Evaluating Wildfire Hazard and Risk for Fire Management Applications

Robert E. Keane, James P. Menakis, Paul F. Hessburg, Keith M. Reynolds and James D. Dickinson

Abstract At several spatial scales, fire managers need accurate and comprehensive assessments of wildfire hazard and risk. Assessments are needed to plan, prioritize, and implement management actions, which can range from pro-active prescribed burning to real-time fire suppression. They can be complex, taking many forms and using few to many variables. Past fire hazard and risk assessment projects often lacked a proper decision support platform (see "An Overview of the Ecosystem Management Decision-Support System") on which to objectively evaluate decision costs, benefits, and trade-offs. However, decision support systems (DSS), like the Ecosystem Management Decision Support System (EMDS), now make such analysis readily within reach. Future fire management decisions will no doubt make increasing use of DSSs in decision-making. This chapter summarizes various methods of computing fire hazard and risk. Then, we present

R. E. Keane (✉) · J. P. Menakis
U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fire Sciences Laboratory, 5775 Hwy 10 West, Missoula, MT 59807, USA
e-mail: rkeane@fs.fed.us

J. P. Menakis
e-mail: jmenakis@fs.fed.us

P. F. Hessburg
U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Wenatchee Forestry Sciences Laboratory, 1133 North Western Avenue, Wenatchee, WA 98801, USA
e-mail: phessburg@fs.fed.us

K. M. Reynolds
U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Corvallis Forestry Sciences Laboratory, 3200 SW Jefferson Way, Corvallis, OR 97331, USA
e-mail: kreynolds@fs.fed.us

J. D. Dickinson
U.S. Department of Agriculture, Forest Service, Okanogan-Wenatchee National Forest, 215 Melody Lane, Wenatchee, WA 98801, USA
e-mail: jddickinson@fs.fed.us

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two projects that use EMDS to prioritize resources for regional and national fire management application. Finally, we discuss additional fire hazard and risk modeling research needs.

Keywords Wildland fire · Forest fuels management · Wildfire hazard · Wildfire risk · Spatial decision support · EMDS

1 Introduction

Fire management in the United States faces some remarkably challenging issues in the coming years. Decades of fire exclusion policies and successful fire suppression programs have resulted in increased canopy and surface fuel loadings that often foster large wildfires, which can potentially damage ecosystems, burn property, and harm people (Laverty and Williams 2000; Keane et al. 2002b). Proposed fuel treatments designed to mitigate these conditions are becoming risky and expensive to implement, and the cost of fighting large wildfires is rapidly growing (Calkin and Gebert 2006; Venn and Calkin 2007). To make matters worse, many people are moving into the nation's fire-prone wildlands, further escalating wildfire-caused risk to life and property. In addition, predicted changes in climate point to increased fire season length, burned area, and fire severity (Brown et al. 2004; Running 2006; Westerling et al. 2006). To face some of these issues, government fire management agencies have implemented the National Fire Plan (NFP). The NFP is a comprehensive strategy to return the landscape to healthy, sustainable, and fire-resilient ecosystems that will provide protection to those who live in the wildland urban interface (GAO/RCED 1999).

One tool to aid fire management in solving complex future issues and implementing the NFP is fire hazard and risk modeling (Hann and Bunnell 2001). Assessing potential damage and benefits of wildland fire to ecosystems, structures, and people will provide fire management with the critical information they need to decide (1) where to allocate funds and fire fighting resources, (2) which landscapes are in need of fuel or ecosystem restoration treatments, and (3) where and how to implement possible mitigation treatments. Fire hazard and risk assessment products can be used to plan, design, prioritize, and implement fire management strategies at several spatial scales, and across many organizational boundaries (Keane et al. 2010). Assessment products can be incorporated into decision support tools, such as the EMDS system, to facilitate fire management planning, and increase transparency of decision-making. Fire management will find EMDS to be a critical decision tool in the future because evaluations of fire hazard and risk will need a generalized, consistent, and transparent context in which to assess possible fire management decisions (Hessburg et al. 2007).

Fire hazard and risk modeling can be accomplished using diverse methods and approaches, each of which has unique limitations. Advances in computer technology, fire behavior modeling, and fire ecology simulation have greatly improved

fire hazard and risk prediction, but further advances in these fields are needed to ensure that fire hazard and risk maps portray the most appropriate and consistent variables for evaluating management concerns. This chapter discusses the use of fire hazard and risk modeling as input in decision support tools. First we define and summarize risk and hazard terminology and methods, and then we describe the use of fire hazard and risk analysis in fire management. The challenges facing fire hazard and risk modeling for decision support are discussed next, along with two detailed examples that illustrates both limitations and benefits of this type of modeling at two spatial scales. Finally, we discuss ongoing research needs.

1.1 Background

In this chapter, "hazard" is considered an act or phenomenon with the potential to do harm (NRC 1989; Hardy 2005). The notion of fire hazard represents the potential susceptibility or vulnerability of existing conditions to wildfires. Fire hazard is typically described independent of weather, using surface and canopy fuel characteristics. It can be either expressed as potential fire behavior (e.g., flame length or fireline intensity) arising from existing fuels, or as a critical fuel property (e.g., loading or biomass) (Hogenbirk and Sarrazin-Delay 1995). The term "risk" is used to describe the probability that a fire event might occur, as affected by other causative agents and interacting factors (Bachmann and Allgower 1999; Bachmann and Allgower 2001). We amend this definition to also include the subsequent ignition of the adjacent fuels (i.e., fire spread) and the potential for that ignition to create a specific fire event. We likewise adopt the Bachmann and Allgower (1999) definition of fire risk as the likelihood a specified event will occur within a specific time period or from the realization of a specified hazard.

