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

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Abstract:

This paper demonstrates possible methods for mapping fire hazard and 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 describe fire hazard over space, then computes risk from the distribution of these measures over time using simulation modeling of weather and fuel moistures. We implemented FIREHARM output into a spatial decision support system called EMDS to demonstrate how to use hazard and risk spatial data to prioritize stands for fuel treatments. Validation of six FIREHARM output variables revealed mixed accuracy rates (20-80 percent correct) but overall accuracies were acceptable for prioritization analysis because precision was high. The advantages and disadvantages of the fire hazard and risk approaches are discussed and a possible agenda for future development of comprehensive fire hazard and risk mapping is presented.

Keywords: Fire hazard, mapping, fuel treatment prioritization

Introduction

Severe fire seasons of the past decade in the western United States has spurred many government agencies to reduce fire intensity and severity to protect human property and life (GAO/RCED 1999, Laverty and Williams 2000, GAO 2003). 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 foster 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 the areas that surround our public wildlands thereby creating and expanding the “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 to the increased severe wildfires, 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). As funds are limited and the cost of these fuel treatments continually increases (Berry et al. 2006), fire management has 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). A quantification of fire hazard and risk is critical for identifying and prioritizing those areas in need of fuels reduction treatment (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 rate fire hazard, and then describes the distribution of these measures over time using simulation modeling of weather and fuel moistures to estimate measures of fire risk. The hazard and risk measures are then represented by digital maps for use in fire management planning and wildfire operations. We implemented FIREHARM maps into a spatial decision support system called EMDS to demonstrate how to prioritize areas based on fuels and FIREHARM variables. Then we validated some FIREHARM output variables to describe model accuracy and precision. Last, we discuss the advantages and disadvantages of the approaches used here and present a possible agenda for future development of comprehensive fire hazard and risk mapping.

Background

In this paper, we follow the lexicon presented by 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 is usually computed or 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 occurs within a specific time period or from the realization of a specified hazard. In our analysis, we assume that the entire 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 the 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 large number of measures that are computed from a variety of methods and computer programs (Sampson et al. 2000). However, many of these measures may be correlated, inappropriate, contradictory, or unsuited for the fire management issue being addressed. For example, some efforts at describing hazard and risk may confuse high fireline intensity with high fire hazard, while others 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, may be described as a hazardous fire, even though high intensity fires in these ecosystems are 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 objective of the hazard analysis, which must always 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 the stands with the greatest potential to have a high intensity fire. While most fire hazard maps can be useful, it is important that their temporal and spatial scales, limitations, and uncertainty be explicitly recognized when interpreting them.

The quantification of fire hazard and risk is often a difficult and contentious task due to the complexity of fire events across multiple time and space scales, the effects of these fire events on the ecosystem, and the diverse fire regimes that are created by these fire events over time (Brown 1995, Agee 1998, Barrett 2001, Finney 2005). Fire hazard has been described by a variety of approaches including expected fire behavior (Hardwick et al. 1998, Hessburg et al. 2007), fuels (Hogenbirk and Sarrazin-Delay 1995), satellite imagery (Cohen 1989, Jain et al. 1996, Ercanoglu et al. 2006), topography (Yool et al. 1985), expert knowledge (Gonzalez et al. 2007), socioeconomic values (Bonazountas et al. 2005), and crown fire index (Fiedler et al. 2001). Fire risk has been described by 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, the diversity of fire hazard and risk measures is because each analysis must be crafted to answer the specific management objectives, and a clear, concise statement of objectives is absolutely critical for any hazard analysis. However, many fire hazard projects design the analysis 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 characteristics of landscape composition and structure is important to estimates of fire hazard as the pattern of fuels will ultimately influence fire spread and subsequent fire intensity (Finney 1998b, Loehle 2004). Moreover, spatial fuel patterns will 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 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 determine 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 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 (Hessburg et al. 2007). Two of these layers describe continuous variables with different units, while the third is a categorical layer with nominal categories. Each layer has a unique spatial error distribution, mapping resolution, map scale, and computational detail that is complicated when merged with other maps. A step in the right direction would be to assume 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). These 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 compute the behavior from the fire model.

Many fire hazard analyses also assume severe fire weather (90^{th} or 99^{th} percentile temperature, wind, fuel moistures) to compute the fire characteristics that describe the hazard 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, for example, 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 90^{th} percentile weather variables arise when assessing fire hazard across large landscapes, especially in mountainous terrain, as the 90^{th} 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 their analysis landscapes computed as 90th percentile from one weather station.

Methods

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 (Figure 1). FIREHARM is more of a platform than a fire model because it integrates previously developed fire simulation models into its structure and does not include 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 therefore simulates the most extreme fire condition from the antecedent weather. FIREHARM does not simulate crown fires directly but calculates 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 list item represents a mapping unit (i.e., polygon) on the simulation landscape, but it can also represent 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 used in FIREHARM are taken from either the Anderson (1982) standard 13 NFFL models or the Scott and Burgan (2005) new 40 fuel models. The fire danger fuel models 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 national LANDFIRE spatial database for fuel loading inputs which includes a layer of called Fuel Loading Models (FLM) that were developed by (Lutes et al. 2007[in prep]). 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 similar in structure to FIREHARM (Keane et al. 2007).

Weather is input into FIREHARM using the DAYMET US database (www.daymet.org) developed by Thornton et al. (1997) (Figure 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 January 1, 1980 and ending December 31, 1997 from over 1,500 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-degree latitude by 2-degree longitude tiles by year and then day of year. This collection of files, nearly 0.5 terabytes in size, is called the DAYMET weather database.

FIREHARM simulates daily moisture values for 1, 10, 100, and 1000 hr fuels for each day of the year using the DAYMET daily weather and a number of standard fire behavior and fire danger algorithms (Deeming et al. 1977, Rothermel et al. 1986, Anderson 1990). Snow and rain dynamics, along with soil moisture, 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 water balance using estimations of soil textural attributes (percent sand, silt, and clay) and leaf area index (LAI) and the algorithms of contained in FireBGC (Keane et al. 1996).

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 integrate Rothermel (1972) fire behavior routines (Figure 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 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 can be run in two modes. In the *event* mode, the user enters fuel moistures and ambient weather conditions for a given situation, such as a wildfire, and the program will calculate all fire variables for this specified situation. Event mode is especially useful to create fire hazard maps or 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 the temporal mode, FIREHARM simulates fuel moistures from DAYMET and computes fire characteristics over the DAYMET temporal domain (18 years). FIREHARM then calculates the probability of a user-specified event occurring during the 18-year record. A user-specified threshold must be exceeded for an event to occur. For example, FIREHARM might calculate the probability of a fire burning a user-specified 50 percent of the total fuel load across the 18-years of daily computations (6,574 days). The user can narrow this temporal range to a set of years and a set of days within the year. 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 fire treatments.

FIREHARM also computes a three category ordinal fire severity index based on the simulated estimates of three FOFEM fire effects variables – fuel consumption, soil heating, and tree mortality. The following thresholds were used:

- *Low severity*. Total fuel consumption less than 20% and soil heating at 2 cm depth less than 60 degrees C, and mortality for trees above 15 cm diameter is less than 30%.
- *Moderate severity*. Total fuel consumption between 20% and 50%, soil heating at 2 cm depth between 60 degrees C and 250 degrees C, and tree mortality is between 30% and 70%.
- *High severity*. Total fuel consumption greater than 50%, soil heating at 2 cm depth greater than 250 degrees C, and tree mortality greater than 70%.

