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# FOFEM: The First-Order Fire Effects Model Adapts to the 21st Century

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The immediate effects of fire, within seconds or minutes of combustion, hold many clues to the future of burned areas. Credit: Bob Keane.

## FOFEM: The First-Order Fire Effects Model Adapts to the 21st Century

### *Summary*

Technology is playing an increasingly pivotal role in the efficiency and effectiveness of fire management. The First Order Fire Effects Model (FOFEM) is a widely used computer application that predicts the immediate or 'first-order' effects of fire: fuel consumption, tree mortality, emissions, and soil heating. FOFEM's simple operation and comprehensive features have made it a workhorse for fire and resource professionals who need to be able to predict, assess and plan for fire's effects. Over the last decade FOFEM has undergone several upgrades as developers continue to improve function and expand applicability to meet the growing needs of managers, planners and analysts.

## Latest First Order Fire Effects Model (FOFEM) upgrades include:

- The FOFEM Mapping Tool which allows the import or input of spatial data layers,
- Extensive additions to tree mortality models that expand scope and application,
- A tree-mortality modification specifically for use in southeastern longleaf pine ecosystems, and
- A web-based version with expanded function, storage, connectivity and customization options.

## What's the status?

Patches of flame and smoldering fuel linger as a fire nears its end. Combustion has consumed fuel and generated heat and smoke. But how much fuel and how much smoke? How hot did it get, and where? What does this all mean for trees, soil and air—right here, right now—and why does it matter?

The imprint of fire on an ecosystem doesn't end when the flames go out. It's easy to think of fire as an isolated event, but it's actually a process. Fire's effects reverberate through an ecosystem over time. The *immediate* effects, known as *first-order* fire effects, influence the way a burned

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area will respond and regenerate over the coming days, months, decades and even centuries. Effects that occur over these longer time spans are called *second-order* fire effects. First-order fire effects drive and shape second-order fire effects, creating a roadmap to a burned area's future and helping to define fire's role in natural ecosystem processes.

## Connecting the dots

First-order effects include plant injury and mortality, soil heating, fuel consumption and smoke production. Second-order effects include vegetation succession, erosion and the eventual atmospheric concentration and dispersion of smoke. Each individual first-order fire effect is an intersection of information connected to the others, and the future, by possibilities. What has taken place and which direction will things go from here?



Credit: Missoula Fire Sciences Laboratory.

Fuel consumption is an important first-order effect that's intricately linked to the others, as well as to the future

of the ecosystem. Fire consumes fuel, in turn producing smoke and generating heat. The intensity and duration of heat determine the degree of vegetation mortality and soil heating. The amount of plant mortality and soil heating influence vegetation dynamics after fire. The composition and structure of this post-fire vegetation community influence the behavior and extent of the next fire.

The details of this dot-to-dot picture are vitally important to resource managers. It's their job to know about the past, current and future conditions of the ecosystems under their purview, and to be able to use that information to shape plans and guide decisions.

Over the years, the Forest Service and science communities have developed different methods and procedures for estimating first-order fire effects. Before the computer age, managers had to rely on experience and knowledge to make general estimations of fire's immediate effects. Today, FOFEM provides managers with consistent and quantitative prediction methods.

*FOFEM provides managers with consistent and quantitative prediction methods.*

## A quick study

In 1989, a new tool emerged from the Forest Service Fire Science Laboratory in Missoula, MT. Bob Keane, Elizabeth Reinhardt and Jim Brown created the first version of a simple computer program that would forever change the process of predicting and planning for the immediate effects of fire—the First Order Fire Effects Model known as FOFEM. It's an all-purpose, easy to use, free, downloadable software package that allows users to quantify the immediate effects of fire. It differs from other first-order effects models in that it combines and integrates results from multiple empirical fire effects studies into one program. Keane explains that their design criterion, as put forth by Brown, was straightforward. "Learn it in an hour, run it in a minute," he says. And apparently, they succeeded.

Since its inception FOFEM has been used by thousands of fire and land managers across the country from a broad spectrum of agencies. It's been endorsed by the National Wildfire Coordinating Group and sponsored by the Washington Office of Fire and Aviation Management. It's used for environmental assessment, fire severity assessment, development of fire and silvicultural prescriptions, and preparation of timber salvage guidelines.

