A Prototype Simulation System for Large Fire Planning in FPA

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SUMMARY

A prototype simulation system was developed and evaluated for purposes of large fire planning. The term "large fire" is used here in reference to fires that may spread far from the ignition location or require management action that extends beyond the initial response phase. No particular size or duration is implied, but these fires tend to burn across heterogeneous fuels and topography, elicit complex suppression strategies, and continue throughout multiple days or weeks with varying weather – all of which obviate simple descriptions or models of fire size, burned area, and fire behavior. A prototype system was developed to represent an integration of new and existing fire modeling components and made use of readily available sources of fuels and weather data. One new component was needed for this system -- a large-fire containment model, which is described in an appendix. The simulations were applied to two test locations: Northwest Montana and the Southern Sierra Nevada, California. On a 16-processor computer, the simulations required 4 to 8 hours of run time for each scenario of 10,000 to 30,000 simulation years. Outputs from the simulation include spatial maps of burn probability, fire behavior distributions, and fire sizes. These were shown to be suitable for addressing the performance metrics identified by FPA.

PURPOSE

This report describes the development and testing of a prototype system for simulating large fires for planning purposes in FPA. The term "large fire" is used here to refer very generally to fires that escape initial attack, irrespective of their actual size. Compared to initial attack, modeling of large fires is relatively new and considerably more difficult. Impacts of large fires derive from fire spread across heterogeneous landscapes far from their ignition sources under highly variable weather. The effectiveness and expense of suppression actions on large fires is also highly variable and poorly understood. Fires that become "large" after initial suppression response are rare, constituting fewer than 3% of all ignitions on average. The rarity of large fires in any particular geographic area suggests the use of probability for characterizing them. It also

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[1] Chuck McHugh (RMRS Missoula Fire Sciences Laboratory) and Isaac Grenfell (Systems for Environmental Management, Missoula) provided essential support in preparing data and assisting with analyses.

contributes to difficulty in fire planning since each large fire incident has unique combinations of weather, fuels, topography, and suppression actions.

The option of modeling large fires as a component of FPA was driven by the desired Performance Measures (Appendix I). These measures identified probabilities of different kinds of impacts (damages, costs) and the locations at which these occur (e.g. WUI, or a fire management unit). Such qualitative descriptions of fire impacts are directly related to quantitative descriptions of probabilities of fire behavior that are spatially variable. Thus, the simulation prototype needed to have the capability of generating quantitative estimates of probability and behavior for large fires caused by fuels, topography, and weather. The simulation system must also be capable of reflecting the effects of suppression activities that presumably alter the progress and duration of large fires (and perhaps the fire behavior). Little research has been done to characterize the consequences of suppression to large fire characteristics (sizes, occurrence, etc.) and this was therefore a separate challenge required for the prototype system (Appendix II).

PROTOTYPE SIMULATION SYSTEM COMPONENTS

A simulation system was constructed and tested for purposes of evaluating its validity, its suitability for addressing the performance measures, and its practicality as an operational system. The prototype system produces numerous output products, particularly spatial outputs that can be used to depict burn probability and fire behaviors. The prototype system had five components:

Spatial Data. Spatial information on fuels and topography was obtained at 30m resolution from local data sources on two prototype areas. For Montana, the data were obtained for an area covering approximately 10.4 million acres from a 2003 fuel mapping assessment (by Missoula Fire Sciences Lab personnel). For California, data produced by the USFS in conjunction with CDF were used for an area covering 14.1 million acres. These data consist of layers describing fuels suitable for calculating wildland fire behavior and are available for the western U.S. as provided by LandFire.

Weather (daily, seasonal, and spatial variation). Weather data are obtained from a local weather station within the FPU that depicts seasonal trends in ERC (Energy Release Component) and patterns of wind speed and direction (Figure 1). For the prototype, only one station was used to represent weather within the FPU. In Montana, the Libby weather station provided data from 1954 through 2006. The Sierra station was located at Uhl Hot Springs and contained data from 1964-2006. The data from these stations were used to obtain monthly distributions of wind speed and direction as well as historic daily patterns of temperature, humidity, and fuel moisture content. Daily values of the NFDRS index ERC are processed using time-series analysis which captures 1) the average trend in ERC throughout the year, 2) the daily standard deviations, and 3) the autocorrelation of the ERC values. These statistics are then used to generate thousands of hypothetical years for fire modeling purposes. Each "year" consists of daily values of ERC, Wind Speed, and Wind Direction for a time period defined for these purposes as starting April 1st and extending through December 31st, although any time period could be used that bounded the active fire season for a particular geographic location.

Large Fire Occurrence. For the prototype, fire occurrence relationships are obtained from historic data. If this kind of system becomes operational, these relationships would be obtained from fires that are designated “escapes” in an Initial Response Simulator (module that simulates ignition and initial attack actions). There are two relationships needed for this prototype to characterize large fire occurrence:

1) The probability of at least one large fire occurring on a particular day produced by logistic regression (Figure 2a, 2b), and
2) The probability of simultaneous large fire numbers occurring per day for a given sized area (Figure 2c, 2d).

The logistic regressions were developed using the FireFamilyPlus software program to relate the probability of occurrence of fires greater than a particular size (Figure 2) to the Energy Release Component on the day the fire started. These regressions were developed for the Montana site (Libby weather station) and the Sierra site (Uhl Hot Springs). From fire danger rating analysis, it is understood that fire occurrence is conditionally dependent upon low fuel moisture. The NFDRS index Energy Release Component (ERC) reflects fuel moisture trends and is used to predict the probability of large fire occurrence. Fuel model “G” was used to calculate the ERC index for both prototype areas, but any fuel model that local managers rely on for fire danger rating would be acceptable. For the Montana and Sierra sites the numbers of large fires occurring on a particular day were obtained from historic data and converted to probabilities (Figure 2). The size of the area from which the large fire data are derived was used to normalize the probabilities for an FPU relative to the area from which the data were obtained (*e.g*. an FPU with area 1/4th the area of the historic record would experience 1/4th the fire occurrence rate).

Fire Growth and Behavior. Large fire occurrence was modeled stochastically using the daily ERC values generated by the time series analysis (Figure 1) and the fire occurrence relationships (Figure 2). The simulation process moves forward day-by-day, determining if one or more large fires start, and then simulating fire growth when fires occur. Spatial locations of large fires are assumed random, but if data were available, would be spatially variable (e.g. proportion of fires by FMU escaping from the Initial Response Simulator). Once started, large fire growth was simulated using the sequence of daily values of fuel moisture and wind speed from the synthetic weather stream (starting with the date of occurrence). The duration of fire growth was entirely determined by the sequence of weather days in the artificial time series following the day of ignition (*i.e*. not set *a priori*) and by a suppression model (see below). A Minimum Travel Time (MTT) algorithm performs the fire growth by searching for the shortest fire travel times among cells on a landscape. This method is computationally efficient in simulating fire growth under complex environmental conditions. It calculates fire behavior at each “cell” (e.g. flame length) on a landscape which is necessary for determining fire effects.

Large-Fire Suppression. The effectiveness of fire suppression efforts on large fires has not previously been characterized. A statistical model of large-fire suppression was developed (see Appendix II) which relies on historic large-fire records from 2000-2005. This model predicts the probability of containment as a function of time periods of fire activity (series of days which the fire grew vs. those which it stayed relatively constant). Containment was found to be more likely when the fire grew slowly, after an increasing number of time periods of slow fire growth, and in non-timber fuels. Containment probability produced by the model was included in the simulation system and was applied to the daily sequence of weather events. For each period in a weather sequence, a containment probability produced by the model is used by the prototype to stochastically estimate the reduced number of days that fire growth occurs. This limits the sizes of most fires, but fires that started near the end of the seasons will be little influenced by suppression whereas fires beginning early in the season were probably greatly affected.

SYSTEM PERFORMANCE

The prototype simulation system was tested on two areas: northwest Montana and southern Sierra Nevada, California. These areas were chosen because they are identified as FPA prototype areas. All simulations were run on a computer with 16 AMD Opteron processors running 64-bit MS Windows Enterprise Server 2003 operating system.

