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Fire spread in chaparral – a comparison of laboratory data and model predictions in burning live fuels

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Abstract. Fire behaviour data from 240 laboratory fires in high-density live chaparral fuel beds were compared with model predictions. Logistic regression was used to develop a model to predict fire spread success in the fuel beds and linear regression was used to predict rate of spread. Predictions from the Rothermel equation and three proposed changes as well as two physically based models were compared with observed spread rates of spread. Flame length–fireline intensity relationships were compared with flame length data. Wind was the most important variable related to spread success. Air temperature, live fuel moisture content, slope angle and fuel bed bulk density were significantly related to spread rate. A flame length–fireline intensity model for Galician shrub fuels was similar to the chaparral data. The Rothermel model failed to predict fire spread in nearly all of the fires that spread using default values. Increasing the moisture of extinction marginally improved its performance. Modifications proposed by Cohen, Wilson and Catchpole also improved predictions. The models successfully predicted fire spread 49 to 69% of the time. Only the physical model predictions fell within a factor of two of actual rates. Mean bias of most models was close to zero. Physically based models generally performed better than empirical models and are recommended for further study.

Additional keywords: *Adenostoma fasciculatum*, *Arctostaphylos glandulosa*, *Ceanothus crassifolius*, *Quercus berberidifolia*.

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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 and in similar fuel beds in both boreal and Mediterranean areas of the world. These fires can be significant events and 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. Empirical models for fire spread in various live fuels from other Mediterranean regions (Marsden-Smedley *et al.* 2001; Fernandes 2001; Bilgili and Saglam 2003; De Luis *et al.* 2004; Saglam *et al.* 2008; Cheney *et al.* 2012; Cruz *et al.* 2013) exist and Anderson *et al.* (2015) recently developed a model using fire spread data from many of these studies. The final variables in the model were wind velocity, shrub height and moisture content for the dead and live components of the fuel complex. The model assumed continuous fire spread and did not predict the threshold conditions under which a fire would transition from no spread to spread (e.g. Weise *et al.* 2005). The Rothermel model (Rothermel 1972) provides the basis for many fire management tools in the USA (Wells 2008). Owing to flexibility of the fuel model concept (Keane 2013), the Rothermel model has been applied to a variety of vegetative fuel beds around the world with varying success (Sylvester and Wein

*Retired.

1981; Van Wilgen 1984; Van Wilgen *et al.* 1985; Malanson and Trabaud 1988; Marsden-Smedley and Catchpole 1995; Blackmore and Vitousek 2000; Dimitrakopoulos 2002; Stocks *et al.* 2004; Streeks *et al.* 2005; Fernandes and Rigolot 2007; Cruz and Fernandes 2008; Cheyette *et al.* 2008; Bacciu 2009; Wu *et al.* 2011). Recognising that fuel models are idealised simplifications of natural fuel beds and do not include many components, Sandberg *et al.* (2007) reformulated the Rothermel model to allow the direct use of inventoried fuel properties in the Fuel Characteristic Classification System (Ottmar *et al.* 2007).

The formulation of the Rothermel model (Frandsen 1971; Rothermel 1972; Albini 1976*a*) assumed that a fire would spread in the absence of wind and slope and required the presence of dead, fine fuels to propagate the fire; however, fire spread in fuel beds of only live material has been reported (Cohen and Bradshaw 1986; Martin and Sapsis 1987). The model does not predict a non-zero rate if wind or slope is required for successful spread (Weise and Biging 1997). The model accuracy was described as 'a factor of two' (Albini 1976*b*). Since its operational deployment, experiments and modelling of the effects of fuel moisture (Wilson 1982, 1985, 1990) and wind (Catchpole *et al.* 1998*b*) have not been implemented. Limited modelling and validation of fire spread in live shrub fuels in the USA has occurred (Albini 1967; Lindenmuth and Davis 1973; Rothermel and Philpot 1973; Hough and Albini 1978; Albini and Anderson 1982; Brown 1982; Frandsen 1983; Cohen 1986*a*), again with varying success. Although many of these models included factors related to the chemical composition of the fuel, its role on ignition and fire spread is still an open question (Finney *et al.* 2013).

