lenihan et al. (2003).

In contrast to MC1, which operates on a monthly time step, MCFire simulates fire on a daily time step by estimating daily weather conditions (fig. 2). MCFire takes the following monthly inputs from MC1: the vegetation type (table 1), climate time series (precipitation, vapor pressure, wind speed, and minimum/maximum temperature), the Palmer Drought Severity Index, and the biomass pools from the MC1 biogeochemistry module. From these, it estimates daily fire weather, fuel loading, fuel moisture, fire occurrence, fire behavior, and the effects of fire behavior. Each of these simulation steps is described below.

Section 2. Fire Weather

MCFire uses monthly climate variables (table 2) to estimate daily weather data (table 3). To estimate daily temperature values (*tmp*, *tmin*, and *tmax*), the values for the first day of the month are set to the monthly values (*m_tmp*, *m_tmin*, and *m_tmax*), and the values for the remaining days in the month are estimated by simple linear interpolation between values for the current month and the values for the next month. Daily values for December are interpolated between the monthly value for December and the monthly value for January of the current year (not January of the next year). For precipitation, the number of days with precipitation are estimated and randomly distributed within the month, and the monthly total precipitation amount is divided evenly among the days with precipitation.

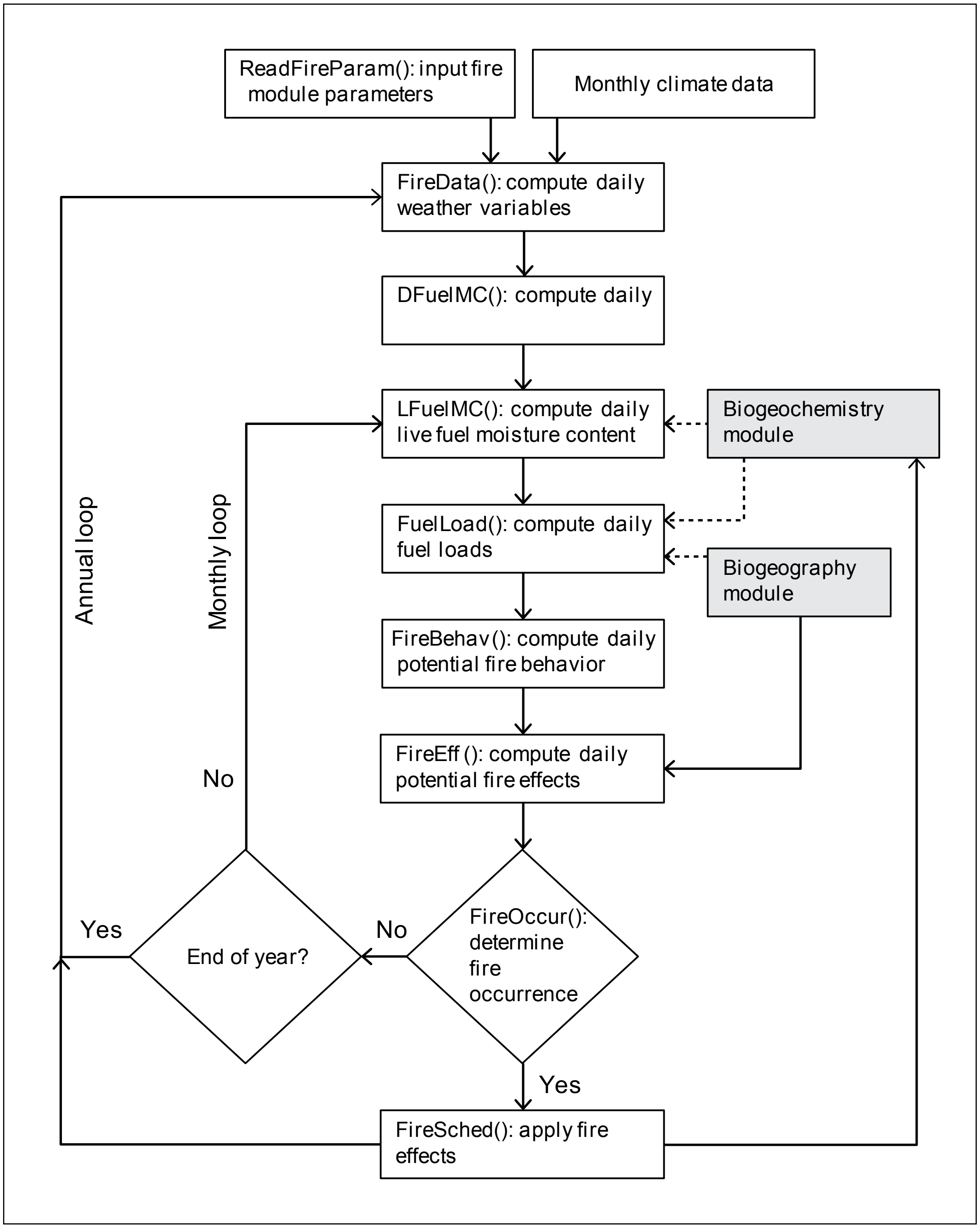

Figure 2—Organization of the MCFire algorithm; note that principal subroutines are identified in parentheses, and that interactions between the fire module and the MC1 biogeography and biogeochemistry modules are shown as dashed lines.

Table 1—Vegetation types simulated by MC1 as adapted from VEMAP (VEMAP Members 1995), with minimum and maximum average fire return intervals (Leenhouts 1998) and CONSUME 3.0 emissions fuel types (Prichard et al. 2007)

Code	Vegetation	Minimum average fire-return interval	Maximum average fire-return interval	CONSUME 3.0 emissions fuel type
1	Tundra	166	230	Mixed conifer slash
2	Boreal coniferous forest	200	225	Mixed conifer slash
3	Maritime temperate coniferous forest	110	184	Douglas-fir slash
4	Continental temperate coniferous forest	47	76	Mixed conifer slash
5	Cool temperate mixed forest	233	348	Mixed conifer slash
6	Warm temperate subtropical mixed forest	17	48	Ponderosa-lodgepole pine slash
7	Temperate deciduous forest	155	237	Hardwoods slash
8	Tropical deciduous forest	200	200	Hardwoods slash
9	Tropical evergreen forest	50	50	Hardwoods slash
10	Temperate mixed xeromorphic woodland	39	75	Juniper slash
11	Temperate conifer xeromorphic woodland	24	56	Ponderosa-lodgepole pine slash
12	Tropical thorn woodland	15	5	Juniper slash
13	Temperate subtropical deciduous savanna	26	80	Hardwoods slash
14	Warm temperate subtropical mixed savanna	8	19	Ponderosa-lodgepole pine slash
15	Temperate conifer savanna	26	62	Ponderosa-lodgepole pine slash
16	Tropical deciduous savanna	7	7	Hardwoods slash
17	C_3 grasslands[a]	15	32	Sagebrush
18	C_4 grasslands[b]	12	24	Sagebrush
19	Mediterranean shrubland	20	43	Chaparral
20	Temperate arid shrubland	48	87	Sagebrush
21	Subtropical arid shrubland	82	319	Sagebrush
22	Taiga	166	230	Mixed conifer slash
23	Boreal larch forest	15	15	Mixed conifer slash

[a] Grasslands adapted to cool seasons.
[b] Grasslands adapted to warm or hot seasons.

Table 2—Monthly climate variables used by the MCFire simulation model

Variable	Description	Time step	Dimensions	Source
m_tmp	Average temperature	Month	°C	Input
m_tmin	Minimum temperature	Month	°C	Input
m_tmax	Maximum temperature	Month	°C	Input
vpr_sacred	Vapor pressure	Month	Pascals	Input
m_ppt	Total precipitation, water equivalent	Month	Millimeters of water	Input
ws	Average wind speed	Month	Meters per second	Input
m_pet	Potential evapotranspiration	Month	Millimeters of water	Calculated
satvp_sacred	Saturated vapor pressure at average temperature	Month	Pascals	Calculated
pdsi	Palmer Drought Severity Index	Month	Dimensionless	Input

Table 3—Daily weather variables calculated by the MCFire simulation model

Variable	Description	Units of measurement	Time step	Source
tmp	Average temperature	°C	Daily	Calculated
tmin	Minimum temperature	°C	Daily	Calculated
tmax	Maximum temperature	°C	Daily	Calculated
rh	Relative humidity	Percent	Daily	Calculated
rhmin	Minimum relative humidity	Percent	Daily	Calculated
rhmax	Maximum relative humidity	Percent	Daily	Calculated
ppt	Total precipitation, water equivalent	Millimeters of water	Daily	Calculated
ppt_dur	Precipitation duration	Hours	Daily	Calculated
snowfall	Snowfall, water equivalent	Millimeters of water	Daily	Calculated
snow	Snowpack, water equivalent	Millimeters of water	Daily	Calculated
ws	Average wind speed	Meters per second	Daily	Calculated
daylit	Length of daylight	Hours	Daily	Calculated

Relative Humidity

MCFire uses daily relative humidity values to calculate daily fuel moisture content. It estimates daily average, minimum, and maximum relative humidity values from monthly vapor pressure and saturated vapor pressure values provided by MC1. First, relative humidity is estimated as:

$$m\_rh[month] = \frac{vpr\_sacred[month]}{satvp\_sacred[month]} \times 100 \tag{1}$$

where *m_rh*[*month*] is the relative humidity as a percentage, *vpr_sacred*[*month*] is the monthly value of vapor pressure from MC1 in pascals, and *satvp_sacred*[*month*] is the monthly value of saturated vapor pressure from MC1 in pascals.

To calculate daily values of relative humidity (*rh*[*day*]), MCFire interpolates linearly between the monthly values for the present month and the next month, as with daily temperatures.

Daily values of minimum and maximum relative humidity (*rhmin*[*day*], *rhmax*[*day*]) are similarly interpolated from their respective monthly values. First, monthly values are calculated:

$$m\_rhmin[month] = \frac{vpr\_sacred[month]}{satvp\_(m\_tmax[month])} \times 100 \tag{2}$$

$$m\_rhmax[month] = \frac{vpr\_sacred[month]}{satvp\_(m\_tmin[month])} \times 100 \tag{3}$$

where *m_rhmin*[*month*] is the monthly value of minimum relative humidity as a percentage, *m_rhmax*[*month*] is the monthly value of maximum relative humidity as a percentage, *vpr_sacred*[*month*] is the monthly value of vapor pressure from MC1 in pascals, *satvp*(*t*) is the saturated vapor pressure in pascals at temperature t in °C, *m_tmin*[*month*] is the monthly minimum temperature in °C, and *m_tmax*[*month*] is the monthly maximum temperature in °C.

Rain and Snow

Daily precipitation estimates are used in the calculation of daily fuel moisture content. MCFire estimates daily precipitation from monthly precipitation values provided by MC1. The number of precipitation events each month is estimated using a regression function derived from weather station data archived by the National Climate Data Center (WeatherDisc Associates 1995). When the monthly potential evapotranspiration (*m_pet*[*month*]) is >100 mm, then:

$$ppt\_events = 0.887 + 0.052 \times m\_ppt[month] \quad (4)$$

but when monthly potential evaporation is ≤100 mm, then:

$$ppt\_events = 2.319 + 0.027 \times m\_ppt[month] \quad (5)$$

where *ppt_events* is the number of precipitation events in the month, rounded up to an integer, with a maximum of 12 events; *m_pet*[*month*] is the total potential evapotranspiration in the given month in millimeters; and *m_ppt*[*month*] is the total precipitation in the month in millimeters.

The fire model assumes that any given day will have either one precipitation event or none at all. The monthly precipitation is evenly divided among the precipitation events:

$$ppt\_per\_event = \frac{m\_ppt[month]}{m\_ppt\_events} \quad (6)$$

where *ppt_per_event* is the amount of precipitation per event in millimeters; *m_ppt*[*month*] is the total precipitation in the month in millimeters; and *ppt_events* is the number of precipitation events in the month, rounded up to an integer, with a maximum of 12 events (eqs. 4, 5).

MCFire calculates dead-fuel moisture by estimating precipitation rate and duration. When monthly potential evapotranspiration is >100 mm, then precipitation rate is set at 0.25 inches of rainfall per hour; otherwise it is set to 0.05 inches per hour. These rates are the same as those used for the rainfall rate *WETRAT* in Cohen and Deeming (1985), although their rates relied on "climate class" rather than potential evapotranspiration as the basis for selecting a precipitation rate. As with estimations of daily temperatures, MCFire first calculates monthly the precipitation rate; daily precipitation rates are then interpolated between the monthly rates of two successive months. MCFire then calculates precipitation duration as:

$$ppt\_dur = \frac{ppt[day]}{ppt\_rat[day]} \quad (7)$$

where *ppt_dur* is the precipitation duration in hours, *ppt*[*day*] is the amount of precipitation on the given day in, and, *ppt_rat*[*day*] is the estimated rate of precipitation (inches per hour) on the given day.

The value of *ppt_dur* (eq. 7) is rounded to the nearest hour with a maximum of 8 hours. When minimum daily temperature (*tmin*) is <32 °F (0 °C), precipitation duration is set to zero.

Four parameters control snow accumulation and melt (table 4). The amount of precipitation that falls as snow is determined by comparing the temperature to two thresholds (*snw0* and *snw1*). When the temperature is less than or equal to *snw1*, then all the precipitation falls as snow and all the rainfall is transformed into snow (*snowfall*). When temperature is higher than or equal to *snw0*, all the precipitation falls as rain (*rainfall*). When the temperature is between *snw0* and *snw1*, then:

$$snowfall[day] = \left(1 - \frac{tmp[day] - snw1}{snow0 - snow1}\right) \times ppt[day] \tag{8}$$

where *snowfall*[*day*] is the snowfall for the day in millimeters (water equivalent), *tmp*[*day*] is the average daily temperature on the given day in °C, *snw*0 is the temperature above which all precipitation is rain in °C, *snw*1 is the temperature below which all precipitation is snow in °C, and *ppt*[*day*] is the precipitation for the day in millimeters.

Table 4—MC1 climate parameters used by the MCFire simulation model, drawn from the MC1 fire_param.dat file

Parameter	Description	Value
*snw*0	Temperature above which all precipitation is rain	3 °C
*snw*1	Temperature below which all precipitation is snow	0 °C
no_melt	Temperature below which snow does not melt	1 °C
melt_b	Snow melt relationship curve	1.5 mm/°C/day
mc_tree_min	Minimum live tree moisture content	80 percent
mc_tree_max	Maximum live tree moisture content	130 percent
mc_grass_min	Minimum live grass moisture content	30 percent
mc_grass_max	Maximum live grass moisture content	120 percent
slp	Slope	0 percent
mc_thres	Moisture content threshold	12 percent
prob_thres	Probability threshold used in the decisions about fine fuel flammability and tree mortality	45 percent
pdsi_thres	Palmer Drought Severity Index below which a fire may occur	-2.25
partial_cell_burn	If >1, fire always burns the entire cell	1

The snowpack (*snow*) is calculated at each time step by adding the amount of snow (eq. 8) and subtracting an estimated snowmelt amount. If the temperature is not higher that the parameter *no_melt*, snowmelt is zero and the new snowpack value is just the sum of *snow* and *snowfall*. Otherwise:

$$snowmelt = (tmp[day] - no\_melt) \times melt\_b \quad (9)$$

$$snow[day] = snow[day - 1] + snowfall[day] - snowmelt \quad (10)$$

where *snowmelt* is the amount of snowmelt in the current day in millimeters (water equivalent), *tmp*[*day*] is the average temperature of the day in °C, *no_melt* is the temperature threshold below which no snow melts in °C (table 4), *melt_b* is the rate of snowmelt per degree temperature in millimeters per °C (table 4), *snow*[*i*] is the snowpack on day *i* in millimeters (water equivalent) from equation 9, and *snowfall*[*day*] is the amount of snowfall on day *day* (eq. 8).

Wind

Wind speed is used in the fire rate-of-spread calculation. Average wind speed (*ws*) for each day is interpolated between the monthly average wind speeds, as with daily temperatures.

Day Length

Day length is used in the calculation of daily fuel moisture content (fig. 3). Day length is calculated as a function of the site latitude and the day of year (Cohen and Deeming 1985):

$$daylit = 24 \times \left[1 - \frac{\mathrm{acos}(\tan(lat \times c1) \times \tan(c2 \times \sin((jdate\text{-}c3) \times c4)))}{\pi} \right] \quad (11)$$

where *daylit* is the duration of daylight in hours, *lat* is the site latitude in decimal degrees, *c*1is 0.01745, *c*2 is 0.41008, *c*3 is 82, *c*4 is 0.01745, and *jdate* is the day of year with 1 representing January 1.

The argument to function acos() is truncated to the range [-1..1] so that daylit (eq. 11) is constrained to a minimum of 0 hours and a maximum of 24 hours.

Keetch-Byram Drought Index

The Keetch-Byram Drought Index is a measure of moisture in the duff and upper soil layers, used in the fire behavior calculations (Keetch and Byram 1968), ranging from 0 for very wet conditions to 800 for very dry conditions. Keetch-Byram

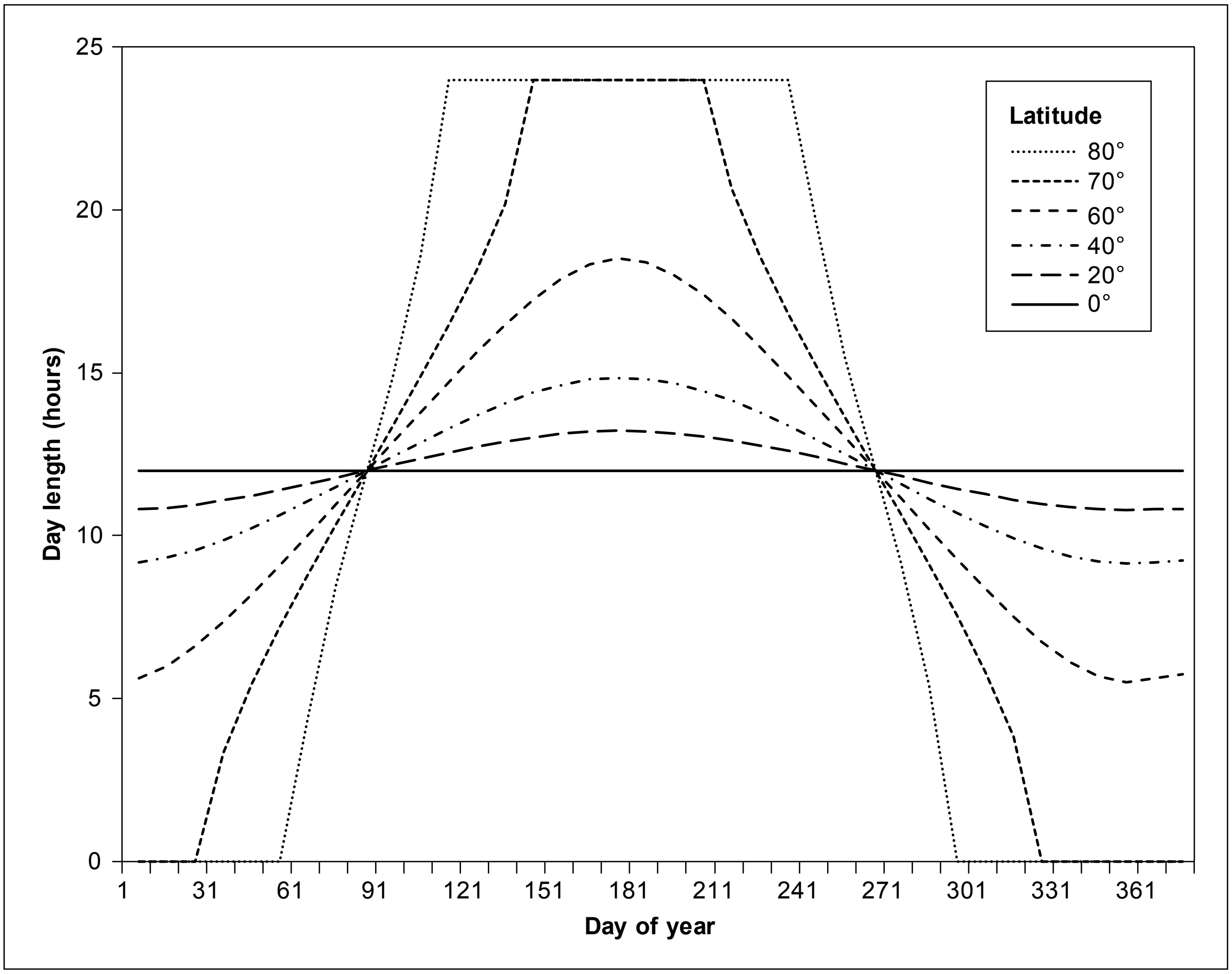

Figure 3—Daylight length for each day of the year plotted for six selected latitudes as a function of latitude.

for any given day depends on its value from the previous day and is initialized to zero for the first day of each simulation. MCFire calculates the drought factor and Keetch-Byram (in annual increments) as:

$$factor = 0.001 \times \left[\frac{(800 - kbdi_{prev})(0.968e^{0.0486 \times Tcurr}) - 0.830)}{1 + (10.88e^{-0.0441 \times Pann})} \right] \tag{12}$$

$$kbdi_{curr} = (kbdi_{prev} - 100 \times Padj) + factor \tag{13}$$

where *factor* is the drought factor, $kbdi_{prev}$ is the Keetch-Byram Drought Index value for the previous day, *Tcurr* is the average temperature for the current day in °F (with a minimum value of 50), *Pann* is the average annual precipitation in inches, $kbdi_{curr}$ is the Keetch-Byram Drought Index value for the current day, *e* is a mathematical constant approximately equal to 2.71828, and *Padj* is the adjusted precipitation in inches.

Adjusted precipitation (*Padj*) is zero on days without precipitation. On a day when fuel is blanketed by snow, *Padj* is equal to precipitation (*Pcurr*) on that day. When precipitation occurs on consecutive days, *Padj* is zero and the cumulative precipitation is <0.2 inches. On the first day that the cumulative precipitation amount is >0.2 inches during the consecutive days of precipitation, *Padj* is set to the cumulative precipitation minus 0.2 inches. In other words, the first 0.2 inches of precipitation is disregarded. Thereafter, *Padj* equals the daily precipitation.

Palmer Drought Severity Index

MCFire uses the Palmer Drought Severity Index (Palmer 1965) to calculate fire occurrence. Monthly values are read from an input file. They are used as is and not interpolated into daily values.

Section 3. Fuel Load

Because the MC1 biogeochemistry module does not resolve the live and dead carbon pools finely enough for fuel loading calculations, MCFire calculates its own set of live and dead carbon pools based on the MC1 carbon pools. MCFire simulates four dead-fuel classes—1-hour, 10-hour, 100-hour, and 1000-hour (appendix 2)—and proportionately allocates the aboveground dead biomass simulated by the biogeochemistry module to the dead-fuel classes as a function of the current vegetation type (Albini 1976, Anderson 1982). MCFire also simulates two live fuels classes—grass biomass and the leaves and twigs of shrubs. Although the MCFire code takes the effect of shrub fuels into account, this program logic has no effect at present because the biogeochemistry module of MC1 does not distinguish shrub biomass pool from other vegetation pools. Therefore, shrub live-fuel pool (*wwood*) is always zero.

Allometric functions keyed to the different vegetation types are used to simulate the depth of surface fuels and the vertical structure—crown height, length, and shape—of the overstory (Keane et al. 1996, Kercher and Axelrod 1984, Means et al. 1996, Peterson 1985,Weller 1987).

Dead Fuels

MCFire calculates fuel weight in terms of dry matter. It calculates the total amount of dead-fuel weight by summing the various aboveground litter and dead wood pools supplied by the biogeochemistry module:

$$tot\_dfuel = mlittr + slittr + dstnd + dwod1 + dwod2 \qquad (14)$$

where *tot_dfuel* is the total amount of dead-fuel weight (limited to a maximum value of 10.0), *mlittr* is metabolic carbon in litter, *slittr* is structural carbon in litter, *dstnd* is standing dead grass, *dwod*1 is fine dead wood, and d*wod*2 is coarse dead wood—all in grams of dry matter per square meter.

The amounts in the four dead-fuel classes—1-hour, 10-hour, 100-hour and 1000-hour—are calculated by multiplying total dead fuel (*tot_dfuel*) from equation 14 by four fractions defined for the vegetation type being simulated in the current grid cell (table 5).

Table 5—Dead-fuel class proportions (required by the MCFire simulation model) and depth ratios for MC1 simulated vegetation; data were synthesized from Albini (1976), Anderson (1982), and Andrews (1986)

	Dead-fuel class				
Vegetation	**1-hour**	**10-hour**	**100-hour**	**1000-hour**	**Depth ratio**[a]
Tundra	0.25	0.25	0.25	0.25	0.400
Boreal coniferous forest	0.27	0.20	0.24	0.29	0.042
Maritime temperate coniferous forest	0.20	0.17	0.20	0.43	0.042
Continental temperate coniferous forest	0.39	0.28	0.14	0.19	0.042
Cool temperate mixed forest	0.37	0.26	0.27	0.10	0.042
Warm temperate subtropical mixed forest	0.45	0.37	0.16	0.02	0.042
Temperate deciduous forest	0.62	0.20	0.18	0.00	0.042
Tropical deciduous forest	0.62	0.20	0.18	0.00	0.042
Tropical evergreen forest	0.62	0.20	0.18	0.00	0.042
Temperate mixed xeromorphic woodland	0.57	0.31	0.07	0.05	0.042
Temperate conifer xeromorphic woodland	0.61	0.31	0.06	0.02	0.042
Tropical thorn woodland	0.70	0.18	0.12	0.00	0.042
Temperate subtropical deciduous savanna	0.83	0.07	0.05	0.05	0.400
Warm temperate subtropical mixed savanna	0.70	0.18	0.12	0.00	0.400
Temperate conifer savanna	0.78	0.19	0.01	0.02	0.400
Tropical deciduous savanna	0.83	0.07	0.05	0.05	0.400
C_3 grasslands[b]	0.93	0.05	0.01	0.01	1.000
C_4 grasslands[c]	0.92	0.07	0.01	0.00	1.000
Mediterranean shrubland	0.49	0.36	0.09	0.06	0.400
Temperate arid shrubland	0.72	0.24	0.02	0.02	0.400
Subtropical arid shrubland	0.75	0.24	0.01	0.00	0.042
Taiga	0.27	0.20	0.24	0.29	0.042

[a] Fuel bed depth (feet) divided by the fuel load (tons of dry matter per acre).
[b] Grasslands adapted to cool seasons.
[c] Grasslands adapted to warm or hot seasons.