Fire hazard has been described using a variety of approaches and variables including expected fire behavior (Hardwick et al. 1998; Hessburg et al. 2007), fuel characteristics (Hogenbirk and Sarrazin-Delay 1995), satellite image classifications (Cohen 1989; Jain et al. 1996; Ercanoglu et al. 2006), topography analysis (Yool et al. 1985), expert knowledge (Gonzalez et al. 2007), socio-economic analysis (Bonazountas et al. 2005), and crown fire index calculations (Fiedler et al. 2001). Fire risk, on the other hand, has been described as the probability of fire weather occurrence (Gill et al. 1987), the frequency of rare fire events (Neuenschwander et al. 2000), the probability of a wildfire causing tree mortality or loss of wildlife habitat (Ager et al. 2011, 2007, respectively), and the probability distribution of ignitions, fire sizes, and burning conditions (Parisien et al. 2005). The diversity of fire risk analysis approaches arises from specialized management objectives, while fire hazard assessment projects are generally designed around the availability of the spatial data layers used to represent hazard. Fire risk, on the other hand, has been described as the probability of fire weather occurrence (Gill et al. 1987), the frequency of rare fire events (Neuenschwander et al. 2000), the probability of a wildfire causing tree mortality or loss of wildlife habitat

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An adequately comprehensive assessment of either fire hazard or risk is difficult because it requires extensive knowledge across a wide variety of disciplines that includes simulation modeling, geographic information system (GIS) analysis, advanced statistics, fire behavior and effects, and fuels sampling and map prediction (Keane et al. 2010, 2013; but see Thompson and Calkin 2011). As a result of limited data and experience, many fire managers find it difficult to create those layers that can be directly used in hazard and risk assessment. Additionally, the ability of managers and scientists to adequately sample fuels and predict much needed fuels maps may be much poorer than originally thought (Keane et al. 2013).

2 Challenges of Fire Hazard and Risk Mapping

2.1 Selected Variables

Most analyses attempt to describe a full range of hazard and risk using multiple variables because of the astounding complexity and variability of wildland fire. These variables are computed using a variety of methods, protocols, and computer programs (Neuenschwander et al. 2000; Sampson and Sampson 2005). For example, to define fire danger in subwatersheds ($\sim$10,000 ha), Hessburg et al. (2007) evaluated three primary topics—fire hazard, fire behavior, and ignition risk. Fire hazard evaluated conditions for surface and canopy fuels; fire behavior evaluated probable spread rate, flame length, fireline intensity, and crownfire potential; ignition risk evaluated relative plant greenness index (NDVI), lightning strike potential, and the Keetch-Byram and Palmer drought indices. In their application, they were working to explain all of the variance in fire danger expressed at the subwatershed scale.

In some applications, use of various combinations of fire hazard measures together may be inappropriate because they are highly correlated, contradictory, or unsuited for the fire management issue being addressed. For example, one hazard analysis effort may use high fireline intensity to connote high fire hazard, while another may use fast fire spread rates (Hardy 2005; Sampson and Sampson 2005). A high intensity fire may be a hazardous fire, but this type of fire can be appropriate and desirable in stand-replacement fire regime ecosystems, such as lodgepole pine (Heinselman 1981; Romme and Knight 1981; Agee 1998). It is clear that the selection of variables and the logic for rating fire hazard and risk is ultimately governed by the objectives of the analysis. A concise statement of objectives is

vitally important before any hazard analysis is initiated, and the variables selected for the analysis must be matched to these objectives.

There is both art and science in deciding which variables to include in the fire hazard and risk analysis. Complexity, uncertainty, and errors tend to increase as more variables are added to hazard analysis, yet too few variables may not adequately answer the hazard analysis objective. A good approach is to select a small set of variables that integrate the behavior of other associated variables. Fireline intensity, for example, is better at describing fire hazard than fire behavior fuel model because it integrates temperature, relative humidity, wind, and slope, along with fuel model, into its calculations (Hough 1968). Scorch height might be even better because it could also be used to evaluate potential tree mortality if that fit the analysis objective. To eliminate potential bias though, it is critical that selected variables are not correlated to each other within the analysis, unless the objective is to explain as much of the variance as is possible.

It is fundamentally important that the origin, temporal domain, spatial scale and resolution, data limitations, and uncertainty of fire hazard variables and maps be recognized when interpreting them (Cohan et al. 1984; Tainaka 1996). Complete metadata on the selection, computation, and units of fire hazard variables is critical for understanding and interpreting analysis results in the decision making process. The quality, type, and source of the data input used to compute fire hazard variables must also be known to facilitate appropriate fire hazard analysis. Finally, the accuracy and error associated with each input, intermediate, and derived variable used in analyses should be evaluated in fire hazard interpretation. Unfortunately, this step is rarely accomplished because it is difficult and expensive to quantify error and uncertainty in most fire hazard and risk variables and maps.

2.2 Analysis

An enormous challenge in fire hazard and risk modeling is adequately translating potential fire behavior and effects from terrain, slope, fuel, and weather characteristics to the appropriate spatial and temporal contexts. One estimate of fire behavior for one point in time and space may over-generalize the complex interactions that occur during a fire, or within a fire regime (Morgan et al. 2001). A common assumption in many fire hazard analyses is that the fire that occurs in a pixel is a head fire and therefore, represents a worst case scenario (Keane et al. 2008). However, that pixel might be in a topographic position where head fires are rare, or that pixel may rarely experience the weather needed to sustain a head fire. A more accurate representation of fire hazard would be to quantify the distribution of probable fire intensities and spread rates at each pixel as would occur under a wide variety of weather conditions, wind directions, fire ignition locations, spread patterns, and suppression strategies. Measures of hazard and risk could then be derived from the distributions, such as the probability of wildfire occurring above a threshold fireline intensity (Farris et al. 2000).