In the Rothermel model, heat transfer mechanisms were not explicitly described; a 'lumped capacity' approach was used. Recent experiments and modelling focussed on ignition of fuels, particularly live fuels, have demonstrated the importance of convection and flame contact to flame propagation (Weise *et al.* 2005; Zhou *et al.* 2005*b*; Fletcher *et al.* 2007; Anderson *et al.* 2010; McAllister *et al.* 2012; Cohen 2015; Yashwanth *et al.* 2015, 2016; Finney *et al.* 2015).

Pagni and Peterson (1973) developed a physical model from the conservation of energy equation that requires flame length as an input. The model explicitly contained several heat-transfer terms and showed good agreement between observed and predicted spread rates in grass and chaparral (Peterson 1972). Koo *et al.* (2005) subsequently modified the original model to account for a finite-width fuel bed.

Balbi and coworkers developed a 3-D simplified physical model based on mass, energy and momentum balances. The original formulation simplified gas-phase equations to produce faster calculations (Balbi *et al.* 2007, 2009). Heat transfer by flame and ember radiation was the dominant mechanism. The model contained a flame height–heat release correlation that was confirmed for chaparral fuels (Sun *et al.* 2006). The original and refined models have been successfully validated and evaluated using data from Portuguese shrub–heathlands and pine needle–palmetto frond fuel beds (Nelson and Adkins 1986; Fernandes 2001).

Although there are several different models and modelling systems that have been reviewed (Catchpole and de Mestre 1986; Weber 1991; Pastor *et al.* 2003; Sullivan 2009*a*, 2009*b*, 2009*c*; Cruz and Alexander 2013; Cruz *et al.* 2015), we chose to focus on Rothermel model variants (Rothermel, Rothermel2, Wilson, Cohen, Catchpole) because the original model is the basis for US fire management systems. Because there is a need to produce a more physically based fire model for operational use, two fast physical models (Pagni/Koo and Balbi) were included. The Lindenmuth and Davis (1973) and Anderson *et al.* (2015) models were not included because our data fell outside the parameters under which the models were fitted or required data were not available. The present paper reports the results of a comparison between observed and predicted fire behaviour in live chaparral fuel beds burned in a laboratory.

Methods

Experimental data

The effects of wind velocity (U), fuel moisture content (LFM), fuel bed depth (δ) and slope (tan (θ)), where θ is slope angle, on flame propagation in live fuels were investigated in a series of 240 experimental fires in single-species fuel beds composed of one of four chaparral shrub species: chamise (*Adenostoma fasciculatum* Hook. & Arn.), hoaryleaf ceanothus (*Ceanothus crassifolius* Torr.), Eastwood's manzanita (*Arctostaphylos glandulosa* Eastw.) and scrub oak (*Quercus berberidifolia* Liebm.) (Natural Resources Conservation Service 2016). Note that Eastwood's manzanita was incorrectly identified as *Arctostaphylos parryana* Lemmon in earlier publications (Engstrom *et al.* 2004; Weise *et al.* 2005; Zhou *et al.* 2005*c*). The objective of the experiment was to identify marginal fire spread conditions for live fuels with moisture content exceeding Wilson's experiments (Wilson 1985). The dataset consists of several different sets of experiments, all of which used the same experimental techniques. The sets consisted of spread under no wind and no slope conditions, spread on slopes (Zhou *et al.* 2007) and spread with wind. A formal exploratory experimental design such as response surface methodology (Khuri and Cornell 1996) was not used, but wind velocity–slope percentage–fuel bed depth combinations that would not likely produce successful spread (based on results of previous experiments in the series) were not attempted. As a result, the matrix representing a full factorial experiment is sparse (see Appendix 1). The only seasonal variable, live moisture content, was treated as a covariate; effects of seasonal changes in non-structural carbohydrates and other compounds, although hypothesised as significant (Philpot 1969; Lindenmuth and Davis 1973; Susott 1982*a*, 1982*b*), were viewed as minor factors and not considered experimentally. The importance of the chemical composition is still an open question (Finney *et al.* 2013; Gallacher 2016). Owing to experimental objective, fuels were typically not collected in the late fall when many wildfires occur in southern California. For chamise, 8 to 20 fires were burned monthly between January and October. Nearly half of the broadleaf fuel beds were burned in April and May when fuel moisture is typically highest owing to the presence of new growth; the remaining 75 fires were evenly distributed between July and November.

