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Analysing initial attack on wildland fires using stochastic simulation*

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Abstract. Stochastic simulation models of initial attack on wildland fire can be designed to reflect the complexity of the environmental, administrative, and institutional context in which wildland fire protection agencies operate, but such complexity may come at the cost of a considerable investment in data acquisition and management. This cost may be well justified when it allows for analysis of a wider spectrum of operational problems in wildland fire protection planning. The California Fire Economics Simulator version 2 (CFES2), is a sophisticated stochastic simulation model designed to facilitate quantitative analysis of the potential effects of changes in many key components of most wildland fire systems, e.g. availability and stationing of resources, dispatch rules, criteria for setting fire dispatch level, staff schedules, and deployment and line-building tactics. The CFES2 model can also be used to support strategic planning with respect to vegetation management programs, development at the wildland–urban interface, reallocation of responsibilities among fire protection agencies, and climatic change. The analytical capacity of stochastic simulations models to address such key issues is demonstrated using the CFES2 model in four case studies addressing the impact on initial attack effectiveness of: (1) multiple fire starts; (2) diversion of firefighting resources to structure protection; (3) alternate stationing of firefighting resources; and (4) multi-agency cooperation.

Additional keywords: California Department of Forestry and Fire Protection; California Fire Economics Simulator; fire protection planning; forest fire; wildfire.

Introduction

Agencies responsible for initial attack on wildland fire have long sought analytical tools capable of guiding decisions about the ‘correct’ amount and configuration of initial attack resources. Sometimes they are driven by the need to maintain initial attack effectiveness in the face of declining real budgets; other times, there is a need to respond to changes in vegetation fuels, or in the distribution of natural resources and values at risk, or a desire to more equitably allocate costs and responsibilities in the context of mutual aid arrangements between different agencies.

During the last two decades, the US Forest Service and other federal fire management agencies have focused on planning approaches that combined variants of the 90-year-old paradigm of cost-plus-loss minimization on simple, deterministic models of initial attack on wildland fires (Donovan *et al*. 1999; Lundgren 1999). There is a rich literature on modeling initial attack, mostly using deterministic methods. Particularly significant are the contributions of: Bratten (1970) on the use of non-linear mathematical programming utility maximization models under constrained resource availability; Mees (1978) on models to integrate dispatching of air and ground initial attack resources; Simard and Young (1977, 1978*a*, 1978*b*, 1978*c*) and Bratten *et al*. (1981) on the deterministic AIRPRO and Fire Operational Characteristics Using Simulation models, respectively, to address the same problem; Mills and Bratten (1982) on the probabilistic Fire Economics Evaluation System; McAlpine and Hirsch (1999) on Ontario’s deterministic Level of Protection Analysis System air resources simulation model; and Finney (1998) on the spatially explicit deterministic fire growth model FARSITE. The California Fire Economics Simulator version 2 (CFES2) model, however, is most significantly indebted to the deterministic US Forest Service National Fire Management and Analysis System model (USDA Forest Service 1985).

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These models have been useful in justifying the fire protection budgets of resource management agencies to state and federal legislatures and to higher levels of administrative oversight. However, the deterministic models supporting this approach have been the target of increasing criticism from fire managers and planners with respect to the extent to which they can be used to analyse operational issues such as 'drawdown' of firefighting resources due to multiple fire starts, the need to divert resources to protect structures in the urban–wildland interface, and tactical options (such as using one type of firefighting resource to back up another) (Gilless and Fried 1991). The deterministic, expected value-based inputs and outputs of these models have also been identified as a critical limitation on their usefulness for planning, in that they provide little guidance on how to prepare for worse-than-average conditions (Alvarado *et al*. 1999; Lundgren 1999; Wiitala 1999).

In 1986, the California Department of Forestry and Fire Protection (CDF) entered into a partnership with the University of California at Berkeley to develop a fire protection planning model that would provide a more realistic treatment of a variety of issues such as firefighting tactics, dispatch policies, fire behavior, and fireline production rates, especially with respect to their stochastic properties (Fried and Gilless 1988*a*). The CFES2, can be used to simulate 'what-if' scenarios for initial attack on wildland fire given hypothetical changes to vegetation fuels, climate, firefighting strategies and tactics, dispatch criteria, fireline productivity, detection time, availability of firefighting resources, fire prevention, deployment rules, accessibility, and staffing schedules (Torn and Fried 1992; Fried and Gilless 1999; Fried *et al*. 2004).

CFES2 simulation outputs include or can be used to calculate:

(1) Expected percentage of fires that would be 'contained' within user-specified size and time limits;
(2) Expected area burned by 'contained' fires;
(3) Distribution of contained fires by fire size and dispatch level;
(4) Expected firefighting costs for contained fires;
(5) Expected numbers of dispatches (missions) for individual firefighting resources; and
(6) Descriptive statistics for the (simulated) distributions of any of the aforementioned criteria, e.g. variances or 90th percentile values.