Finney et al. (2011) have implemented this strategy in the FSPro simulation package, which simulates the probability of fire spread based on thousands of FARSITE[1] runs with multiple weather scenarios and random ignition locations for real-time, operational wildfire application. The down-side of this approach is that it is computationally demanding, making it difficult to complete for large regions, at resolutions that are often required of hazard analysis (Keane et al. 2008). Moreover, it is somewhat problematic to implement a temporal component because the fuels are considered static for the entire simulation, and a finite set of historical weather scenarios are used.

Some efforts at describing fire hazard have taken disparate GIS layers and merged them together to create a final layer (Sampson and Sampson 2005). A typical example would be merging the flame length, surface fuel model, and canopy bulk density map layers to create a fire hazard map: two layers describe continuous variables with differing units, while the third is a categorical variable. This approach has its own problems since each layer has a unique error distribution, mapping resolution, analysis scale, and computational detail, all of which are compromised when merged. That is, the solution acquires the lowest significant figure of the components. An approach that might result in lower error propagation might be to explicitly set a threshold value for continuous maps or a set of values for categorical maps, above which fire hazard is high and below which hazard is low. This could be used to create a binary variable data layer that can then be merged with other binary maps (Hessburg et al. 2007). Threshold values could be based on a theoretical or physical context, and take into account the sensitivity and error of the parameters that were used to create the continuous data layer or to compute the behavior from the fire model.

2.3 Weather

The use of weather in fire analyses is also quite challenging. Many efforts assume severe fire weather (e.g., 90 or 99th percentile temperature, high wind, low fuel moistures) to compute the fire characteristics that describe "worst-case" hazard or risk, in the context of a specific management objective. These analyses, however, rarely describe the frequency of that severe weather event for all ecosystems within the analysis area. Extremely dry conditions, for example, may occur frequently in low-elevation pinyon-juniper patches, but they may be relatively rare in high-elevation lodgepole pine ecosystems, yet both may have the same hazard value. It is important that analysis weights the frequency of the fire event with the severity of impacts when describing hazard and risk.

[1] FARSITE is a Windows-based fire behavior and growth simulator used widely by USDA and US Department of Interior agencies (Finney 1998).

A similar problem with percentile weather variables arises when assessing fire hazard across large landscapes, especially in mountainous terrain, as 90, 95, and 99th percentile fire weather differs across diverse topography. Severe fire weather at low-elevation, south-facing, and ridgetop sites may be quite different from severe fire weather in high-elevation, north-facing, or valley bottom settings. Some hazard analyses use only one fire weather scenario across the analysis landscapes taken from a single weather station, which can grossly underestimate weather variability.

Some fire management analyses include weather variables as a rating of fire hazard or risk (Gill et al. 1987). While this provides a useful representation of the climate that fosters high fire hazard, the rating is not useful as a measure to detect changes in hazard as a result of fire management activities. Weather is the one factor in fire dynamics over which managers have the least control. The challenge then is to select a fire hazard or risk variable that integrates the weather with fuel conditions, such that it can be used to monitor changes in fire hazard as fuel treatments are implemented, and as wildfires burn. Smoke emissions, for example, is a valuable variable for predicting the likelihood of fire effects because it integrates fuel loadings by size class with weather to compute consumption and then emissions (Lutes et al. 2009).

Wind also presents a special challenge in simulating fire hazard and risk even though it is a major factor governing fire behavior, because it is difficult to quantify in a spatial and temporal domain for many fire analyses (Forthofer et al. 2003). Wind is complex because it has a magnitude (wind speed), duration (gusts), and direction, all of which can heavily influence predicted fire behavior and subsequent fire hazard. Moreover, these three properties are correlated with each other and often vary by geography and with the terrain (Rehm and Mell 2009). Therefore, it may be difficult to derive wind scenarios that have adequate spatial resolution, and are applicable across large regions and long time periods. It is critical that wind scenarios in fire hazard analysis also match management objectives and be described in sufficient detail so that results are interpreted in the proper context.

2.4 Scale

Many fire hazard analyses tend to concentrate on stand-level fuels and their characteristics without recognizing the spatial influence of topography, winds, and adjacent fuels on wildland fire (Finney 2005). The spatial patterns of landscape composition and structure are important to fire hazard because fuel pattern will influence fire spread and intensity (Loehle 2004). Spatial patterns of fuels can also dictate the design and placement of fuel treatments on the landscape (Agee et al. 2000; Finney 2001). However, as spatial resolution decreases and the extent of the analysis area increases, spatial relationships may become less important. Regional and national evaluations of fire hazard and risk to prioritize watersheds for fuels treatments, for example, may not require detailed analysis of spatial pattern as

much as project-level analyses conducted to optimize fuel treatment locations (Hessburg et al. 2007).

Scale is also an important consideration in determining the size of the fire hazard analysis area, especially if spatial interactions of fire spread are included (Bourgeron and Jensen 1994; Tang and Gustafson 1997; White et al. 2000). If the analysis area is too small, the spatial representation of simulated fires will be truncated because most fires will encounter the defined landscape border before they reach their full size (Keane et al. 2002a). However, if the landscape is too big, the high data and computational requirements may prohibit a statistically sufficient number of fire simulations. The challenge is to select a landscape extent that adequately represents the spatial dynamics of disturbance, while still being appropriate for the management objective. Karau and Keane (2007) found that approximately 100 km^2 is adequate for many spatially explicit simulations of fire spread, but this varies by topography, ecosystem, and geography. They also found that the simulation area must contain sufficient buffer around the analysis landscape to minimize bias in fire spread. Keane et al. (2002a) found that this bias becomes negligible when the size of the surrounding buffer area is roughly eight to ten times the size of the focal landscape.

