J6E.3 FIRE SPREAD IN CHAPARRAL – "GO OR NO-GO?"

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ABSTRACT

Current fire models are designed to model the spread of a linear fire front in dead, small-diameter fuels. Fires in predominantly living vegetation account for a large proportion of annual burned area nationally. Prescribed burning is used to manage living fuels; however, prescribed burning is currently conducted under conditions that result in marginal burning. We do not quantitatively understand the relative importance of the fuel and environmental variables that determine spread in live vegetation. Laboratory fires have been burned to determine the effects of wind, slope, moisture content, and fuel characteristics on fire spread in fuel beds of common chaparral species. Four species (*Manzanita sp., Ceanothus sp., Quercus sp., or Arctostaphylos sp*.), two wind velocities (0 and 2 m/s) and three slope percents (0, 40, or 70%) were used. Oven-dry moisture content of fine fuels (< 6.25 mm diameter) ranged from 30% to 105%. Forty-nine of 90 fires successfully propagated the length (2.0 m) of the elevated fuel bed. A logistic model to predict the probability of successful fire spread was developed using stepwise logistic regression. The variables selected to predict propagation were wind speed, slope percent, moisture content, fuel loading, and relative humidity.

1. INTRODUCTION

Fire burns large areas in living fuels such as chaparral in California, sagebrush and pinyon-juniper woodlands in the interior West, palmetto-gallberry in the southeastern coastal plain, and coniferous forests in the U.S. annually. While these fires are significant events, our ability to predict when fire will spread in these fuels is limited by two factors: 1) current fire spread models were not designed primarily for live fuels and 2) a limited set of experimental data to develop and test models exists. This problem has been recognized for over 60 years (e.g., Buck et al 1941, Nelson and Bruce 1958). In the U.S., limited modeling of fire spread in live fuels has occurred (e.g., Albini 1967, Rothermel and Philpot 1973, Albini and Anderson 1982, Cohen 1986, Albini and Stocks 1986). While these various models exist and may be used by fire managers, empirical approaches to predict fire spread in live fuels are also used (e.g., Green 1981, Raybould and Roberts 1983, Campbell 1995).

In California, several different tools are used by fire managers to aid in the use of prescribed fire in chaparral. The key to successful use of prescribed burning is the development of a "prescription" that defines the fuel, weather, and fire conditions necessary to accomplish the objectives of the prescribed burn. BEHAVE (Andrews 1986) and FIRECAST (Cohen 1986), both computer implementations of the Rothermel spread model (Rothermel 1972) are used to estimate fire behavior under various weather settings. The matrix approach (Raybould and Roberts 1983) links a quasi-quantitative description of fire behavior and effects to a score computed from severity points assigned to various values of fuel and weather variables. Both the matrix approach and the Campbell Prediction System (Campbell 1995) utilize basic understanding of the variables that influence fire behavior to arrive at predictions.

Prescribed burning in chaparral is typically attempted in the spring to early summer when fuel moistures are higher in most cases than when wildfires occur (Green 1981). Burning conditions are often marginal and there seems to be a threshold between no fire spread and successful propagation. Others have reported thresholds in fire behavior as influenced by various fuel and environmental variables (Bruner and Klebenow 1979). McCaw (1997) summarized many of these studies. While the factors influencing the spread thresholds in chaparral may be understood by successful prescribed fire managers, no designed experiments have been conducted to methodically describe these threshold conditions quantitatively.

The basic formulation of the Rothermel model assumed fire spread in the absence of wind and slope. Wind and slope functioned as multipliers of rate of spread. The model does not predict rate of spread when wind is required for successful spread (Weise and Biging 1997). The Rothermel model was derived based on several simplifying assumptions. Fuels were assumed to be uniform, dominated by dead material, and in close proximity to the ground. Environmental conditions were assumed constant. The various heat transfer mechanisms of radiation, convection, and conduction were not explicitly described; a "lumped capacity" approach was used. Fire spreads successfully in chaparral fuels at higher fuel moistures than most of the experimental data used to develop the Rothermel model.