Depth of the Fuel Bed

The total fuel-bed biomass is the sum of the dead fuel and the aboveground live grass biomass:

$$tot\_fuel\_bed\_bio = 0.0044409(lgras + dstnd + dwod1 + dwod2) \qquad (15)$$

where *tot_fuel_bed_bio* is the total fuel-bed biomass (limited to a maximum of 10 500), *lgras* is aboveground live grass biomass, *dstnd* is standing dead grass, *dwod*1 is fine dead wood, and *dwod*2 is coarse dead wood—all in grams of dry matter per square meter—and 0.0044409 is the conversion factor (from grams per square meter to tons per acre).

To calculate the fuel-bed depth, the fuel-bed biomass is multiplied by a load-to-depth ratio specific to each vegetation type MC1 simulates (table 5):

$$fuel\_depth = (tot\_fuel\_bed\_bio \times 0.0044409) \times depth\_ratio \times 0.3048 \qquad (16)$$

where *fuel_depth* is the fuel-bed depth in meters (limited to a maximum of 2), *tot_fuel_bed_bio* is the total fuel-bed biomass in grams of dry matter per square meter (eq. 15), 0.0044409 is the conversion factor (from grams per square meter to tons per acre), *depth_ratio* is the fuel load to depth ratio per vegetation type in feet per ton of dry matter per acre, and 0.3048 is the conversion factor (from feet to meters).

Live Fuels

Amounts of aboveground grass (*lgras*), tree leaf (*lleaf*), and tree wood (*lwod1* and *lwod100*) biomass are provided to MCFire by the MC1 biogeochemistry module. All aboveground grass biomass is placed in the grass class. For trees, the total biomass, leaf biomass, and vegetation type are used to estimate characteristics of the stand: number of stems per unit area, diameter at breast height (DBH), height, crown length, and bark thickness. Values for DBH, total aboveground tree biomass, and vegetation type are then used to estimate the biomass of leaves, branches, bark, and stem wood. Height, crown length, and bark thickness are subsequently used to simulate the crown fire occurrence (sec. 6) and consumption of biomass by fire. Branch biomass is used in the calculations of consumption and emissions (below).

Stand characteristics are calculated following the methods of Weller (1989) and the JABOWA model in Botkin et al. (1972a, 1972b). Parameters for these calculations are given in table 6. The calculations for deciduous trees and shrubs use parameters for California black oak (*Quercus kelloggii*); those for evergreens use parameters for Douglas-fir (*Pseudotsuga menziesii*).

Table 6—Parameters used by MCFire for calculating stand characteristics—live-tree biomass, stem density, leaf area, and diameter at breast height (DBH)—for deciduous and evergreen stands

Parameter	Description	Deciduous[a]	Evergreen[b]
k	Stand thinning constant[c]	8696	5073
dbh_max	Maximum DBH	349 cm	220 cm
ht_max	Maximum tree height	3960 cm	8000 cm
c	Constant in DBH equation[d]	0.451	0.116
d	Constant in DBH equation[d]	1.60	1.89
specific_area	Specific leaf area	0.012 m^2/g (dry matter)	0.003 m^2g (dry matter)

[a] Model is California black oak.
[b] Model is Douglas-fir.
[c] From Weller (1989).
[d] From Kercher and Axelrod (1984).

The estimation of DBH is based on the SILVA model in Kercher and Axelrod (1984). The calculation of DBH requires preliminary calculations of tree leaf area index and stand closure index:

$$tree\_lai = lleaf \times specific\_area \tag{17}$$

$$stnd\_clos = tree\_lai/3.75 \tag{18}$$

where *lleaf* is the portion of total tree biomass attributed to leaves in grams of dry matter per square meter, *specific_area* is specific leaf area in square meters per gram of dry matter, *tree_lai* is an estimate of tree leaf area index in square meters per square meter, and *stnd_clos* is an index of stand closure (with a maximum of 1).

The tree leaf area index (*tree_lai*) calculated in equation 17 is used only for calculating the stand characteristics of live fuels in this section, and should not be confused with other measures of leaf area in other parts of MCFire and MC1. Specific leaf area (*specific_area*) in equation 15 is parameterized for just two categories of vegetation, deciduous and evergreen (table 6)

Once the tree leaf area index and stand closure index are calculated, MCFire calculates live tree biomass, stem density, leaf area, and DBH:

$$ltree = lleaf + lwod1 + lwod100 \tag{19}$$

$$stems = \left(\frac{k}{ltree}\right)^2 \times stnd\_clos \tag{20}$$

$$la = (tree\_lai)/stems \tag{21}$$

$$dbh = (la/c)^{1/d} \tag{22}$$

where *ltree* is the live tree biomass, *lleaf* is leaves of woody vegetation , *lwod*1 is branches of woody vegetation, *lwod*100 is stems of woody vegetation—all in grams of dry matter per square meter; *stems* is the stem density in stems per square meter; *k*, *c*, and *d* are constants (table 6); *stnd_clos* is the index of stand closure (eq. 18); *la* is leaf area in square meters per stem; *tree_lai* is leaf area index in square meters per square meter (eq. 17); and *dbh* is diameter at breast height in centimeters (table 6).

DBH (eq. 22) is constrained to be between 0.001 cm and a maximum value defined for two types of trees, evergreen and deciduous (table 6). Parameters *k* in equation 20 and parameters *c* and *d* in equation 22 are also defined for deciduous or evergreen vegetation (table 6).

MCFire uses DBH (eq. 22) to calculate bark thickness, tree height, and crown length, based on equations from the JABOWA model (Botkin et al. 1972a, 1972b):

$$bark\_thick = dbh \times thick\_ratio \tag{23}$$

$$tree\_ht = 0.01\left[137 + 2(ht\_max - 137)\left(\frac{dbh}{dbh\_max}\right) - (ht\_max - 137)\left(\frac{dbh}{dbh\_max}\right)^2\right] \tag{24}$$

$$crown\_length = dbh \times thick\_ratio \tag{25}$$

where *bark_thick* is the stem bark thickness in centimeters, *thick_ratio* and *cl_ratio* are constants defined for each plant functional type (table 7), *tree_ht* is the canopy height in meters, *ht_max* is maximum tree height defined for deciduous or evergreen trees (table 6) in centimeters, *dbh* is diameter at breast height in centimeters (eq. 22), *dbh_max* is maximum diameter at breast height defined for deciduous or evergreen trees (table 6) in centimeters, and *crown_length* is the crown length in meters.

Note that crown length (eq. 25), DBH (eq. 22), and maximum tree height (table 6) are expressed in centimeters, but that equation 24 estimates tree height in meters. MCFire currently calculates allometry in terms of just two categories of trees: evergreen and deciduous trees (fig. 4).

Table 7—Parameters used by MCFire in calculating crown length and bark thickness for MC1-simulated vegetation, taken from Keane et al. (1996)

Vegetation	Bark-thickness ratio[a]	Crown-length ratio[b]
Tundra	0.022	0.8
Boreal coniferous forest	0.022	0.8
Maritime temperate coniferous forest	0.062	0.7
Continental temperate coniferous forest	0.043	0.5
Cool temperate mixed forest	0.043	0.5
Warm temperate subtropical mixed forest	0.043	0.5
Temperate deciduous forest	0.033	0.4
Tropical deciduous forest	0.033	0.4
Tropical evergreen forest	0.033	0.4
Temperate mixed xeromorphic woodland	0.043	0.5
Temperate conifer xeromorphic woodland	0.062	0.4
Tropical thorn woodland	0.043	0.5
Temperate subtropical deciduous savanna	0.033	0.4
Warm temperate subtropical mixed savanna	0.043	0.5
Temperate conifer savanna	0.062	0.4
Tropical deciduous savanna	0.033	0.4
C_3 grasslands[c]	0.022	0.8
C_4 grasslands[d]	0.022	0.8
Mediterranean shrubland	0.043	0.7
Temperate arid shrubland	0.043	0.7
Subtropical arid shrubland	0.043	0.7
Taiga	0.022	0.8

[a] Ratio of stem-bark thickness (centimeters) to stem diameter at breast height (centimeters).
[b] Ratio of crown length (meters) to canopy height (meters).
[c] Grasslands adapted to cool seasons.
[d] Grasslands adapted to warm or hot seasons.

MCFire also uses DBH (eq. 22) to calculate the fraction of aboveground live wood biomass in branches, distinct from biomass in stem wood or stem bark. The equation for deciduous broadleaf trees and shrubs is based on that for black oak, (*Q. velutina*) (Stanek and State 1978):

$$btt = 10^{1.00005+[2.10621 \times log(dbh\_in)]} \tag{26}$$

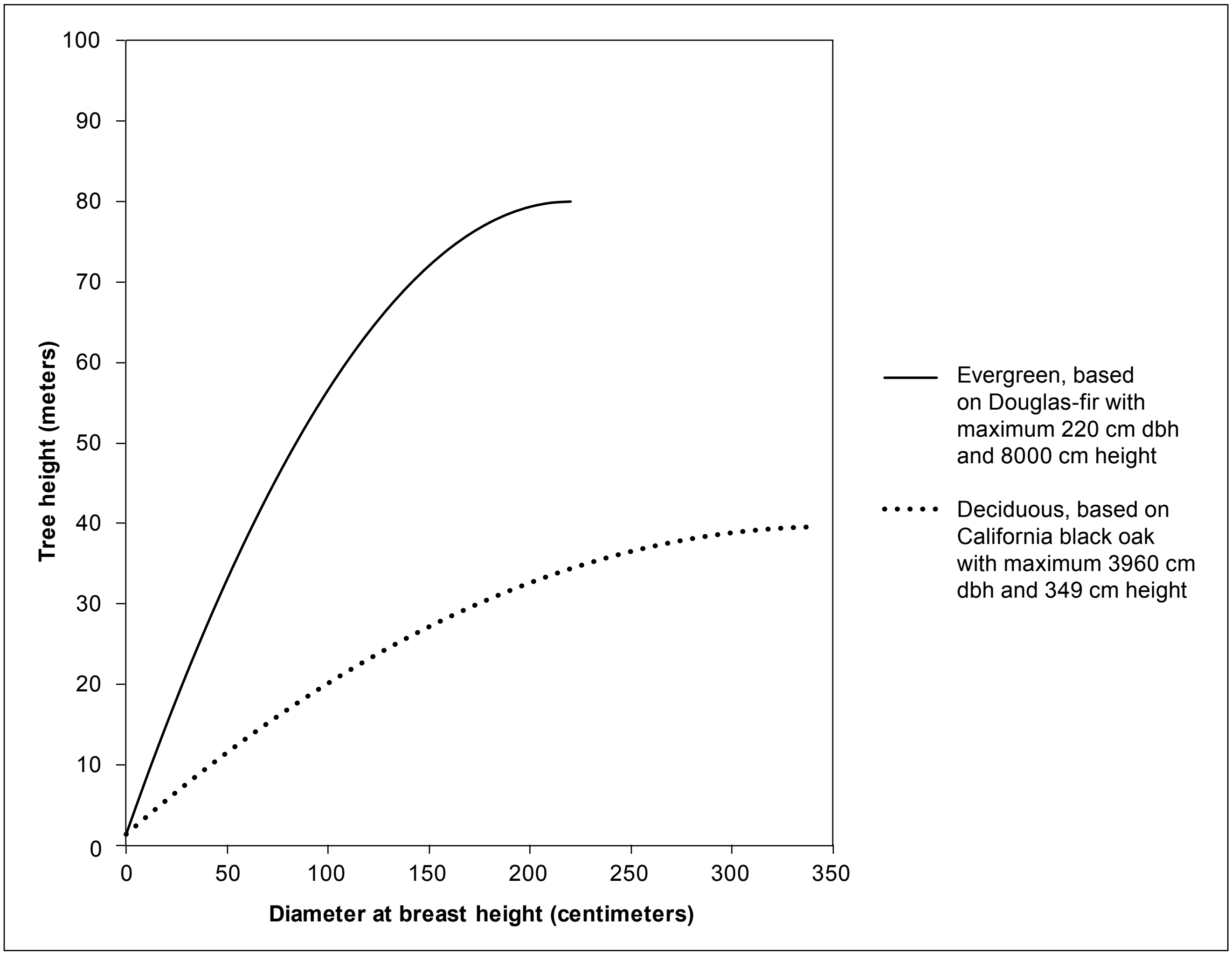

Figure 4—Tree height as a function of diameter at breast height (DBH) for evergreen and deciduous trees, estimated using the MCFire simulation-model equation $t0.01\left[137+2\ (ht\_max - 137)(\frac{dbh}{dbh\_max}) - (ht\_max - 137)(\frac{dbh}{dbh\_max})^2\right]$ where *bark_thick* is the stem bark thickness in centimeters, *thick_ratio* and *cl_ratio* are constants defined for each plant functional type, *tree_ht* is the canopy height in meters, *ht_max* is maximum tree height defined for deciduous or evergreen trees in centimeters, *dbh* is diameter at breast height in centimeters, *dbh_max* is maximum diameter at breast height defined for deciduous or evergreen trees in centimeters, and *crown_length* is the crown length in meters.

$$bbl = 10^{0.50580+[2.09357 \times log(dbh\_in)]} \tag{27}$$

$$branch\_frac = \frac{bbl}{bbt} \tag{28}$$

where *btt* is total aboveground tree biomass in pounds of dry matter per stem, *dbh_in* is diameter at breast height in inches, *bbl* is branch biomass in pounds of dry matter per stem, and *branch_frac* is the portion of total aboveground tree biomass that is branches.

The equation to estimate aboveground live wood biomass in branches for evergreen needleleaf trees and shrubs is based on equations for ponderosa pine (*Pinus ponderosa*) (Means et al. 1994):

$$\text{bbl} = e^{1.5223+[2.7185 \times ln(dbh)]} \tag{29}$$

$$\text{bsw} = e^{2.4171+[2.7587 \times ln(dbh)]} \tag{30}$$

$$bsb = e^{2.7015+[2.2312 \times ln(dbh)]} \tag{31}$$

$$branch\_frac = \frac{bbl}{(bbt+bsw+bsb)} \tag{32}$$

where *bbl* is branch biomass in grams of dry matter per stem, *e* is a mathematical constant approximately equal to 2.71828, *dbh* is diameter at breast height in centimeters (eq. 22), *bsw* is stem wood biomass in grams of dry matter per stem, *bsb* is stem bark biomass in grams of dry matter per stem, and *branch_frac* is the fraction of total aboveground tree biomass that is branches.

Once branch fraction is calculated, it is combined with the total aboveground wood biomass to calculate live fuel in branches and live fuel in stems:

$$lbranch = lwood \times branch\_frac \tag{33}$$

$$lstem = lwood - lbranch \tag{34}$$

where *lbranch* is the portion of live fuel that is branches in grams of dry matter per square meter, *lwood* is the total aboveground wood biomass in live trees and shrubs in grams of dry matter per square meter, *branch_frac* is the fraction of total aboveground tree biomass that is branches (eqs. 28, 32), and *lstem* is the live fuel in stems in grams of dry matter per square meter.

Live fuel in branches (eq. 33) is used in the calculations of fire consumption and emissions. Live fuel in stems (eq. 34) is not used in the calculation of fire consumption and emissions in the current version of MCFire, because sufficient information on consumption of live fuel in stems is not available.

Section 4. Fuel Moisture

Within MCFire, moisture content of vegetation is defined as a fraction of the dry weight of the vegetation:

$$moisture\ content = \frac{weight_{wet} - weight_{dry}}{weight_{dry}} \tag{35}$$

The moisture content of each live-fuel class is a function of the soil moisture content to a specific depth in the profile (Howard 1978). The moisture content of each dead-fuel size class is a function of previous weather conditions averaged over a period, with the number of day based on size class (Cohen and Deeming 1985).

Estimating Moisture from Live Fuels

The biogeochemistry module in MC1 calculates a production-limiting factor for plants based on the effects of precipitation. This factor (*pptprd*), which ranges from 0 to 1 and is calculated for a tree vegetation type and grass vegetation type, essentially represents the ratio of available water to potential evapotranspiration on a monthly basis taking into account the different rooting depths of trees and grasses. MCFire translates *pptprd* to a percentage of maximum fuel moisture (fig. 5) following Howard (1978):

$$pct\_of\_max = 16.99365 + \frac{84.59560}{1+e^{(11.5694-19.2443\times pptprd)}} \tag{36}$$

where pct_of_max is the percentage of maximum moisture content (limited to a maximum of 100), e is a mathematical constant approximately equal to 2.71828, and *pptprd* is the precipitation-based production-limiting factor from MC1.

The percentage of maximum moisture content (eq. 36) has a minimum value of 16.99365 percent, which should be taken into account when setting the maximum moisture content parameters (table 4).

To determine the moisture content of a vegetation type (tree or grass), MCFire applies maximum moisture content (eq. 36) to the range of moisture content defined by parameters (table 4). For example, the moisture content of trees is calculated as,

$$moisture\_content = mc\_tree\_min + (mc\_tree\_max - mc\_tree\_min) \times \frac{pct\_of\_max}{100} \tag{37}$$

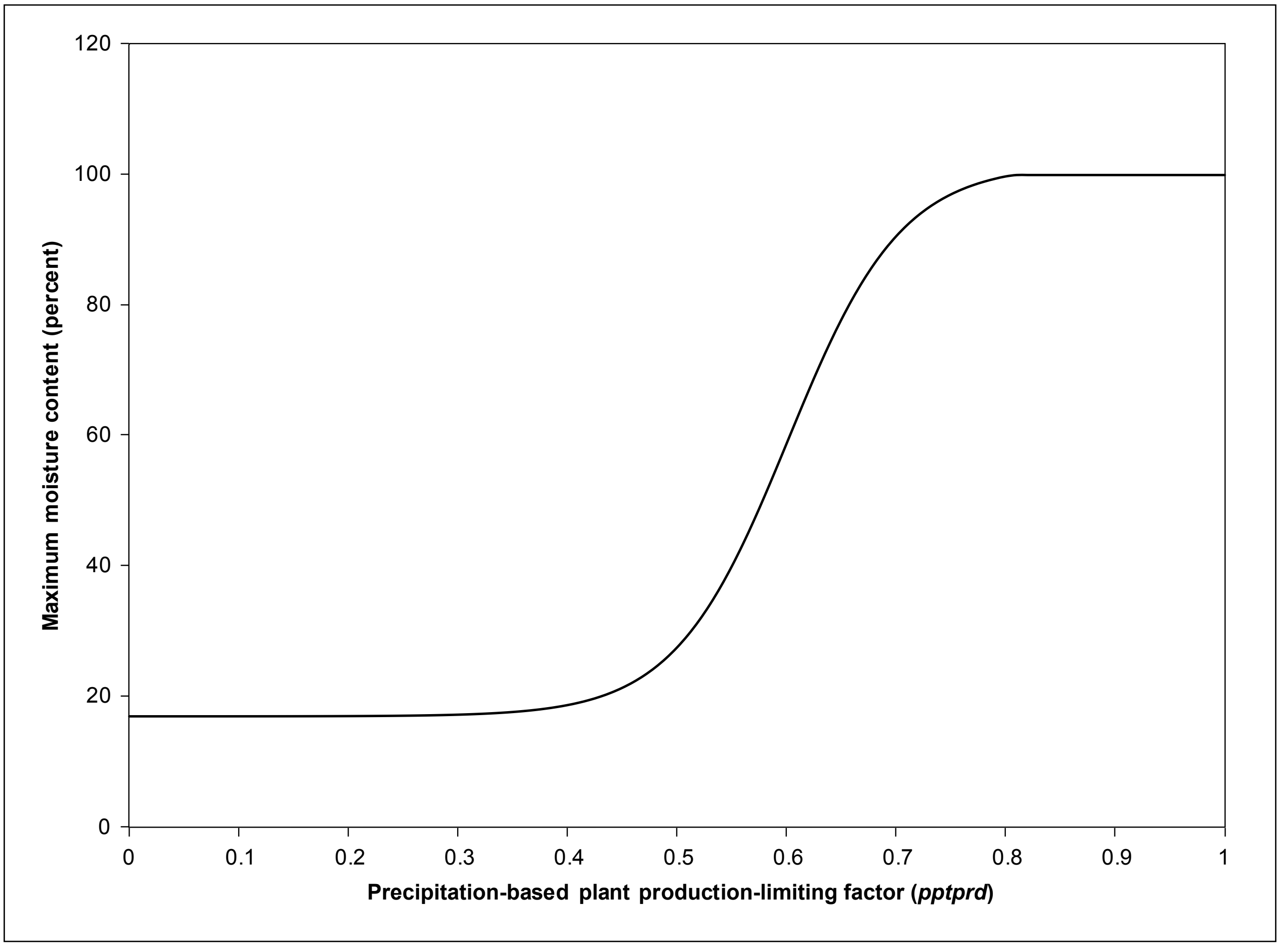

Figure 5—Maximum moisture percentage of live vegetation as a function of the precipitation-based plant production-limiting factor (Howard 1978), provided by the biogeochemistry module of MC1, estimated using the MCFire simulation-model equation $16.99365 + \frac{84.59560}{1+e^{(11.5694-19.2443 \times pptprd)}}$ where *pptprd* is the precipitation-based production-limiting factor; this percentage is used to determine the maximum moisture content for trees and grass.

where *moisture_content* is the moisture content of tree , *mc_tree_min* is the minimum moisture parameter, *mc_tree_max* and is the maximum moisture parameter (table 4), and *pct_of _max* is the maximum moisture content (eq. 36)—all as percentages.

Moisture content of grass is calculated in the same way (eq. 32). Note that because moisture content is defined relative to the dry weight of vegetation (eq. 35), its value can be >100 percent. Currently MCFire is parameterized to have moisture content of live grass range from 30 to 120 percent, and to have moisture content of live trees range from 80 to 130 percent (table 4).

The moisture content calculations described above are performed for the entire month, and then MCFire interpolates linearly the value for each day in the month (*mc_tree*[*day*] for trees and *mc_grass*[*day*] for grass). The moisture content for the last day of the month is set to the monthly value, and the daily values are linearly interpolated between the last day of the previous month and the last day of the current month.

Estimating the Moisture Content of Dead Fuels

MCFire calculates moisture content (eq. 35) of dead-fuel classes for each day of the month. The calculations are done in English units for exact correspondence to originally published equations.

Lower fuel classes—

MCFire calculates the moisture content of 1-hour and 10-hour fuels by calculating the minimum moisture content, and multiplying it by constants. To estimate the conditions of the air in contact with the fuels in each class (Cohen and Deeming 1985), MCFire adds 15 °F to adjust air temperature and multiplies by 0.87 to adjust humidity. When the (unadjusted) daily minimum temperature is below freezing, relative humidity is assumed to be 100 percent (Cohen and Deeming 1985).

Equilibrium moisture content is calculated as a function of the temperature and relative humidity (Cohen and Deeming 1985), using a set of equations (fig. 6). When relative humidity is <10 percent:

$$emc = 0.03229 + 0.281073 \times rh - 0.000578 \times t \times rh \tag{38}$$

when relative humidity is ≥10 percent but <50 percent:

$$emc = 2.22749 + 0.160107 \times rh - 0.014787 \times t \tag{39}$$

and finally, when relative humidity is >50 percent:

$$emc = 21.06060 + 0.005565 \times rh^2 - 0.00035 \times rh \times t - 0.483199 \times \mathrm{rh} \tag{40}$$

where *emc* is the equilibrium moisture content as a percentage, *rh* is the relative humidity as a percentage, and *t* is the air temperature in °F.

For these classes of fuels, the minimum equilibrium moisture content is calculated by using equations 38 through 40 with the adjusted daily maximum temperature and the adjusted minimum daily humidity values. The minimum equilibrium moisture content is multiplied by 1.0329 to calculate the moisture content of 1-hour fuels, and multiplied by 1.2815 to calculate the moisture content of 10-hour fuels. When precipitation occurs or when the unadjusted air temperature is <32 °F (0 °C), the moisture content of both fuel types is set to 35 percent.

