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A method for mapping fire hazard and risk across multiple scales and its application in fire management☆,☆☆

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ABSTRACT

This paper presents modeling methods for mapping fire hazard and fire risk using a research model called FIREHARM (FIRE Hazard and Risk Model) that computes common measures of fire behavior, fire danger, and fire effects to spatially portray fire hazard over space. FIREHARM can compute a measure of risk associated with the distribution of these measures over time using 18 years of gridded DAYMET daily weather data used to simulate fuel moistures to compute fire variables. We detail the background, structure, and application of FIREHARM and then present validation results of six of the FIREHARM output variables that revealed accuracy rates ranging from 20 to 80% correct depending on the quality of input data and the behavior of the fire behavior simulation framework. Overall accuracies appeared acceptable for prioritization analysis and large scale assessments because precision was high. We discuss advantages and disadvantages of the fire hazard and risk approaches and a possible agenda for future development of comprehensive fire hazard and risk mapping is presented.

1. Introduction

Severe fire seasons of the past decade in the western United States have spurred many government agencies to manage lands to reduce fire intensity and severity to ultimately protect human life and property (GAO/RCED, 1999; Laverty and Williams, 2000; GAO, 2003). However, seven decades of fire exclusion policies have resulted in the dense forest canopies, high surface fuel accumulations, and increased fuel continuity across large regions where fires were historically frequent (Brown, 1985; Mutch, 1994; Ferry et al., 1995). These abnormal fuel conditions will likely foster abnormally severe wildfires that are projected to increase with global warming (Brown et al., 2004; Running, 2006; Westerling et al., 2006). The western US has also experienced a marked increase in human development in areas surrounding public wildlands thereby creating and expanding a "wildland urban interface" (Radeloff et al., 2005; Berry et al., 2006; Blanchard and Ryan, 2007). With this expansion comes an increased risk to human life and property as severe wildfires become common.

In response, federal agencies have advocated fuels reduction treatments to mitigate the risk and hazard of severe wildfires, particularly in the wildland urban interface (GAO/RCED, 1999; Laverty and Williams, 2000; GAO, 2002, 2003, 2004). With limited available funding and the cost of fuel treatments continually increasing (Berry et al., 2006), fire managers have been charged with developing a detailed methodology for identifying and prioritizing which federal lands are in the greatest need for fuels reduction treatments (GAO, 2003, 2007; Hessburg et al., 2007). A quantification of fire hazard and risk is critical for identifying and prioritizing areas for fuel fuels treatments (Hardy, 2005), and comprehensive fire models are an important first step towards providing spatially explicit estimates of fire risk and hazard over a range of spatial and temporal scales (Hessburg et al., 2007).

This paper presents a research computer model called FIREHARM (FIRE HAzard and Risk Model) that computes common measures of fire behavior, fire danger, and fire effects over space to use as variables to portray fire hazard spatially, and then computes fire risk by simulating daily fuel moistures over 18 years to compute fire measures over time. The hazard and risk digital maps can then be used for fire management planning and real-time wildfire operations. We also validated six FIREHARM output variables to estimate model accuracy and precision to aid in the interpreta-

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tion of results. Last, we discuss advantages and disadvantages of the approaches used here and present a possible agenda for the future of comprehensive fire hazard and risk mapping.

1.1. Background

In this paper, we follow the lexicon of Hardy (2005) where the term fire "hazard" is considered an act or phenomenon with the potential to do harm (NRC, 1989). Fire hazard is usually independent of weather and often describes fuel characteristics at one point in time. Hazard can be expressed as potential fire behavior (e.g., fireline intensity) or fuel property (e.g., loading or biomass) (Hogenbirk and Sarrazin-Delay, 1995). The term "risk" is used to describe the probability that a fire might start, as affected by the nature and incidence of causative agents (Bachmann and Allgower, 2001; Hardy, 2005). While this refers to the initial ignition of a wildland fire, we amend the definition to include the subsequent ignition of the adjacent fuels (i.e., fire spread) in a spatial domain and the potential for that ignition to create a specific fire event. We also follow 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. In our analysis, we assume that an area has the potential to burn because it is difficult to determine the probability of ignition, so we call this potential risk. To avoid confusing fire hazard with fire intensity or fire severity, we define fire intensity as the energy produced by a fire (Albini, 1976) and use the term fire severity to refer to the impact of that energy on the environment (Simard, 1996; DeBano et al., 1998).

Fire hazard and risk can be described by a number of measures computed from a variety of methods and computer programs (Sampson et al., 2000). However, many measures may be correlated, inappropriate, contradictory, or unsuited for the fire management issue being addressed. For example, some efforts at describing hazard and risk seem to confuse high fireline intensity with high fire hazard, while others might mistake high intensity for high fire severity (Hardy, 2005; Sampson and Sampson, 2005). A high intensity fire in long fire return interval ecosystem, for example, could be described as a hazardous fire, even though it might be common, appropriate, and desirable (Heinselman, 1981; Romme and Knight, 1981; Agee, 1998). Therefore, the selection of variables to rate fire hazard is ultimately dependent on the objectives of the hazard analysis, which must be explicitly stated. A map portraying the risk of loss of property from fire, for example, would be quite different from a map that describes forest stands with the greatest potential of experiencing high intensity fire. While most fire hazard maps may be useful, it is important that their temporal and spatial scales, limitations, and uncertainty be recognized when interpreting them.

Quantification of fire hazard and risk often is a difficult and contentious task due to (1) the complexity of fire events across multiple time and space scales, (2) the effects of these fires on the ecosystem, and (3) the diverse fire regimes that are created by these fire events over time (Brown, 1995; Agee, 1998; Barrett, 2004; Finney, 2005). 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 classification (Cohen, 1989; Jain et al., 1996; Ercanoglu et al., 2006), topography analysis (Yool et al., 1985), expert knowledge (Gonzalez et al., 2007), socioeconomic analysis (Bonazountas et al., 2005), and crown fire index calculations (Fiedler et al., 2003). Fire risk, on the other hand, has been described as the probability of a fire causing loss of owl habitat (Ager et al., 2007), probability distribution of ignitions, fire sizes, and burning conditions (Parisien et al., 2005), fire weather occurrence (Gill et al., 1987), and frequency of rare fire events (Neuenschwander et al., 2000). Again, this diversity of fire hazard and risk approaches and measures exists because each analysis must be crafted to address specific management objectives, so a clear, concise statement of objectives is critical for any hazard analysis. However, many fire hazard projects are designed around the availability of commonly used, well accepted spatial data layers that indirectly represent fire hazard, rather than create those layers that are directly important to the management objective.

Most fire hazard efforts tend to concentrate on stand-level fuels and their characteristics without recognizing the spatial influence of topography, winds, and adjacent fuels (Finney, 2005). The spatial patterns of landscape composition and structure are important to fire hazard because fuel pattern will ultimately influence fire spread and intensity (Finney, 1998b; Loehle, 2004). Moreover, spatial patterns of fuels ultimately dictate the design and placement of fuel treatments on the landscape (Agee et al., 2000; Finney, 2001). However, as the map scale and extent of the analysis increases, spatial relationships may become less important. Regional and national evaluations of fire hazard and risk to prioritize watersheds for fuels treatments may not require detailed analysis of spatial pattern as much as project-level analyses conducted to optimize treatment locations (Hessburg et al., 2007).

Some efforts at describing fire hazard have taken disparate GIS layers with conflicting characteristics and have merged them together to create a final layer that may often contain limitations (Klaver et al., 1998; Sampson and Sampson, 2005). A typical example would be merging the three layers of flame length, surface fuel model, and canopy bulk density to create a fire hazard map; two layers describe continuous variables with different units, while the third is a categorical variable with nominal categories. Each layer has a unique spatial error distribution, mapping resolution, map scale, and computational detail that is complicated and compromised when merged. A step in the right direction would be to explicitly set a threshold value for continuous maps or set of values for categorical maps, above which fire hazard is high and below which hazard is low to use 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.

Many fire hazard analyses assume severe fire weather (90th or 99th percentile temperature, wind, fuel moistures) to compute the fire characteristics that describe hazard and risk in the context of the management objective. These analyses, however, rarely describe the frequency of that weather event across the weather record. Extremely dry conditions may occur frequently in low elevation pinyon-juniper stands, but they may be relatively rare in high elevation lodgepole pine ecosystems, yet both may have the same hazard value. It is important that the manager weight the frequency of the fire event with the severity of impacts when the event occurs. Other problems with the use of severe weather variables arise when assessing fire hazard across large landscapes, especially in mountainous terrain, as the 90th percentile is quite different across diverse topographic settings. Severe fire weather at low elevations may be quite different from severe fire weather in high elevations. Some hazard analyses may use only one fire weather scenario across the analysis landscapes taken from one weather station.

2. Methods

The objective of this study was to develop methods of computing fire hazard and risk that minimize the limitations and drawbacks of previous efforts. To accomplish this we created the FIREHARM computer model that (1) increased consistency across hazard and risk layers, (2) standardized weather inputs, (3) employed a multiple

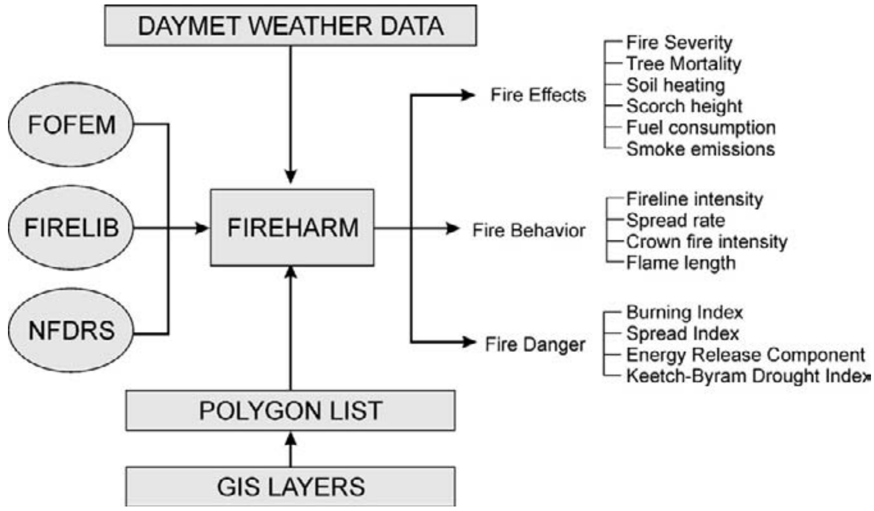

Fig. 1. Compartment diagram of the FIREHARM model showing input requirements and output data.

scale analysis into its structure, (4) included some spatial effects, and (5) expanded the number of fire hazard and risk variables. The next section generally describes FIREHARM structure and design and all details are contained in the associated references.

2.1. The FIREHARM model

FIREHARM is a C++ program that computes landscape changes in fire characteristics over time by using a spatial daily climate database to simulate fuel moisture which is then used to calculate commonly used measures of fire behavior, danger, and effects (Fig. 1). FIREHARM is more of a modeling platform than a fire model because it integrates previously developed fire simulation models into its structure and does not include any new fire behavior or effects simulation methods. The model assumes static fuel characteristics so it does not simulate vegetation development or fuel accumulation over time. Although FIREHARM input and output are spatial, the model is not spatially explicit because it does not simulate spatially explicit processes such as fire spread. Instead, the model assumes that every pixel or polygon experiences a head fire 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, 1998a).

The input landscape in FIREHARM is represented by a list of polygons that define areas of similar vegetation, fuel, and site conditions (Keane and Holsinger, 2006). This list is structured so that each item in the list represents a mapping unit (i.e., polygon) on the simulation landscape at any scale (e.g., a point, pixel, or watershed). Each polygon is assigned a unique ID number which is then used to create output GIS layers of computed fire hazard when cross referenced to the GIS layer of polygon IDs. Each polygon is also assigned a set of attributes that are used as input to the fire behavior, fire danger, and fire effects simulation modules. The most important input parameters include fire behavior fuel models, fire danger fuel models, and fire effects fuel models. Each polygon is also assigned a tree list (list of trees with the attributes of species, diameter, height to base of crown, and tree height) to compute tree mortality.

