STOCHASTIC REPRESENTATION OF FIRE BEHAVIOR IN A WILDLAND FIRE PROTECTION PLANNING MODEL FOR CALIFORNIA

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ABSTRACT

A fire behavior module was developed for the California Fire Economics Simulator version 2 (CFES2), a stochastic simulation model of initial attack on wildland fire used by the California Department of Forestry and Fire Protection. Fire rate of spread (ROS) and fire dispatch level (FDL) for simulated fires "occurring" on the same day are determined by making coordinated draws from compound distributions characterizing 2 PM fire behavior indexes such as ROS, then adjusting these draws using diurnal adjustment coefficients derived from hourly fire weather observations. Statistical examination of historical fire occurrence and predicted behavior data provide general validation for CFES2's use of independent fire occurrence and fire behavior modeling processes.

KEYWORDS

CFES2, CFES-IAM, initial attack, fire rate of spread, burning index, fire dispatch level

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INTRODUCTION

Simulation models of initial attack on wildland fire are important tools for wildland fire protection planning, and several new models are currently being developed (Fried and Gilless 1997, Hirsch 1997, Julio et al. 1997, Rodriguez y Silva 1997, Shur 1995, USDA Forest Service 1985). Sensitivity analysis indicates that these models will be particularly sensitive to the methods and parameters used to characterize fire behavior (Dimitrakopoulos 1985).

The fire behavior component of a simulation model of initial attack on wildland fire usually determines, for each simulated fire: (1) fire rate of spread (ROS); and (2) fire dispatch level (FDL) [or fire intensity level]. ROS is particularly important in models that explicitly track the perimeter growth of simulated fires during initial attack. FDL, which is usually determined by reference to some index of fire behavior (e.g., ROS, burning index (BI), flame length, energy release component), plays a role in the selection of firefighting resources to be dispatched and in the specification of firefighting tactics (e.g., head or tail attack).

Simulation models of initial attack usually determine ROS by either: (1) simulating each fire that occurred in some “historical season”; or (2) simulating a limited number of “representative fires” at specific percentile values (e.g., 50th and 90th) from the ROS distribution defined by reference to the fires that occurred in one or more prior fire seasons. Either approach requires that a database of historical fires be queried to identify the date, time, and appropriate fuel model for the fires that occurred in a given protection area. These data must then be matched with predicted 2 PM fire behavior indices (ROS, BI, etc.) for the corresponding dates and fuel models, possibly adjusting the index values for the time of day at which fires occurred. A FDL is then determined for each fire by comparing one of these indexes with previously established thresholds. Selected percentile values (e.g., 50th and 90th) for ROS can then be determined, by FDL, for representative fire simulations.

Both the historical season and representative fire approaches have serious limitations for representing the stochastic processes underlying fire occurrence and behavior. Simulating sequences of historical fires may mask or overstate localized problems in the fire protection system. Limited historical records are likely to understate or overstate the relative frequency of days on which very high numbers of fires occur, and to increase the error associated with estimates of non-robust statistics such as the 90th percentile values. Both methods, by using fires rather than days as the basis for an observation, employ a sampling frame that may be problematic in areas where the fire load is largely the result of human activity rather than natural causes. A particularly subtle problem with using fires rather than days as the basis for an observation is that gaps in fire weather data most frequently occur at the onset of a period of significant fire activity because the firefighters responsible for gathering data have been reassigned to other duties (Bunton 1997).

A particularly severe limitation of the representative fire method is the assumption that results from simulating initial attack on fires at an "average" ROS (i.e., 50th percentile value) can be extrapolated to characterize the results of initial attack over a wide range of ROS values.

CALIFORNIA FIRE ECONOMICS SIMULATOR VERSION 2

The California Fire Economics Simulator version 2 (CFES2) is a clock-driven, event-based, quasi-spatial stochastic simulator of initial attack on wildland fires. CFES2 was developed to assist wildland fire protection planning by the California Department of Forestry and Fire Protection (CDF) (Fried and Gilless 1997). The design and validation of CFES2's stochastic modules for fire containment (Fried and Fried 1996), fireline production rates (Fried and Gilless 1989), and fire occurrence (Fried and Gilless 1988a) have been previously reported in this journal. This paper describes the design and validation of CFES2's fire behavior module.

The design objectives for CFES2's fire behavior module were to: (1) fully utilize historical fire occurrence and behavior data; (2) allow for fire behavior indexes other than ROS to be used to determine FDL; (3) base fire simulations on the full potential distribution ROS; and (4) ensure consistent fire behavior for all fires that "occur" on the same day.

These design objectives highlight the importance of the linkages between the representation of fire behavior and fire occurrence in a stochastic simulation model of initial attack. CFES2's occurrence module was designed to generate stochastic sequences of fire ignitions in time and space that would mimic historically observed patterns, primarily because of the CDF's need for a model that was capable of realistic simulation of the consequences of multiple fires occurring on the same day within a ranger unit. Evaluation of the degree to which the design objectives for CFES2's fire behavior module were met therefore necessarily involves evaluation of its interactions with the fire occurrence module.