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

Simulation Specifics

We demonstrate the use of FIREHARM hazard and potential risk mapping in fire management across multiple scales by performing several nested, multi-scale simulations in a study area. First, we constructed a simple but focused fire hazard analysis to use as context for this study. Our objective with this analysis was to prioritize areas in the greatest need of fuel treatment based on their potential to sustain a fire of high intensity that can cause unwanted ecological impacts. To this end, we created a series of maps of fire hazard and potential risk across a designated study area using a dry climate scenario designed to simulate extreme fire weather and the potential for extreme fire events (Figure 2). We them implemented these maps into a decision support system called EMDS (Ecosystem Management Decision Support)(Reynolds and Hessburg 2005) to demonstrate how FIREHARM output can be merged into a application designed to prioritize watersheds for treatment (Figure 2). Last, we field tested FIREHARM model output validity by comparing model output with measured fire severity, fire effects, and fire behavior characteristics across a number of watersheds that contained three Montana wildfires – the 2003 Cooney Ridge and Mineral Primm fires and the 2007 Jocko Lakes fire.

We ran FIREHARM in the event mode for the entire study area at 100 meter pixel resolution using a severe wildfire weather scenario (Table 1). The temporal mode of FIREHARM was not used for the entire study area because of the huge computation requirements needed for such a large simulation extent and high resolution. The severe fire weather conditions are based on the Scott and Burgan (2005) fuel moisture scenarios (Table 1).

Study Area

We chose the LANDFIRE Northern Rocky Mountains Mapping Zone 19 (Rollins and Frame 2006) for our study area (Figure 3). Extending from the Canadian border in northern Montana into eastern Idaho, this approximately 11 million ha landscape contains many diverse ecosystems (Figure 3), which enabled us to fully evaluate our model. We divided the study area into nested watersheds at both the 4^{th} code and 6^{th} code level using the USGS watershed Hydrologic Unit Code classification (Figure 3) (Seaber et al. 1987). We then selected the Blackfoot River watershed as our fourth 4^{th} code watershed to demonstrate mid-scale FIREHARM hazard analysis and several 6th code watersheds to demonstrate fine scale analysis (Figure 3).

Much of the ecosystem diversity in the study area can be attributed to the highly variable topography and the wide range in elevation (760 to 3,400 m) within the zone. Alpine communities are prevalent at higher elevations (~3,400 meters to timberline) with spruce-fir forests ranging from timberline down to approximately 1,800 meters (Figure 3; (Rydberg 1915). Montane forests of lodgepole pine, western larch, Douglas-fir and ponderosa pine cover much of the middle elevation landscape within the zone, while prairie grasslands exist in the lower elevations east of the Rocky Mountains (Figure 3) (Arno 1979).

Climate patterns within the zone are heavily influenced by the presence of the Continental Divide; west of the divide can be classified as a north Pacific coast type while east of the divide experiences a continental climate (WRCC 2008). Winters are generally cold with a few periods of extremely cold weather during normal years (WRCC 2008). Winter temperatures vary across the zone (Figure 4) with January the coldest month on average (WRCC 2008). Summers are warm to hot with temperatures often above 32 ^{o}C (90 ^{o}F). Precipitation is heavily influenced by topography throughout the test area (WRCC 2008) where most precipitation falls in the mountainous regions than on the lower elevations areas (Figure 4). Snowfall levels also vary throughout the zone with mountain regions receiving up to 760 cm (300 inches) annually while many valley areas receive from 75 cm (30 inches) to 125 cm (50 inches) on a yearly basis (Fig 4; WRCC 2008).

The convergence of maritime and continental climates, in combination with topographic complexity inherent to the study area, result in diverse mosaics of vegetation communities that are ultimately shaped by complex and dynamic fire regimes (Habeck and Mutch 1973, Arno 1980, Philpot 1990). Prior to the modern fire suppression era (1900 to present) frequent, low severity fires were common in low elevation, dry forests, mixed-severity fires occurred at longer (30 to 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 observed increase in flammable fuels and the resulting tendency towards more severe fires makes this an ideal study area to test a model designed to identify which areas are at greater risk to experience hazardous fire, and then prioritize where fuel treatments should be placed to efficiently reduce the risk and hazard of future fires.

FIREHARM input map development

All data used as input to FIREHARM to quantify the fire hazard variables in Figure 2 for our study area (Figure 3) were taken from the national LANDFIRE spatial database (www.landfire.gov). The National LANDFIRE project mapped existing and potential vegetation using a combination of remote sensing, landscape metrics, and environmental gradient modeling (Holsinger et al. 2006, Zhu et al. 2006, Keane et al. 2007). Surface fuel models were then assigned to combinations of three vegetation classifications of biophysical setting, cover type, and structural stage while canopy fuel characteristics were mapped using environmental gradients, spectral 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). The soils textural information 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. Polygons were created for the study area based on the methods presented in Holsinger et al. (2006) and Keane and Holsinger (2006).

FIREHARM Validation

FIREHARM output was tested for accuracy by collecting field samples of fire effects, fire severity, and fire behavior variables on a series of ground plots (sample points) in areas burned by wildfires in 2003 and 2007. We employed a paired-sample approach where one sample point was established in an unburned area to represent pre-burn conditions, and another sample point was established in an adjacent burned area to represent post-fire conditions. Each sample point consisted of one 400 m^2 circular plot. These paired points 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), it is difficult to establish real time, pre-burn sample plots under wildfire conditions.

We were able to assess the accuracy of six FIREHARM output variables: 1) surface fuel consumption, 2) tree mortality (%), 3) burn severity index, 4) flame length, 5) scorch height (m), and 6) crown fire potential. We computed FIREHARM predictions of the six output variables using the unburned plot conditions as inputs. Measurements in the paired burned area (observed) were then compared to the FIREHARM output (predicted) using a variety of methods. Tree mortality, burn severity, and canopy fire potential were compared with the field observations using percentage agreement calculations as these data were more categorical in nature than the fuel consumption measurements. We were able to compare fuel consumption measurements as continuous variables as fuel consumption was based on surface fuel consumption and the surface fuels burned in all sample points. However, all other variables were categorical since each point burned either as a surface fire or a crown fire.

Surface fuel consumption -- Downed and dead woody fuel biomass was estimated using a modified version of the planar intercept approach described by Brown (1974). All downed woody debris encountered along predetermined sections of the 25 meter 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 debris (1-hr, 10-hr, 100-hr fuels) were along 2, 2, and 5 meter sections, respectively, on each transect, while coarse woody debris (1000-hr, > 8cm diameter) was tallied along the final 20 meter length of the fuels transect. Diameters and decay states (see Lutes et al. 2006) for each intersected coarse woody debris section was recorded at the point where the material intersects the planar transect. The fuels counts were then input into the fuel loading calculator within FIREMON to calculate woody fuel biomass (woody fuel loadings) in kg m^{-2} using Brown's (1974) woody fuel biomass equations.

Litter and duff biomass was estimated by taking combined litter and duff depth measurements at two points along the 25 meter fuels transect. The proportion of litter depth to the combined duff+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 by bulk densities of 44.1 kg m^{-3} 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. FIREHARM predictions were evaluated for agreement with these measured estimations using a combination of linear regressions (Blanco et al. 2007), chi-square 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 (citation).