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Wilson (1982, 1985) examined fire spread in moist fuel and proposed changes to the moisture content formulation in the Rothermel model. As part of this work, Wilson developed a "predictive rule of thumb" to determine if fires would burn in wooden fuel beds. The rule of thumb was that a fire would not burn if $M_f \geq (\ln(2\sigma\beta\delta))/4$ where M_f, σ, δ, and β are moisture content, fuel particle surface area to volume ratio, fuel bed depth, and packing ratio (eq. 1), respectively. This rule of thumb was developed using data from fuel beds constructed of poplar excelsior, 0.64 and 1.27 *cm* ponderosa pine sticks. In Wilson's experiments, fuel depth ranged from 2.5 to 20 *cm*, σ was 3.2, 6.3, or 81.3 cm^{-1}, and β ranged from 0.005 to 0.32. Fuel depths observed in chaparral crowns range from 30 to >120 *cm*, σ varies between various species from 20 to 60 cm^{-1}, and the crowns tend to be fairly porous (low packing ratio). Wilson (1990) also suggested that a term in the spread model involving wind and fuel moisture might be appropriate.

$$\beta = \frac{W}{(M+1)A\delta\rho_p} \tag{1}$$

where *W* is the total fuel bed mass (kg) bed, *M* is the live fuel moisture content, *A* is the surface area of the fuel bed, and ρ_p is the fuel particle density.

Countryman and Philpot (1970) reported packing ratios ranging from 0.00068 to 0.00374 for 16 chamise plants. Reported fine fuel (leaves and stems < 0.64 *cm*) loading in various chaparral species mixes ranged from 0.71 to 3.33 $kg\ m^{-2}$ (e.g., Countryman 1964, Ottmar et al. 2000). The application of Wilson's rule of thumb to shrub fuel beds such as chaparral is currently unknown. Given that current operational models do not adequately model fire spread in chaparral fuels and that data describing marginal burning conditions in chaparral do not currently exist, we have embarked upon an experimental effort to determine the important fuel and environmental variables that determine propagation success in laboratory-scale fires in chaparral fuels.

2. METHODS

The effects of wind, fuel moisture content, fuel bed height and slope on flame propagation in live fuels were investigated in a series of 90 experimental fires burned between 1/2003 and 7/2003. Fuel beds (2 *m* long x 1.0 *m* wide x various depths) were constructed of live branch and foliage material collected from living chaparral growing at an elevation of 1160 *m* at an experimental area 50 *km* east of Riverside, CA. Branches < 0.64 *cm* from manzanita (*Arctostaphylos parryana*), chamise (*Adenostoma fasciculatum*), hoaryleaf ceanothus (*Ceanothus crassifolius*), and scrub oak (*Quercus berberidifolia*) plants comprised the fuel. The fuel beds were elevated above the surface of a tilting platform by 40 *cm* to simulate an aerial fuel. Air could be entrained from the ends of fuel bed; air entrainment from the sides was prevented by metal sheeting. Fuel was collected in the morning so as to minimize moisture loss through transpiration. Dead fuel was removed to the extent possible. The fuels were then bagged and transported to the burn facility at the Forest Fire Laboratory. For the experiments from 1/16/2003 to 2/7/2003, the live fuel was stored in a large refrigerator after being harvested and burned within the next 24 hours. Fuels collected after 2/2003 were burned on the day of collection to reduce moisture loss.

The fuel was uniformly distributed (Fig. 1) to the greatest extent possible. Fires were ignited from one side in a 50 *cm* section along the length of the live fuel bed. Between 150 ~ 200 *ml* of isopropyl alcohol was added uniformly in the ignition zone to help the ignition. Air flow to simulate wind was induced using 3 rotary box fans which were turned on simultaneously. No attempt was made to "smooth" out the vorticity in the flow. The fans produced an average velocity of 2 $m\ s^{-1}$. An experiment was described as successful if the live brush ignited from the burning zone and then propagated the length of the 2 *m* fuel bed. The experiment was unsuccessful if the fire did not propagate.

