SIMULATING INITIAL ATTACK: STOCHASTIC FORMULATION BRINGS RISK CONSIDERATION TO FIRE PROTECTION PLANNING.

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Abstract

An overview of the California Fire Economics Simulator (CFES) Version 2, a stochastic, microcomputer based simulation system for modeling initial attack on wildland fires, is provided, and the structure and parameter estimation procedures of its fundamental modules (fire occurrence, fire behavior, fireline production, and initial attack containment) are outlined. CFES Version 2's capabilities are demonstrated using a data set describing the California Department of Forestry and Fire Protection's Santa Clara ranger unit. Stochastic simulation results compare favorably with historical statistics, and in most instances, CFES Version 2 succeeded in generating appropriate sequences of fire occurrences with plausible outcomes, and resulted in expected value fire statistics generally more credible than those obtained from the deterministic CFES Version 1. The stochastic formulation of the model makes possible more sophisticated analysis and presentation of the likely impacts of proposed policy changes on the wildland fire system, and opens the door to explicit consideration of risk in the economics of wildland fire protection.

Introduction

Most applications of simulation modeling of wildfire initial attack systems have employed deterministic formulations that do not adequately reflect the importance of the stochastic elements in these systems. Models which have attempted to do so have not been extensively utilized as decision support tools due to computational or conceptual limitations relative to the needs and capabilities of fire control agencies (Gilless and Fried, 1991). This paper describes a new microcomputer simulation model, the California Fire Economics Simulator (CFES) version 2, that overcomes many of these limitations. This model incorporates stochastic representations of fire occurrence (over space and time), fire behavior, and fireline production with an improved treatment of fireline containment and institutional constraints on the use of firefighting resource. In so doing, the model allows fire planners to more accurately assess the capacity of their initial attack resources and policies to meet the challenges posed by peak-demand situations (e.g., multiple fire starts on days with extreme fire behavior).

Geographic representation

CFES version 2 retains the NFMAS/CFES version 1 approach to stratifying protected lands into homogeneous fire management analysis zones (FMAZs) for modeling. To realistically model fire behavior, firefighting responses, and fire damages, FMAZs must be relatively uniform with respect to fuel type, slope, and population density. A geographic information system (GIS) can be helpful both in delineating and characterizing FMAZs (e.g., by acreage or number of historical ignitions by time of year). Finer stratification can result in more homogenous

FMAZs which in total can increase model accuracy; however, because CFES version 2 requires the fitting of historical, FMAZ-specific stochastic distributions for several model elements, finer spatial resolution must be traded off against decreased precision in these elements. This problem will diminish over time as historical fire records are augmented. CFES version 2 differs from NFMAS/CFES version 1 in that the latter provides only for simulation of representative fires in one FMAZ at a time (Fried and Gilless, 1988a), while CFES version 2 simulates the operation of the initial attack system for an entire ranger unit simultaneously (i.e., including multiple FMAZs)(Fried and Gilless, 1988b).

Model structure

Wildfire protection is an inherently complex system encompassing a variety of environmental, mechanical, and human subsystems. CFES was developed as an integrated decision support tool for projecting the likely impacts of specific changes in one or more of these subsystems (Figure 1).

CFES version 2 is most accurately described as a collection of several conceptual modules which were independently designed, fitted and tested, each intended to represent some element or subsystem of the wildland fire protection system (specifically, fire occurrence, behavior, fireline production, dispatch and containment). Within modules, some parameters are treated stochastically and others deterministically (Table 1). Some modules, such as containment and parts of dispatch, are mechanistic and deterministic in that they are intended to mimic a real-world activity through mathematical representation of the processes integral to that activity. Processes that are treated with independent stochastic representations, such as fire occurrence and fireline production, are handled with statistical modules that mimic the perceived or recorded variability of prior events, because the complexity of these processes precludes a fully causal model.

The fire behavior module is a hybrid, because a mechanistic fire behavior model applied to historical weather observations was used to generate the statistical distributions from which fire behaviors are sampled in a CFES 2 simulation.

To the extent possible, the simulator's Pascal code and logical relationships have also been modularized to facilitate the inclusion of more or less sophisticated representation of some system elements, depending on the adequacy of the available data. Some stochastic modules can be parameterized into a deterministic mode.
This paper outlines the most substantial modules of CFES 2, illustrating their derivation and operation with data from the California Department of Forestry and Fire Protection's Santa Clara ranger unit (located in the San Francisco Bay Area). Six FMAZs represent the diversity of fuel and population density combinations found in the ranger unit (Figure 2). Most of the area is covered with flammable, dry grass during the summer months, and some of it is densely populated. The FMAZ labeled SCUBM includes the Oakland/Berkeley Hills, site of a catastrophic wildfire in 1991 that consumed more than 2000 homes and caused 25 fatalities.

