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FIRST-ORDER FIRE EFFECTS MODELS FOR LAND MANAGEMENT: OVERVIEW AND ISSUES

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ABSTRACT

We give an overview of the science application process at work in supporting fire management. First-order fire effects models, such as those discussed in accompanying papers, are the building blocks of software systems designed for application to landscapes over time scales from days to centuries. Fire effects may be modeled using empirical, rule based, or process approaches. Fire effects software systems can be used to conduct risk assessments, develop prescriptions for fuel treatments or prescribed fire, or support long-term planning. A brief review of the software systems available and the fire effects models on which they are based is presented. We consider the future of software systems for fire management and, given gaps in fire effects modeling capabilities, how to strengthen their foundation.

Keywords: empirical models, first-order fire effects, land management applications, process models, rule-based models

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INTRODUCTION

Fire effects are the results of combustion. They include direct, or first-order effects on a wide variety of ecosystem components—plants, animals, dead biomass, soils, and air, as well as indirect, or second-order effects that take place over time and depend in large part on post-fire phenomena such as weather, land-use, seed availability, and insect and disease occurrence (Reinhardt *et al.* 2001). Important first-order fire effects include plant injury and mortality, fuel consumption, smoke production, and soil heating. They occur at the time of the fire or within seconds or minutes afterward, and they are generally restricted to the location of the fire. Second-order effects, which are those that are often of most interest to land managers, include vegetation succession, fuel dynamics, erosion, air quality, and water quality. They may take place over days or years following a fire, and may occur off-site. Knowledge of first-order fire effects is necessary but not sufficient to predict second-order effects. Modeling fire effects to provide information for land managers is difficult for three reasons: 1) the intrinsic variability of the natural systems being modeled is large; 2) the data needed for modeling with precision may not be available to decision-makers; and 3) the information needs of land managers are diverse and require predictions at a variety of temporal and spatial scales.

MODELS AND SOFTWARE SYSTEMS

In this paper, we use the term model to refer to predictive relationships representing natural phenomena that may be housed in various software systems, and used to answer a variety of management questions (Figure 1). A software system might contain one or several models, packaged in such a way as to support use for a particular management application. For practical purposes, in an extremely applied field such as forestry or fire science, the line between a model and a software system is often blurred. Table 1 lists a number of fire effects models and the software systems that house them. Many other models may incorporate fire effects as one aspect of a more general vegetation model. This list is limited to models whose primary purpose is predicting fire effects. Some fire effects models are included in a number of software systems. For example, a single model of fire caused tree mortality (Ryan and Reinhardt 1988) is used in the First Order Fire Effects Model (FOFEM, Reinhardt 2003), the Fire Behavior Prediction System (BEHAVE+, Andrews *et al.* 2005), and the Fire and Fuels Extension of the Forest Vegetation Simulator (FFE-FVS, Reinhardt and Crookson 2003). Ideally, the converse would also be true—a software system might include a number of alternative fire effects models. FOFEM was designed with this intent; however, in practice, alternative models are provided only for tree mortality and duff consumption predictions.

WHY MODEL FIRST-ORDER FIRE EFFECTS?

What kinds of management needs have driven software development? Table 2 lists a number of software systems used for a variety of land management applications. Fundamentally, managers want to understand how their