The present paper summarizes the structure of the CFES2 simulator and describes four CFES2 analyses that demonstrate the policy analysis capabilities of a complex stochastic simulation model of initial attack on wildland fire. Three of these are based on data from the CDF's Nevada-Yuba-Placer (NEU) Ranger Unit. The first analysis concerns changing a 'current practice' of diverting first-arriving fire engines from fireline production to protect threatened structures. The second assesses interactions between 'Schedule B' firefighting resources, i.e. those funded by the CDF to provide wildland fire protection, and 'non-Schedule B' resources, including CDF engines designed for structure protection that are funded by counties and local government, and firefighting resources operated by the US Forest Service, local governments, and volunteer fire departments. The third analysis explores the effectiveness of initial attack when more than one fire occurs on a given day (i.e. when there are multiple fire starts). The last analysis is based on data from the CDF's Humboldt-Del Norte (HUU) Ranger Unit, and illustrates the use of CFES2 to consider the impacts of alternative locations for infrastructure investments.

CFES2 system overview

Geographic representation

CFES2 simulations are run at the ranger unit level, an administrative area composed of from one to three counties, although all firefighting resources in adjacent ranger units that are close enough to be called on for initial attack purposes are also considered. Ranger units are stratified, typically with the aid of a geographic information system (GIS), into one or more fire management analysis zones (FMAZ) that are relatively homogenous with respect to fuels, slope, and any other characteristics (such as values at risk) that affect fire behavior, resistance to control, or the definition of 'success' for initial attack. CFES2 inputs defined at the FMAZ level include share of a ranger unit's fire load, simulation size, and time limits beyond which fires are classified as exceeded simulation limit (ESL) fires; the weather stations, fuel models, and slope classes used to characterize fire rate of spread (ROS) and fire dispatch level (FDL); size classes for tabulating the results of simulations; backup and structure protection requirements for firefighting resources; and per acre suppression costs.

Representative fire locations (RFL) within each FMAZ reflect the historical or anticipated spatial distribution of fires within the FMAZ, or in the resources dispatched, resistance to control, or values at risk. CFES2 inputs defined at the RFL level include dispatch policies, firefighting productivity and tactics, and resource response times. The NEU Ranger Unit is shown in Fig. 1.

Program modules

Five program modules control most of the simulation activity in CFES2: occurrence (Fried and Gilless 1988*b*), behavior (Gilless and Fried 1999), dispatch, fireline production rate (Fried and Gilless 1989; Gilless and Fried 2000), and containment (Fried and Fried 1996) (Fig. 2). The key parameters for these modules are generated via Monte Carlo selections (random draws) from mathematical frequency distributions generated from the historical parameters. Occurrence, behavior, and fireline production rate constitute true stochastic representations of those processes, using parameters estimated from historical data. Containment and (parts of)

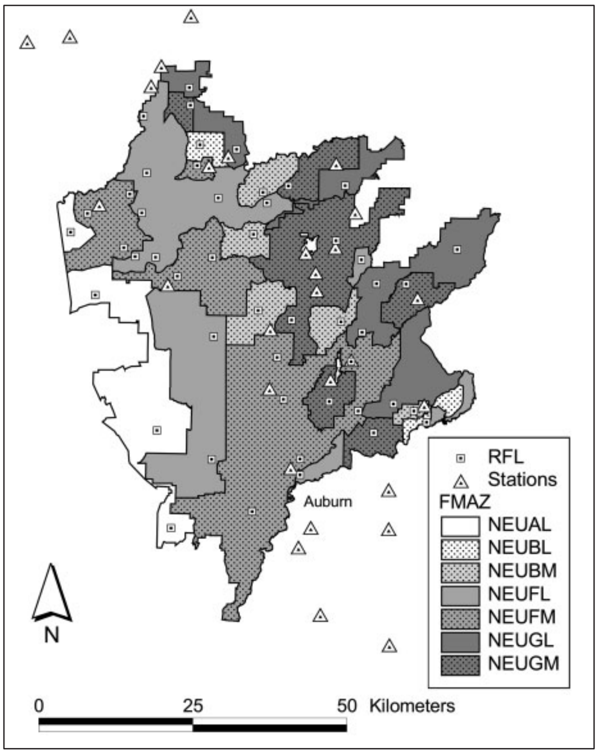

Fig. 1. Fire management analysis zones (FMAZ), representative fire locations (RFL), and stations for firefighting resources on the Nevada-Yuba-Placer (NEU) Ranger Unit. See Table 1 note for explanation of FMAZ codes.

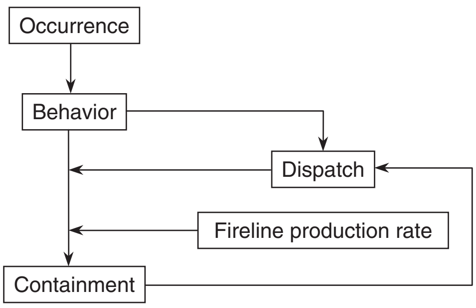

Fig. 2. California Fire Economics Simulator version 2 modules and their interactions.

dispatch are deterministic in that, while they utilize data generated by stochastic processes, the same input data will always produce the same outcome. The stochastic properties of the CFES2 program modules are a direct reflection of the CDF's desire to have a simulation model that would explicitly account for the year-to-year variability in initial attack effectiveness, in recognition that preparing an efficient organization to handle the average fire year would likely result in under-preparedness in more extreme fire years.

Simulation process

CFES2 is an event-driven, clock-based simulator. It simulates initial attack one day at a time, progressing through the calendar year. For each simulated day, the occurrence module determines if any fires take place. If no fires occur, the simulation clock advances to the next day. If one or more fires occur, the occurrence module determines how many, and the time(s) of day at which they start. The behavior module selects a 2 p.m. behavior index for the day, then generates a time-of-day adjusted ROS and dispatch index (either an ROS or burning index) for each fire.