Fire occurrence

The fire occurrence module, as reported on elsewhere (Fried and Gilless, 1988c), employs a daily three stage stochastic selection process. First, a Bernoulli distribution is sampled to determine whether or not any fires occur on a given day. If so, then a geometric multiplicity distribution is sampled to determine how many fires occur (Figure 3). Then, for each simulated fire, a time is chosen from a beta distribution (Figure 4). Except for time of day, distributions are specified separately for low, transition and high fire seasons. This process realistically reflects the problem of simultaneous fire occurrences and allows for a straightforward treatment of diurnal variation in fire behavior.

Fire locations are selected randomly according to the expected proportion of the fire activity represented by each Representative Fire Location (RFL) in an FMAZ.

Fireline

The fireline production rate module (Fried and Gilless, 1989) is based on a statewide, expert opinion survey of engine captains, bulldozer operators and handcrew bosses that elicited best case, worst case and most likely estimates of how long it would take their crew and equipment to build a given length of fireline under specified conditions. The survey was conducted in the field at sites chosen to represent different firefighting control conditions. Site and equipment specific beta distributions for time to complete a fixed length of line were then derived from these estimates. The beta distribution has a very flexible form, and the advantage of being bounded above and below. A statewide compendium of this information for each of 200 control conditions has been published (Lee et al., 1991). Each control condition is documented by a two page description that includes wide angle and close-up photos of the site, and the following: a short description, a plot of the fitted beta distribution for each resource category (Figure 5), and for each firefighting resource type, the best case and worst case estimates and the parameters of the beta distribution (Figure 6). The fields labeled "till dropoff" and "time after" account for the drop in productivity that occurs when crews get tired and engines exhaust their supplies of water. "Till dropoff" is the number of feet of line that can be built at the rate chosen from the beta distribution; "time after" is the amount of time required to build the next N feet of line, where N is, for example, 1320 feet.

Fire behavior

Although it is reasonable to use independent stochastic selections in the modeling of fire occurrence and fireline production rates, it is quite unreasonable to do so in the modeling of fire behavior for fires occurring on a given day. To do so could result in consecutive fires, just minutes and a few miles apart, with wildly different rates of spread. Modeling of fire behavior is further complicated by the practice of relying on Fire Dispatch Levels (FDLs) to determine the number of each type of firefighting resource to send as the initial response. in practice, FDLs may be determined either by predicted either burning index (BI) or rate of spread (ROS). The predictions are based on hourly weather observations from a local station, and conditions, like fuel type, which may, or may not, be the same as those used to represent fire behavior. It would be unrealistic to generate a sequence of fires in a particular FMAZ at 10 AM, 1PM and 3PM with FDLs High, Low, Medium and spread rates of 80, 10, and 20. Yet an independent selection process would certainly generate such scenarios. CFES version 2 employs a linked behavior selection process to ensure consistency in the estimated fire behavior values parameters for fires on a single day.

In CFES 2, there is one "fuel combination" for determining FDL and one for ROS for each FMAZ. A fuel combination is a combination of weather station, fuel model, slope class, climate class and type of herbaceous vegetation. The fuel combinations might be the same for analysis zones in which FDLs are based on ROS. However, FDL is often based on BI and, for simplicity in dispatch, FDL is sometimes based on data from a weather station that is different from the one that best represents fire behavior for a particular fire. Threshold values defining the low/medium and medium/high FDL boundaries are analyst specified.

For each fuel combination, CFES 2 requires the entry of behavior records containing parameters that are used to characterize fire behavior (FDL and ROS) for fires in the FMAZs to which they are linked (Fried, 1992). A behavior record consists of parameters for compound ROS or BI distributions, by season, and diurnal adjustment factors for normal and special conditions for a single weather station and fuel combination (e.g., Santa Ana winds).

One part of the compound distribution is a low, constant value which represents the many fires that have low ROS's or low Bl's, while the other part of the compound distribution characterizes the behavior of all other fires using a beta distribution (Figure 7). Calculation of the Bernoulli parameter defining the relative frequency of days appropriately modeled by either part of the compound distribution is quite straightforward. The data pertaining to higher ROS Or BI fires is then scaled to a (0-1) interval and a beta distribution is fit.

The rest of the behavior record consists of the two, 24 element vectors of diurnal adjustment multipliers that are used to modify the selected 2PM ROS and BI values to reflect the time of day of a particular fire. East winds (which are usually strong and gusty in both California and Chile) might be a special condition worthy of separating from the rest of the data, for example. The data for estimating these parameters are derived by processing a database of hourly weather observations with the BEHAVE fire modeling system to obtain fuel combination specific estimates of hourly ROS and BI. These hourly values are then converted to multipliers relative to the 2PM observation by dividing each one by the 2PM value (Figure 8). Finally, the average multiplier value for each hour is calculated from all of the available data for that hour. By definition, the 2PM element of a diurnal adjustment matrix is equal to one.