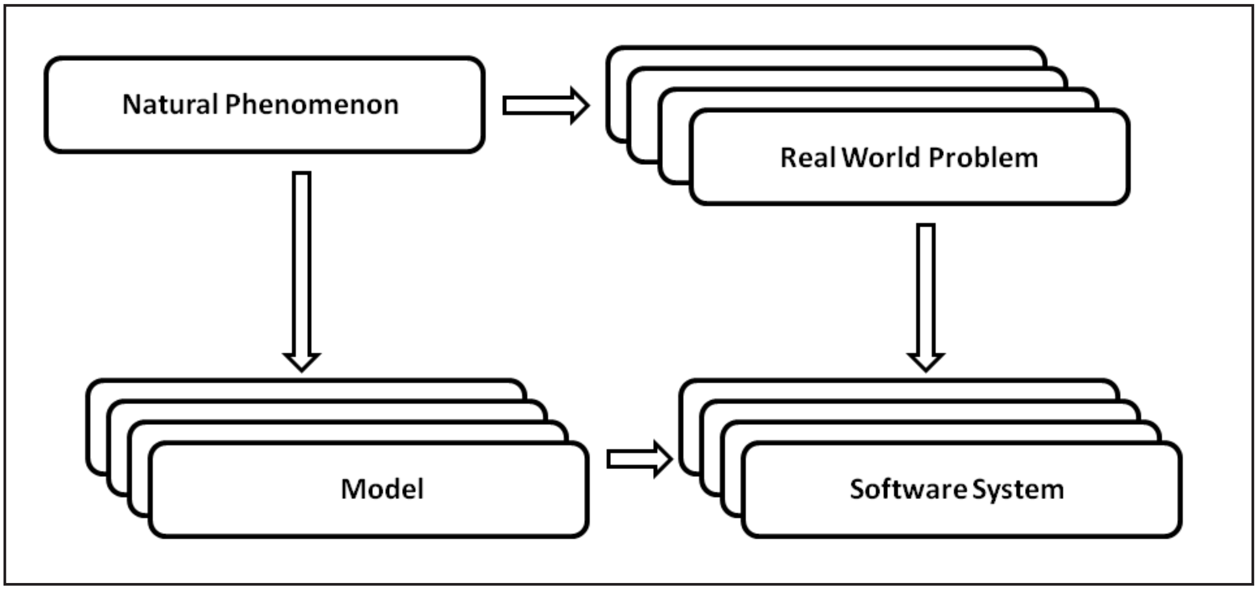

Figure 1. Models describe natural phenomena and are integral to software systems designed to help land managers answer questions about the ecosystems they manage.

Table 1. Some fire effects models and the software systems that house them. This is not an exhaustive list.

Fire effect type	Model	Data requirements	Modeling approach	Software system(s)
First-order effects				
Tree mortality	FireStem (Jones *et al*. 2006)	Tree diameter, species, bark and wood moisture and thermophysical properties, thermal tolerance model parameters, incident heat flux at stem surface	Process	Self-contained
	Ryan and Reinhardt (1988)	Tree diameter, height, crown base height, species, and flame length or scorch height	Empirical	FOFEM, IFT-DSS, BEHAVE+, FFE-FVS, FOFEM-MT (Helmbrecht *et al.* in press)
	Hood *et al.* (2007)	Crown scorch, species, cambial damage	Empirical	FOFEM, IFT-DSS
Soil heating	Campbell *et al.* (1994, 1995)	Heat release rate and duration at the soil surface, soil moisture and texture, soil bulk density, particle density, temperature and thermal conductivity	Process	FOFEM, IFT-DSS
Fuel consumption	Burnup (Albini *et al.* 1995)	Fuel characteristics by class: quantity, particle bulk density, moisture content, surface area to volume ratio; duff depth and moisture	Process	FOFEM, IFT-DSS, FARSITE
	Consume (Prichard *et al*. 2006)	Fuel characteristics including loading, moisture.	Empirical	Self-contained Also, BlueSky, IFT-DSS
Smoke production	Burnup (Albini *et al.* 1995)	Woody fuel by size class: moisture content, particle density, surface area to volume ratio; duff depth and moisture content.	Process	FOFEM, IFT-DSS, FARSITE
	FEPS (Anderson *et al*. 2004)	Fuel loading and moisture, fire growth rate	Empirical	Self-contained Also BlueSky
Second-order effects				
Air quality/ smoke dispersion	CalPuff (Scire *et al*. 2000)	Hourly gridded weather data (3-d wind and temperature), emission sources	Process	BlueSky (O'Neill *et al.* 2003)
Erosion	WEPP (Flanagan and Livingston 1995)	Descriptors of soil, climate, ground cover and topography	Process	ERMit, FSWEPP (Robichaud *et al.* 2007*a, b*)
Vegetation change	VDDT (ESSA Tech. 2007)	Vegetation states, transition probabilities	State-transition rule-based	Self-contained
	FIRESUM (Keane *et al*. 1989)	Species and site parameters, stand inventory data	Process	Self-contained
	FIRE-BGC (Keane *et al.* 1995)	Daily weather, species and site parameters	Process	Self-contained
	SIMMPLLE (Chew *et al*. 2004)	Spatial vegetation, spatially driven disturbance probabilities.	Rule based	Self-contained

Table 2. Software systems delivering fire effects model predictions to support land management applications.