DATA

Parameterization of CFES2's fire behavior module draws on three data sources: (1) fire history databases for CDF ranger units; (2) 2 PM fire weather observations from AFFIRMS weather stations (Helfman et al. 1980); and (3) hourly fire weather observations from Remote Automated Weather Stations (RAWS) (Warren and Vance 1981) (Table 1). Data from the Santa Clara, Riverside, and Nevada-Yuba-Placer ranger units were analyzed for this paper (Figure 1). These ranger units span a wide range of vegetation types, topographic conditions, climatic conditions, and values at risk. Because of the similarity of the results of this analysis for the three ranger units, only results from the Santa Clara ranger unit are presented below. [Validation results for the other ranger units can be viewed at www.for.msu.edu/~jeremy/research/behavior/] Fire management analysis zones (FMAZs) and AFFIRMS and RAWS weather stations for the Santa Clara ranger unit are shown in Figure 2.

Daily observations from AFFIRMS weather stations were processed with FBDMOD (CDF 1991), a PC version of FIRDAT (Main et al. 1990, Andrews and Chase 1989, Andrews 1986, and Burgan and Rothermal 1984), for all NFDRS fuel models (Cohen and Deeming 1985, Burgan 1988) designated by ranger unit staff as descriptive of their FMAZs. For each ranger unit, this process generated a database of fuel model-specific, 2 PM fire behavior indexes.

The merged databases were queried to generate two variables characterizing fire occurrence: (1) Fireday (equal to 1 for days on which fires occurred, and equal to 0 otherwise); and (2) Multiplicity (equal to the number of fires that occurred on the ranger unit on a given day). The frequency distribution for Multiplicity for the Santa Clara ranger unit is shown in Figure 3. As noted in Fried and Gilless (1988a), Multiplicity for days on which Fireday = 1 (i.e., for days on which a fire occurs) is well characterized by a geometric distribution.

Hourly observations from RAWS weather stations were processed with the HISTROS program (CDF 1991) for the same NFDRS fuel models for each ranger unit to produce databases of hourly fire behavior indexes for use in characterizing diurnal variation in fire behavior.

2 PM ROS AND BI DISTRIBUTIONS

The distributions of 2 PM ROS and BI values were consistently bimodal, for all fuel models, for all ranger units (Figures 4a and 5a). Each distribution had one peak corresponding to days with low ROS (or BI), and another corresponding to days with high ROS (or BI).

CFES2's fire behavior module therefore characterizes 2 PM ROS (or BI) using a compound distribution. Low values are described by two parameters: (1) the probability of 2 PM fire behavior being "drawn" from this portion of the distribution; and (2) a constant ROS (or BI) value to describe the behavior of such fires. High values are described by: (1) α and β parameters of a beta distribution; and (2) minimum and maximum ROS (or BI) values (Figures 4b and 5b). Distributions are separately estimated for low, transition, and high fire seasons defined for each ranger unit.

ROS AND FDL BEHAVIOR LINKS

For each FMAZ in a ranger unit, CFES2 uses one behavior link to determine a fire's FDL and one to determine its ROS – a behavior link being defined by a weather station, a fuel model, a slope class, a climate class, and a type of herbaceous vegetation. The FDL and ROS behavior links might be the same for a given FMAZ if FDL is based upon ROS. However, many CDF ranger units currently base FDL on BI or some other index of fire behavior, so CFES2 was designed to allow for flexibility in this regard. Whatever index is used for setting FDL, the thresholds between low and medium and between medium and high FDL must be specified for each FMAZ.

COORDINATED FIRE BEHAVIOR

CFES2's fire behavior module employs a coordinated fire behavior modeling process to ensure consistency in the behavior of fires that occur on the same day: (1) a single random draw is made for the day from a uniform random distribution between 0 and 100; (2) the percentile position thus determined is used to select 2 PM values from all of the ROS (or BI) distributions that must be sampled to determine ROS and FDL for the fires occurring on that day; and (3) these 2 PM values are adjusted for the time of day at which each fire occurs.

DIURNAL ADJUSTMENT COEFFICIENTS

CFES2's fire occurrence module assigns start times to simulated fires based upon random draws from beta or Poisson distributions for time of day. For the fire behavior module, diurnal adjustment coefficients for 2PM ROS (or BI) values were derived by: (1) taking hourly fire behavior index values estimated from

RAWS data; (2) dividing each value by the value at 2 PM for the same index; and then (3) determining the median ratio for each index, for each hour of the day. Diurnal adjustment coefficients for one ROS and one BI distribution for the Santa Clara ranger unit are shown in Table 2. Note that the 2PM coefficient for any set of diurnal adjustment coefficients is always equal to one.