The most significant version of FOFEM (v.4.0) was developed by Reinhardt and Keane in 1997 with Joint Fire Science support. It included the Albin BURNUP model which simulates heat transfer to fuels, consumption rate and resulting heat. BURNUP can also model heat transfer to other ecosystem components like the living tissue under tree bark, the mineral soil underneath the fire, or the smoke above it. “BURNUP is the heart of the whole model,” says Keane. “We run it for almost everything now.”

## What it does

FOFEM has continued to evolve and is now in version 5.2. FOFEM fire effects analyses can guide prescribed fire activities and wildfire response, help design and evaluate treatments for desired and potential fire effects, and compare the potential ecological consequences of varying alternatives. It can simulate effects of different prescribed treatment alternatives and can be used to customize prescribed fire treatments to meet specific objectives.

FOFEM v5.2 can be downloaded to computers running a Microsoft Windows environment. Users can select analysis for tree mortality, fuel consumption, smoke or soil. A different input interface appears with each choice. Realistic default values are provided, or you can enter your own custom information. It generates results in reports or graph that are appropriate for inclusion in planning documents.

## How it does it

### *Fuel loads*

FOFEM provides default fuel loads by fuel component (such as litter, duff, and woody fuel by size class). Default values depend on cover type and on fuel type (i.e., natural or slash fuels). The defaults are based on an extensive literature search summarized in the Mincemoyer Fuels Database, which is a major component of FOFEM. The defaults can be adjusted or replaced. Because fuels vary so much within cover type, Reinhardt recommends entering fuel loads directly if you can.

### *Tree mortality*

To predict tree mortality, users enter a tree list or stand table that lists species, diameter, height, crown ratio and trees per acre. Tree mortality increases with increasing crown scorch, and decreases with increasing bark thickness, so FOFEM uses bark thickness and the percentage of crown volume scorched for prediction. Bark thickness is derived from species and tree diameter. Crown volume scorch is calculated using tree height and crown base height, and scorch height *or* flame length.

Reinhardt recommends avoiding flame length as an input when possible, however. This is because scorch height will actually *decrease* for a given flame length at higher wind speeds typical of many wildfires. Entering flame length may cause over-prediction of scorch height—and therefore tree mortality. Using scorch height is especially

appropriate when using FOFEM to predict fire effects after the fact, when scorch height can be directly observed.



To predict tree mortality, FOFEM users enter a tree list or stand table of species, diameter, height, crown ratio and trees per acre.

When predicting stand mortality, FOFEM assumes that the fire is continuous across the entire area of concern. In the case of discontinuous or patchy fire, the user can estimate the proportion of area burned to adjust estimated tree mortality per acre.

### *Fuel consumption*

Here again the model assumes continuous fire over the entire area of concern. As with tree mortality, if you're dealing with patchy fire you should estimate the percentage of area burned and adjust per acre estimates. FOFEM predicts the quantity of fuel consumed by prescribed or wildfire for six different fuel components and predicts mineral soil exposed by fire as a result of duff and litter consumption. Consumption of different fuel types is predicted using a mix of empirical equations, rules of thumb and modeling. Although herbaceous fuels are generally a small component of fuel load, they are calculated by FOFEM because of their contribution to emissions. Calculated by rule of thumb, FOFEM assumes that 100 percent of herbaceous fuels are consumed. The exception is when spring is selected as the burning season, and grass selected as the cover type. Consumption then drops to 90 percent.

Shrub fuels are also modeled with rules of thumb. For example, if the cover type is sagebrush and the season is fall, shrub consumption is predicted at 90 percent. For all other seasons it drops to 50 percent.

When predicting canopy fuel consumption, FOFEM requires the user to estimate the proportion of a given stand that will be affected by crown fire. The consumption of crown fuels is represented for the purposes of estimating smoke production or carbon budget. FOFEM does not predict *whether* a crown fire will occur or if canopy layers will be consumed.

## Fuel moisture

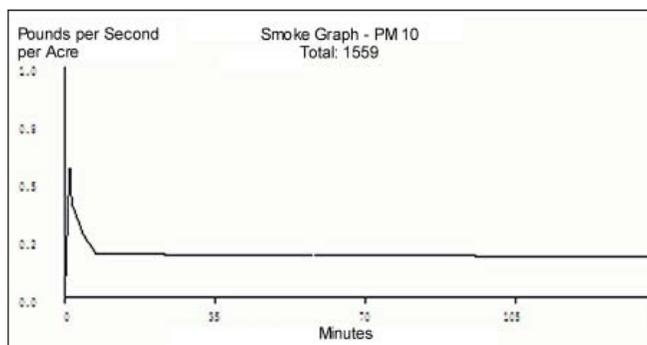
You can select very dry, dry, moderate or wet burn conditions. FOFEM applies default moisture percentages for each. You can enter fuel moistures directly for duff, 0.25 to 1 inch, and greater than 3 inch woody fuels. If you want to set fuel moistures for all woody fuel size classes, or separate moistures for sound and rotten fuel, you can bypass the FOFEM interface and use BURNUP.