Fires are simulated in chronological order. As each fire starts, the dispatch module identifies the closest firefighting resources of the user-specified types to dispatch, while accounting for resources previously committed to earlier fires and resources unavailable due to scheduled maintenance or staffing limitations. Resource response times are typically calculated from each firefighting resource base (e.g. a fire station) to each RFL using the speed attributes of a GIS road layer. As dispatched resources arrive at a fire, the fireline production rate module assigns a production rate to each, and the containment module evaluates the cumulative interaction of fire behavior and containment efforts. For fires that would be contained within simulation size and time limits, a final fire size is calculated, along with total mission and per acre suppression costs. Resources that have been dispatched to a fire, whether or not that fire is contained, remain unavailable for dispatch to other fires for an appropriate time interval. When all of the day's fires have been contained or declared ESL, the simulation clock is advanced to the next day and the process repeated. At the end of a year of simulated fire activity, the simulation clock is reset to 1 January, and the process is repeated until the desired number of years of fire activity has been simulated. Examining the results of many (e.g. 100) simulated years allows for statistical characterization of the natural variation in fire occurrence, fire behavior, and the effectiveness of initial attack efforts under different stationing and dispatch polices, conditions of resource availability and fuel management programs.

Simulation outputs

For each simulated fire, CFES2 generates event statistics (e.g. outcome, size, location, duration) and utilization data for every resource selected for dispatch (e.g. how and whether used, production rate, arrival time). Using a relational database, these outputs can be aggregated spatially and temporally to calculate expected values for annual area burned and number of fires by size class, mission and suppression cost, and containment success, as well as estimates of the variability that can be anticipated in these statistics.

Given the interaction of stochastic components, lengthy simulations sometimes generate a few years in which statistics like number of ESL fires or area burned in contained fires are as much as 2–10 times greater than median values. Presented in a percentile or odds table that includes extreme, mean, and median summary statistics, this information can be both understandable and useful to fire planners and their clientele. It is important to know the magnitude of the differences between mean outcomes and extreme outcomes, because any fire organization that concentrates on preparing efficiently for average fire years may be ill-prepared to handle the worse-than-average years.

Simulation results and inputs can be easily transferred to a relational database to enable analysis that addresses almost any kind of question concerning initial attack performance. Running time for the simulations described in this paper on a 1.8 GHz Pentium 4 processor-based system averaged under 2 s per realization (year) simulated. A 100-year simulation, generally sufficient for expected values of most outputs to become quite stable, can be completed in well under 2 min.

Analysis

Most CFES2 simulations are best interpreted via marginal analysis, specifically by comparing simulation outputs for the scenario of interest against the outputs from a 'base-case' (BASE) scenario designed to represent the current status of an initial attack system, regardless of whether this scenario exactly mirrors recorded history. This approach enables rapid formulation of alternative policy scenarios via modification of the BASE dataset. Comparisons to the BASE may involve a hierarchy of criteria. In descending order of importance to most fire managers in the CDF, these criteria include: the number of ESL fires per year; the area burned per year (by size class) in contained fires; and the number of fires per year (by size class). Differences in the expected number of ESL fires are typically of greater interest because there is no upper bound on the area that may be burned by an ESL fire, or on the resulting damage.

It is relatively easy to compare expected values of such annual statistics; it is almost as easy to compare values at selected percentiles of the distributions of such statistics. For example, analysts interested primarily in the effectiveness of initial attack in years with extreme fire weather or high fire incidence may choose to compare 90th or 95th percentile values.

Simulation outputs can be compared at any level in the spatial or temporal hierarchy (i.e. from an individual RFL up to the entire state, or for a time of day, a day of the week, a season of the year, or any other arbitrarily specified interval of time). Making comparisons at the ranger unit level is easier in that it means tracking fewer statistics. On the other hand, simulation results at the ranger unit level may conceal as much as they reveal when FMAZ differ significantly in conditions, practices, or objectives (e.g. in the size or time limits defining ESL fires). Comparisons can also be made using arbitrarily determined spatial/temporal aggregations of raw simulation outputs (e.g. for RFL at which a disproportionate number of ESL fires are observed, or for a particular season or day of the week when evaluating possible changes in staff schedules).

In each of the CFES2 analyses that follow, the problem that motivated the analysis is described briefly, followed by the steps undertaken to conduct the analysis, the results obtained, and the implications of these results.

Structure protection

Some fire managers and planners have speculated that the current practice of diverting first-arriving firefighting resources to protect structures threatened by wildland–urban interface fires may result in larger, more damaging fires because fireline production at the active fire perimeter is delayed or reduced. CFES2 simulations conducted with, and then without, diversion of firefighting resources to structure protection can be used to quantitatively assess the increase in initial attack effectiveness that would result from relying only on local and volunteer resources to provide structure protection, or equivalently, the cost of the current practice in terms of reduced effectiveness.