Fire behavior fuel models describe expected fire behavior and are used as inputs to simulate fire behavior (Burgan and Rothermal, 1984). FIREHARM can use either the Anderson (1982) standard 13 models or the Scott and Burgan (2005) 40 fuel models. The fire danger fuel models, used to compute five measures of fire danger, are taken from the National Fire Danger Rating System set of 24 fuel models developed by Deeming et al. (1977). Fire effects fuel models describe actual fuel loadings so they can be used in fire effects prediction systems, such as CONSUME (Ottmar et al., 1993) or FOFEM (Reinhardt et al., 1997), to simulate major fire effects, such as fuel consumption, smoke, and soil heating. FIREHARM uses the Fuel Loading Models (FLM) developed by Lutes et al. (in preparation) for fuel loading inputs. FLMs are a classification of fuel beds based on simulated fire effects as calculated from over 4000 plots across the continental US. Each FLM is described by unique fuel loadings by fuelbed components needed to simulate fire effects (Sikkink et al., in press). Other polygon attributes used by FIREHARM include topography (slope, aspect, and elevation), geographic location (latitude, latitude), leaf area index (LAI), and soils information (soil depth and percent sand, silt, and clay). A complete discussion of the all inputs and how to quantify them from other GIS layers is contained in Keane and Holsinger (2006) which describes the WXFIRE program that was designed to be use the same inputs as FIREHARM (Keane et al., 2007).

Weather data are input into FIREHARM using the DAYMET US database (www.daymet.org) developed by Thornton et al. (1997) (Fig. 1). DAYMET is a computer model that was used to generate daily spatial surfaces of temperature, precipitation, humidity, and radiation over large regions of complex terrain (Thornton and Running, 1999; Thornton et al., 2000). Using digital elevation data and observations of maximum temperature, minimum temperature, and precipitation from ground-based meteorological stations, DAYMET extrapolated weather from the stations across a 1-km grid based on the spatial convolution of a truncated Gaussian weighting filter. Sensitivity to the typical heterogeneous distribution of stations in complex terrain was accomplished with an iterative station density algorithm. Surfaces of humidity (vapor pressure deficit) were generated as a function of the predicted daily minimum temperature and the predicted daily average daytime temperature. Daily surfaces of incident solar radiation were generated as a function of sun-slope geometry and interpolated diurnal temperature range. The DAYMET program was executed for the contiguous United States using 18 years of daily weather data starting from 1 January 1980 and ending 31 December 1997 from over 1500 weather stations (http://daymet.org). The output of this effort is stored in binary format in a series of hierarchically nested files structured by 2° latitude by 2° longitude tiles by year and then day of year called the DAYMET weather database.

FIREHARM simulates daily moisture values for 1-, 10-, 100-, and 1000-h downed dead woody fuels and live shrub, tree, and herbaceous fuels for each day of the year using the DAYMET daily weather (radiation, temperature, and humidity) and standard fire behavior and fire danger algorithms (Deeming et al., 1977; Rothermel et al., 1986; Anderson, 1990). Snow and rain dynamics are simulated using the routines in the WXFIRE model (Keane and Holsinger, 2006) which are based on several ecosystem models (Running and Coughlan, 1988; Keane et al., 1996). Radiation fluxes are simulated using the routines of Thornton and Running (1999) and Deeming et al. (1977). FIREHARM simulates soil water balance using the radiation and available water computations above with inputs of soil textural attributes (percent sand, silt, and clay) and leaf area index (LAI) and the algorithms of the ecosystem process model Fire-BGC (Keane et al., 1996). Shrub and tree live moisture contents are simulated by scaling minimum and maximum leaf moisture contents (input by user) to the soil water potential (MPa) (Keane and Holsinger, 2006).

FIREHARM calculates the fire behavior variables of fireline intensity, spread rate, flame length, and crown fire intensity using the FireLib C routines developed by (Bevins, 1996) that codify the Rothermel (1972) fire behavior algorithms (Fig. 1). Fire danger variables (spread component, burning index, energy release component, and Keetch-Byram drought index) are calculated using the NFDRS routines (Keetch and Byram, 1968; Deeming et al., 1977; Burgan, 1993; Andrews and Bradshaw, 1997). Fire effects variables of smoke emissions, fuel consumption, soil heating, and scorch height are computed from the First Order Fire Effects Model FOFEM (Reinhardt et al., 1997) that is also embedded in FIREHARM. All fire variables are computed for each day in the DAYMET 18-year record and for each polygon in a user-specified list that comprise the input landscape.

FIREHARM also computes an ordinal, three category fire severity index based on the simulated estimates of three FOFEM fire effects variables – fuel consumption, soil heating, and tree mortality.

- *Low severity*. Total fuel consumption <20%, soil heating at 2 cm depth <60 °C, and mortality for trees above 15 cm diameter <30%.
- *Moderate severity*. Total fuel consumption is 20–50%, soil heating at 2 cm depth is 60–250 °C, and tree mortality is 30–70%.
- *High severity*. Total fuel consumption >50%, soil heating at 2 cm depth >250 °C, and tree mortality >70%.

These classes were designed to match severity classes used in common fire severity applications (Ryan and Noste, 1985; Simard, 1996; Lentile et al., 2007).

FIREHARM can be run in two modes: in *event* mode, the user enters fuel moistures and ambient weather conditions for a given situation or event, such as a wildfire, and the program will calculate all fire variables for this specified situation. The event mode is mostly used for mapping fire hazard and is especially useful if a fire severity map is desired to evaluate fire damage and design rehabilitation treatments. The DAYMET weather data are not used when FIREHARM is run in the event mode. In *temporal* mode, FIREHARM simulates fuel moistures from DAYMET and computes fire characteristics over the DAYMET temporal domain (18 years) using input fuels data. FIREHARM 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. A user-specified threshold must be exceeded for an event to occur in the temporal mode. For example, FIREHARM might calculate the probability of a fire burning a user-specified 50% of the total fuel load for each day of the 18-year record (6574 days). The user can narrow this temporal range to a set of years and a set of days within those years. FIREHARM then computes the probabilities and annual averages for all fire behavior, danger, and effects variables for all polygons in the user-created list. These probabilities can then be mapped onto the landscape using GIS techniques and the resultant layers can be used to prioritize, plan, and implement fuel treatments.

Table 1
Weather and fuel condition variables for the dry climate event mode. Values follow the Scott and Burgan (2005) for very low moisture conditions.

Fire and fuel weather variables	
Temperature, T_{MAX} (°C)	32.2
Temperature, T_{MIN} (°C)	10.0
Relative humidity (%)	20
Wind speed (mph)	15.0
Wind direction	220
Dead fuel moisture (%)	
1 h fuel	3.0
10 h fuel	4.0
100 h	5.0
1000 h	50.0
Litter	20.0
Duff	30.0
Live fuel moisture (%)	
Foliage	50
Shrub	60.0

2.2. FIREHARM simulations

In this paper we demonstrate the use of FIREHARM for hazard and potential risk mapping in fire management by performing several nested, multi-scale simulations in a study area. First, we ran FIREHARM in the event mode for the entire study area at 100 m pixel resolution using a severe wildfire weather scenario (Table 1) to simulate extreme fire events for computing fire hazard. The severe fire weather conditions are based on the Scott and Burgan (2005) fuel moisture scenarios (Table 1). Next, we created probability maps using the temporal model in FIREHARM to create risk maps for a portion of the study area. The entire study area was not used because of the huge computation requirements needed for such a large simulation extent and high resolution. Last, we tested FIREHARM model output validity by comparing model output with field measured fire severity, fire effects, and fire behavior characteristics for three Montana wildfires.

2.3. Study area

We chose the LANDFIRE Northern Rocky Mountains Mapping Zone 19 (Rollins and Frame, 2006) for our study area (Fig. 2). Extending from the Canadian border in northern Montana into eastern Idaho, this approximately 11 million ha landscape contains many diverse ecosystems (Fig. 2), which enabled us to fully evaluate our model. We divided the study area into nested watersheds at both the 4th and 6th code level using the USGS watershed Hydrologic Unit Code (HUC) classification (Fig. 2) (Seaber et al., 1987). We then selected the Blackfoot River watershed as our 4th code sub-basin to demonstrate mid-scale FIREHARM hazard analysis and several 6th code subwatersheds to demonstrate fine scale analysis (Fig. 2).

Much of the ecological diversity in the study area can be attributed to the highly variable topography and wide range in elevation (760–3400 m). Alpine communities are prevalent at higher elevations (∼3400 m for timberline) with spruce-fir forests ranging from timberline to approximately 1800 m (Fig. 2; Rydberg, 1915). Montane forests of lodgepole pine, western larch, Douglas-fir and ponderosa pine cover much of the middle elevation landscape, while prairie grasslands exist in the lower elevations east of the Rocky Mountains (Fig. 2) (Arno, 1979).

Climatic patterns within the study area are influenced by the Continental Divide; west of the divide climates are mostly maritime (north Pacific coast) while east of the divide, a continental climate dominates (WRCC, 2008). Winters are generally cold with a few periods of extremely cold weather during normal years with January the coldest month on average (WRCC, 2008) (Fig. 3). Summers are warm to hot with temperatures often above 32 °C. Precipi-

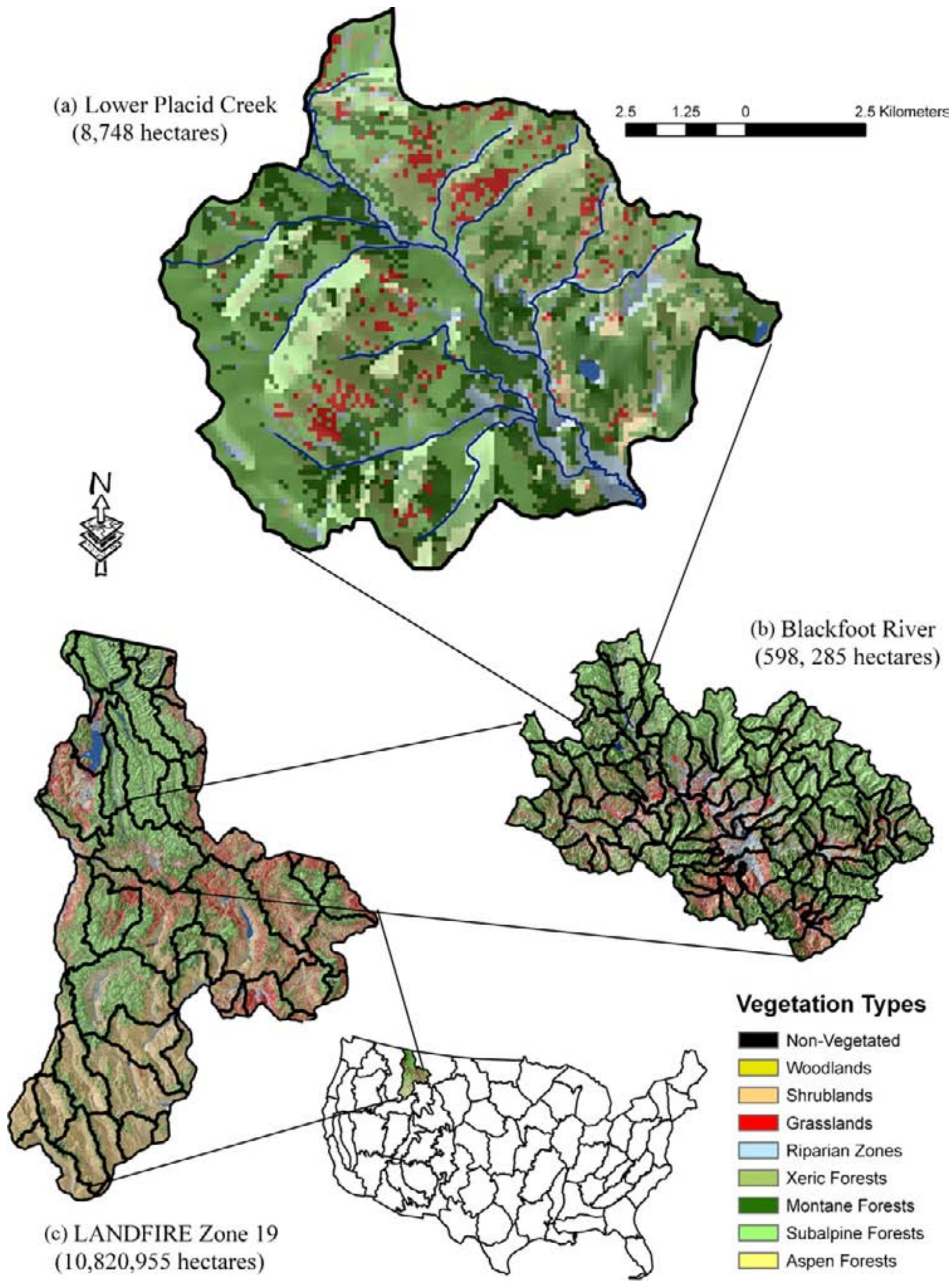

Fig. 2. Map of the study area showing the nested watersheds defined by USGS hydrological unit code classification. Individual pixels represent site types ranging from high elevation meadows to prairies and grasslands.

tation is heavily influenced by topography throughout the area where most precipitation falls as snow in the mountainous regions (Fig. 3). Snowfall levels also vary throughout the zone with mountain regions receiving up to 760 cm annually while many valley areas receive from 75 to 125 cm on a yearly basis (Fig. 3; WRCC, 2008).