Tree Mortality -- Tree mortality was calculated as the ratio of pre-burn live trees to post-burn dead trees on within the burned sample plot in our three wildfire burn areas. Each tree within the burned 400 m^2 circular vegetation plot was visually assessed to determine if the tree survived the wildfire based on the amount of green canopy present and consumption of surface fuels around the base of the tree. Field observations of tree mortality were compared with predicted tree mortality percents from FIREHARM.

Burn Severity-- Burn severity was assessed on each burned sample points using the Composite Burn Index (CBI) sampling strategy by Key and Benson (1999) in FIREMON. To specifically 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 took a holistic approach to burn severity evaluation as we were looking for an aggregate, or average, burn severity index that evaluated the overall burn severity throughout the plot that we could use to compare with the FIREHARM burn severity index output.

Field assessed composite burn indexes were compared directly with the FIREHARM burn severity indices using linear regressions and quantile plots. In addition, percentage agreement values were calculated based five categories of prediction accuracy: 1) correct prediction, 2) under predicting by one severity class, 3) under predicting by two severity classes, 4) over predicting by one severity class, and 5) over predicting by two severity classes.

Flame length -- FIREHARM model predictions for flame length were compared with char height measurements from the burned sample points. We defined bole char height as the vertical height of the bole from the ground up that was blackened by the wildfire (Cain 1984). Bole char height (meters) was measured to the nearest 1/3 meter on the downhill portion of each tree ≥ 10 cm dbh within each of the 400 m^2 sample points. Mean char heights were used to evaluate the flame length predictions from FIREHARM (Cain 1984).

Crown Scorch Heights -- We d measured the percent of pre-fire live crown volume scorched for each individual tree on each of the burn sample points using a modified version 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. Our 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 percent crown scorch to scorch heights by multiplying field measures of tree height and crown base height by percent crown scorch to get a coarse field measure of crown scorch height. The field estimates of crown scorch height were later compared directly with the FIREHARM model output using linear regressions, quantile plots, and percent agreement values. For consistency we also transformed the FIREHARM model output to crown scorch percent by dividing the model output for crown scorch height (meters) by the mapped tree heights from the LANDFIRE coverage layer and multiplying by 100.

Canopy Fire Potential -- The potential for canopy fire was assessed using the FIEHARM model output predictions for fire line intensity (kW m^{-1}) and crown fire intensity (kW m^{-}

^{1}) following the general rules of thumb on interpreting fire behavior and predicting fire growth published in Rothermel (1983). In this set of scenarios fire line intensity between 0 – 346 kW m^{-1} are low intensity fires, 346 to 1,732 kW m^{-1} are intense fires that cannot be managed by personnel on the ground, 1,732 to 3,464 kW m^{-1} torching, crowning and spotting may occur, > 3,464 kW m^{-1} crowning, spotting and major runs are probable (Rothermel 1983). If fireline intensity was greater than 800 kW m^{-1} and crown fire intensity was greater than 10,000 kW m^{-1}, we categorized the sample point as potentially a canopy fire. We compared the predictions for canopy fire occurrence with field observations of whether the burned sample point burned as a canopy fire (value of 1) or a ground fire (value of 0) using percent agreement statistics.

Results

FIREHARM output map layers

Event Mode -- The FIREHARM input layers were created in less than ten days using the LANDFIRE data layers. It took approximately 14 days for FIREHARM to simulate the seven hazard rating variables in Figure 2 across the entire study area using the event mode. An example of one of the fire variables (surface fireline intensity, kW m^{-1}) is shown in Figure 5. The highest surface fire intensities occurred in shrublands, grasslands because LANDFIRE had mapped those areas to high intensity fuel models.

We also found fuel consumption tended to exceed the 50% fuel consumption threshold in most vegetation types except in the subalpine forests (Figure 6). Moreover fuel consumption often exceeded 75% in the central 1/3 of the study area where large concentrations of montane forests characterized by deeper duff layers and heavier concentrations of woody fuels exist (Figure 6). As emissions are linked to fuel consumption in FIREHARM, the greatest potential risk of high smoke emissions followed the fuel consumption trend (i.e. the areas with greatest predicted fuel consumption were also predicted to have the greatest quantities of emitted smoke particles). Grasslands, shrublands, and woodlands were predicted to have a high potential risk of ≥ 50% but the predicted quantities of emitted smoke particles are low for these areas due to the different chemical quantities of the fuels. Soil heating in the upper two centimeters was commonly predicted to be above 60°C in the event scenario as the insulating duff layer lying above the soil was predicted to be removed (Figure 6). High tree mortality rates were predicted for most vegetation types, however lower tree mortality rates were predicted in areas most heavily influenced by xeric and montane forests (Figure 6).

The fire behavior values of scorch height and flame length from FIREHARM followed the same trends as tree mortality (Figure 6). Although large percentages of each vegetation type were predicted to exceed the high potential risk threshold of ≥ 2 meters in the study area, the shrubland and woodland dominated southern 1/3 of the area had consistently greater predicted flame lengths and higher predicted crown scorch percentages. These trends extended into the fireline intensity values (based on surface fire calculations) where the highest fireline intensities for surface fires were predicted for the shrublands and grassland areas due to the higher concentrations of fine, flashy fuels in these vegetation types. However a high percentage of the subalpine forest type exceeded 400 kW m^{-1}. As scorch height and flame length, the highest rates of spread were found in shrublands, woodlands, and grasslands, which were concentrated in the lower 1/3 of the study area (Figure 5).

Temporal Mode – An example of the FIREHARM potential risks maps using the temporal mode where DAYMET data are used to simulate fuel moistures and subsequent daily fire hazard values is shown in Figure 7. In general, we find the highest probabilities of undesirable fire events (greater than specified threshold) 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 logs, litter, and duff. Unacceptable tree mortality (>50%) is more probable in areas that have small trees, high fireline intensity, and crown fire intensity (Figure 7).

FIREHARM validation

In 2004, we established 54 paired sample points within the burn perimeters of the Cooney Ridge (26 sample points) and the Mineral Primm (28 sample points) wildfires (Figure 8). An additional 13 sample points were established within the Jocko Lakes fire perimeter in November of 2007 (Figure 8). Our field sample points covered a range of species types, stand ages and topographic positions that 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 our range of field sampled points with an r^2 value of 0.69 and the slope of the trend line around 0.91 (Figure 9). The bias value (observed – predicted) of -1.175 kg/m^2 indicate that the model tends to over predict fuel consumption, particularly at lower fuel loadings. The Freese (1960) accuracy test is significant (alpha = 0.05) when we accept an error of $\pm$3.8 kg m^{-2} ($\pm$ 58 %). Moreover, the 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 of 0.54 (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, 35% of plots in the 25% agreement category, and 71% in the 50% category (Table 2), which suggests that the model is somewhat inaccurate if small error margins are needed, but does provide good coarse estimates of fuel consumption.

FIREHARM simulates tree mortality most accurately when canopy fire occurrence is predicted accurately (Table 2; Figures 10a and 10b). However, FIREHARM tended to under predict tree mortality in areas that experienced low intensity fires, particularly when all trees were predicted to survive (i.e. mortality = 0; Figure 10b). While no linear relationships were found between model output and field observations of tree mortality, the percent agreement statistics in Table 2 indicate that in some cases the model is predicting correctly (p10 = 21%; p25 = 40%; p50 = 64%). If field sample points are stratified into crown fire sample points (mortality > 60%) and non-crown fire sample points (mortality < 60), we find that mortality predictions improve (Table 2). Percent agreement, for example, improved to 77% for crown fire sample points when the margin of acceptable error was increased to 50% which may be acceptable under some wildfire situations.