On the basis of consultations with the CDF's NEU Ranger Unit staff, current practice for the BASE for this analysis was defined as: (1) in low population density FMAZ, divert one engine to structure protection at both medium and high FDL; and (2) in moderate and high population density FMAZ, divert one engine at low FDL, and three at medium and high FDL. After running a BASE simulation of 600 replications of a single fire season reflecting these assumptions, the BASE dataset was modified such that no engines were diverted to structure protection at any FDL in any FMAZ (the no structure protection [NOSTR] scenario). A second 600-year simulation was conducted using the NOSTR dataset, and BASE and NOSTR simulation outputs were loaded into a relational database for further analysis.

Differences in the expected numbers of ESL fires between the BASE and NOSTR simulations were small, though their magnitude varied among FMAZ. For the entire NEU Ranger Unit, the expected number of ESL per year dropped from 8.27 in the BASE simulation to 6.68 in the NOSTR simulation (Table 1). For both the moderate population density, forested FMAZ (NEUGM) and the moderate population density, brush-covered FMAZ (NEUBM), the expected number of ESL fires was substantially lower in the NOSTR simulation (1.49 *v.* 2.67 for NEUGM and 2.06 *v.* 2.45 for NEUBM). Both of these changes were statistically significant ($P = 0.05$).

At the ranger unit level, the expected acres[1] burned annually by contained fires dropped from 2343 in the BASE simulation to 2016 in the NOSTR simulation (Table 2). Changes were significant ($P = 0.05$) for all FMAZ except NEUGL and NEUBL. It is beyond the scope of the data available to assess the monetary value of the expected decrease in acres burned by eliminating diversion of resources to structure protection,

[1]Metric area units are not used in this paper because the CFES version 2 simulation model was designed to have size classes and simulation limits expressed in acres to be consistent with the incident reporting system used by the California Department of Forestry and Fire Protection, and with that agency's preference for using English units in their planning documents.

Table 1. Expected values for the number of fires per year by size class, number of exceeded simulation limit (ESL) fires, total number of fires, and fire containment success for base-case (BASE) and no structure protection (NOSTR) simulations

The first three letters of a fire management analysis zone (FMAZ) code indicate a ranger unit, the fourth character indicates the FMAZ's predominant National Fire Danger Rating System fuel model (Deeming *et al.* 1977), and the last character indicates low, medium, or high population density. The size classes chosen by a ranger unit's staff to summarize simulation results reflect different protection objectives for different FMAZ. BASE values are bolded for FMAZ where the BASE and NOSTR values are significantly different ($P = 0.05$)

FMAZ	Simulation	Size class (acres)						Total	Contained (%)
		0–0.25	0.25–20	20–50	50–100	100–300	ESL		
NEUAL	BASE	4.71	**26.95**	**9.07**	4.10	**1.65**	0.23	46.70	99.50
	NOSTR	4.66	28.59	8.44	3.85	1.44	0.20	47.17	99.57
		0–0.25	0.25–3	3–20	20–50	50–100			
NEUBL	BASE	2.80	4.29	1.72	0.14	0.02	**0.02**	8.99	99.83
	NOSTR	2.79	4.21	1.71	0.14	0.02	0.00	8.85	100.00
NEUBM	BASE	**12.03**	**26.44**	**9.37**	**0.66**	**0.10**	**2.45**	51.05	95.19
	NOSTR	16.14	24.36	7.68	0.24	0.04	2.06	50.51	95.92
NEUFL	BASE	**40.75**	**23.49**	8.35	1.16	0.09	1.17	75.00	98.44
	NOSTR	43.60	20.41	8.13	0.99	0.08	1.12	74.33	98.49
NEUFM	BASE	**212.71**	**89.30**	**36.36**	**3.47**	**0.37**	0.89	343.10	99.74
	NOSTR	254.67	55.49	28.95	2.43	0.18	0.93	342.65	99.73
		0–0.25	0.25–3	3–10	10–25	25–50			
NEUGL	BASE	7.37	16.49	11.57	0.55	1.05	0.84	37.86	97.79
	NOSTR	7.54	16.79	11.24	0.56	1.09	0.88	38.10	97.68
NEUGM	BASE	**28.13**	**58.45**	**37.69**	**1.28**	**1.67**	**2.67**	129.90	97.94
	NOSTR	32.01	64.25	28.73	0.60	0.70	1.49	127.77	98.84

Table 2. Expected values for the area burned (acres) by contained fires per year by size class, total area burned by contained fires, and mean fire size for base-case (BASE) and no structure protection (NOSTR) simulations

See Table 1 note for explanations

FMAZ	Simulation	Size class (acres)					Total	Mean size
		0–0.25	0.25–20	20–50	50–100	100–300		
NEUAL	BASE	0.40	**193.20**	**288.78**	283.49	235.96	**1001.82**	**21.56**
	NOSTR	0.41	204.36	268.21	267.89	208.15	949.02	20.21
		0–0.25	0.25–3	3–20	20–50	50–100		
NEUBL	BASE	0.40	3.28	13.26	3.94	1.42	22.30	2.49
	NOSTR	0.40	3.07	12.93	3.72	1.16	21.29	2.41
NEUBM	BASE	**1.69**	**19.33**	**68.02**	**19.38**	**6.49**	**114.92**	**2.36**
	NOSTR	2.29	17.76	51.35	6.79	2.54	80.73	1.67
NEUFL	BASE	**4.95**	**16.42**	66.85	32.56	5.89	**126.66**	**1.72**
	NOSTR	5.36	15.13	64.48	28.06	5.25	118.28	1.62
NEUFM	BASE	**23.36**	**74.02**	**276.24**	**96.02**	**24.54**	**494.17**	**1.44**
	NOSTR	24.83	62.06	217.39	66.56	12.23	383.07	1.12
		0–0.25	0.25–3	3–10	10–25	25–50		
NEUGL	BASE	0.61	20.08	87.56	12.14	36.25	156.64	4.23
	NOSTR	0.63	20.37	85.73	12.34	37.52	156.58	4.21
NEUGM	BASE	**2.41**	**69.31**	**271.34**	**28.45**	**55.92**	**427.42**	**3.36**
	NOSTR	2.93	73.34	195.13	13.40	22.66	307.46	2.43