The convergence of maritime and continental climates, in combination with topographic complexity, result in diverse mosaics of vegetation in the study area that are ultimately shaped by complex and dynamic fire regimes (Habeck and Mutch, 1973; Arno, 1980; Philpot, 1990). Prior to the modern era of fire suppression (circa 1900 to present), frequent, low severity fires were common in low elevation, dry forests, mixed-severity fires occurred at longer (30–100 year) intervals in moister, mid-elevation forests, and infrequent, stand-replacement fires dominated the subalpine forests (Habeck and Mutch, 1973; Arno, 1980). With increasing time intervals between subsequent fires during the fire suppression era, flammable fuel quantities have also increased (Arno et al., 2000; Keane et al., 2002), and this increase has resulted in a tendency towards more severe fires, making this an ideal study area to test the model. We selected three wildfires within our study areas to perform an accuracy assessment – the 2003 Cooney Ridge and Mineral Primm fires, and the 2007 Jocko Lakes fire.

2.4. FIREHARM input data

The national LANDFIRE spatial database (www.landfire.gov) provided all FIREHARM input data used to quantify the fire hazard variables in Fig. 1 for our study area (Fig. 3). LANDFIRE mapped existing and potential vegetation using a combination of remote

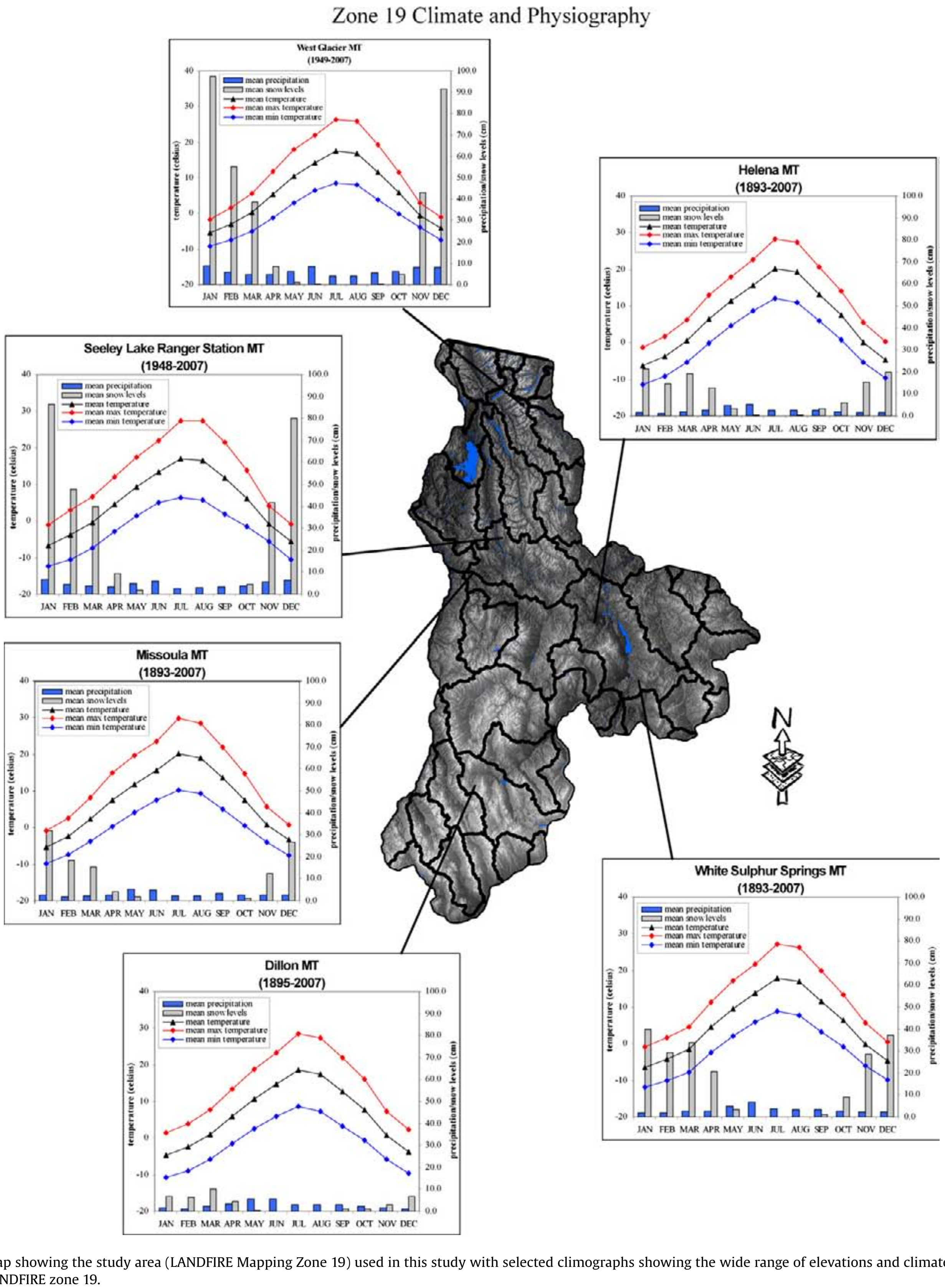

Fig. 3. Map showing the study area (LANDFIRE Mapping Zone 19) used in this study with selected climographs showing the wide range of elevations and climate patterns within LANDFIRE zone 19.

sensing, landscape metrics, and environmental gradient modeling (Holsinger et al., 2006; Zhu et al., 2006; Keane et al., 2007). Surface fuel models (Scott and Burgan, 2005) were then assigned to all possible combinations of the categories in the three vegetation classifications of biophysical setting, cover type, and structural stage. Canopy fuel characteristics were mapped using empirical modeling relating canopy bulk density, base height, and canopy total height calculated from field plots to environmental gradients, satellite imagery, and the vegetation classifications (Keane et al., 2006). Topography was taken from the National Elevation Database (http://edc.usgs.gov/products/elevation/ned.html). Soils inputs were summarized from the STATSGO database using techniques presented in Keane and Holsinger (2006) while the LAI information was assigned to each polygon from MODIS data (Holsinger et al., 2006). Polygons were created for the study area based on the methods presented in (Holsinger et al., 2006; Keane and Holsinger, 2006) where each polygon represented unique combinations of biophysical setting, cover type, and structural stage.

2.5. Validation

FIREHARM output was tested for accuracy by assessing fire effects and fire severity variables on ground plots in areas burned by the three wildfires of 2003 and 2007. We employed a paired-sample approach where one sample plot was established in an unburned area to represent pre-burn conditions, and another sample plot was established in an adjacent and biophysically similar burned area to represent post-fire conditions. Each pair was required to have the same pre-burn habitat type (Pfister et al., 1977), cover type (Eyre, 1980), and structural stage (O'Hara et al., 1996) to ensure similarity. Each sample plot consisted of one 400 m^2 circular plot. These paired plots were located across a wide variety of burn severities, topographic settings, and vegetation types. While problems with paired-plot space-for-time substitution strategies exist (Pickett, 1989), we were unable to establish real time, pre-burn sample plots under wildfire conditions for this study.

Six FIREHARM output variables were calculated from the paired plot data: (1) surface fuel consumption, (2) tree mortality (%), (3) fire severity index, (4) flame length, (5) scorch height (m), and (6) crown fire potential. These variables were computed using the LANDFIRE digital spatial data as inputs to FIREHARM. Measurements in the burned area (observed) were compared to the FIREHARM output (predicted) using a variety of methods. Tree mortality, fire severity, and canopy fire potential were compared with the field observations using percentage agreement calculations. Regression analysis was used to contrast fuel consumption predicted and observed estimates because consumption is a continuous variable. All other variables were categorical since each plot burned either as a surface fire or a crown fire.

2.5.1. Surface fuel consumption

Downed and dead woody fuel biomass was estimated using a modified version of the planar intercept approach described by Brown (1974) as implemented in FIREMON (FIRe Effects MONitoring and inventory system) (Lutes et al., 2006). All downed woody debris encountered along predetermined sections of three, 25 m fuels transects (a vertical plane that extends from ground level to a height of 2 meters) (Lutes et al., 2006) were tallied by diameter classes. Fine woody fuels (1-h, 10-h, 100-h fuels) were tallied along 2, 2, and 5-m sections, respectively, on each transect, while coarse woody debris (1000-h, >8 cm diameter) was tallied along the final 20 m length of the fuels transect. Diameters and decay states (see Lutes et al., 2006) for each intersected coarse woody debris section were recorded at the point where the material intersects the planar transect. Fuel tallies were input into the fuel loading calculator within FIREMON to calculate woody fuel biomass (woody fuel loadings) in kg m^{-2} using Brown's (1974) equations.

Litter and duff biomass were estimated by taking combined litter and duff depth measurements at two points along the 25-m fuels transect. The proportion of litter depth to the combined duff and litter depth was then visually estimated to obtain individual litter and duff depths for each measurement. Litter and duff depth measurements were converted to litter and duff biomass (kg m^{-2}) by multiplying them by bulk densities of 44.1 and 88.1 kg m^{-3}, respectively (Lutes et al., 2006).

Fuel consumption was computed as unburned plot biomass minus the burned plot biomass for each fuel component. This is the only variable that used the paired unburned plot observations. FIREHARM predictions were evaluated for agreement with these measured estimates using a combination of linear regression (Blanco et al., 2007), chi-square goodness of fit tests (Freese, 1960), model accuracy analysis (bias, mean absolute error, mean square error, mean relative prediction error), and the modeling efficiency statistic (Reynolds, 1984; Mayer and Butler, 1993). In addition, percentage agreement values were calculated at 10% agreement, 25% agreement, and 50% agreement (Keane and Dickinson, 2007).

2.5.2. Tree mortality

Tree mortality was calculated as the ratio of pre-burn live trees to post-burn dead trees within the burned sample plot in the three wildfire burn areas. Each dead and live tree within the burned plot was visually assessed to determine if the tree was living or dead prior to the wildfire and whether it survived the wildfire based on the amount of green canopy remaining and consumption of surface fuels around the base of the tree. Field observations of tree mortality were compared with predicted percentage of tree mortality from FIREHARM.

2.5.3. Fire severity

Fire severity was assessed on each burned sample plot using the Composite Burn Index (CBI) sampling strategy by Key and Benson (2006) in FIREMON (Lutes et al., 2006). To assess CBI, we visually evaluated the physical and chemical changes to the soil, vegetation, and surface fuels that could be directly attributed to burning. We evaluated severity based on an aggregate, or average, fire severity CBI index throughout the plot because we thought this best matched the FIREHARM fire severity index output. Field assessed composite burn indices were compared directly with the FIREHARM fire severity indices using linear regressions and quantile plots. In addition, percentage agreement values were calculated based on five categories of prediction accuracy: (1) correct prediction, (2) under predicted by one severity class, (3) under predicted by two severity classes, (4) over predicted by one severity class, and (5) over predicted by two severity classes.

2.5.4. Flame length

FIREHARM model predictions for flame length were compared with bole char height measurements from the burned sample plots (Cain, 1984). We defined bole char height as the vertical height above the ground that the tree bole was blackened by the wildfire (Cain, 1984). Bole char heights (m) were measured to the nearest 0.3 m on the downhill portion of each tree ≥10 cm dbh within each of the plots. Mean char heights were used to evaluate the flame length predictions from FIREHARM.

2.5.5. Crown scorch heights

We visually estimated the percent of pre-fire live crown volume scorched for each individual tree on each of the burn sample plots using a modified version of the crown scorch volume and scorch height estimations of Peterson (1985), which involved reconstructing the probable shape and extent of the pre-burn canopy and comparing that to the post-burn canopy remaining on each tree. Assessments of percent crown scorch included both foliage that had experienced a color change due to the fire and foliage that was consumed by the fire (similar to the total crown damage estimate of McHugh and Kolb (2003)). We converted percentage crown scorch to scorch heights by multiplying field measures of tree height minus crown base height by proportion crown scorch to get a coarse field estimate of crown scorch height that was then compared directly with the FIREHARM model output using linear regressions, quantile plots, and percentage agreement values. For consistency, we also transformed the FIREHARM model output to crown scorch percent by dividing the model output for crown scorch height (m) by the mapped tree heights from the LANDFIRE and multiplying by 100.