Simulations were performed for the following scenarios:

1. **Standard** -- simulations used historic large fire occurrence data (Figure 2), landscape data that represent as accurately as possible the current state of the fuels, weather data generated by the time-series approach, and use of the large-fire suppression model
2. **No Large-Fire Suppression** – same as standard but suppression of large fires turned off.
3. **Constant Fuels** – same as Standard but all fuels set to a single fuel type. This was done for purposes of examining sensitivity of the simulation outputs to fuel conditions.
4. **Constant weather** – same as Standard but with a single set of burning conditions (wind speed, direction, fuel moisture content) and burn duration. This was done for purposes of examining sensitivity of the simulation outputs to weather variability.
5. **Fuel Treatment** – same as Standard but with treatment units emplaced to test sensitivity of outputs. Treatments were implemented solely as a test of the system and consisted of changes to surface fuels, increased crown base heights and decreased canopy bulk density within randomly placed units in conifer forest types.

The simulations took 4 to 8 hours to run for each scenario. Preparation of the data, including weather station data, GIS data, and analysis of historic fire distributions took approximately one day for each study area. This time does not allow for the effort required to verify fuels data, which would be considerably longer. **The number of simulation "years" chosen for these tests was subjective**. Research work will be required to understand the consequences of different numbers of years and develop guidelines for selecting appropriate numbers of years. Each simulation generated fire size distributions, burn probability maps, and fire behavior maps.

Table 1. Information on prototype performance on two FPU areas.

	Northwest Montana	**Southern Sierra**
Total Area Size (ac)	10.4 million	14.1 million
Number of Years	30,000	10,000
Spatial Resolution	270 meters	270 meters
Numbers of Simulated Fires (Total)	7597	5516
Computing Time Required (for each scenario)	4-8 hours	4-8 hours
Data Preparation Time	1 day (does not include fuel verification)	1 day (does not include fuel verification)
Scenario	Standard, No Large Fire Suppression Constant Fuels, Constant Weather, Fuel Treatment	Standard, No Large Fire Suppression Constant Fuels, Constant Weather, Fuel Treatment
Simulated Average Burn Probability for Standard Scenario	0.0003	0.0022
Observed Average Burn Probability (fire records)	0.00103 (years 1970-2002, fires>10ac)	0.0019 (years 1970-2005, fires>10ac)

SIMULATION RESULTS

Validation. The possibilities for comparing large-fire simulation results with observations are limited because large fires are very rare at any particular location (probability ~1/1000 per year). But, comparisons must be made to verify that the simulation is producing credible information that is useful for decision making. It is too early to in the process to fully understand how to make useful comparisons of large-fire simulation output, but two possible comparisons involve the average burn probability and the distribution of fire sizes. For **average burn probability**, the Southern Sierra site compared favorably with the average burn probability from fires greater than 10 acres recorded during the past three decades (Table 1). A possible cause of the relatively low burn probability in Montana is the fuels data which have not been verified. The prototype period did not allow time for examining the fuels layers of the entire landscape used for each study area. The **distribution of simulated fire sizes** was remarkably similar to the observed distributions of large fires (Figure 3). Some larger fires were simulated than have been observed, probably because the simulations of 10,000 to 30,000 years included very rare weather sequences than have not been observed during the 32-35 years in the fire records.

The reasons are not well understood as to why slopes of the fire size distributions are so similar. Simulated fire sizes result from the combination of 1) fire weather sequence, 2) ignition location relative to the spatial fuels/topography patterns, and 3) fire suppression. The fire size distributions were not simple transformations of the inputs because none of the inputs had anything to do with fire sizes. So, it seems likely that the simulated fire size distribution reflects the use of proper descriptions of spatial and temporal variability provided to the simulation model. However, historical fire sizes were determined by many factors including occasional interactions of burn patterns among succeeding fires that are not represented by the simulation in which all fires are simulated independently. If interference of fire patterns frequently limited the extent of historic fires, then we might expect a flatter slope to the size distribution than produced by the simulation.

Burn Probability and Fire Behavior Maps. Map outputs for burn probability represent an estimate of the spatial variability in probability of burning from large fires. Fires contained in initial attack are typically small and therefore contribute little to the burn probability and are ignored in this simulation system. The map outputs of burn probability and average flame length reveal strong differences between these components of fire risk. Highest burn probabilities are found at the low elevations in Montana (Figure 4) and Southern Sierra California (Figure 5) because grass fuels dominate in these locations. Expected flame lengths are relatively low in these fuel types (Figure 4d, 5d). Areas of conifer forests and at high elevation tend to have lower burn probabilities because timber fuels have lower spread rates. However, expected flame lengths in these fuel types are higher because they are more likely to burn as crown fires under the weather circumstances that allow them to burn.

Sensitivity to Fire Suppression and Fuel Treatment

The impact of different management actions can be estimated by comparing simulated burn probability and severity from scenarios with fuel treatment or suppression alternatives with those from the standard scenario. For this prototype, fuel management consisted of randomly placed treatment units covering from up to 50% of a localized patch within the larger landscape. Fuel treatment consisted of changes to surface fuel models, increased crown base height, and reduced canopy cover & bulk density. Treatments reduced burn probability (Figure 4c, 5c) compared to the Standard scenario (Figure 4a, 5a). However, because of the reduced burn probability, fuel treatment also resulted in **increased expected flame length in some areas** (Figure 4e, 5e) compared to the Standard scenario (Figure 4d, 5d). This occurred because treatments limit fire sizes under most weather conditions (lowering the chance of burning and lowering the incidence of low-intensity fires). This allows burning of large areas primarily under extreme weather conditions when intensities are highest.

Simulations in which the suppression effect was removed depicted the consequence of not containing any fire that escapes initial attack. Compared to the California site (Figure 5b), the large fire suppression module (Appendex II) had relatively little effect on the Montana burn probability (Figure 4b), but this is suspected to be an artifact of the Montana fuel type accuracy contributing to the underestimated burn probability.

Fire Sizes and Duration Maps. In general, one should expect longer burning fires to be larger, but the degree to which this is true depends on the landscape and the location of a fire within the landscape. Effects of location were clearly evident in the different spatial patterns of fire sizes and durations (Figure 6 and Figure 7). The largest fires occurred in the areas with high burn probability in both Montana and California. Larger fires burn a larger proportion of the area and, thus, confer a higher probability of burning of any given portion of the landscape. Burn duration however, shows little spatial pattern because this depends mostly on weather sequences that were constant for the whole landscape.

CALIBRATION AND ADJUSTMENT OF THE SIMULATION

The prototype simulations described in this report were not subjected to a calibration procedure whereby inputs were modified to improve correspondence between outputs and observations of fire sizes or burn probabilities. For practical implementation of the system, however, many components can and should be adjusted to calibrate the output with observations. All adjustments are best done by local experts who understand the fire environment of the local planning unit and the modeling techniques. Calibrated simulations may be expected to yield average burn probabilities and fire size distributions (Table 2, Figure 3) that are comparable with observations. However, data may be insufficient for a confident comparison within ecosystems where fires are infrequent (high elevation, moist coastal sites).

1. Spatial fuels information. Data from LandFire or from local sources should be verified and modified where necessary to include recent wildfires and fuel treatments or adjusted where incorrect fuel assignments are present.
2. Weather data. Data from different weather stations should be considered especially for larger analysis areas. This is especially important for developing the predictive equation for probability of large fires in relation to ERC(g). Some stations are less representative of the weather in an FMU or FPU.
3. Suppression effects. Prior to this effort, no quantitative relationships had been developed to predict the probability of large-fire containment. The equation developed here (Appendix II) is very general for the entire U.S. and may require some adjustment when implemented for a local FPU, although it is not known at this time whether data sources are sufficient to determine if more localized models are possible or different from the general model reported here.
4. Tuning of the fire behavior models. Minor changes in the settings of the fire behavior models can be used to fine-tune the results. For example, altering the length of the afternoon burning period for different moisture conditions can affect fire sizes and the lower limit on ERC where active burning occurs can affect numbers and sizes of fires.