Higher fuel classes—

To determine the moisture content of 100-hour and 1000-hour fuels, the overall approach is to calculate the 24-hour equilibrium moisture content estimates, the boundary conditions of moisture content of 100-hour and 1000-hour fuels, and then calculate the moisture contents based on those boundary conditions. The 24-hour

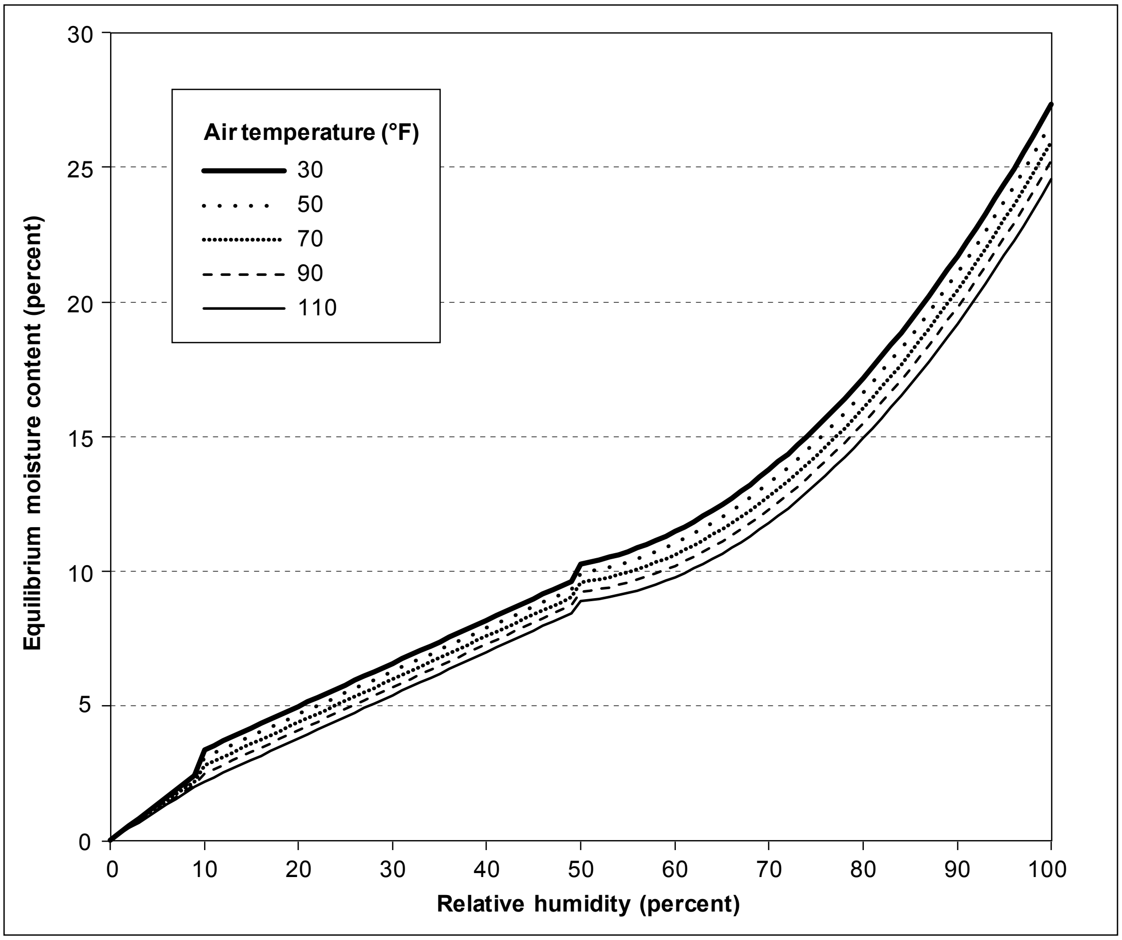

Figure 6—Equilibrium moisture content as a function of temperature and relative humidity (Cohen and Deeming 1985), plotted for five selected temperatures.

equilibrium moisture content is calculated by weighting the maximum moisture content by night length and minimum moisture content by day length (Cohen and Deeming 1985):

$$emc\_bar = \frac{(daylit \times emc\_min) + (24 - daylit) \times emc\_max}{24} \tag{41}$$

where *emc_bar* is the 24-hour equilibrium moisture content as a percentage, daylit is the length of daylight in hours (eq. 11), *emc_min* is the minimum equilibrium moisture content as a percentage, and *emc_max* is the maximum equilibrium moisture content as a percentage.

Minimum and maximum equilibrium moisture content values in equation 41 are calculated using equations 33 through 35. For the minimum equilibrium moisture content, the daily maximum air temperature and the minimum relative humidity values are used. For the maximum equilibrium moisture content, daily minimum air temperature and the maximum relative humidity are used. For both the minimum and the maximum equilibrium moisture content values, the unadjusted air-temperature and relative-humidity values are used, unlike the procedure for calculating 1-hour and 10-hour fuel moisture contents.

Boundary conditions of the 100-hour and 1000-hour fuel moisture content (Cohen and Deeming 1985) are calculated as a function of the precipitation duration for the day and the 24-hour equilibrium moisture content (fig. 7):

$$bnd = \frac{(24 - ppt\_dur) \times emc\_bar + ppt\_dur \times (C_1 \times ppt\_dur + C_2)}{24} \qquad (42)$$

where *bnd* is the boundary condition moisture content as a percentage, *ppt_dur* is the daily precipitation duration in hours (eq. 7), *emc_bar* is the 24-hour average equilibrium moisture content as a percentage (eq. 41), C_1 is 0.5 for 100-hour fuels and 2.7 for 1000-hour fuels, and C_2 is 41 for 100-hour fuels and 76 for 1000-hour fuels.

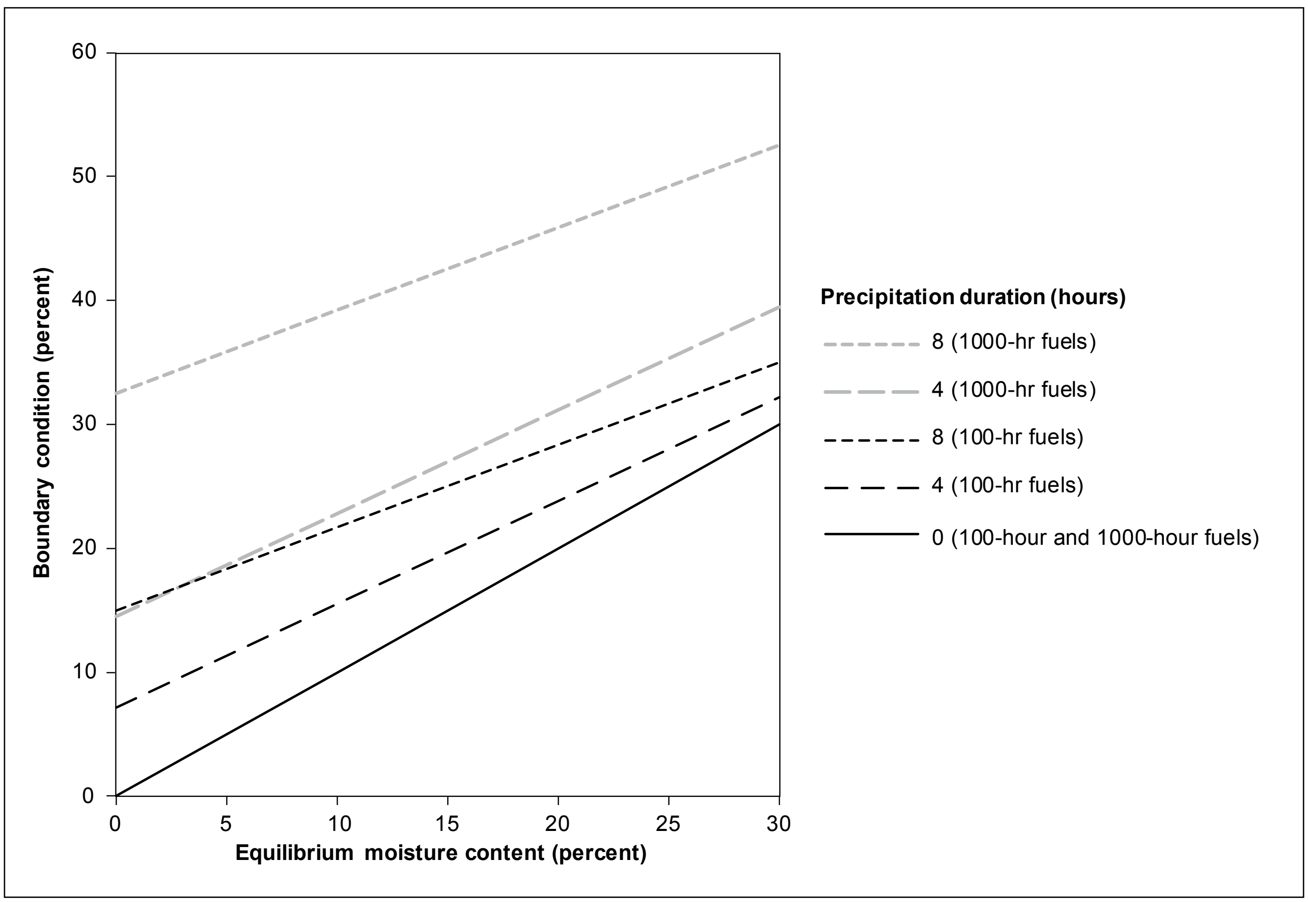

Figure 7—Boundary conditions for 100-hour and 1000-hour fuel moisture content as a function of 24-hour average equilibrium moisture content and precipitation duration; boundary conditions are plotted using the MCFire simulation-model equation $\frac{(24-ppt\_dur)\times emc\_bar+ppt\_dur\times(C_1\times ppt\_dur+)C_2}{24}$ where *ppt_dur* is the daily precipitation duration in hours, *emc_bar* is the 24-hour average equilibrium moisture content as a percentage, C_1 is 0.5 for 100-hour fuels and 2.7 for 1000-hour fuels, and C_2 is 41 for 100-hour fuels and 76 for 1000-hour fuels.

The 100-hour and 1000-hour fuel moisture content is calculated from corresponding boundary condition and a moisture content value from a prior day (Cohen and Deeming 1985):

$$mc = C \times (bnd - ymc) + ymc \qquad (43)$$

where *mc* is the fuel moisture content as a percentage (limited to a maximum of 35), *C* is 0.315634 for 100-hour fuels and 0.306810 for 1000-hour fuels, *bnd* is the corresponding boundary condition as a percentage (eq. 42), and *ymc* is a moisture content value from a prior day as a percentage.

For the 100-hour fuel class, the moisture content value (*ymc*) from the previous day is used in equation 43. For the 1000-hour fuel class, the moisture content value from the past seven days is used, and the corresponding boundary condition value is averaged across those seven days.

Section 5. Fire Occurrence

MCFire simulates only one fire occurrence per year for the grid cell being simulated. Rather than explicitly simulating ignition, MCFire assumes that a source of ignition is always available when fuel conditions reach thresholds and that fire occurs in the month with the lowest 1000-hour fuel moisture content. Within that month, it occurs on the first day when all of three conditions are met:

- Fuels must have been exposed to extended drought and have become sufficiently dry to justify the fire occurrence, as represented by Palmer Drought Severity Index (Palmer 1965); the value for the current month (sec. 2) must exceed a parameterized threshold (table 4).
- Coarse dead fuels must be dry, as represented by 1000-hour fuel moisture content (Fosberg et al. 1981); the 1000-hour fuel moisture content (sec. 4) must exceed a parameterized threshold (table 4).
- Fine dead fuels must be highly flammable, as represented by the fine-fuel flammability metric (Cohen and Deeming 1985), with flammability (below) exceeding a parameterized threshold (table 4).

MCFire calculates fine-fuel flammability as a function of the heat required to produce ignition in the 1-hour fuel class. The heat of ignition of the 1-hour fuel class (Cohen and Deeming 1985) is calculated (fig. 8) as:

$$qign = 144.5 - 0.266t - 0.00058t^2 - 0.01t \cdot mc + 18.54(1.0 - e^{-0.151mc}) + 6.4mc \qquad (44)$$

where *qign* is the heat of ignition in joules per gram of dry matter (limited to a maximum of 344), *t* is the adjusted daily maximum temperature in °C (sec. 4), *e* is a mathematical constant approximately equal to 2.71828, and *mc* is the moisture content of the 1-hour dead fuels as a percentage (sec. 4).

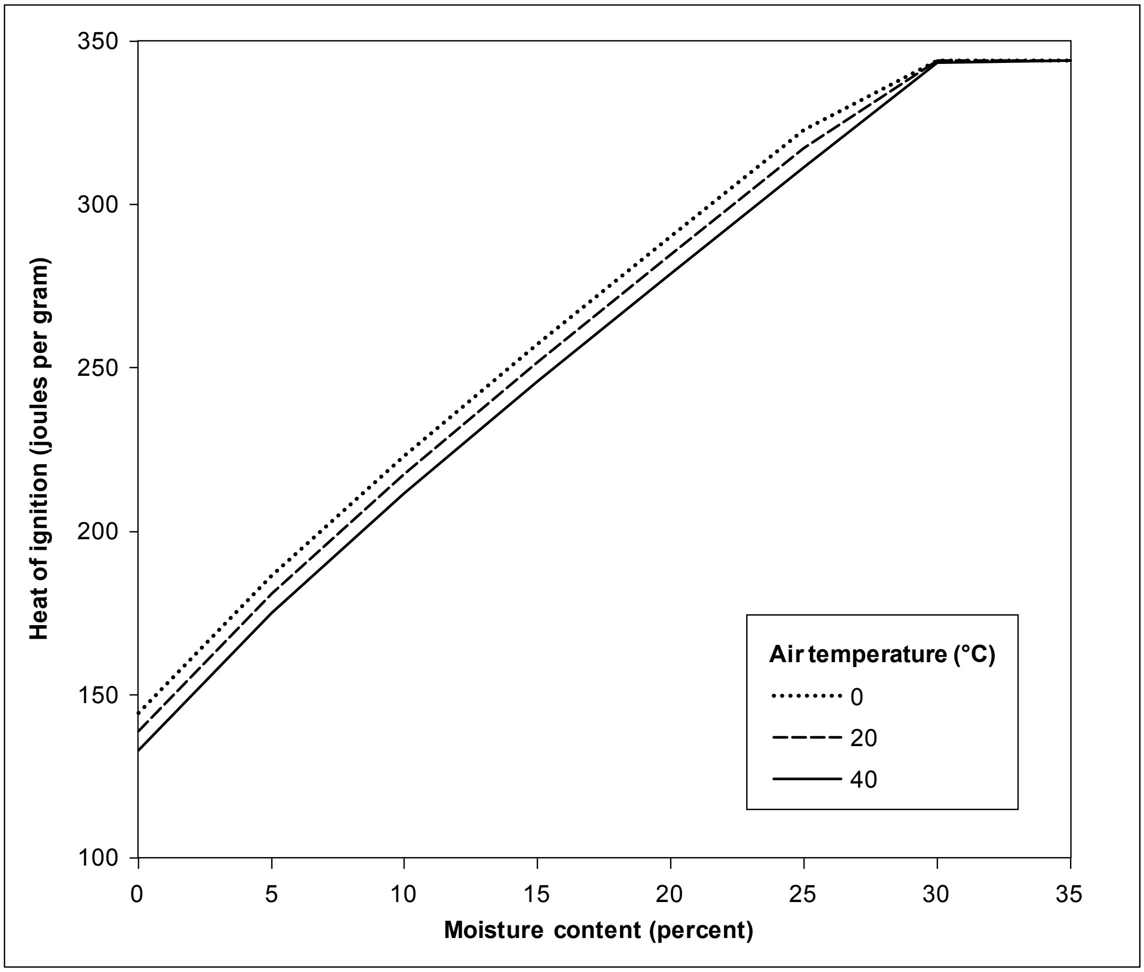

Figure 8—Heat of ignition as a function of moisture content for three selected temperatures; heat of ignition is plotted using the MCFire simulation-model equation (Cohen and Deeming 1985) $144.5 - 0.266t - 0.00058t^2 - 0.01t \cdot mc + 18.54(1.0 - e^{-0.151mc}) + 6.4mc$ where, t is the adjusted daily maximum temperature in °C, and mc is the moisture content of the 1-hour dead fuels as a percentage.

Before MCFire calculates fine-fuel flammability, it calculates an intermediate variable:

$$chi = (344 - qign) / 10 \tag{45}$$

where *chi* is the intermediate variable, and *qign* is the heat of ignition in joules per gram of dry matter (eq. 44).

The fine-fuel flammability (fig. 9) is calculated as a function of the intermediate variable:

$$p\_flamm = (0.0000185 \cdot chi^{3.6} - 0.00232) / 0.0099767 \tag{46}$$

where *p_flamm* is the fine-fuel flammability as a percentage (limited to the range of 0 to 100) and *chi* is the intermediate variable from equation 45.

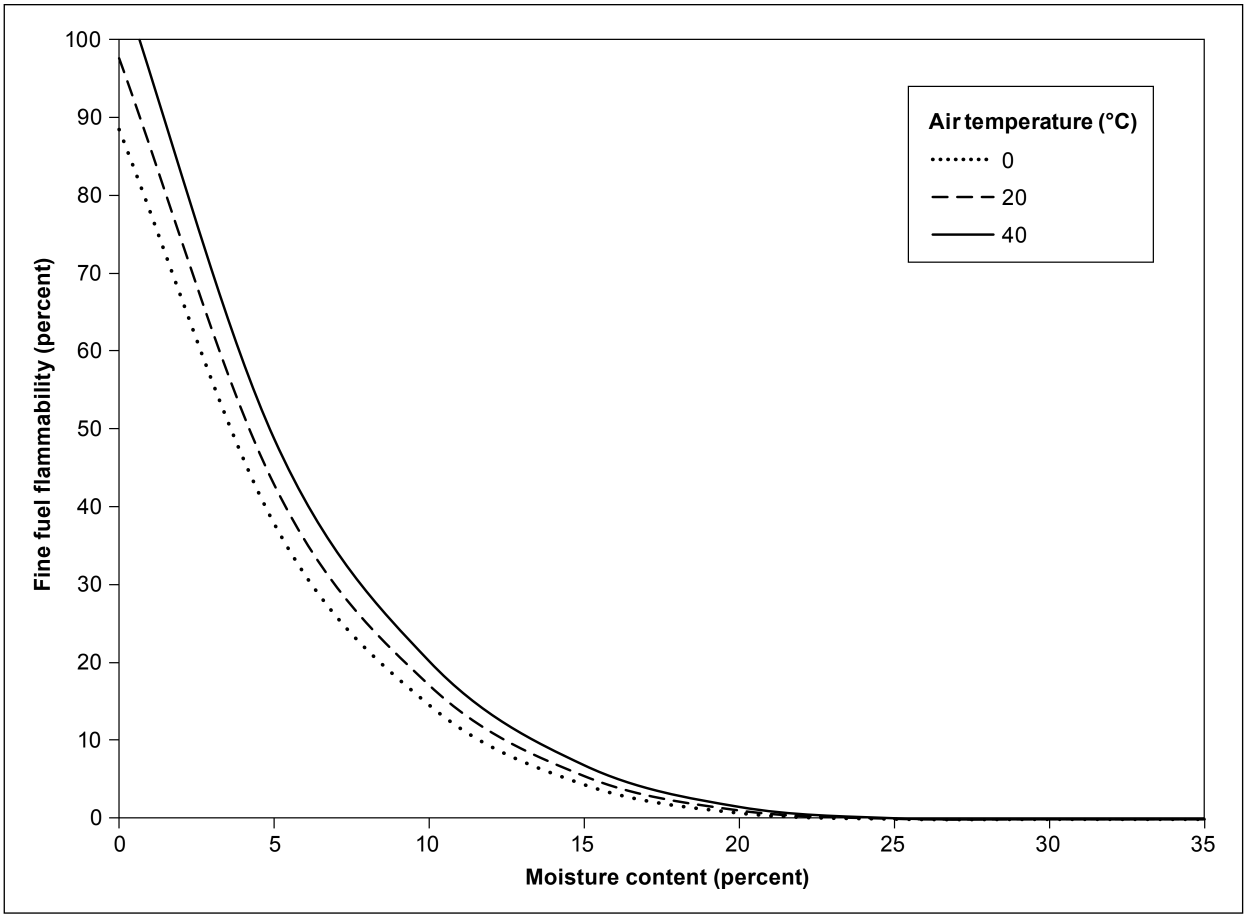

Figure 9—Fine-fuel flammability as a function of fine-fuel moisture content for three selected temperatures; fine-fuel flammability is plotted using the MCFire simulation-model equation $(0.0000185 \cdot chi^{3.6} - 0.00232) / 0.0099767$ where *chi* is an intermediate variable.

Section 6. Fire Behavior

MCFire calculates potential fire behavior based on current weather and estimates of the mass, vertical structure, and moisture content of several live- and dead-fuel size classes. Figure 10 illustrates the organization of the MCFire algorithm.

Fuel Characteristics

Fuel characteristics are used in nearly all calculations of fire behavior. MCFire calculates fuel loads for the day when a fire occurs. The dead-fuel load (*wtotd*) is the sum of the daily values of the 1-, 10-, 100- and 1000-hour dead fuels (pounds of dry matter per square foot). Daily values of the dead and live fuels (sec. 3) are interpolated from monthly values. Live fuel load (*wtotl*) is taken as the sum of live grass fuel load and live shrub fuel load in pounds per dry matter per square foot (sec. 3). Because MC1 does not simulate shrubs, live-fuel load is currently equal to the grass fuel load. The total fuel load (*wtot*) for the day is the sum of the dead and live-fuel loads.

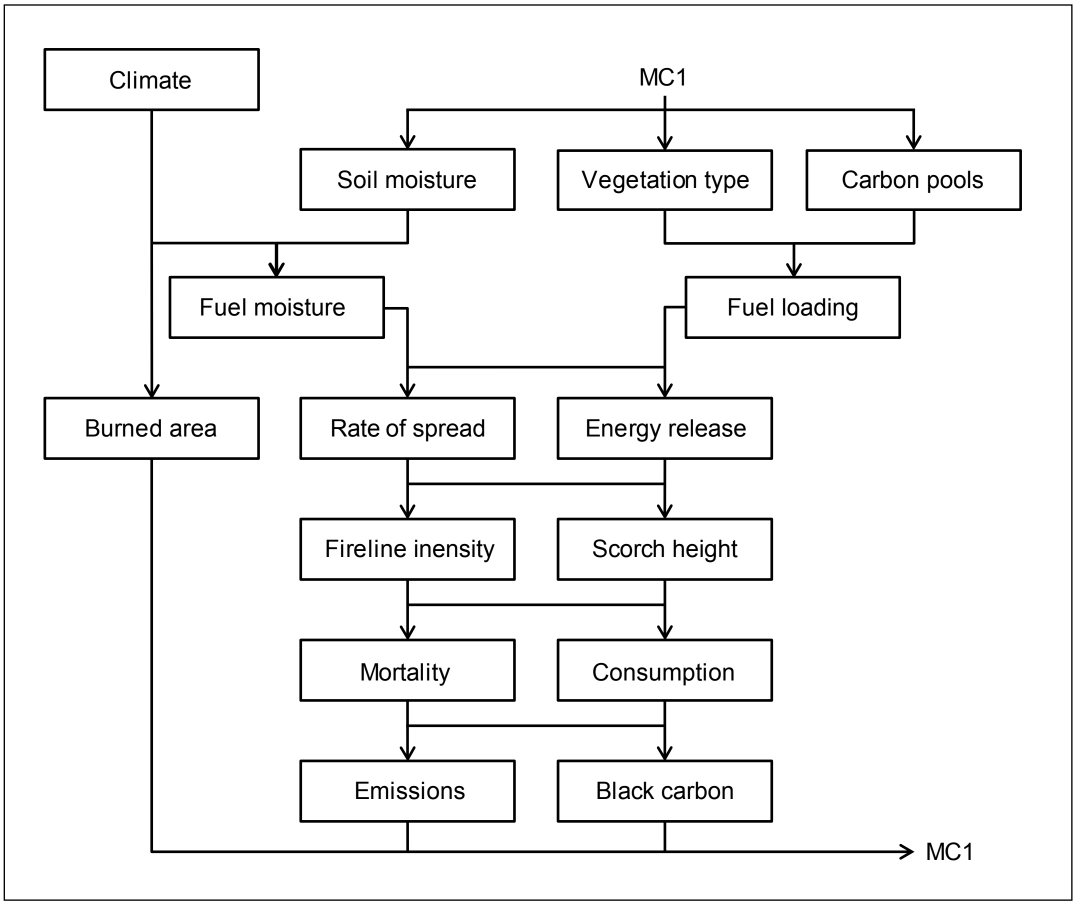

Figure 10—Organization of the MCFire simulation-model algorithm.

If the Keetch-Byram Drought Index for the day (eq. 13) is >100, an adjustment increment is calculated following Burgan (1979, 1988):

$$tot\_incr = (kbdi - 100)\left(\frac{w1p}{700}\right) \quad (47)$$

where *tot_incr* is the adjustment increment in pounds of dry matter per square foot, *kbdi* is the daily value of the Keetch-Byram Drought Index (eq. 13), and *w1p* is the 1-hour dead fuel of the day in pounds of dry matter per square foot.

The adjustment increment (eq. 47) is added to each of the dead-fuel classes (1-, 10-, 100- and 1000-hour fuels), weighted by the proportion of each class to the total dead fuels. The adjusted dead-fuel amounts are used only in fire behavior calculations, and do not affect other parts of MCFire.

Fuel density characteristics are calculated assuming that both live-fuel density and dead-fuel density are 32 pounds per cubic foot (Cohen and Deeming 1985):

$$rhobed = (wtot - w1000)/depth \quad (48)$$

$$betbar = rhobed/32 \tag{49}$$

where *rhobed* is bulk density of the fuel bed in pounds per cubic foot, *wtot* is the total fuel in pounds of dry matter per square foot, *w*1000 is the 1000-hour dead fuel in pounds of dry matter per square foot, *depth* is effective fuel-bed depth in feet, and *betbar* is the fuel packing ratio. Fuel packing ratio is a measure of fuelbed compactness and is defined as the fraction of the fuel array volume that is occupied by fuel.

The energy release calculations described below use daily net fuel-load amounts for five combustible fuel classes: 1-hour (*w*1*n*), 10-hour (*w*10*n*), 100-hour (*w*100*n*), live herbaceous fuels (*wherbn*), and live woody fuels (*wwoodn*). Each net fuel load amount is calculated by reducing the corresponding daily dead or live-fuel loads (*w*1*p*, *w*10*p*, *w*100*p*, *wherbp*, and *wwood*) by a noncombustible fraction. Currently the noncombustible fraction is simply assumed to be 0.0555 for all fuel classes (Cohen and Deeming 1985). The rate-of-spread calculations (below) also use net fuel loadings (*wdeadn* and *wliven*). However, instead of reducing fuel load by a noncombustible fraction for these calculations, MCFire weights the fuel classes in proportion to their surface areas.

Mineral-damping coefficients represent the reduction in reaction velocity by minerals (Rothermel 1972), and are used in the rate-of-spread calculations and energy-release calculations described below. The mineral-damping coefficient of live fuels is calculated (Cohen and Deeming 1985) as:

$$etasl = 0.174 \times sl^{-0.19} \tag{50}$$

where *etasl* is the mineral-damping coefficient of live fuels, and *sl* is the fraction of live fuels made up of silica-free noncombustible materials.

Currently MCFire sets the fraction of live fuels made up of silica-free non-combustible materials (*sl*) to 0.01. The mineral-damping coefficient of dead fuels (*etasd*) is calculated the same way using equation 50, and the fraction of silica-free noncombustible materials for dead fuels is also set to 0.01.