The resolution and detail of the primary data layers used to create hazard maps are also important. The fire behavior fuel models that are used in many fire hazard analyses, for example, are simplified classifications of fire observations that result in a decreased resolution of output (Scott and Burgan 2005). And while the LANDFIRE project[2] represents significant progress in providing the fine-scale spatial data needed in fire management across the conterminous US (Rollins et al. 2009), its national scope demands a coarser treatment of vegetation and fuels descriptions that sometimes result in moderate or lower map accuracy at local scales (Keane et al. 2013). Fuel characteristics are notoriously variable and scale-dependent, making them difficult to sample and map (Keane et al. 2013), and few fire behavior and fire growth models have sufficient resolution and detail to adequately represent actual fuel load distributions (Keane et al. 2001, 2013; Keane 2013). It is important that users and decision-makers recognize the scale and resolution limitations of the input spatial data when interpreting the fire hazard and risk assessment outputs. Elaborate and detailed analysis may actually expand rather than contract modeling error and uncertainty in comparison to more simplified analysis.

3 The PNW EMDS Fuels Management Project

A regional-scale decision support system (DSS) was developed for the Pacific Northwest Region (PNW) of the US Forest Service based on wildland fire hazard and risk analysis. The PNW fire danger model was designed to aid fire managers,

[2] A nation-wide geospatial mapping project offering data layers at the landscape-scale. For more information go to http://www.landfire.gov.

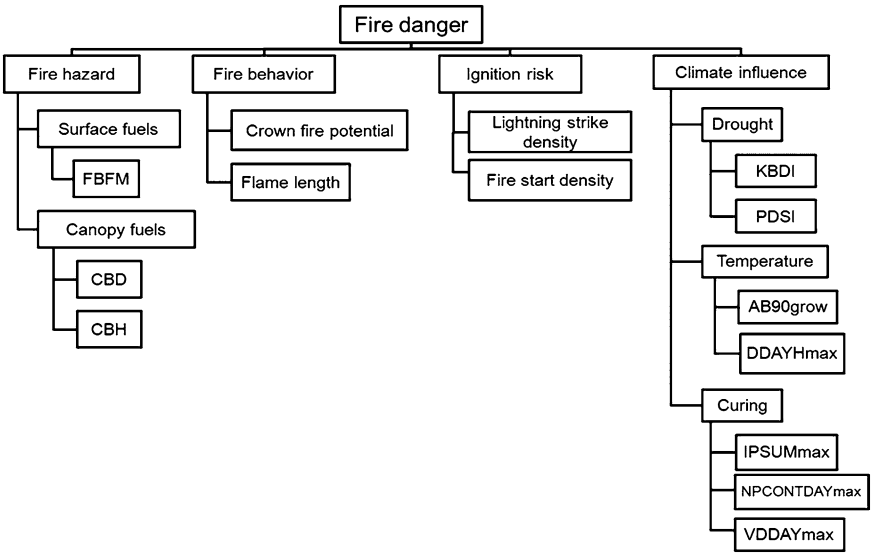


Fig. 1 Dendrogram showing organization of the PNW EMDS fire danger model. The evaluation of fire danger is composed of four primary topics—fire hazard, fire behavior, ignition risk, and climate influence. Under each of these four primary topics are secondary and elementary topics, where data are evaluated. Abbreviations are: FBFM = the fire behavior fuel models of Scott and Burgan (2004), CBD = canopy bulk density ($kg \cdot m^{-3}$), CBH = canopy base height (m), KBDI = the Keetch Byram Drought Index, PDSI = Palmer Drought Severity Index, AB90grow = the number of days above 90 °F (32.2 °C) during the local growing season, DDAYHmax = the mean penultimate maximum degree-days heating during the local growing season while temperatures were >18 °C, IPSUMmax = an inverted precipitation index for the local growing season, NPCONTDAYmax = the mean penultimate maximum consecutive days without measurable precipitation (<0.3 cm), while temperatures were ≥10 °C, and VDDAYmax = the mean penultimate maximum days with a vapor pressure deficit <1000 Pa while temperatures are ≥10 °C during the local growing season

who were interested in preventing large wildfires, with prioritizing watersheds for possible ecosystem restoration and fuel reduction treatments. This is a prevention-oriented model that is designed to detect changes in an analysis area as treatments are implemented, and as controlled and uncontrolled wildfires modify the landscape. In contrast, a suppression-oriented model would be designed to aid in predicting which subwatersheds of a Region might experience a large-scale and severe wildfire in a given fire season. Suppression-oriented models are often used to strategically allocate fire preparedness and suppression resources where the threat of a large and rapidly expanding fire are likely.

The PNW fire danger model consists of logic and decision models. The logic model (which we discuss here) evaluates the state of each landscape (in this example, each subwatershed) as a function of four primary topics: fire hazard, fire behavior, ignition risk, and climate influence (Fig. 1) (Hessburg et al. 2007). Each primary topic has secondary topics under which data are evaluated. Surface

(FBFM, fire behavior fuel model) and canopy fuels (crown base height and crown bulk density) were included under fire hazard. Under fire behavior, flame length and crown fire potential were computed assuming an escaped wildfire burn scenario. Lightning strike and fire start density were computed under ignition risk. Climate influence evaluated three secondary subtopics: drought likelihood (drought), fire season temperature (temperature), and fuel curing likelihood (curing) topic. The long and short term drought descriptors of Palmer drought severity index (PDSI) and the Keetch-Byram drought index (KBDI), respectively, were evaluated under the drought subtopic. Under the temperature subtopic, the effects of two temperature variables on fire danger were considered; "the number of hot days during the growing season", which was computed as the number of days above 90 °F (32.2 °C) during the local growing season (AB90grow), and "growing season degree-day heat sums", which was computed as the mean penultimate maximum degree-days heating during the local growing season while temperatures were >18 °C (DDAYHmax). These data were obtained from Oak Ridge National Laboratory (ORNL, Hargrove et al. 2004). Subwatershed values were calculated as zonal means.

