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Chapter 9:

Fire Effects and Soil Erosion Models

Introduction

In many cases, decisions about fire have to be made in short timeframes with limited information. Fire effects models have been developed or adapted to help land and fire managers make decisions on the potential and actual effects of both prescribed fires and wildfires on ecosystem resources (fig. 9.1). Fire effects models and associated erosion and runoff models apply the best fire science to crucial management decisions. These models are undergoing constant revision and update to make the latest information available to fire managers using the state-of-the-art computer hardware and software. Use of these models requires a commitment to understand their assumptions, benefits, and shortcomings, and a commitment to constant professional development.

First Order Fire Effects Model (FOFEM)

FOFEM (First Order Fire Effects Model) is a computer program that was developed to meet the needs of resource managers, planners, and analysts in

Figure 9.1—Wildland fires such as the Rodeo-Chediski Fire of 2002 affect the complete range of physical, chemical, and biological components of ecosystems. (Photo by USDA Forest Service).

predicting and planning for fire effects. FOFEM provides quantitative predictions of fire effects for planning prescribed fires that best accomplish resource needs, for impact assessment, and for long-range planning and policy development. FOFEM was developed from long-term fire effects data collected by USDA Forest Service and other scientists across the United States and Canada (fig. 9.2).

Description, Overview, and Features

First order fire effects are those that concern the direct or indirect of immediate consequences of fire. First order fire effects form an important basis for predicting secondary effects such as tree regeneration plant succession, soil erosion, 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. FOFEM predicts fuel consumption, smoke production, and tree mortality. The area of applicability is nationwide on forest and nonforest vegetation types. FOFEM also contains a planning mode for prescription development.

Applications, Potential Uses, Capabilities, and Goals

FOFEM makes fire effects research results readily available to managers. Potential uses include wildfire impact assessment, development of salvage specifications, design of fire prescriptions, environmental assessment, and fire management planning. FOFEM can also be used in real time, quickly estimating tree mortality, smoke generation, and fuel consumption of ongoing fires.

Figure 9.2—Development of FOFEM and other fire effects models stemmed from long-term fire effects data collected by USDA Forest Service and other scientists across North America. (Photo by USDA Forest Service).

Scope and Primary Geographic Applications

FOFEM—national in scope—uses four geographic regions: Pacific West, Interior West, Northeast, and Southeast. Forest cover types provide an additional level of resolution within each region, and SAF and FRES vegetation types to stratify data and methods. Geographic regions and cover types are used both as part of the algorithm selection key, and also as a key to default input values. FOFEM contains data and prediction equations that apply throughout the United States for most forest and rangeland vegetation types that experience fire.

Input Variables and Data Requirements

FOFEM was designed so that data requirements are minimal and flexible. Default values are provided for almost all inputs, but users can modify any or all defaults to provide custom inputs.

Output, Products, and Performance

FOFEM computes the direct effects of prescribed fire or wildfire. It estimates fuel consumption by fuel component for duff, litter, small and large woody fuels, herbs, shrubs and tree regeneration, and crown foliage and branchwood. It also estimates mineral soil exposure, smoke production of CO, PM10, and PM2.5, and percent tree mortality by species and size class. Alternatively, if the user enters desired levels of these fire effects, FOFEM computes fuel moistures and fire intensities that should result in desired effects.

Advantages, Benefits, and Disadvantages

FOFEM is easy to use, applies to most vegetation types and geographic areas, synthesizes and makes available a broad range of available research results, incorporates planning and prediction modes, and provides a wide range of data in the form of default inputs for different vegetation and fuel types. The main disadvantage is that FOFEM is not currently linked to any other models (fire behavior, smoke dispersion, postfire succession).

System and Computer Requirements

FOFEM version 5.0 is available for IBM-compatible PCs with Windows 98 and Windows 2000 operating systems. FOFEM is supported by the Fire Effects Research Work Unit, Intermountain Fire Sciences

Lab, Missoula, MT 59807. Additional information can be obtained from:

http://www.fire.org/
http://www.firelab.org/

FOFEM includes embedded help and user's information. The current version (5.21) can be downloaded for use with WINDOWS@ 98, 2000, and XP at:

http://www.fire.org/index.php?option=com_content&task=view&id=58&Itemid=25

POWERPOINT@ tutorials provide a FOFEM overview and information for basic and advanced users. FOFEM 4.0 should be replaced with FOFEM 5.21. For more detailed information contact Elizabeth Reinhardt at: ereinhardt@fs.fed.us