Both scorch height and burn severity predictions did not agree well with observed conditions (Table 2; Figure 10), even when crown scorch values were converted to field scorch heights using tree heights. Burn 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 (Figure 10d). In contrast, FIREHARM tended to under predict flame length (Figures 10e and f) and crown fire occurrence, but there was good agreement between FIREHARM canopy fire potential indices (fire line intensity and crown fire intensity). Canopy fires occurred on 44% of the field sample points 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, the FIREHARM successfully predicted 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 to no agreement when compared directly. However, when $\pm$ 2 meters 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 points (68% agreement) than during canopy fires (31%).

Discussion

This study demonstrates new approaches for mapping fire hazard and risk across large regions, diverse ecosystems, and complex geography. 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 resolution using only fire danger indices, but this FIREHARM effort included fire behavior and fire effects in the analysis (Figure 6). Merging multiple maps of probabilities of specific fire events provides a consistent and comprehensive final risk digital map (Preisler et al. 2004) and allows the maps to be integrated into a cohesive risk assessment process (Fairbrother and Turnley 2005).

Our approach also integrates fire effects into hazard mapping (Figure 6), along with fire behavior and danger variables, which are arguably more important to long term fire management. Moreover, the integration of fire effects with behavior facilitates the use of FIREHARM for many other applications. For example, Karau and Keane (2009[in prep]) use FIREHARM to create fire severity 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 the local layers.

In the end, it is usually the available computational resources and input data that dictate the rigor of most hazard assessments for fire management. The spatial simulation 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, spatially consistent input data (Finney 2006). Even more computationally demanding would be to perform these simulations for all possible future landscapes. Currently, many of these computational demanding techniques may be beyond the resources available to fire management, so any quantification of fire hazard will necessitate a compromise between the management objective and available computer resources, modeling expertise, and time. Therefore, it is important to recognize the limitations of each hazard and risk analysis to more accurately interpret and utilize results of the analyses.

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 assumes all pixels burn from a heading fire, 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 possible fire intensities and spread rates at each pixel and then derive measure of hazard from that distribution, such as the probability of wildfire occurring above a threshold intensity. Finney et al. (2009[in prep]) have implemented this strategy in the FSPRO simulation package which simulates the probability of fire spread based on multiple weather scenarios for real time wildfire operational use. Again, the down-side of the FSPRO approach is that it is computationally demanding making it difficult to complete for the large analysis landscapes required in many hazard analysis. Moreover, it would be problematic to implement a temporal component into this approach because the fuels are considered static for the entire simulation and it uses only a finite set of weather scenarios.

The simulation of fuel moisture in the temporal mode is somewhat 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 computer resources of 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 LANDFIRE spatial data represent 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 questionable 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 could increase the price and time-span of the fire hazard project 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. 2007[in prep]), 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, Keane et al. 2006). Therefore, the user must recognize the coarseness of LANDFIRE data when interpreting the FIREHARM products in this study.

The FIREHARM program is currently only 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 the fire event probabilities under the temporal option 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.

FIREHARM validation

It was impossible in this study 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 on some sites. For example, FIREHARM predicted that the first two centimeters of soil would be heated above 60 ^{o}C on all canopy fire and non-canopy fire sample points. 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} (100 lbs acre^{-1}) on 42% of the sample points. This is also in general agreement with fire reports as high smoke production rates were commonly observed during the fire.

The low accuracy of FIREHARM predictions for the six variables (Table 2) are a result of problems in simulation algorithms and inaccurate input data. The assumption of a heading fire in FIREHARM provides a “worst case” prediction that doesn’t always occur in many wildfires (Figure 7). 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 algorithms to predict crown fire initiation and spread are overly simplistic and general. Weather and fuel moisture input data for the validation plots are difficult to obtain at the time of burning, so our estimates were from distant stations and approximate times which may contain high errors. Most importantly, the difference in fuel loadings and vegetation conditions across the two paired plots (burned, unburned) can be significantly different but impossible to document once the wildfire has occurred. 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.

Summary and Management Implications

Currently, fuel hazard mapping for fire management is limited by four major factors: 1) computational resources available to fire management, 2) high quality, spatially consistent, management-oriented spatial data layers, 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. We also demonstrate how this data can be used in a decision support system to prioritize landscapes for treatment.

There are many 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 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 should use the potential risk maps.

We admit that while FIREHARM isn't the perfect solution to quantifying fire hazard and risk across multiple scales, it appears to be 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). Finney(in prep) FSPRO approach where fire probability maps and 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 simulates 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 fire hazard and risk analysis.

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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} (^oC)	Temperature T_{MIN} (^oC)	Relative Humidity (%)	Wind speed (mph)	Wind direction	
32.2	10.0	20	15.0	220	
Dead fuel moisture conditions					
1 hr fuel moisture (%)	10 hr fuel moisture (%)	100 hr fuel moisture (%)	1000 hr fuel moisture (%)	Litter	Duff
3.0	4.0	5.0	50.0	20.0	30.0
Live fuel moisture conditions					
Foliar Moisture (%)	Shrub Moisture (%)				
50	60.0				

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

Model variable	**Within 10% agreement**	**Within 25% agreement**	**Within 50% agreement**		
	Percent of plots (%)				
Fuel Consumption (kg m^{-2})	14	48	68		
Tree Mortality (%)	21	40	64		
Tree Mortality (%) when observed mortality ≥ 60	35	52	77		
Tree Mortality (%) when observed mortality ≤ 60	4	35	61		
Flame length (m)	6	14	29		
Scorch height (m)	0	2	11		
Crown scorch Percent (%)	20	25	27		
	Correct	**Over-predicted by 1**	**Over-predicted by 2**	**Under-predicted by one**	**Under-predicted by two**
Burn Severity	42	37	6	15	0
	Observed canopy fires	**Predicted canopy fires**	**Predicted correctly**	**Canopy fire predicted correctly**	**Non-Canopy fire predicted correctly**
Canopy Fire Potential	44	35	60	45	72

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

Figure 2. Decision tree to prioritized watersheds in the study area for fuel treatments based on the Fuel Treatment Rating. This rating is computed within EMDS based on the simulated FIREHARM variables and their threshold value for deciding if that watershed is in need of treatment. This EMDS application replicates the same methods used in Hessburg et al. 2007).

Figure 3. 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.

Figure 4. Map and selected climographs showing the wide range of elevations and climate patterns within LANDFIRE zone 19.

Figure 5. Output FIREHARM maps of simulated fireline intensity (kW m^{-1}) for the a) lower Placid Creek 6^{th} Code HUC watershed, b) Blackfoot River 4^{th} Code watershed and c) the entire study area of LANDFIRE Map Zone 19.

Figure 6. Example FIREHARM output for all data layers required as input to the EMDS application shown in Figure 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 (m min^{-1}), g) flame length (m), h) scorch height (m), i) fireline intensity (kW m^{-1}), j) soil heating (^{o}C), k) crown fire intensity (kW m^{-1}), and l) EMDS prioritization.

Figure 7. Example of the FIREHARM potential risk map output using the temporal mode option for the lower Placid Creek 6^{th} Code HUC watershed 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 (%).

Figure 8. 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

Figure 9. Plot of observed fuel consumption (kg m^{-2}) from field validation plots (x-values) verses 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).

