P5.2

USING FOFEM 5.0 TO ESTIMATE TREE MORTALITY, FUEL CONSUMPTION, SMOKE PRODUCTION AND SOIL HEATING FROM WILDLAND FIRE

Elizabeth Reinhardt*
USDA Forest Service
Missoula Fire Sciences Lab, Missoula, MT

1. INTRODUCTION

FOFEM 5.0 (**First Order Fire Effects Model**) is a computer program that was developed to meet needs of resource managers, planners, and analysts in predicting and planning for fire effects. FOFEM predicts tree mortality from surface fire, based on flame length or scorch height, and tree species and size. It predicts consumption of down woody fuels by size class, and the resultant fire intensity over time using the BURNUP model. It predicts emissions (and emission rate) of PM10, PM2.5, CO, CO_2, CH_4, NO_X and SO_2 by flaming and smoldering combustion. It predicts soil heating at a range of soil depths over time since ignition.

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

FOFEM can be used in a variety of situations. Examples include: setting acceptable upper and lower fuel moistures for conducting prescribed burns; determining the number of acres that may be burned on a given day without exceeding particulate emission limits; assessing effects of wildland fire; developing timber salvage guidelines following fire; and comparing expected outcomes of alternative actions. It has been incorporated in several analysis packages including BlueSky and SIS (Smoke Impact Spreadsheet) for modeling smoke dispersion, and FIREHARM, a landscape fire hazard assessment model.

*Author address: Elizabeth Reinhardt, Missoula Fire Sciences Lab, P.O. Box 8089, Missoula, MT 59807

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

Realistic default values have been provided for many inputs, minimizing the data required. These defaults were derived from a variety of research studies. Any of these default values can be overridden by the user, allowing the use of this program at different levels of resolution and knowledge. FOFEM 5.0 has a user interface that allows the user to choose or alter inputs, make runs and file output. It also exists in batch mode suitable for incorporating in other software products, linking to GIS, or for making large numbers of runs.

2. FUEL LOADS

Default fuel loads by fuel component are always provided by FOFEM. These loads depend on cover type and on fuel type (natural or slash fuels). These default loads can be adjusted (using the typical, light, heavy adjustment buttons) or replaced. It is always good to enter fuel loadings directly if you have a good estimate, since fuels vary greatly within cover type.

To provide default fuel loads, an exhaustive search of fuels literature was conducted. The resulting database (Mincemoyer 2002) is posted at www.fire.org and is a major component of FOFEM. However, FOFEM can be used without relying on this data at all, if preferred.

3. TREE MORTALITY

Tree mortality in FOFEM is computed using the algorithm developed by Ryan and Reinhardt (1988). It uses bark thickness and percent crown volume scorched as predictive variables (figure 1). This method implicitly assumes that variations in fire-caused tree mortality in trees of different species and sizes can be accounted for primarily by differences in bark thickness and proportion of crown killed. This assumption, while undoubtedly extremely simplistic, allows us to predict mortality for trees of any species and size. Bark thickness is computed from species and diameter, and crown volume scorch is computed from scorch height, tree height and crown base height. To predict tree mortality, users enter a tree list or stand table describing species, diameter, height, crown ratio and trees per acre.

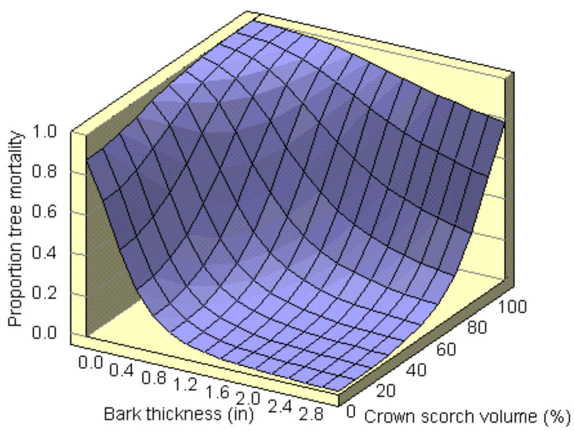

Figure 1. Tree mortality increases with increasing crown scorch and decreases with increasing bark thickness.