Models for Heat and Moisture Transport in Soils

Transfer of heat into the soil beneath a fire produces a large number of onsite fire effects to the physical, chemical, and biological properties of soils (Hungerford 1990) that include:

- plant mortality and injury
- soil organism mortality and injury
- thermal decomposition of organic matter
- oxidation or volatilization of chemical components of the upper soil profile
- other physiochemical changes

To predict the nature and extent of these effects, we need to understand temperature profiles within the soil beneath burned areas (Albini and others 1996). Temperature profiles are rarely measured in actual fires, so some type of model is needed to predict soil temperatures and the response of soils to the thermal input. Albini and others (1996) reviewed a number of existing models to determine their applicability and recommend future development goals.

The Albini and others (1996) review of heat transfer models from the soil science, engineering, and geophysics fields concluded that the only useful models for describing heat transfer phenomena for wildland fires come from the soil science arena. The models of Campbell and others (1992, 1995) seem to function well in predicting temperature histories and profiles of soils heated at rates and temperatures consistent with wildland fires. Their model did not perform as well with soil moisture contents as with temperatures. Because many of the heating effects are a function of soil moisture, this is an important ability for heat transfer prediction models.

Albini and others (1996) identified the omission of a number of important features in the soil science models. These include diffusive transport of water as a vapor or liquid, momentum equations, predictions of the transient movement of phase-change boundaries, lateral nonhomogeneity of soils, and the rapid decline of wetting attraction of liquid water to quartz near 149 °F (65 °C).

Finally, Albini and others (1996) made recommendations for further model development and simplifications of the existing models. They believed that some simplification would improve the use of the existing models without much sacrifice in the fidelity of their predictions.

WEPP, WATSED, and RUSLE Soil Erosion Models

Following a fire, it is often necessary to use some standard prediction technology to evaluate the risk of soil erosion. For forests that tend to regenerate rapidly, the risk of erosion decreases quickly after the first year, at a rate of almost 90 percent each year. For example, the year following a fire may experience 0.4 to 0.9 tons/acre (1 to 2 Mg/ha) erosion, the second year less than 0.04 to 0.10 tons/acre (0.1 to 0.3 Mg/ha), and the third year may be negligible (Robichaud and Brown 1999). The erosion rate depends on the climate, topography, soil properties (including hydrophobicity), and amount of surface cover. Surface cover may include unburned duff, rock, and needle cast following fire.

Three models are commonly used after soil erosion. In USDA Forest Service Regions 1 and 4, the WATSED and similar models have frequently been used (USDA Forest Service 1990b). The Universal Soil Loss Equation (USLE) has been used widely for many years, and more recently, the Revised USLE, or RUSLE, has become common (Renard and others 1997). The Water Erosion Prediction Project (WEPP) model has recently been parameterized for predicting erosion after fire, and an interface has been developed to aid in that prediction. Improvements in the usability of both the RUSLE and WEPP prediction technologies are ongoing. The WATSED model is intended to be a cumulative affects model, to be applied at watershed scale. RUSLE and WEPP are hillslope models. WEPP has a watershed version under development, but it has received little use outside of research evaluation.

WATSED is intended as a watershed model to combine the cumulative effects of forest operations, fires, and roads on runoff and sediment yield for a given watershed. Factors that account for burned area within the watershed, soil properties, topography, and delivery ratios are identified, and an average sediment delivery is calculated. This sediment delivery is reduced over a 15-year period following a fire before the impact is assumed to be zero. Within the Western geographical territory of the Forest Service Regions, some of the factors have been adjusted to calibrate the model for local conditions, leading to the development of models such as NEZSED and BOISED. The erosion predictions are based on observations in the mountains in Regions 1 and 4, and are not intended for use elsewhere. Table 9.1 provides the erosion rates predicted in WATSED, corrected for a USLE *LS* factor of 11.2 (Wischmeier and Smith 1978). These rates are adjusted for topography, landscape, and soil properties before arriving at a final prediction. A variation of the technology in WATSED has been adopted by the State of Washington for its Watershed Analysis procedure (Washington Forest Practices Board 1997).