Figure 10. Scatterplots of observed (plot data) with predicted (FIREHARM estimates) for five fire hazard variables used for model validation along with quantile plots: a, b) tree mortality, c,d) burn severity,e,f) scorch height, and g,h) flame lengths.

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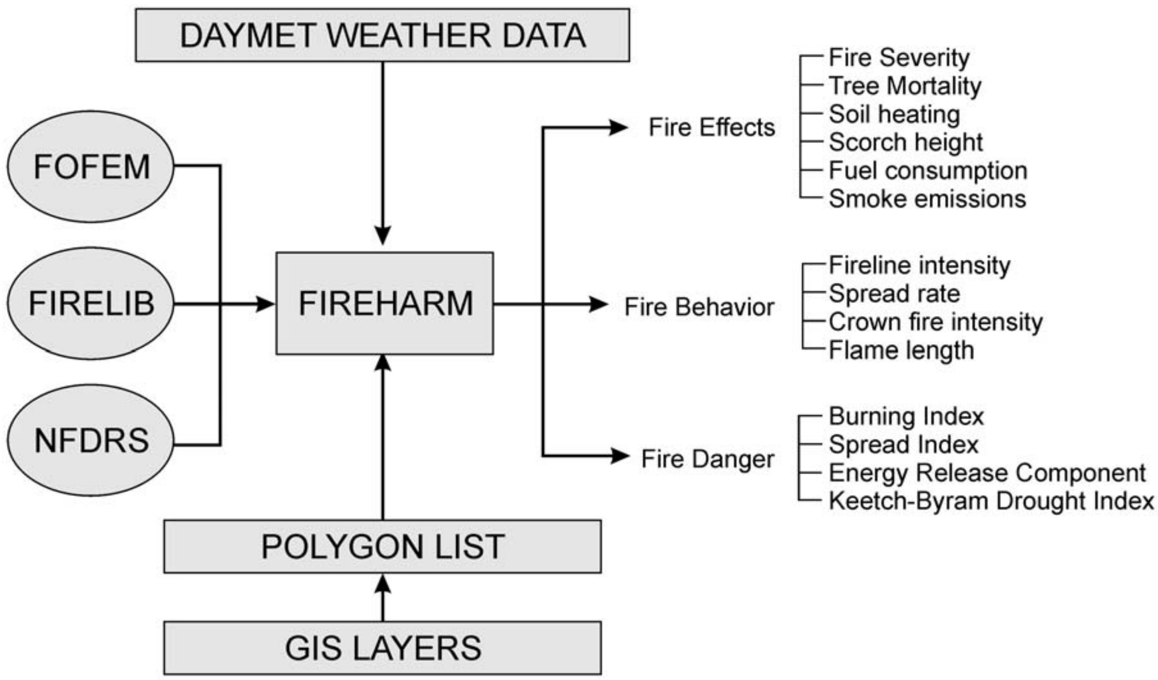

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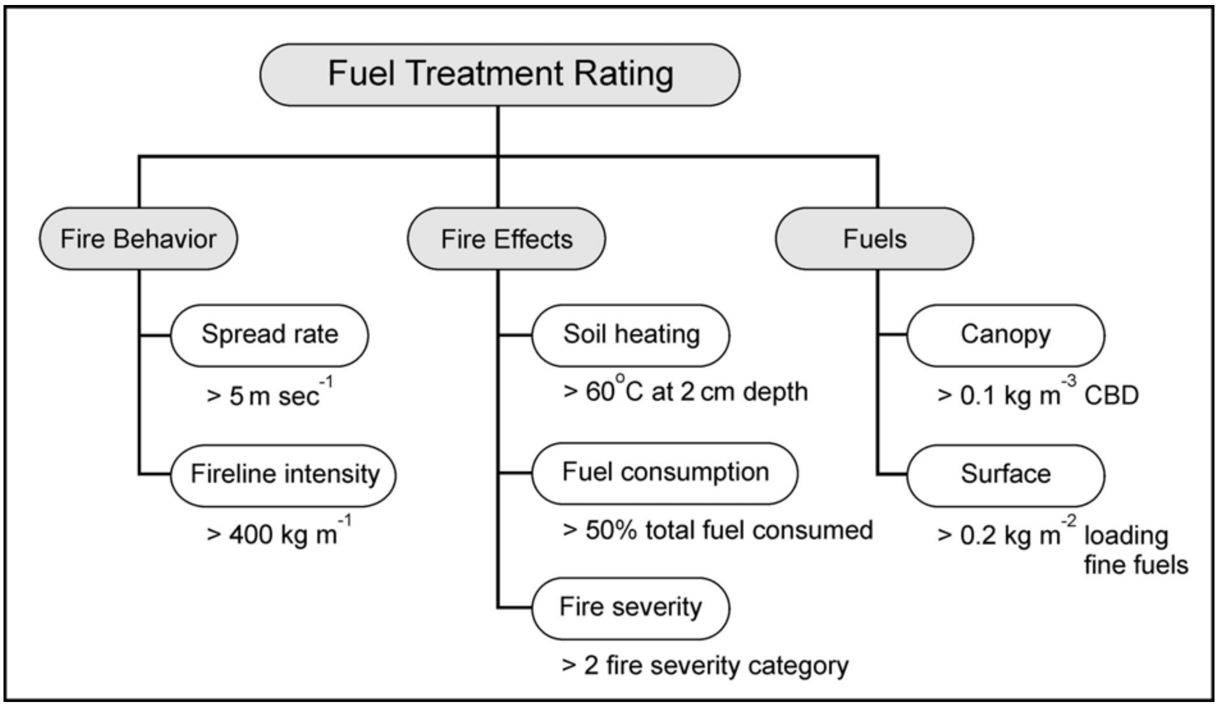