VALIDATION

For all three ranger units, Tukey HSD plots of 2 PM ROS (and BI) percentile values for days on which fires did (Fireday = 1) and did not (Fireday = 0) occur, by fuel model, provided only weak support for complete independence between fire occurrence and fire behavior, with ROS clearly being drawn from a distribution of higher values for days on which fires occurred (Figure 6). However, the magnitude of the difference in mean percentile values was generally no more than ten points. Considering only days on which fires had occurred, 2 PM ROS (and BI) percentile values were unaffected by Multiplicity (Figure 7).

To evaluate CFES2's method of coordinating fire behavior by using a draw from a uniform random distribution between 0 and 100 to generate a percentile on which to base all draws from 2 PM ROS (or BI) distributions, Pearson correlation coefficients were calculated between the percentile ROS and BI values, across

NFDRS fuel models. For all three ranger units, these correlations were generally very high and significant, lying between 0.7 and 1.0 (Table 3).

SUMMARY AND CONCLUSIONS

It was clear from the beginning of CFES2's development that independence of the fire occurrence and fire behavior modules would dramatically reduce the difficulty of parameterizing the model. The failure of others to validate the relationship between fire danger rating and fire load (Haines et al. 1983) encouraged us to pursue such a strategy, although independence was never actually made a design objective. The results presented in this paper generally confirm the legitimacy of an assumption that fire occurrence and fire behavior can be modeled independently, although they do suggest that the distributions for fire behavior indexes be estimated using data only from days on which fires did occur.

However legitimate the assumption of independence between fire occurrence and fire behavior, assuming independence in fire behavior for fires that occur on the same day is clearly inappropriate. This could produce contemporaneous fires in the same FMAZ with wildly different ROS values. Modeling fire behavior for fires occurring on the same day is further complicated by the use of a fire behavior index other than ROS to determine FDL. Predictions of these indexes are often based an NFDRS fuel different from the one used to predict fire behavior. CFES2 solves this problem by allowing flexibility in the specification of fire behavior links to determine ROS and FDL, but using a random draw from a uniform random distribution to coordinate the values drawn from different fire behavior distributions for a given day.

For the CDF ranger units considered in this study, AFFIRMS fire weather data was available for two or three decades, while RAWS fire weather data was available for less than two years. Utilizing AFFIRMS data to estimate 2 PM ROS (or BI) distributions, and utilizing RAWS data to estimate diurnal adjustment coefficients for values drawn from these distributions, represents a practical and efficient approach to characterizing fire behavior for simulation models. As additional RAWS data is archived, it might be possible to use RAWS data to directly estimate time-of-day specific distributions for fire behavior indexes.

Additional research is needed to modify the procedure for diurnal adjustment of fire behavior to account for special events (e.g., Santa Ana winds in Southern California) where unusual diurnal patterns in fire behavior are observed. CFES2 was actually designed in anticipation of such research, and is coded to allow for probabilistic utilization of two sets of diurnal adjustment coefficients corresponding to “normal” or “special” conditions.

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Table 1. Historical fire and weather data for the Santa Clara ranger unit.

Period of fire history coverage	1986-1994
Mean number of fires per year	557
Mean number of days per year with one or more fires	207
Mean acres burned per year	5263
AFFIRMS station name	Morgan Hill
AFFIRMS station identifier	43903
AFFIRMS station location	37.10N 121.70W
AFFIRMS station elevation (feet)	320
NFDRS fuel models used	A, B, F, G
RAWS station name	Livermore
Years of RAWS data	< 2

Table 2. Diurnal adjustment coefficients for 2 PM ROS and BI values calculated using Livermore RAWS data, fuel model A, slope class 2, high fire season.

AM Hour	ROS	BI	PM Hour	ROS	BI
12	0.06	0.08	12	0.78	0.81
1	0.05	0.06	1	0.94	0.95
2	0.05	0.06	2	1.00	1.00
3	0.04	0.06	3	0.95	0.95
4	0.05	0.06	4	0.84	0.83
5	0.04	0.06	5	0.67	0.62
6	0.04	0.05	6	0.43	0.40
7	0.04	0.05	7	0.22	0.22
8	0.06	0.07	8	0.13	0.14
9	0.17	0.21	9	0.08	0.10
10	0.34	0.37	10	0.06	0.08
11	0.58	0.60	11	0.06	0.07

Table 3. Pearson correlations between 2 PM ROS and BI percentile values for different NFDRS fuel models, for the high fire season, for the Santa Clara ranger unit (n = 858).

	ROS Model B	ROS Model F	ROS Model G	BI Model A	BI Model B	BI Model F	BI Model G
ROS Model A	0.81	0.81	0.86	0.94	0.73	0.74	0.89
ROS Model B		0.98	0.97	0.70	0.89	0.90	0.93
ROS Model F			0.97	0.69	0.87	0.89	0.93
ROS Model G				0.77	0.88	0.89	0.96
BI Model A					0.73	0.74	0.86
BI Model B						0.99	0.91
BI Model F							0.93

FIGURE CAPTIONS

Figure 1. Nevada-Yuba-Placer (NEU), Santa Clara (SCU), and Riverside (RRU) ranger units.