The Revised USLE was developed not only for agriculture, but also included rangeland conditions. The RUSLE base equation is:

$$A = R\ K\ LS\ C\ P \qquad (1)$$

Where A is the average annual erosion rate, R is the rainfall erosivity factor, K is the soil erodibility factor, LS is the slope length and steepness factor, C is the cover management factor, and P is the conservation management factor. Although it has not been widely tested, the RUSLE values appear to give reasonable erosion values for rangelands (Renard and Simanton 1990, Elliot and others 2000) and will likely do the same for forests. There are no forest climates available in the RUSLE database. Table 9.1 provides some assumptions about rate of vegetation regeneration and typical erosion rates estimated for burned and recovering forest conditions based on those assumed cover values. The RUSLE *LS* factor was about 6.54, almost half of the USLE C-factor used for WATSED. The RUSLE *LS* factor is based on more recent research and the analysis of a greater number of plots (McCool and others 1987, 1989), so it should probably be used with the WATSED technology to adjust for slope length and steepness. The RUSLE *R* factor was estimated as 20 from the documentation (Renard and others 1997). This is a relatively low value because much of the precipitation in the Northern Rockies comes as snowfall, and snowmelt events cause much less erosion than rainfall events.

The most recent erosion prediction technology is the Water Erosion Prediction Project (WEPP) model (Flanagan and Livingston 1995). WEPP is a complex process-based computer model that predicts soil erosion by modeling the processes that cause erosion. These processes include daily plant growth, residue accumulation and decomposition, and daily soil water balance. Each day that has a precipitation or snow melt event, WEPP calculates the infiltration, runoff, and sediment detachment, transport, deposition, and yield.

WEPP was released for general use in 1995, with an MS DOS text-based interface. Currently a Windows interface is under development and is available for general use (USDA 2000). Elliot and Hall (1997) developed a set of input templates to describe forest conditions for the WEPP model, for the MS DOS interface. The WEPP model allows the user to describe the site conditions with hundreds of variables, making the model extremely flexible, but also making it difficult for the casual user to apply to a given set of conditions. To make the WEPP model run more easily for forest conditions, Elliot and others (2000) developed a suite of interfaces to run WEPP over the Internet using Web browsers. The forest version of WEPP can be found at:

http://forest.moscowfsl.wsu.edu/fswepp

One of the interfaces is Disturbed WEPP, which allows the user to select from a set of vegetation conditions that describe the fire severity and recovering conditions. The Disturbed WEPP alters both the soil and the vegetation properties when a given vegetation treatment is selected. Table 9.2 shows the vegetation treatment selected for each of the years of recovery. In all cases, the cover input was calibrated to ensure that WEPP generated the desired cover given

Table 9.1—Erosion rates observed and predicted by WATSED, RUSLE, and WEPP for the cover shown, for a 30 percent steepness, 60-m long slope.

Year after fire	Estimated cover	Observed erosion rate	Predicted erosion rate WATSED	 RUSLE	 WEPP
	Percent	*Mg/ha*	- - - - - - - - - -	*Mg/ha*	- - - - - - - - - -
1	50	2.2	1.92	3.35	1.74
2	65	0.02	1.64	1.30	0.37
3	80	0.01	0.96	0.54	0.02
4	95	0.00	0.48	0.20	0.00
5	97	0.00	0.29	0.16	0.00
6	99	0.00	0.15	0.09	0.00
7	100	0.00	0.06	0.07	0.00

[1] From Robichaud and Brown (1999)

Table 9.2—Vegetation treatment selected for each year of recovery with the Disturbed WEPP interface.

Years since fire	Disturbed WEPP vegetation treatment
0	High severity fire
1	Low severity fire
3	Short grass
4	Tall grass
5	Shrubs
6	5-year-old forest (99 percent cover)
7	5-year-old forest (100 percent cover)

in table 9.1. The Disturbed WEPP interface has access to a database of more than 2,600 weather stations to allow the user to select the nearest station to the disturbed site. The values in table 9.3 were predicted for Warren, ID, climate. Warren climate is similar to the climate for Robichaud and Brown's study, and also near the site where the WATSED base erosion rates were developed in central Idaho.