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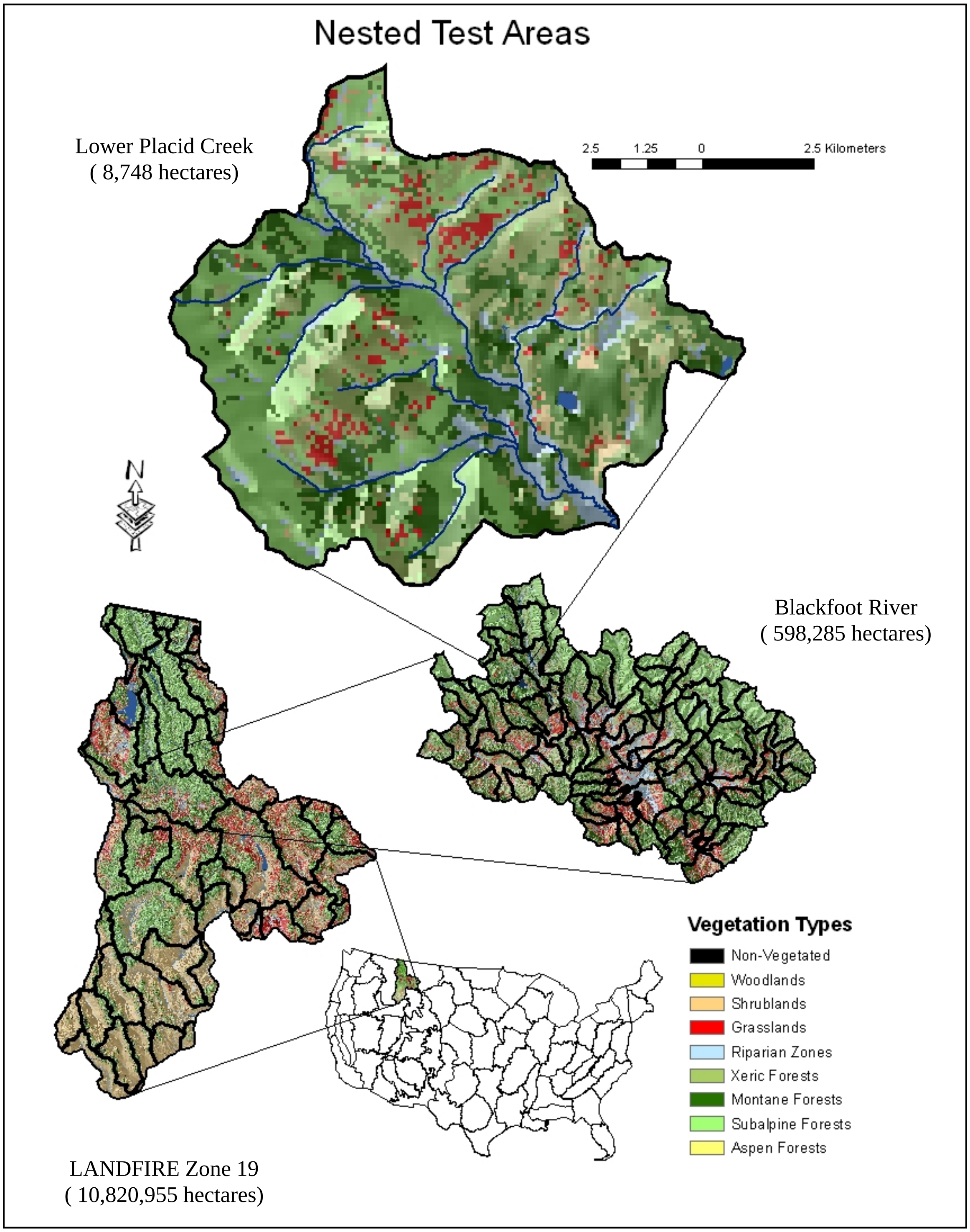

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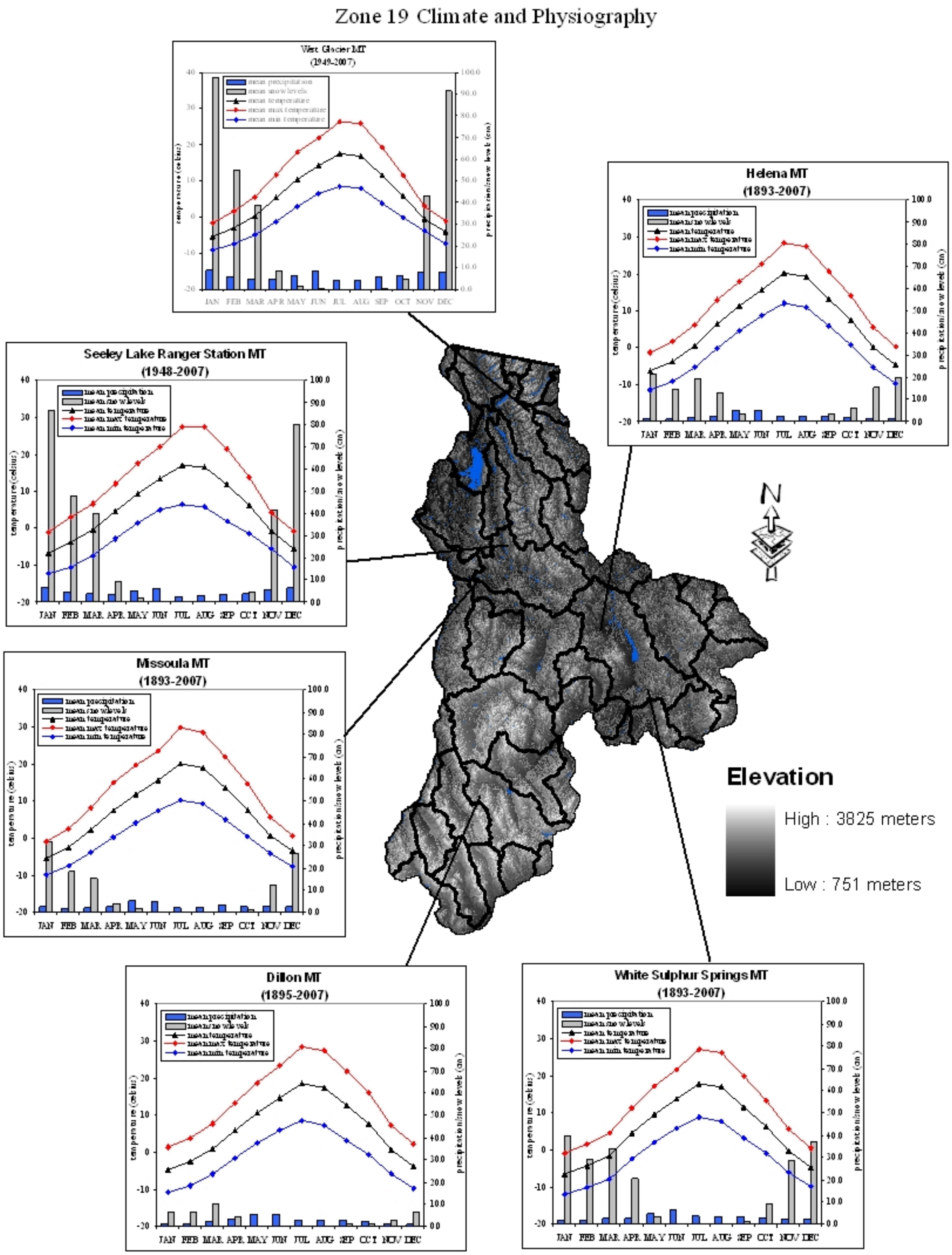