Fuel beds (2 m long × 1 m wide × various depths) were constructed of live branch and foliage material collected from living chaparral growing nearby in the morning and burned within a few hours to minimise moisture loss. Flowers and fruits were removed to reduce variation in the fuel bed. Branches

<0.63 cm in diameter with foliage comprised the fuels. Although shrub fuel beds often contain a mixture of live and dead fuels, homogenous beds composed of only live material were the only feasible method to extend Wilson's experiments because it is not possible to saturate woody fuels much above 40%. The fuel beds were raised by 40 cm to simulate a shrub canopy with an open gap underneath (e.g. Albini 1967). Air could be entrained from the fuel bed ends; metal sheeting prevented side entrainment. Moisture content of a 5-g sample was determined immediately before ignition using a Computrac[1] moisture analyser. Each fire was ignited along the 1-m side with a 50-cm flame zone using excelsior and a small amount of isopropyl alcohol.

Three 50.8-cm fans (Air King Model 9700) induced air flow to simulate wind. No attempt was made to 'smooth' out the fan-induced vorticity or produce laminar flow; observed flame behaviour appeared natural, suggesting that the vorticity was not excessive. See Pitts (1991) for a discussion of laminar and turbulent flow and effects on laboratory fire experiments. Velocity profiles measured above the fuel bed without a fire indicated the formation of a boundary layer near the surface and an area with average velocity between 1.5 and 2 m s^{-1} above the fuel bed (Fig. 1). Above the fan height, the velocity dropped off rapidly. The flames were contained within and sometimes extended above this zone; direct measurement of velocity in the flame environment was not possible with available instrumentation and the thermal particle image velocity (TPIV) (Zhou *et al.* 2003) algorithm was not used because of the experimental configuration. The original experiment was designed to determine if wind presence was important to fire spread success so lack of a logarithmic wind profile (Albini and Baughman 1979) was not considered a limiting factor. If a fire spread the length of the fuel bed, rate of spread (ROS) was calculated from thermocouples and video images. Mean flame length, angle (from horizontal) and depth were estimated for the 60 fires with video.

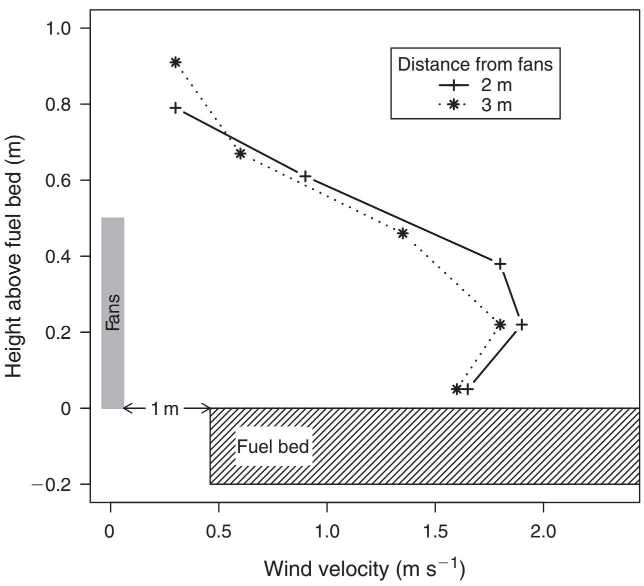

Fig. 1. Mean centre-line wind velocity profiles in laboratory above live chaparral high-density fuel beds. Mean calculated from 1-min duration 1-Hz point samples in vertical and horizontal transects above the fuel bed with an air flow mass velocity transducer (FMA-903). No variability estimated because original data not available.

Model evaluation

Fire spread predictions were made for seven models: Rothermel, Rothermel2, Cohen, Wilson, Catchpole, Pagni/Koo and Balbi. Parameters describing two fuel bed types were used – the original static chaparral fuel model adjusted for depth and loading (Albini 1976*b*) and the dynamic chaparral models (Rothermel and Philpot 1973). Chamise and broadleaf surface area to volume ratios (σ) for foliage and branches <0.63 cm in diameter were 72, 58, 21 and 10.5 cm^{-1} respectively (Countryman 1982; Cohen 1986*b*). The broadleaf values were obtained by averaging the values for *Arctostaphylos patula* Greene, *Ceanothus velutinus* Douglas ex Hook., and *Castanopsis sempervirens* (Kellogg) Hjelmqvist.