Three precipitation/moisture variables were considered for their effects on fuel curing; "seasonal dryness"—an inverted precipitation index for the local growing season (IPSUMmax), "mild to hot days without rain"—the mean penultimate maximum consecutive days without measurable precipitation (<0.3 cm), while temperatures were ≥10 °C (NPCONTDAYmax), and "mild to hot days with low humidity"—the mean penultimate maximum days with a vapor pressure deficit <1000 Pa while temperatures are ≥10 °C during the local growing season (VDDAYmax). These data were also obtained from ORNL, (Hargrove et al. 2004). Subwatershed values were calculated as zonal means.

All mapped continuous and ordinal fire hazard variables were evaluated based on a threshold value and then summarized to subwatersheds (12-digit Hydrologic Unit Code or HUC), to create new, spatially-descriptive variables. For example, pixels with canopy bulk density (CBD) values exceeding 0.15 $kg \cdot m^{-3}$ were analyzed to compute area (CBDarea) and level of aggregation (CBDaggregation) of high crown fuels for the subwatershed. Values of these new subwatershed variables were then evaluated based on a threshold value and a fuzzy membership function that computed a value between zero (meaning no strength of evidence that the watershed is above the threshold) and 1.0 (maximum evidence that the watershed is above threshold) (Hessburg et al. 2007).

The FIRE HAzard and Risk Model (FIREHARM) was used to compute all pixel variables for the fire behavior topics and KBDI (Fig. 2) (Keane et al. 2010). FIREHARM is a C++ program that computes fire characteristics over time using spatially-explicit daily climate data to simulate fuel moisture and a host of embedded routines that calculate commonly used measures of fire behavior, fire danger, and fire effects (Fig. 2). FIREHARM is a modeling platform that integrates previously developed fire simulation models into its structure and contains no new fire behavior or effects simulation methods. Although FIREHARM's input and output are spatial, the model is not spatially explicit because it does not simulate

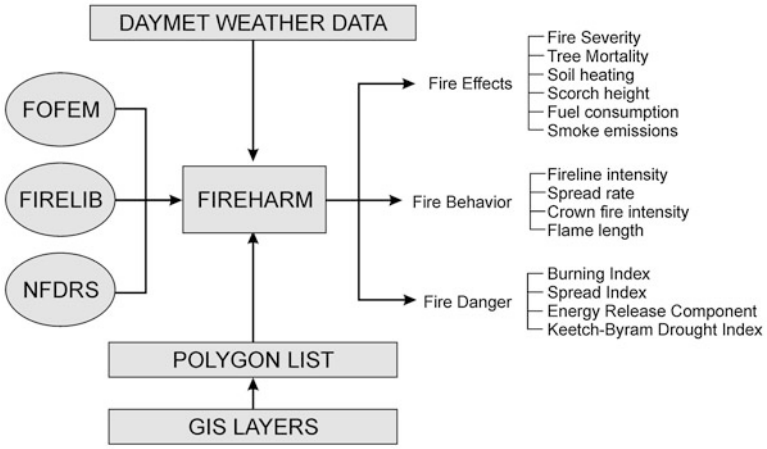


Fig. 2 Compartment diagram of the FIREHARM model showing input requirements and output data. FOFEM is the First Order Fire Effects model (Reinhardt and Keane 1998), FIRELIB is a set of functions for predicting fire behavior (Bevins 1996), and NFDRS is the National Fire Danger Rating System (Deeming et al. 1977)

interactions across pixels, such as fire spread. Instead, the model assumes that pixels (or polygons) experience head fires, and then simulates the fire characteristics from antecedent weather. FIREHARM does not simulate crown fires directly, but it does calculate crown fire intensity (Rothermel 1991; Finney 1998).

FIREHARM can be run in two modes. In the event mode, which is used for most fire hazard mapping, the user enters fuel moistures and ambient weather conditions for a given situation or event, such as a worst case wildfire, and the program will calculate all fire variables for this specified situation. In the temporal mode, FIREHARM simulates fuel moistures from daily weather to compute daily fire characteristics over 18 years. The program then calculates the probability of a user-specified event occurring during the 18-year weather record and this probability value is used to describe potential risk.

Most of the data used to support this project came from the National LANDFIRE mapping project (www.landfire.gov). Seven LANDFIRE map zones (1, 2, 3, 7, 8, 9, 10, 18) defined the project area (www.nationalmap.gov). Map zones are broad biophysical land units represented by similar surface landforms, land-cover conditions, and natural resources (Fig. 3). Subwatersheds, defined by the US Geological Survey (Seaber et al. 1987, http://nhd.usgs.gov/wbd.html) as nationally consistent, 12-digit hydrologic units, were the smallest subunits within map zones, and all data were summarized to them. All spatial data representing the fire hazard topic (surface and canopy fuels) were taken directly from LANDFIRE for the analysis area. These same data were also used as input to the FIREHARM program. Weather data are input into FIREHARM using the DAYMET US database (http://ww.daymet.org) developed by Thornton et al. (1997). DAYMET is a computer model that was used to generate daily spatial surfaces of temperature,