Figure 2. FMAZs, AFFIRMS and RAWS weather stations for the Santa Clara ranger unit.

Figure 3. Multiplicity history for the Santa Clara ranger unit, transition and high fire seasons, 1980-1988.

Figure 4. BI calculated using data from AFFIRMS weather station 43903, fuel model A, slope class 2, high fire season: (a) frequency histogram, with dashed vertical line defining ranges modeled with Bernoulli (left) and beta (right) distributions; (b) beta range frequency histogram and fitted beta distribution, with BI values scaled to the interval between zero and one.

Figure 5. ROS calculated using data from the AFFIRMS weather station 43903, fuel model A, slope class 2, high fire season: (a) frequency histogram, with dashed vertical line defining ranges modeled with Bernoulli (left) and beta (right) distributions; (b) beta range frequency histogram and fitted beta distribution, with ROS values scaled to the interval between zero and one.

Figure 6. Means and 95.0 percent Tukey HSD intervals for ROS percentile values by Fireday, by NFDRS fuel model, for the Santa Clara ranger unit.

Figure 7. Means and 95.0 percent Tukey HSD intervals for ROS percentile values by Multiplicity, by NFDRS fuel model, for the Santa Clara ranger unit

Figure 1

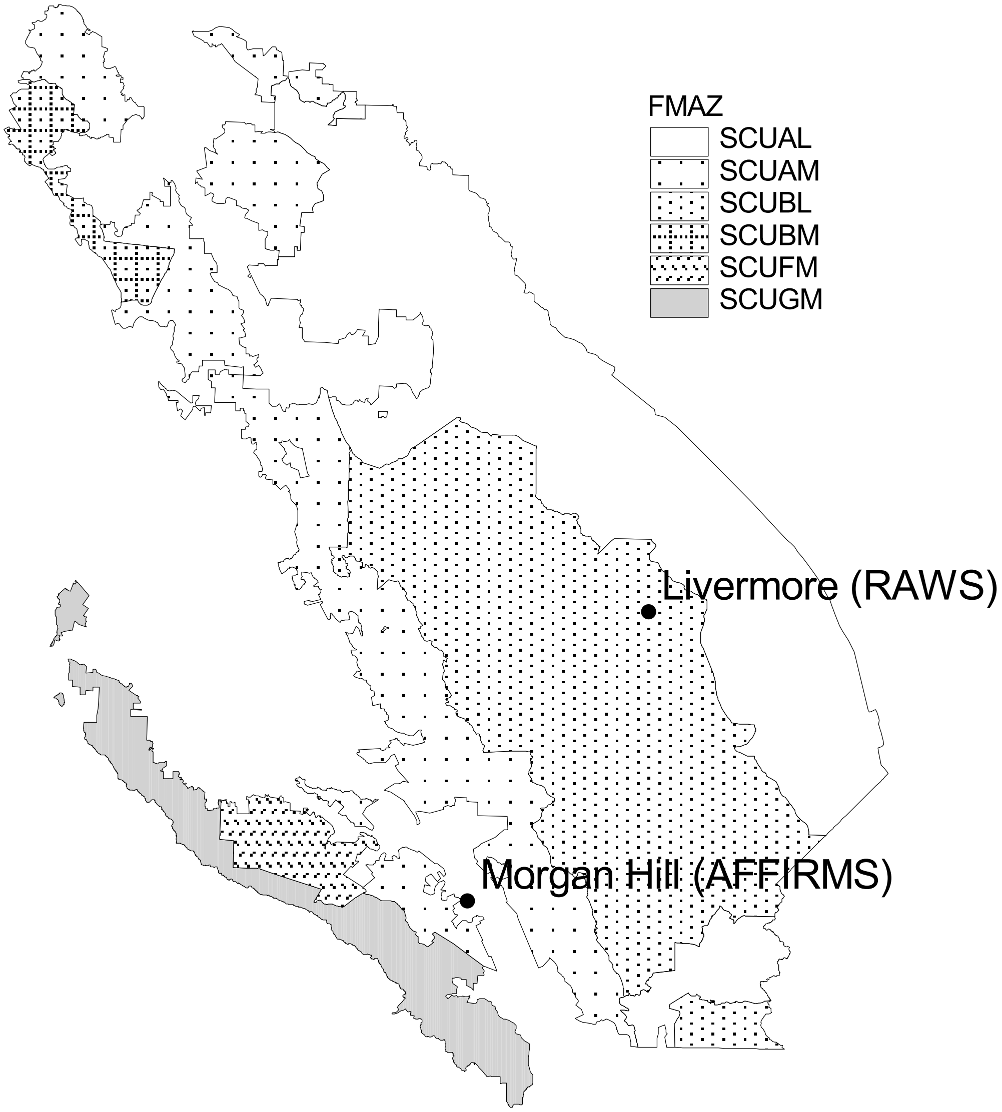

FMAZ
SCUAL
SCUAM
SCUBL
SCUBM
SCUFM
SCUGM
Livermore (RAWS)
Morgan Hill (AFFIRMS)