The procedure for selecting fire behavior can then be summarized as follows. For a simulated day on which fires occur, a uniform random variable on the interval (0-1) is chosen as a Two PM Behavior Percentile (TBP). The selection of 2PM FDL and ROS for each fire on that day are then tied to the TBP, but subject to modification based on the fire's time of day using the specified diurnal adjustment vector.

That is to say, for each fire, a 2PM FDL index value is calculated by numerically integrating the season-specific ROS or BI distribution specified for the analysis zone in which the fire occurs, up to the TBP. The FDL index value is determined by satisfying the equation shown here.

$$\int_0^{\text{fdl index}} \text{ROS or BI distribution} = \text{TBP}$$

The FDL factor is then multiplied by the diurnal adjustment factor for the hour closest to the fire's ignition time to obtain a time-of-day adjusted FDL index. The FDL is then determined to be Low, Medium or High by comparing the index value to the appropriate (ROS or BI based) thresholds for the analysis zone in which the fire occurs. The procedure for selecting a spread rate for the fire is essentially identical, except that only ROS distributions are used, and that distributions can be specific to a particular representative fire location rather than an analysis zone.

Fireline containment

Previous operational fire models (e.g., CFES version 1, USFS IAA) have relied on the assumption that initial attack fires spread in the form of an ellipse, and that line-building efforts have no impact on the spread of the fire until it has been contained. The elliptical assumption has been borne out in several studies of fire shape, and the eccentricity of the ellipse, or length to width ratio, has generally been found to be well correlated with wind speed and slope. However, the failure to consider the impact of containment on fire spread has led to overestimation of total area burned, containment time and resources employed.

CFES 2 allows specification of the eccentricity of fires by dispatch level and location. More importantly, it incorporates a containment algorithm that features a parametric representation of the ratio of line building to rate of spread as a first order differential equation in an angular variable u that represents the current point of line building activity, and h, which represents the horizontal distance over which the head of the fire has progressed (Fried and Fried, 1993). The equation is amenable to solution via Runge-Kutta, can accommodate any mathematically represented shape (not just ellipses), and can be extended to model a parallel attack tactic under which fireline is built at some distance away from and parallel to the fire in conjunction with firing out or setting backfires.

One can think of an aggregate production rate for all of the resources at a fire at a given point in time. Typically, the rate is rising as more resources arrive, and falls as water and crews become exhausted. Air tanker and helicopter water and retardent drops can be represented as a brief, but large, increase in the fireline production rate.

Simulation Results

CFES version 1 reports expected annual area burned and number of fires by size class, along with the number of fires that exceed simulation limits, resource utilization, and containment success. CFES version 2 can report these statistics too; far more valuable is its ability to predict the variability of these variables.

Simulated fires that exceed specified time or size limits are declared Exceed Simulation Limit (ESL) fires. Because these fires may grow to be quite large and could damage a large area, they are often the first simulation statistic examined. If there are ESLs, then the area burned by contained fires may be trivial in comparison. If there are no ESLs, then area burned becomes a more meaningful statistic.

The results of a 100 year, base (current initial attack configuration) simulation of the Santa Clara Ranger Unit demonstrate considerable year-toyear variability in annual number of ESLs (for the grass fuel, low population density and the grass fuel, medium population density zones) and area burned (for the analysis zones without projected ESLs) (Figure 9). Not surprisingly, nearly every distribution is skewed such that there are a few years with a very large predicted area burned or number of ESLs: as much as two to ten times the median year value. Presented in a percentile or odds table that includes extreme as well as mean and median summary statistics, this information can be understandable and useful to fire managers (Table 2). It is interesting to note the magnitude of the difference between mean values and the once in ten or twenty years events. Any organization that concentrates on preparing for average fire years will be ill-prepared to handle a great many worse than average years.

It is worth noting the rare cases of simulated years in which a fire exceeded simulation limits (and possibly escaped) in the young-growth redwood, medium population density analysis zone (Table 3). Though one might be tempted to dismiss them as "exceptions" or "noise" that can be discounted or ignored, they are in fact a principle reason for taking a stochastic approach to modeling this system. A deterministic analysis of this same zone using CFES version 1 projected no ESL fires, despite the reality of the 1985 Lexington Reservoir fire that occurred in this area, destroying thousands of hectares of forest and dozens of homes. CFES 2 offers a projection that better reflects reality and yields an estimate of a the likely frequency of such dreaded events.