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

The data from which the tree mortality algorithm was developed was limited to western conifers greater than 5 inches dbh underburned with prescribed fire. The predictions should apply reasonably well to wildfires. Some post fire insect damage is implicitly included in these predictions, as trees damaged by insects after burning were not excluded from the data. Major post fire insect attacks are not modeled however. Root damage is not explicitly modeled, although it may be correlated with cambial damage in many cases. Several tree mortality studies have found the FOFEM predictions to be robust and reasonably accurate (Ryan and Amman 1993, Ryan and others 1993, Weatherby and others 1994).

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

4. FUEL CONSUMPTION

FOFEM predicts the quantity of fuel consumed by prescribed fire or wildfire (figure 2). Fuel components include duff, litter, 0-1/4 inch, ¼-1 inch, 1-3 inch, 3 inch plus dead woody fuels (sound and rotten), herbaceous fuels, shrubs, and canopy fuels affected by crown fire. Mineral soil exposed by fire as a result of duff and litter consumption is also predicted (figure 2).

FUEL CONSUMPTION TABLE

Fuel Component Name	Preburn Load (t/acre)	Consumed Load (t/acre)	Postburn Load (t/acre)	Percent Reduced (%)	Equation Reference Number	Moisture (%)
Litter	0.60	0.60	0.00	100.0	999	
Wood (0-1/4 inch)	0.23	0.23	0.00	100.0	999	
Wood (1/4-1 inch)	0.67	0.67	0.00	100.0	999	25.0
Wood (1-3 inch)	0.80	0.58	0.22	72.4	999	
Wood (3+ inch) Sound	6.30	1.01	5.29	16.0	999	20.0
Wood (3+ inch) Rotten	0.70	0.22	0.48	31.3	999	20.0
Duff	10.00	4.11	5.89	41.1	2	100.0
Herbaceous	0.20	0.20	0.00	100.0	22	
Shrubs	0.35	0.21	0.14	60.0	23	
Crown foliage	6.00	0.00	6.00	0.0	37	
Crown branchwood	3.00	0.00	3.00	0.0	38	
Total Fuels	28.85	7.82	21.03	27.1		

FIRE EFFECTS ON FOREST FLOOR COMPONENTS

Duff Depth Consumed (in)	0.4	Equation: 6
Mineral Soil Exposed (%)	21.9	Equation: 10

Figure 2. An example of the FOFEM fuel output report.

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

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

4.1 Litter

The consumption of litter is calculated by Burnup. Generally 100% of the litter is consumed.

4.2 Duff

A number of different duff consumption algorithms are incorporated into FOFEM. Separate predictions are made of percent duff consumption and duff depth consumed. Algorithms were taken from (Brown and others 1985, Harrington 1987, Hough 1978, Reinhardt and others 1991).

4.3 Herbaceous

Herbaceous fuels generally are a small component of the total fuel load. However, for completeness, especially in modeling emission production, their consumption is computed by FOFEM. Generally, all the herbaceous fuels are assumed to burn. If the cover type is a grass type, and the season of burn is spring, only 90% of the herbaceous fuels are consumed.

4.4 Shrubs

Shrub consumption is modeled with rules of thumb that will eventually be replaced when more shrub consumption work is available. The rules of thumb can be summarized as follows:

If the cover type is sagebrush and the season is fall, shrub consumption is 90%, for all other seasons 50%.

For the southeastern region, for the pocosin cover type, in spring or winter shrub consumption is 90%, in summer or fall 80%.

For non-pocosin types in the southeast, Hough’s (1968, 1978) research was used to predict shrub consumption. For other cover types dominated by shrubs (except in the southeast), shrub consumption is assumed to be 80%.