Figure 2

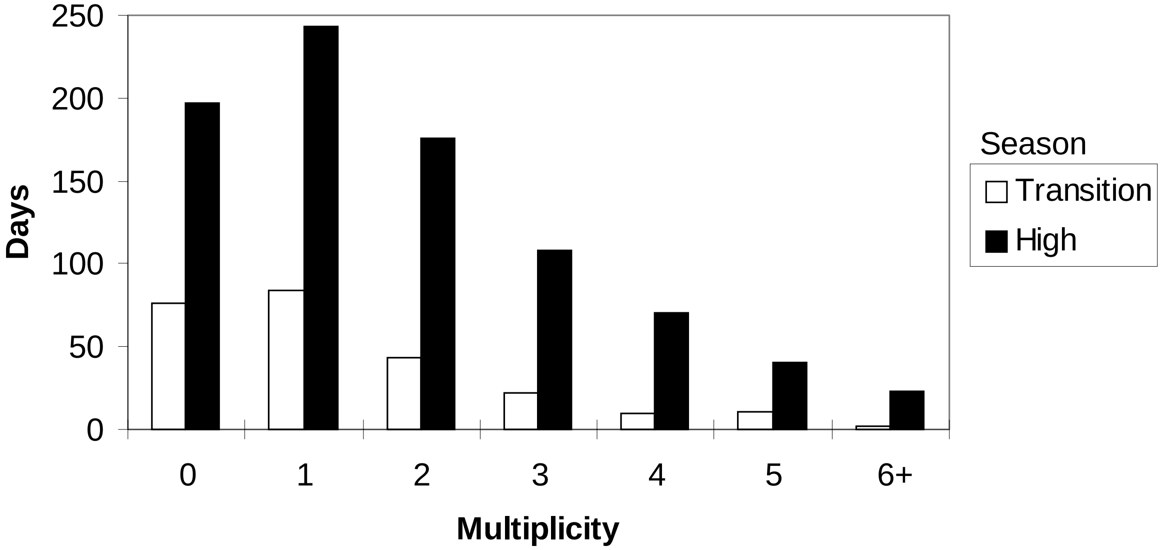

250
200
150
100
50
0
Days
0
1
2
3
4
5
6+
Multiplicity
Season
□ Transition
■ High

Figure 3