ABILITY TO ADDRESS PERFORMANCE MEASURES

The spatial simulation outputs are well suited to addressing the identified performance metrics because they address likelihood and magnitude of fire behavior. Burn probability is an output that represents likelihood of all fire behaviors, but the distribution of fire behavior (e.g. flame length) is stored for each "cell" on the landscape so that damages from varying fire behavior can be assessed. The data are also sensitive to factors controllable by management action, namely fuel treatment, large-fire suppression, initial attack success.

Table 2. Relationship of simulation outputs to management performance measures.

Performance Metric	**Relevant Simulation Outputs**
1. Reducing the probability of occurrence of costly fires	*Probability of fire size (Figure 6, Figure 7).* Cost can be estimated using relationships such as the Stratified Cost Index. SCI requires size and location relative to structures. Change can be measured as a function of management activities
2. Reducing the probability of occurrence of costly fires within the WUI	*Probability of fire sizes (Figure 6 and Figure 7).* These can be calculated within WUI zones. (performance metric #1 above). Simulations of fuel and management options can be compared *(Figure 4c, 5c)*.
3. Increasing the proportion of land meeting or trending toward the attainment of fire and fuels mgt objectives.	*Flame length and burn probability (Figure 4 and Figure 5).* Flame length can be related to benefits and losses for areas with and without alternative treatment efforts. Simulations can be run with different fuel management options *(Figure 4c, 5c)*.
4. Protecting highly valued resource areas from unwanted fire	*Flame length distributions and burn probability (Figure 4 and Figure 5).* Flame length can be related to benefits and losses for particular resource values (e.g. wildlife, hydrologic, timber etc.). Simulations can be run with and without fuel treatment and under different organizational configurations *(Figure 4d,e, 5d,e)*.
5. Maintaining a high initial attack (IA) success rate	*Burn probability (Figure 4 and Figure 5).* Initial attack success as derived from the Initial Response Simulator would affect the probability of large fires and fire behaviors.

COMPARISON WITH OTHER APPROACHES

The WFSI calculation (developed by Don Carlton, Sanborn Map Company, Inc) approximates large fire probabilities in a non-spatial fashion and has been considered by FPA for use in characterizing the large fire component of fire management. For this reason, the large fire simulation system prototype was compared with WFSI. WFSI requires the same inputs as the simulation approach (spatial fuel data, weather records, ignition histories). The principal difference involves the estimation of fire sizes as a conversion from local spread rates. Fire spread rate is calculated for specific weather condition percentiles and is converted to a final fire size based only on the independent pixel properties (irrespective of the spatial arrangements of the fuels or topography). The conversion implicitly includes historic suppression responses (meaning that alternative future suppression responses cannot be examined). Because WFSI does not represent the spatial movement of fires from one area to another and does not reflect fire probabilities occurring distant from ignitions, it is better suited to estimating burn probabilities where fires remain relatively small (i.e. close to their ignition source).

Table 3. Comparison of major aspects of Fire Simulation and WFSI approaches to estimating large fire probabilities and impacts.

	Fire Simulation	**WFSI**
Input Requirements		
LandFire Fuels Data	Yes	Yes
Historical Weather Data	Yes	Yes
Ignition Density/Frequency	Yes	Yes
Modeling Approach		
Spatial Fire spread	Yes	No
Contrast Suppression Effects	Yes, toggle on/off	No, implicit suppression only
Capable of linking to Initial Response Simulator	Yes	Yes
Outputs		
Burn probabilities	Yes	Yes, index
Fire behavior distributions	Yes, reflects variability from spread directions, spread conditions, and weather	Yes, limited to reflecting variability in weather and fire behavior in heading direction
Effects of off-site ignitions (on fire behavior, burn probability, WUI, etc.)	Yes, spread from ignition to impact	No

PROSPECTS FOR OPERATIONAL IMPLEMENTATION

The prototype large-fire simulation has demonstrated that FPU-scale simulations are technically feasible. The necessary computer hardware, spatial data, weather data, and historical fire data are available or can be readily acquired (funding notwithstanding). The prototype system proved to be functional and produce outputs on fire behavior and burn probability that could be checked against observations and directly used to address the management performance metrics. Two options for implementing large-fire simulation for FPA are identified:

1) **Intensive Simulation Option**: simulation of standard and custom scenarios designed for each FPU to reflect spatially explicit management options (e.g. fuel treatment, suppression etc.).

   This option will require more simulations (compared to option #2) and more dedicated involvement of the FPU planners in devising the scenarios, running them, and summarizing the results.

   Advantages of the intensive option include:
   a) spatial display of burn probabilities, fire behaviors and values,

b) capturing explicit impacts of strategically placed fuel treatments on specific fire probability or behavior outcomes,
c) ability to calculate expected damages for specific geographic locations (i.e. watersheds, habitat, WUI, etc),
d) make fire effects responsive to changes in initial attack performance as produced by the Initial Response Simulator, and
e) generate data for risk and hazard assessments that serve multiple uses beyond FPA, including hazard and risk monitoring and guiding field-level fuel and fire management.

2) **Statistical Option**: simulation of a smaller number of predetermined scenarios (see "Scenario" above and in Table 1) that would supply data for inclusion in a decision support system.

   This option has been tested to a limited degree in the prototype phase and involves perhaps 5 to 7 predetermined scenarios representing combinations of suppression, fuel treatment, and sensitivity analysis to weather and fuel variation. The results of these simulations are summarized statistically to reveal the major trends and sensitivities to the input variables (fuel treatment, suppression, etc) but the results are not explicit spatially to finer scales than the FPU.

   Advantages of the statistical option are:
   a) limited number of simulation runs for each FPU,
   b) direct utility of the results for inclusion into a decision support system (for example, a Bayesian Belief Network).
   c) clearly identifies the major trends and sensitivities of fire at the FPU level,

Irrespective of the exact usage of simulation, the following issues must be addressed:

Computing Hardware. All simulations described here were performed on a research computer running a 64-bit operating system. This configuration met the memory and processing demands of the simulation. More computers would definitely be required to handle the workload for simulations on all FPUs. Given advances in computing (now and within the upcoming year planned for the development phase), it may be possible to support the National needs for FPA on about 10 such computers at a cost of about $500,000. It is likely that these computers would be available for shared-uses with the Wildland Fire Decision Support System, especially during seasonal periods of low fire activity. Data storage might be upwards of 50 TB for inputs as well as outputs from multiple simulation runs.

Data Access. The LandFire dataset is available for the western half of the continental US but will require some local adjustments to improve accuracy before being used in simulations. Some areas (*e.g.* California) have developed their own separate data sets as well. Data derived for the 13 southern states are also suitable for these simulations. Weather data are available at 32 km^2 for the entire US (Western Regional Climate Center) and from specific weather stations accessible via the internet from the Weather Information Management System (WIMS) (http://famweb.nwcg.gov/) and the Western Regional Climate Center (http://www.raws.dri.edu).

Modeling Expertise. For any fire modeling, experts will be required to handle and modify the GIS data sets, acquire and critique the weather data, understand and interpret the fire simulation model, and design and run the simulation scenarios. The process will require comparison of simulation output with observed historical data (burn probability, fire size distributions) and make adjustments as needed. Sources of this expertise include:

1. Forests and Districts. Familiarity at this level with fuels and vegetation is essential to verifying spatial fuels data.
2. FPU planning level. The planners at this level should have access to GIS capability, and be able to assemble weather data, historic fire data, and coordinate any local adjustments to fuels information so that they are consistent among FMUs.
3. National. The FPA team should be able to provide training and consulting on fire modeling and compare simulation results among FPUs. This might involve organizing workshops and arranging for modeling assistance from FS Research and fire behavior analysts Nationwide.