For other cover types dominated by shrubs, shrub consumption is assumed to be 80%.

For cover types not dominated by shrubs, shrub consumption is set to 60%.

4.5 Canopy Fuels

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

4.6 Fuel Moisture

Fuel moistures can be entered directly for duff, 10- hour (1/4-1 inch) woody fuel, and 3+ inch woody fuel. Users can also select very dry, dry, moderate or wet burn conditions to have these moisture contents set by default. For duff moisture, users can enter entire duff moisture content, lower duff moisture content, NFDR 1000 hour index values, or adjusted NFDR 1000 hour values (Ottmar and Sandberg 1983). If you want to set fuel moistures for all woody fuel size classes, or separately for sound and rotten fuels, you can run Burnup from an input file, bypassing the FOFEM user interface.

4.7 Burnup

Burnup is a physical model of heat transfer and burning rate of woody fuel particles as they interact over the duration of a burn (Albini and Reinhardt, 1995, 1997; Albini and others 1995). Duff consumption rate is assumed to be constant (Frandsen 1991). Duff consumption amount is computed as described above, depending on cover type and duff moisture. Duff consumption duration is computed from total consumption and consumption rate. At each time step, fuel consumption of each woody fuel size class is determined by modeling the heat transfer at intersections with other fuel particles and with the duff. Fire intensity is derived from the combustion of fuels in each time step. This in turn determines fuel temperature and combustion rate in the following time step. Typically intensity increases after ignition, as combustion of the finest fuels produces heat which ignites progressively larger and wetter fuels. As smaller fuels burn up, intensity begins to drop. The fire is assumed to go out when the overall fire intensity is too low to sustain further combustion. Burnup thus provides estimates of total fuel consumption by size class, and also of consumption rate and fire intensity over time.

5. SMOKE EMISSIONS

The Burnup model was modified (Finney 2001) to provide separate estimates of flaming and smoldering consumption in each time step for each fuel component by assuming that flaming combustion cannot be sustained below an intensity of about 15 kW/m^2. Since Burnup computes a local intensity at the point of intersection of fuels, flaming and smoldering combustion can be simulated simultaneously – i.e. at fuel concentrations flaming combustion may occur in the same time step that smoldering combustion is occurring in the duff or in isolated woody fuels.

By distinguishing fuel weight consumed in flaming and smoldering phases of combustion, the Burnup model allows emission factors to be applied separately to the fuel consumed in each phase. Emission factors for particulate and chemical emission species (Ward et al. 1993) were applied to the fuel consumed in flaming and smoldering combustion assuming the values of combustion efficiencies of 0.95 for flaming and 0.75 for smoldering. Thus, unit average combustion efficiency changes over the duration of a burn. Total emissions are the sum of the emissions calculated separately from fuel weight consumed in flaming and smoldering.

In the Smoke Emissions Report produced by FOFEM, total emissions of PM2.5, PM10, CH4, CO, CO2, NOx and SO_2 are listed, as well as burn duration. If desired burn intensity and emissions over time can be simulated. This information (figure 3) is suitable for use in predicting smoke dispersion.

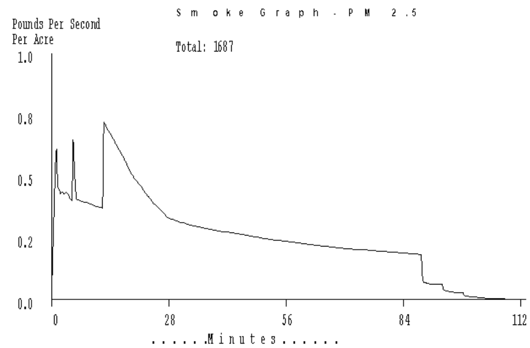

Figure 3. An example of emissions production over time as predicted by FOFEM.

