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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 in the United States. Prescribed burning is used to manage living fuels; however, prescribed burning is currently conducted under conditions that result in marginal burning. We do not understand quantitatively the relative importance of the fuel and environmental variables that determine spread in live vegetation. To address these weaknesses, 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 (*Adenostoma fasciculatum*, *Ceanothus crassifolius*, *Quercus berberidifolia*, *Arctostaphylos parryana*), two wind velocities (0 and $2\,m\,s^{-1}$) and two fuel bed depths (20 and 40 cm) were used. Oven-dry moisture content of fine fuels (<0.63 cm diameter) ranged from 0.09 to 1.06. Seventy of 125 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 velocity, slope percent, moisture content, fuel loading, species and air temperature. Air temperature and species terms were removed from the model for parsimony. The final model correctly classified 94% of the observations. Comparison of results with an empirical decision matrix for prescribed burning in chaparral suggested some agreement between the laboratory data and the empirical tool.

Introduction

Fire burns in living fuels such as chaparral in California, sagebrush and pinyon-juniper woodlands in the interior West, palmetto-gallberry in the south-eastern coastal plain, and coniferous forests in the USA annually. While these fires can be 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) only a limited set of experimental data to develop and test models exists. Recent work in Europe and Australia has measured and modeled fire spread in various live fuels (Fernandes 2001; Marsden-Smedley *et al*. 2001; Bilgili and Saglam 2003; De Luis *et al*. 2004; Morvan and Dupuy 2004). In the USA, limited modeling of fire spread in live fuels has occurred (e.g. Albini 1967; Rothermel and Philpot 1973; Albini and Anderson 1982; Albini and Stocks 1986; Cohen 1986; Butler *et al*. 2004). 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), FIRECAST (Cohen 1986) and BRNPLN (Hilbruner 1988), all computer implementations of the Rothermal spread model (Rothermel 1972), can be 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

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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, a systematic experimental investigation designed specifically to document these threshold conditions is currently lacking.

The basic formulation of the Rothermel model assumed that a fire would spread in the absence of wind and slope (R_0) (Rothermel 1972). Wind and slope functioned as multipliers of rate of spread:

$$R = R_0(1 + \phi_w + \phi_s),$$

where ϕ_w and ϕ_s are wind and slope multipliers respectively. The model does not predict a non-zero rate of spread in situations when wind or slope is required. For $R_0 = 0$, $R > 0$ if and only if $\phi_w > 0,\ or\ \phi_s > 0$ (Weise and Biging 1997). This phenomenon requires a different formulation for the effects of wind and slope on rate of spread. 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. Under the influence of strong Santa Ana winds, nearly 304 000 ha were burned in southern California from 21 October to 4 November 2003 (Campbell 2004). Fuel moisture content in chamise chaparral in Los Angeles County was near 60% at this time (http://www.lacofd.org/Forestry_folder/LFM/Malibu.pdf). This level of live fuel moisture (60% or 0.6) is viewed by some southern California fire managers as a critical level indicative of high fire danger.

Wilson (1982, 1985, 1990) 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 predicted that a fire would not burn if $M \geq (\ln(2\sigma\beta\delta))/4$, where M, σ, δ and β are moisture content (expressed as proportion of oven-dry mass), fuel particle surface area-to-volume ratio (cm^{-1}), fuel bed depth (cm) and packing ratio (dimensionless, equation 1) respectively. Wilson (1990) also suggested that a term in the spread model involving wind and fuel moisture might be appropriate:

$$\beta = \frac{w_m}{(M+1)A\delta\rho_p} = \frac{w_o}{A\delta\rho_p} = \frac{\rho_b}{\rho_p}, \qquad (1)$$

where w_m and w_o are total fuel bed wet and dry mass (kg), respectively, M is the live fuel moisture content, A is the surface area of the fuel bed, and ρ_p and ρ_b are fuel particle density and fuel bed bulk density (kg m^{-3}) respectively.