2.5.6. Canopy fire potential

The potential for canopy fire was assessed using the FIREHARM model output predictions for fireline intensity (kW m^{-1}) and crown fire intensity (kW m^{-1}) following the rules of thumb on interpreting fire behavior and predicting fire growth published in Rothermel (1983). In this set of scenarios, fireline intensities between 0 and 346 kW m^{-1} are classified as low intensity fires, intensities from 346 to 1732 kW m^{-1} are considered intense fires that cannot be managed by personnel on the ground, intensities of 1732–3464 kW m^{-1} are fires where torching, crowning and spotting may occur, and above 3464 kW m^{-1} are considered crown fires where crowning, spotting and major runs are probable (Rothermel, 1983). If fireline intensity was >800 kW m^{-1} and crown fire intensity was >10,000 kW m^{-1}, we categorized the plot as a crown fire. We compared canopy fire predictions with field observations of whether the burned sample plot experienced a canopy fire (value of 1) or ground fire (value of 0) using percentage agreement statistics.

3. Results

3.1. FIREHARM output map layers

3.1.1. Event mode

FIREHARM input layers were created in less than 10 days using the LANDFIRE data layers. It took approximately 14 days for FIREHARM to simulate the fire variables in Fig. 1 across the entire study area. An example of one of the fire variables (surface fireline intensity, kW m^{-1}) is shown in Fig. 4 for three spatial scales.

We found that fuel consumption tended to exceed the 50% fuel consumption threshold in most vegetation types except in the subalpine forests (Fig. 5). Moreover fuel consumption often exceeded 75% in the central third of the study area where large concentrations of montane forests characterized by deeper duff layers and heavier concentrations of woody fuels exist (Fig. 5c). Because smoke production is linked to fuel consumption in FIREHARM, the greatest potential risk of high emissions followed the fuel consumption trend (i.e., areas with greatest fuel consumption were also predicted to have the greatest quantities of emitted smoke particles; Fig. 5d). Grasslands, shrublands, and woodlands were predicted to have a high fire hazard but the predicted emissions were low for these areas due low quantities of fuels. Soil heating in the upper 2 cm was commonly predicted to be above 60 °C as the insulating duff layer lying above the soil was removed (Fig. 5j). High rates of tree mortality were predicted for most forest vegetation types; however the lowest tree mortality rates were predicted in xeric and montane forests (Fig. 5e).

Fire behavior characteristics of scorch height and flame length from FIREHARM followed the same trends as tree mortality (Fig. 5g and f). Although large percentages of each vegetation type were predicted to exceed 2 m in the study area, the southern shrubland- and woodland-dominated areas had consistently higher flame lengths and crown scorch percentages (Fig. 5h and g). These trends were mirrored by the surface fireline intensity values where the highest fireline intensities for surface fires were predicted for shrublands and grasslands due to the relatively higher concentrations of fine, flashy fuels (Fig. 5i and k). However, a high percentage of the subalpine forest type had fires that exceeded 400 kW m^{-1}. The highest surface fire intensities occurred in shrublands, because LANDFIRE had mapped those areas to high intensity shrub fuel models. The highest rates of spread were found in shrublands, woodlands, and grasslands, which were concentrated in the lower third of the study area (Figs 4 and 5f).

3.1.2. Temporal mode

Examples of FIREHARM potential risk maps created using the temporal mode (i.e., DAYMET data are used to simulate fuel moistures and subsequent daily fire hazard values) are shown in Fig. 6 for the Lower Placid watershed. In general, we find the highest probabilities of undesirable fire events (greater than the threshold values in Fig. 6) occur on productive north slopes where fuel loadings are higher. The probability that fuel consumption is greater than 50% is greatest in polygons that have high loadings of logs, litter, and duff. This high tree mortality (>50%) is also more probable in areas that have small trees, high fireline intensity, and high crown fire intensity (Figs. 5 and 6).

3.2. FIREHARM validation

In 2004, we established 54 paired sample plots within the burn perimeters of the Cooney Ridge (26 sample plots) and the Mineral Primm (28 sample plots) wildfires (Fig. 7). An additional 13 sample plots were established within the Jocko Lakes fire perimeter in November of 2007 (Fig. 7). Our field sample plots covered a range of vegetation types, structural stages, and topographic positions that had burned under varied fire intensities and fire severities, resulting in a wide range of fire effects for use in testing FIREHARM.

FIREHARM adequately predicted fuel consumption across a range of field sampled plots with an r^2 value of 0.69 and the slope of the trend line around 0.91 (Fig. 8). The bias (observed – predicted) of −1.175 kg m^{-2} indicated that the model tends to over predict fuel consumption, particularly at lower fuel loadings. The Freese (1960) accuracy test was significant (α = 0.05) when we accepted an error of ± 3.8 kg m^{-2} (±58%). Moreover, mean absolute error (1.57 kg m^{-2}), mean square error (4.62 kg m^{-2}), mean relative prediction error (64%), and modeling efficiency statistic (0.54 – a value of one indicates perfect agreement) all indicate general agreement but large error potential. In addition, we found 14% of the plots were within the 10% agreement category (p10), 35% of plots in the 25% agreement category (p25), and 71% in the 50% category (p50) (Table 2), which suggests that the model provided adequate estimates of fuel consumption.

FIREHARM simulated tree mortality most accurately when the occurrence of canopy fire is predicted accurately (Table 2; Fig. 9a and b). However, FIREHARM tended to under-predict tree mortality in areas that experienced low intensity fires, particularly when all trees were predicted to survive (Fig. 9b). While no significant linear relationships were found between model output and field observations of tree mortality, the statistics on percent agreement statistics in Table 2 indicate that in some cases the model is predicting correctly (p10 = 17%; p25 = 35%; p50 = 56%). When field data were stratified by crown fires (mortality >60%) and non-crown fires (mortality <60), we found that mortality predictions improve significantly (p10 = 27%; p25 = 50%; p50 = 73%) (Table 2).

Predictions of both scorch height and fire severity predictions compared well with observed conditions (Table 2; Fig. 9c–f), even when crown scorch values were converted to field scorch heights using tree heights. Fire severity was correctly predicted in 42% of the test cases (Table 2), but in general FIREHARM tended to over predict fire severity by one severity class (Fig. 9d). In contrast, FIREHARM tended to under predict flame length (Fig. 9e and f) and crown fire occurrence, but there was good agreement between FIREHARM canopy fire potential indices (fire line intensity and crown fire intensity) (Fig. 9). Crown fires occurred on 44% of the field sample plots while the FIREHARM fireline intensity and crown fire intensity output indicated high potential for crown fire initiation on 35% of the test areas (Table 2). Moreover, FIREHARM successfully predicted

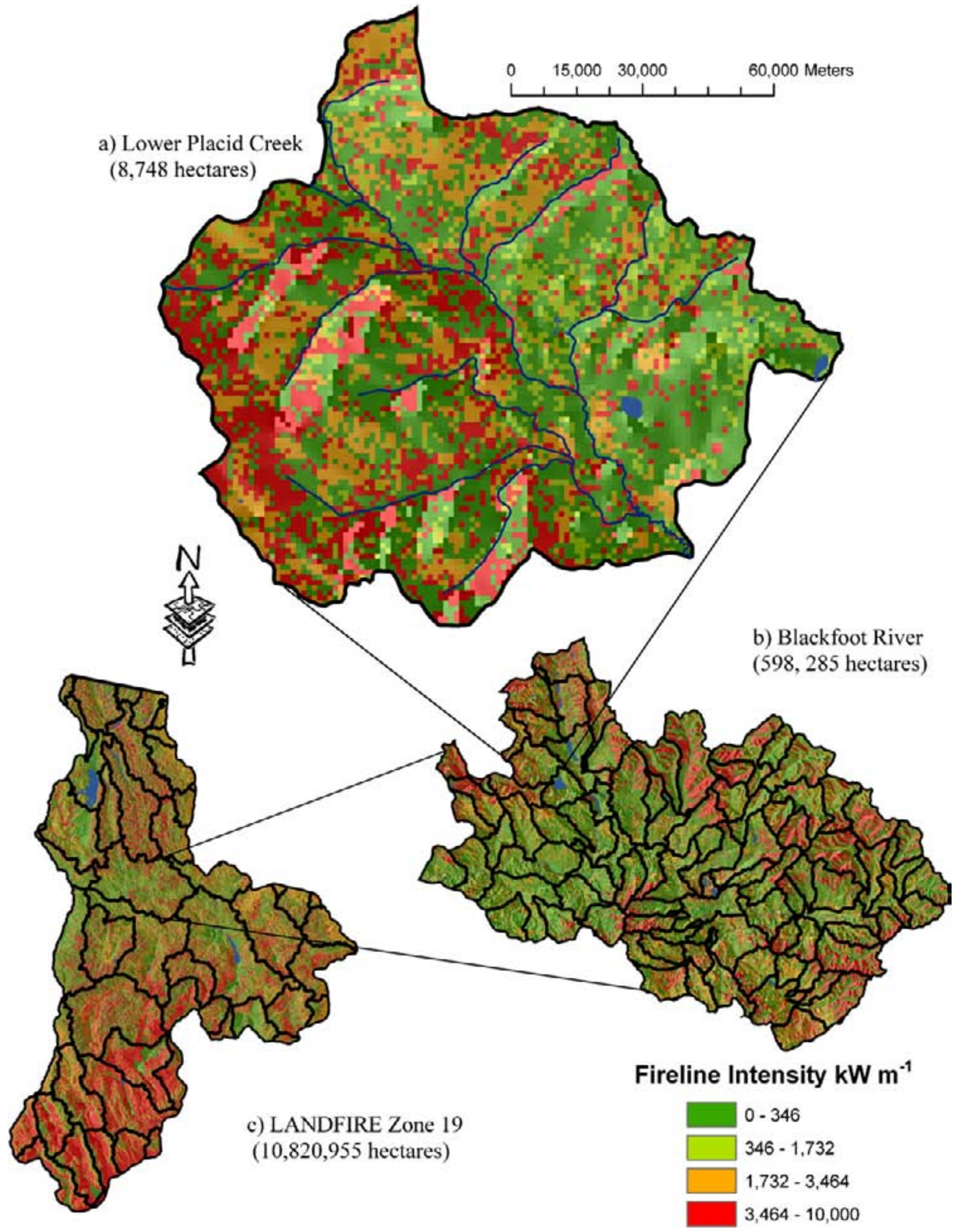

Fig. 4. Output FIREHARM maps of simulated fireline intensity (kW m^{-1}) for the (a) lower Placid Creek 6th Code HUC subbasin, (b) Blackfoot River 4th Code watershed and (c) the entire study area of LANDFIRE Map Zone 19.

whether a canopy or non-canopy fire occurred approximately 60% of the time (Table 2). Comparisons between predicted flame lengths and tree bole char heights showed little agreement when compared, but, when ±2 m were added to observed char heights, some general agreement (44%) was noted. Flame length predictions were closer to the observed char heights on lightly burned sample plots (68% agreement) than during canopy fires (31%).

4. Discussion

This study presents new approaches for mapping fire hazard and risk across large regions, diverse ecosystems, complex geography, and multiple scales. Our approach uses the probability of occurrence of a specific fire event to quantify risk. While others have used similar approaches for approximating fire risk from single variables (Wiitala and Carlton, 1994), we use a number of fire related descriptors that are selected based on management objectives. Preisler et al. (2004) performed a similar analysis for Oregon at 1-km^2 pixel resolution using only fire danger indices, but this FIREHARM effort included fire behavior and fire effects in the analysis (Fig. 5). Merging multiple maps of probabilities of specific fire events provides a consistent and comprehensive digital risk map (Preisler et al., 2004) and allows the maps to be integrated into a cohesive risk assessment process (Fairbrother and Turnley, 2005). For example, our potential risk map could be improved to more fully describe “risk” by dividing our computed probabilities by fire frequency quantified from either historical evidence or current data (Keane et al., 2003).