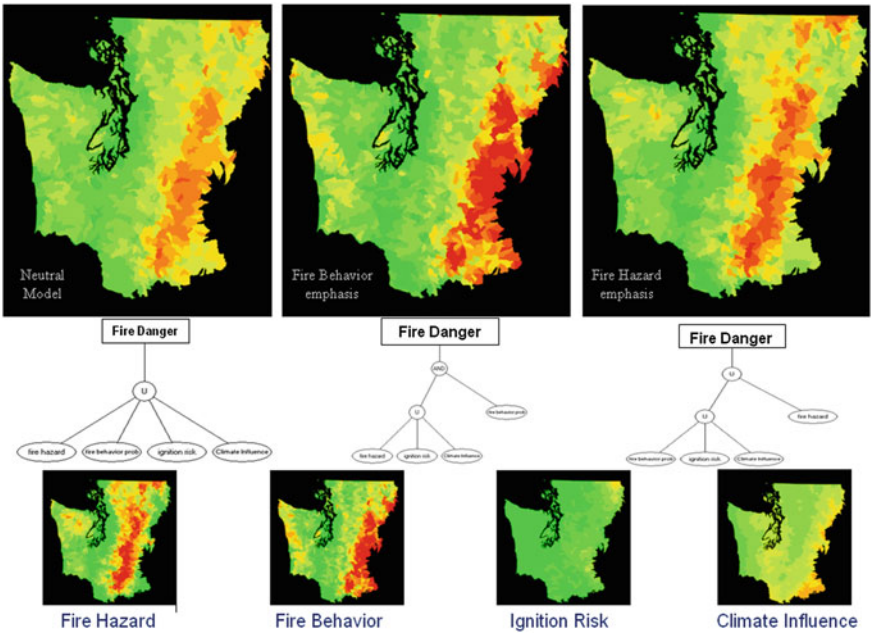


Fig. 3 Example EMDS fire danger model outputs for map zone 1 of the PNW study area. Three sets of outputs are shown for a single map zone (zone 1, western Washington State). The *top row* of maps shows differences in *fire danger* when changing the logical operators used. The *middle panel* shows the differences in the logical operators used to evaluate the data in the NetWeaver models. The *bottom row* of maps shows the results after evaluating each primary topic—*fire hazard*, *fire behavior*, *ignition risk*, and *climate influence*. The results of primary topic evaluations do not vary among the three examples, only the use of operators. The union (U) operator in the left example treats the data associated with each primary topic as equivalently compensating factors. This is the neutral model. The middle example uses the AND operator to set off fire behavior as the limiting factor (*fire behavior emphasis*). The right example uses the union operator to evaluate fire hazard after the other three topic evaluation results have been considered as equal and compensating, effectively weighting fire hazard threefold over each of the other topics (*fire hazard emphasis*)

precipitation, humidity, and radiation over large regions of complex terrain (Thornton et al. 1997, 2000). Additional spatial data comes from other established sources such as PDSI (http://www.ncdc.noaa.gov/data-access), the National Climate Data Center, or derived using existing, published, and documented models and modeling procedures.

In Fig. 3, we show three fire danger evaluation outputs for a single map zone (zone 1, western Washington State). The results of primary topic evaluations do not vary among the three examples, only the use of operators. These input data layers for the map zone 1 evaluations were created by running FIREHARM in the temporal or probabilistic mode. The example in Fig. 3 shows how decision-makers and analysts can "game" the fire danger model to develop alternative ways of emphasizing or considering the data. The fire danger output layers can be then

used to create ordered lists of watersheds for use in prioritizing areas geographic areas for fuel treatments.

Independent of the DSS model development, there were issues that had to be addressed during development. First, LANDFIRE base layers could not be edge-matched across zones to create seamless regional or national layers. This was due to the well-known and pre-existing problem of satellite imagery radiometric readings being calibrated by map zone, rather across map zones; an intractable task due to the larger extent of the area and the variability represented across satellite scenes. The result of calibration was high integrity of satellite sensor values within a map zone, but somewhat differing numerical values for the same conditions across map zone boundaries. That is, map zones could not be edge-matched in terms of their numerical data. This affected all vegetation, fire effects, and fire behavior base layers that were based on satellite imagery, or their derivatives. To resolve this problem, all fire danger calculations were relativized within each map zone so that map zone outputs could be evaluated side-by-side, on a common footing. Second, regional fire managers were more interested in a simple suppression-oriented than prevention-oriented model for operational use, because of upper level management emphasis on wildfire protection rather than pro-active fuel treatments. Their selected variables mostly concerned fire weather rather than fuels conditions. This would make the task of detecting change in fire hazard and risk as a result of fuel treatments problematic.

4 National EMDS Fuels Treatment Prioritization Project

A national-scale DSS was developed across multiple land management agencies (Department of Agriculture's Forest Service; and Department of the Interior's Bureau of Land Management, Bureau of Indian Affairs, National Park Service, and Fish and Wildlife Service) to allocate the substantial fuel-treatment budget on federal lands within and across agencies. To address the concerns by Congress and the General Accountability Office for a rational, transparent, and reproducible process for allocating the fuels-treatment budget (GAO 2002, 2003, 2004, 2007), the National EMDS Fuels Budget decision support model was designed to evaluate wildfire potential across all administrative units in the continental US, and to establish priorities for allocating the fuel-treatment budgets within the agencies.

The National EMDS Fuels Budget model consists of both logic and decision models (Reynolds et al. 2009). The logic model delineates wildland fire potential in terms of fire behavior and fire probability of occurrence under extreme fire weather conditions. Fire behavior is represented by crown fire potential and surface fire potential, in terms of fireline intensity, rate of spread, and flame length. Crown fire potential was delineated by assigning relative classes (such as very low to extreme) to spatial data of existing vegetation types based on expert knowledge (Menakis et al. 2003; Menakis 2008). Surface fire potential was represented by surface fuels, which were calculated either using the Fuels Characteristic

Classification System (Ottmar et al. 2007), or the BehavePlus fire behavior model (Andrews 2008) and the Scott and Burgan (2005) fire behavior fuel models mapped by LANDFIRE.

Fire probability was represented by both fire weather and fire occurrence. Fire weather included problem fire days and length of fire seasons, with problem fire days computed as an average number of days a year from 1982 to 1997 that a fire could experience extreme fire weather, based on thresholds of high temperature, high wind, and low humidity (Menakis et al. 2003). Fire season length was based on the average number of days per year that the relative energy release component (RERC) was above 95 % based on daily RERC maps from 1980 to 2005 (Jolly 2008). Fire occurrence was based on small and large fire occurrence from 1980 to 2003. Small fires were defined as any fire greater than 0.1 acre and large fires were any fire greater than 500 acres.