Software System	Land management application	Spatial scale	Temporal scale
CONSUME (Prichard *et al.* 2006)/FEPS (Anderson *et al*. 2004)	Permitting, prescribed fire planning	Stand	Minutes to hours
BlueSky (O'Neill *et al.* 2003)	Forecasting, permitting	Region	Minutes to days
FOFEM (Reinhardt 2003)	Prescribed fire planning, permitting,	Stand	Minutes to 2 years
FOFEM-MT and Wildland Fire Assessment Tool (www.niftt.gov)	Mapping fire-caused changes in fuels	Watershed to landscape	Minutes to 2 years
ERMit (Robichaud *et al.* 2007*a*)	Design post-fire erosion mitigation treatments	Hillslope to watershed	Years
Disturbed WEPP (Spigel and Robichaud 2007)	Erosion—effects of fire and other disturbances	Hillslope to watershed	Years to decades
FFE-FVS (Reinhardt and Crookston 2003)	Risk assessment, fuel treatment design	Stand	Many decades
IFT-DSS (Wells 2009)	Fuel treatment design	Landscape	Years to decades

decisions and actions can be expected to play out through time, and how to achieve the best outcomes and minimize damage. Management needs can be characterized as falling into the categories of risk assessment, prescription development, or long-term planning.

Risk Assessment

Managers may predict fire effects in order to assess a variety of kinds of risk. For example, tree mortality and duff consumption models might be used to assess which areas are most vulnerable to undesirable fire effects and should therefore have priority for fuel treatment. Often qualitative, rule based predictions may be sufficient for this purpose; for example, areas with high fuel loadings and steep slopes are more at risk of erosion following wildfire. Another kind of risk assessment for which first-order models are useful is smoke impacts. In this case, first-order fuel consumption and smoke production models are primarily useful as inputs to a smoke transport or air quality model. For example, the BlueSky modeling framework (http://www.airfire.org/bluesky/) takes emission production estimates from the Fire Emission Production Simulator (FEPS, http://www.fs.fed.us/pnw/fera/feps/index.shtml) and feeds them to an air dispersion model (CALPUFF, O'Neill *et al.* 2003; http://www.getbluesky.org/home.cfm). Air quality is clearly a much more difficult prediction problem than smoke production. It varies over time and space and is dependent not only on burn-site conditions and fire characteristics, but also on topography, air movement, atmospheric chemistry, and weather after the fire. Air quality may be impacted many days after a fire and hundreds of miles away.

The US federal fire policy revision (Fire Executive Council 2009) calls for replacement of existing tactical to strategic analysis and decision processes by the web-based Wildland Fire Decision Support System (WFDSS). Agency use of WFDSS began in 2009. A key innovation of the WFDSS software system (http://wfdss.usgs.gov/wfdss/WFDSS_Home.shtml) is that it is a one-stop shop for a series of tools used in wildland fire decision-making. Although no fire effects models are currently included, the intent is to add fire effects assessments (T. Zimmerman, Forest Service, personal communication). Probabilistic fire growth predictions such as Fire Spread Probability (FSPro, Andrews and Finney 2007) are based on the Landscape Fire and Resource Management Tools (LANDFIRE, Rollins *et al.* 2006) and local datasets and can provide a foundation for fire effects prediction. Risk to economic, cultural, water and natural resources, and other values are assessed by a Rapid Assessment of Values-at-Risk process (http://www.fs.fed.us/rm/wfdss_ravar/index.shtml).

Prescription Development

Fire effects models might be used to develop management prescriptions either before or after a fire occurs. Before a fire occurs, a fire effects model might be used to design fuel treatments or plan prescribed fires. In this case, the purpose of the modeling exercise is to choose conditions in which desirable or acceptable fire effects can be achieved, by choosing burn conditions or designing fuel modifications. For example, a burn prescription might be designed to kill small encroaching Douglas-fir (*Psuedotsuga menziesii* [Mirb.] Franco.) without killing larger ponderosa pine (*Pinus ponderosa* Lawson). After the fact, a fire effects model might be used to develop salvage logging guidelines or post-fire rehabilitation plans. In this case, a fire has already occurred, injury to trees or other effects on the site can be observed, and a fire effects model can be used to assess the likely outcomes of the effects. Hood *et al*. (2007) have developed a post-fire tree mortality model that includes cambial damage as a predictive variable.