or the impact on total structure losses of the reduction in acres burned in contained fires; however, given an estimate of the per-acre or per-ESL costs of such structure losses, one could project their distribution. Alternatively, an assessment of such losses could be made post-simulation based on the projected distribution of acres burned and the numbers of escaped fires.

Selected percentile values for the expected number of acres burned each year by contained fires for one FMAZ (NEUAL) are given in Table 3. Relative to the BASE simulation, the NOSTR simulation values were consistently lower, and with the differences accentuated at the higher percentiles corresponding to extreme 5 years. Given that the number of expected ESL fires was also lower for the NOSTR simulation, such a drop in expected acres burned is unambiguous evidence of an increase in the effectiveness of initial attack.

In this example, one might suppose that eliminating the requirement to divert first-arriving resources to structure protection would reduce the response time for the first line-building resource. Exactly this result was observed when

Table 3. Acres burned at selected percentiles of the distribution of acres burned by contained fires in the NEUAL fire management analysis zone for base-case (BASE) and no structure protection (NOSTR) simulations

Percentile	BASE	NOSTR
1st	441	387
5th	585	531
10th	663	607
25th	808	739
50th	979	941
75th	1180	1120
90th	1359	1325
95th	1491	1432
99th	1732	1696

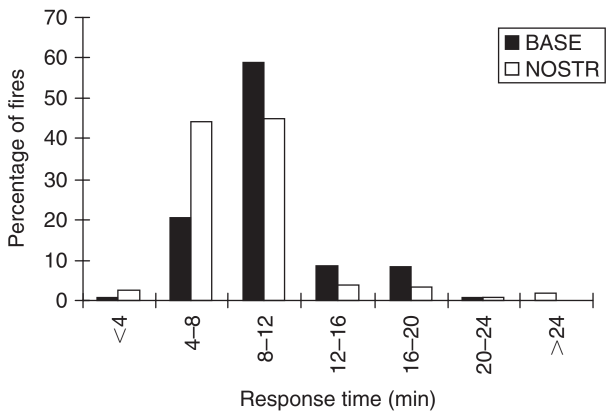

Fig. 3. Relative frequency histograms for response time of first-arriving resource, which produces fireline for the base-case (BASE) and no structure protection (NOSTR) simulations.

the simulated dispatch data was analysed to identify the first-arriving, line-building resource for each fire (Fig. 3).

Schedule B resources only

Local and volunteer firefighting resources provide valuable support to the state-funded wildland resources with primary responsibility for initial attack ('Schedule B' resources). Information on the contributions of 'non-Schedule B' resources to initial attack effectiveness is generally lacking, despite its potential value to decision makers allocating public funds or making operational decisions relating to the stationing of firefighting resources.

To analyse this issue, the BASE dataset described above was modified to create a dataset in which all non-Schedule B firefighting resources were eliminated (Schedule B only [BONLY]). A 600-year BONLY simulation was then run, and BASE and BONLY simulation outputs were loaded into a relational database for further analysis.

For the BASE and BONLY simulations, despite elimination of more than one-third of the resources (24 of 69) deployable on the ranger unit, expected containment success (percentage of fires prevented from exceeding simulation limits) remained very high (>95% in all cases) (Table 4). Some variation in the effect of eliminating these resources from initial attack was observed by FMAZ. However, with a fire load of several hundred fires each year in a given ranger unit, and given the downside risk of fatalities or large property losses, a simulated drop in initial attack effectiveness of even 1% would probably be considered significant by a fire manager.

The largest relative change in the expected number of ESL fires was projected for the low population density grassland

Table 4. Expected values for the number of fires per year by size class, number of exceeded simulation limit (ESL) fires, total number of fires, and containment success for base-case (BASE) and Schedule B only (BONLY) simulations

See Table 1 note for explanations

FMAZ	Simulation	Size class (acres)						Total	Contained (%)
		0–0.25	0.25–20	20–50	50–100	100–300	ESL		
NEUAL	BASE	4.71	**26.95**	**9.07**	**4.10**	**1.65**	**0.23**	46.70	99.50
	BONLY	4.38	23.23	10.58	5.36	2.87	0.48	46.89	98.98
		0–0.25	0.25–3	3–20	20–50	50–100			
NEUBL	BASE	2.80	4.29	1.72	0.14	0.02	0.02	8.99	99.83
	BONLY	2.93	4.21	1.72	0.17	0.04	0.02	9.08	99.78
NEUBM	BASE	**12.03**	26.44	**9.37**	**0.66**	0.10	2.45	51.05	95.19
	BONLY	10.79	26.95	9.97	0.91	0.12	2.55	51.28	95.04
NEUFL	BASE	**40.75**	23.49	8.35	1.16	0.09	**1.17**	75.00	98.44
	BONLY	39.03	24.17	8.55	1.20	0.12	1.69	74.74	97.74
NEUFM	BASE	**212.71**	**89.30**	36.36	3.47	0.37	**0.89**	343.10	99.74
	BONLY	205.48	94.36	37.44	3.68	0.40	1.12	342.47	99.67
		0–0.25	0.25–3	3–10	10–25	25–50			
NEUGL	BASE	7.37	16.49	11.57	0.55	1.05	0.84	37.86	97.79
	BONLY	7.41	16.35	11.83	0.57	1.07	0.88	38.12	97.68
NEUGM	BASE	**28.13**	58.45	37.69	1.28	**1.67**	**2.67**	129.90	97.94
	BONLY	26.72	57.94	37.30	1.34	1.93	3.00	128.23	97.66