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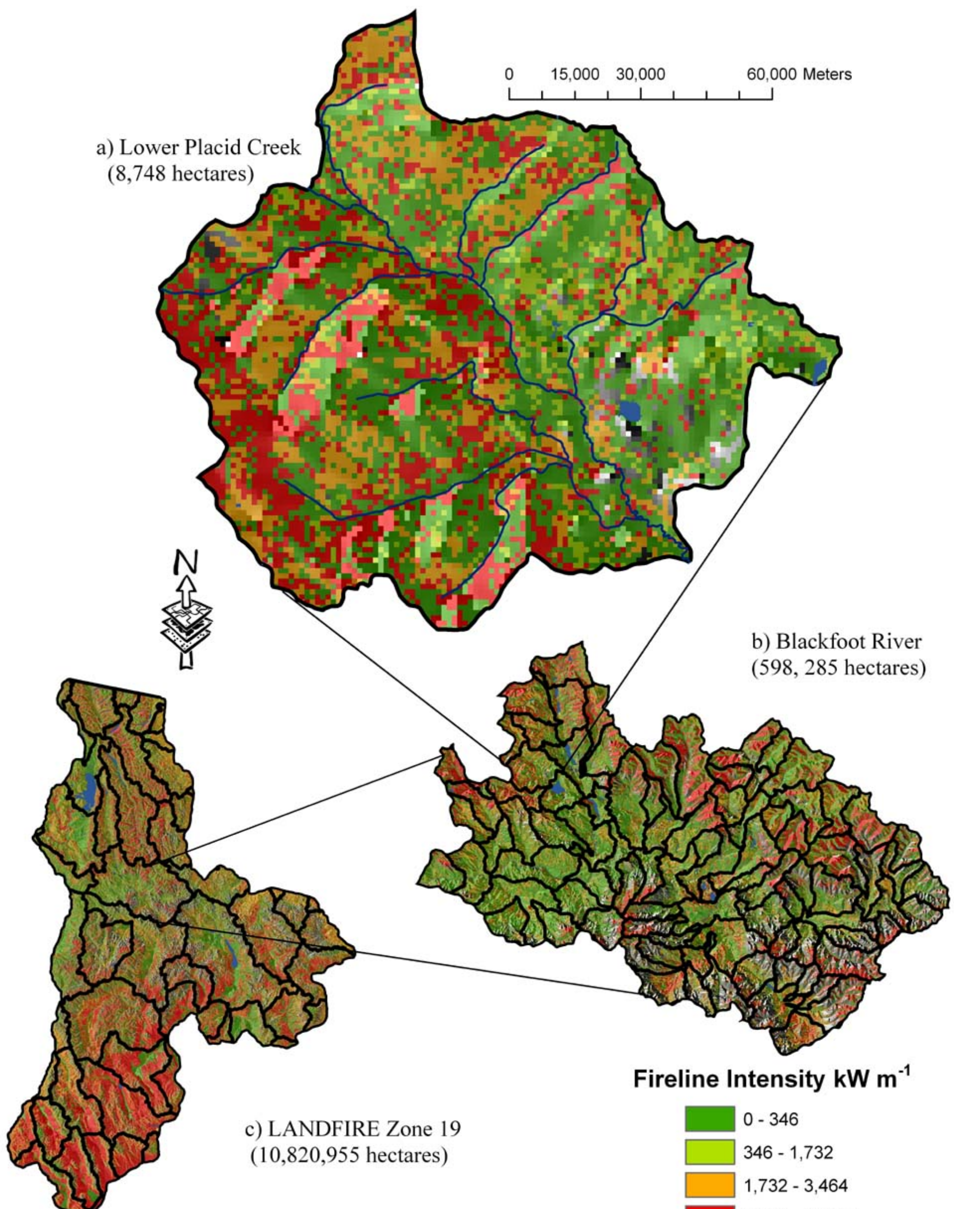

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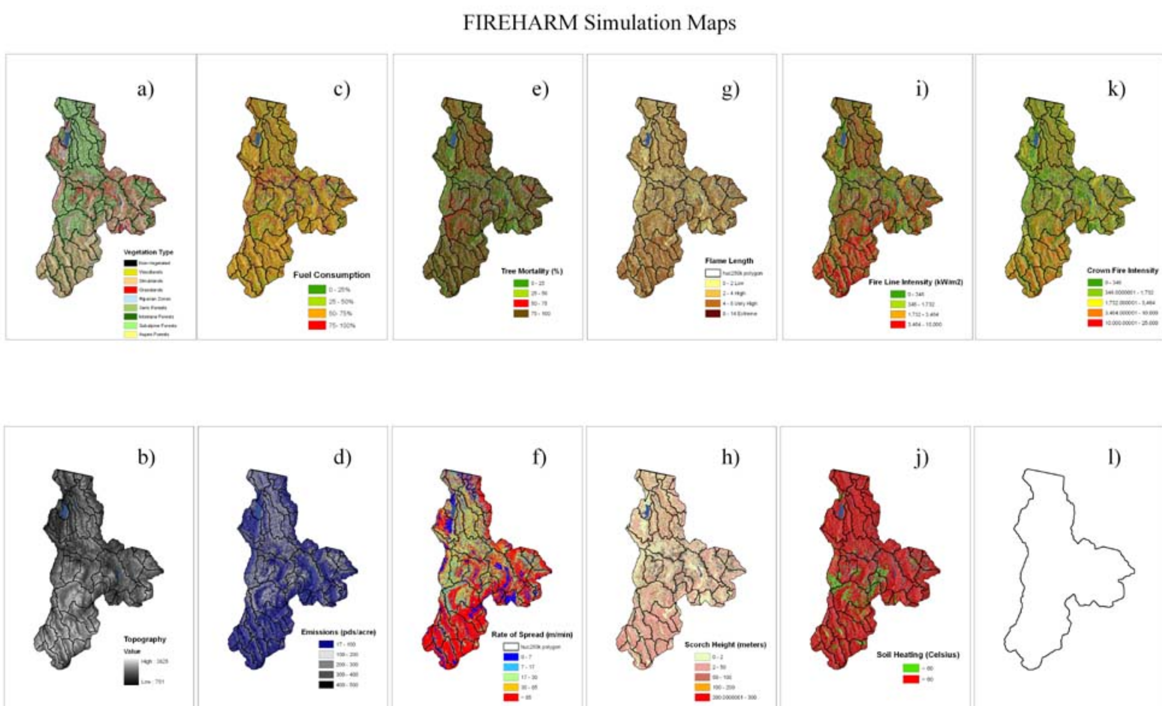

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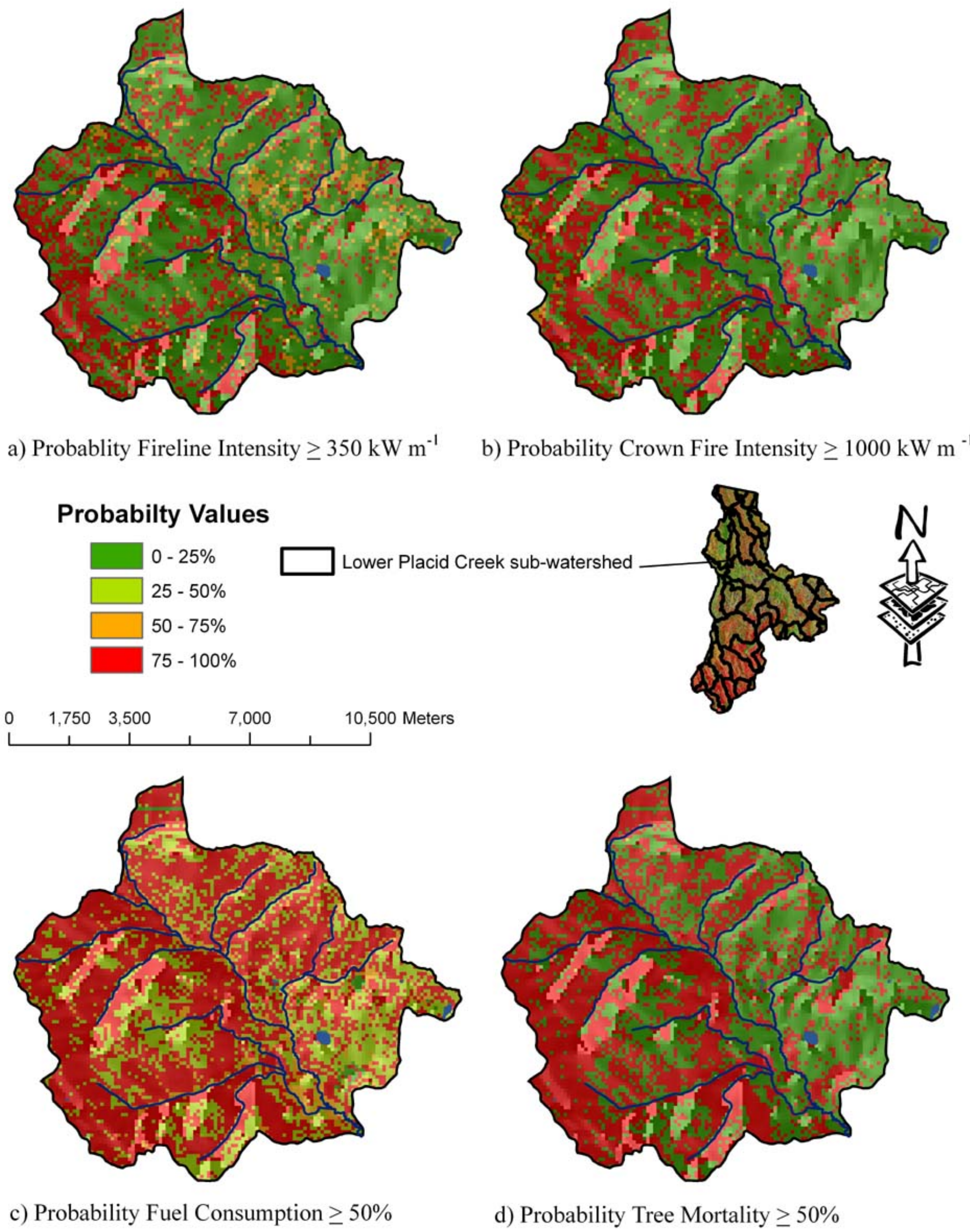