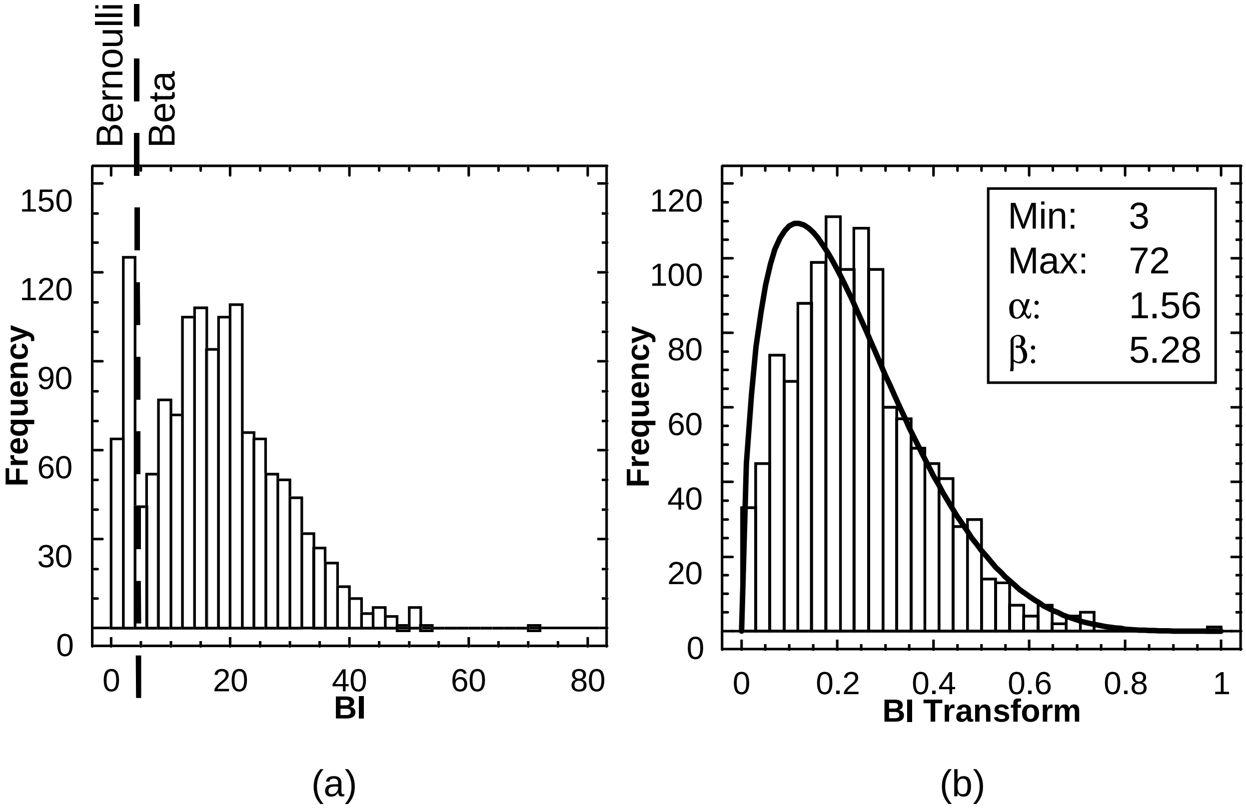

Bernoulli
Beta
Frequency
150
120
90
60
30
0
0
20
40
60
80
BI
(a)
Frequency
120
100
80
60
40
20
0
0
0.2
0.4
0.6