Moisture-of-extinction estimates, to be used in energy release calculations (above), require heating-number estimates for fuel classes. The heating number is the amount of the fuel that is heated to the ignition temperature at the time that flaming combustion starts. A heating number for the 1-hour dead-fuel class is calculated (Cohen and Deeming 1985 p. 10) as:

$$hn1 = w1n \times e^{\frac{-138}{sg1}} \tag{51}$$

where *hn*1 is the heating number of the 1-hour dead fuels in pounds of dry matter per square foot, *w*1*n* is net fuel loading of 1-hour dead fuels in pounds of dry matter per square foot, *e* is a mathematical constant approximately equal to 2.71828, and *sg1* is the surface-to-volume ratios specific to the vegetation being simulated in square meters per cubic meter (table 8).

Heating numbers of 10-hour dead fuels (*h*10*n*), 100-hour dead fuels (*h*100*n*), live herbaceous fuels (*hnwood*), and wood fuels (*hnwood*) are calculated the same way, using corresponding net fuel loadings and surface-to-volume ratios (table 8).

Table 8—Surface-to-volume ratio of dead and live fuels used in MCFire calculations (fuel characteristics, rate of spread, and energy release) for MC1-simulated vegetation

Vegetation	Ratio of dead fuels			Ratio of live fuels		
	1-hour (*sg*1)	10-hour (*sg*10)	100-hour (*sg*100)	1000-hour (*sg*1000)	Woody (*sgwood*)	Herbaceous (*sgherb*)
	m^2/m^3					
Tundra	1959	109	30	8	1462	1950
Boreal coniferous forest	1852	109	30	8	1470	1984
Maritime temperate coniferous forest	1960	109	30	8	1488	2045
Continental temperate coniferous forest	1937	109	30	8	1489	2120
Cool temperate mixed forest	1634	109	30	8	1478	1967
Warm temperate subtropical mixed forest	1670	109	30	8	1499	2012
Temperate deciduous forest	1730	109	30	8	1499	2003
Tropical deciduous forest	1730	109	30	8	1499	2003
Tropical evergreen forest	1730	109	30	8	1499	2003
Temperate mixed xeromorphic woodland	1789	109	30	8	1432	2060
Temperate conifer xeromorphic woodland	2072	109	30	8	1451	2059
Tropical thorn woodland	1906	109	30	8	1442	1909
Temperate subtropical deciduous savanna	1906	109	30	8	1442	1909
Warm temperate subtropical mixed savanna	1433	109	30	8	1386	2000
Temperate conifer savanna	2232	109	30	8	1500	2023
Tropical deciduous savanna	1906	109	30	8	1442	1909
C_3 grasslands[a]	2020	109	30	8	1498	2021
C_4 grasslands[b]	2040	109	30	8	1495	2003
Mediterranean shrubland	1673	109	30	8	1409	2057
Temperate arid shrubland	2326	109	30	8	1497	1978
Subtropical arid shrubland	2425	109	30	8	1488	1750
Taiga	1852	109	30	8	1470	1984

[a] Grasslands adapted to cool seasons.
[b] Grasslands adapted to warm or hot seasons.

Moisture-of-extinction estimates also require the ratio of dead-to-live fuel heating numbers (Cohen and Deeming 1985):

$$wrat = \frac{hn1 + hn10 + hn100}{hnherb + hnwood} \tag{52}$$

where *wrat* is the ratio of dead-to-live heating numbers; *hn*1 is the heating number of the 1-hour dead-fuel class, *hn*10 is the heating number of the 10-hour dead-fuel class, and *hn*100 is the heating number of the 100-hour dead-fuel class—all in pounds of dry matter per square foot (eq. 51); *hnher* is the heating number of the live herbaceous fuel class, and *hnwood* is the heating number of the live wood fuel class, both in pounds of dry matter per square foot.

Moisture extinction for dead fuels is parameterized for each kind of vegetation that MC1 simulates (table 9). Live-fuel moisture of extinction depends on the moisture content of the dead fuels as well as on the heating numbers (Cohen and Deeming 1985):

$$mclfe = \frac{mc\_1 \times hn1 + mc\_10 \times hn10 + mc\_100 \times hn100}{hn1 + hn10 + hn100} \tag{53}$$

$$mxl = 2.9\ wrat\left(1 - \frac{mclfe}{mxd}\right) - 0.226 \tag{54}$$

where *mclfe* is the weighted dead-fuel moisture content; *mc*_1 is the moisture content of 1-hour dead fuels, *mc*_10 is the moisture content of 10-hour dead fuels, and *mc*_100 is the moisture contents of 100-hour dead fuels—all as percentages; *hn*1is the heating number of 1-hour dead fuels, *hn*10 is the heating number of 10-hour dead fuels, and *hn*100 is the heating number of 100-hour dead fuels—all in pounds of dry matter per square foot (eq. 51); *wrat* is the ratio of dead-to-live fuel heating numbers (eq. 52); *mxd* is the moisture of extinction for dead fuels (table 9), and *mxl* is the moisture of extinction for live fuels, set to be no less than mxd.

Rate of Spread

Rate of spread is used to calculate the depth of the flaming zone (below), which in turn affects scorch-height and crown-kill calculations. Rate of spread is a function of fuel characteristics, topography, and wind (Cohen and Deeming 1985). The 1000-hour fuels class is not included in the rate of spread calculations because it has a relatively low surface-to-volume ratio. The rate of spread is calculated as:

$$ros = \frac{ir \times zeta \times (1 + phislp + phiwnd)}{htsink} \tag{55}$$

Table 9—Fuel characteristics used in calculations by the MCFire model simulations for MC1-simulated vegetation—combustion for live and dead fuels, used for rate-of-spread and energy release calculations; moisture of extinction, used for fuel characteristics calculations; and wind-reduction factor, used for rate-of-spread calculations

Vegetation	Heat of combustion: Live fuels (*hl*)	Heat of combustion: Dead fuels (*hd*)	Moisture of extinction of dead fuels (*mxd*)	Wind-reduction factor (*wndfac*)
	- - BTUs per pound - -		*Percent*	
Tundra	8001	8001	30	0.5
Boreal coniferous forest	8039	8039	30	0.4
Maritime temperate coniferous forest	8068	8068	23	0.4
Continental temperate coniferous forest	8053	8053	21	0.5
Cool temperate mixed forest	8026	8026	30	0.4
Warm temperate subtropical mixed forest	8210	8210	30	0.4
Temperate deciduous forest	8006	8006	30	0.5
Tropical deciduous forest	8006	8006	30	0.5
Tropical evergreen forest	8006	8006	30	0.5
Temperate mixed xeromorphic woodland	8406	8406	16	0.5
Temperate conifer xeromorphic woodland	8293	8293	16	0.6
Tropical thorn woodland	8016	8016	17	0.6
Temperate subtropical deciduous savanna	8016	8016	17	0.6
Warm temperate subtropical mixed savanna	8680	8680	15	0.6
Temperate conifer savanna	8001	8001	16	0.6
Tropical deciduous savanna	8016	8016	17	0.6
C_3 grasslands[a]	8014	8014	16	0.6
C_4 grasslands[b]	8028	8028	15	0.6
Mediterranean shrubland	8547	8547	17	0.5
Temperate arid shrubland	8020	8020	16	0.6
Subtropical arid shrubland	8072	8072	15	0.6
Taiga	8039	8039	30	0.4

[a] Grasslands adapted to cool seasons.
[b] Grasslands adapted to warm or hot seasons.

where *ros* is the rate of spread in feet per minute, *ir* is the reaction intensity in BTUs per square foot per minute, *zeta* is the no-wind propagating flux ratio, *phislp* is the slope effect multiplier coefficient, *phiwnd* is the wind effect multiplier, and *htsink* is the heat sink in BTUs per cubic foot of fuel—all described in the sections below.

Reaction intensity—
Reaction intensity is the heat release rate per unit area of the fire front (Rothermel 1972). It is calculated as a sum of the reaction intensity of dead-fuel classes (except for the 1000-hour dead fuels) and the live-fuel classes. Reaction intensity for dead fuels is:

$$ir = gmaop \times [(wdeadn \times hd \times etasd \times etamd) + (wliven \times hl \times etasl \times etaml)] \quad (56)$$

where *ir* is the reaction intensity in BTUs per cubic foot per minute; *gmaop* is the optimum reaction velocity (eq. 58) per minute (Rothermel 1972); *wdeadn* is the surface-area weighted dead-fuel density and *wliven* is the surface-area weighted live-fuel density—both in pounds of fuel per square foot; *hd* and is the heat of combustion of dead fuels and *hl* is the heat of combustion of live fuels—both in BTUs per pound (table 9); *etasd* is the mineral-damping coefficient of dead fuels and *etasl* is the mineral damping coefficient of live fuels (eq. 50); *etamd* is the moisture-damping coefficient of live fuels; and etaml is the moisture-damping coefficient of dead fuels.

The optimum reaction velocity in equation 56 is calculated after the maximum reaction velocity is calculated (fig. 11), following Cohen and Deeming (1985):

$$gmamx = \frac{sgbrt^{1.5}}{495 + 0.0594 \times sgbrt^{1.5}} \quad (57)$$

where gmamx is the maximum reaction velocity per minute, and sgbrt is the characteristic surface-to-volume ratio of the fuel in square meters per cubic meter.

The characteristic surface-to-volume ratio of the fuels (*sgbrt*) in equation 19 is calculated taking a sum of the characteristic surface-to-volume ratio of dead fuels (*sgbrd*) and live fuels (*sgbrl*) weighted by their respective fraction of the total surface area of fuels. The two component characteristic surface-to-volume ratios are calculated in an analogous way: for dead fuels (*sgbrd*) by computing the sum of the surface-to-volume ratios of the 1-, 10- and 100-hour fuels (table 8) weighted by their respective fraction of the total surface area of dead fuels; and for live fuels (*sgbrl*) by computing the sum of the surface-to-volume ratios of the two live-fuel classes (table 8) weighted by their respective fraction of the total surface area of live fuels.

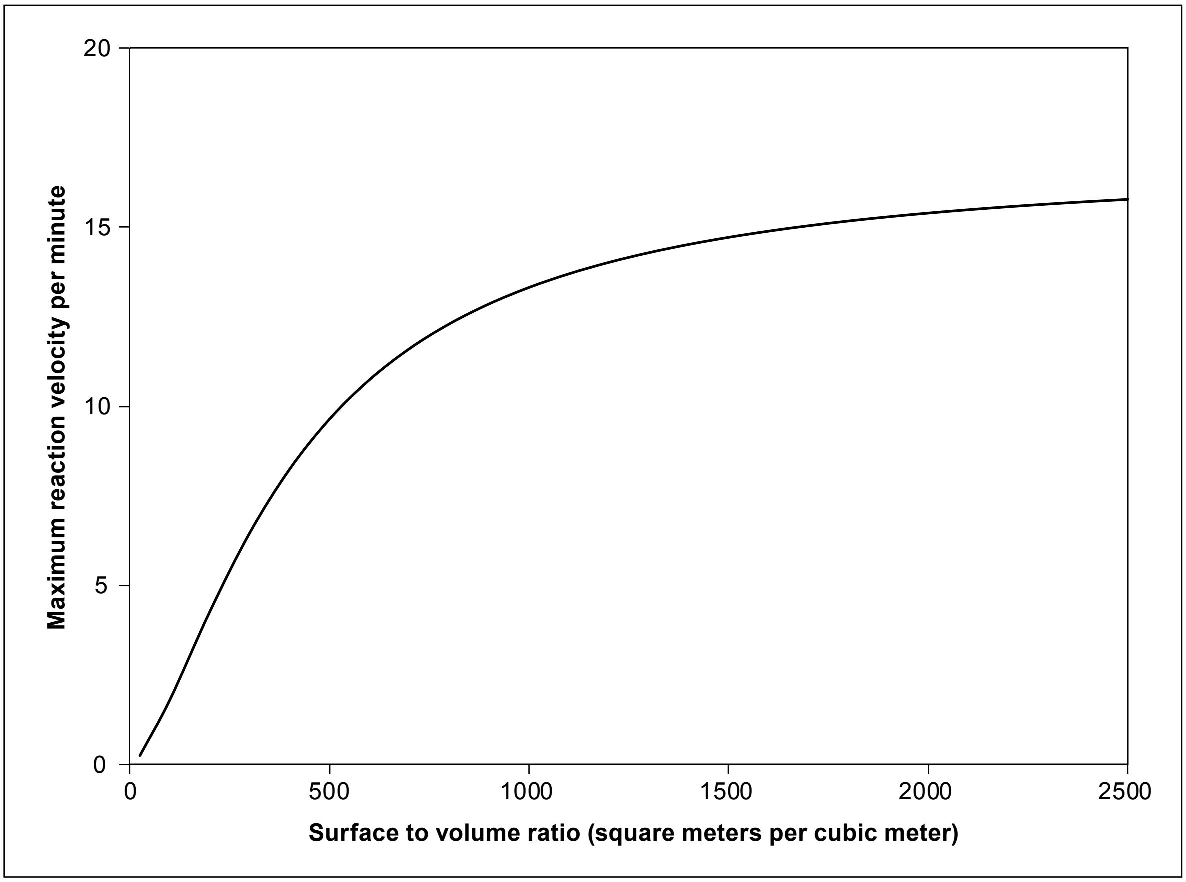

Figure 11—Maximum reaction velocity as a function of the surface-to-volume ratio.

Reaction velocity is ratio of the reaction zone efficiency (unitless) to the reaction time per minute (Rothermel 1972). Once the maximum reaction velocity (eq. 57) has been calculated, it is used to calculate optimum reaction velocity (figs. 12, 13):

$$gmaop = gmamx \times pr\_frac^{133(sgbr^{-0.7913})} \times e^{(1 - pr\_frac) \cdot 133 \cdot (sgbr^{-0.7913})} \quad (58)$$

where *gmaop* is the optimal reaction velocity in per minute, *gmamx* is the maximum reaction velocity per minute (eq. 57), *e* is a mathematical constant approximately equal to 2.71828, *pr_frac* is the ratio of actual-to-optimal fuel packing, and *sgbrt* is the characteristic surface-to-volume ratio in square meters per cubic meter.

To calculate the ratio of actual-to-optimal packing (*pr_frac*), the optimal packing ratio (fig. 14) must be calculated first:

$$betop = 3.348 \times sgbrt^{-0.8189} \quad (59)$$

where *betop* is the optimal packing ratio and *sgbrt* is the characteristic surface-to-volume ratio in square meters per cubic meter.

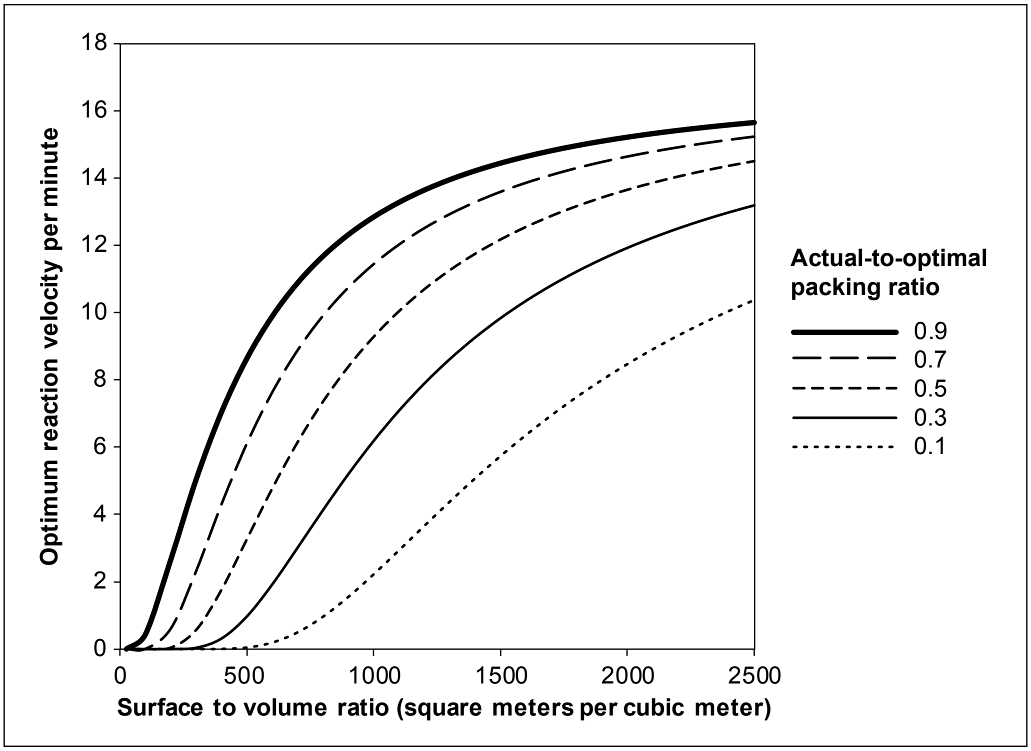

Figure 12—Optimum reaction velocity for selected values of ratio of actual-to-optimum packing as a function of surface-to-volume ratio of fuels.

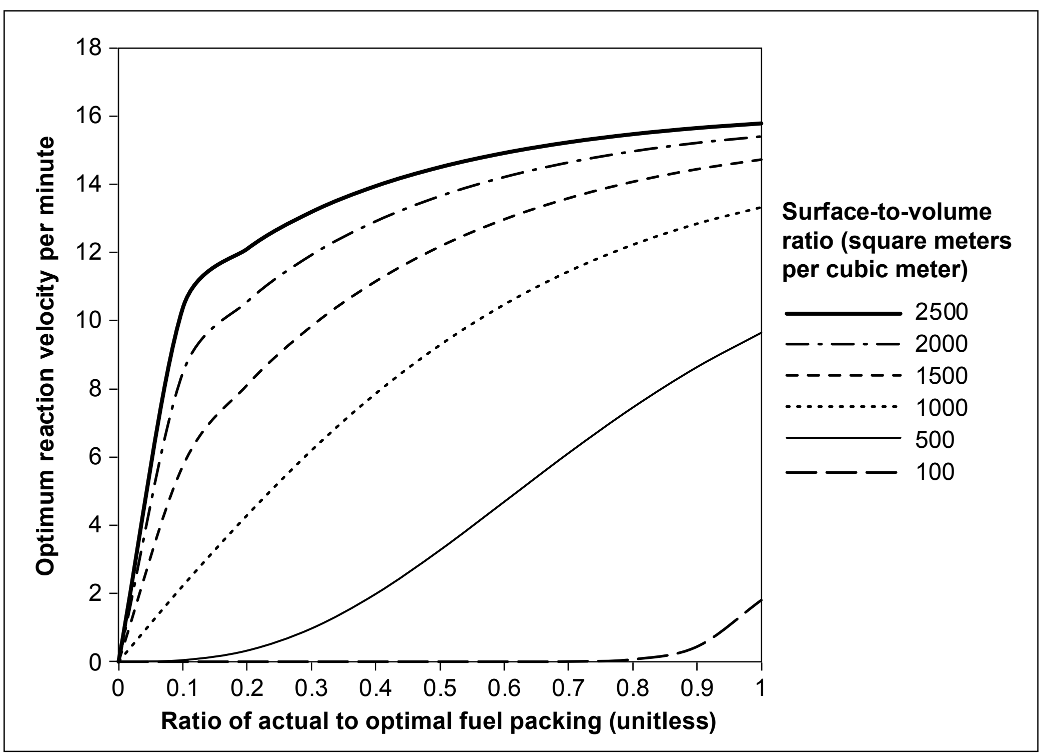

Figure 13—Optimum reaction velocity for selected values of surface-to-volume ratios as a function of ratio of actual-to-optimum packing of fuels.

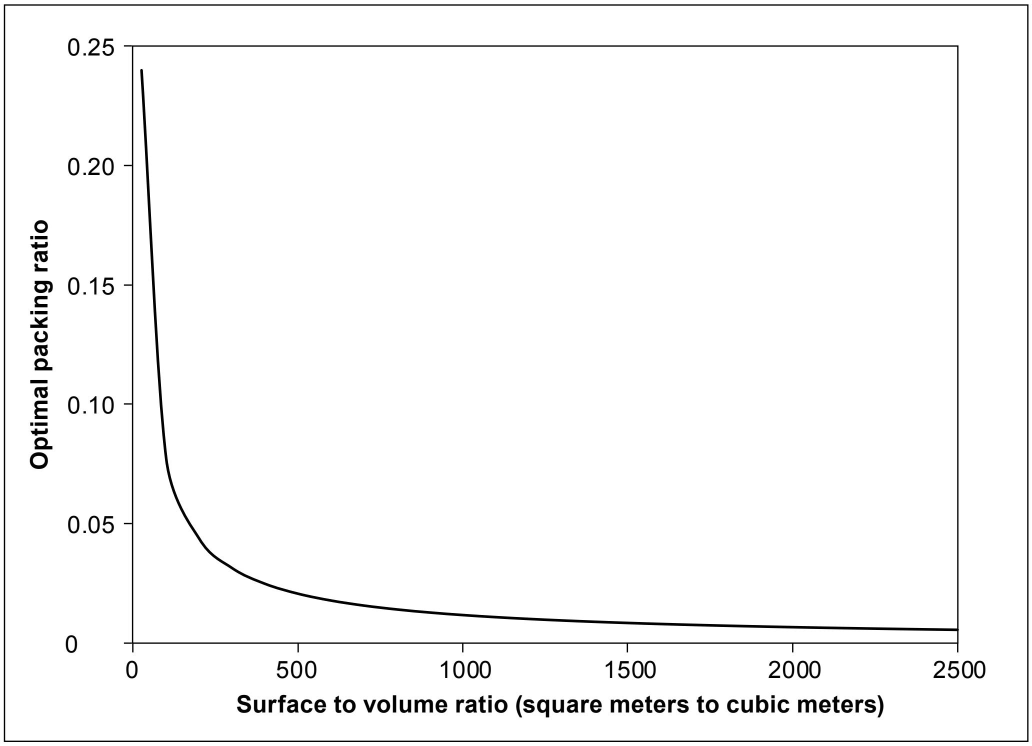

Figure 14—Optimum packing ratio as a function of surface-to-volume ratio of fine fuels.

The ratio of actual-to-optimal packing is then a simple ratio:

$$pr\_frac = \frac{betbar}{betop} \tag{60}$$

where *pr_frac* is the ratio of actual-to-optimal packing, *betbar* is the actual packing ratio (eq. 49), and *betop* is the optimal packing ratio (eq. 59).

To determine the surface-area weighted fuel densities of dead fuels (*wdeadn*) and live fuels used in equation 50 (*wliven*), MCFire first estimates the surface area of each fuel class under consideration. To do so, MCFire first divides the weight of each fuel class by a packing ratio for dead fuels (*rhod*) and a packing ratio for live fuels (*rhol*)—both assumed to be 32 pounds per cubic foot—and then multiplies the result by the surface-to-volume ratio for the fuel (table 8). Then the net fuel loading values of the three dead-fuel classes—*w*1*n*, *w*10, or *w*100 (above)—are weighted by the proportion of the surface area of each fuel class to the sum of all surface area of the dead fuels to determine the surface-area weighted fuel density of dead fuels (*wdeadn*). Similarly, the net fuel-loading values of the two live-fuel classes—*wherbn* and *wwoodn* (above)—are weighted by the proportion of the surface area of each fuel class to the sum of all surface area of the live fuels to determining the surface-area weighted fuel density of live fuels (*wliven*).

The heat-of-combustion rates of the dead fuels (*hd*) and live fuels (*hl*) used in equation 56 are set as parameters for each kind of vegetation simulated by MC1 (table 9).

The calculation of mineral-damping coefficients for dead (*etasd*) and live (*etasl*) fuels used in equation 56 is described above.

The moisture-damping coefficients used in equation 56 (*etamd* and *etaml*) represent the reduction in reaction velocity by fuel moisture (Rothermel 1972). The moisture-damping coefficient of dead fuels (fig. 15) is:

$$etamd = 1 - 2.59\ dedrt + 5.11\ dedrt^2 - 3.52\ dedrt^3 \tag{61}$$

where *etamd* is the moisture damping coefficient of dead fuels, and *dedrt* is the fraction of the moisture of extinction in dead fuels represented by the actual moisture content.

The fraction of the moisture of extinction represented by the actual moisture content of dead fuels (*dedrt*) in equation 61 is determined by calculating the ratio of the surface-area weighted sum of 1-hour, 10-hour, and 100-hour fuel moisture to

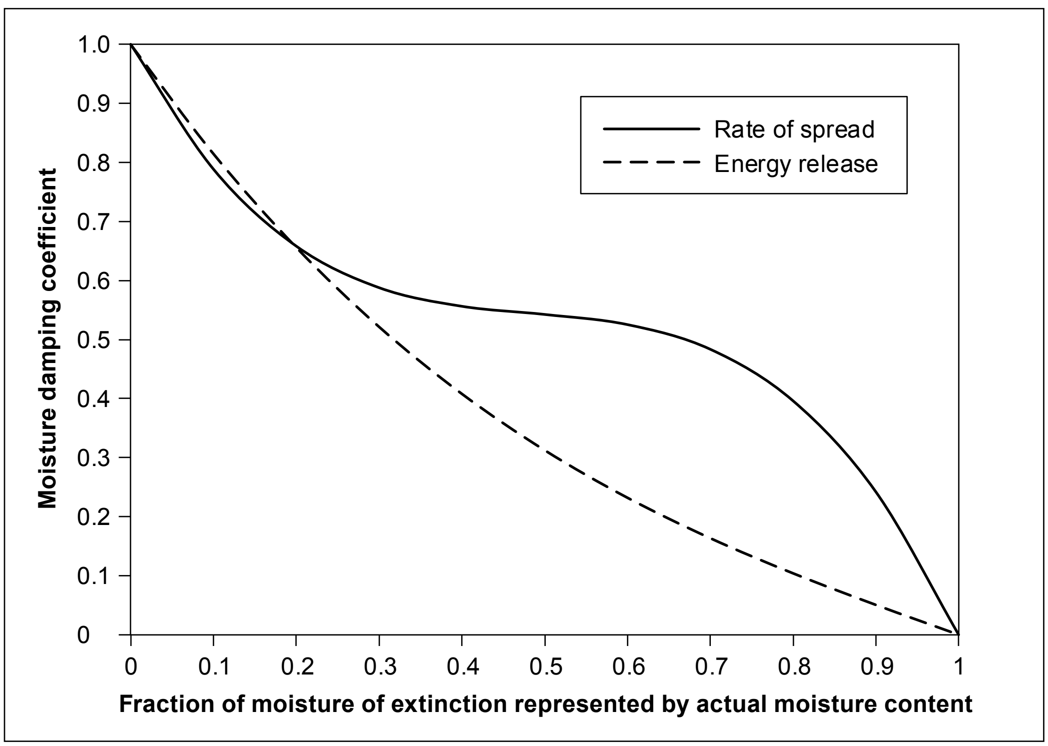

Figure 15—Moisture-damping coefficient as a function of the fraction of the moisture of extinction in fuels represented by the actual moisture content, using different calculations or rate of spread and for energy release (Cohen and Deeming 1985): for rate of spread, the MCFire simulation-model equation used is $1 - 2.59\ dedrt + 5.11\ dedrt^2 - 3.52\ dedrt^3$ where *dedrt* is the fraction of the moisture of extinction in dead fuels represented by the actual moisture content; for energy release, the same equation is used, but with substitutions (-2.0 for -2.59, 1.5 for 5.11, and -0.5 for -3.52).

the moisture of extinction (*mxd*) for the vegetation being simulated. Moisture-of-extinction (*mxd*) values are specified as parameters (table 9). The moisture-damping coefficient (*etaml*) of live fuels (fig. 15) is calculated in a similar way, using equation 61, with one difference: for live fuels, the moisture fraction does not use the parameterized moisture of extinction (*mxd*) values. Instead, the surface-area weighted sum of the two live-fuel classes is divided by the moisture of extinction of live fuels (eqs. 51 to 54), which is calculated daily.