Figure 1. Fuel bed constructed of live foliage and branches < 0.64 cm diameter of *Ceanothus crassifolius*.

Because the response variable (spread success) was binary, logistic regression was used to develop a model to predict spread success (eq. 2). The logit $\log(p/(1-p))$ of the probability of spread success was set equal to a linear function $X\beta$ of the predictor variables and the parameter estimates were determined by maximum likelihood estimation. Stepwise logistic regression was used to select the fuel bed and environmental variables to predict fire spread success.

$$\log\left(\frac{p}{1-p}\right) = X\beta$$
$$\Pr(spread = Y) = \frac{e^{X\beta}}{1+e^{X\beta}} \tag{2}$$

3. RESULTS

A total of 90 tests of fire spread success were conducted between 1/2003 and 7/2003. Forty-nine (or

54%) of the 90 tests resulted in successful fire spread. Most of the tests (54 of 90) we conducted used chamise as the fuel (Table 1). Similarly, a majority (58 of 90) of the tests had no slope and no wind (53 of 90). The unbalance in the data will become less important as we continue to conduct more experiments.

Fuel moisture content of samples burned on the day of collection ranged from 75% for chamise to 106% for manzanita. Chamise fuel moisture was 80% on 3/7/2003, 91% on 5/9/2003, and 77% on 7/2/2003 which indicated that new growth occurred between 3/7 and 5/9 and the new growth was drying out by 7/2 – a typical annual trend in live fuel moisture in chamise. Manzanita fuel moisture content increased from 95% in May 2003 to 105% in early July. Ceanothus and scrub oak exhibited increases in fuel moisture content similar to the manzanita increase. Fuel moisture content of the chamise burned the day after collection ranged from a low of about 30% in January to 64% in February 2003.

Table 1. Summary of fire spread success in live fuels by species, slope percent, wind velocity, and fuel bed depth.

Variable	Value	Fire Spread Success		
		No	Yes	ROS*
Species	Ceanothus	3	8	0.42
	Chamise	22	32	0.56
	Manzanita	9	6	0.19
	Scrub Oak	7	3	0.74
Slope (%)	0	31	27	0.28
	27	3	6	0.66
	40	5	7	0.48
	70	2	9	1.09
Fuel Depth**	20	23	15	0.61
	40	18	34	0.44
Wind Velocity***	0	34	19	0.70
	2	7	30	0.37
Total		41	49	

* Average Rate of Spread (ROS) in m min^{-1} when successful.

** Fuel bed depth in cm.

***In m s^{-1}.

Of the tests performed to date, wind was required in 1/3 of the fires to insure successful spread (Table 1). Because several experimental variables were examined in conjunction, care should be taken in identifying data trends from Table 1. For example, the 22 chamise fires that did not spread had different slope percents, fuel bed depths and wind velocities.

In the experiments reported here, the physical fuel properties varied between species, but were assumed constant within a species. The exceptions to this were moisture content and packing ratio (Table 2). Manzanita, scrub oak, and ceanothus are all species with leaves that are generally ovoid in shape (Figure 2). The leaf thickness varied between species with manzanita having the thickest leaves and scrub oak having the thinnest. In contrast, chamise leaves are linear in shape.

Table 2. Physical properties of several chaparral species and fuel beds used in marginal burning study.

Species	σ^*	β^{**}
Chamise	66	0.009 – 0.013
Ceanothus	58	0.012, 0.013
Manzanita	41	0.014, 0.016, 0.019, 0.020
Scrub oak		0.009, 0.013, 0.017

*Surface area to volume ratio (cm^{-1}). Assumed 2000 ft-1 for chamise (Cohen 1986), used 1771 ft-1 for ceanothus (from *Ceanothus velutinous*, Countryman 1982), measured sample for manzanita, unknown for scrub oak.