Handoff and Implementation. Although the simulation system is technically feasible, a dedicated effort will be required to develop the prototype into an operational system for general use. The main steps in implementing this system include:

1. Designing the system architecture. A system must be designed that will enable users to generate and review inputs to the simulation code, run the simulations, review the outputs, prepare the necessary reports and data, and the make these outputs available for analysis at any level (National, Regional, Local).
2. Building the computing infrastructure. This system includes simulation servers, GIS data servers, web servers, and other hardware components. Questions on where to locate, maintain, and update the hardware need to be resolved. Possible shared uses with WFDSS also need to be addressed since much of the hardware is the same.
3. Documenting and training. The simulation system needs to have technical and user documents prepared as well as training materials.
4. Maintaining and updating simulation codes. A procedure for incorporating the inevitable improvements to the simulation code must be developed.
5. Maintaining a technical support staff to assist FPU planners and with future training needs (employee turnover, improvements in simulation code etc.).

DESIRED IMPROVEMENTS

Some further development would be desirable before the prototype simulation system would be ready for implementation. Improvements in the following model capability would include:

1. Adding spatial weather variability
2. Linking the fire occurrence with output from the IRS
3. Incorporating benefit-loss functions for risk calculations

Spatial variability in weather (primarily fuel moisture, but winds also) would be incorporated through spatial correlation among weather stations or among gridded historic weather data at 32km (~20miles) resolution and inclusion of wind model running at finer resolutions (~1km). These changes would make the simulation sensitive to variability in moisture due to mountain ranges and wind flow patterns. Several months of development and evaluation will be required for these improvements but little additional computing power would be needed to accommodate them.

Ideally, the historical relationships used for fire occurrence (Figure 2) would be replaced with similar functions obtained from an initial response simulator. This would allow the large-fire probabilities to become sensitive to changes in initial attack policies or to organizational variations. These modifications will probably require several months of programming and testing.

The system as reported here intentionally stops short of producing an actuarial estimate of fire risk. The simulation outputs are, however, necessary components of an actuarial risk assessment once benefit-loss functions are incorporated. An actuarial definition of risk implies an estimate of expected loss or expected net value change E*nvc*. To get E*nvc*, the fire behavior distributions produced by this simulation system must be indexed to loss or benefit (for example, effects of fire on a particular value across the range of fire intensity). Losses and benefits vary among geographic areas and among ecosystem values (e.g. timber, owls, soils, fish etc.) and human developments (i.e. structures, bridges, watersheds etc.), meaning that many benefit-loss functions would be required for each FPU depending on the particular values of concern that exist in that FPU.

Figure 1. Three example years show daily and seasonal variation in Energy Release Component (ERC) of the National Fire Danger Rating System (a) that reflects changes in fuel moisture content. For each day, the moisture content is combined with wind speed and direction drawn stochastically from the historic probability distributions (b) to produce a fire weather scenario. The daily scenarios are used as input to calculate fire behavior and perform fire growth simulation.

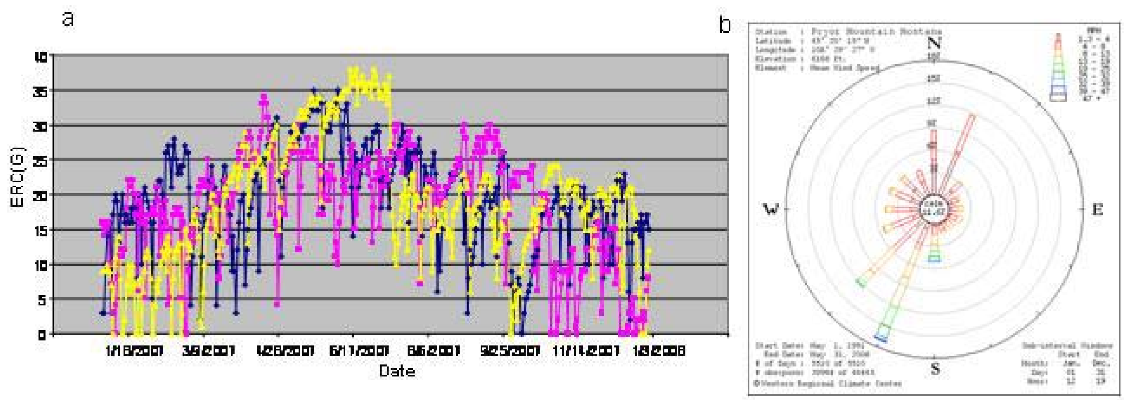


Figure 2. Large-fire occurrence relationships are shown for the Montana area (10.4 million acres) and California (14.1 million acres) prototype area. The probability of large-fire occurrence is related to ERC for each location (a, b) and is used to stochastically simulate the occurrence of a large-fire day (at least one large fire). The historical numbers of large fires per day is different for each area (c, d) and is used in the simulation to determine how many large fires occur on a "large fire" day.

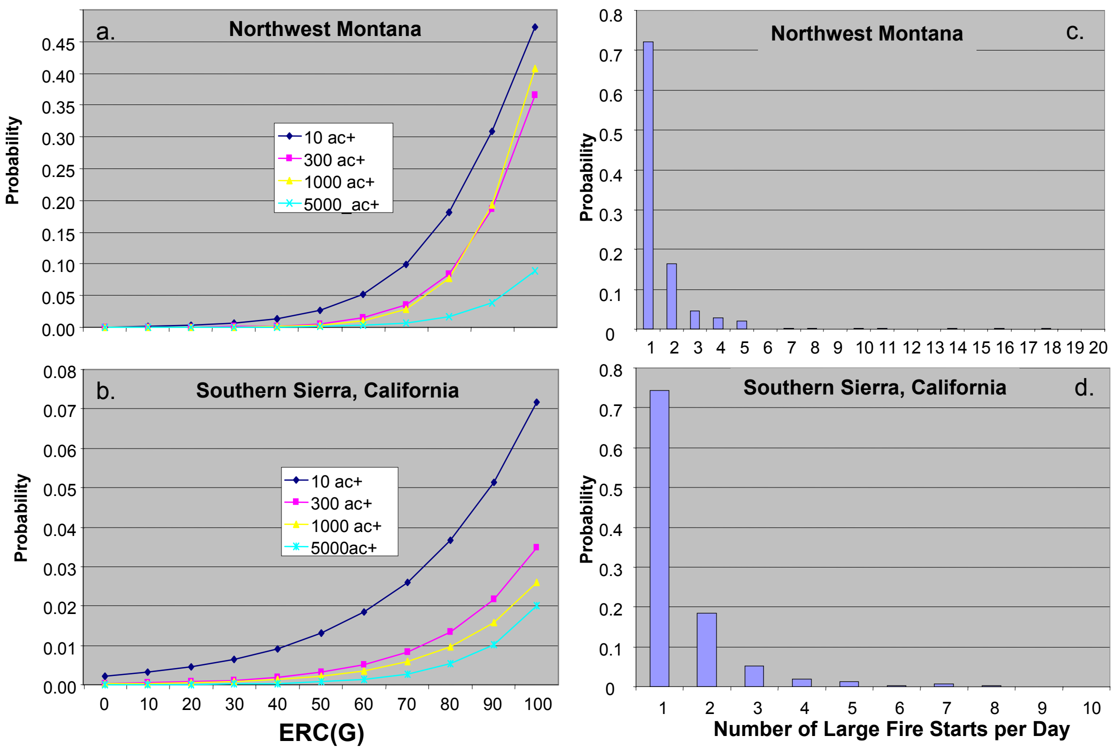


Figure 3. Comparisons of observed and predicted fire size distributions for the Montana and California prototype areas. Close agreement for each area suggests that the simulation produces a reasonable distribution of fires by size class.