6. SOIL HEATING

Smoldering duff fires involve the pyrolysis and oxidation of tightly packed fuel materials on the forest floor. Spread rates of these duff fires are slow; three orders of magnitude slower than flaming (Hungerford et al. 1991). Temperatures of burning duff are also lower than flaming temperatures, but heating of deep soil layers by duff fires is often greater because of the intimate contact of the fire with the mineral soil surface and the long duration of the fire.

The soil heating model was developed at the Rocky Mountain Research Station Fire Sciences Laboratory in a joint effort with Dr. Gaylon S. Campbell and staff at Washington State University. The model has been thoroughly tested and refined both in the field and in the laboratory and is able to predict soil temperature reliably, whatever the moisture, density, or mineralogy of the soil might be.

The soil heating model has been set up so that heat from the surface fire, as modeled in predicting fuel consumption, is used as the source of soil heat. Heat production rate and duration are important. If there is duff, the model assumes that duff is the source of the soil heat; if not, other fuels drive the soil heating model.

The results of each soil heating run can be viewed in either graphical or report form. The graphical format (figure 4) plots temperature in Celsius versus time in minutes and allows for scaling adjustments along the x and y-axis. The graph displays temperature at each depth and highlights temperatures that exceed 60 degrees Celsius. This temperature is often referred to as the lethal temperature for living organisms; therefore it is highlighted to allow the user to identify which burning scenarios exceed this temperature at various depths beneath the soil surface. The default lethal temperature for each graphical output is set for 60°C, but the user can change this for each plot setup simply by typing in the desired temperature. The graphical output also includes the maximum temperature reached at the soil surface, amount of duff consumed, soil type, and starting soil moisture.

Users can also view the output of each soil heating simulation in report form. The report form contains everything that the graphical format contains, but also includes a complete summary of the FOFEM pre-burn and post-burn conditions. This option is useful for comparing several scenarios against one another.

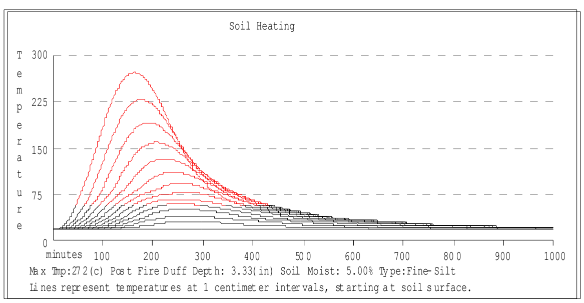

Figure 4. An example of FOFEM's soil heating predictions. Each line represents a different depth below the soil surface.

It is worth noting that the soil heating model in FOFEM predicts various fire effects on a stand level scale, but the reality is that soiling heating will vary in a mosaic pattern throughout a burn unit. Fires often burn at varying intensities and spread rates depending on a wide range of variables and the corresponding soil heating will vary equally as much. In FOFEM we attempt to predict expected average soil heating across a user specified unit.

7. CONCLUSIONS

FOFEM 5.0 is a versatile, simple program for predicting first order fire effects. It has been widely used in project planning, environmental assessment, and broad scale analysis.

8. CITATIONS

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

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

Albini, F.A.; Reinhardt, E.D. Improved Calibration of a Large Fuel Burnout Model. International Journal of Wildland Fire 7(1): 21- 28, 1997.

Brown, J.K., Marsden, M.M., Ryan, K.C., Reinhardt, E.D. 1985. Predicting duff and woody fuel consumed by prescribed fire in the northern Rocky Mountains. USDA Forest Service Res. Pap. INT-337.

Campbell, G.S. Simulation of soil heating under smoldering duff fires. Unpublished report on file at the Missoula Fire Sciences Lab.

Campbell, G.S., J.D. Jungbauer, Jr., S. Shiozawa, and R.D. Hungerford. 1993. A one-parameter equation for water sorption isotherms of soils. Soil Science 156(5): 302-305.