The criteria in the decision model for assessing priorities were the wildland fire potential from the logic model, and its consequences, along with performance and opportunity criteria (Reynolds et al. 2009). The consequences criterion described the negative effects of wildland fire associated with untreated fuels, and included measures of proximity to wildland urban interface (WUI), ecosystem vulnerability, potential emissions, and potential water quality impacts. WUI data (Radeloff et al. 2005) were used to measure the number of structures that could be affected from a wildfire on federal lands. Ecosystem vulnerability measured the risk of losing key ecosystem components from a wildfire, as measured by the FRCC (Schmidt et al. 2002, http://www.frames.gov/partner-sites/frcc/frcc-home). Emissions measured the amount of smoke that would likely be produced by a wildfire and its impact on people. Lastly, water quality measured the impact of wildland fire to mapped municipal watersheds. The performance criterion was designed into the model to gauge administrative-unit performance in terms of efficiency and effectiveness of fuel treatments. Unfortunately, since data were unavailable in the agency databases for this criterion, it remained unimplemented in the decision model (Reynolds et al. 2009). However, the percent of land with minimal departure from frequent, low-severity fires that occurred historically was included as proxy for efficiency, since these lands are typically more economically efficient to maintain than to rehabilitate once fire has been removed for several years (Schmidt et al. 2002; Reynolds et al. 2009).

The opportunities criterion described other resource benefits that could be accomplished with fuels management. The two major measures included in this criterion were ecosystem restoration and biomass opportunities. Ecosystem restoration focused on fuel treatments that would restore ecosystems back to their historic condition, and was based on the FRCC metric (Schmidt et al. 2002). Biomass opportunity focused on the availability of biomass to produce bio-energy and bio-based products (such as lumber, composites, paper and pulp, furniture), and included both the availability of biomass and its proximity to processing plants. For information security reasons, in these analyses we only had the amount of biomass available on federal lands (Blackard et al. 2008).

The National EMDS Fuels Budget decision support model has vastly improved since it was first implemented in 2006. Further improvements could be gained with respect to the extent of data coverage, data quality, and the sophistication of the available models (Reynolds et al. 2009). As national, consistent data become available, more refined methods should be incorporated into this decision model (such as the methods used in the aforementioned PNW fire danger model). This is especially true with the simplistic methods used to calculate wildland fire potential. Nevertheless, this approach has proved to be successful in providing an accountable and transparent methodology in setting budget priorities for fuel-treatment nationally. This success can be attributed to the effective engagement of scientists, managers, and technical specialists at various levels of the agencies.

5 Research and Management Needs

5.1 Fire Simulation Models

The single biggest need for future fire hazard and risk projects is the development of new fire behavior and effects models that are spatially explicit and integrate cross-scale dynamic factors into their design. While contemporary one-dimensional point models of fire behavior (e.g., BEHAVE) represented a major advancement in wildland fire science in the early 1970s, they are now over 30 years old, and fail to fully account for the multitude of three-dimensional spatial interactions of fire spread and intensity. Crown fires, for example, are poorly simulated in current fire behavior models because heat transfer properties of convection and radiation are not directly simulated in all three dimensions. Matching the scale of fire behavior and effects with the scale of simulation is also a research need. Smoldering combustion, for example, must be simulated at finer scales than the scales used to simulate crown fires.

It is also critical that these new fire models use inputs and outputs that are measurable on the landscape. Many inputs and most outputs of the Rothermel (1972) spread model are difficult, if not impossible, to measure with any degree of precision or accuracy. Designing models around output variables that can be precisely measured in the field using standardized protocols is important because it will allow the manager to evaluate the performance of fire models with confidence. It is also important that the inputs are easily and accurately measured so that high quality digital input maps can be created and used in hazard and risk projects.

Fire management will probably not be able to use the new and improved three-dimensional spatially-explicit fire behavior models in the near future because the complexity of the models will make them unwieldy to use. Therefore, a critical research need is the proper synthesis of complex fire behavior model results into simplified management-oriented models for easily accomplished fire hazard analysis. For example, results from complex fire models that simulated fire behavior for many environmental conditions (weather, fuels, and topography) can

then be used to develop empirical models, following the physical relationships used in Rothermel (1972), to make a more simplified fire behavior model for managers. Or, complex models can be run using different parameterizations to determine thresholds of response that identify when the Rothermel (1972) algorithms are weak and should be modified to correct limitations. Or, scale adjustment factors could be approximated for the Rothermel (1972) model from response surfaces of the complex fire models.

5.2 Fuels

Considerable research in the field of wildland fuel science is needed to meet the burgeoning needs of fire management in the coming years. Most fire behavior models use simplistic fuel models to represent complex fuelbeds (Burgan and Rothermal 1984). Fire managers often used the standard 13 Northern Forest Fire Laboratory (NFFL) fuels models (Anderson 1982) until Scott and Burgan (2005) created a new set of 40+ models. These fuel models do not describe actual fuelbed loadings on the ground, rather they contain fuel characteristics that are calibrated to agree with observed fire behavior. Therefore, fuel models can never be used to quantitatively describe fuelbed characteristics (e.g., fuel loadings, the key fuelbed property) because they are abstract representations of fire behavior. These coarse fuel models represent the finest resolution that can be used currently to describe fire hazard and they are too broad to adequately represent significant changes in the fuelbed. Effective fire analyses will depend on the subtle differences in fuels to characterize relative differences in fire hazard and risk across the landscape.