Our approach also integrates fire effects into hazard mapping (Fig. 5), which is arguably more important to long-term fire and ecosystem management, along with fire behavior and fire danger variables. Moreover, the integration of fire effects with behavior facilitates the use of FIREHARM for other applications. For example, Karau and Keane (in preparation) use FIREHARM to create fire sever-

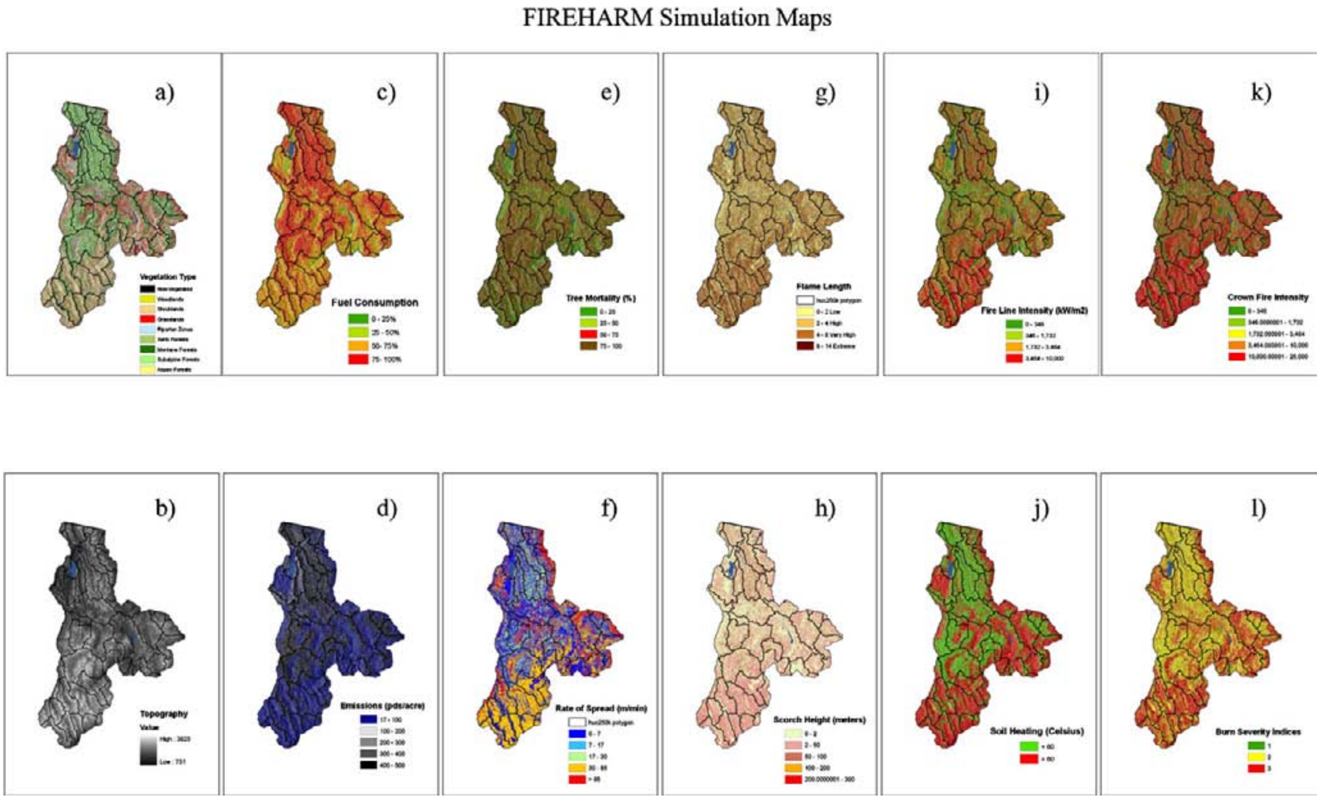

Fig. 5. Example FIREHARM output for all data layers required as input to the EMDS application shown in Fig. 2. These outputs were created using the event mode: (a) vegetation type and (b) topography (included for reference), (c) fuel consumption, (d) smoke emissions, (e) tree mortality (%), (f) rate of spread ($\mathrm{m\,min^{-1}}$), (g) flame length (m), (h) scorch height (m), (i) fireline intensity ($\mathrm{kW\,m^{-1}}$), (j) soil heating (°C), and (k) crown fire intensity ($\mathrm{kW\,m^{-1}}$).

ity maps for real-time wildfire operational use. Since FIREHARM is intimately linked to the LANDFIRE spatial database, it provides a seamless computation of fire hazard without the time-intensive task of compiling required data layers from local sources. While locally derived data layers are probably more accurate and reliable, there are rarely sufficient layers available to quantify all inputs to FIREHARM and there may be many areas that are not covered by local layers, such as private lands.

In the end, it is usually the available computational resources and input data that dictate the rigor of most hazard assessments for fire management. Spatial simulations of fire spread for multiple weather and fuel scenarios to obtain probability distributions of high impact fire events would require thousands of simulations using complex computer programs that rely on high quality, high resolution, and spatially consistent input data (Finney, 2006). It would be even more computationally demanding to perform

Table 2
Summary table of accuracy assessment for FIREHARM model validation. Values in the table represent the percent of plots that are within the 10, 20, and 50% agreement of the sampled value.

Model variable	Percent of plots (%)		
	Within 10% agreement	Within 25% agreement	Within 50% agreement
Fuel consumption ($\mathrm{kg\,m^{-2}}$)	14	48	68
Tree mortality (%)	17	35	56
Tree mortality (%) when observed mortality >60	27	50	73
Tree mortality (%) when observed mortality ≤60	4	13	26
Flame length (m)	6	14	29
Scorch height (m)	0	2	11
Crown scorch (%)	21	25	29
Fire severity			
Correct			42
Over-predicted by 1			37
Over-predicted by 2			6
Under-predicted by one			15
Under-predicted by two			0
Canopy fire potential			
Observed canopy fires			44
Predicted canopy fires			35
Predicted correctly			60
Canopy fire predicted correctly			45
Non-canopy fire predicted correctly			72

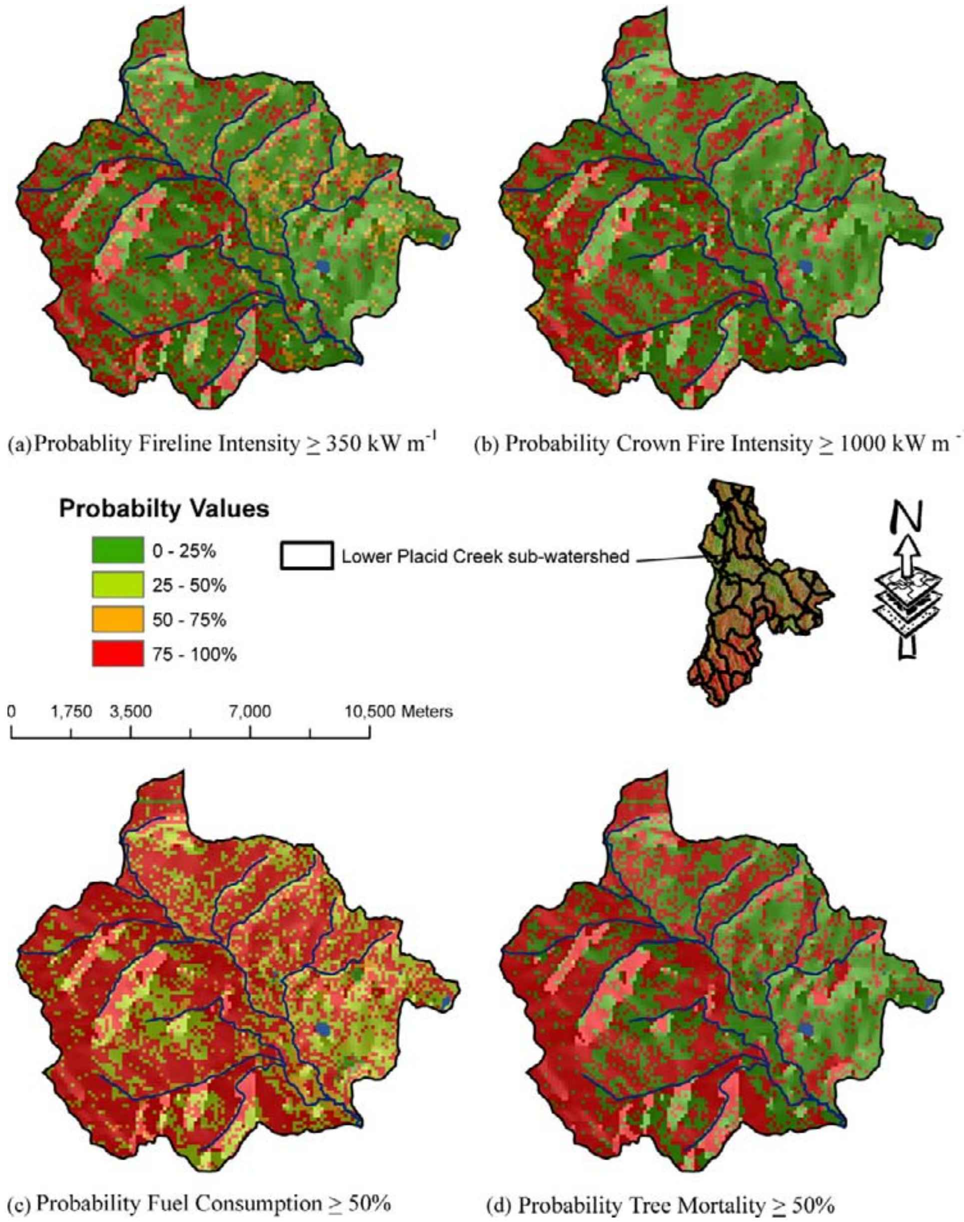

Fig. 6. Example of the FIREHARM potential risk map output using the temporal mode option for the Lower Placid Creek 6th Code HUC sub-basin showing the probability of occurrence of specific fire events concerning (a) fireline intensity ($kW\,m^{-1}$), (b) crown fire intensity ($kW\,m^{-1}$), (c) fuel consumption (%), and (d) tree mortality (%).

these simulations for all possible future landscapes resulting from vegetation development, disturbance, and management policies (Keane and Finney, 2003). Currently, these computational intensive techniques may be beyond the resources available to fire management, so any quantification of fire hazard will require a compromise between the management objective and available computer resources, modeling expertise, and time. Thus, it is important to recognize the limitations of each hazard and risk analysis to more accurately interpret and utilize results of the analyses.

4.1. Limitations of this approach

The most significant limitation of the FIREHARM approach for quantifying fire hazard is the lack of a spatial representation of fire spread and intensity. FIREHARM simulates a heading fire in all pixels, but in reality many pixels may burn from a flanking or backing fire with lower intensities and spread rates causing less impacts and damage. A more accurate representation of fire hazard would be to quantify the distribution of probable fire intensities and spread rates at each pixel, such as that used by Liedloff and Cook (2007), and then derive measure of hazard from that distribution, such as the probability of wildfire occurring above a threshold intensity. Andrews (2007) have implemented this strategy in the FSPRO simulation package which simulates the probability of fire spread based on multiple weather scenarios for real time, operational wildfire application. The down-side of the FSPRO approach is that it is computationally demanding making it difficult to complete for the large scale analysis required in many hazard analyses. Moreover, it is problematic to implement a temporal component with this approach because the fuels are considered static for the entire simulation and only a finite set of weather scenarios are used.

The simulation of fuel moisture in the temporal mode might be too coarse because of the lack of rigor in the NFDRS moisture and water balance algorithms. Better fuel moisture simulation modules are available (Nelson, 2002), but they come at an increased computational burden that may be too much for computing resources of

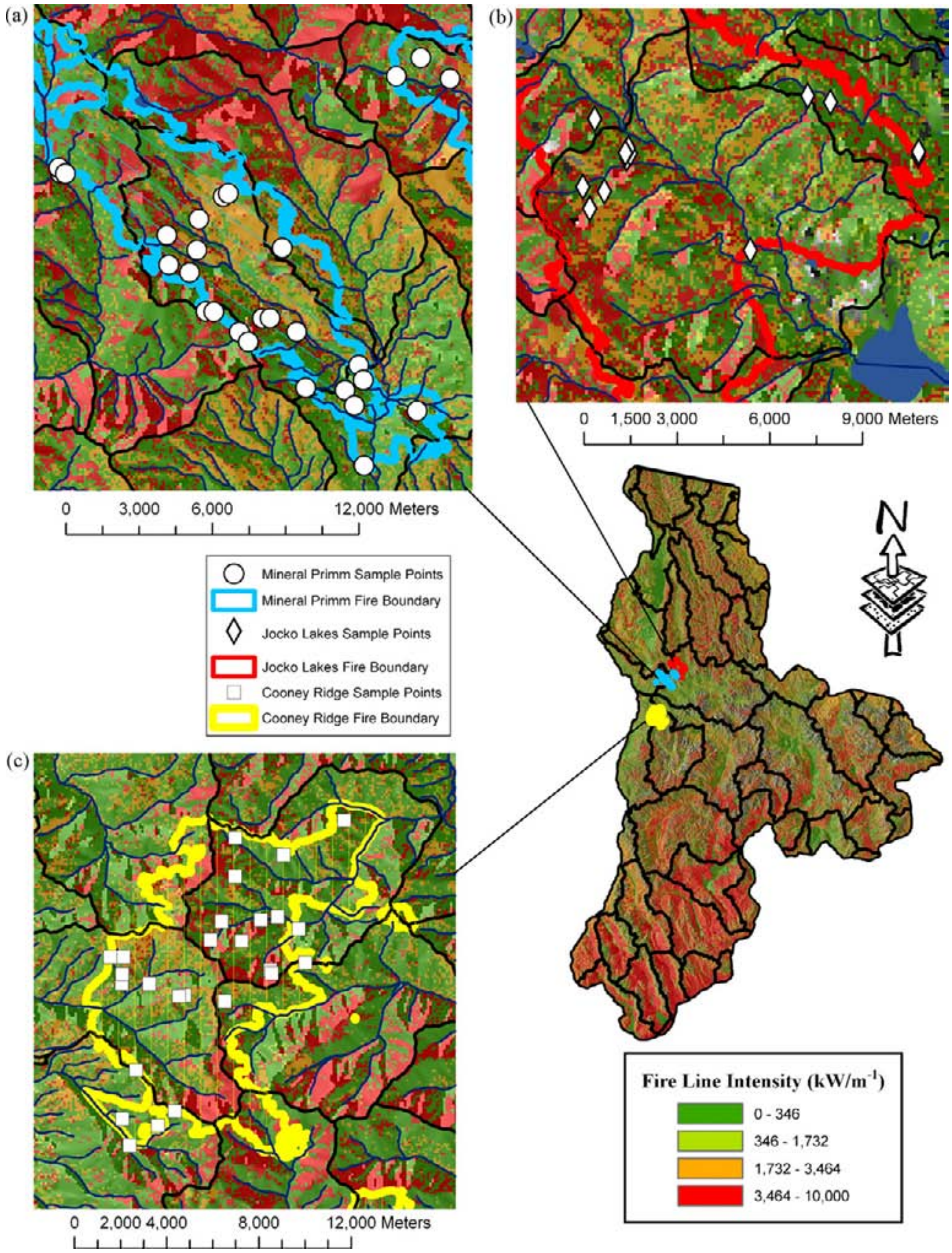

Fig. 7. Plot locations in each of the three wildfires: (a) Mineral Primm, (b) Jocko Lakes, and (c) Cooney Ridge. Background for each fire is the predicted fireline intensity as computed from FIREHARM.

many managers. Quantifying fire risk across time requires accurate and consistent fuel moisture modeling techniques and new technology must be integrated into FIREHARM as it becomes available.