Campbell, G.S., J.D. Jungbauer, Jr., W.R. Bidlake, and R.D. Hungerford. 1994. Predicting the effect of temperature on soil thermal conductivity. Soil Science 158(5): 307-313.

Campbell, G.S., J.D. Jungbauer, Jr., K.L. Bristow, and R.D. Hungerford. 1995. Soil temperature and water content beneath a surface fire. Soil Science 159(6): 363-374.

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

Frandsen, W.H. 1991. Heat evolved from smoldering peat. International Journal of Wildland Fire 1:197-204.

Frandsen, W.H. 1991. Smoldering spread rate: a preliminary estimate. 1991. Proceedings of the 11th Conference on Fire and Forest Meteorology, pp 168-172.

Hardy, C.C., Burgan, R.E., Ottmar, R.D., Deeming, J.C. 1996. A database for spatial assessments of fire characteristics, fuel profiles, and PM10 emissions. Unpublished paper on file at USDA Forest Service, Missoula Fire Sciences Laboratory, Missoula, MT.

Harrington, M.G. 1987. Predicting reduction of natural fuels by prescribed burning under ponderosa pine in southeastern Arizona. USDA Forest Service Res. Note RM-472.

Hough, W.A. 1968. Fuel consumption and fire behavior of hazard reduction burns. USDA Forest Service Res. Pap. SE-36.

Hough, W.A. 1978. Estimating available fuel weight consumed by prescribed fires in the south. USDA Forest Service Res. Pap. SE-187.

Hungerford, R.D. 1996. personal communication.

Hungerford, R.D., M.G. Harrington, W.H. Frandsen, K.C. Ryan, and G.J. Niehoff. 1991. Influence of fire on factors that affect soil productivity. U.S. Forest Service Intermountain Research Station General Technical Report INT-280.

Lutes, D. 2001. Diameter bark thickness relationships. Unpublished report on file at the Missoula Fire Science Lab.

Mincemoyer, S. 2002.

Ottmar, R.D., Sandberg, D.V. 1983. Estimating 1000-hour fuel moistures in the Douglas fir subregion. In: Proceedings of the 7th conference on fire and forest meteorology; Fort Collins, CO: 22-26.

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

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

Reinhardt, E.D.; K.C. Ryan. 1988. How to estimate tree mortality resulting from under burning. Fire Management Notes 49(4):30-36.

Ryan, K.C.; Amman, G.D. 1993. Interactions between fire-injured trees and insects in the greater Yellowstone Area. In: Plants and their Environments: Proceedings of the First Biennial Acientific Conference on the Greater Yellowstone Ecosystem, Technical Report NPS/NRYELL/NRTR-93. pp 89-101.

Ryan, K.C.; Rigolot, E.; Botelho, H. 1993. Comparative analysis of fire resistance and survival of Mediterranean and western north American conifers. In Proceedings of the 12th Conference on Fire and Forest Meteorology. pp 701-708.

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

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

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

Weatherby, J.C.; Mocettini, P.; Gardner, B.R. 1994. A biological evaluation of tree survivorship within the Lowman fire boundary. 1989-1993. USDA Forest Service Report #R4-94-06. 9 pp.

9. ACKNOWLEDGMENTS

FOFEM 5.0 was developed in collaboration with Robert E. Keane of the Missoula Fire Sciences Lab. FOFEM 5.0 was developed with funds provided by the Joint Fire Science Program, the USDA Forest Service Rocky Mountain Research Station, and Systems for Environmental Management.

Scott Mincemoyer developed the fuels database for FOFEM 5.0. Duncan Lutes conducted a sensitivity analysis and developed the size class distribution scheme for Burnup, and assembled the diameter bark-thickness relationships for predicting tree mortality. Mark Finney reprogrammed Burnup, and added the smoke computations to it. Melanie Miller and Deb Tirmenstein tested and debugged. Dan Jimenez assisted in the incorporation of the soil heating model. Courtney Couch created the artwork used as FOFEM's splash screen on startup.