**Packing ratio (eq. 1)

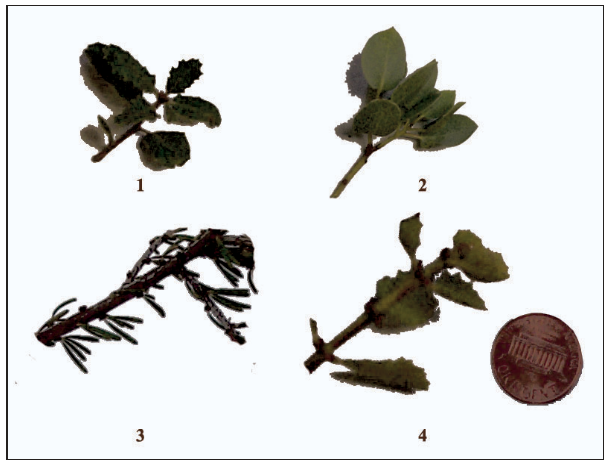

Figure 2. Foliage and fine branch samples of 4 chaparral species used in marginal burning experiment: 1) scrub oak (*Quercus berberidifolia*), 2) manzanita (*Arctostaphylos parryana*), 3) chamise (*Adenostoma fasciculatum*), and hoaryleaf ceanothus (*Ceanothus crassifolius*).

Several predictor variables were considered in the logistic equation: species, slope, moisture content, wind velocity, fuel bed depth, packing ratio, relative humidity, absolute temperature, fuel loading, and fuel orientation (horizontal, vertical). The stepwise regression process built the regression model by choosing the variable with the largest χ^2 value to add to the model and removing any variables already in the model that did not meet the Wald criterion (SAS Institute 1999). Of the predictor variables considered, wind velocity was the 1st variable selected (Table 3) and slope was the 2nd. Of ten variables considered, five were selected to predict the probability of fire spread success. Three of the variables were environmental (wind velocity, slope %, and relative humidity) and two were fuel (fuel loading, moisture content) variables.

It is interesting to note that both relative humidity and fuel moisture content were selected. For dead fuels that respond passively to changes in atmospheric temperature and moisture content (Nelson 2001), relative humidity and dead fuel moisture content would be highly correlated and the assumption of independence of the variables would be suspect. The live fuels we are studying actively regulate their moisture content. It is currently not known if changes in relative humidity affect the processes the plants use to regulate their moisture content.

Table 3. Variables selected to predict fire spread success using a logistic model.

Variable	N	χ^2	Pr	$\hat{\beta}$	Odds Ratio
Wind velocity	1	17.97	<.001	5.14	171.47
Slope	2	22.00	<.001	0.18	1.20
Moist. Cont.	3	11.72	.001	-0.25	0.78
Fuel loading	4	17.30	<.001	0.75	2.11
Rel. humidity	5	5.44	.020	-0.07	0.93

Since the fuels were cut, they were unable to regulate their moisture content; however, the predominant process that occurred between sample collection and burning was moisture loss. The equation that resulted from the stepwise logistic regression is:

$$X\hat{\beta} = 9.66 + 5.14WS + 0.18Sl + 0.75L - 0.07RH - 0.25MC$$

$$\Pr(success = Y) = \frac{\exp(X\hat{\beta})}{1 + \exp(X\hat{\beta})} \qquad (3)$$

where *WS* is wind velocity (ms^{-1}), *Sl* is slope (%), *L* is fuel loading ($kg\ m^{-2}$), RH is relative humidity (%), and MC is live fuel moisture content (%).