This simulation produced results in terms of annual number of fires, ESL fires and area burned by contained fires that compare favorably with corresponding data over the past ten years (Figure 10). Although not a validation in a predictive sense, this correspondence does imply a representation that is consistent with the historical data from which the model was developed.

Also encouraging is the rapidity with which simulation results stabilize. A test for which 50, 100, 150 and 200 consecutive years worth of simulation results were summarized showed that the shape of frequency distributions for both ESLs and annual area burned had essentially reached a terminal form after 100 years, changing very little with additional years of simulation. The pattern evident in the results for the grass fuel, low population density analysis zone displayed in Figure 11 was essentially identical for all other analysis zones. In fact, results were often stable by 50 years, except that in the case of area burned, there was an enrichment in the population of "outliers" with longer simulations. One hundred year simulations for this ranger unit required approximately eight hours on a 486based PC.

CFES version 2 represents a significant advance over existing simulation models of wildfire initial attack systems. By allowing more accurate assessment of system performance in peakdemand situations, it provides planners with the means to both rationalize their budgetary requests and improve their resource deployment. Simulation results for acres burned in contained fires or numbers of fires exceeding simulation limits can be presented in a variety of ways, depending upon the sophistication of the audience -- including probability density functions, measures of central tendency, quartiles, or 1-in-X year terms.

Much more can be done to improve the model. Housing losses are not currently addressed in determination of losses to wildfire, although a data handle (specification of average parcel size) has been included in the model with this issue in mind. Sensitivity analysis will need to be performed on many of the system specifications to assess, for example, the importance of backup relationships and tactical decisions.

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Table 1. Stochastic and deterministic elements of the CFES Version 2 model.

Stochastic Elements	Deterministic Elements
Occurrence in time	Response times
Occurrence in space	Resources requested
Fireline production rates	Commitment time following containment or escape
Fire dispatch level	Containment tactics
Fire spread r	
Resources dispatched	
Resource availability	

Table 2. Means and selected percentiles from the distributions of area burned in contained fires per year, for selected FMAZs on the Santa Clara ranger unit.

FMAZ	Mean	50th	80th	90th	95th	98th	99th
Odds:		1:10	1:2	1:10	1:20	1:50	1:100
SCUBL	4.36	1	5	9	16	20	23
SCUBM	10.07	7	14	18	24	40	52
SCUFM	3.90	2	5	7	9	17	28
SCUGM	21.19	17	28	37	47	56	62

Table 3. Means and selected percentiles from the distributions of number of ESL fires per year, by FMAZ, for the Santa Clara ranger unit.

FMAZ	Mean	50th	80th	90th	95th	98th	99th
Odds:		1:2	1:5	1:10	1:20	1:50	1:100
SCUAL	5.66	5	8	9	11	11	11
SCUAM	4.24	4	6.5	8	8.5	10.5	15.5
SCUBL	0.00	0	0	0	0	0	0
SCUBM	0.00	0	0	0	0	0	0
SCUFM	0.00	0	0	0	0	0	0
SCUGM	0.04	0	0	0	0	1	1.5

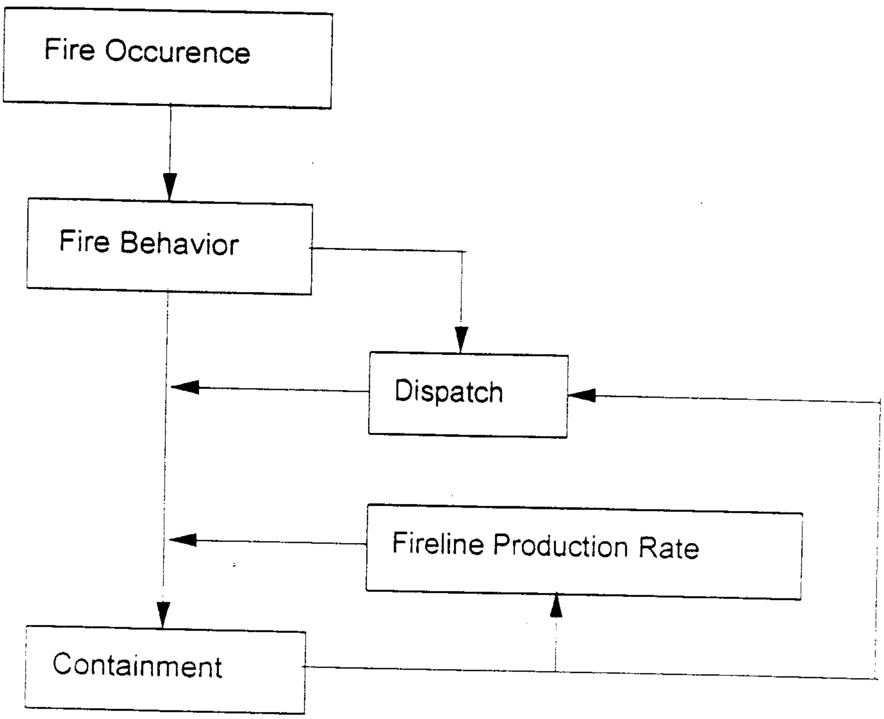


Figure 1. Organization of the modules in CFES Version 2.