0.8
1
BI Transform
Min: 3
Max: 72
α: 1.56
β: 5.28
(b)

Figure 4

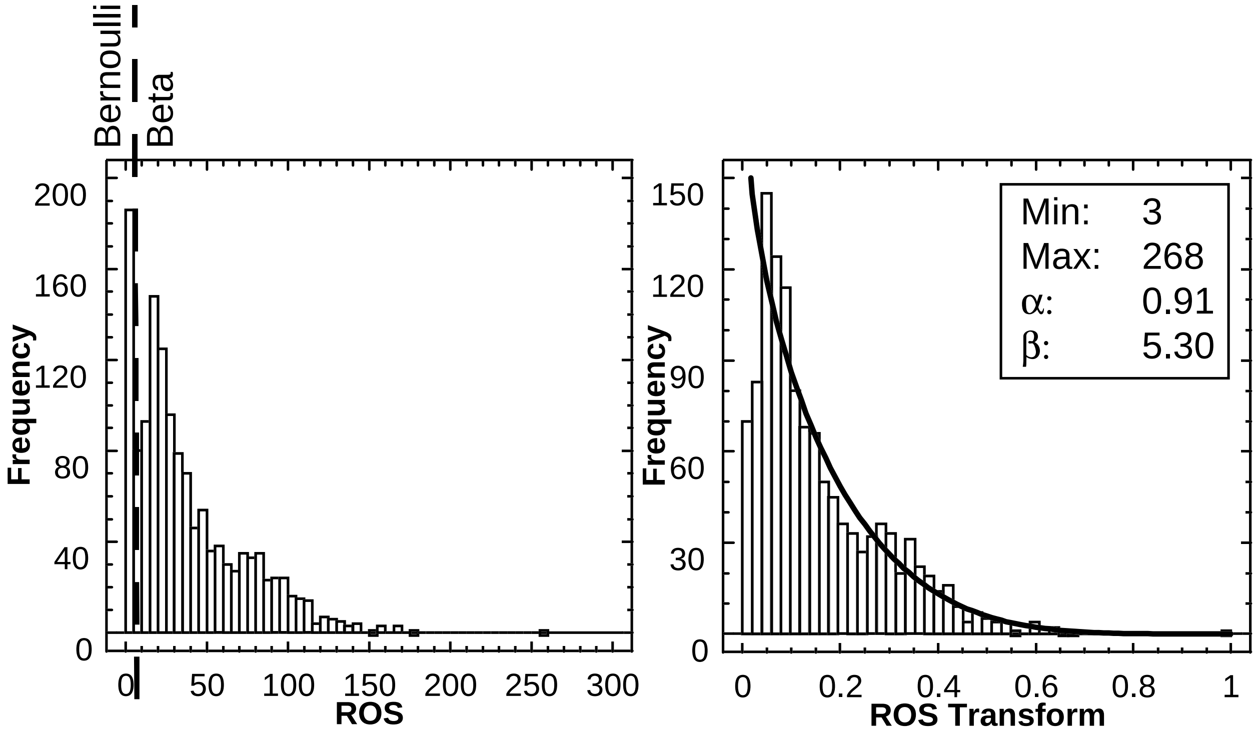
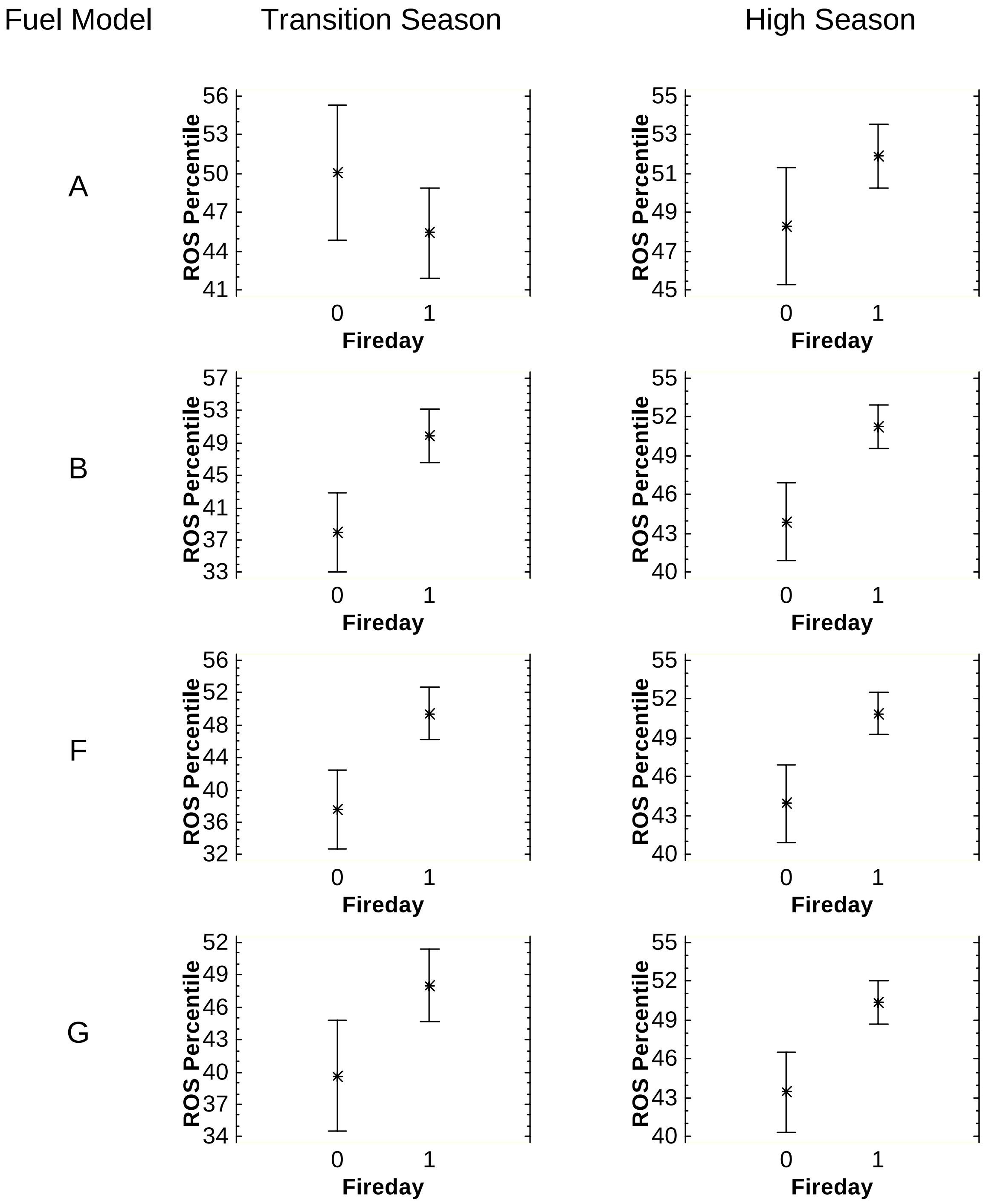