An important aspect of soil erosion following a fire is that the degree of erosion depends on the weather the year immediately following the fire. Table 9.1 shows the rapid recovery of a forest in the years after fire. If the year after the fire has a number of erosive storms, then the erosion rate will be high. If the year after the fire is relatively dry, then the erosion rate will be low. The values presented in table 9.1 are all average values. There is a 50 percent chance that the erosion in this most susceptible year will be less than the average value. To allow managers to better evaluate the risk of a given level of erosion following a fire, the Disturbed WEPP interface includes some probability analyses with the output, giving the user an indication of the probability associated with a given level of erosion. Table 9.3 shows that there is a one in 50, or 2 percent, chance that the erosion rate from the specified hill will exceed 3.18 tons/acre (7.12 Mg/ha), and the sediment delivery will exceed 2.88 tons/acre (6.45 Mg/ha). There is a one in 10, or 10 percent, chance that the erosion and sediment delivery rate will exceed 2.11 tons/acre (4.72 Mg/ha), and so forth. This feature will allow users to evaluate risks of upland erosion and sediment delivery to better determine the degree of mitigation that may be justified following a given fire. In California, for example, erosion is often estimated for a 5-year condition, which in this case is 1.47 tons/acre (3.3 Mg/ha). Disturbed WEPP also predicted that there was an 80 percent chance that there would be erosion on this hillslope the year following the fire.

The variability of erosion following a fire due to the climate makes any measurements difficult to evaluate. Note in table 9.1 the large drop from year 1 to year 2 in erosion rate. This decline was likely due not only to regeneration but also to the lower precipitation in 1996. In the nearby Warren, ID, climate, the average precipitation is 696 mm; the year following the fire it was 722 mm, and the second year after the fire only 537 mm. These variations from the mean also help explain why the Disturbed WEPP predicted erosion rates in table 9.1 for "average" conditions were below the observed value the first year but above the observed value the second year.

The variability in erosion observations and predictions is influenced not only by climate but also by spatial variability of soil and topographic properties. In soil erosion research to determine soil properties, it is not uncommon to have a standard deviation in observations from identical plots greater than the mean. A rule of thumb in interpreting erosion observations or predictions is that the true "average" value is likely to be within plus or minus 50 percent of the observed value. In other words, if a value of 0.9 tons/acre (2 Mg/ha) is observed in the field from a single observation, the true "average" erosion from that hillside is likely to be between 0.4 and 1.3 tons/acre (1 and 3 Mg/ha). Following this rule leads to the conclusions that WATSED, RUSLE, and WEPP predictions in table 9.1 are not different from the observed erosion rates.

Table 9.3—Exceedance probabilities associated with different levels of precipitation, runoff, and soil erosion for the year following a severe wild fire in central Idaho.

Return period	Precipitation		Runoff		Erosion		Sediment	
Years	*mm*	*in*	*mm*	*in*	*Mg/ha*	*tons/ac*	*Mg/ha*	*tons/ac*
50.0	973.60	38.33	31.82	1.25	7.12	3.18	6.45	2.88
25.0	892.80	35.15	31.79	1.25	6.45	2.88	6.32	2.82
10.0	811.50	31.95	27.65	1.09	4.72	2.11	4.72	2.11
5.0	756.10	29.77	20.56	0.81	3.30	1.47	3.30	1.47
2.5	671.80	26.45	14.74	0.58	1.80	0.80	1.80	0.80
Average	670.92	26.41	12.47	0.49	1.74	0.78	1.74	0.78

In the years of regeneration, it appears that both WATSED and RUSLE are overpredicting observed erosion rates, whereas the Disturbed WEPP predictions are nearer to the observed values. WATSED, as a cumulative effects model, is considering the impact of the disturbance on a watershed scale. Frequently eroded sediments following a disturbance may take several years to be routed through the watershed, whereas WEPP is only considering the hillslope in its predictions. RUSLE is also a hillslope model but considers only the upland eroding part of the hillside and does not consider any downslope deposition. This means that RUSLE values will frequently be overpredicted unless methods to estimate delivery ratio are considered. A RUSLE2 model currently under development addresses downslope deposition and sediment delivery.

Model Selection

Managers must determine which model most suits the problem at hand. The WATSED technology is geographic specific, as is the Washington Forest Practices model. These models should not be used outside of the areas for which they were developed. The WATSED technology is intended to assist in watershed analysis and not necessarily intended for estimating soil erosion after fires. RUSLE is intended to predict upland erosion and is best suited for estimating potential impacts of erosion on onsite productivity. It is less well suited for predicting offsite sediment delivery. The WEPP technology provides estimates of both upland erosion for soil productivity considerations and sediment delivery for offsite water quality concerns. The WEPP DOS and Windows technology requires skill to apply and should be considered only by trained specialists. The Disturbed WEPP interface requires little training, and documentation with examples is included on the Web site, making it available to a wider range of users.