Equation (1) can be simplified to Rothermel's definition of packing ratio (Rothermel 1972); we used this form because our fuels were weighed when moist, not oven-dry as in other experiments. Wilson's rule of thumb was developed using data from fuel beds constructed of *Populus tremuloides* excelsior (shredded wood), and 0.64 and 1.27 cm diameter *Pinus ponderosa* 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).

Countryman and Philpot (1970) reported packing ratios ranging from 0.00068 to 0.00374 for 16 chamise plants sampled near the location where fuels were collected for the current study. Reported fine fuel (leaves and stems <0.64 cm diameter) 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 on an experimental effort to determine the important fuel and environmental variables that determine propagation success in laboratory-scale fires in chaparral fuels.

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 125 experimental fires. Fuel beds (2 m long × 1.0 m wide × 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, USA (Fig. 1*a*). Branches <0.64 cm diameter from manzanita (*Arctostaphylos parryana*), chamise (*Adenostoma fasciculatum*), hoaryleaf ceanothus (*Ceanothus crassifolius*) and scrub oak (*Quercus berberidifolia*) plants made up the fuels. 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 beds; metal sheeting prevented air entrainment from the sides to reduce the curvature of the flame front and simulate a line fire. Plant material was generally 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. Moisture content was determined immediately before

Fig. 1. (*a*) Fuel collection site located 50 km east of Riverside, CA, USA at an elevation of 1300 m in a mixed chaparral stand. Shrubs are young *Ceanothus crassifolius*. (*b*) Fuel bed constructed of live foliage and branches <0.64 cm diameter of *C. crassifolius*.

ignition. Fuel temperature was assumed in equilibrium with air temperature because air temperature at the collection site was generally only a few degrees different from the laboratory temperature. The five fuel beds constructed 24 h after collection using refrigerated fuels were allowed a few hours to come to equilibrium with ambient air temperature before ignition. The fuel was distributed uniformly in the fuel bed (Fig. 1*b*) to the greatest extent possible. Fires were ignited along the 1 m side with a flame zone depth of 50 cm section along the length of the live fuel bed. Between 300 and 400 g of excelsior and a small amount of isopropyl alcohol were added uniformly in the ignition zone to initiate and sustain the ignition.

While several variables potentially influence fire spread in live fuels, we selected three variables to control directly—wind velocity (0 or 2 m s^{-1}), species and fuel bed depth (20 or 40 cm). While we have the ability to impose slope, we have not completed a full set of experiments in which slope was a design variable. To date, 125 fires have been ignited (Table 1)—a fraction of the full factorial experiment, which will take several years to complete. The data are not

Table 1. Summary of experimental chaparral laboratory fires

Ceanothus, *Ceanothus crassifolius*; chamise, *Adenostoma fasciculatum*; manzanita, *Arctostaphylos parryana*; scrub oak, *Quercus berberidifolia*. Moisture content = (wet mass – dry mass)/dry mass

Species	Wind speed (m s^{-1})	Fuel bed depth (cm)	*N*	Moisture content range	Slope (%)
Ceanothus	0	20	6	0.66–0.93	0–70
	0	40	10	0.66–0.93	0–70
	2	20	5	0.66–0.88	0
	2	40	4	0.68–0.88	0
Chamise	0	20	19	0.09–0.91	0–70
	0	40	27	0.30–0.91	0–70
	2	20	9	0.39–0.91	0–40
	2	40	14	0.26–0.91	0–27
Manzanita	0	20	5	0.84–1.06	0–70
	0	40	6	0.84–1.06	0–70
	2	20	6	0.84–1.06	0
	2	40	4	0.84–1.06	0
Scrub oak	0	20	4	0.86–1.00	0–70
	0	40	2	0.86–1.00	0–40
	2	20	1	0.86–1.00	0
	2	40	3	0.86–1.00	0

balanced. As a result, individual species effects were not replicated evenly, were possibly confounded with other effects (for scrub oak), and may not have been captured in the analyses presented here.