Table 5. Expected values of the area burned (acres) by contained fires per year by size class, total area burned by contained fires, and mean fire size for base-case (BASE) and Schedule B only (BONLY) simulations
See Table 1 note for explanations

FMAZ	Simulation	Size class (acres)					Total	Mean size
		0–0.25	0.25–20	20–50	50–100	100–300		
NEUAL	BASE	0.40	**193.20**	**288.78**	**283.49**	**235.96**	**1001.82**	**21.56**
	BONLY	0.38	170.35	343.45	372.43	447.41	1334.02	28.74
		0–0.25	0.25–3	3–20	20–50	50–100		
NEUBL	BASE	0.40	3.28	13.26	3.94	1.42	22.30	2.49
	BONLY	0.42	3.11	13.69	4.69	2.85	24.75	2.73
NEUBM	BASE	**1.69**	**19.33**	**68.02**	**19.38**	6.49	**114.92**	**2.36**
	BONLY	1.51	20.23	76.32	26.51	7.85	132.41	2.72
NEUFL	BASE	**4.95**	16.42	66.85	32.56	5.89	126.66	1.72
	BONLY	4.79	16.28	69.65	33.85	7.55	132.12	1.81
NEUFM	BASE	23.36	74.02	276.24	96.02	24.54	**494.17**	**1.44**
	BONLY	23.20	76.04	284.57	101.94	27.11	512.87	1.50
		0–0.25	0.25–3	3–10	10–25	25–50		
NEUGL	BASE	0.61	20.08	87.56	12.14	36.25	156.64	4.23
	BONLY	0.62	20.02	89.97	12.70	36.76	160.07	4.30
NEUGM	BASE	**2.41**	69.31	271.34	28.45	**55.92**	**427.42**	**3.36**
	BONLY	2.23	69.71	270.77	29.79	65.07	437.57	3.49

FMAZ (NEUAL). With the non-Schedule B resources available in the BASE simulation, 0.23 ESL fires would be expected per year in this FMAZ (i.e. an ESL fire would be expected about once in 5 years). Without the non-Schedule B resources, however, the expected number of ESL fires per year increased to 0.48 (i.e. an ESL fire would be expected about once every 2 years). A smaller increase in expected ESL fires was observed for the medium population density, brush FMAZ (NEUFM): from 0.89 to 1.12 per year. Although this absolute increase in expected ESLs fires is smaller, fire planners might find it of greater concern because of the higher population density in NEUFM.

Most of the increase in expected area burned by contained fires projected to result from eliminating non-Schedule B resources occurs in the low population density, grassland FMAZ (NEUAL) (Table 5). Whether or not this would pose a serious problem would depend on the fire management objectives for that FMAZ. The increased area burned due to the FMAZ's higher number of expected ESL fires might well exceed the projected 333 acres increase in acres burned by contained fires. Furthermore, grassland acres that burn in contained fires might be less likely to entail significant property damage.

Histograms of the sort shown in Fig. 4 provide an alternative way to visualize the expected values and distributional characteristics of the projected numbers of ESL fires for different scenarios. This figure clearly shows how the projected distribution of ESL fires shifts to the right without the contributions of non-Schedule B resources, and to the left without the diversion of resources to structure protection.

These simulation results suggest that, while non-Schedule B resources contribute to initial attack effectiveness in the NEUAL and NEUGM FMAZ, they have little impact elsewhere in the NEU Ranger Unit. However, the elimination of these resources could increase the frequency with which the Schedule B resources are dispatched, possibly resulting in higher overtime costs, or reducing opportunities to deploy Schedule B resources for other fire management activities such as prescribed burning.

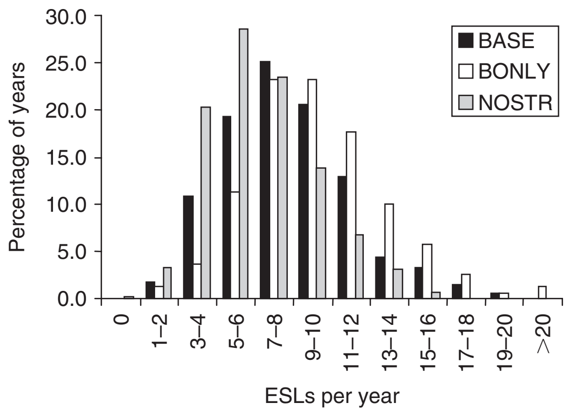

Fig. 4. Relative frequency histograms of number of exceeded simulation limit (ESL) fires per year on the Nevada-Yuba-Placer Ranger Unit, for the base-case (BASE), Schedule B only (BONLY) simulation, and the no structure protection (NOSTR) simulation.