No-wind propagation flux ratio—

The no-wind propagating flux ratio represents the amount of heat available to propagate to new fuels, and is calculated as (Cohen and Deeming 1985):

$$zeta = \frac{e^{(0.792 + 0.681\sqrt{sgbrt})(betbar + 0.1)}}{192 + 0.2595\, sgbrt} \qquad (62)$$

where *zeta* is the no-wind propagating flux ratio, *sgbrt* is the characteristic surface-to-volume ratio for the five fuel classes under consideration in square meters per cubic meter, and *betbar* is the actual packing ratio (eq. 49).

Slope-effect multiplier—

The slope-effect multiplier is calculated (Cohen and Deeming 1985) as:

$$phislp = slpfct \times betbar \qquad (63)$$

where *phislp* is the slope effect multiplier; *betbar* is the actual packing ratio (eq. 49); and *slpfct* is the slope-effect multiplier coefficient: 0.267 when slope is ≤25 percent, 0.533 when slope is >25 percent but ≤40 percent, 1.068 when slope is >40 percent but ≤55 percent, 2.134 when slope is >55 percent but ≤75 percent, and 4.273 when slope is >75 percent.

Wind-effect multiplier—

The wind-effect multiplier is calculated in one of two ways (Cohen and Deeming 1985 p. 11). MCFire first tests whether:

$$ws \times 88.0 \times wndfact \leq ir \qquad (64)$$

where *ws* is the average windspeed in miles per hour, *wndfac* is the fuel model wind-reduction factor (table 9), and *ir* is the reaction intensity (eq. 56) in BTUs per square foot per minute.

For relatively low wind speeds, when reaction intensity is larger as in equation 64, the wind effect multiplier is calculated in the following steps:

$$b\_eff = 0.02526 \times sgbrt^{0.54} \qquad (65)$$

$$c\_var = 7.47 \times e^{-0.133\mathrm{sgbrt}^{0.55}} \qquad (66)$$

$$e\_eff = 0.715 \times e^{-0.000359 sgbrt} \tag{67}$$

$$ufact = c\_var \times pr\_frac^{-e\_eff} \tag{68}$$

$$phiwnd = ufact \times (ws \times 88 \times wndfac)^{(b\_eff)} \tag{69}$$

where *b_eff*, *c_var*, *e_eff* and ufact are intermediate variables, *sgbrt* is the characteristic surface-to-volume ratio for the five fuel classes under consideration in square meters per cubic meter, *pr_frac* is the ratio of actual-to-optimal packing (eq. 60), *ws* is wind speed in miles per hour, *wndfac* is the wind reduction factor for the vegetation being simulated (table 9), and *phiwnd* is the wind-effect multiplier.

When wind speeds are higher, resulting in the balance shifting away from reaction intensity in equation 64, the wind effect multiplier is calculated as a function of reaction intensity:

$$phiwnd = ufact \times (0.9 \times ir)^{b\_eff} \tag{70}$$

where *phiwnd* is the wind effect multiplier, *ufact* and *b_eff* are the same intermediate variables as above (eqs. 68, 65), and *ir* is the reaction intensity in BTUs per square foot per minute (eq. 56).

Heat sink—

Heat sink is the product of the fuel-bed bulk density and a surface-area weighted average of the moisture-content dependent terms for each fuel class (Cohen and Deeming 1985):

$$htsink = rhobed \, \frac{\sum_{fuels} sa(250 + 1116\ mc)\ e^{-138/sg}}{satot} \tag{71}$$

where *htsink* is the size of the heat sink in BTUs per cubic foot; *rhobed* is the fuel-bed bulk density in pounds of fuel per cubic foot (eq. 48); *fuels* are the 1-hour, 10-hour, 100-hour dead fuels and the herbaceous and woody live-fuel classes; *sa* is the surface area of the fuel class (*sa*1, *sa*10, *sa*100, *saherb*, or *sawood*) in square feet per square foot; *mc* is the fractional moisture content of the fuel class (*mc*_1, *mc*_10, *mc*_100, *mc_grass*, or *mc_tree*) as a percentage; e is a mathematical constant approximately equal to 2.71828; sg is the surface-to-volume ratio of the fuel class in square meters per cubic meter (table 8); and *satot* is the total surface area of all the fuels in square feet per square foot.

Energy Release

Energy release is a principal component in the calculation of fire-line intensity and the energy-release component (below). Many calculations in this section are analogous to those done for the rate of spread (above), with two important differences: (1) the 1000-hour dead fuels are included in reaction intensity calculations; and (2) when calculating the combined characteristic surface-to-volume ratio, the values from the fuel classes are weighted by their mass, rather than by their volume.

Reaction intensity for energy release is calculated as a weighted average of the reaction intensities for the dead and live fuels. The weightings are the fractions calculated by dividing each of the two fuel types—dead and live—by total fuel (Cohen and Deeming 1985):

$$ire = gmaope \times [(fdeade \times wdedne \times hd \times etasd \times etamde) + (flivee \times wlivene \times hl \times etasl \times etamle)] \tag{72}$$

where *ire* is the reaction intensity for energy release in BTUs per square foot per minute; *gmaope* is the weighted optimum reaction velocity of loading (described below) per minute; *fdeade* is the ratio of dead-fuel weight (*wtotd*) to all fuel weight (*wtot*); *flivee* is the ratio of live-fuel weight (*wtotl*) to all fuel weight (*wtot*); *wdedne* is dead-fuel weight minus the noncombustible fraction (assumed to be 0.0555 for both fuels) and *wlivne* is live-fuel weight minus the noncombustible fraction (assumed to be 0.0555 for both fuels)—both in pounds of dry matter per square foot; *hdis* the heat of combustion of the dead fuels and *hl* is the heat of combustion of the live fuels—both in BTUs per pound (table 9); *etasdetasl* is the mineral damping coefficient for dead fuels and *etasl* is the mineral damping coefficient for live fuels (eq. 50); and *etamde* is the energy release moisture damping coefficient for dead fuels and *etamle* is the energy release moisture damping coefficient for live fuels, described below.

The optimum reaction velocity (figs. 12, 13) is calculated the same way as the optimum reaction velocity (eq. 58) for rate of spread (above), with two small differences: (1) the 1000-hour dead-fuel class is included in all fuel-related calculations, and (2) the characteristic surface-to-volume ratio is calculated as a mass-weighted average—not a volume-weighted average—of the surface-to-volume ratios of the component fuel classes.

The energy release moisture damping coefficients for dead fuels and live fuels (fig. 15) are calculated as they were calculated for rate of spread (above) using equation 61, but the coefficients -2.59, 5.11 and -3.52 are replaced with -2.0, 1.5, and -0.5 (Cohen and Deeming 1985). As noted above, the 1000-hour fuel class is included in the calculation.

Fireline Intensity and Lethal Scorch Height

Fireline intensity is used to determine the occurrence of crown fire (below), and lethal scorch height is used to simulate crown kill in the absence of a crown fire (sec. 7). All equations are from Cohen and Deeming (1985), except where noted. To calculate fireline intensity, residence time of the flaming front is first calculated as:

$$tau = \frac{384}{sgbrt} \tag{73}$$

where *tau* is the residence time of flaming front in minutes, and *sgbrt* is the characteristic surface-to-volume ratio for all fuels in square meters per cubic meter.

Then depth of the flaming zone is calculated as:

$$fd = ros \times tau \tag{74}$$

where *fd* is the depth of the flaming zone in feet, *ros* is the rate of spread in feet per minute (eq. 55), and *tau* is the residence time of flaming front in minutes (eq. 73).

Finally, fireline intensity is calculated as:

$$fi = ire \times \frac{fd}{60} \tag{75}$$

where *fi* is the fireline intensity in BTUs per foot per second, *ire* is reaction intensity in BTUs per square foot per minute (eq. 72), and *fd* is depth of the flaming zone in feet (eq. 74).

Given fireline intensity, lethal scorch height can be calculated following Van Wagner (1973) as:

$$sh = \frac{63}{158\text{-}tmp} \times \frac{fi^{7/6}}{\sqrt{fi + ws^3}} \tag{76}$$

where *sh* is the lethal scorch height in feet, *tmp* is the daily average air temperature in °F, *fi* is the fireline intensity in BTUs per foot per second (eq. 75), and *ws* is the wind speed in miles per hour.

Crown Fire

MCFire simulates a crown fire when fireline intensity (eq. 75)—converted from BTUs per second per foot to kilowatts per meter using a conversion factor of 0.288895—exceeds a threshold value (Van Wagner 1977). First, the estimated heat of canopy ignition is calculated as:

$$h = 460 + 26 \times mc\_tree \tag{77}$$

where *h* is the estimated heat of canopy ignition in kilojoules per kilogram, and *mc_tree* is the daily tree-moisture content as a percentage (sec. 4).

Then the crown fire threshold is calculated as:

$$fli\_crit = (0.010 \times z \times h)^{1.5} \quad (78)$$

where fli_crit is the threshold for crown fire in kilowatts per meter, z is height of the bottom of the crown in meters calculated as the difference between tree height (eq. 24) and crown length (eq. 25), and h is the estimated heat of canopy ignition in kilojoules per kilogram (eq. 77).

Section 7. Fire Effects

Whenever a fire occurs, MCFire can estimate its effects on vegetation and the effects of its emissions on the environment using fuel characteristics and fire behavior metrics. Figure 10 illustrates the organization of algorithm by which MCFire simulates fire behavior from fuel loading and moisture, which in turn drive mortality and consumption of fuels (Peterson and Ryan 1986, Ryan and Reinhardt 1988). Consumption is partitioned into two distinct types, flaming and smoldering; each type is linked to gaseous and particulate fire emissions using emission models and rates from CONSUME 3.0 (Prichard et al. 2007). Fire-induced fluxes of carbon are calculated on a per-unit area basis. MCFire also calculates black-carbon production as a separate process from emissions, following Kuhlbusch and Crutzen (1995). Finally, MCFire calculates the fraction of the grid cell area burned, used to prorate the estimated fire effects before values are passed back to MC1.

Crown Kill

When a crown fire occurs (sec. 6), MCFire assumes that all of the leaves and branches are consumed, that the stems and roots are killed without being consumed (table 10), and that 90 percent of live aboveground grass is consumed.

Absent a crown fire, MCFire estimates partial crown kill by comparing the lethal scorch height (eq. 76) with the tree height and crown height. The crown height is the height of the bottom of the canopy, calculated by subtracting the tree height (eq. 24) from the crown length (eq. 25). MCFire assigns a one to the crown-kill fraction if the lethal scorch height exceeds the tree height, and a zero if it fails to reach the bottom of the canopy. If it is between tree height and crown height, crown-kill fraction (Peterson and Ryan 1986) is estimated (fig. 16) as:

$$ck = 1 - \left(\frac{ht - hk}{cl}\right)^2 \quad (79)$$

where ck is the fraction of crown volume killed, ht is the tree height in meters (eq. 24); hk is the lethal scorch height in meters, converted from sh, the lethal scorch height calculated in feet (eq. 76); cl is the crown length in meters (eq. 25); and $\left(\frac{ht - hk}{cl}\right)^2$ represents the square of the unscorched fraction of the crown.

Table 10—Fire effects on live biomass pools simulated by the MCFire model under three kinds of fire events: crown fire, tree mortality without crown fire, and fire with partial mortality

Fire event	Biomass pool	Consumed	Killed
		Percent	
Crown fire	Aboveground grass	90	—
	Tree leaves	100	0
	Tree branches	100	0
	Tree stems	—	100
	Roots	—	100
Mortality but no crown fire	Aboveground grass	90	—
	Tree leaves	0	100
	Tree branches	0	100
	Tree stems	—	100
	Roots	—	100
Partial mortality[a]	Aboveground grass	90	—
	Tree leaves	0	ck × 100
	Tree branches	0	ck × 100
	Tree stems	—	ck × 100
	Roots	—	ck × 100

— = No results because MCFire does not estimate percent killed for aboveground grass, tree stems, or tree roots.
[a] When there is mortality is incomplete, MCFire uses crown kill fraction (eq. 79) to estimate percent killed: $ck = 1 - ((ht - hk)/cl)^2$ where ck is the fraction of crown volume killed; ht is the tree height in meters (eq. 24); hk is the lethal scorch height in meters, converted from sh, the lethal scorch height in feet (eq. 76); cl is the crown length in meters (eq. 25); and $((ht - hk)/cl)^2$ represents the square of the unscorched fraction of the crown.

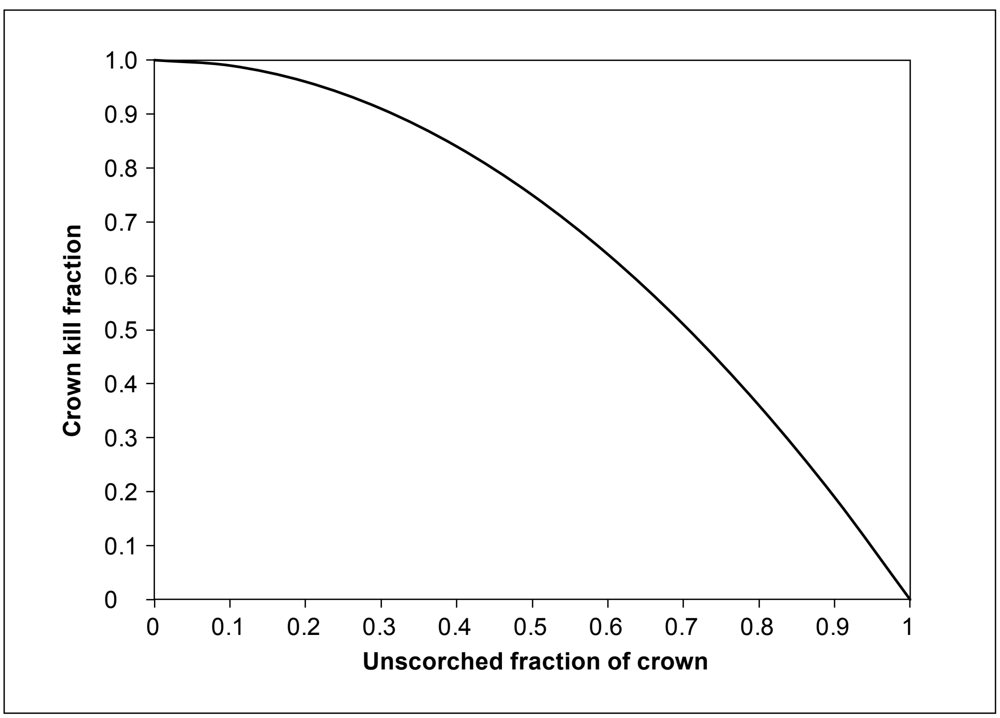

Figure 16—Crown-kill fraction (the proportion of crown volume killed by fire) as a function of the unscorched fraction of the crown length (tree height minus scorch height divided by the crown length).

Tree Mortality

When a crown fire occurs, MCFire assumes that all woody vegetation is killed (table 10). Absent a crown fire, MCFire estimates the probability that trees are killed (fig. 17) based on their bark thickness and the fraction crown kill fraction:

$$prob\_mort = \frac{1}{1+e^{-1.466 + 1.910bt - 0.1775bt^2 - 5.4ck^2}} \times 100 \qquad (80)$$

where *prob_mort* is the probability that the trees are killed as a percentage, *bt* is bark thickness (eq. 23) in centimeters (limited to a maximum of 5), *e* is a mathematical constant approximately equal to 2.71828, *e* is a mathematical constant approximately equal to 2.71828, and *ck* is the crown kill fraction (eq. 79).

If the probability of mortality (eq. 80) exceeds a parameterized threshold, all trees in the grid cell are considered to be killed. Currently MC1 uses the threshold value for testing fine-fuel flammability (*prob_thres* in sec. 5 and table 4) and assumes that all the trees will survive the fire if the probability of mortality (*prob_mort*) does not exceed the threshold.

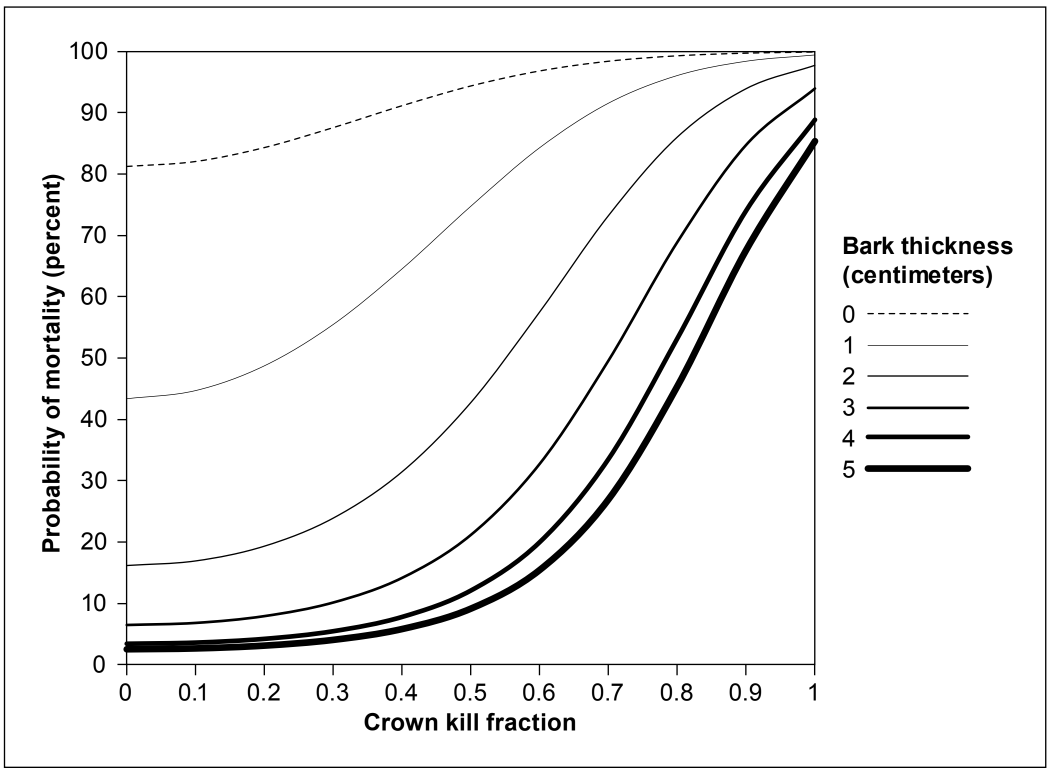

Figure 17—Probability of tree mortality for selected bark thicknesses as a function of crown-kill fraction; probability of tree mortality is plotted using the MCFire simulation-model equation $\frac{1}{1+e^{-1.466+1.910bt-0.1775bt^2-5.4ck^2}} \times 100$ where *bt* is bark thickness (eq. 23) in centimeters (limited to a maximum of 5) and *ck* is the crown kill fraction (the proportion of crown volume killed by fire); the probability of mortality is high for all crown kill fractions when bark thickness is very low, but it is low when bark thickness is high.

Biomass Consumption and Partial Mortality

MCFire calculates fire effects for five live biomass pools (aboveground live-grass biomass, live-tree leaves, live-tree branches, live-tree stems, and live roots) and four dead biomass pools (1-hour, 10-hour, 100-hour and 1000-hour fuels). In every fire event, MCFire estimates that 90 percent of aboveground live grass biomass is consumed. For each of the other biomass pools, MCFire calculates the percentage consumed (*consumed*) and percentage killed (*killed*), depending on which of these three fire events has occurred (table 10):

1. When a crown fire occurs (above), all live tree leaves and live tree branches are consumed, and live tree stems and live roots are marked as killed.
2. When tree mortality occurs without a crown fire (above), all live tree biomass pools and the live roots pool are marked as killed.
3. In all other situations, mortality is considered incomplete and all live-tree biomass pools and the live-roots pool are marked as having the same percentage killed as the crown-kill fraction (eq. 79).

After the biomass consumption has been calculated as percentages, MCFire applies the percentages to live grass pools (*lgrass*), live-tree leaf pools (*lleaf*), and live-tree branch pools (*lbranch*) to calculate consumption amounts as weight (tons of dry matter per acre). The consumed weights are used in the emissions calculations (below).

Estimates of the proportions of the dead-fuel pools that are consumed are based on equations in CONSUME version 3.0 (Prichard et al. 2007). The amounts of 1-hour, 10-hour, and 100-hour dead fuels consumed are estimated as:

$$c\_1hr = 0.9 \times d1 \tag{81}$$

$$c\_10hr = -0.048132 + 0.917393 \times d10 \tag{82}$$

$$c\_100hr = -0.124649 + 0.869309 \times d100 - 0.004804 \times mc\_duff \tag{83}$$

where c_1hr is the amount of 1-hour dead fuels consumed, c_10hr is the amount of 10- hour dead fuels consumed, and c_100hr is the amount of 100-hour dead fuels consumed—all in tons of dry matter per acre; $d1$ is the daily amount of 1-hour dead fuels, $d10$ is the daily amount of 10-hour dead fuels, and $d100$ is the daily amount of 100-hour dead fuels—all in tons of dry matter per acre (sec. 3); and mc_duff is an estimate of the moisture content of the duff as a percentage, set to the precipitation-based production coefficient (*pptprd*) for grass from the MC1 biogeochemistry module.

To estimate the amount of the 1000-hour dead fuels consumed, reduction in diameter is first estimated. When the moisture content of the duff (*mc_duff*) is ≤70 percent:

$$dia\_reduc = -1.465442 + 0.466083 \times preburn\_dia - 0.014756 \times mc\_duff \qquad (84)$$

When moisture content is >70 percent:

$$dia\_reduc = 0.5779 \times e^{-0.03(mc\_duff - 70)} \qquad (85)$$

where *dia_reduc* is the reduction in the diameter of the large coarse wood in inches, *preburn_dia* is preburn fuel diameter set to 6.6 inches (Ottmar 1998, Peterson and Ottmar 1991), *e* is a mathematical constant approximately equal to 2.71828, and *mc_duff* is an estimate of the moisture content of the duff as a percentage, set to the precipitation-based production coefficient (*pptprd*) for grass from the MC1 biogeochemistry module.

The fractional reduction in volume is calculated from the diameter reduction, and used to estimate the amount of the 1000-hour dead-fuel class consumed:

$$vol\_reduc = 1 - \left(\frac{QMD - dia\_reduc}{QMD}\right)^2 \qquad (86)$$

$$c\_1000hr = vol\_reduc \times d1000 \qquad (87)$$

where *vol_reduc* is the fractional reduction in volume of the 1000-hour dead fuel, *QMD* is the quadratic average diameter of fuels set to 6.6 inches (Ottmar 1998, Peterson and Ottmar 1991), *dia_reduc* is the reduction in the diameter of the large coarse wood in inches (eqs. 84, 85), *c_*1000*hr* is the amount of 1000-hour fuel consumed in tons of dry matter per acre, and *d*1000 is the amount of 1000-hour fuel on the current day in tons of dry matter per acre.

Emissions

After MCFire calculates the total amount of fuel consumed by flaming combustion and the total amount consumed by smoldering combustion, emissions are calculated for each total. The equations used in this section are based on the CONSUME version 3.0 (Prichard et al. 2007).

Flaming versus smoldering combustion—

MCFire assumes that all fine fuels are consumed by flaming combustion: live grass (*lgrass*), leaves of woody vegetation (*lleaf*), branches of woody vegetation (*lbranch*), 1-hour (*d*1) dead fuels, and 10-hour dead fuels (*d*10).

For the 100-hour fuels, the flaming portion of combustion is first calculated (fig. 18). The equation for flaming portion of combustion given in CONSUME 3.0 user guide (Prichard et al. 2007) has been adjusted to correct an error and simplified to:

$$f\_portion = 1 - e^{-(0.216169\, c\_100hr)^{2.26}} \tag{88}$$

where *f_portion* is the flaming portion of combustion, *e* is a mathematical constant approximately equal to 2.71828, and *c*_100*hr* is the amount of 100-hour fuel consumed in tons of dry matter per acre (eq. 87).