While the LANDFIRE project represents significant progress in providing the spatial data critically needed in fire management (Rollins et al., 2006), its national scope demanded a mid-scale implementation that sometimes results in inadequate quality and accuracy of spatial fuel data at local scales (Keane et al., 2007). The alternative is for local agencies to develop better fine scale fuels maps, but this factor alone could increase the price and time-span of fire hazard assessments by orders of magnitude (Keane et al., 2001). The fuel models used in FIREHARM are simplified classifications of fuel characteristics that result in a decreased resolution of FIREHARM output (Scott and Burgan, 2005; Lutes et al., in preparation), but fuel characteristics are notoriously variable and scale dependent making them difficult to sample and map, and few fire behavior models have sufficient resolution and detail to accept actual loadings (Keane et al., 2001, 2006). Therefore, the user must recognize the coarseness of LANDFIRE data when interpreting the FIREHARM products.

The FIREHARM program is currently a research tool and has not yet been implemented into a system for use by fire management. While fire managers can use the program in its current form, it would take extensive training and computer experience to apply this program in specific projects. Instead of releasing yet another fire hazard analysis tool to the already overburdened fire analyst, we recommend that FIREHARM algorithms or concepts be implemented in commonly used software systems, such as FOFEM-MT (www.fmi.gov), FARSITE, or FLAMMAP (Finney, 2005). Computing probabilities of specific fire events under the temporal option

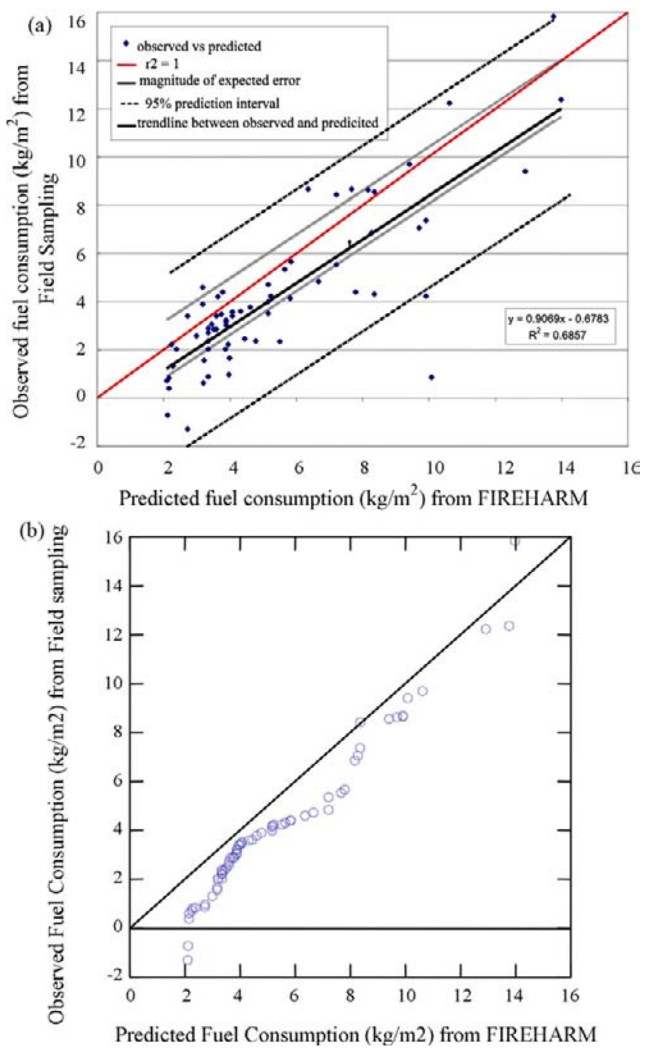

Fig. 8. Plot of observed fuel consumption (kg m^{-2}) from field validation plots (*x*-values) versus FIREHARM output for fuel consumption ($N = 66$; *y*-values: kg m^{-2}). Solid black line is the fitted trend line. Outer confidence limits are the maximum errors that can be expected following Reynolds (1984).

in FIREHARM is computationally intensive often requiring several days to compute probabilities for large regions. This often precludes large area estimation of fire risk for most management agencies without extensive computational resources.

4.2. FIREHARM validation

It was difficult to directly compare FIREHARM outputs for soil heating, spread rate, and emissions with any of the measured field variables. However, qualified assessments of six fire variables indicate that FIREHARM predicted most of these variables adequately for planning and prioritization applications on some sites (Table 2). The observed variability in FIREHARM output was in general agreement with field observations and fire behavior reports posted during the wildfires evaluated. FIREHARM predicted emissions would exceed a high emission production rate of 0.112 kg m^{-1} on 42% of the sample plots. This is also in general agreement with fire reports because high rates of smoke production were commonly observed during the wildfires.

The mixed accuracy of FIREHARM predictions for the six variables (Table 2) is a result of problems in simulation algorithms and generalized input data. The assumption of a heading fire in FIREHARM provides a "worst case" prediction that does not always occur in many wildfires (Fig. 6). FIREHARM uses only one estimate of scorch height for an entire pixel, whereas real fires tend to have high variability in scorch height within a small area. And, FIREHARM surface and crown fire algorithms are overly simplistic and general, and they were designed for point simulations (1D simulations). The over generalized fuel model information coupled with the outdated fire simulation algorithms could also contribute to significant error in predicting fire effects and behavior. Weather and fuel moisture input information for the validation plots are difficult to obtain at the time of burning, so our estimates were from distant stations at approximate times which may contain significant errors. Most importantly, the difference in fuel loadings across the two paired plots (burned, unburned) to compute fuel consumption can be significantly different and difficult to document once the wildfire has occurred. Last, we found bole char height is not a good variable to represent flame length because char is also dependent on residence time which may be unrelated to flame length. A better approach would involve establishing plots just prior to wildfire occurrence and sampling weather and fuel moistures at the time of burning, both of which can be difficult, hazardous, and ineffective.

5. Summary and management implications

Currently, fuel hazard mapping for fire management is limited by four major factors: (1) computational resources available to fire management organizations, (2) high quality, spatially consistent, management-oriented spatial data layers at the appropriate scale and resolution, (3) lack of error and uncertainty estimates for the spatial data layers, and (4) improper spatial analysis techniques. This study presents a method for generating spatially consistent spatial data appropriate for fire hazard analysis with the level of quality dependent on available input data, scale of analysis, and management objective.

There are advantages and disadvantages of using FIREHARM hazard (event mode) or potential risk (temporal mode) maps. While hazard maps can be quickly created by assuming representative fuel moistures, they can be difficult to interpret because they do not incorporate the temporal frequency of the representative fuel moistures in the assessment. On the other hand, potential risk maps are difficult to create because FIREHARM (1) requires accurate estimations of site conditions (soil depth, texture, leaf area index), (2) must be linked to the very large DAYMET weather database, (3) must simulate fire characteristics for every day in the DAYMET record, and (4) must simulate daily ecosystem process (water budget) along with fire characteristics. FIREHARM risk maps may take days to create while hazard maps can be created in hours depending on the size and resolution of the landscape. We find that large, regional analysis can be successfully accomplished using the hazard maps, but fine scale project level analysis are more appropriate for the potential risk maps.

We acknowledge that FIREHARM is not the perfect solution to quantifying fire hazard and risk across multiple scales, but we feel it is a step in the right direction. Recent efforts to incorporate fine scale fire spread dynamics into hazard and risk are also important (Agee et al., 2000; Finney, 2001, 2005). Andrews (2007) FSPRO approach in which maps of fire intensity distributions are computed from thousands of FARSITE runs is perhaps the most significant step towards fine scale risk mapping. Fire management planning needs additional fire behavior and effects characteristics to implement realistic fuel treatment regimes. Fire effects, for example, will be needed to determine impact to soils or carbon inputs to the atmosphere. Future fire hazard and risk projects for fire management and planning may require a tool that links a comprehensive fire spread simulation model like FARSITE (Finney, 1998a) to a detailed landscape vegetation simulation model that mechanistically sim-

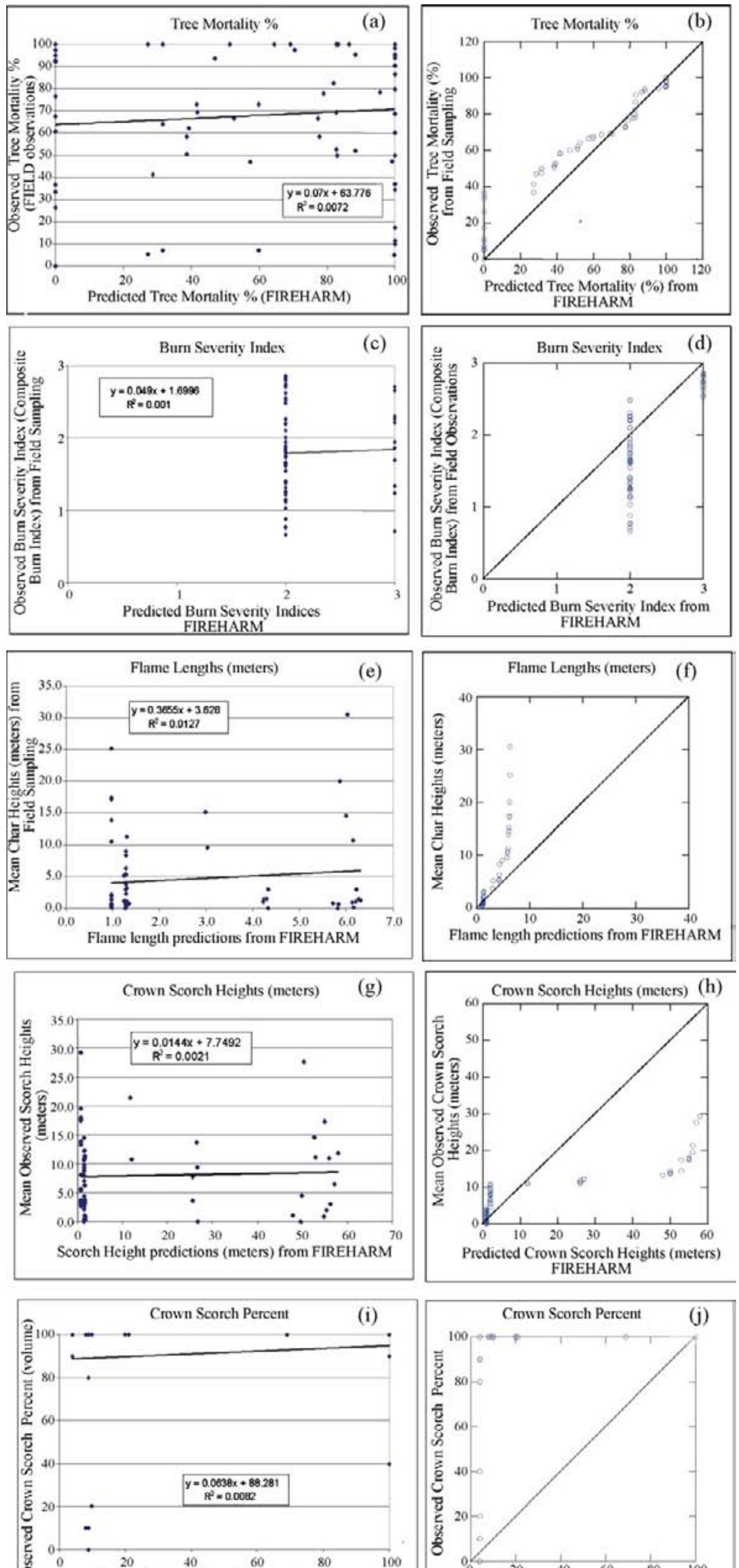

Fig. 9. Scatterplots of observed (plot data) with predicted (FIREHARM estimates) for five fire hazard variables used for model validation along with quantile plots: (a and b) tree mortality, (c and d) burn severity, (e and f) scorch height, and (g and h) flame lengths.

ulates fuel conditions from vegetation, climate, and disturbance dynamics, and this model would be executed many times over large landscapes to produce a wide variety of hazard and risk measures. Moreover, additional issues such as the wildland urban interface, threatened and endangered species, and climate change, can be added to the linked models to create a fully integrated platform for analysis of fire hazard and risk.