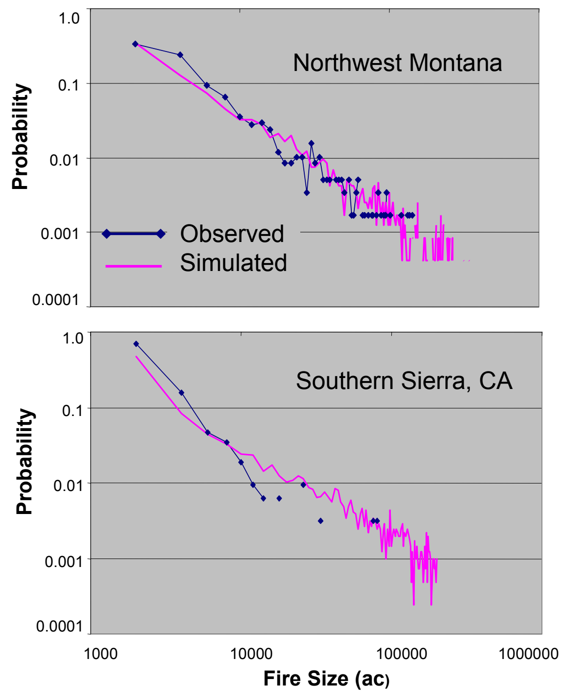


Figure 4. Simulated burn probability maps for the Northwest Montana prototype area with historical suppression (a), without suppression (b), and with fuel treatment (c). High burn probability does not imply intense fires as indicated by the expected flame length (d) because grass and shrub fuels have high spread rates (and thus high burn probability) but lower intensities than crown fires in forested areas. Burn probability was reduced by fuel treatment (c) compared to (a) but expected flame length increased slightly in some treated areas (e) compared because burning occurred under more restricted set of extreme conditions that produced higher intensities.

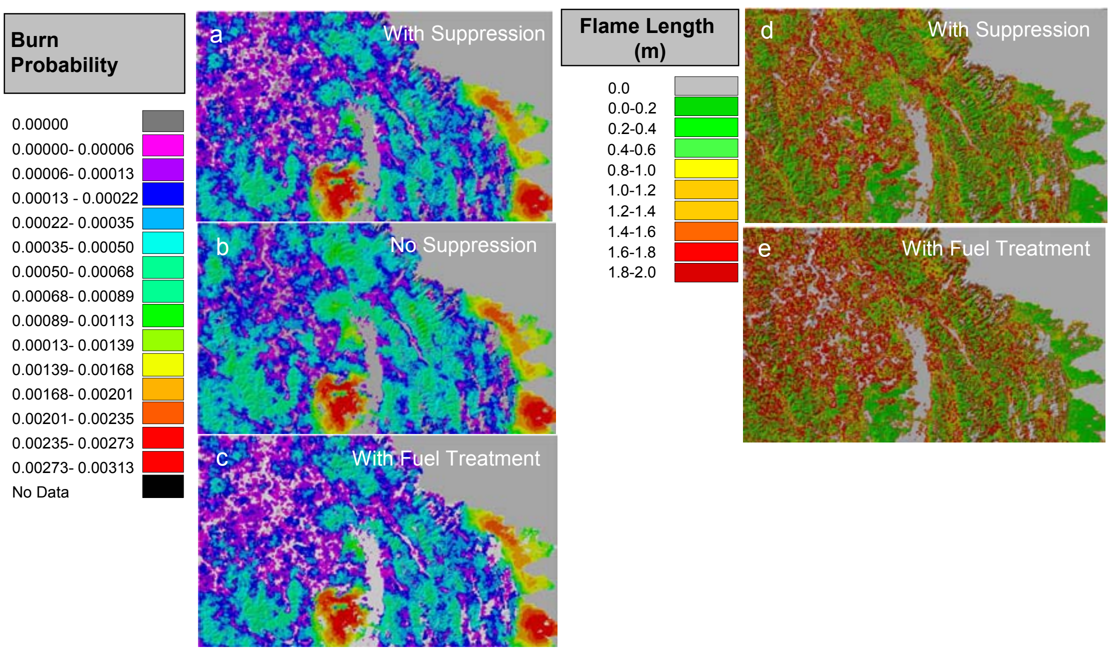


Figure 5. Simulated burn probability maps for the Southern Sierra California prototype area with historical suppression (a), without suppression (b), and with fuel treatment (c). High burn probability does not imply intense fires as indicated by the expected flame length (d) because grass and shrub fuels have high spread rates (and thus high burn probability) but lower intensities than crown fires in forested areas. Burn probability was reduced by fuel treatment (c) compared to (a) but expected flame length increased slightly in some treated areas (e) compared because burning occurred under more restricted set of extreme conditions that produced higher intensities.

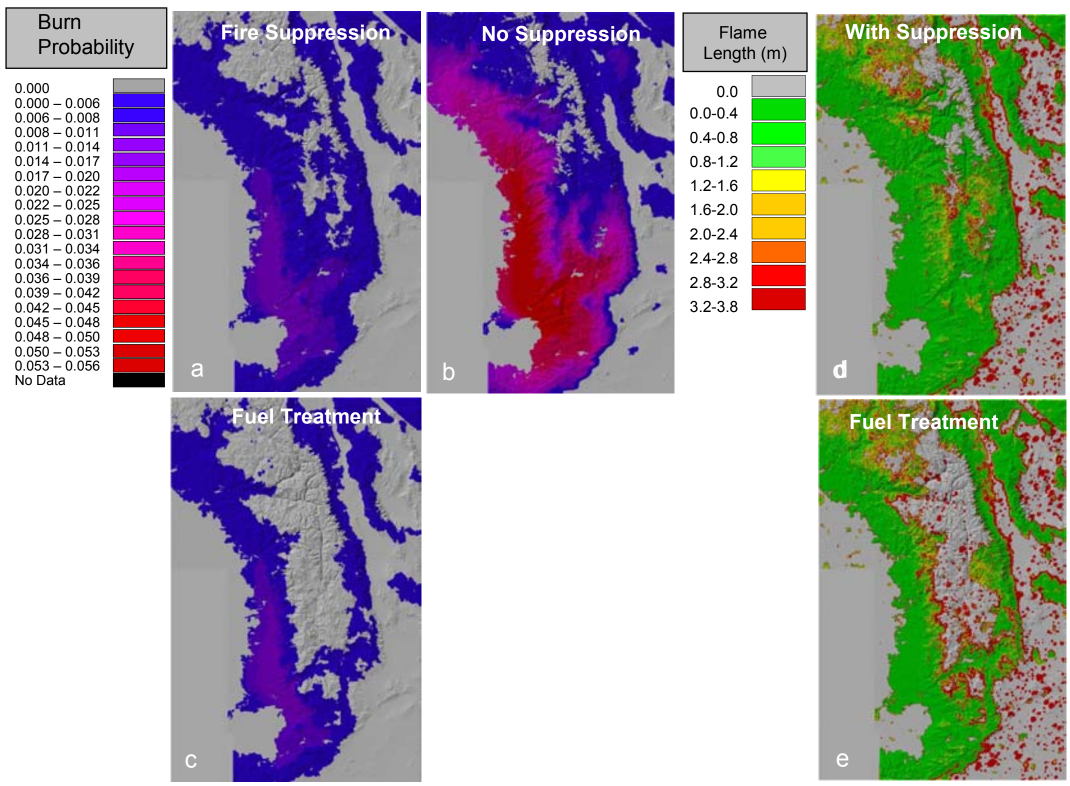


Figure 6. Fire locations plotted by size (a) and duration (b) for the Montana prototype area. These point data can be smoothed (c), (d) to analyze average sizes and durations for larger geographic areas. Note that areas with large-fire sizes also have high burn probabilities (see Figure 4) but fire duration is more evenly distributed.