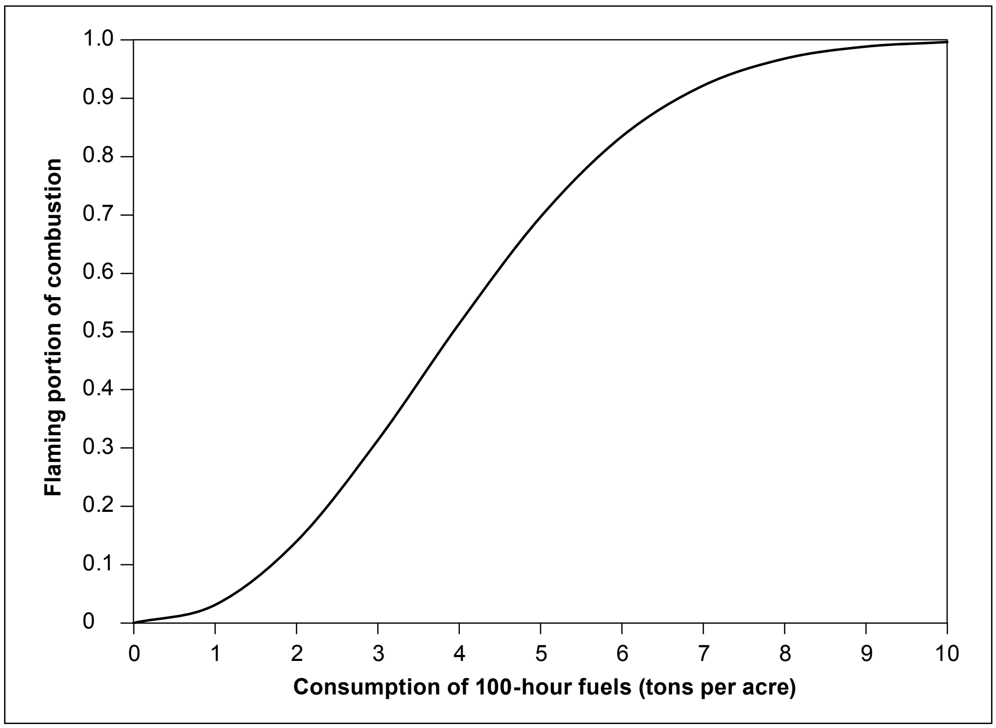

Figure 18—Flaming portion of combustion as a function of total consumption of 100-hour dead fuel, plotted using the MCFire simulation-model equation $1 - e^{-(0.216169\, c\_100hr)^{2.26}}$ where *c*_100*hr* is the amount of 100-hour fuel consumed in tons of dry matter per acre.

If the diameter reduction from flaming combustion is >1.68 inches, then flaming combustion is assumed to account for all the consumption of the 100-hour fuels. If the diameter reduction is ≤1.68 inches, the amount consumed by flaming is calculated as:

$$fc\_100hr = d100 \times \left(1 - \frac{[1.68 - (dia\_reduc \times f\_portion)]^2}{1.68^2}\right) \tag{89}$$

where *fc*_100*hr* is the amount of 100-hour fuel consumed by flaming combustion in tons of dry matter per acre, *d*100 is the original amount of 100-hour fuel in tons of dry matter per acre, *dia_reduc* is the diameter reduction attributable to fire in inches (eqs. 84, 85), and *f_portion* is the flaming portion of combustion (eq. 88).

For 1000-hour fuels, the amount consumed by flaming combustion (*fc*_1000*hr*) is calculated with equation 89, substituting the weight of 1000-hour fuels (*d*1000) for 100-hour fuels (*d*100), and replacing all occurrences of the constant 1.68 with 6.6, representing the quadratic average diameter of 1000-hour fuels (Ottmar 1998, Peterson and Ottmar 1991).

Once all the flaming combustion amounts have been calculated, MCFire calculates the total smoldering combustion amount (in tons of dry matter per acre) by calculating the difference between the total combustion amount (*tot_c*) and the total flaming combustion amount (*tot_fc*). The total combustion amount is the sum of 1-hour, 10-hour, 100-hour, and 1000-hour dead-fuel combustion, plus live grass, leaf, and branch combustion (above). The total flaming-combustion amount is the sum of fine fuels—live grass (*lgrass*), leaves of woody vegetation (lleaf), branches of woody vegetation (*lbranch*), 1-hour dead fuels (*d*1), and 10-hour dead fuels (*d*10)—plus the portion of 100-hour fuel consumption amounts (*d*100) that was not consumed (*fc*_100*hr*) and the portion of 1000-hour fuel consumption amounts (*d*1000) that was not consumed (*fc*_1000*hr*).

Emissions species—
MCFire translates the amounts of fuel burned by flaming and smoldering combustion (above) using emission rates for seven types of unmounded vegetation (table 11). Because MC1 does not directly use the seven unmounded fuel types in table 11, MCFire selects the fuel type that most closely matches the MC1 vegetation type being simulated in the current grid cell (table 1).

To calculate total quantities (table 11) for the seven emission components—carbon monoxide, carbon dioxide, methane, nonmethane hydrocarbons, total particulate matter, particulate matter <10 µm (PM10), and particulate matter <2.5 µm (PM2.5)—MCFire multiplies the flaming (*tot_fc*) and smoldering (*tot_sc*) combustion quantities by the corresponding emissions rates for each vegetation type.

Black Carbon

MCFire calculates fuel conversion to black carbon for six fuel classes: live grass, live tree leaves, live tree branches, and the four dead-fuel classes (1-hour, 10-hour, 100-hour, and 1000-hour). The calculation follows Kuhlbusch and Crutzen (1995), and is the same for all six fuel classes under consideration:

$$blkc = \left(\frac{28.5}{1.3^{88.2 - consumed} + 1}\right) \times \left(\frac{100 - consumed}{consumed}\right) \tag{90}$$

where *blkc* is portion of fuel converted to black carbon as a percentage, and *consumed* is the portion the pool consumed by the fire as a percentage.

Table 11—Comparative amounts of seven emission components calculated by the MCFire model for MCI-simulated vegetation—particulate matter (PM), particulates <10 µm (PM_{10}), particulates <2.5 µm ($PM_{2.5}$), carbon monoxide (CO), carbon dioxide (CO_2), methane (CH_4), nonmethane hydrocarbons (NMHC)—under flaming and smoldering conditions; emission rates are from Prichard et al. (2007)

Emissions fuel type (MCI vegetation)	Flaming combustion							Smoldering combustion						
	PM	PM_{10}	$PM_{2.5}$	CO	CO_2	CH_4	NMHC	PM	PM_{10}	PM2.5	CO	CO_2	CH_4	NMHC
	Pounds per ton combusted													
Douglas-fir slash (Maritime temperate coniferous forest)	24.7	16.6	14.9	143	3,385	4.6	4.2	35.0	27.6	26.1	463	2,804	15.2	8.4
Hardwoods slash (Temperate deciduous forest)	23.0	14.0	12.2	92	3,389	4.4	5.2	38.0	25.9	23.4	366	2,851	19.6	14.0
Ponderosa-lodgepole pine slash (Warm temperate subtropical mixed forest)	18.8	11.5	10.0	89	3,401	3.0	3.6	48.6	36.7	34.2	285	2,971	14.6	9.6
Mixed conifer slash (Continental temperate coniferous forest)	22.0	11.7	9.6	53	3,458	3.0	3.2	33.6	25.3	23.6	273	3,023	17.6	13.2
Juniper slash (Tropical thorn woodland)	21.9	15.3	13.9	82	3,401	3.9	5.5	35.1	25.8	23.8	250	3,050	20.5	15.5
Sagebrush (C_3 or C_4 grasslands)[a]	45.0	31.8	29.1	155	3,197	7.4	6.8	45.3	29.6	26.4	212	3,118	12.4	14.5
Chaparral (Mediterranean shrubland)	31.6	16.5	13.5	119	3,326	3.4	17.2	40.0	24.7	21.6	197	3,144	9.0	30.6
Average values	26.7	16.8	14.7	105	3,365	4.2	6.5	39.4	30.0	25.6	292	2,994	15.6	15.1

[a] C3 is grassland adapted to cool seasons and C4 is grassland adapted to warm or hot seasons.

The percentage of pool consumed by fire (*consumed*) is calculated above, and can range from 0 to 100. For black-carbon calculations, however, values are only calculated for the upper end of that range—70 to 100 percent (fig 19).

To calculate the mass of black carbon produced in each of the six fuel classes, MCFire multiplies the black carbon conversion percentage (*blkc*) by the corresponding carbon pool in the MC1 biogeochemistry module (appendix 2). The conversion percentage for:

- Live grass is applied to the live grass-carbon pool (*lgras*)
- Live trees is applied to the live tree-leaves carbon pool (*lleaf*)
- Live branches is applied to both the fine woody pools (*lwod*1) and coarse woody pools (*lwod2*)

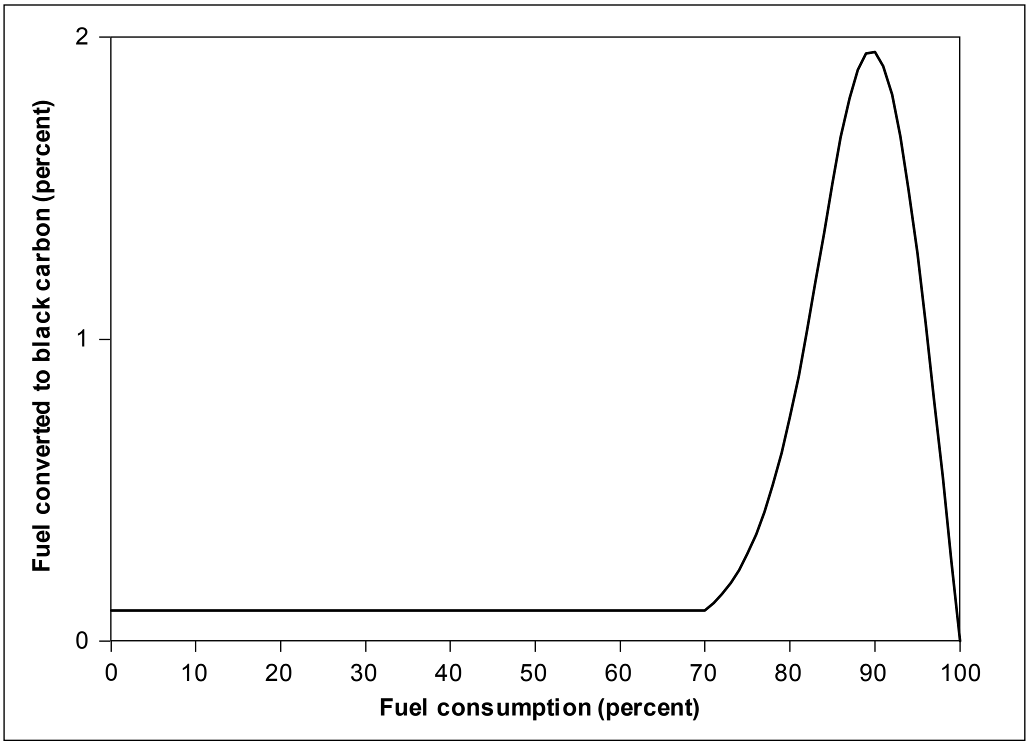

Figure 19—Black-carbon production as a function of fuel consumption, estimated as a function of the portion of the fuel being consumed by fire; because the MCFire simulation model calculates black carbon conversion and consumption as distinct pathways for carbon, black carbon conversion is zero when consumption is 100 percent.

- One-hour dead fuels is applied to the litter (*littr*), standing dead grass (*dstnd*), and fine dead wood carbon pools (*dwod*1)
- Hundred-hour dead fuels is applied to coarse wood carbon pool (*dwod*2)

Although the black-carbon conversion percentage is calculated as a function of fuel consumed by fire, the two pools are distinct and fuel converted to black carbon is not included in fuel consumed by fire. Therefore black carbon is not regarded as an emission; instead MC1 transfers black carbon to a highly recalcitrant soil carbon pool. This distinction is essential in understanding the incongruent structures of black-carbon production and fuel-consumption calculations. For fuel consumption, MCFire combines the MC1 fine woody pools (*lwod*1) and coarse woody pools (*lwod*2), and then partitions them into branches (*lbranch*) and stems (*lstem*), for which independent consumption rates are calculated. For black-carbon conversion, MCFire only uses the consumption rate of branches to calculate a black-carbon conversion percentage, but applies that percentage to the sum of fine woody pools (*lwod1*) and coarse woody pools (*lwod*2), some portion of which contains stems. Another incongruence is that MCFire does not calculate a 10-hour black-carbon conversion percentage. For fuel consumption calculations, MCFire combines MC1's dead carbon pools (eq. 5), and then partitions them into 1-hour, 10-hour, 100-hour, and 1000-hour fuel classes using parameterized fractions (table 5). For black carbon, MCFire applies conversion rates for 1-hour fuels to fine dead-wood carbon pools (*dwod*1) and 100-hour fuels to coarse dead wood carbon pools (*dwod*2), but does not use the conversion rates for 10-hour and 1000-hour fuels, because corresponding dead carbon pools were not readily identified. Harmonizing the black carbon calculations with fuel consumption calculations would improve overall model skill.

Area Burned

For each fire occurrence, MCFire calculates the area burned as a fraction of the grid cell being simulated but does not identify the location of the area burned within the cell. Nor does it calculate the area burned directly from weather and fire behavior, but instead as function of the current vegetation type, drought conditions, and the time since the last fire in the grid cell. MC1 and MCFire do not simulate any interaction among cells. In particular MCFire does not simulate fire spread among grid cells.

MCFire first estimates a current fire-return interval based on the drought conditions of the current simulation time step and historical minimum and maximum fire-return intervals:

$$curr\_fri = min\_mfri + \left(\frac{pdsi - pdsi\_min}{pdsi\_max - pdsi\_min}\right) \times (max\_mfri - min\_mfri) \qquad (91)$$

where *curr_fri* is the estimate of the current fire-return interval in years; *min_mfri* and *max_mfri* are the minimum and maximum average fire-return intervals in years (table 1); *pdsi* is the current monthly value of the Palmer Drought Severity Index; *pdsi_min* is the minimum Palmer Drought Severity Index value assumed to be -4; and *pdsi_max* is the maximum Palmer Drought Severity Index value. The value of *pdsi_max* is set to the value of the input parameter *pdsi_thresh* (table 4), the threshold above which fire is not simulated.

The minimum and maximum historical fire-return interval values (eq. 91) are parameterized for each type of vegetation that MC1 simulates (table 1). The drought condition of the current simulation time step, as represented by the Palmer Drought Severity Index value, is used to select a value in the interval between the minimum and maximum fire-return intervals. The values used in equation 91 do not represent the full range of Palmer Drought Severity Index values naturally observed, but rather a range of dry conditions under which fire is likely to occur.

MCFire calculates the burned area as a reciprocal of the estimated current fire-return interval (eq. 91):

$$part = \frac{burn\_count + 1}{curr\_fri} \qquad (92)$$

where *part* is the fraction of the cell burned, *burn_count* is the number of full calendar years since the last fire, and *curr_fri* is the estimated current fire-return interval in years (eq. 91).

Area burned (*part*) is limited to a maximum of 1.0 (100 percent burned), so the fraction ranges from the simple reciprocal of the *curr_fri* (eq. 91) to 1.0. If fire were to occur at a regular interval under the same drought conditions, then the sum of area burned (*part*) would not reach 1.0 until simulation is complete for the *curr_fri* years.

Acknowledgments

Funding for MCFire model development was provided by the U.S. Forest Service, the U.S. Department of Energy—National Institute for Global Environmental Change, and the U.S. Geological Survey—Biological Resources Division.

English and Metric Equivalents

These conversion factors are accurate to six significant digits.

English Equivalents

When you know:	Multiply by:	To find:
Millimeters (mm)	0.0393701	Inches
Centimeters (cm)	0.393701	Inches
Meters (m)	3.28084	Feet
Meters (m)	0.000621371	Miles
Meters per second ($m\ s^{-1}$)	196.850	Feet per minute
Meters per second ($m\ s^{-1}$)	2.23694	Miles per hour
Mils	25.6410256	Micrometers (µm)
Grams (g)	0.00220462	Pounds
Grams (g)	1.10231×10^{-6}	Tons
Grams per square meter ($g\ m^{-2}$)	0.000204816	Pounds per square foot
Grams per square meter ($g\ m^{-2}$)	8.92179	Pounds per acre
Grams per square meter ($g\ m^{-2}$)	0.00446090	Tons per acre
Grams per cubic meter ($g\ m^{-3}$)	62.4280×10^{-6}	Pounds per cubic foot
Joules (J)	0.000947817	British thermal units
Joules per gram ($J\ g^{-1}$)	0.429923	British thermal units per pound
Degrees Celsius (C)	1.8 °C + 32	Degrees Fahrenheit
Pascals (Pa)	0.000145038	Pounds per square inch
Stems per square meter (stems m^{-2})	4046.86	Stems per acre
Kilowatts per meter ($kW\ m^{-1}$)	0.288895	British thermal units per second per foot

Metric Equivalents

When you know:	Multiply by:	To find:
Inches (in)	25.4000	Millimeters
Inches (in)	2.54000	Centimeters
Feet (ft)	0.304800	Meters
Feet per minute (ft minute^{-1})	0.005080	Meters per second
Micrometers (µm)	0.039	Mils
Miles (mi)	1609.34	Meters
Miles per hour (mph)	0.44704	Meters per second
Pounds (lb)	453.592	Grams
Pounds per square inch (psi)	6894.76	Pa
Pounds per square foot (lb ft^{-2})	4882.43	Grams per square meter
Pounds per acre (pound ac^{-1})	0.112085	Grams per square meter
Pounds per cubic foot (pound foot^{-3})	16018.50	Grams per cubic meter
Tons (T)	907185.00	Grams
Tons per acre (T ac-1)	224.170	Grams per square meter
British thermal units (BTU)	1055.06	Joules
British thermal units per pound (BTU pound^{-1})	2.32600	Joules per gram
Degrees Fahrenheit (°F)	(°F – 32)/1.8	Degrees Celsius
Stems per acre (stems ac^{-1})	0.000247105	Stems per square meter
British thermal units per second per foot (BTU sec^{-1} foot^{-1})	3.46147	Kilowatts per meter

References

Aber, J.; Neilson, R.; McNulty, S. [et al.]. 2001. Forest processes and global environmental change: predicting the effects of individual and multiple stressors. Bioscience. 51(9): 735–751.

Albini, F.A. 1976. Estimating wildfire behavior and effects. Gen. Tech. Rep. INT-30. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 92 p.

Anderson, H.E. 1982. Aids to determining fuel models for estimating fire behavior. Gen. Tech. Rep. INT-122. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 22 p.

Andrews, P.L. 1986. BEHAVE: fire behavior prediction and fuel modeling system–BURN subsystem, part 1. Gen. Tech. Rep. INT-194. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 130 p.

Bachelet, D.; Lenihan, J.M.; Daly, C. [et al.]. 2001a. MC1, a dynamic vegetation model for estimating the distribution of vegetation and associated carbon and nutrient fluxes. Tech. Documentation. Version 1.0. Gen. Tech. Rep. PNW-GTR-508. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 95 p.

Bachelet, D.; Lenihan, J.M.; Neilson, R.P.; Drapek, R.J.; Kittel, T. 2005. Simulating the response of natural ecosystems and their fire regimes to climatic variability in Alaska. Canadian Journal of Forest Research. 35: 2073–2293.

Bachelet, D.; Neilson, R.P.; Hickler, T. [et al.]. 2003. Simulating past and future dynamics of natural ecosystems in the United States. Global Biogeochemical Cycles. 17(2): 1045. DOI: 10.1029/2001GB001508.

Bachelet, D.; Neilson, R.P.; Lenihan, J.M.; Drapek, R.J. 2001b. Climate change effects on vegetation distribution and carbon budget in the U.S. Ecosystems. 4: 164–185.

Bachelet, D.; Neilson, R.P.; Lenihan, J.M.; Drapek, R.J. 2004. Regional differences in the carbon source-sink potential of natural vegetation in the U.S. Environmental Management. 33 (Supp. 1): S23–S43. DOI: 10.1007/s00267-003-9115-4.

Botkin, D.B.; Janak, J.F.; Wallis, J.R. 1972a. Rationale, limitations and assumptions of a northeastern forest growth simulator. IBM Journal of Research and Development. 16: 101–116. [Reference for the JABOWA model].

Botkin, D.B.; Janak, J.F.; Wallis, J.R. 1972b. Some ecological consequences of a computer model of forest growth. Journal of Ecology. 60: 849–872.

Burgan, R.E. 1979. Estimating live fuel moisture for the 1978 National Fire Danger Rating System—1978. Res. Pap. INT-226. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 16 p.

Burgan, R.E. 1988. Revisions to the 1978 National Fire Danger Rating System. Res. Pap. SE-273. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station. 144 p.

Cohen, J.D.; Deeming, J.E. 1985. The National Fire-Danger Rating System: basic equations. Gen. Tech. Rep. PSW-GTR-82. Berkeley, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station. http://www.fs.fed.us/psw/publications/gtrs.shtml. (20 June 2015).

Daly, C.; Bachelet, D.; Lenihan, J. [et al.]. 2000. Dynamic simulations of tree-grass interactions for global change studies. Ecological Applications. 10: 449–469.

Fosberg, M.A.; Rothermel, R.C.; Andrews, P.L. 1981. Moisture content calculations for 1000-hr timelag fuels. Forest Science. 27(1): 19–26.

Howard, E.A. 1978. A simple model for estimating the moisture content of living vegetation as potential wildfire fuel. In: Fifth conference on fire and forest meteorology. Boston, MA: American Meteorological Society: 20–23.

Keane, R.E.; Morgan, P.; Running, S.W. 1996. FIRE-BGC–a mechanistic ecological process model for simulating fire succession on coniferous forest landscapes of the northern Rocky Mountains. Res. Pap. INT-484. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 122 p.

Keetch, J.J.; Byram, G. 1968. A drought index for forest fire control. Rev. Res. Paper SE-38. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station. 32 p.

Kercher, J.R.; Axelrod, M.C. 1984. A process model of fire ecology and succession in a mixed-conifer forest. Ecology. 65(6): 1725–1742. [Reference for the SILVA model].

Kuhlbusch, T.A.J.; Crutzen, P.J. 1995. Toward a global estimate of black carbon in residues of vegetation fires representing a sink of atmospheric CO_2 and a source of O_2. Global Biogeochemical Cycles. 9.4 (1995): 491–501.

Leenhouts, B. 1998. Assessment of biomass burning in the conterminous United States. Conservation Ecology (now called Ecology and Society). Vol. 2, Article 1. www.ecologyandsociety.org. (17 June 2015). [Click on Archives].

Lenihan, J.M.; Daly, C.; Bachelet, D.; Neilson, R.P. 1998. Simulating broad-scale fire severity in a dynamic global vegetation model. Northwest Science. 72: 91–103.

Lenihan, J.M.; Drapek, R.J.; Bachelet, D.; Neilson, R.P. 2003. Climate changes effects on vegetation distribution, carbon, and fire in California. Ecological Applications. 13(6): 1667–1681.

Means, J.E.; Hansen, H.A.; Koerper, G.J.; Alaback, P.B.; Klopsch, M.W. 1994. Software for computing plant biomass—BIOPAK users guide. Gen. Tech. Rep. PNW-GTR-340. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 180 p.

Means, J.E.; Krankina, O.N.; Jiang, H.; Li, H.Y. 1996. Estimating live fuels for shrubs and herbs with BIOPAK. Gen. Tech. Rep. PNW-GTR-372. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 21 p.

Neilson, R.P. 1995. A model for predicting continental-scale vegetation distribution and water balance. Ecological Applications. 5: 362–385.

Ottmar, R.D. 1998. Fuel consumption in natural fuels. Internal report. On file with: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Seattle Forestry Sciences Laboratory, 4043 Roosevelt Way N.E., Seattle, WA 98105.

Ottmar, R.D.; Burns, M.F.; Hall, J.N.; Hanson, A.D. 1993. CONSUME user's guide. Gen. Tech. Rep. PNW-GTR-304. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

Palmer, W.C. 1965. Meteorological drought. Res. Pap. 45. Washington, DC: U.S. Department of Commerce, Weather Bureau. 58 p.

Parton, W.J.; Schimel, D.S.; Cole, C.V.; Ojima, D.S. 1987. Analysis of factors controlling soil organic matter levels in Great Plains grasslands. Soil Science Society of America Journal. 51: 1173–1179.

Peterson, D.L. 1985. Crown scorch volume and scorch height: estimates of postfire tree condition. Canadian Journal of Forest Research. 15: 596–598.

Peterson, D.L.; Ryan, K.C. 1986. Modeling postfire conifer mortality for long-range planning. Environmental Management. 10(6): 797–808.

Peterson, J.L.; Ottmar, R.D. 1991. Computer applications for prescribed fire and air quality management in the Pacific Northwest. In: Andrews, P.L.; Potts, D.F., eds. Proceedings of the 11th conference on fire and forest meteorology. Boston, MA: American Meteorological Society: 455–459.

Prichard, S.J.; Ottmar, R.D.; Anderson, G.K. 2007. Consume 3.0 user's guide. Seattle, WA: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Pacific Wildland Fire Sciences Laboratory. 234 p. http://www.fs.fed.us/pnw/fera/research/smoke/consume/consume30_users_guide.pdf. (12 February 2015).

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

Ryan, K.C.; Reinhardt, E.D. 1988. Predicting postfire mortality of seven western conifers. Canadian Journal of Forest Research. 18: 1291–1297.

Stanek, W.; State, D. 1978. Equations predicting primary productivity (biomass) of trees, shrubs and lesser vegetation based on current literature. Victoria, B.C.: Environment Canada, Forestry Service, Pacific Forest Research Centre, BC-X, 183.

Van Wagner, C.E. 1973. Height of crown scorch in forest fires. Canadian Journal of Forest Research. 3: 373–378.

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

Van Wagner, C.E. 1987. Development and structure of the Canadian Forest Fire Weather Index System. Forestry Tech. Rep. 35. Ottawa, Canada: Canadian Forestry Service. 35 p. https://cfs.nrcan.gc.ca/publications?id=19927. (2 March 2015).

VEMAP Members. 1995. Vegetation/ecosystem modeling and analysis project: comparing biogeography and biogeochemistry models in a continental-scale study of terrestrial ecosystem responses to climate change and CO^2 doubling. Global Biogeochemical Cycles. 9(4): 407–437.

WeatherDisc Associates. 1995. World weatherDisc: climate data for planet earth. Seattle, WA: WeatherDisc Associates.

Weller, D.E. 1987. A reevaluation of the -3/2 power rule of plant self-thinning. Ecological Monographs. 57: 23–43.

Weller, D.E. 1989. The interspecific size-density relationship among crowded plant stands and its implications for the -3/2 power rule of self-thinning. The American Naturalist. 133: 20–41.

Appendix 1: Key Variables in MCFire Source Code

Key variables in MCFire source code are listed below, along with their dimensions (unless dimensionless), description, and the parts of this report where they are addressed.