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References

Agee, J.K., 1998. The landscape ecology of western forest fire regimes. Northwest Science 72, 24–34.
Agee, J.K., Bahro, B., Finney, M.A., Omi, P.N., Sapsis, D.B., Skinner, C.N., van Wagtendonk, J.W., Weatherspoon, C.W., 2000. The use of shaded fuelbreaks in landscape fire management. Forest Ecology and Management 127, 55–66.
Ager, A.A., Finney, M.A., Kerns, B.K., Maffei, H., 2007. Modeling wildfire risk to northern spotted owl (*Strix occidentalis* caurina) habitat in Central Oregon, USA. Forest Ecology and Management 246, 45–56.
Albini, F.A., 1976. Estimating wildfire behavior and effects. General Technical Report INT-30, USDA Forest Service.
Anderson, H.E., 1982. Aids to determining fuel models for estimating fire behavior. General Technical Report INT-122, USDA Forest Service Intermountain Research Station, Ogden, UT, USA.
Anderson, H.E., 1990. Predicting equilibrium moisture content of some foliar forest litter in the Northern Rocky Mountains. Research Paper INT-429, USDA Forest Service, Intermountain Research Station, Ogden, UT, USA.
Andrews, P.L., 2007. BehavePlus fire modeling system: past, present, and future. In: Proceedings of 7th Symposium on Fire and Forest Meteorological Society, 23–25 October, Bar Harbor, Maine, p. 13.
Andrews, P.L., Bradshaw, L.S., 1997. FIRES: fire information retrieval and evaluation system—a program for fire danger analysis. General Technical Report INT-GTR-367, USDA Forest Service Intermountain Research Station, Ogden, UT.
Arno, S.F., 1979. Forest regions of Montana. Research Paper INT-218, USDA Forest Service, Ogden, UT.
Arno, S.F., 1980. Forest fire history of the northern Rockies. Journal of Forestry 78, 460–465.
Arno, S.F., Parsons, D.J., Keane, R.E., 2000. Mixed-severity fire regimes in the northern Rocky Mountains: consequences of fire exclusion and options for the future. In: Wilderness science in a time of change conference, vol. 5: wilderness ecosystems, threat, and management, Missoula, Montana, May 23–27, 1999. U.S. Dept. of Agriculture Forest Service Rocky Mountain Research Station 2000, Fort Collins, CO, pp. 225–232.
Bachmann, A., Allgower, B., 1999. Framework for wildfire risk analysis. In: International Conference on forest fire research; Conference on fire and forest meteorology, Lusa, Portugal, pp. 2177–2190.
Bachmann, A., Allgower, B., 2001. A consistent wildland fire risk terminology is needed. Fire Management Today 61, 28–33.
Barrett, S.W., 2004. A fire regimes classification for Northern Rocky Mountain forests. Fire Management Today 64, 25–29.
Berry, A.H., Donovan, G., Hesseln, H., 2006. Prescribed burning costs and the WUI: economic effects in the Pacific Northwest. Western Journal of Applied Forestry 21, 72–78.
Bevins, C.D., 1996. fireLib: User Manual and Technical Reference. SEM Technical Document Systems for Environmental Management, Missoula, MT.
Blanchard, B., Ryan, R.L., 2007. Managing the Wildland-Urban interface in the Northeast: perceptions of fire risk and hazard reduction strategies. Northern Journal of Applied Forestry, 24.
Blanco, J.A., Seely, B., Welham, C., Kimmins, J.P.H., Seebacher, T.M., 2007. Testing the performance of a forest ecosystem model (FORECAST) against 29 years of field data in a Pseudotsuga menziesii plantation. Canadian Journal of Forest Research 37, 1808–1820.
Bonazountas, M., Kallidromitou, D., Kassomenos, P.A., Passas, N., 2005. Forest fire risk analysis. Human and Ecological Risk Assessment 11, 617–626.
Brown, J.K., 1974. Handbook for inventorying downed woody material. General Technical Report GTR-INT-16, USDA Forest Service, Intermountain Forest and Range Experiment Station, Ogden, UT, USA.
Brown, J.K., 1985. The "unnatural fuel buildup" issue. In: Lotan, J.E., Kilgore, B.M., Fischer, W.C., Mutch, R.W. (Eds.), Symposium and Workshop on Wilderness Fire. U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station, Missoula, MT, pp. 127–128.
Brown, J.K., 1995. Fire regimes and their relevance to ecosystem management. In: Proceedings of the Society of American Foresters 1994 Annual Meeting, Society of American Foresters, Washington, DC, Bethesda, MD, pp. 171–178.
Brown, T.J., Hall, B.L., Westerling, A.L., 2004. The impact of twenty-first century climate change on wildland fire danger in the western United States: an applications perspective. Climatic Change 62, 365–388.
Burgan, R.E., 1993. A method to initialize the Keetch-Byram Drought Index. Western Journal of Applied Forestry 8, 109–115.
Burgan, R.E., Rothermal, R.C., 1984. BEHAVE: fire behavior prediction and fuel modeling system—FUEL subsystem. General Technical Report INT-167, USDA Forest Service.
Cain, M.D., 1984. Height of stem-bark char underestimates flame length in prescribed burns. Fire Management Notes 45, 17–21.
Cohen, W.B., 1989. Potential utility of the TM tasseled cap multspectral data transformation for crown fire hazard assessment. In: Agenda for the Nineties, ASPRS/ACSM Annual Convention, Baltimore, MD, pp. 118–127.
DeBano, L.F., Neary, D.G., Ffolliott, P.F., 1998. Fire's Effect on Ecosystems. John Wiley and Sons, New York, NY, USA.
Deeming, J.E., Burgan, R.E., Cohen, J.D., 1977. The national fire danger rating system—1978. General Technical Report INT-39 USDA Forest Service Intermountain Forest and Range Experiment Station, Ogden, UT.
Ercanoglu, M., Weber, K.T., Langille, J., Neves, R., 2006. Modeling wildland fire susceptibility using fuzzy systems. GIScience and Remote Sensing 43, 268–282.
Eyre, F.H.E., 1980. Forest Cover Types of the United States and Canada. Society of American Foresters, Washington, DC, USA.
Fairbrother, A., Turnley, J.G., 2005. Predicting risks of uncharacteristic wildfires: application of the risk assessment process. Forest Ecology and Management 211, 28–35.
Ferry, G.W., Clark, R.G., Montgomery, R.E., Mutch, R.W., Leenhouts, W.P., Zimmerman, G.T., 1995. Altered Fire Regimes within Fire-Adapted Ecosystems. U.S Department of the Interior, National Biological Service, Washington, DC.
Fiedler, C.E., Keegan, C.E., Woodall, C.W., Morgan, T.A., Robertson, S.H., Chmelik, J.T., 2003. A strategic assessment of fire hazard in Montana. A report submitted to the Joint Fire Sciences Program, Boise, Idaho, USA. 39 pages. [see http://www.nifc.gov/joint_fire_sci/deliverables.html].
Finney, M.A., 1998a. FARSITE: fire area simulator—model development and evaluation. Research Paper RMRS-RP-4, United States Department of Agriculture, Forest Service Rocky Mountain Research Station, Ft. Collins, CO, USA.
Finney, M.A., 1998b. Relationships between landscape fuel patterns and fire growth. Working draft.
Finney, M.A., 2001. Design of regular landscape fuel treatment patterns for modifying fire growth and behavior. Forest Science 47, 219–228.
Finney, M.A., 2005. The challenge of quantitative risk analysis for wildland fire. Forest Ecology and Management 211, 97–108.
Finney, M.A., 2006. A Computational Method for Optimizing Fuel Treatment Locations. USDA Forest Service Proceedings RMRS-P-41. pp. 107–123.
Freese, F., 1960. Testing accuracy. Forest Science 6, 139–145.
GAO, 2002. Severe wildland fires: leadership and accountability needed to reduce risks to communities and resources. Report to Congressional Requesters GAO-02-259, United States General Accounting Office, Washington, DC.
GAO, 2003. Additional actions required to better identify and prioritize lands needing fuels reduction. Report to Congressional Requesters GAO-03-805, United States General Accounting Office, Washington DC.
GAO, 2004. Forest Service and BLM need better information and a systematic approach for assessing risks of environmental effects. GAO-04-705, United States General Accounting Office, Washington, DC.
GAO, 2007. Wildland fire management: better information and a systematic process could improve agencies approach to allocating fuel redcution funds and selecting projects. GAO-07-1168, United States General Accounting Office, Washington DC.
GAO/RCED, 1999. Western National Forests—a cohesive strategy is needed to address catastrophic wildfire threats. GAO report GAO/RCED-99-65, United States General Accounting Office, Washington, DC.
Gill, A.M., Christian, K.R., Moore, P.H.R., Forrester, R.I., 1987. Bushfire incidence, fire hazard, and fuel reduction burning. Australian Journal of Ecology 12, 299–306.
Gonzalez, J.R., Kolehmainen, O., Pukkala, T., 2007. Using expert knowledge to model forest stand vulnerability to fire. Computers and Electronics in Agriculture 55, 107–114.
Habeck, J.R., Mutch, R.W., 1973. Fire-dependant forests in the northern Rocky Mountains. Quaternary Research 3, 408–424.
Hardwick, P.E., Lachowski, H., Forbes, J., Olson, R.J., Roby, K., Fites, J., 1998. Fuel loading and risk assessment Lassen National Forest. In: Greer, J.D. (Ed.), Proceedings of the seventh Forest Service remote sensing applications conference. American Society for Photogrammetry and Remote Sensing, Bethesda, MD, Nassau Bay, TX, USA, pp. 328–339.
Hardy, C.C., 2005. Wildland fire hazard and risk: problems, definitions, and context. Forest Ecology and Management 211, 73–82.
Heinselman, M.L., 1981. Fire intensity and frequency as factors in the distribution and structure of northern ecosystems. In: Mooney, H.A., Bonnicksen, T.M., Christensen, N.L., Lotan, J.E., Reiners, W.A. (Technical Coordinators) (Eds)., Proceedings of the Conference Fire Regimes and Ecosystem Properties. USDA Forest Service General Technical Report WO-26, pp. 7–55.
Hessburg, P.F., Reynolds, K.M., Keane, R.E., James, K.M., Salter, R.B., 2007. Evaluating wildland fire danger and prioritizing vegetation and fuels treatments. Forest Ecology and Management 247, 1–17.
Hogenbirk, J.C., Sarrazin-Delay, C.L., 1995. Using fuel characteristics to estimate plant ignitability for fire hazard reduction. Water, Air and Soil Pollution 82, 161–170.

Holsinger, L., Keane, R.E., Parsons, R., Karau, E., 2006. Development of biophysical gradient layers. General Technical Report RMRS-GTR-175, USDA Forest Service Rocky Mountain Research Station, Fort Collins, CO, USA.

Jain, A., Ravan, S.A., Singh, R.K., Das, K.K., Roy, P.S., 1996. Forest fire risk modelling using remote sensing and geographic information systems. Current Science 70, 928–933.

Karau, E., Keane, R.E., in preparation. Burn severity mapping using simulation modeling and satellite imagery. International Journal of Wildland Fire.

Keane, R.E., Burgan, R.E., Wagtendonk, J.V., 2001. Mapping wildland fuels for fire management across multiple scales: integrating remote sensing, GIS, and biophysical modeling. International Journal of Wildland Fire 10, 301–319.

Keane, R.E., Cary, G.J., Parsons, R., 2003. Using simulation to map fire regimes: an evaluation of approaches, strategies, and limitations. International Journal of Wildland Fire 12, 309–322.