## BURNUP bonus

BURNUP physically models heat transfer and burning rate of woody fuel particles as they interact over the duration of a burn. It estimates total fuel consumption by size class, as well as consumption rate and fire intensity over time. FOFEM uses BURNUP to predict woody fuel litter consumption (100 percent of litter is generally consumed) and smoke/emissions predictions.

BURNUP estimates flaming and smoldering consumption simultaneously in each time step. A fuelbed may produce flames in local concentrations of woody fuels at the same time that duff and isolated woody fuels burn in smolder combustion. Flaming and smoldering combustion burn with different combustion efficiencies and produce emissions at different rates. By modeling the two processes separately and simultaneously, BURNUP is able to take both into account in estimating emissions.

Fire intensity is derived from combustion of fuels in each time step, in turn determining fuel temperatures and combustion rates for the next time step. Immediately after ignition, intensity increases as the finest fuel burn. This generates more and more heat, progressively igniting larger and wetter fuel. As the smaller fuel burns up, intensity drops. The fire is assumed to go out when fire intensity is too low to sustain further combustion.



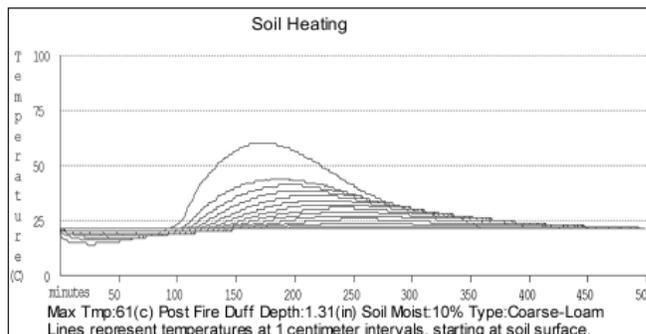
A sample graph of emissions production over time generated by FOFEM.

BURNUP computes different species of smoke emissions (chemical and particulate) in each time step. The FOFEM/BURNUP includes a graph and Smoke Emissions Report listing total emissions of  $PM_{2.5}$ ,  $PM_{10}$ ,  $CH_4$ ,  $CO$ ,  $CO_2$ , nitrogen oxide and sulfur dioxide. This information can then be used in other modeling systems to predict smoke dispersion and concentrations.

## Soil heating

FOFEM predicts soil temperature over time at the soil surface and several depths below. It predicts expected average soil heating across the area because soil heating varies considerably within a burn unit. The model has been set up so that heat from surface fire (as modeled in prediction of fuel consumption) is used as the source of soil heat. If duff is present then the model assumes the duff is the source of soil heat. Duff fires have low intensity and spread much slower than flaming fire, but heating of deep soil layers is often greater in duff fires because they burn for a longer time in direct contact with the surface of mineral soil.

The graphic format of the soil heating report plots temperature vs. time, and displays temperature at several depths. Temperatures that exceed the  $60^\circ C$  (considered the lethal temperature for living organisms) are highlighted so you can identify which burning scenarios exceed this temperature at various soil depths. This lethal temperature is the default for the highlight, but you can change that by simply typing in a new number. The graph also includes the maximum temperature reached at the soil surface, the amount of duff consumed, the soil type, and starting soil temperature. The soil heating report contains a complete summary of FOFEM pre- and post-burn conditions, in addition to all the information displayed in the graph, which is useful for comparing scenarios.



A sample soil-heating prediction graph from FOFEM.

## New features and functions

### FOFEM mapping tool

The new FOFEM MT (FOFEM Mapping Tool) will have the capacity to automatically import LANDFIRE spatial data layers. You will also have the option of entering any spatial data layers you want, from any source. This feature can be used to calculate fire effects across the landscape for use in fire and fuel hazard analysis. This is useful for prioritizing fuel treatment or burn recovery activities.