Variable	Description
ad	Exponent in optimum reaction velocity calculation
b_eff	Exponent in wind effect multiplier calculation (eq. 65)
bark_thick	Stem bark thickness in centimeters (eq. 23)
bbl	Branch biomass in pounds or grams of dry matter per stem (eqs. 27, 29)
betop	Expression for optimum packing ratio (eq. 59)
betbar	Packing ratio (eq. 49)
bi	Burning index
blkc[fuelpool]	Percentage of black carbon produced from each fuel pool (eq. 90)
blkc_totbio	Black carbon produced by fire in grams per square meter
bnd_100	100-hour fuel moisture content boundary condition as a percentage (eq. 42)
bnd_1000[day]	1,000-hour fuel moisture content boundary condition as a percentage (eq. 42)
bnd_bar	Average of the 1000-hour fuel moisture boundary conditions for the previous week as a percentage
branch_frac	Branch biomass as a fraction of total aboveground biomass (eqs. 28, 32)
bsb	Stem bark biomass in grams of dry matter per stem (eq. 31)
bsw	Stem wood biomass in grams of dry matter per stem
bt	Bark thickness in centimeters
btt	Aboveground tree biomass in grams of dry matter per stem (eq. 26)
burn_day	Day of fire occurrence (Jan 1 = 0)
burn_day[day]	Fire occurrence (Boolean)
burn_mo[month]	Fire occurrence (Boolean)
burn_year	Fire occurrence (Boolean)
c	Parameter used to calculate diameter at breast height
c_1000hr	1,000-hour fuel consumed by the fire in tons of dry matter per acre (eq. 87)
c_100hr	100-hour fuel consumed by the fire in tons of dry matter per acre (eq. 83)
c_10hr	10-hour fuel consumed by the fire in tons of dry matter per acre (eq. 82)
c_1hr	1-hour fuel consumed by the fire in tons of dry matter per acre (eq. 81)
c_lbranch	Live branches fuel consumed by the fire in tons of dry matter per acre
c_lgrass	Live grass consumed by the fire in tons of dry matter per acre
c_lleaf	Tree leaves consumed by the fire in tons of dry matter per acre
c_var	Multiplicative factor in the wind-effect multiplier calculation (eq. 66)
cen_outvars[3]	Live-grass output from the MC1 biogeochemistry module in grams of carbon per square meter
cen_outvars[104]	Metabolic litter output from the MC1 biogeochemistry module in grams of carbon per square meter
cen_outvars[251]	Structural litter output from the MC1 biogeochemistry module in grams of carbon per square meter
cen_outvars[262]	Standing dead-grass output from MC1 biogeochemistry module in grams of carbon per square meter
cen_outvars[419]	Live fine-wood output from the MC1 biogeochemistry module in grams of carbon per square meter

Variable	Description
cen_outvars[445]	Woody-vegetation live-leaf output from the MC1 biogeochemistry module in grams of carbon per square meter
cen_outvars[452]	Live coarse-wood output from the MC1 biogeochemistry module in grams of carbon per square meter
cen_outvars[482]	Fine dead-wood output from the MC1 biogeochemistry module in grams of carbon per square meter
cen_outvars[483]	Coarse dead-wood output from the MC1 biogeochemistry module in grams of carbon per square meter
chi	Intermediate variable in firestart probability calculation (eq. 45)
ck	Fraction of crown volume killed (eq. 79)
cl	Crown length in meters (eq. 25)
cl_ratio	Crown length as a fraction of canopy height (table 7)
consume_dead	Dead fuels consumed by fire in grams of carbon per square meter
consume_live	Live fuels consumed by fire in grams of carbon per square meter
consume_totbio	All fuels consumed by fire in grams of carbon per square meter
consumed [fuelpool]	Percentage of each fuelpool consumed by the fire
cterm	Intermediate value in black carbon calculation
curr_fri	Current fire return interval in years (eq. 91)
d	Parameter used in the calculation of diameter at breast height (eq. 22, table 6)
d_1000hr	1,000-hour dead fuel in grams of dry matter per square meter
d_100hr	100-hour dead fuel in grams of dry matter per square meter
d_10hr	10-hour dead fuel in grams of dry matter per square meter
d_1hr	1-hour dead fuel in grams of dry matter per square meter
d1	Daily amount of 1-hour fuel in tons of dry matter per acre
d10	Daily amount of 10-hour fuel in tons of dry matter per acre
d100	Daily amount of 100-hour fuel in tons of dry matter per acre
d1000	Daily amount of 1,000-hour fuel in tons of dry matter per acre
daylit	Length of day in hours (eq. 11, fig. 3, table 3)
dbh	Diameter at breast height in centimeters (eq. 22)
dbh_in	Diameter at breast height in inches
dbh_max	Maximum diameter at breast height defined for deciduous or evergreen trees in centimeters (table 6)
death_stem	Carbon in stems killed by fire in grams per square meter
death_totbio	Carbon in woody vegetation killed by fire in grams per square meter
dedrt	Ratio of the surface area-weighted dead fuel moisture content to the moisture of extinction for dead fuels
dedrte	Ratio of the mass-weighted dead fuel moisture content to the moisture of extinction for dead fuels
depth[month]	Fuel-bed depth in meters, calculated on a monthly basis in accordance with the fuel loading algorithm (eq. 16)
depth[day]	Daily fuel-bed depth in feet, interpolated between monthly values for estimating fire behavior
depth_ratio	Ratio of fuel-bed volume to fuel mass in feet per tons of dry matter per acre (table 5)
dia_reduc	Reduction in diameters of large dead fuels in inches (eqs. 84, 85)
dstnd	Standing dead grass in grams of dry matter per square meter
dwod1	Fine dead wood in grams of dry matter and grams of carbon per square meter

Variable	Description
dwod2, dwod100	Coarse dead wood in grams of carbon per square meter
e_eff	Exponent in wind effect multiplier calculation (eq. 67)
em_ch4[day]	Methane emissions in grams per square meter
em_co[day]	Carbon monoxide emissions in grams per square meter
em_co2[day]	Carbon dioxide emissions in grams per square meter
em_nmhc[day]	Nonmethane hydrocarbon emissions in grams per square meter
em_pm[day]	Particulate emissions in grams per square meter
em_pm10[day]	Emissions from particulate ≤10 micrometers in grams per square meter
em_pm2p5[day]	Emissions from particulate ≤2.5 micrometers in grams per square meter
emc	Equilibrium moisture content as a percentage (eqs. 38 to 40; fig. 6)
emc_bar	Weighted 24-hour average equilibrium moisture content as a percentage (eq. 41)
emc_max	Minimum equilibrium moisture content as a percentage
emc_min	Maximum equilibrium moisture content as a percentage
erc	Energy release component in BTUs per square foot
EtaM()	Expression for moisture-damping coefficient
etamd	Moisture-damping coefficient for dead fuels for spread calculations (eq. 61)
etamde	Moisture-damping coefficient for dead fuels for energy release calculation as a fraction
etaml	Moisture-damping coefficient for live fuels for spread calculations
etamle	Moisture-damping coefficient for live fuels for energy release calculation as a fraction
etasd	Mineral-damping coefficient for dead fuels as a fraction
etasl	Mineral-damping coefficient for live fuels as a fraction (eq. 50)
event_erc	Energy release component in BTUs per square foot
event_fli	Fireline intensity in BTUs per square foot per second
event_lsh	Lethal scorch height in feet (Van Wagner 1973)
event_mc	1,000-hour fuel moisture content as a percentage
event_month	Month of fire (1 to 12)
event_pflamm	Probability of a fire starting as a percentage
event_ros	Rate of spread in feet per minute
f_dia_reduc	Diameter reduction from flaming combustion in inches
f_portion	Fraction of diameter reduction that is caused by flaming combustion
f1000e	Weighting factor for 1,000-hour dead fuel class as a fraction
f100e	Weighting factor for 100-hour dead fuel class as a fraction
f10e	Weighting factor for 10-hour dead fuel class as a fraction
f1e	Weighting factor for 1-hour dead fuel class as a fraction
factor	Drought factor in Keetch-Byram Drought Index calculations (eq. 12)
fc_1000hr	Flaming combustion from 1,000-hour fuel in tons of dry matter per acre (eq. 89)
fc_100hr	Flaming combustion from 100-hour fuel in tons of dry matter per acre (eq. 89)
fc_10hr	Flaming combustion from 10-hour fuel in tons of dry matter per acre
fc_1hr	Flaming combustion from 1-hour fuel in tons of dry matter per acre
fc_lbranch	Flaming combustion from live branches in tons of dry matter per acre
fc_lgrass	Flaming combustion from live grass in tons of dry matter per acre
fc_lleaf	Flaming combustion from live tree leaves in tons of dry matter per acre
fd	Depth of the flaming zone in feet (eq. 74)
fdeade	Weighting factor for dead fuel as a fraction
fef_ch4	Pounds of methane emitted per ton of fuel combusted (table 11)

Variable	Description
fef_co	Pounds of carbon monoxide emitted per ton of fuel combusted (table 11)
fef_co2	Pounds of carbon dioxide emitted per ton of fuel combusted (table 11)
fef_nmhc	Pounds of nonmethane hydrocarbons emitted per ton of fuel combusted (table 11)
fef_pm	Pounds of particulates emitted per ton of fuel combusted (table 11)
fef_pm10	Pounds of particulate ≤10 micrometers emitted per ton of fuel combusted (table 11)
fef_pm25	Pounds of particulate ≤2.5 micrometers emitted per ton of fuel combusted (table 11)
fem_ch4	Flaming emissions of methane in pounds per acre
fem_co	Flaming emissions of carbon monoxide in pounds per acre
fem_co2	Flaming emissions of carbon dioxide in pounds per acre
fem_nmhc	Flaming emissions of nonmethane hydrocarbons in pounds per acre
fem_pm	Flaming emissions of particulates in pounds per acre
fem_pm10	Flaming emissions of particulates ≤10 micrometers in pounds per acre
fem_pm25	Flaming emissions of particulate ≤2.5 micrometers in pounds per acre
fi	Fireline intensity in BTUs per foot per second
fii	Fireline intensity in kilowatts per meter
fl	Flame length in feet
fli_crit	Critical fireline intensity in kilowatts per meter (eq. 78)
fuel_depth	Fuel-bed depth in meters
gmamx	Maximum reaction velocity (eq. 57)
gmaop	Expression for optimum reaction velocity (eq. 58)
grass	Current moisture content of live grass as a percentage
h	Estimated heat of canopy ignition in kilojoules per kilogram (eq. 77)
hd	Dead fuel heat of combustion in BTUs per pound (table 9)
hk	Lethal scorch height in meters (eq. 79)
hl	Live fuel heat of combustion in BTUs per pound (eqs. 56, 72; table 9)
hn1	Heating number of 1-hour fuel (eq. 51)
hn10	Heating number of 10-hour fuel (eq. 51)
hn100	Heating number of 100-hour fuel (eq. 51)
hnherb	Heating number of live grass fuel (eq. 51)
hnwood	Heating number of live wood fuel (eq. 51)
ht	Canopy height in meters
ht_max	Maximum canopy height in centimeters (table 6)
htsink	Heat sink in BTUs per cubic foot of fuel (eq. 71)
Intensity()	Expression for reaction intensity in BTUs per foot per minute
ir	Reaction intensity for spread calculations in BTUs per square foot per minute (eq. 56)
ire	Reaction intensity for energy release calculations in BTUs per square foot per minute (eq. 72)
jdate	Julian date (January 1 = 1)
k	Thinning constant (table 6)
kbdi	Keetch-Byram Drought Index for the current day (eq. 13)
killed[]	Percent of live biomass pool killed by the fire
la	Leaf area in square meters per stem (eq. 21)
lat	Site latitude in degrees

Variable	Description
lbranch	Live branches in grams of dry matter per square meter (eq. 33)
	Live branches in tons of dry matter per square meter
	Live branches in grams of carbon per square meter
lgras	Live grass in grams of carbon per square meter
lgrass	Live grass in grams of dry matter per square meter
	Live grass in tons of dry matter per square meter
littr	Litter in grams of dry matter per square meter
	Litter in grams of carbon per square meter
livrt	Ratio of the surface-area weighted live-fuel moisture content to the moisture of extinction for live fuels
livrte	Ratio of the mass-weighted live-fuel moisture content to the moisture of extinction for live fuels
lleaf	Leaves of woody vegetation in grams of dry matter per square meter
	Leaves of woody vegetation in tons of dry matter per square meter
	Leaves of woody vegetation in grams of carbon per square meter
lstem	Stems of woody vegetation in grams of dry matter per square meter (eq. 34)
ltree	Live tree biomass in grams of dry matter per square meter (eq. 19)
lwod1	Live fine wood in grams of dry matter per square meter
	Live fine wood in grams of carbon per square meter
lwod100	Live coarse wood in grams of dry matter per square meter
lwod2	Live coarse wood in grams of carbon per square meter
lwood	Live wood in grams of dry matter per square meter
m_pet[month]	Monthly potential evapotranspiration in millimeters (table 3)
m_ppt[month]	Monthly precipitation in millimeters (table 3)
m_rh[month]	Monthly average relative humidity as a percentage (eq. 1)
m_rhmax[month]	Monthly maximum relative humidity a s percentage (eq. 3)
m_rhmin[month]	Monthly minimum relative humidity as a percentage (eq. 2)
m_tmax	Monthly maximum temperature in °C (table 3)
m_tmin	Monthly minimum temperature in °C (table 3)
m_tmp	Monthly average temperature in °C (table 3)
max_mfri	Maximum average fire return interval in years (table 1)
mc_1	Moisture content of 1-hour dead fuel class as a fraction (eq. 53)
mc_10	Moisture content of 10-hour dead fuel class as a fraction (eq. 53)
mc_100	Moisture content of 100-hour dead fuel class as a fraction (eq. 53)
mc_1000	Moisture content of 1,000-hour dead fuel class as a fraction (eq. 43)
mc_1000hr	Moisture content of 1,000-hour dead fuel class as a percentage (eq. 43)
mc_100hr	Moisture content of 100-hour dead fuel class as a percentage (eq. 53)
mc_10hr	Moisture content of 10-hour dead fuel class as a percentage (eq. 53)
mc_1hr	Moisture content of 1-hour dead fuel class as a percentage (eq. 53)
mc_duff	Moisture content of duff as a percentage
mc_grass[month]	Monthly moisture content of grass as a percentage
mc_grass[day]	Daily moisture content of grass as a fraction
mc_grass_max	Maximum moisture content of grass as a percentage (table 4)
mc_grass_min	Minimum moisture content of grass as a percentage (table 4)
mc_thres	1,000-hour fuel moisture content threshold as a percentage (table 4)
mc_tree[month]	Monthly moisture content of trees as a percentage
mc_tree[day]	Daily moisture content of trees as a percentage

Variable	Description
mc_tree_max	Maximum moisture content of trees and shrubs as a percentage (table 4)
mc_tree_min	Maximum moisture content of trees and shrubs as a percentage (table 4)
mclfe	Weighted dead-fuel moisture content for the live fuel moisture of extinction calculation as a fraction (eq. 53)
melt_b	Slope of snow melt equation in millimeters of water per °C
min_mfri	Minimum average fire return interval in years (table 1)
mlittr	Metabolic litter carbon in grams of dry matter per square meter
mxd	Moisture of extinction of dead fuels as a percentage (table 9)
	Moisture of extinction of dead fuels as a fraction (table 9)
mxf	Fraction of the moisture of extinction represented by the actual moisture content
mxl	Moisture of extinction of live fuels as a fraction (eq. 54)
no_melt	The temperature below which snow does not melt in °C (table 4)
p_flamm	The probability of a fire starting as a percentage (eq. 46)
Padj	Keetch-Byram Drought Index adjusted precipitation
Pann	Average annual precipitation in inches of water
part	Fraction of the cell area burned (eq. 92)
pct_of_max	Current moisture content as a percentage of the maximum moisture content (eq. 36)
pdsi	Current monthly value of the Palmer Drought Severity Index—standard deviation (tables 2, 4)
pdsi_max	Upper end of the Palmer Drought Severity Index range used to calculate *part*, above—standard deviation
pdsi_min	Lower end of the Palmer Drought Severity Index range used to calculate *part*, above—standard deviation
pdsi_thres	Palmer Drought Severity Index threshold for fire occurrence—standard deviation (table 4)
phislp	Slope effect multiplier (eq. 63)
phiwnd	Wind effect multiplier (eqs. 69, 70)
ppt[day]	Daily precipitation in millimeters of water
ppt_dur	Number of hours of rain in the day (eq. 7)
ppt_events	Number of days of rain in the month (eqs. 4, 5)
ppt_per_event	Precipitation per rain or snow event in millimeters of water (eq. 6)
ppt_rat[day]	Rainfall intensity in inches per hour
pptprd	Moisture availability ratio as a fraction
pr_frac	Packing ratio as a fraction of the optimum packing ratio as a fraction (eq. 60)
preburn_dia	Large dead wood diameter before fire in inches
prob_mort	Probability that the trees will be killed as a percentage (eq. 80)
prob_thres	Probability threshold used for decisions about fine-fuel flammability and tree mortality as a percentage (table 4)
qign	Heat of ignition in joules per gram (eq. 44)
QMD	Quadratic average diameter of 1,000-hour dead fuel before fire in inches
rand_seed	Seed for random number generator used to pick rain days
rh[day]	Daily average relative humidity as a percentage (eq. 1)
rh_corr	Value of relative humidity used in the calculation of dead fuel moisture content as a percentage
rhmax	Daily maximum relative humidity as a percentage
rhmin	Daily minimum relative humidity as a percentage
rhobar	Weighted fuel density in pounds of fuel per cubic foot

Variable	Description
rhobed	Bulk density of fuel bed in pounds of fuel per cubic foot (eq. 48)
rhod	Dead fuel particle density in pounds of fuel per cubic foot
rhol	Live fuel particle density in pounds of fuel per cubic foot
ros	Rate of spread in feet per minute (eq. 55)
sa1	Surface area of 1-hour dead fuel class in square feet of fuel per square foot of ground
sa10	Surface area of 10-hour dead fuel class in square feet of fuel per square foot of ground
sa100	Surface area of 100-hour dead fuel class in square feet of fuel per square foot of ground
sadead	Surface area of dead fuel in square feet of fuel per square foot of ground
saherb	Surface area of live grass fuel in square feet of fuel per square foot of ground
salive	Surface area of live fuels in square feet of fuel per square foot of ground
satot	Surface area of all fuels in square feet of fuel per square foot of ground
satvp()	Expression for saturated vapor pressure in pascals as a function of temperature
satvp_sacred [month]	Monthly saturated vapor pressure in pascals
sawood	Surface area of live shrub fuel in square feet of fuel per square foot of ground
sd	Silica-free mineral fraction of dead fuels
sef_ch4	Emissions of methane from smoldering combustion in pounds per ton (table 11)
sef_co	Emissions of carbon monoxide from smoldering combustion in pounds per ton (table 11)
sef_co2	Emissions of carbon dioxide from smoldering combustion in pounds per ton (table 11)
sef_nmhc	Emissions of nonmethane hydrocarbons from smoldering combustion in pounds per ton (table 11)
sef_pm	Emissions of particulates from smoldering combustion in pounds per ton (table 11)
sef_pm10	Emissions of particulates ≤10 micrometers from smoldering combustion in pounds per ton (table 11)
sef_pm25	Emissions of particulate ≤2.5 micrometers from smoldering combustion in pounds per ton (table 11)
sem_ch4	Methane produced by smoldering combustion in pounds per acre
sem_co	Carbon monoxide produced by smoldering combustion in pounds per acre
sem_co2	Carbon dioxide produced by smoldering combustion in pounds per acre
sem_nmhc	Nonmethane hydrocarbons produced by smoldering combustion in pounds per acre
sem_pm	Particulate produced by smoldering combustion in pounds per acre
sem_pm10	Particulate ≤10 micrometers produced by smoldering combustion in pounds per acre
sem_pm25	Particulate ≤2.5 micrometers produced by smoldering combustion in pounds per acre
sg1	Surface-to-volume ratio for 1-hour fuels in square meters per cubic meter (table 8)
sg10	Surface-to-volume ratio for 10-hour fuels in square meters per cubic meter (table 8)
sg100	Surface-to-volume ratio for 100-hour fuels in square meters per cubic meter (table 8)
sg1000	Surface-to-volume ratio for 1,000-hour fuels in square meters per cubic meter (table 8)

Variable	Description
sgbrde	Average surface-to-volume ratio for dead fuels in square meters per cubic meter
sgbrle	Average surface-to-volume ratio for live fuels in square meters per cubic meter
sgbrt	Average surface-to-volume ratio for all fuels in square meters per cubic meter, for rate of spread calculation
sgbrte	Average surface- to-volume ratio for all fuels in square meters per cubic meter, for energy release calculation
sgherb	Surface-to-volume ratio for live grass fuel in square meters per cubic meter (table 8)
sgwood	Surface-to-volume ratio for live shrub fuel in square meters per cubic meter (table 8)
sh	Lethal scorch height in feet (eq. 76)
sl	Silica-free mineral fraction of live fuels
slittr	Structural litter carbon in grams of dry matter per cubic meter
slp	Ground slope as a percentage (table 4)
slpfct	Slope effect multiplier coefficient (eq. 63)
snow[day]	Daily snowpack in millimeters of water (eq. 10)
snowfall[day]	Daily snowfall in millimeters of water (eq. 8)
snowmelt	Snow melt in the current day in millimeters of water (eq. 9)
snw0	The temperature above which all precipitation is rain in °C (table 4)
snw1	The temperature below which all precipitation is snow °C (table 4)
specific_area	Specific leaf area in square meters per gram of dry matter (table 6)
std	0.0555, the fraction of dead fuels made up of inert, noncombustible materials
stems	Number of stems per unit area (eq. 20)
stl	0.0555, the fraction of dead fuels made up of inert, noncombustible materials
stnd_clos	Stand closure fraction (eq. 18)
stress_pct	Vegetation water stress as a percentage
tau	Residence time of flaming front in minutes (eq. 73)
TCurr	Average temperature for the current day in °F
temp_corr	Daily temperature used in dead fuel moisture calculation in °F
thick_ratio	Ratio of bark thickness to diameter at breast height (table 7)
tmax[day]	Daily maximum temperature in °C
	Daily maximum temperature in °F
tmin[day]	Daily minimum temperature in °C
	Daily minimum temperature in °F
tmp[day]	Daily average temperature in °C
	Daily average temperature in °F
tot_c	Total combustion in tons of dry matter per acre
tot_dfuel	Total dead fuel in grams of dry matter per square meter (eq. 14)
tot_fc	Total flaming combustion in tons of dry matter per acre
tot_fuel_bed_bio	Total fuel-bed biomass in tons of dry matter per acre (eq. 15)
tot_incr	Adjustment in dead fuel mass when daily Keetch-Byram Drought Index is >100, in pounds of dry matter per square foot (eq. 47)
tot_sc	Total smoldering combustion in tons of dry matter per acre
tree	Current moisture content of live trees as a percentage
tree_ht	Canopy height in meters (eq. 24)
tree_lai	Tree leaf area index used in calculation of stand characteristics as a ratio (eq. 17)
uf	Unscorched fraction of the crown length as a fraction
ufact	Wind effect multiplier coefficient (eq. 68)

Variable	Description
v1	Volume of 1-hour dead fuel in cubic feet of fuel per square foot of ground
v10	Volume of 10-hour dead fuel in cubic feet of fuel per square foot of ground
v100	Volume of 100-hour dead fuel in cubic feet of fuel per square foot of ground
vclass	VEMAP2 vegetation class (VEMAP Members 1995)
vherb	Volume of live grass fuel in cubic feet of fuel per square foot of ground
vol_reduc	Reduction in volume of the 1,000-hour dead fuel as a fraction (eq. 86)
vpr_sacred[month]	Monthly average vapor pressure in pascals (table 2)
vwood	Volume of live wood fuel in cubic feet of fuel per square foot of ground
w10	Daily value of the amount of 10-hour dead fuel in grams of dry matter per square meter
	Daily value of the amount of 10-hour dead fuel in pounds of dry matter per square foot
w100	Daily value of the amount of 100-hour dead fuel in grams of dry matter per square meter
	Daily value of the amount of 100-hour dead fuel in pounds of dry matter per square foot
w1000	Daily value of the amount of 1,000-hour dead fuel in grams of dry matter per square meter
	Daily value of the amount of 1,000-hour dead fuel in pounds of dry matter per square foot
w100n	Daily net fuel loading of the 100-hour fuel class in pounds of dry matter per square foot
w10n	Daily net fuel loading of the 10-hour fuel class in pounds of dry matter per square foot
w1n	Daily net fuel loading of the 1-hour fuel class in pounds of dry matter per square foot
w1p	Daily value of the amount of 1-hour dead fuel in grams of dry matter per square meter
	Daily value of the amount of 1-hour dead fuel in pounds of dry matter per square foot
wdeadn	Net loading of dead fuels for spread calculation in pounds of dry matter per square foot
wdedne	Net loading of dead fuels for energy release calculation in pounds of dry matter per square foot
wherbn	Net fuel loading of live grass fuel in pounds of dry matter per square foot
wherbp	Daily value of the amount of live grass in grams of dry matter per square meter
	Daily value of the amount of live grass in pounds of dry matter per square foot
wliven	Net loading of live fuels for spread calculation in pounds of dry matter per square foot
wlivne	Net loading of live fuels for energy release calculation in pounds of dry matter per square foot
wndfac	Wind factor (table 9)
wrat	Ratio of dead-to-live fuel heating numbers (eq. 52)
ws	Wind speed in meters per second (table 2)
	Wind speed in miles per hour (table 2)
wtmcd	Surface-area weighted moisture content of dead fuels as a fraction
wtmcde	Mass-weighted moisture content of dead fuels as a fraction
wtmcl	Surface-area weighted moisture content of live fuels as a fraction

Variable	Description
wtmcle	Mass-weighted moisture content of live fuels as a fraction
wtot	Total fuel load in pounds of dry matter per square foot
wtotd	Total dead fuel load in pounds of dry matter per square foot
wtotl	Total live fuel load in pounds of dry matter per square foot
wwood	Live shrub wood fuel, currently set at zero in grams of dry matter per square meter
	Live shrub wood fuel, currently set at zero in pounds of dry matter per square foot
wwoodn	Net load of live shrub wood fuel in pounds of dry matter per square foot
ymc_100	Moisture content of 100-hour dead fuel for the previous day as a percentage
ymc_1000	Moisture content of 1000-hour dead fuel 7 days ago as a percentage
z	Distance from the ground to the bottom of the crown in meters
zeta	No-wind propagating flux ratio (eq. 62)

Appendix 2: MCFire Source Code Organization

This appendix provides additional information about the MCFire source code organization and structure. MCFire fire model is written in C programming language, and compiled with MC1 source code, and run as a submodel within MC1. The source code for MCFire is maintained in a version management system (also known as revision control system, or RCS). The source code file names and their version numbers that comprise the MCFire model at the initial draft of this report are listed in table 12. Model development has been and is ongoing, with code updates occurring frequently, causing the version number to evolve. However, the general organization of the code has remained stable.