Bernoulli
Beta
Frequency
200
160
120
80
40
0
0
50
100
150
200
250
300
ROS
Min: 3
Max: 268
α: 0.91
β: 5.30
Frequency
150
120
90
60
30
0
0
0.2
0.4
0.6
0.8
1
ROS Transform

Figure 5


Fuel Model
Transition Season
High Season
A
B
F
G
ROS Percentile
Fireday
0
1
56
53
50
47
44
41
55
53
51
49
47
45
57
53
49
45
41
37
33
55
52
49
46
43
40
56
52
48
44
40
36
32
55
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37
34
55
52
49
46
43
40

Figure 6

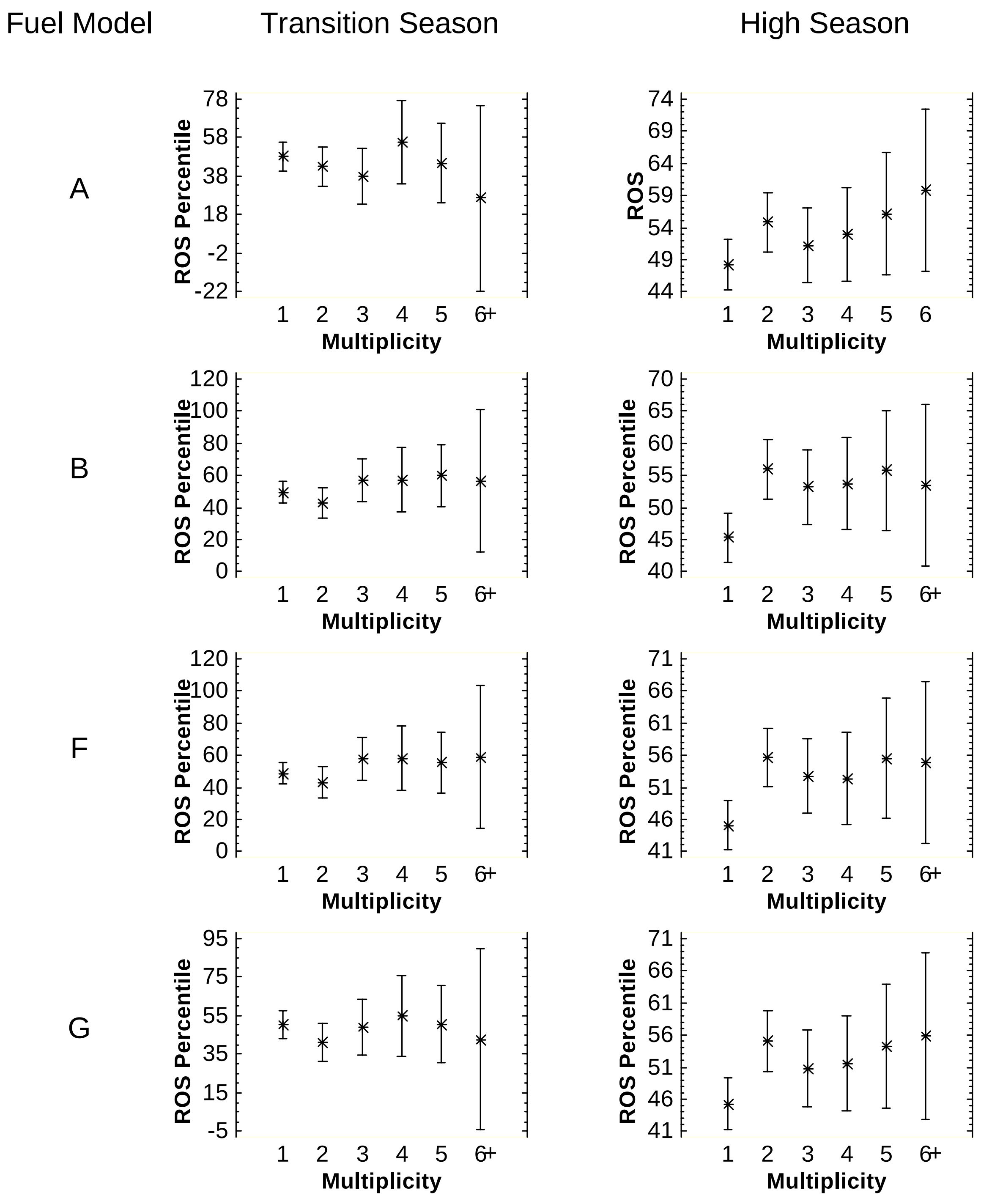
Fuel Model
Transition Season
High Season
A
B
F
G
ROS Percentile
ROS
Multiplicity
1
2
3
4
5
6+
6
78
58
38
18
-2
-22
74
69
64
59
54
49
44
120
100
80
60
40
20
0
70
65
60
55
50
45
40
71
66
61
56
51
46
41
95
75
55
35
15
-5

Figure 7

NOTES

Used cfes2research option on fbdmod.exe to generate ASCII output file.

Data files …

Season definitions, by ranger unit.

CDF ranger unit	Low to transition	Transition to high	High to transition	Transition to low
NEU	May 15	June 15	October 15	November 15
RRU	April 15	June 1	October 31	December 15
SCU	May 15	June 15	October 15	November 15

Description of historical fire and weather data sets, by CDF ranger unit.

CDF ranger unit	Nevada-Yuba-Placer	Riverside	Santa Clara
Ranger unit identifier	NEU	RRU	SCU
Period of fire history coverage	1986-1994	1984-1991	1986-1994
Years of historical fire records	9	8	9
Mean number of fires per year	539	1290	557
Mean number of days per year with one or more fires	205	251	207
Mean acres burned per year	5253	10005	5263
Weather station name	Wolf Creek Lookout	Anza	Morgan Hill
Weather station identifier	41805	45616	43903
Weather station location	39.10N 121.10W	33.56N 116.67W	37.10N 121.70W
Weather station elevation (feet)	2636	3980	320
NFDRS fuel models used	A, B, F, G	A, B, T	A, B, F, G

October 24, 1997

Constance A. Harrington
Editor, Forest Science
Pacific Northwest Research Station
Forestry Sciences Laboratory
3625 93rd Avenue SW
Olympia, WA 98512-9193

Dear Dr. Harrington:

Enclosed are four copies of a manuscript that I have authored with Jeremy S. Fried, titled "Stochastic representation of fire behavior in a wildland fire protection planning model for California." We are submitting this manuscript for your consideration for publication in Forest Science.

Some potential reviewers you may wish to consider for this manuscript could include:

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I will be the corresponding author for this manuscript, and will be happy to answer any questions you may have. I can be reached at 510/642-6388 or gilless@nature.berkeley.edu.

Sincerely,

J. Keith Gilless
Associate Dean for Forestry