The relative sensitivity of fire spread to each of the predictor variables can be found by examining the odds ratio (Table 3). The odds ratio describes the change in risk of fire spread that is associated with a change in the predictor variable. The higher the odds ratio is for a variable, the greater the change in risk if the predictor variable changes. This analysis indicated the extreme importance of wind velocity to risk of fire spread for these data. The relative change in risk for the other four variables is small in comparison. The fitted model correctly classified nearly 97% of the 90 fires in the data.

In an attempt to determine if the laboratory results were similar to the guidelines developed for prescribed fire use in chaparral, we selected several combinations of fire prescription variables and estimated the score following Raybould and Roberts (1983), (Table 4). We calculated the probability of fire spread using eq. 3 for both SCAL fuel model B (mixed brush) and fuel model C (chamise). We assumed fuel continuity of 100% (severity points=9), fuel bed percent dead = 15% (1 point), aspect = north (1), season = July (3), 10 hr stick fuel moisture = 15% (1), time of day = 1300 (7) and age=20 years. For the 2 SCAL fuel models, only the foliage and 1 hr fuel loading were used (eq. 4).

Table 4. Prescribed fire conditions and composite severity score for several chaparral scenarios.

F[1]	D[2]	M[3]	S[4]	R[5]	W[6]	T[7]	X[8]	Pr[9]
B	0.3	90	0	60	0	294	40	0.000
	0.3	90	0	60	2.2	294	43	0.029
	0.3	90	0	60	4.5	294	47	0.999
	0.9	70	20	50	2.2	300	48	0.996
	1.5	70	20	40	4.5	305	55	1.000
C	0.3	90	0	60	0	294	43	0.000
	0.9	70	20	50	2.2	300	51	0.993
	1.5	70	20	40	4.5	305	58	1.000

[1] SCAL fuel model B – mixed brush, C - chamise
[2] Fuel bed depth (cm).
[3] Live fuel moisture content (%)
[4] Slope (%)
[5] Relative humidity (%)
[6] Wind velocity (m s^{-1})
[7] Absolute temperature (ºK)
[8] Severity score (Raybould and Roberts 1983)
[9] Probability of fire spread success (eq. 3)

$$\text{SCAL B} \quad L = 0.224\frac{Age}{0.4849 + 0.0170\,Age}(.4373 - .561FD)$$

$$\text{SCAL C} \quad L = 0.224\frac{Age}{1.4459 + 0.0347\,Age}(.4373 - .561FD) \qquad (4)$$

where *L* = fuel loading ($kg\ m^{-2}$), *Age* is chaparral stand age (*years*), and *FD* is the fraction of the total fuel bed that is dead. The loading for the foliage and live wood < 0.64 cm was calculated using FIRECAST fuel load equations (Cohen 1986).

Raybould and Roberts (1983) related the severity score to a general description of fire behavior and effects in chaparral. The severity scores for the 6 scenarios in Table 4 would be considered “moderate burns” in which 50% of the area might be burned, the fuel burned easily, and flame lengths of 1.2-1.8 m would be observed. It is not possible to directly relate the severity score and associated fire behavior to our data. However, burning half of the area implies that fire would spread successfully in half of the area. Stated differently, fire spread success = 0 for the unburned half. The severity scores in Table 4 are in the prescription window where marginal burning in chaparral has been observed to occur. While these results do not indicate that equation 3 can be used to predict prescribed fire success, they suggest that the experimental work we are conducting may be similar to the field scale prescribed burns that we hope to better model.

4. SUMMARY

Current fire spread models do not adequately model the transition between no spread and spread in live fuels. We have conducted 90 experiments to determine the importance of fuel and environmental variables on fire spread success for 4 different species of chaparral in the laboratory. Analysis of these 90 fires indicated the importance of wind velocity on fire spread success using logistic regression. The other variables in the model included slope, moisture content, relative humidity, and fuel loading. Comparison of results with a tool designed to determine fire behavior and effects in chaparral suggested that the laboratory data for marginal fire spread in chaparral are in general agreement with the empirical tool.

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