Fig 2

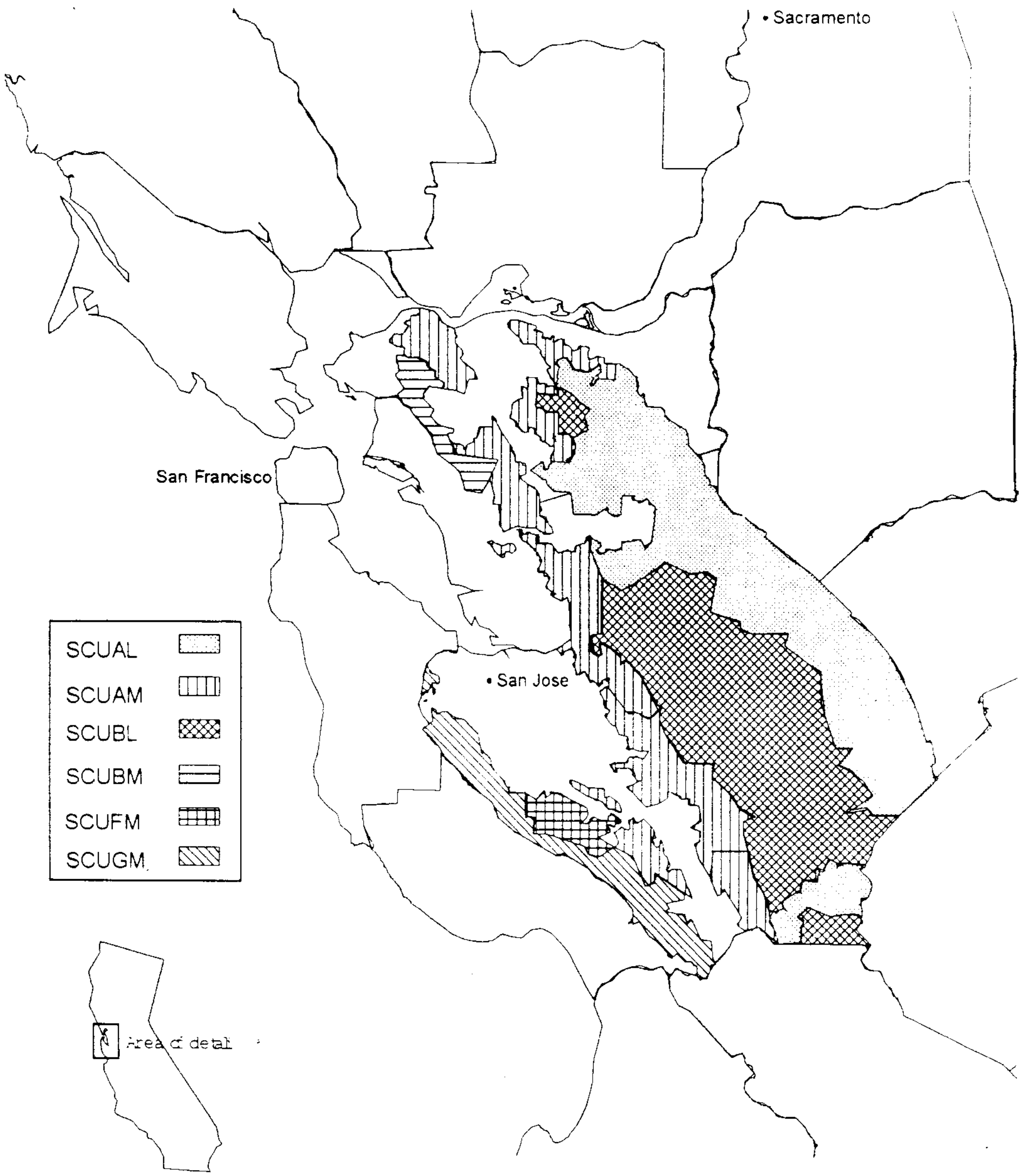


Figure 2. Map showing the locations of the six FMAZs designated in the Santa Clara ranger unit, California.