Three rotary box fans (Model 9700*, 50.8 cm box fan; Air King Ventilation Products, West Chester, PA, USA) induced air flow to simulate wind. No attempt was made to 'smooth' out the vorticity in the flow. The fans produced an average velocity of 2 m s^{-1} above the fuel bed. We determined mean wind velocity by collecting 1-min point samples in vertical and horizontal transects above the fuel bed with an air flow mass velocity transducer (FMA-903; Omega Engineering, Stamford, CT, USA). The slope effect was generated by raising the down-wind end of the tilting platform. Ambient air temperature and relative humidity in the burn facility were measured at the beginning of each experiment using a Kestrel 3000 Pocket Weather Meter (Nielsen-Kellerman, Boothwyn, PA, USA). 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 (Fig. 2). The experiment was unsuccessful if the fire did not propagate. In the case of successful fire spread, the resulting rate of spread (ROS) was measured using data from 0.51 mm diameter type K thermocouples buried in the fuel bed and/or direct video image analysis from digital imagery collected at 30 Hz (Canon ZR10; Canon USA, Lake Success, NY, USA).

Because the response variable (spread success) was binary, logistic regression was used to develop a model to predict spread success (equation 2). The logit, $\log(p/(1-p))$, of the

* The use of trade names and model numbers is for information purposes only and does not constitute endorsement by the U.S. Department of Agriculture.

Fig. 2. A successful fire spread case in an *Adenostoma fasciculatum* fuel bed 40 cm deep with wind velocity of 2 m s^{-1} and no slope.

probability of spread success (p) was set equal to a linear function $X\theta$ of the predictor variables and the parameter estimates were determined by maximum likelihood estimation. Stepwise selection was used to choose the fuel bed and environmental variables to predict fire spread success. In order to compare the potential utility of the logistic model, several fire spread scenarios were developed and scored using the matrix approach of Raybould and Roberts (1983). Scenarios of air temperature, fuel moisture, wind velocity and fuel loading that were close to the laboratory conditions were developed:

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

Results

In total, 125 tests of fire spread success were conducted (Table 2). Over half of the experiments used chamise as the fuel: ceanothus, 25 tests; chamise, 69; manzanita, 21; scrub oak, 10. Of the 125 tests, 79 were 'no wind' tests and 55 had a fuel bed depth of 20 cm. Seventy (or 56%) of the 125 tests resulted in successful fire spread. Chamise has been the dominant fuel tested because it is the dominant fuel at the collection site and it is the easiest to handle and produce uniform fuel beds (Table 2). A majority of the tests had no slope (93 of 125) or no wind (79 of 125).

The range in fuel moisture content for chamise was greatest (0.09–0.91). Most fuel beds were burned on the day of fuel collection to minimize moisture loss. Fuel beds burned 1–2 days after collection lost nearly half of their moisture, with resulting moisture content of 0.26–0.38. A single chamise fuel bed was allowed to dry for several weeks resulting in a moisture content of 0.09. For chamise fuel beds burned on the day of collection, moisture content exhibited a smaller range (0.64–0.91). This range is similar to that for the ceanothus fuel beds. The moisture content of the manzanita and scrub oak fuel beds was slightly higher. These fuel types do not typically have moisture contents that drop as low as chamise during the long summer droughts. The moisture content of the chamise fuel beds followed the typical annual trend in live fuel moisture in chamise, which is typical for many species in Mediterranean-type climates with mild, moist winters with rain followed by hot, dry summers with little rain (Fig. 3). Manzanita fuel moisture content increased from 0.95 in May 2003 to 1.06 in early July 2003, during which time new foliage was produced. Ceanothus and scrub oak exhibited increases in fuel moisture content similar to the manzanita increase.