Multiple fires

One of the reasons for commissioning CFES2 was interest on the part of fire protection planners in being able to explicitly address the impacts of multiple fire starts on the availability of firefighting resources for dispatch. It is widely believed that such draw-down situations account for many of the cases in which fires escape initial attack. The relatively short period for which historical fire data are generally available for most

Table 6. Mean multiplicity for all fires by fire management analysis zone (FMAZ) and containment outcome, for the historical period 1986–1994 and the base-case (BASE) simulation

See Table 1 note for explanation of FMAZ codes. Dashes indicate no exceeded simulation limit (ESL) fires predicted

FMAZ	1986–1994		BASE	
	ESL	Contained	ESL	Contained
NEUAL	2.5	3.7	6.3	4.4
NEUBL	–	3.2	6.5	4.6
NEUBM	–	3.3	–	4.6
NEUFL	3.1	3.7	–	4.4
NEUFM	4.0	3.7	7.8	4.5
NEUGL	–	4.6	6.6	4.5
NEUGM	5.7	3.7	6.7	4.5

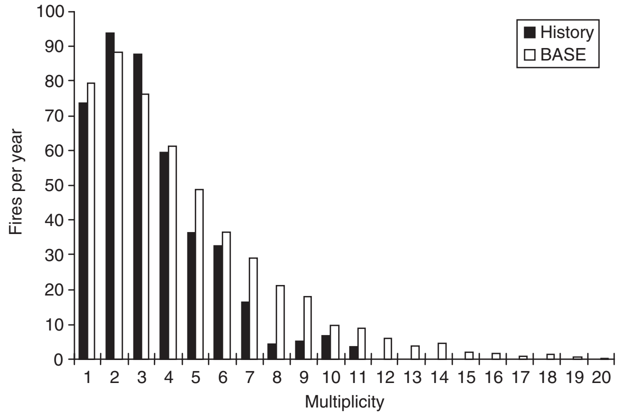

Fig. 5. Multiplicity for all fires in the historical period 1986–1994 and the base-case (BASE) simulation.

ranger units makes it very difficult to reach definitive conclusions about this hypothesis using conventional statistical analysis, as Allen *et al*. (1987) clearly demonstrated using California datasets very similar to those available for this study.

An event-based simulation model like CFES2, however, can provide valuable insight into the problem, by virtue of outputs that include start times, containment times, and containment outcomes – the fundamental statistics needed for a quantitative analysis of the problem. A simple indicator of the extent to which a multiple fire situation may affect the outcome of any given fire is the total number of fires occurring on the same day. Referred to elsewhere in the fire literature as 'multiplicity', this value figures prominently in CFES2's occurrence module (Fried and Gilless 1988*b*).

Although a clear relationship between ESL fires and high multiplicity is not apparent in the available historical records for the Nevada-Yuba-Placer Range Unit (1986–1994), such a relationship is observable in the simulation outputs from the BASE simulation (Table 6). The validity of this inference is supported by the similarity of the historical and simulated multiplicity values for the NEU Ranger Unit (Fig. 5). As expected, the simulation results closely track the historical values up to multiplicity = 11, but also include some fires on days with greater multiplicity, as would likely be observed in a historical record that was longer than the 9 years available in this case.

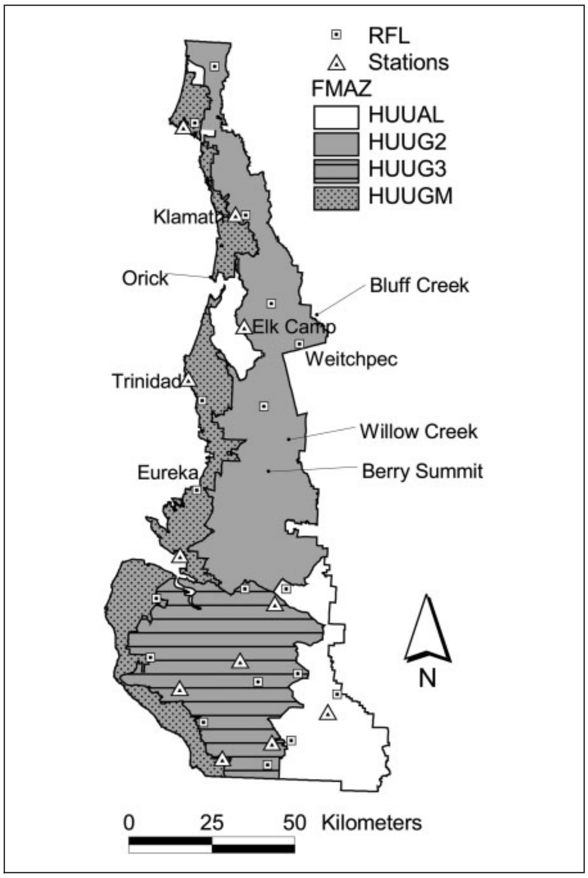

Fig. 6. Fire management analysis zones (FMAZ), stations and alternative station locations for firefighting resources on the Humboldt-Del Norte (HUU) Ranger Unit. See Table 1 note for explanation of FMAZ codes.