### FRAMES online portal

FOFEM will soon be functional as an online tool that allows users to skip downloading and installation. It will be accessible via FRAMES (Fire Research and

Management Exchange System) which adapts fire research and management tools for use in a web-based environment. FRAMES project manager Greg Gollberg selected FOFEM as one of the models to be modified for online ease of use. "It's a solid, simple program. A lot of people are familiar with it and it's been around for a while," he says. "It gave us the chance to start out small and see how it goes. We have hopes for adding more function, data storage and exchange, and new customization options." The FRAMES website will house not only the web version of FOFEM but all of the downloadable versions too.

## Expanded scope for tree mortality

The FOFEM tree mortality module was developed with data from western conifer forests. Although it works well in the western U.S., it's commonly acknowledged that problems can arise with over-prediction of tree mortality when FOFEM is applied to other regions and forest types.

But plenty of work is underway to change that. Managers in the southeast will benefit from a new tree mortality model developed by Geoff Wang, with support from the Joint Fire Science Program and Clemson University. Wang created a modified version of FOFEM for use in longleaf pine and longleaf/slash cover types in the Southeastern U.S. Keane is hopeful that this will happen for other parts of the country too. "We constantly scour the literature for new tree mortality equations," he says. "I've got file cabinets full of this stuff. When anyone does work on a new species it goes right into in the next revision."

In addition, a team led by Sharon Hood at the Fire Modeling Institute at the Rocky Mountain Research Station in Missoula, is analyzing fire injury data on more than 16,000 trees from 82 wild and prescribed fires from 5 western states. They're testing existing tree mortality models and developing new ones where necessary and incorporating it all into FOFEM.

## Keeping pace with management needs

"The beauty of FOFEM is that it combines all the first-order effects under one roof," says Keane. "The more we can add to it, the better off managers will be. It's still the same nuts and bolts model. It still has the same guts. It's just that it's been repackaged again with new capacities. Next,

we want to put in more emission elements and even more tree mortality. That will continue to increase applicability."

So stay tuned for what are sure to be more changes and features that will keep FOFEM in the top tray of the fire planning and prediction toolbox well into the 21st century.

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## Further Information: Publications and Web Resources

FOFEM download and tutorials:

[http://www.fire.org/index.php?option=com\\_content&task=view&id=58&Itemid=31](http://www.fire.org/index.php?option=com_content&task=view&id=58&Itemid=31)

Fire Modeling Institute, Missoula Fire Sciences Lab:

<http://www.fs.fed.us/fmi/index.html>

FOFEM MT (mapping tool), Don Helmbrecht /  
Fire Modeling Institute / 406-829-7370 FMI:  
[dhelmbrecht@fs.fed.us](mailto:dhelmbrecht@fs.fed.us)  
[http://www.fs.fed.us/fmi/projects/abstracts/  
Helmbrecht\\_SpatialFOFEM\\_abstract.html](http://www.fs.fed.us/fmi/projects/abstracts/Helmbrecht_SpatialFOFEM_abstract.html)

FRAMES Fire Research and Management Exchange  
System, Greg Gollberg / 208-885-9756, [gollberg@uidaho.edu](mailto:gollberg@uidaho.edu): <http://frames.nbii.gov/portal/server.pt>

Delayed Tree Mortality Following Fire in Western Conifers,  
Sharon Hood / Fire Modeling Institute / 406-329-  
4818: [shood@fs.fed.us](mailto:shood@fs.fed.us)  
[http://www.firelab.org/index.php?option=com\\_content  
&task=view&id=690&Itemid=262](http://www.firelab.org/index.php?option=com_content&task=view&id=690&Itemid=262)

Modifying FOFEM for use in the Coastal Plain Region of  
the U.S., Geoff Wang / Principle Investigator/ 864-  
656-4864: [gwang@clemson.edu](mailto:gwang@clemson.edu)  
[http://www.firescience.gov/  
projects/05-4-3-06/05-4-3-06\\_final\\_report.pdf](http://www.firescience.gov/projects/05-4-3-06/05-4-3-06_final_report.pdf)

## Scientist Profiles

Dr. Elizabeth Reinhardt is a Research Forester with the Rocky Mountain Research Station, Missoula Fire Sciences Laboratory, Missoula, MT. She has degrees in English (A.B., Harvard University), and Forestry (M.S. 1982, and Ph.D. 1991, University of Montana). Her research has included studies of tree mortality, fuel consumption, modeling fire effects, and canopy fuels.



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