Organization of MCFire Procedures

MCFire source code consists of nine primary procedures, which in turn call one or more secondary procedures (table 12). Secondary procedures can be called by one of the primary or secondary procedures. Although a procedure named "assign()" appears twice in table 12 and they appear to perform similar work, they are intended to be unique and operate distinctly.

Organization of MCFire Data

Variable declarations are structured to mirror the overall structure of the code. The source file mapss_types.h defines a data structure named DataInputs, which is used to pass data between the biogeochemistry module and the fire module and among the primary procedures of the fire module. Moreover, the conceptual namespaces associated with some of the primary procedures contain additional variable declarations. These variables are used to share data between a primary procedure and its associated secondary procedures (fig. 20).

The DataInputs structure itself includes six substructures, one containing variables required for saving internal MC1 components and restarting MC1, and the others containing data associated with particular primary procedures. Substructure fire_param is associated with ReadFireParams(). Substructure fire_state contains fire model variables required for saving internal MC1 components and restarting MC1. Substructure fire_data is associated with FireData(). Substructure fuel_data is associated with FuelLoad(), DFuelMC(), and LFuelMC(). Substructure fire_behav is associated with FireBehavior(). Substructure fire_eff is associated with FireEffect() and FireSched(). These substructures of DataInputs are not the same as the variables declared in the conceptual namespaces of the primary procedures.

Many variables contain amounts of fuel or biomass of various types. Table 13 lists these variables organized by conceptual types, to aid in reader understanding.

Table 12—Primary procedures, secondary procedures, and source files for the MCFire simulation model

Primary procedure	Description	Time step	Secondary procedure(s)	Source file (version)
ReadFireParams()	Reads parameter file	Once	None	fire_param.h (1.2),fir_params.c (1.6)
FireData()	Estimates daily weather variables from monthly climate data	Year	init1(), daily_ppt(), daily_dat(), snow_cond(), kbdi()	fire_data.h (1.3), fire_data.c (1.11)
DFuelMC()	Calculates moisture content of dead fuels	Year	init2(), cnvrt_units(), fuel_mc(), flammability(), min_mc_month()	dfuel_mc.h (1.4), dfuel_mc.c (1.9)
LFuelMC()	Calculates moisture content of live fuels	Month	live_mc()	lfuel_mc.h (1.2), lfuel_mc.c (1.4)
FuelLoad()	Calculates fuel load characteristics	Month	tree_dim(), live_wood(), dead_wood(), bed_deptth(), vveg2load()	fuel_load.h (1.4), fuel_load.c (1.2)
FireBehavior()	Calculates fire behavior, including rate of spread and reaction intensity	Month	init3(), get_jul(), get_daily(), assign(), prelim(), spread(), release(), intensity(), crown_fire(), vveg2fuel()	fire_behav.h (1.2), fire_behav.c (1.7)
FireEffect()	Calculates fire effects, including mortality, consumption, emissions, and black carbon production	Month	init4(), assign(), crown_kill(), mortality(), consump(), emissions(), vveg2emfac(), black_carbon()	fire_eff.h (1.2), fire_eff.c (1.6)
FireOccur()	Determines occurrence of fire	Month	None	fire_occur.c (1.6)
FireSched()	Calculates area burned	Fire onset occurs	part_burn(), ann_effect(), vveg_mfri()	fire_sched.h (1.2), fire_sched.c (1.5)

MC1 Invocation of MCFire

MC1 executes MCFire by calling sets of MCFire procedures. The calls to MCFire procedures take place in three locations in the source code, all within the mapss_1t() procedure in mapss_1t.c version 1.22 source file. They occur:

- At the beginning of the simulation, when MC1 calls ReadFireParams() to read the fire parameters

Secondary Procedures of the MCFire Source Code

Secondary procedures are listed below, along with their associated sections in this report. Secondary procedures are called by primary procedures or by other secondary procedures.

Procedure	Definition	File name	Calling procedure	Further described in
ann_effect()	Summarize fire effects	fire_sched.c	FireSched()	Appendix 2
bed_depth()	Calculate fuel-bed depth	fuel_load.c	FuelLoad()	Section 3
black_carbon()	Calculate fractions of fuels converted to black carbon	fire_eff.c	FireEffect()	Section 7
consump()	Calculate amounts of fuel consumed and vegetation killed	fire_eff.c	FireEffect()	Section 7
crown_fire()	Decide whether there is a crown fire	fire_behav.c	FireBehavior()	Section 6
crown_kill()	Calculate fraction of crown volume killed	fire_eff.c	FireEffect()	Section 7
daily_dat()	Construct daily climate variables (except precipitation) from monthly climate inputs	fire_data.c	FireData()	Section 2
daily_ppt()	Construct daily precipitation series from monthly precipitation amounts	fire_data.c	FireData()	Section 2
dead_wood()	Divide dead fuels into size classes	fuel_load.c	FuelLoad()	Section 3
emissions()	Calculate amounts of seven emissions (particulate matter, particulates <10 µm, particulates <2.5 µm, carbon monoxide carbon dioxide, methane, and nonmethane hydrocarbons)	fire_eff.c	FireEffect()	Section 7
flammability()	Calculate probability of fire start	dfuel_mc.c	DFuelMC()	Section 5
fuel_mc()	Calculate moisture content of dead fuels	dfuel_mc.c	DFuelMC()	Section 4
intensity()	Calculate fireline intensity and related measures	fire_behav.c	FireBehavior()	Section 6
live_mc()	Calculate moisture content of trees and grass	lfuel_mc.c	LFuelMC()	Section 4
live_wood()	Calculate live wood fuel class sizes	fuel_load.c	FuelLoad()	Section 3
mortality()	Decide whether the trees are killed	fire_eff.c	FireEffect()	Section 7
part_burn()	Calculate fraction of cell burned	fire_sched.c	FireSched()	Section 7
prelim()	Do preliminary calculations such as packing ratio and net fuel loading	fire_behav.c	FireBehavior()	Section 6
release()	Calculate reaction velocity and energy release	fire_behav.c	FireBehavior()	Section 6
snow_cond()	Determine snow, update snowpack	fire_data.c	FireData()	Section 2
spread()	Calculate rate of spread	fire_behav.c	FireBehavior()	Section 6
tree_dim()	Calculate stand characteristics	fuel_load.c	FuelLoad()	Section 3
vveg2emfac()	Look up emission factors based on vegetation class	fire_eff.c	FireEffect()	Section 7
vveg2load()	Look up fuel load factors based on vegetation class	fuel_load.c	FuelLoad()	Section 3

- In mapss_1d(), which is called by mapps_1t(), where two MCFire procedures are called—at the beginning of each simulated year, MC1 calls FireData() to estimate daily weather and DFuelMC() to calculate moisture content of dead fuels
- Also in the mapss_1d() procedure, where, for each simulated month, MC1 calls LFuelMC(), FuelLoad(), FireBehavior(), FireEffect(), FireOccur(), and FireSched(); these procedures calculate daily fuel conditions, fire behavior, fir effects, and fire occurrence (table 12).

FireBehavior() and FireEffect() are called even in months when no fire occurs. Although calls to these procedures are not strictly necessary, the procedures support possible future development of the fire occurrence algorithm that would rely on potential fire behavior (for example, the rate of spread).

MCFire Data Passed to MC1

When a fire is simulated, FireSched() and ann_effect() procedures pass data back to MC1 to characterize the fire event. MCFire calls the part_burn() procedure to determine the fraction of the cell that is affected by the event, and ensures that fire fluxes are scaled appropriately before transmittal to MC1. The fire event data, after scaling and aggregation, are stored in three data structures: *fire_behav* and *fire_eff* substructures within data_point structure and the *cen_state* array (table 14). The ann_effect() procedure performs postprocessing of the fire simulation results to format them for use by the MC1 biogeochemistry module.

Appendix 3: Revised Fire Occurrence Algorithm

In 2005, the fire occurrence algorithm was revised to use different thresholds for determining the day on which a fire will occur. The revised logic was introduced in revision 1.6 of fire_occur.c file, and remains in place with all subsequent revisions, including MC2—MC1 rewritten in C++ to improve computational efficiency. With the revised algorithm, fire still occurs in the month with the lowest 1000-hour fuel moisture content, but instead of using Palmer Drought Severity Index (Palmer 1965), the 1000-hour fuel moisture content (Fosberg et al. 1981), and fine-fuel flammability (Cohen and Deeming 1985) to determine whether fire occurs on a given day, MCFire uses a fine-fuel moisture code and build-up index from the Canadian Forest Fire Weather Index System (Van Wagner 1987). Fire occurs on the first day of the month when both the fine-fuel moisture code and build-up index exceed threshold values. In addition, only one fire is simulated per year per grid cell. The fine-fuel moisture code and build-up index threshold values are parameterized for the eight tree types simulated by MC1, within each climate zone delineated by MC1 (table 15).

```
BEGIN simulation
    READ fire parameters^a
    FOR each year to simulate
        CALL FireData() to estimate daily values of fire weather^a
            Estimate rainfall intensity
            CALL daily_ppt() to estimate daily precipitation amounts
            CALL daily_dat() to estimate other daily variables
            CALL snow_cond() to calculate snowpack and snowmelt
            CALL kbdi() to estimate Keetch-Byram Drought Index
        CALL DFuelMC() to estimate daily moisture content and flammability of dead fuels^a
            CALL fuel_mc() to estimate dead-fuel moisture
            CALL flammability() to calculate flammability of fine fuels
            CALL min_mc_data() to find the month with the minimum 1,000-hour fuel moisture content
        FOR each month of the year
            CALL LFuelMC() to estimate moisture content of live fuels^a
                CALL live_mc() to estimate live-fuel moisture.
            CALL FuelLoad() to estimate live and dead fuel loading^a
                CALL vveg2load() to get vclass-dependent parameters
                IF trees are included in fuel load
                    CALL tree_dim() to estimate diameter at breast height and height
                    CALL live_wood() to estimate loads of live branch and stem wood classes
                END IF
                IF dead fuels are included in fuel load
                    CALL dead_wood() estimate loads of dead-fuel classes
                END IF
                CALL bed_depth() to calculate fuel bed depth
            CALL FireBehavior() to estimate fire behavior^a
                FOR each day of the month
                    CALL prelim() to perform calculations common to other functions
                    CALL spread() to calculate rate of spread
                    CALL release() to calculate energy release
                    CALL intensity() to calculate fireline intensity
                    CALL crown_fire() to determine if crown fire would occur
                END FOR
            CALL FireEffect() to estimate fire effects^a
                FOR each day of the month
                    CALL vveg2emfac() to get emission factors for current vegetation
                    CALL crown_kill() to calculate percentage of crown killed
                    CALL mortality() to determine tree mortality
                    CALL consump() to calculate carbon consumed by fire
                    CALL emissions() to calculate emissions
                    CALL black_carbon() to calculate carbon conversion to black carbon
                END FOR
            CALL FireOccur() to determine whether to simulate fire, and, if so, the day of occurrence^a
            CALL FireSched() to apply the effects of a fire^a
            IF a fire occurred this month
                CALL part_burn() to calculate area burned
                Scale emissions to area burned
                Scale mortality and consumption fluxes to area burned
                CALL ann_effect() to record fire effects
            END IF
        END FOR each month of the year
    END FOR each year to simulate
END simulation
```

[a] = Primary procedure.

Figure 20—Pseudocode of MCFire showing the general structure of the MCFire algorithm.

Table 13—MCFire variables organized by concept; note that the dimension of some variables are metric and the dimension of the other variables are in Imperial units

Conceptual type	Variable	Description	Dimension
Incoming MC1 carbon pools (monthly)	*aglivc*	Aboveground live grass	Grams of carbon per square meter
	rleavc	Leaves of woody vegetation	Grams of carbon per square meter
	fbrchc	Fine branches of woody vegetation	Grams of carbon per square meter
	rlwodc	Coarse branches and boles of woody vegetation	Grams of carbon per square meter
	metabc_1	Metabolic carbon in litter	Grams of carbon per square meter
	strucc_1	Structural carbon in litter	Grams of carbon per square meter
	stdedc	Standing dead grass	Grams of carbon per square meter
	wood1c	Fine dead wood	Grams of carbon per square meter
	wood2c	Coarse dead wood	Grams of carbon per square meter
MCFire carbon pools (monthly)	*lgras*	Corresponds to *aglivc*	Grams of dry matter per square meter
	lleaf	Corresponds to *rleavc*	Grams of dry matter per square meter
	lwod1	Corresponds to *fbrchc*	Grams of dry matter per square meter
	lwod100	Corresponds to *rlwodc*	Grams of dry matter per square meter
	lwood	= *lwod1* + *lwod100*; not in fire_sched.c	Grams of dry matter per square meter
	lbranch	= *branch_frac* × *lwood*; not in fire_sched.c	Grams of dry matter per square meter
	ltree	= *lleaf* + *lwod1* + *lwod100*; not in fire_sched.c	Grams of dry matter per square meter
	mlittr	Corresponds to *metabc_1*	Grams of dry matter per square meter
	slittr	Corresponds to *strucc_1*	Grams of dry matter per square meter
	littr	= *mlittr* + *slittr*	Grams of dry matter per square meter
	dstnd	Corresponds to *stdedc*	Grams of dry matter per square meter
	dwod1	Corresponds to *wood1c*	Grams of dry matter per square meter
	dwod2, dwod100	Correspond to *wood2c*	Grams of dry matter per square meter
	tot_dfuel	= *littr* + *dstnd* + *dwod1* + *dwod100*	Grams of dry matter per square meter
MCFire fuel pools (monthly)	*l_1hr, lgrass*	Correspond to *lgras* above	Grams of dry matter per square meter
	d_1hr	*frac_1hr* of *tot_dfuel*	Grams of dry matter per square meter
	d_10hr	*frac_10hr* of *tot_dfuel*	Grams of dry matter per square meter
	d_100hr	*frac_100hr* of *tot_dfuel*	Grams of dry matter per square meter
	d_1000hr	*frac_1000hr* of *tot_dfuel*	Grams of dry matter per square meter
	lgrass	Monthly, converted from *lgrass* in grams of dry matter per square meter above	Tons of dry matter per acre
	lleaf	Monthly, converted from *lleaf* in grams of dry matter per square meter above	Tons of dry matter per acre
	lbranch	Monthly, converted from *lbranch* in grams of dry matter per square meter above	Tons of dry matter per acre
MCFire daily fuel pools (daily)	*wherbp, wherbn*	Corresponds to *lgras*	Grams of dry matter per square meter
	wwood, wwoodn	0	Grams of dry matter per square meter
	w1p, w1n	Corresponds to *d_1hr*	Grams of dry matter per square meter
	w10, w10n	Corresponds to *d_10hr*	Grams of dry matter per square meter
	w100, w100n	Corresponds to *d_100hr*	Grams of dry matter per square meter
	w1000	Corresponds to *d_1000hr*	Grams of dry matter per square meter
	d1	Daily, converted from *w1p*	Tons of dry matter per acre
	d10	Daily, converted from *w10*	Tons of dry matter per acre
	d100	Daily, converted from *w100*	Tons of dry matter per acre
	d1000	Daily, converted from *w1000*	Tons of dry matter per acre

MCFire calculates fine-fuel moisture daily, closely following Van Wagner (1987). The fine-fuel moisture code is a dimensionless value ranging from 0 to 101, representing the moisture conditions of the litter layer on a given day. It is calculated as a function of the litter layer's moisture content (percent) that is computed in one of three ways on a given day: under a drying regime, under a wetting regime, or under neither regime. To determine which regime is in place, MCFire calculates a drying equilibrium and a wetting equilibrium of moisture content, both calculated from the relatively humidity and temperature on the day in question. If the drying equilibrium for that day is lower than the moisture content of the previous day,

Table 14—Structures, each with multiple variables, used for passing MCFire data to MC1; note that the data structure cen_state is directly used by MC1's biogeochemistry module

Data structure	Variable	Value	Corresponding variable in MC1 biogeochemistry module
fire_behav	*burn_mo[burn_month]*	true	None
	burn_yr	true	None
	burn_day[burn_month]	burn_day	None
	event_ros	ros	None
	event_mc	mc_1000hr	None
	event_pflamm	p_flamm	None
	event_kbdi	kbdi	None
	event_erc	erc	None
	event_fli	fli	None
	event_lsh	lsh	None
	event_month	burn_month	None
fire_eff	*em_co2[burn_day]*	—[a]	None
	em_co[burn_day]	—[a]	None
	em_ch4[burn_day]	—[a]	None
	em_nmhc[burn_day]	—[a]	None
	em_pm[burn_day]	—[a]	None
	em_2p5[burn_day]	—[a]	None
	em_10[burn_day]	—[a]	None
	consume_totbio	—[a]	None
	consume_live	—[a]	None
	consume_dead	—[a]	None
	blkc_totbio	—[a]	None
	death_totbio	—[a]	None
	death_stem	—[a]	None
cen_state	*cen_state[0]*	consume[1] × pb	frac live leaf consumed, REMF(1)
	cen_state[1]	consume[2] × pb	frac live fine branch consumed, REMF(2)
	cen_state[2]	consume[2] × pb	frac live large wood consumed, REMF(3)
	cen_state[3]	consume[3] × pb	frac dead fine branch consumed, REMF(4)
	cen_state[4]	consume[5] × pb	frac dead large wood consumed, REMF(5)
	cen_state[5]	consume[0] × pb	frac live grass consumed, FLFREM
	cen_state[6]	consume[3] × pb	frac dead standing fuel consumd FDFREM(1)
	cen_state[7]	consume[3] × pb	frac litter consumed, FDFREM(2)
	cen_state[8]	turnover[0] × pb	live leaf turnover rate from fire, LEAFDR(MO)
	cen_state[9]	turnover[1] × pb	live fine branch turnover rate from fire, WOODDR(3)
	cen_state[10]	turnover[2] × pb	live coarse wood turnover rate from fire, WOODDR(4)
	cen_state[11]	rootd × pb	fine roots killed, FD(1)
	cen_state[12]	rootd × pb	coarse roots killed, FD(2)
	cen_state[13]	true	fire signal, DID_BURN

[a] Fire effects are scaled by the burned area (*pb*).

moisture content is calculated by applying a drying rate—calculated from relative humidity, temperature, and wind speed—to the moisture content of the previous day. If the moisture content of the previous day is lower, then a wetting rate—calculated from relatively humidity and wind speed—is applied to the moisture content. If the moisture content of the previous day is between the drying equilibrium and a wetting equilibrium, then moisture content is assumed to be the same as moisture content for the previous day.

MCFire accounts for the effect of rainfall on moisture content as modeled by Van Wagner (1987): it assumes 0.5 mm of rain is intercepted by the canopy, and applies the remainder to increase the moisture content of the litter layer. MCFire uses the empirical formula from Van Wagner (1987) to calculate the rate at which rainfall increases moisture content. As the rainfall amount or the current moisture content increases, less rainfall is held by the litter.

MCFire also calculates the build-up index daily, closely following Van Wagner (1987). The build-up index is a dimensionless value representing total fuel available to a flaming front, ranging from 0 to 281 (fig. 21). The build-up index is a harmonic average of the duff moisture code and the drought code, both computed daily. The duff moisture code is an index of the moisture content of the duff layer, ranging from 0 to 250. It is calculated as a log function of the moisture content (percent). If rainfall is ≤1.5 mm on a given day, moisture content is initially the same as the duff moisture code for the previous day; on the first day simulated, MCFire assumes that the duff moisture code for the previous day is 6. If rainfall >1.5 mm, higher moisture content is calculated as a function of the duff moisture code from the previous day and that the rainfall amount for the previous day is >1.5 mm. In either

Table 15—Fine-fuel moisture code and build-up index thresholds, used to by MCFire determine occurrence of fire on a given day for each tree type that MC1 simulates and for each climate zone and variable that MC1 defines

		Tree type[a]							
Threshold	**Climate zone**	**EN**	**EN-DB**	**DB**	**DB-EB**	**EN-EB**	**EB**	**DN**	**DN-EN**
Fine-fuel moisture code	Arctic	94	94	94	94	94	94	94	94
	Boreal	83.95	92	92	87	91.42	91.42	83.95	83.95
	Temperate	89.13744	92	92	87	91.42	91.42	89.13744	89.13744
	Subtropical	89.13744	92	92	87	91.42	91.42	89.13744	89.13744
	Tropical	89.13744	92	92	87	91.42	91.42	89.13744	89.13744
Build-up index	Arctic	147	147	147	147	147	147	147	147
	Boreal	38.2	150	150	110	223.11	223.11	38.2	38.2
	Temperate	245	150	150	110	223.11	223.11	245	245
	Subtropical	245	150	150	110	223.11	223.11	245	245
	Tropical	245	150	150	110	223.11	223.11	245	245

[a] Evergreen (E), needleleaf (N), deciduous (D), and broadleaf (B).

circumstance, the initial moisture content is reduced using a drying rate, calculated from temperature, humidity, and day length.

Drought code is an index of very slow drying moisture in the system, ranging from 0 to 800. The overall logical structure of drought code calculation is similar to that for the duff moisture code. On a given day, if rainfall is ≤2.8 mm, moisture content for the day is initially the same as the drought code for the previous day; on the first day simulated, MCFire assumes that the drought code for the previous day is 15. If rainfall on that day is >2.8 mm, a higher moisture content is calculated as a function of the drought code and effective rainfall for the previous day. In either circumstance, the initial moisture content is reduced using a drying rate, calculated from temperature and day length.

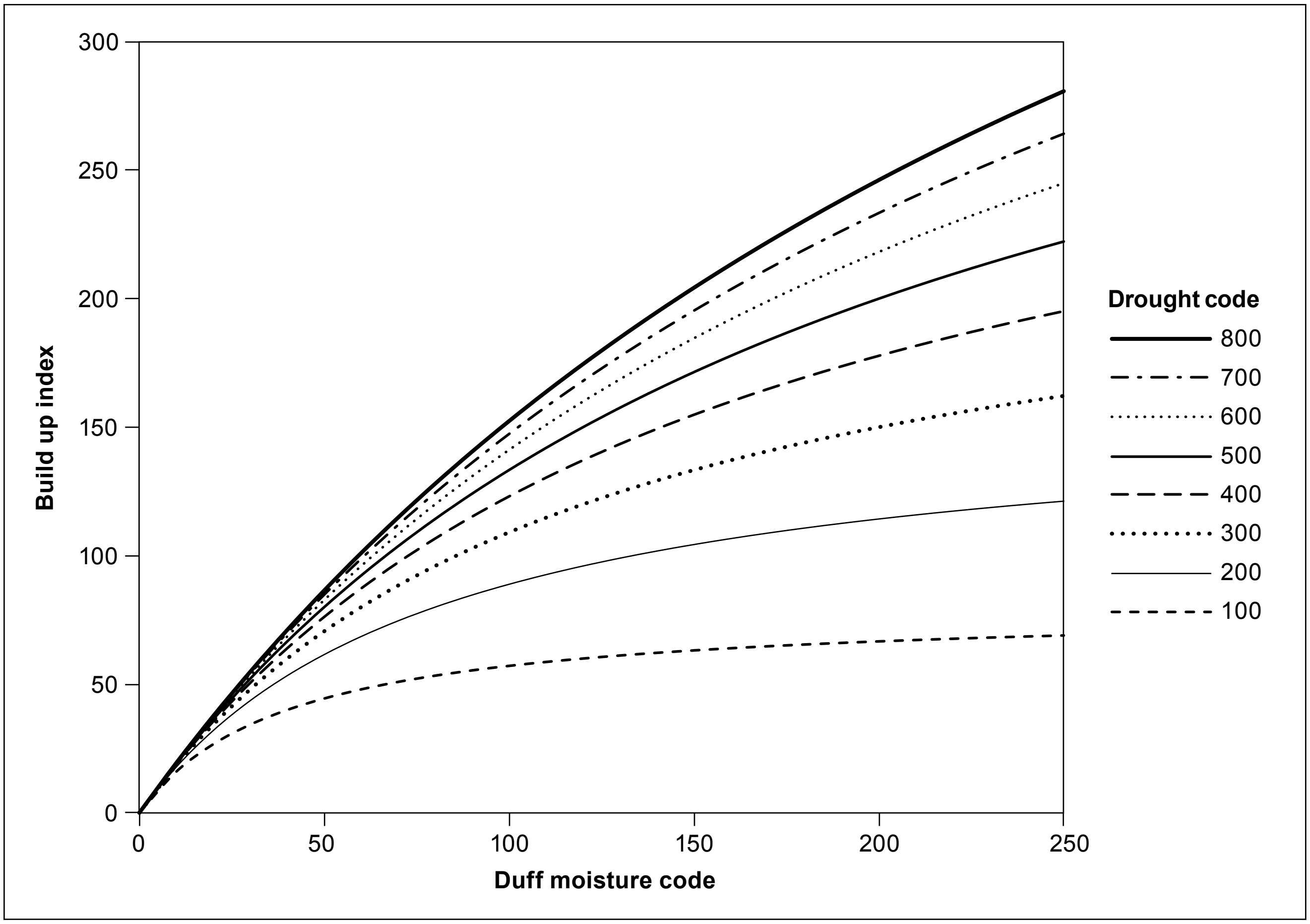

Figure 21—Build-up index plotted as a function of duff moisture code, for selected values of drought code; the index, a dimensionless value representing total fuel available to a flaming front ranging from 0 to 281, is a harmonic average of duff moisture code and drought code, both computed daily.

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