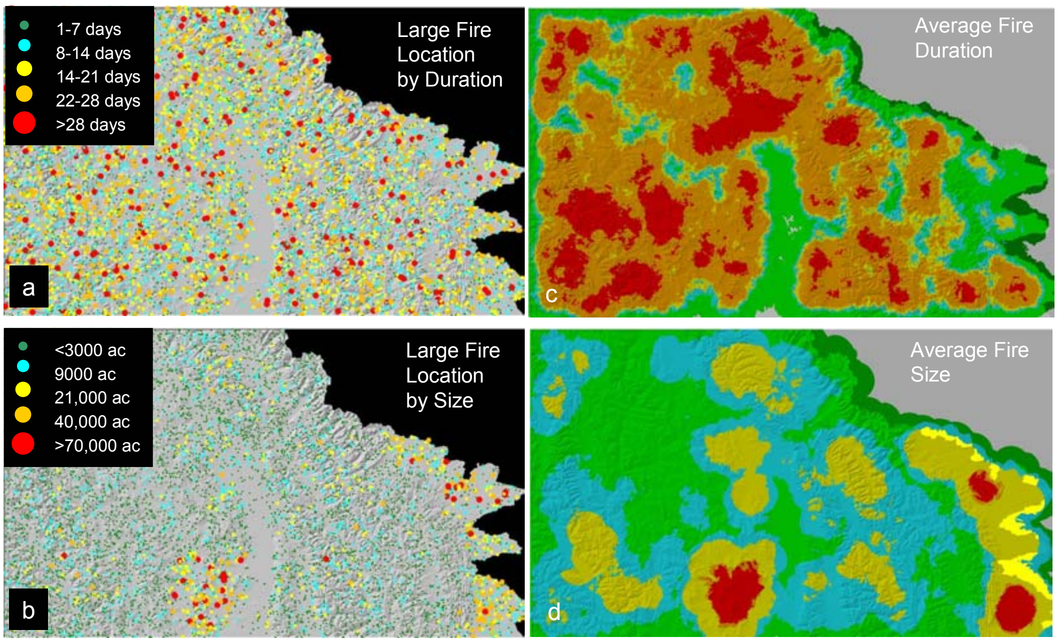
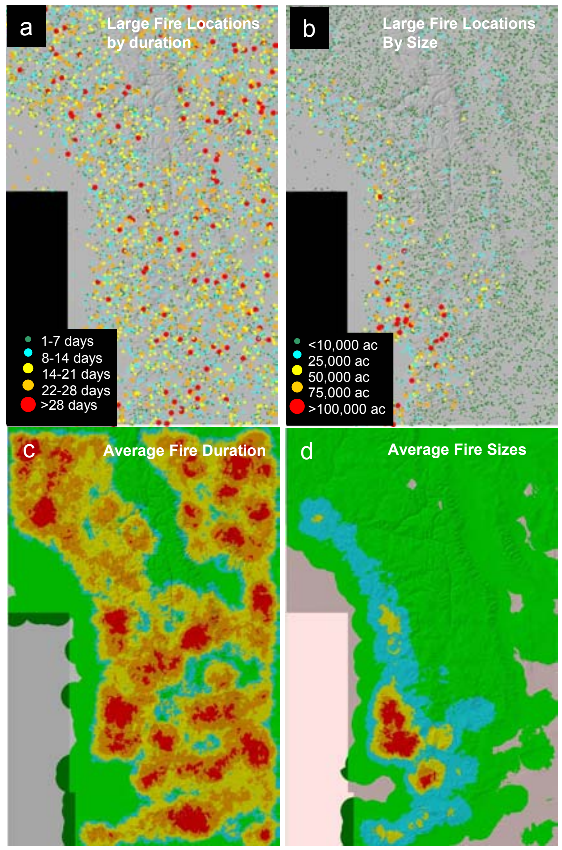


Figure 7. Fire locations plotted by size (a) and duration (b) for the Southern Sierra California prototype area. These point data can be smoothed (c), (d) to analyze average sizes and durations for larger geographic areas. Note that areas with large-fire sizes also have high burn probabilities (see Figure 5) but fire duration is more evenly distributed.



Appendix I. Performance measures identified for FPA

1. Reducing the probability of occurrence of costly fires.
2. Reducing the probability of occurrence of costly fires within the WUI
3. Increasing the proportion of land meeting or trending toward the attainment of fire and fuels management objectives.
4. Protecting highly valued resource areas from unwanted fire.
5. Maintaining a high initial attack (IA) success rate.

Appendix II. Description of the large-fire containment model.

General Linear Mixed Model Analysis of Wildfire Containment Probabilities

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Abstract

Billions of dollars are spent annually to contain large wildand fires but the factors contributing to suppression success are poorly understood and have not been modeled. We used a general linear mixed model (GLMM) to predict containment probability of individual fires assuming containment was a repeated measures problem (fixed effect) and individual fires were random effects. Changes in daily fire size from 314 fires occurring in years 2001-2005 were processed to identify intervals of high spread from those of low spread. The analysis suggested that containment was positively related to the number of consecutive days where the fire grew little and the number of previous such quiescent intervals. Containment probability was negatively related to the length of intervals where the fire exhibited high spread and the presence of timber fuel types. Fire size was not a significant predictor. Characterizing containment probability may be useful component of a cost-benefit analysis of large fire management and planning systems.

Key Words: Wildfire containment, large wildfires, fire suppression, general linear mixed-models.

Introduction

Thousands of fires start annually in the wildlands of the United States but most are contained by initial attack efforts. Studies suggest that only about 1-2% of wildland fires in the western U.S. grow beyond 100 ha (Neuenschwander *et al.* 2000, NIFC 2002). The largest 1% has been estimated to be responsible for 83 to 96% of the burned area (Strauss et al. 1989, Calkin et al. 2005) and elicit suppression responses that, in recent years, seems to be increasing to about one billion dollars annually (Donovan and Brown 2005, Gebert et al. 2006). Nevertheless, the effectiveness of suppression efforts on large fires has not been modeled or even characterized, and it is presently not known what or how different factors are related to successful containment. With quantification of suppression effects on large fires, it might be possible to begin assessing the cost-effectiveness of suppression actions or consequences of alternative management strategies.

Suppression of large fires is considerably more complex than initial attack (IA) of small fires. Small fires exist in a more restricted fire environment (fuels, weather, topography), with far fewer resources assigned to fire fighting. Modeling has typically assumed a direct attack at the combustion edge (Anderson 1989, Mees 1985) or at some fixed distance from it (Fried and Fried 1996). Initial attack models anchor fireline from a point on the fire's edge and construct line in opposite directions around an assumed elliptical fire perimeter until containment is achieved.

For large fires, fireline construction is typically applied simultaneously along multiple sectors and may involve indirect fireline (NWCG 2006) constructed at a distance from the active fire edge and accompanied by burnout operations.

The main factors controlling initial attack success are often assumed deterministic *(i.e.* fire line production rates, fire behavior, and crew arrival time)(Dimitrakopolous and Omi 2003), but uncertainty in these factors (Haven et al. 1982, Smith 1986) has also led to consideration of stochastic simulations (Smith 1987, Fried and Gilless 1989, Mees et al. 1993, Fried et al. 2006). By contrast, large fires are characterized by heterogeneous fuels, vegetation, and weather over many days or weeks. This variability produces much more complicated perimeter growth and associated suppression tactics, prompting the use of probability for characterizing large fire containment (Flowers et al. 1983, Mills and Bratten 1989, Mees and Strauss 1992). Such variability and heterogeneity among the relatively few large wildfires presents many challenges for modeling. In this paper we applied a general linear mixed-model analysis to data derived from records of recent large fires in attempt to understand what factors contribute to the probability of containment.

Methods

Our approach to modeling containment of large fires followed field-level experience that these efforts are essentially opportunistic-- suppression success depends on having time-periods of moderate weather last long enough for fire crews to complete containment lines before an extreme episode of weather recurs. For individual fires, the time-series of daily fire sizes shows that increased growth occurs during intermittent episodes of extreme weather (Mees and Bednar 1989) with the interim periods promoting suppression progress (Flowers et al. 1983). These patterns of alternating containment opportunity suggested that containment probability may be predictable using the intervals of fire activity available from fire records. Predicting the probability of containment would then be a repeated measurement problem where the intervals constitute repeated measurements on each fire. Thus, the measurements taken at the intervals (high spread vs. low spread, length of the interval, number of previous low-spread intervals) would be considered fixed effects, and the fires themselves would be random effects (each fire having its unique identifier as a grouping variable).

We obtained data for this analysis from the Incident Status Summary ICS-209 reports required for fires administered by U.S. Federal land management agencies (available at http://famweb.nwcg.gov). The ICS-209 program is a U.S. Fire and Aviation Management Web application (FAMWEB) which Incident Management Teams (IMT) use to report incident specific information on over 40 items such as acres burned, percent containment, number of personnel assigned, and costs to date (USDA-USDI 2003). An ICS-209 form is completed for large wildfires, wildland fire use events, and any other significant events (e.g., hurricanes, volcanoes, hazardous materials) on lands under U.S. Federal protection or ownership. Large fires are defined as 40 hectares or larger in timber fuel types and 120 hectares or larger in grass or brush fuel types. The ICS-209 is submitted daily for an incident and is used by the National Interagency Coordination Center (NICC) to prepare the daily National Incident Management Situation Report.