Long-Term Planning

Fire effects modeling may be useful for land managers in developing targets and managing for sustainability, carbon storage, and forest resilience. Fire effects models may be used as a subcomponent of broader ecological simulation models to understand historic vegetation dynamics and to set targets and constraints for management. For this kind of application, first-order fire effects models are useful in conjunction with, or as drivers of, second-order models of vegetation dynamics. As such, models of vegetation change following fire, a second-order fire effect, depend on predictions of first-order fire effects. That is, first-order fire effects models are often embedded in models of vegetation change. For example, simulations based on a mechanistic ecosystem process model for simulating fire succession (FIRE-BGC, Keane *et al.* 1996) depend on a suite of first-order effects predictions. Similarly, the process-based Mapped Atmosphere Plant-Soil System model (MAPSS) relies on a broad scale fire severity model (MCFIRE) for its first-order effects predictions (Lenihan *et al*. 1998).

Under development, the Integrated Fuels Treatment Decision Support System (IFT-DSS) is intended to support the efficient implementation of fuel treatment programs (Wells 2009). Like WFDSS, IFT-DSS integrates multiple datasets, models, and a user interface into a single system. Point and gridded fire behavior predictions are provided by a variety of models, while fuel consumption and other ecological effects are predicted by CONSUME and FOFEM. Future integration of IFT-DSS and WFDSS is contemplated. Datasets include those available through the LANDFIRE program (Rollins and Frame 2006) and those supplied by users. If feedback loops among researchers, users, software developers, and funding agencies are functioning (Figure 2), IFT-DSS (and WFDSS expanded to include fire effects predictions) would be expected to be a significant driver of development in fire effects models and the databases on which predictions will be based. Already, the IFT-DSS has catalyzed code improvements and improved integration of the Digital Photo Series, Fuel Characteristics Classification System, CONSUME, and Fire Emissions Production

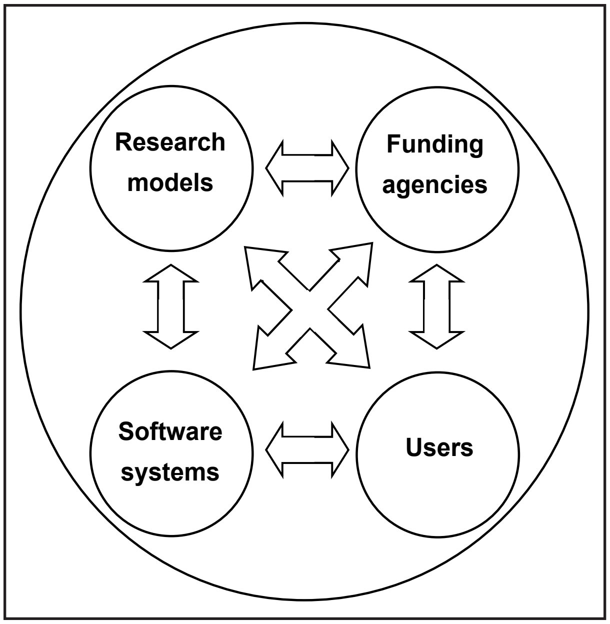

Figure 2. Feedbacks within and among researchers, software developers, users, and funding agencies that affect the development of fire effects software systems.

Simulator developed by the Fire and Environmental Applications Research Team (http://www.fs.fed.us/pnw/fera/).

BEING STRATEGIC ABOUT SOFTWARE DEVELOPMENT

From a land manager's perspective, what is important is not the order of the model, or the degree to which it is process-based. What is important is whether the software housing the model provides information in a form that supports a particular decision-making need. To be most useful for land management decision support, software should be designed to be relatively easy to learn and use, offer support in developing required data inputs, and provide information at the temporal and spatial scales needed by decision makers. The trend toward consolidation (i.e., one-stop shopping) facilitates adoption, training, and support (Wells 2009). Well-designed software systems can incorporate new scientific content with a minimal impact on either the end user or, ideally, the developer.