Accurate fuel sampling techniques must be developed to quantify key fuel characteristics (e.g., loading, specific density, surface-area-to-volume ratio) across multiple new and existing fuel components (e.g., logs, duff, litter) (Keane et al. 2013). These sampling techniques must be easy for management to learn and implement, and they must also provide for accurate assessments at the scale of evaluation. Canopy fuels represent a special challenge because it is the three-dimensional distribution of canopy fuels that ultimately governs crown fire behavior (Reinhardt et al. 2006). Ideally, researchers should develop a variety of sampling techniques and methods so that managers can select the most appropriate technique for their application. Moreover, the next generation of fuel models must describe real fuels across multiple fuel components (e.g., size classes), and also the spatial variability of these fuels as they are distributed across the simulation landscape, both within and among stands (Keane et al. 2001).

5.3 Weather

Creation of comprehensive weather and climate databases is a critical need to support wildland fire hazard and risk analysis. Spatially-explicit, long-term

historical databases are needed that ensure consistent hazard and risk analysis over large regions, and across diverse weather conditions. These data should be readily accessible and contain understandable formats with complete metadata documentation. Hourly weather data are needed to support spatial fire spread modeling, but daily, monthy, and annual summaries can facilitate coarser-scale fire analyses.

Future weather and climate databases should also be developed for use in fire hazard simulations and quantifying conditions under climate change (Millar et al. 2007). Historical and future climate variables should be the same and should be derived for comparable spatial scales and domains to facilitate direct comparison of fire hazard and risk analysis outputs, and statistical modeling of changes in key fire behavior covariates.

We also suggest the development of several comprehensive, standardized climate and weather scenarios for comparative fire hazard analysis that encompass conditions of interest to fire management. A diverse set of weather scenarios that specify weather-related inputs such as fuel moistures, maximum temperature, wind, and relative humidity, can be developed for various fire management applications. For example, weather scenarios are needed for prescribed burning, wildfire, and wildland fire use conditions. A more representative set of weather scenarios is also needed to represent expected variation in climatic severity, such as moist, dry, very dry, and extreme weather conditions; examples of which can be seen in the First-Order Fire Effects Model (FOFEM) fire effects program (Reinhardt and Keane 1998). These scenarios could be hierarchically nested by geographical area using climate severity designations appropriate to the areas. The advantage of common weather scenarios is that they would aid in standardizing fire hazard and risk analysis across agencies, geographical areas, and management applications.

5.4 Analysis and Decision Support

One problem with many hazard and risk analyses is that there are few statistical techniques that can be used to compute the significance or uncertainty in the selected variables and final assessment. New statistical methods are needed to aid managers in the evaluations of uncertainty associated with results, and these results need to be factored into overall decision-making. These multivariate statistical methods need to be easy to implement and interpret for fire managers. Since many variables are computed from simulation models, it is critical that the models themselves be evaluated for accuracy, precision, and error rate. This will require novel statistical analysis techniques because they must assess accuracy across models, input map layers, and input parameters. Advanced sensitivity analysis, for example, could be used to assess the accuracy and significance of variables simulated from a model. Map accuracies for fire analysis variables must be assessed at multiple levels such as the geograpical accuracy, model accuracy, and input data accuracy.

Managers and researchers will also require significant increased computing resources and expertise to conduct future fire hazard and risk analysis projects. Spatial simulations of fire spread for multiple weather and fuel scenarios requires thousands of simulations using multi-processor computers, and complex computer programs that rely on high quality, high resolution, and spatially consistent input data for good results (Finney et al. 2011). It would be even more computationally demanding to perform these simulations for all possible future fuel conditions resulting from vegetation development, disturbance, climate change, and management policies (Keane and Finney 2003). Currently, these computationally intensive techniques are beyond the technical and computing resources available to fire management, so any quantification of fire hazard probably will require a compromise between the management objective, available computing resources, modeling expertise, and time. Both scientists and managers will need extensive training and background in fire modeling to understand and interpret future fire hazard analyses, which may be impractical to implement across fire management agencies. Moreover, developing management-friendly, easy-to-use software tools for complex hazard analysis may be difficult because of the complicated set of inputs, parameters, and outputs involved in fire behavior and effects simulation. We feel the best route might be the creation of computing centers with highly trained experts in the fields of fire behavior modeling, fuels, GIS, and landscape ecology who could run these models and train people on how to use and interpret the results. It is usually the availability of computational resources, input data, and modeling expertise that dictate the rigor of most hazard assessments for fire management (Keane et al. 2008).

Finally, flexibility is required in decision support tools to accommodate results from multiple model run scenarios and multiple analyses. Results from a single EMDS run, for example, do not fully describe the decision space for fire managers because the full range, dimensionality, and behavior of fire hazard predictions may not be fully represented across the landscape. Varying logical operators within a given logic model in EMDS, while using the same input data, will yield highly differing landscape prioritizations (Fig. 3). Moreover, these disparate results provide critical information on the sensitivity and importance of the key input variables.

Reassigning weights and importance in the EMDS decision model will also expand the decision space and account for possible uncertainty in allocating weights across hazard variables. For example, programming a Monte Carlo simulation across a characteristic distribution of weights might clearly illustrate uncertainty in the decision space. Adding results from multiple weather scenarios for fire hazard variables into the EMDS logic model will also provide greater depth of insight into the uncertainties associated with fire management decision-making.

Synthesizing critical landscape variables from pixel-level fire hazard predictions to local landscape predictions (e.g., Hessburg et al. 2007, summarize the area and aggregation of area of key fire danger variables within subwatersheds) is also important for future analyses, so as to integrate spatial contagion considerations into hazard evaluations. Ultimately, it is critically important to have standardized

models using defined sets of fire hazard variables, so that comparative analyses can be done across multiple scales and geographical areas by different agencies (e.g., Reynolds et al. 2009; Hessburg et al. 2007).

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