Keane, R.E., Dickinson, L.J., 2007. Development and evaluation of the photoload sampling technique. Research Paper RMRS-RP-61CD, USDA Forest Service Rocky Mountain Research Station.

Keane, R.E., Finney, M.A., 2003. The simulation of landscape fire, climate, and ecosystem dynamics. In: Veblen, T.T., Baker, W.L., Montenegro, G., Swetnam, T.W. (Eds.), Fire and Global Change in Temperate Ecosystems of the Western Americas. Springer-Verlag, New York, NY, USA, pp. 32–68.

Keane, R.E., Frescino, T.L., Reeves, M.C., Long, J., 2006. Mapping wildland fuels across large regions for the LANDFIRE prototype project. In: Rollins, M.G., Frame, C. (Eds.), The LANDFIRE Prototype Project: Nationally Consistent and Locally Relevant Geospatial Data for Wildland Fire Management. USDA Forest Service Rocky Mountain Research Station, pp. 367–396.

Keane, R.E., Holsinger, L., 2006. Simulating biophysical environment for gradient modeling and ecosystem mapping using the WXFIRE program: Model documentation and application. Research Paper RMRS-GTR-168CD, USDA Forest Service Rocky Mountain Research Station, Fort Collins, CO, USA.

Keane, R.E., Morgan, P., Running, S.W., 1996. FIRE-BGC—a mechanistic ecological process model for simulating fire succession on coniferous forest landscapes of the northern Rocky Mountains. Research Paper INT-RP-484, United States Department of Agriculture, Forest Service Intermountain Forest and Range Experiment Station, Ogden, UT, USA.

Keane, R.E., Rollins, M.G., Zhu, Z., 2007. Using simulated historical time series to prioritize fuel treatments on landscapes across the United States: the LANDFIRE prototype project. Ecological Modelling 204, 485–502.

Keane, R.E., Veblen, T., Ryan, K.C., Logan, J., Allen, C., Hawkes, B., 2002. The cascading effects of fire exclusion in the Rocky Mountains. In: Baron, J. (Ed.), Rocky Mountain Futures: An Ecological Perspective. Island Press, Washington, DC, USA, pp. 133–153.

Keetch, J.J., Byram, G.M., 1968. A drought index for forest fire control. Research Paper SE-38, USDA Forest Service Southeast Forest Experiment Station.

Key, C.H., Benson, N.C., 2006. Landscape Assessment: Ground measure of severity, the Composite Burn Index; and Remote sensing of severity, the Normalized Burn Ratio. In: Lutes, D.C., Keane, R.E., Caratti, J.F., Key, C.H., Benson, N.C., Sutherland, S., Gangi, L.J. FIREMON: Fire Effects Monitoring and Inventory System. USDA Forest Service, Rocky Mountain Research Station, Ogden, UT. Gen. Tech. Rep. RMRS-GTR-164-CD: LA 1–51. See http://frames.nbii.gov/projects/firemon/FIREMON_LandscapeAssessment.pdf.

Klaver, J.M., Klaver, R.W., Burgan, R.E., 1998. Using GIS to assess forest fire hazard in the Mediterranean region of the United States. ESRI Users Conference, http://www.esri.com/base/common/userconf/proc97/HOME.HTM.

Laverty, L., Williams, J., 2000. Protecting people and sustaining resources in fire-adapted ecosystems—a cohesive strategy. Forest Service response to GAO Report GAO/RCED 99-65 USDA Forest Service, Washington, DC.

Lentile, L.B., Morgan, P., Hudak, A.T., Bobbitt, M.J., Lewis, S.A., Smith, A.M., Robichaud, P.R., 2007. Post-fire burn severity and vegetation response following eight large wildfires across the western United States. Fire Ecology 3, 91–101.

Liedloff, A.C., Cook, G.D., 2007. Modelling the effects of rainfall variability and fire on tree populations in an Australian tropical savanna with the FLAMES simulation model. Ecological Modelling 201, 269–282.

Loehle, C., 2004. Applying landscape principles to fire hazard reduction. Forest Ecology and Management 198, 261–267.

Lutes, D.C., Keane, R.E., Caratti, J.F., in preparation. Fuel loading models: a national classification of wildland fuelbeds for fire effects modeling. International Journal Wildland Fire.

Lutes, D.C., Keane, R.E., Caratti, J.F., Key, C.H., Benson, N.C., Sutherland, S., Gangi, L.J., 2006. FIREMON: fire effects monitoring and inventory system. General Technical Report RMRS-GTR-164-CD, USDA Forest Service Rocky Mountain Research Station, Fort Collins, CO, USA.

Mayer, D.G., Butler, D.G., 1993. Statistical validation. Ecological Modeling 68, 21–32.

McHugh, C.W., Kolb, T.E., 2003. Ponderosa pine mortality following fire in northern Arizona. International Journal of Wildland Fire 12, 7–22.

Mutch, R.W., 1994. Fighting fire with fire: a return to ecosystem health. Journal of Forestry 92, 31–33.

Nelson, R.M., 2002. Prediction of diurnal change in 10-h fuel stick moisture content. Canadian Journal of Forest Research 30, 1071–1087.

Neuenschwander, L.F., Menakis, J., Miller, M., Sampson, R.N., Hardy, C.C., Averill, R., Mask, R., 2000. Indexing Colorado watersheds to risk of wildfire. Journal of Sustainable Forestry 11, 35–56.

NRC, 1989. Improving Risk Communication. National Academy Press, Washington, DC, USA.

O'Hara, K.L., Latham, P.A., Hessburg, P.F., Smith, B.G., 1996. A structural classification for Inland Northwest vegetation. Western Journal of Applied Forestry. 11, 97–102.

Ottmar, R.D., Burns, M.F., Hall, J.N., Hanson, A.D., 1993. CONSUME users guide. General Technical Report PNW-GTR-304, USDA Forest Service.

Parisien, M.A., Kafka, V.G., Hirsch, K.G., Todd, J.B., Lavoie, S.G., Maczek, P.D., 2005. Mapping wildfire susceptibility with the BURN-P3 simulation model. Informational Report NOR-X-405, Canadian Forest Service Northern Forestry Centre, Edmonton Alberta, Canada.

Peterson, D.L., 1985. Crown scorch volume and scorch height: estimates of post-fire tree condition. Canadian Journal of Forest Research 15, 596–598.

Pfister, R.D., Kovalchik, B.L., Arno, S.F., Presby, R.C., 1977. Forest habitat types of Montana. General Technical Report INT-34, U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station, Ogden, UT, USA.

Philpot, C.W., 1990. The wildfires in the northern Rocky Mountains and greater Yellowstone Area-1988. In: McCabe, R.E. (Ed.), Transactions of the Fifth-fifth North American Wildlife and Natural Resources Conference. Denver, CO, USA, pp. 185–187.

Pickett, S.T.A., 1989. Space-for-time substitution as an alternative to long-term studies. In: Likens, G.E. (Ed.), Long-term Studies in Ecology: Approaches and Alternatives. Springer-Verlag, New York, NY, pp. 110–135.

Preisler, H.K., Brillinger, D.R., Burgan, R.E., Benoit, J.W., 2004. Probability based models for estimating fire risk. International Journal of Wildland Fire 13, 133–142.

Radeloff, V.C., Hammer, R.B., Stewart, S.I., Fried, J.S., Holcomb, S.S., McKeefry, J.F., 2005. The wildland-urban interface in the United States. Ecological Applications 15, 799–805.

Reinhardt, E., Keane, R.E., Brown, J.K., 1997. First order fire effects model: FOFEM 4.0 user's guide. General Technical Report INT-GTR-344, USDA Forest Service.

Reynolds, M.R., 1984. Estimating the error in model predictions. Forest Science 30, 454–469.

Rollins, M.G., Frame, C., 2006. The LANDFIRE prototype project: nationally consistent and locally relevant geospatial data for wildland fire management. General Technical Report RMRS-GTR-175, USDA Forest Service Rocky Mountain Research Station, Fort Collins, CO.

Rollins, M.G., Keane, R.E., Zhu, Z., 2006. An overview of the LANDFIRE prototype project. General Technical Report RMRS-GTR-175, USDA Forest Service Rocky Mountain Research Station, Fort Collins, CO, USA.

Romme, W.H., Knight, D.H., 1981. Fire frequency and subalpine forest succession along a topographic gradient in Wyoming. Ecology 62, 319–326.

Rothermel, R.C., 1972. A mathematical model for predicting fire spread in wildland fuels. Research Paper INT-115, United States Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station, Ogden, UT.

Rothermel, R.C., 1983. How to predict the spread and intensity of forest and range fires. General Technical Report INT-143, United States Department of Agriculture Forest Service, Ogdon, UT.

Rothermel, R.C., 1991. Predicting behavior and size of crown fires in the Northern Rocky Mountains. Research Paper INT-438, United States Department of Agriculture, Forest Service Intermountain Forest and Range Experiment Station, Ogden, UT, USA.

Rothermel, R.C., Wilson, R.A.J., Morris, G.A., Sackett, S.S., 1986. Modeling moisture content of fine dead wildland fuels: input to the BEHAVE fire prediction system. Research Paper INT-359, USDA Forest Service Intermountain Research Station, Ogden, UT.

Running, S.W., 2006. Is global warming causing more, larger wildfires. Science 313, 927–928.

Running, S.W., Coughlan, J.C., 1988. A general model of forest ecosystem processes for regional applications. I. Hydrologic balance, canopy gas exchange and primary production processes. Ecological Modelling 42, 125–154.

Ryan, K.C., Noste, N.V., 1985. Evaluating prescribed fires. In: Lotan, J.E., Kilgore, B.M., Fischer, W.C., Mutch, R.W. (Eds.), Wilderness Fire Symposium. USDA Forest Service General Technical Report INT-182, Intermountain Research Station, Ogden UT, USA, Missoula, MT, 230–237.

Rydberg, P.A., 1915. Phytogeographical notes on the Rocky Mountain region IV. Forests of the Subalpine and Montane Zones. Bulletin of the Torrey Botanical Club 42, 11–25.

Sampson, R.N., Atkinson, R.D., Lewis, J.W., 2000. Indexing resource data for forest health decision making. Journal of Sustainable Forestry 11, 1–14.

Sampson, R.N., Sampson, R.W., 2005. Application of hazard and risk analysis at the project level to assess ecologic impact. Forest Ecology and Management 211, 109–116.

Scott, J., Burgan, R.E., 2005. A new set of standard fire behavior fuel models for use with Rothermel's surface fire spread model. General Technical Report RMRS-GTR-153, USDA Forest Service Rocky Mountain Research Station, Fort Collins, CO.

Seaber, P.R., Kapinos, P., Knapp, G.L., 1987. Hydrologic unit maps. US Geological Survey Water-Supply Paper 2294, USDI US Geological Survey, Denver, CO.

Sikkink, P., Keane, R.E., Lutes, D.C., in press. A user's guide to fuel loading models. General Technical Report RMRS-GTR-XX, USDA Forest Service Rocky Mountain Research Station, Fort Collins, CO, USA.

Simard, A.J., 1996. Fire severity, changing scales, and how things hang together. International Journal of Wildland Fire 1, 23–34.

Thornton, P., Steven, E., Running, W., White, M.A., 1997. Generating surfaces of daily meteorological variables over large regions of complex terrain. Journal of Hydrology 190, 214–251.

Thornton, P.E., Hasenauer, H., White, M.A., 2000. Simultaneous estimation of daily solar radiation and humidity from observed temperature and precipitation: an application over complex terrain in Austria. Agricultural and Forest Meteorology 104, 255–271.

Thornton, P.E., Running, S.W., 1999. An improved algorithm for estimating incident daily solar radiation from measurements of temperature, humidity, and precipitation. Agricultural and Forest Meteorology 93, 211–228.

Westerling, A.L., Hidalgo, H.G., Cayan, D.R., Swetnam, T.W., 2006. Warming and earlier spring increase in western US forest wildfire activity. Science 313, 940–943.

Wiitala, M., Carlton, D.W., 1994. Assessing long term fire movement risk in wilderness fire management. In: Proceedings of the Conference on Fire and Forest Meteorology. Society of American Foresters, Jekyll Island, GA, USA, pp. 123–128.

WRCC, 2008. Western Regional Climate Center: Historical Climate Information. Western Regional Climate Center.

Yool, S.R., Eckhardt, D.W., Estes, J.E., Cosentino, M.J., 1985. Describing the brushfire hazard in Southern California. In: Annual Association of American Geography, vol. 75, pp. 417–430.

Zhu, Z., Vogelmann, J., Ohlen, D., Kost, J., Chen, S., Tolk, B., Rollins, M.G., 2006. Mapping existing vegetation composition and structure. General Technical Report RMRS-GTR-175, USDA Forest Service Rocky Mountain Research Station, Fort Collins, CO, USA.