Table 2. Spread success of laboratory fires by species, slope percent, wind velocity and fuel bed depth

ROS, mean rate of spread (m min^{-1}) for success = 'Y' fires. Ceanothus, *Ceanothus crassifolius*; chamise, *Adenostoma fasciculatum*; manzanita, *Arctostaphylos parryana*; scrub oak, *Quercus berberidifolia*

Variable	Value	Firespread success			
		No	Yes	Total	ROS
Species	Ceanothus	10	15	25	0.22
	Chamise	25	44	69	0.34[A]
	Manzanita	13	8	21	0.20
	Scrub oak	7	3	10	0.74
Slope (%)	0	45	48	93	0.20
	27	3	6	9	0.38
	40	5	7	12	0.48
	70	2	9	11	0.72
Fuel depth (cm)	20	31	24	55	0.32
	40	24	46	70	0.31
Wind velocity (m s^{-1})	0	47	32	79	0.39
	2	8	38	46	0.26
Total		55	70	125	

[A]Missing ROS observation for two tests of chamise with experimental settings of 0% slope, 40 cm depth and 0 m s^{-1} wind velocity.

Of the tests performed to date, wind was present in 30% (38/125) of the fires, aiding successful spread (Table 2). Because several experimental variables were examined in conjunction, care should be taken in identifying data trends from Table 2. For example, the 25 chamise fires that did not spread had different slope percents, fuel bed depths and wind velocities.

In the experiments reported here, physical fuel properties varied between species, but were assumed constant within a species. The exceptions to this were moisture content and packing ratio (Table 3). Manzanita, scrub oak, and ceanothus are all species with leaves that are generally ovoid in shape (Fig. 4). 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.

Several predictor variables were considered in the logistic equation: species, slope, moisture content, wind velocity, fuel bed depth, packing ratio, relative humidity, absolute temperature and fuel loading. Of the predictor variables considered,

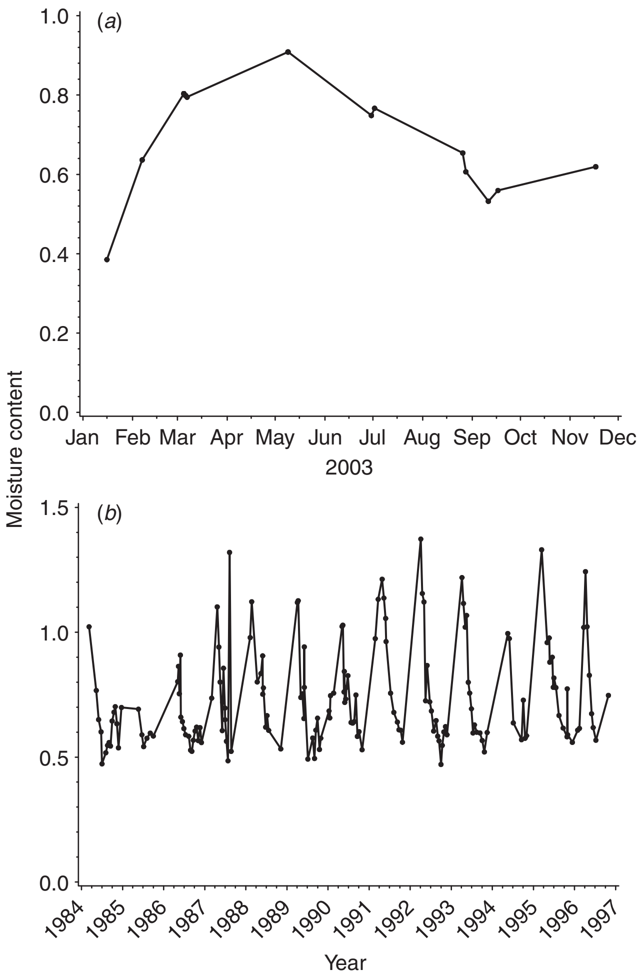

Fig. 3. Annual trend in chamise (*Adenostoma fasciculatum*) fuel moisture content for (*a*) laboratory fuel beds and (*b*) Strawberry fuel moisture sample site, San Bernardino National Forest.