Station relocation

Given that the locations of CDF's fire stations have remained largely unchanged for several decades, despite substantial changes in the distribution of values at risk, it is not surprising that CDF managers are increasingly interested in exploring alternative spatial deployments of firefighting resources. Using CFES2, they have found it possible to model and compare relatively complex alternatives, though the most common approach is a marginal analysis in which simulations from a BASE dataset are compared with those from scenario datasets in which a single resource is relocated.

Weitchpec was an area of special concern to managers of CDF's HUU (Fig. 6). Half of the fire ignitions in HUU's

Table 7. Scenario descriptions for station relocation simulation scenarios

Scenario	Dispatch assumptions
BASE	Current resource list and dispatching policies
Orick	Baseline, but move Elk Camp Engine to Orick
Bluff Creek	Baseline, but move Elk Camp Engine to Bluff Creek
Willow Creek	Baseline, but move Elk Camp Engine to Willow Creek
Berry Summit	Baseline, but move Elk Camp Engine to Berry Summit
No Elk Camp	Baseline, but close Elk Camp Station

Table 8. Expected values for the number of exceeded simulation limit fires in the low population density conifer fire management analysis zone (HUUG2) and its Weitchpec representative fire location (RFL) on the Humboldt-Del Norte Ranger Unit for relocation simulation scenarios

Scenario	HUUG2	Weitchpec RFL
BASE	1.8	1.4
Orick	1.9	1.4
Bluff Creek	1.3	0.9
Willow Creek	1.4	1.1
Berry Summit	1.6	1.2
No Elk Camp	1.9	1.5

low population density conifer FMAZ (HUUG2) are in the Weitchpec area, and 2% of the fires there exceed the containment objective of 50 acres. Because the closest CDF engine (Elk Camp) has a response time of 75 min, managers sought to assess the benefits of relocating this station and its engine to one of four alternative locations (Table 7). They were also willing to investigate a fifth scenario, for purposes of comparisons, in which the Elk Camp station was simply closed without redeploying its fire engine locally. A BASE dataset for HUU was prepared, and scenario datasets corresponding to different relocation sites were generated from this dataset by modifying the response times for the Elk Camp engine to different RFL. Six-hundred-year simulations were then run using each dataset.

Simulation results indicate that ESL frequencies might be reduced by relocating the station to Bluff Creek, Willow Creek, or possibly Berry Summit (Table 8), without reducing initial attack success elsewhere in the HUUG2 FMAZ. The reduction in ESL frequency was greatest for the Bluff Creek option, for which CFES2 projected a one-third reduction in ESL fires at the Weitchpec RFL without any offsetting increase elsewhere in the FMAZ. This result was statistically significant ($P = 0.05$). While CFES2 projected a small increase in ESL fires for the FMAZ for both the Orick and No Elk Camp options, these changes were not statistically significant.

Discussion and conclusions

Complex simulation models can be used to support operational decision-making in wildland fire protection by facilitating quantitative analysis of the potential effects of changes in the availability and stationing of resources, dispatch rules, criteria for setting fire dispatch level, staff schedules, and deployment and line-building tactics. These can also be used to support strategic planning with respect to vegetation management programs, development at the wildland–urban interface, reallocation of responsibilities among fire protection agencies, and climatic change. The analytic scope and flexibility of a CFES2-type decision support system, however, comes at the cost of a considerable investment in data acquisition and management. A significant proportion of this investment is associated with developing a BASE dataset that produces simulation results that are reasonably consistent with historical statistics for fire occurrence, behavior, and containment success. Once the BASE dataset has been developed, analyses like those reported in this paper can be completed in several hours to a few days. In most cases, communication of the results of such analyses has generally been most successful by comparisons to the BASE, rather than to actual historical statistics.

The CDF has now been utilizing CFES2 as a planning framework for several years. Model documentation is extensive, both in help screens accessible when running the software, and in an exhaustive user's guide documenting input and output file conventions (Fried and Gilless 1999). The model is complex but, with the support of staff at the CDF's Sacramento headquarters, analysts at the ranger unit level are capable of conducting analyses relatively independently. With minor reprogramming, the CFES2 model could be used to perform simultaneous multi-ranger unit simulations, but the single ranger unit level of spatial resolution has proven satisfactory for all of the analyses performed thus far. Although the model has been designed to reflect a variety of nuances of the CDF's physical and institutional environment (e.g. ranger units or the availability of volunteer firefighting resources), the way in which nuances are treated is not integral to the model's logic or data structure, and could be dispensed with by other fire protection organizations that faced less complex planning environments.

The simulation findings reported in the analyses presented in this paper are typical in that they demonstrate that, in a well-managed agency, marginal changes to the availability of firefighting resources produce no dramatic changes in outcomes. Though rarely popular among agency managers, such findings highlight the need to put simulation results from a model of initial attack into a wider context – one in which the resources allocated to a wildland fire protection organization must also reflect the need to meet demands for auxiliary responsibilities such as emergency medical assistance, structure fire protection, prescribed fire, and maintaining the capacity to deal with catastrophic fire events that are only partially accounted for in the CFES2 model by its endogenous treatment of multiplicity. Findings of modest changes in the expected values of outcomes, in fact, can serve to increase the credibility of an agency's analysis of its own effectiveness and efficiency. The stochastic simulation approach has the additional benefit of providing information on the range and probabilities of different outcomes that deterministic examination of 'most-likely' cases cannot.

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