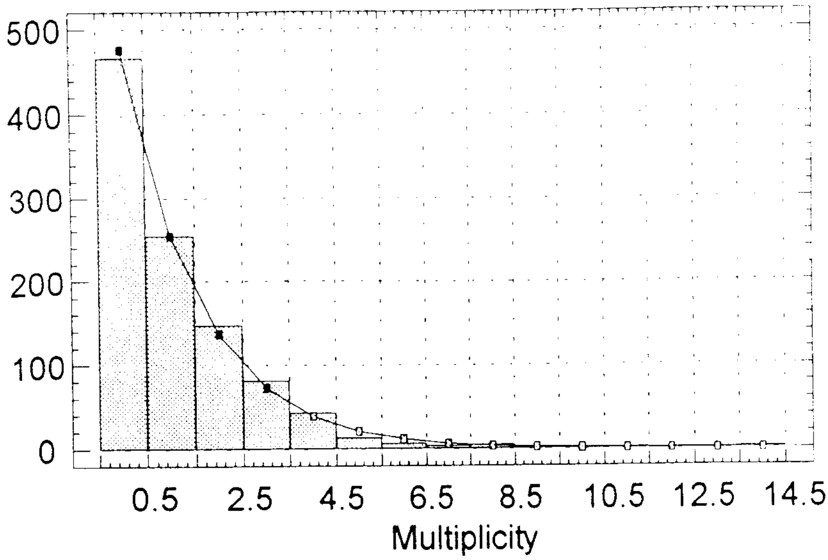


Figure 3. Fitted distributions for High Season Multiplicity (number of fires on a day), used in the CFES Version 2 occurrence module for the Santa Clara ranger unit, California.

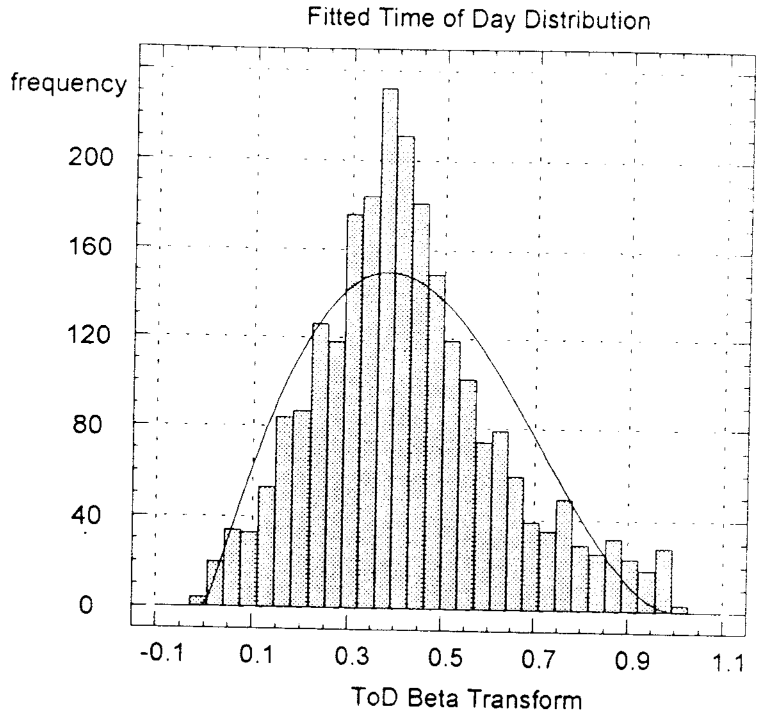
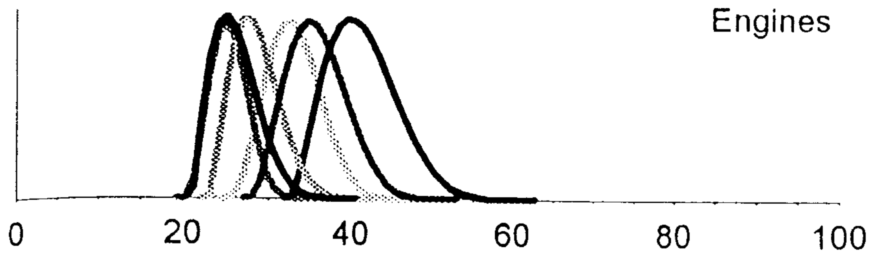


Figure 4. Fitted distributions for Time of Day used in the CFES Version 2 occurrence module for the Santa Clara ranger unit, California. The Time of Day transform value of 0 corresponds to 5 AM.