Fig. 4. Foliage and fine branch samples of four chaparral species used in marginal burning experiment: (1) scrub oak (*Quercus berberidifolia*); (2) manzanita (*Arctostaphylos parryana*); (3) chamise (*Adenostoma fasciculatum*) and (4) hoaryleaf ceanothus (*Ceanothus crassifolius*). Coin = 1.9 cm diameter.

Table 3. Physical properties of several chaparral species and fuel beds

Ceanothus, *Ceanothus crassifolius*; chamise, *Adenostoma fasciculatum*; manzanita, *Arctostaphylos parryana*; scrub oak, *Quercus berberidifolia*. Surface area-to-volume ratio: assumed 2000 ft^{-1} for chamise (Cohen 1986), used 1771 ft^{-1} for ceanothus (*Ceanothus velutinous*, Countryman 1982), measured sample for manzanita, unknown for scrub oak. Packing ratio, see equation (1)

Species	Surface area-to-volume ratio (σ) (cm^{-1})	Packing ratio (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

wind velocity was selected as the best single predictor of fire spread success (Table 4). Of nine variables considered, five were selected to predict the probability of fire spread success. Three of the variables were environmental (wind velocity, slope %, air temperature) and two were fuel (fuel loading, moisture content) variables. Plant species was also selected as a significant variable; however, for parsimony, species was not included in the final model because it was the last variable selected and inclusion of species in the model increased the classification accuracy only from 96 to 98% (Table 4). Correlation between the parameter estimates was examined and air temperature was also removed from the equation as it was highly correlated with the intercept term (correlation = −0.99). The equation that resulted from the stepwise logistic regression is:

$$X\hat{\theta} = 1.65 + 2.99WS + 0.10Sl + 2.03L - 12.55M$$
$$\Pr(success = Y) = \frac{\exp(X\hat{\theta})}{1 + \exp(X\hat{\theta})}, \quad (3)$$

where WS is wind velocity (m s^{-1}), Sl is slope (%), L is fuel loading (kg m^{-2}) and M is live fuel moisture content (proportion). Correlation of parameter estimates for moisture content with wind velocity and slope was between 0.7 and 0.8; correlation between wind and slope was also in this range. The correlation between wind velocity and slope is most likely due to the limited number of tests with slope. This simplified model (equation 3) correctly classified 94% of the 125 tests. The Hosmer and Lemeshow (2000) lack of fit test indicated no significant lack of fit of this model ($P > 0.1$).

The following discussion was condensed from Hosmer and Lemeshow (2000) to explain the odds ratio. For a dichotomous discrete variable $z = 0,1$, the odds ratio approximates

Table 4. Variables selected to predict fire spread success

d.f., degrees of freedom. Ceanothus, *Ceanothus crassifolius*; chamise, *Adenostoma fasciculatum*; manzanita, *Arctostaphylos parryana*; scrub oak, *Quercus berberidifolia*

Variable	Selection order[A]	d.f.	$\hat{\theta}$		Odds ratio	
			With species	Without species	With species	Without species
Intercept		1	−118.70	1.65		
Wind velocity	1	1	7.29	2.99	>0.999	19.85
Slope	3	1	0.19	0.10	1.2	1.10
Moisture content	4	1	−21.25	−12.55	<0.001	<0.001
Dry fuel loading ($kg\,m^{-2}$)	2	1	3.65	2.03	38.3	7.65
Air temperature (K)	5	1	0.39		1.5	
Species						
Ceanothus	6	1	1.54		10.4[B]	
Chamise	6	1	2.39		24.3	
Manzanita	6	1	−3.13		<0.01	
Fires classified correctly (%)			98	93		

[A]Effect of intercept (overall mean) is removed first by algorithm, then variables are selected according to criteria.
[B]Odds ratio for individual species in comparison with Scrub oak.