Limits and Alternatives to the Application of Process Models

Process models are relatively robust and applicable across ecological boundaries (Dickinson 2010). However, process models may require inputs that are not widely available to land managers. For example, Campbell's soil heating model (Campbell *et al*. 1994, 1995) requires initialization data (e.g., soil moisture and texture, soil bulk density, particle density, initial temperature, and thermal conductivity) and boundary conditions (e.g., heat release rate and duration of heating at the soil surface) in the form of an input file (see also Massman *et al*. 2010). For most management applications, it is simply not feasible to acquire these data. FOFEM, which houses this model, attempts to support the model's use by providing default values for many of these inputs. Soil surface heating inputs (boundary conditions) are provided by other models in FOFEM (e.g., the burnout model for large woody debris [Burnup, Albini *et al.* 1995], Table 1). Similar initialization and fire-behavior-related boundary conditions are required for other process models that would predict tree injury and mortality (Butler and Dickinson 2010) and effects on shrub and herbaceous species (Stephan *et al.* 2010). To apply existing and future fire effects models, considerable effort will be required in developing datasets and methods for estimating initialization variables and predicting boundary conditions from fire behavior models and measurements (Kremens *et al.* 2010). In fact, a primary challenge in implementing WFDSS has been obtaining required locally-developed data sources to supplement available LANDFIRE data (T. Zimmerman, personal communication).

Fire effects process models are typically designed to operate at a small spatial scale (e.g., at the scale of an individual plant or in homogeneous landscape patches) and require either assumptions of homogeneity or extensive, spatially explicit initialization and boundary condition information to operate at landscape scales (McKenzie *et al*. 1996). Reinhardt *et al*. (2001) suggest a rough correspondence between simulation approach and spatial and temporal scales (Table 3), but point out that many models contain aspects of more than one simulation method. Differences among process, statistical, and stochastic models in their data requirements are only in degree.

Coordinating but Separating Research and Development

In wildland fire science, model development and model delivery have often been conducted simultaneously. A model and the software that houses it often have the same name and the same developers. This is a natural result of scientists hoping to make their work useful to managers, but it has not proven to be conducive to the production of high quality software systems that consolidate available fire effects models (Wells 2009). Ideally, scientists should design research to address knowledge gaps. Using process-based models is likely to contribute to a deeper understanding of natural systems and thus is intrinsically desirable. Separately, software engineers should design software systems to address managers' needs. These software systems would incorporate whatever models are available and useful in addressing the management needs. When new science becomes available, it could be plugged in to the existing software such as is contemplated for IFT-DSS and WFDSS. Over time, one would expect to see a trend of empirical models being replaced by process models. Ideally, this could occur without a software end-user being retrained and having to learn an entirely new user interface.

Synergy between Science and Application

Feedback loops within and among the research community, system developers, users, and funding bodies govern the development of software systems that involve fire effects predictions. Recently, the interagency Joint Fire Sciences Program has reviewed fire-related

Table 3. Characteristics of alternate simulation approaches in fire effects modeling.

Simulation Approach	Mechanistic / process	Statistical	Stochastic
Temporal scale	Seconds to hours	Year to decades	Centuries
Spatial scale	Individual organism to stand	Stand to watershed	Region
Data requirements	Moderate to high	Low	High
Processing time	Moderate to high	Low	High
Explanatory ability	High	Low	Low
Advantages	Lend insight into underlying process. Extrapolate well to changing conditions. Provide robust building block for linkage to other models.	Associated estimates of error. High accuracy when used within range.	Relatively easy to develop. May provide measure of variability.
Disadvantages	Difficult to develop and calibrate for natural systems that are intrinsically variable. May have extensive input requirements.	May be inapplicable under novel (e.g., new species or ecosystems) or changing conditions (e.g., climate change).	Need for repeated simulations. Difficulty of interpreting model output.

software systems. The program is funding development of an IFT-DSS and further development in BlueSky as models of software platforms that support distributed collaboration among fire and fuel managers (Wells 2009). Sporadic funding by funding bodies of the process-based research models that will form the foundation of future fire effects software systems is of concern to researchers. Funding bodies are concerned that the research community has developed a profusion of software systems, while users are calling for one-stop-shopping. Given the several kinds of information needed by users, a handful of software systems will result (e.g., BlueSky, WFDSS, IFT-DSS). A commitment to steady funding support of research model development by the funding agencies, acknowledgement of the value in the separation of research and software development functions by researchers, and funding support for the coordinated development of fewer, yet more comprehensive software systems are all needed.