Engines
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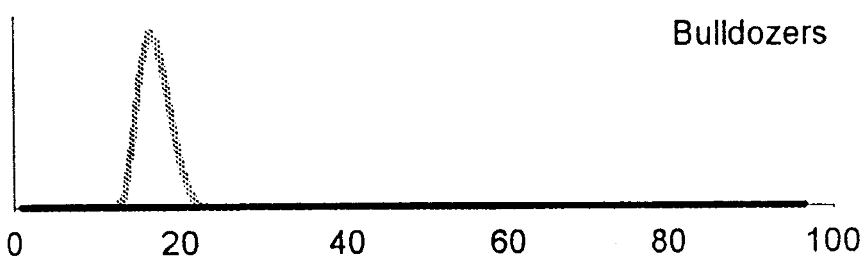
20
40
60
80
100


Bulldozers
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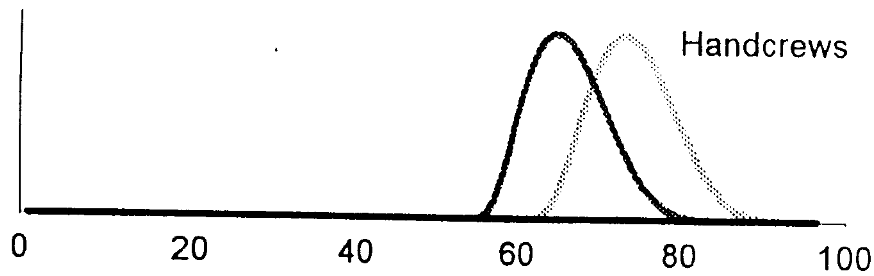

Figure 5. Production rate distributions for a grass fuel control condition on the Santa Clara ranger unit.

Source	Tactic	Type	Crew size	N	Estimation distance (feet)	Avg. rate (feet/ min)	Avg. time (min)	Min. time (min)	Max. time (min)	Alpha	Beta	Distance till dropoff (feet)	Avg. time after (minutes)
D		2		3	1320	77.4	17.1	12.7	25.0	3.9050	7.0520		
E	H	1	2	2	1320	39.8	33.2	25.0	47.5	4.0201	7.0403	750.0	68.5
E	M	1	2	1	1320	51.9	25.5	20.0	35.0	4.0201	7.0403	1000.0	30.0
E	H	3	3	2	1320	31.8	41.5	32.5	62.5	2.9880	8.9640	750.0	67.5
E	H	3	4	2	1320	36.7	35.9	27.5	52.5	3.5969	7.0593	900.0	50.0
E	M	3	3	2	1320	46.2	28.6	23.0	42.5	2.7669	6.8897	1310.0	43.5
E	M	3	4	2	1320	50.4	26.2	21.0	40.0	2.5442	6.7909	1320.0	38.5
H		1	13	3	1320	17.7	74.4	61.7	96.7	4.0201	7.0403	2266.7	86.7
H		1	16	3	1320	19.9	66.3	55.0	88.3	3.5969	7.0593	2433.3	78.7

Figure 6. Production rate parameters for a grass fuel control condition on the Santa Clara ranger unit for dozers (D), engines (E) using hoselay (H) and mobile attack (M) tactics, and hand crews (H).

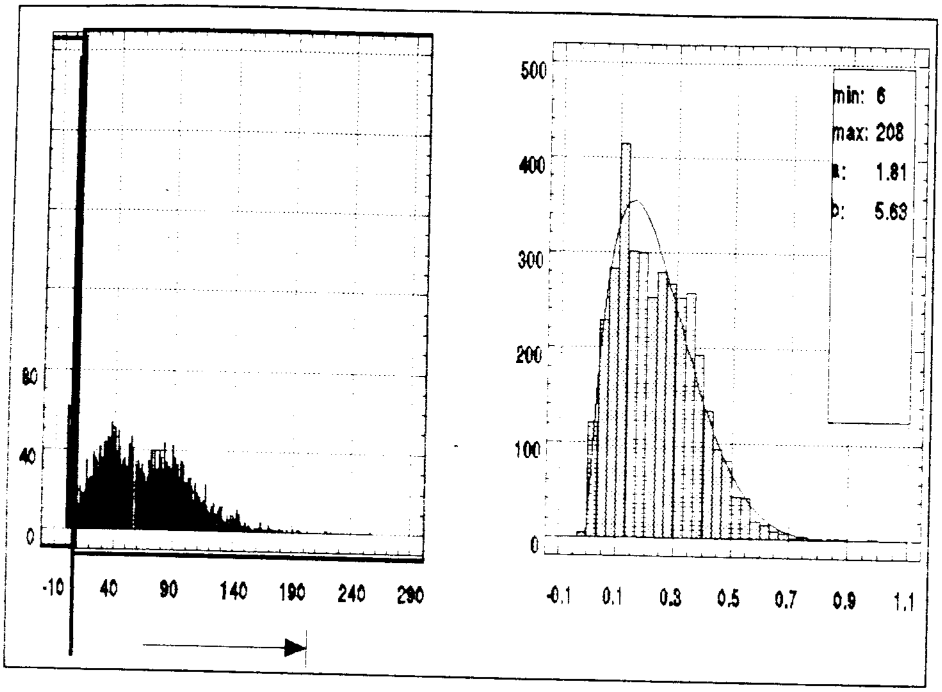

Figure 7. Frequency histogram (covering both the Bernoulli and Beta range) and fitted distribution (covering only the Beta range) for burning index (BI) for the Arroyo Seco weather station, fuel model A3 (grass with overstory), and slope class 2 (26-40%), for the high fire season, for the Santa Clara ranger unit.