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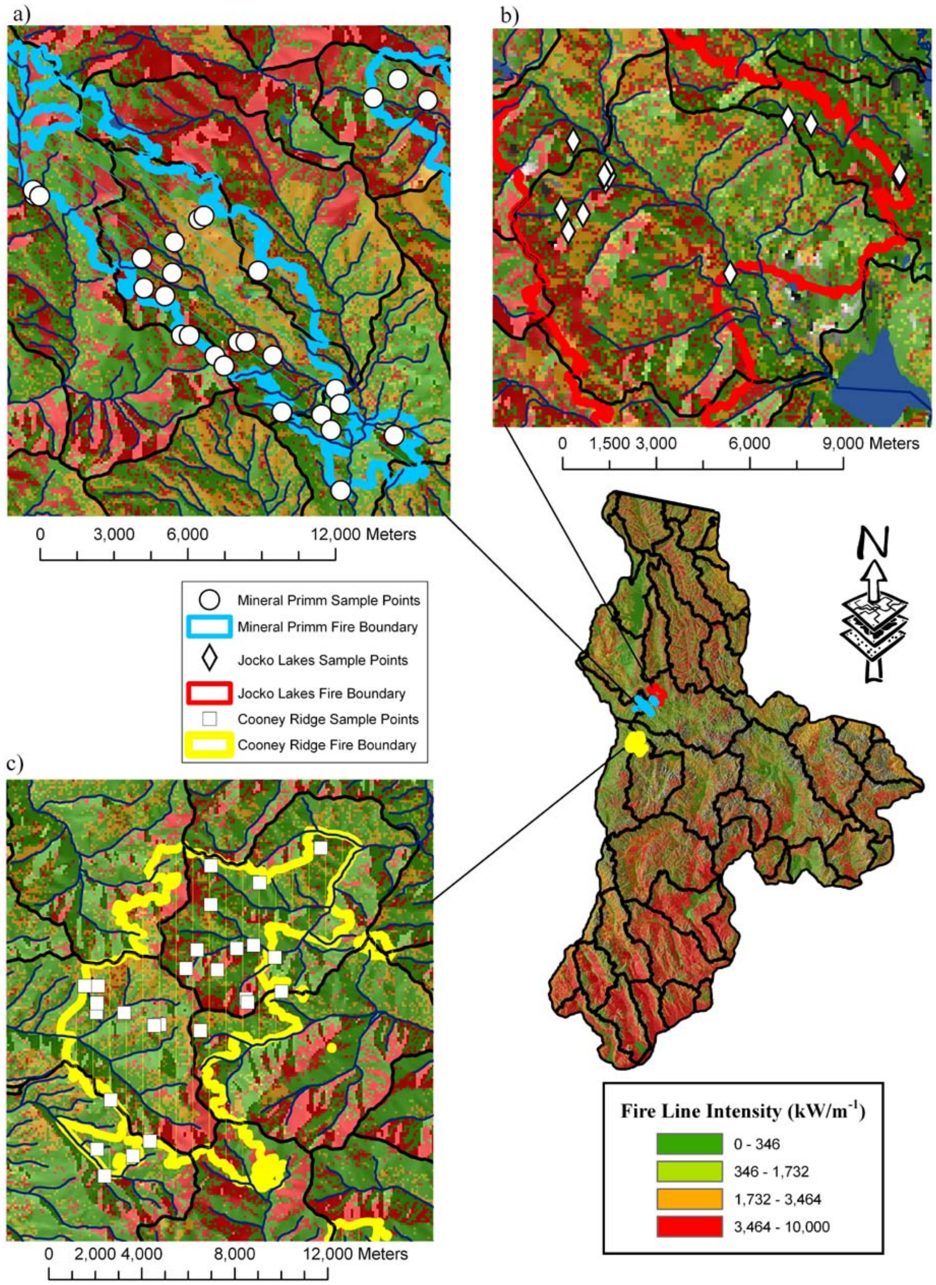

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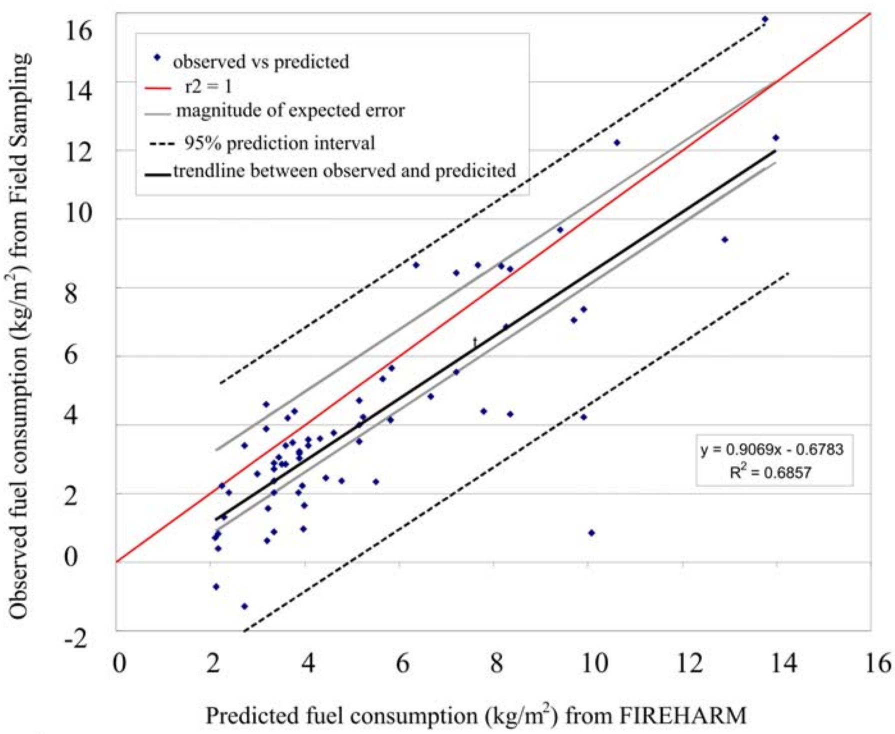

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