From these detailed reports, we used only the reporting date, daily fire size, and fuel types identified daily as involved (grass, brush, timber). We did not use data recorded for estimated costs or assigned personnel because there are only ambiguous connections between these general figures and relevant fire fighting tactics. Data were extracted for all fires in the data base for years 2001-2005 (earlier records did not contain information on fuel types). Fires were included for analysis if they met criteria for being designated as a suppression fire only (*i.e.* no modified suppression or wilderness fires managed for resource benefits), lasted longer than seven days, and were 70 ha or larger. Our analysis did not attempt to account for tactics or decisions using the various crew and equipment categories reported for the large fires because their actual uses on the fire could not be known. Instead, we reasoned that rates of change in fire size through time were reflective of fire behavior opportunities (or lack of them) as influenced by weather, topography, and fuels, and ultimate suppression success.

For each fire, intervals of high and low fire-growth were determined (Figure 1). These intervals are a collection of sequential days for which the rate of fire area growth was either greater or less than the average growth rate for an individual fire. A high-spread interval is defined as any sequence of days that remained above the average area change for the individual fire while a low-spread interval exhibits daily growth which never exceeds the average area change for the individual fire (Figure 1). The number of days in each interval was recorded along with number of previous low-spread intervals (Figure 1). The end point of each interval was also identified as either the permanent end of fire growth (successful containment) or not (*i.e.* the fire gained in size in later periods) (Figure 1). This procedure assumed that each fire represented a history of opportunities for complete containment (little or no growth) as well as a record of the outcome of containment efforts (containment or not).

Statistical analysis of the derived containment data was performed using a Generalized Linear Mixed Model (GLMM) in the statistics program S+ (Insightful Corporation). Models of this type allow for explicit separation of terms for random and fixed effects (Schall 1991). Using the GLMM, we considered all measured variables with first-order interactions. We then culled all insignificant interactions (P>0.05) and lower-order terms based on the Akaiki Information Criterion (AIC) (Sakamoto 1986). The AIC reflects both explanatory value of the predictors as well as penalties for model over-specification.

The quality of the model predictions were assessed using the "hold-one-back" analysis where one fire (and associated intervals) is removed from the sample and the prediction is compared with the observed containment probability for that fire. When done for all fires, the Pearson's product-moment correlation was used to examine the correlation of observed and predicted containment probability. A receiver operating characteristic (ROC) plot was also constructed to examine the effect of varying the classification rule for contained versus uncontained fires and to assess model fit.

Results

Fires from the ICS-209 forms produced a total of 314 fires and data for 1571 intervals (Table 1). Fires varied in size from 70 hectares to 205972 hectares and burned for time periods ranging from 1 to 60 days.

The GLMM regression analysis produced predictions of containment probability on a logit scale (Table 2) and suggested that successful containment was positively related to the number of days in an interval (high-*spread* or low-spread) and the number of previous low-spread intervals (*npi*) (Figure 2). Probability of containment was much higher during low-spread intervals (Figure 2) than during high-spread intervals.

The regression model with the best AIC included significant two-way interactions of *timber* and *spread* with interval length (*ndays*) (Table 2). These interaction terms improved the model (lower AIC) but rendered the individual *timber* and *spread* terms not significant (these were retained in the final model because of the significant interactions). The individual terms (*timber*, *spread*) were shown to be significant in models without the interactions as well. When graphed, the *timber* and *spread* interactions suggest that containment probabilities in non-timber fuel types increased with the length of intervals (both high-spread and low-spread), but probabilities decreased with longer high-spread intervals when timber fuels are present (Figure 2). Fire size was not significant in any of the regression models.

The Pearson's product-moment correlation for the regression was 0.6774 suggesting that observed and predicted containment probabilities are highly correlated. The ROC plot (Figure 3) revealed a total misclassification rate of 0.1502 given the assumption that containment occurred when predicted at a probability of 0.8 or greater. The area under the ROC curve was 0.924.

Discussion

The statistical predictors of containment success seemed to support the intuition of fire fighters that large fires are contained opportunistically. The opportunities for successful containment were significantly higher during periods of low fire spread (Table 2, Figure 2). Thus, the consequence of containment success is reflected in the area not burned during future periods of extreme weather. Increase in containment probability was also found on fires that had been burning longer (more previous low-spread intervals). This likely reflects the increased size and organization of the suppression response (management team, crews and equipment) as well as the accumulation of partial perimeter containment achieved during earlier intervals (making ultimate containment easier). Since fire size was not found to be a significant predictor of containment in this analysis, these factors (increased organization and accumulated containment) may possibly compensate for the expected increase in suppression difficulty associated with larger fires.

Timber fuel types were associated with lower probability of containment success. This may partly reflect fire occurrence in mountainous terrain where access is more limited. It could also reflect a greater likelihood that timber fuels will be encompassed by fires as they become larger (and burn longer) or that fires burning in woody fuels can smolder and resume spreading after enduring many days of unfavorable weather (unlike grass fires). Such “holdover” fires offer more possibilities for escape during return episodes of extreme weather even after nominal containment is achieved. Spotting and crown fire present particular control problems in timber fuels and may be responsible for the regression trend showing longer intervals of high spread associated with decreasing containment probabilities but increasing probability of containment on fires without timber fuels (Figure 1). Perhaps these issues with containment difficulty underlie the recent finding that timber fuel types were associated with the highest suppression costs (Gebert *et al*. 2006).

Compared to the mechanistic approaches used for initial attack (e.g. Anderson 1989, Fried and Fried 1996), our statistical model cannot be used to examine tradeoffs in suppression resource use. The data and model presented here assume implicitly the use of resources according to generic historic strategies. We did not have data that would allow us to separate fires according to management strategy (*e.g*. full suppression vs. modified or no suppression). These data also did not allow analysis of effects of resource scarcity on containment success (Bednar et al. 1990, Fried et al. 2003), although constraints of fire fighting resources would be generally expected to diminish successful containment probability.

Statistical models of containment success might be useful for fire planning and budgeting. Given the assumption of the historic suppression response, a probability model like the one reported here could be used to make predictions of the successful containment of active fires provided the availability of a weather forecast. If the forecast could be interpreted to suggest the lengths and sequences of quiescent and active periods, the containment probability could be anticipated by using other attributes of the fire known to date (number of previous low spread intervals etc.). By combining the probability of containment with predictions of fire growth, two fire progression scenarios (with and without suppression) could contribute to benefit-cost analysis when combined with values at risk. Benefit-cost analysis could also be applied to past fires as a metric to explore effects of alternative fire management strategies as well as questions over the role of 20th century suppression policies in altering burning rates and fire size distributions. The latter subject is controversial because large fires exhibit uncontrollable behavior (Miyanishi and Johnson 2001) but empirical data suggest dramatic decreases in burned area (Ward et al. 2001) and escape frequencies (Cumming 2005) coincident with implementation of modern suppression organizations.

Conclusions

The general linear mixed-model analysis performed using data on size changes in historic large fires lends support for the idea that suppression effects are opportunistic and dependent on the duration of moderate fire behavior. This modeling is a first step in trying to understand how suppression affects fires. Better models are needed to describe large fire responses to resources and budget variables but must await the availability of better data.

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Table 1. Summary of ICS-209 data used for modeling of large wildland fire suppression probability.