how much more likely it is for a fire to spread when $z = 1$ than when $z = 0$. The odds ratio is

$$\frac{\pi(1)/[1-\pi(1)]}{\pi(0)/[1-\pi(0)]},$$

where $\pi(z)$ is the conditional probability that the outcome is present given z. The odds ratio approximates relative risk and is estimated with $\exp(\hat{\theta}_i)$. For polytomous discrete variables, the calculation of the odds ratio is slightly more involved and depends on how the polytomous variable is coded. In our study, we used effects coding for the species variable:

$\hat{\theta}_1$ estimates the effect of species = 'ceanothus';
$\hat{\theta}_2$ estimates the effect of species = 'chamise';
$\hat{\theta}_3$ estimates the effect of species = 'manzanita'; and
$-\hat{\theta}_1 - \hat{\theta}_2 - \hat{\theta}_3$ estimates the effect of species = 'scrub oak'.

The odds ratio of Ceanothus relative to Scrub oak is

$$\exp(\hat{\theta}_1 - (-\hat{\theta}_1 - \hat{\theta}_2 - \hat{\theta}_3)) = \exp(2\hat{\theta}_1 + \hat{\theta}_2 + \hat{\theta}_3).$$

Substituting in the estimates from Table 4 yielded $\exp(2(1.54) + 2.39 - 3.13) = 10.38$. For the continuous variables wind velocity, dry loading, etc., the coefficient ($\hat{\theta}_i$) 'gives the change in the log odds for an increase of '1' unit in' the continuous variable. The odds ratio for an arbitrary change c in a continuous variable is $\exp(c\theta_i)$ (Hosmer and Lemeshow 2000: 63). In Table 4, the odds ratios presented are for $c = 1$. The odds ratio for wind velocity in the 'without species' model is $\exp(2.99) = 19.89$. The difference is due to rounding. The odds ratio describes the change in risk (or likelihood of occurrence) of fire spread that is associated with a change in the predictor variable. The higher the odds ratio is for a variable, the higher the likelihood that the outcome will occur if the predictor variable changes. This analysis indicated that fire spread was more likely to occur with a wind velocity of $2\,m\,s^{-1}$ than with no wind. As moisture content increased, the likelihood that fire spread would occur decreased (indicated by a small odds ratio <1). For the 'with species' model, fire spread was more likely to occur (relative to scrub oak) in fuel beds of ceanothus and chamise. Fire spread in manzanita fuel beds was less likely than fire spread in scrub oak fuel beds. Increased fuel loading increased the likelihood of fire spread success.

Table 5. Selected prescribed fire scenarios and severity scores

SCAL fuel model: B, mixed brush; C, chamise (Cohen 1986). Assumed a fuel bed depth of 30 cm, air temperature of 294 K, slope = 0 and relative humidity = 60% for all predictions. Loading in $kg\,m^{-2}$. Severity score: see Raybould and Roberts (1983). Pr, estimated probability of successful fire spread (equation 3)

Fuel model/ loading	Scenario	Live fuel moisture content (%)	Wind velocity ($m\,s^{-1}$)	Severity score	Pr
B: 1.92	1	0.9	0.0	40	0.003
	2	0.9	2.2	43	0.718
	3	0.9	4.5	47	1.000
	4	0.7	0.0	41	0.038
	5	0.7	2.2	44	0.969
	6	0.7	4.5	48	1.000
C: 0.74	7	0.9	0.0	43	0.000
	8	0.9	2.2	46	0.189
	9	0.9	4.5	50	0.995
	10	0.7	0.0	44	0.004
	11	0.7	2.2	47	0.741
	12	0.7	4.5	51	1.000

In an attempt to determine if laboratory results were similar to guidelines developed for prescribed fire use in chaparral, we selected 12 combinations of fire prescription variables and estimated a severity score following Raybould and Roberts (1983) (Table 5). The scenarios were created to mimic conditions as close to what was observed in the laboratory as could be accomplished. The matrix has discrete classes for each fire prescription variable, which are assigned severity points. We calculated the probability of fire spread using equation (3) for both SCAL fuel model B (mixed brush) and fuel model C (chamise) (Cohen 1986). We assumed fuel continuity of 100% (severity points = 9), fuel bed percent dead = 15% (lowest possible value, 1 point), aspect = north (1), season = July (3), 10 h stick fuel moisture = 0.15 (1), time of day = 1300 (7) and age = 20 years. Loading for foliage and live wood <0.64 cm diameter was calculated using FIRECAST fuel load equations (Cohen 1986). For the two SCAL fuel models, only the foliage and 1 h fuel loading were used (equation 4) because the fuel beds were constructed from this size of fuel:

SCAL B

$$L = 0.224\frac{Age}{0.4849 + 0.0170Age}(0.4373 - 0.561FD)$$

SCAL C

$$L = 0.224\frac{Age}{1.4459 + 0.0347Age}(0.4373 - 0.561FD), \qquad (4)$$

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 scenarios in Table 5 illustrate the relative sensitivity of the fitted logistic model to changes in wind velocity and fuel loading. If fuel model was held constant, the predicted probability of spread success increased appreciably when wind velocity increased from 0 to 2.2 m s^{-1} (scenarios 1,2; 4,5; 10,11). For both fuel models, predicted spread success was unity for wind velocity of 4.5 m s^{-1}. The combined effect of loading and species on predicted probability can be seen when comparing predicted probabilities for scenarios 2 and 8. It is not possible to separate the effect of loading from the effect of species. However, the effect of species differences in physical properties such as surface area-to-volume ratio is reflected in the score for these same scenarios. We anticipate that species will have a significant effect on prediction of fire spread success as the dataset becomes more balanced.

Raybould and Roberts (1983) related the severity score to a general description of fire behavior and effects in chaparral. The severity scores for the 12 scenarios in Table 5 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 might spread successfully in half of the area. Stated differently, fire spread success = 0 for the unburned half. The severity scores in Table 5 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. These results also suggest that the transition from no spread to successful spread in live fuels is a step function influenced by wind velocity.

With these data, it was not possible to determine if live fuels burn like wet dead fuels. Several authors have reported that rate of spread is reduced as fuel moisture content of dead fuels increases (e.g. Wilson 1990; Catchpole *et al*. 1998). For woody fuels, moisture content has been manipulated experimentally to produce a range of 0.02–0.33 in work at the Forest Service Fire Laboratory in Missoula, MT, USA. This range of moisture content is representative of the range reported by numerous authors over several decades for studies of fine, dead woody fuels. Catchpole *et al*. (1998) reported that fuel bed depth had little effect on spread rate in woody fuels. The stepwise logistic regression procedure did not select fuel bed depth as a predictor of fire spread success even though the data suggested otherwise (Table 2). Additional experiments may clarify this relationship. These data illustrate that wind is sometimes required for successful ignition and propagation in live fuels. This suggests that convective heating may play a more significant role in flame spread in live fuels than in dead fuels. The recent radiation-based crown fire model may need an additional heat transfer term for convection (Butler *et al*. 2004). Other concurrent work is examining combustion aspects of live fuels (Engstrom *et al*. 2004) and physical modeling of marginal burning (Zhou *et al*. 2005). With additional laboratory experimentation and field validation, we hope to provide land managers with a tool to improve their ability to predict prescribed burn success in live fuels.

Summary

Current fire spread models do not adequately model the transition between no spread and spread in live fuels. We conducted 125 experiments to determine the importance of fuel and environmental variables on fire spread success for four different species of chaparral in the laboratory. Analysis of these 125 fires indicated the importance of wind velocity and dry loading on fire spread success in live fuels. Fuel bed depth did not affect fire spread success. Increasing moisture content decreased the probability of successful spread. This has also been observed in dead woody fuels. Sustained wind-aided fire spread in live fuels has been demonstrated at moisture contents higher than previous dead woody fuel experiments. A logistic model to predict fire spread success using wind velocity, slope, moisture content and fuel loading has been developed. 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. Additional laboratory experimentation and comparison with field scale results are necessary before equation (3) can be used by land managers to predict the success of planned prescribed fire operations.

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