Multiple feedback loops need to be robust (Figure 2). One benefit of the current one-scientist (or group of scientists), one-software-system approach is that feedback from user groups is relatively direct. Model validation exercises may be valuable, particularly when data from prescribed and wildfire effects monitoring provide feedback on model performance. Fire Effects Monitors (FEMOs) working within the National Incident Management System and trained to use available software would facilitate feedback. Coordination on fire effects prediction and monitoring with the University of Montana's National Center for Landscape Fire Analysis (http://firecenter.umt.edu/) and the Fire Behavior Assessment Team (www.fs.fed.us/adaptivemanagement/) might also foster valuable feedback.

Improved functioning within the research community is also needed—something that increased or refocused funding cannot bring about alone. The community model concept provides a mechanism for improved coordination, model integration, and continual improvement of research models. At its most basic, a community model implies open source code and version control by some central arbiter. In the more organized form of community model development, researchers organize themselves around the goal of developing and improving software systems by coordinating and prioritizing their work and providing a mechanism whereby research users provide feedback to researchers and developers. Examples of research models under development by a community model process include the Community Ice Sheet Model (Lipscomb *et al*. 2009), the Weather Research and Forecasting Model (WRF Research Applications Board 2006), and the Fire Dynamics Simulator (McGrattan 2005). These research models are characterized by modular construction that facilitates improvement of submodels.

The First Order Fire Effects Model has the potential to become a full-fledged community model, already involving version control and the distribution of source code. Increased coordination with the Core Fire Science community (Sandberg *et al*. 2003) would facilitate the development of approaches to provide boundary conditions from fire models that are needed by FOFEM's component submodels. Ensemble predictions, an approach used extensively in meteorology, has its start in FOFEM with inclusion of more than one tree mortality and duff consumption model. Of particular interest would be the inclusion of more process-based submodels whose results can be compared with existing statistical models. IFT-DSS, by including multiple fire and effects models, also has the potential to provide ensemble predictions (e.g., Burnup vs. CONSUME).

Gaps in Fire Effects Software Systems

Substantial advances have been made recently on software needed for two tasks that are increasingly important to fire managers, particularly in the dry interior west: decision support for wildland fire use and fuel treatment design. Both of these problem areas require software that fully integrates predictions of fire behavior and fire effects, in a spatial context.

Wildland fire use holds enormous promise as a way to allow more land to burn, with the goal of ultimately reducing large, severe wildfires and restoring fire adapted ecosystems (van Wagtendonk 2007; Fire Executive Council 2009). For areas where fuels are excessive or where houses and other high-value resources are in close proximity to wildland fuels, mechanical fuel treatments may be useful in meeting these same goals. There is a need to develop decision support tools to examine ecological outcomes (e.g., tree mortality, erosion, air quality impacts, invasive establishment, wildlife habitat effects, ecosystem recovery) from a range of fire scenarios in a spatial context using a range of inputs (e.g., output from the Fire Area Simulator [FARSITE, Finney 2005], LANDFIRE layers, and weather information). Current efforts supported by the National Interagency Fuels Coordinating Group and the Joint Fire Science Program to design an integrated fuels treatment decision support system IFT-DSS (Wells 2009) recognize many of the concerns and opportunities discussed in this paper, although the focus is not simply modeling fire effects. The Wildland Fire Leadership Council has supported the development of WFDSS, which is currently providing information on fire growth and values-at-risk to support tactical decisions on wildland fires. Though WFDSS does not currently provide fire effects information, the need for such information is recognized.

Any software system will be limited by the availability of validated fire effects models appropriate for the species and ecosystems of interest to fire managers. The availability and capabilities of models describing first-order fire effects on trees (Butler and Dickinson 2010, Kavanagh *et al*. 2010), shrub and herbaceous communities (Stephan *et al.* 2010), and soils (Massman *et al.* 2010) are discussed in accompanying papers. Ultimately, funding agencies and agency administrators need to be willing to adequately fund the basic research that supports software systems (Figure 2).

CONCLUSIONS

Fire effects have been modeled using a variety of approaches, and the resultant models are used in a variety of software systems to meet a variety of land management needs. The current trends in software system development toward consolidated one-stop shopping are expected to have several desirable results. First, duplication of effort on the part of software designers could be avoided. Users would also benefit from having to learn how to use fewer software packages. Finally, development of software systems that are effective in meeting the information needs of fire managers should result in greater focus being given to the continued development of fire effects models that support the software systems.

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