State	Number of Fires	Average Number of Intervals (min,max)	Average Duration of Fire (Days) (min,max)	Average Fire Size (hectares) (min,max)	Percentage of Intervals with Timber Fuels
AZ	39	4.3(1,9)	14.6(3,54)	15173(385,189732)	46
CA	37	4.5(1,10)	11.2(3,39)	12631(526,113473)	65
CO	20	4.8(1,7)	13.2(1,31)	5833(585,55773)	75
FL	3	4.0(1,8)	17.7(13,21)	8357(587,13846)	33
HI	1	2.0(2,2)	17.0(17,17)	824(824,824)	0
ID	27	5.4(2,14)	17.1(7,56)	3544(289,16546)	96
LA	1	2.0(2,2)	7.0(7,7)	1433(1433,1433)	0
MN	1	6.0(6,6)	15.0(15,15)	540(540,540)	100
MT	43	6.6(2,20)	23.0(5,60)	7277(344,53007)	98
NM	22	5.3(1,17)	13.0(4,38)	7074(451,37449)	95
NV	15	4.3(2,8)	10.5(7,20)	23414(483,205972)	27
OK	1	2.0(2,2)	11.0(11,11)	1417(1417,1417)	100
OR	33	5.1(2,23)	15.6(6,54)	8331(567,48617)	88
SC	1	2.0(2,2)	7.0(7,7)	743(743,743)	0
SD	6	4.8(4,6)	10.2(6,13)	6543(1238,19433)	100
TX	2	2.5(2,3)	7.5(5,10)	4599(3073,6126)	0
UT	22	4.2(1,8)	13.7(3,35)	6872(630,38267)	64
VA	1	7.0(7,7)	15.0(15,15)	1532(1532,1532)	100
WA	23	7.3(2,22)	26.0(6,98)	4765(69,32932)	100
WY	16	4.4(2,9)	16.3(7,55)	4501(486,9717)	94
Total	314				

Table 2. Results of the GLMM analysis showing the statistical model predicting large fire containment probability (logit). The variables are *ndays*=number of days in an interval (both high-spread and low-spread), *npi* =number of previous low-spread intervals, *spread*=interval exhibited high spread, *timber*=presence of timber fuels.

	Value	**Std.Error**	**p-value**
Intercept	-3.145778	0.5640164	<.0001
timber	0.480347	0.5904293	0.4161
ndays	0.981733	0.2036769	<.0001
npi	0.071124	0.0295386	0.0162
spread	-0.988527	0.6392541	0.1223
timber:ndays	-0.599104	0.2067536	0.0038
spread:ndays	-0.820806	0.3113147	0.0085

Number of Intervals:	1571
Number of Fires:	314
Degrees of Freedom:	1252
AIC:	10147.39

Figure 1. Graph showing how changes in daily fire size were converted into interval-based data for regression analysis. Vertical lines divide the daily fire sizes into intervals. Data at the top of the graph represent the independent variables by interval used to predict containment by the end of the interval (*ndays*=number of days in an interval (both high-spread and low-spread), *npi* =number of previous low-spread intervals, *spread*=interval exhibited high fire spread, *timber*=presence of timber fuels, *grass*=presence of grass fuels, *brush*=presence of brush fuels). This example is from the Apple fire that occurred in Oregon in 2002.

spreading	**1**	**0**	**1**	**0**	**1**	**0**	**1**	**0**	**1**	**0**
ndays	**3**	**6**	**1**	**3**	**2**	**1**	**1**	**4**	**1**	**4**
npi	**0**	**0**	**1**	**1**	**2**	**2**	**3**	**3**	**4**	**4**
grass	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
brush	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
tmber	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
contained	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**

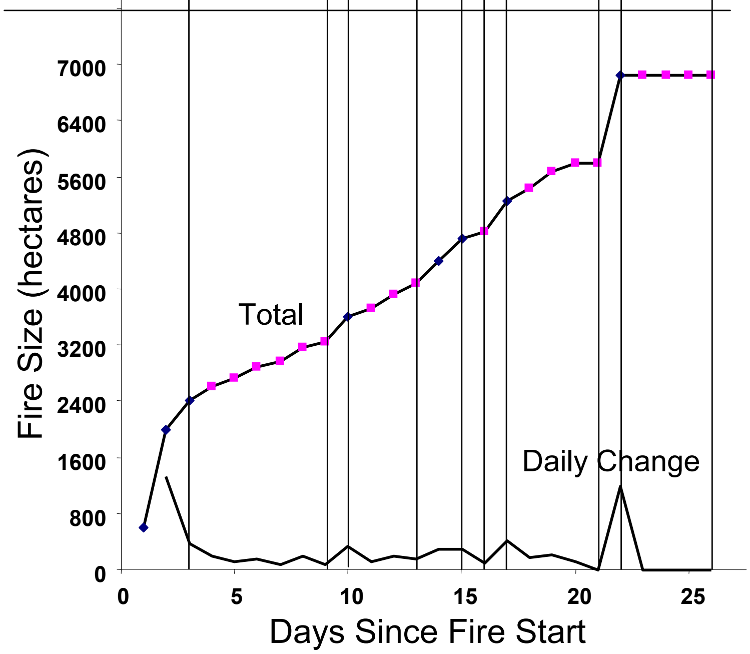

Figure 2. Graph showing the effects of the main variables on containment success (NPI= number of previous low-spread intervals). The comparison of A) the low probability of containing fires during high-spread intervals compared to low-spread intervals in fuel types that do not include timber fuel types, and B) the lower probability of containing fires when timber fuel types are present. Probability of containment during high-spread intervals increased where timber fuels were absent (A) but increased when present (B).

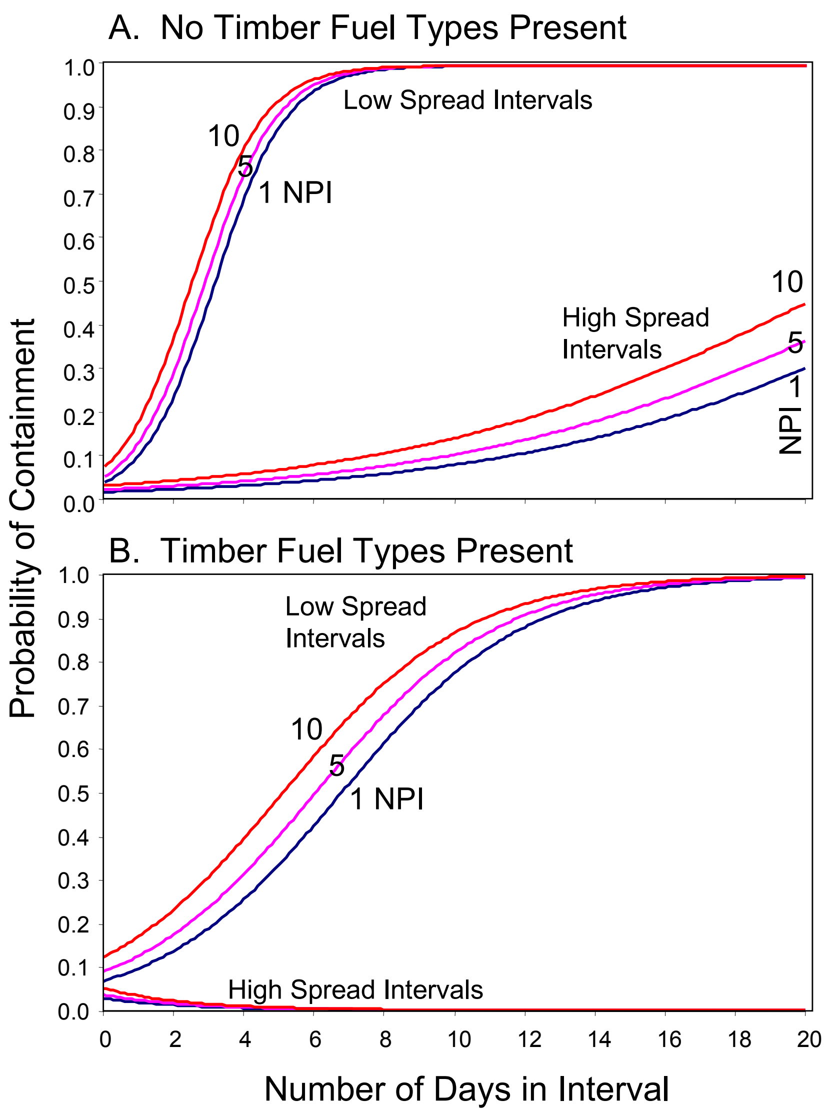

Figure 3. Model performance and behavior are depicted by (A) the Receiver Operating Characteristic, and (B) distributions observed intervals where containment occurred and did not occur compared to predicted containment probability.