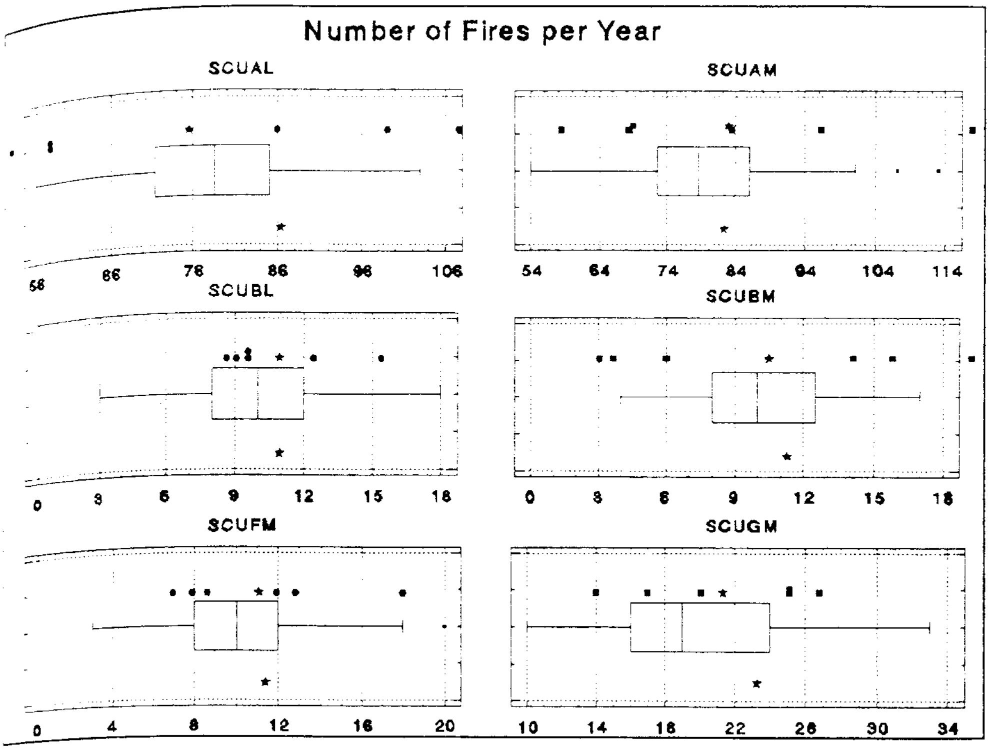

Figure 10. Box and whisker plots of the number of fires per year in simulations generated by CFES Version 2, by FMAZ, for 100 simulated years on the Santa Clara ranger unit. Points (filled circles or squares) plotted above the box and whisker represent the 6 years of historical data. Points outside the graph boundary are out of the x-axis range. The star above each box and whisker indicates the historical (6 year) mean, and the star below indicates the mean historical value used in the deterministic CFES Version 1 simulation.

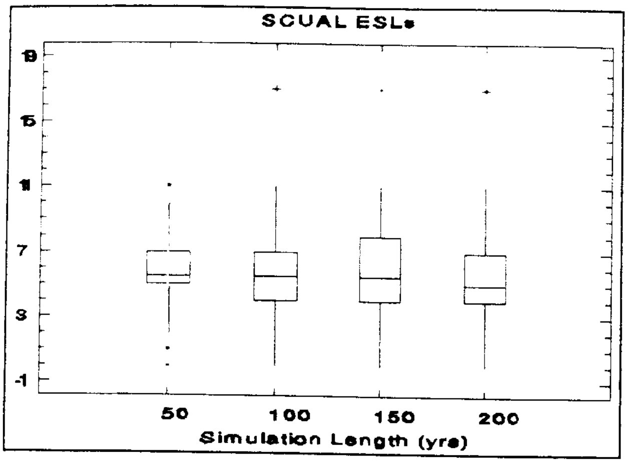

Figure 11. Box and whisker plots of the CFES version 2 projections of the number of ESL fires per year in the Santa Clara ranger unit's grass fuel, low population density analysis zone for four different simulation lengths.