DELTA-Q and FOREST Models

Two other models warrant brief mentioning. They can assist fire managers in dealing with watershed scale changes in water flow and erosion. These are DELTA-Q and FOREST. Both programs require an ESRI Arc 8.x license. Further documentation can be found at:

http://www.cnr.colostate.edu/frws/people/faculty macdonald/model.htm.

One of the difficult tasks facing land managers, fire managers, and hydrologists is quantifying the changes in streamflow after forest disturbances such as fire. The changes of interest are alteration of peak, median, and low flows as well as the degradation of water quality due to increased sediment delivery to channels or channel degradation.

DELTA-Q is a model designed to calculate the cumulative changes in streamflow on a watershed scale from areas subjected to the combination of harvesting and road construction. Flow changes due to forest cover removal by wildfire can also be calculated. A current data limitation in the model is that it evaluates only changes due to vegetation combustion, not the possible effects of alterations to runoff and streamflow generation processes. The objective of DELTA-Q is to provide fire and watershed managers with a GIS-based tool that can quickly approximate the sizes of changes in different flow percentiles. The model does not estimate the increases in streamflow from extreme events (see chapters 2 and 5). The model was designed to be used for planning at watershed scales of 5 to 50 mi^2 (3,200 to 32,000 acres, or 1,300 to 13,000 ha).

The FOREST (FORest Erosion Simulation Tools) model functions with DELTA-Q. It calculates changes in the sediment regime due to forest disturbances. It consists of a hillslope model that uses a polygon GIS layer of land disturbances to calculate sediment production. Road-related sediment is treated separately because roads are linear features in the landscape. Input values for the road segment can be generated by several means including WEPP.Road. FOREST does not deal with changes in channel stability.

Models Summary

This chapter is not meant as a comprehensive look at simulation models. Several older modeling technologies commonly used estimate fire effects during and after fire (FOFEM, WATSED, WEPP, RUSLE, and others). New ones such as DELTA-Q, FOREST have been recently developed, and others are under construction. These process-based models provide managers with additional tools to estimate the magnitude of fire effects on soil and water produced by land disturbance. FOFEM was developed to meet needs of resource managers, planners, and analysts in predicting and planning for fire effects. Quantitative predictions of fire effects are needed for planning prescribed fires that best accomplish resource needs, for impact assessment, and for long-range planning and policy development. FOFEM was developed to meet this information need. The WATSED technology was developed for watershed analysis. The RUSLE model was developed for agriculture and rangeland hillslopes and has been extended to forest lands. The WEPP model was designed as an improvement over RUSLE that can either be run as a stand-alone computer model by specialists, or accessed through a special Internet interface designed for forest applications, including wild fires.

All of these models have limitations that must be understood by fire managers or watershed specialists before they are applied. The models are only as good as the data used to create and validate them. Some processes such as extreme flow and erosion events are not simulated very well because of the lack of good data or the complexity of the processes. However, they do provide useful tools to estimate landscape changes to disturbances such as fire. Potential users should make use of the extensive documentation of these models and consult with the developers to ensure the most appropriate application of the models.

USDA United States Department of Agriculture

Forest Service

Rocky Mountain Research Station

General Technical Report RMRS-GTR-42-volume 4

September 2005

Wildland Fire in Ecosystems

Effects of Fire on Soil and Water

Abstract

Neary, Daniel G.; Ryan, Kevin C.; DeBano, Leonard F., eds. 2005. **Wildland fire in ecosystems: effects of fire on soils and water**. Gen. Tech. Rep. RMRS-GTR-42-vol.4. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 250 p.

This state-of-knowledge review about the effects of fire on soils and water can assist land and fire managers with information on the physical, chemical, and biological effects of fire needed to successfully conduct ecosystem management, and effectively inform others about the role and impacts of wildland fire. Chapter topics include the soil resource, soil physical properties and fire, soil chemistry effects, soil biology responses, the hydrologic cycle and water resources, water quality, aquatic biology, fire effects on wetland and riparian systems, fire effects models, and watershed rehabilitation.

Keywords: ecosystem, fire effects, fire regime, fire severity, soil, water, watersheds, rehabilitation, soil properties, hydrology, hydrologic cycle, soil chemistry, soil biology, fire effects models

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Cover photo—Left photo: Wildfire encroaching on a riparian area, Montana, 2002. (Photo courtesy of the Bureau of Land Management, National Interagency Fire Center, Image Portal); Right photo: BAER team member, Norm Ambos, Tonto National Forest, testing for water repellancy, Coon Creek Fire 2002, Sierra Ancha Experimental Forest, Arizona.