Rothermel required moisture of extinction for live and dead fuels, which can be user-determined (Burgan 1987). Estimating live fuel extinction moisture based on fractional loading did not work for our purely live fuel beds (Fosberg and Schroeder 1971; Albini 1976*a*). Similarly to Sylvester and Wein (1981), we set extinction moisture content at the maximum moisture content we observed spread under no-wind and no-slope conditions (Weise *et al.* 2015): 0.65 and 0.74 for chamise and broadleaf respectively. Live fuel extinction moisture of fuel model 4 (Rothermel) and the experimental values (Rothermel2) were used. Sampling determined the foliage and branch mass proportions of 0.10/0.90 and 0.27/0.73 for chamise and broadleaf respectively.

Modelling of the amount of energy in the fuel beds differed between models. A low heat of combustion (18 608 kJ kg^{-1}) was used for Rothermel and Rothermel2. Heat of combustion of pyrolysed gases was used for Wilson and Catchpole (Susott 1982*a*): 12 960, 11 790 kJ kg^{-1} for chamise and broadleaf respectively. For Cohen, the heat of combustion *h* was calculated dynamically (Eqn 1):

$$
\begin{aligned}
&h = 2.326(9613 - D + 0.1369D^2 - 0.000365D^3) \qquad \text{foliage}\\
&h = 2.326(9509 - 10.74D + 0.1359D^2 - 0.000405D^3) \quad \text{branches}\\
&\qquad \text{FIRECAST redefinition of } D\\
&\mathit{if}\ (month < 5)\ \mathit{then}\ month = 11\\
&D = (month \times 30 + day\ of\ month) - 150\\
&\mathit{if}\ (month > 9) D = D - 60 \qquad (1)^2
\end{aligned}
$$

For fires without video, we estimated flame length using the average of flame length correlations using mass-loss rate (Byram 1959; Fons *et al.* 1963; Thomas 1963; Albini 1981), which was estimated as 0.67ROS(*oven-dry loading*).

Statistical analysis

Version 3.2.2 of the *R* statistical package (R Core Team 2015) was used for analyses and plotting. As only subsets of the data

[1]The use of trade names and model numbers is for informational purposes only and does not constitute endorsement by the USDA.
[2]The computer code (Cohen 1986*b*) is available in Weise *et al.* (2015) and contains the equations.

have been previously analysed (Weise *et al.* 2005; Zhou *et al.* 2005*c*), the full dataset was analysed in two steps: fire spread success and rate of spread. Fire spread success was related to fuel and environmental variables using stepwise logistic regression (*stepAIC*, *glm* (Venables and Ripley 2002)) and a classification tree (Breiman *et al.* 1998). Only the logistic regression results will be presented because both methods generally agreed in variable selection. Deviance and odds ratios measured relative importance to spread success. Area under the receiver operating characteristics curve (*auc* (Robin *et al.* 2011)) measured the quality of the classification. Stepwise linear regression identified the variables affecting ROS including $\sigma\beta\delta$ and $(\sigma\lambda)^{0.5}$ where $\sigma, \beta, \delta, \lambda$ are fuel particle surface area to volume ratio (cm^{-1}), fuel bed packing ratio, fuel bed depth (cm) and porosity respectively: $(\sigma\lambda)^{0.5} = [(1-\beta)/\beta]^{0.5}$ (Curry and Fons 1940; Anderson and Rothermel 1965; Pagni and Peterson 1973).

Non-linear least-squares (*nls* routine) fitted $L_f = \alpha_0 I_B{}^{\alpha_1}$ and its inverse relationship $I_B = \alpha_2 L_f{}^{\alpha_3}$ where L_f and I_B are flame length and fireline intensity respectively and α_x are the regression coefficients (Byram 1959). Intensity was calculated using fixed and variable heat content and two models were fitted. The Akaike Information Criterion (AIC, Sakamoto *et al.* (1986)) determined the better model. Confidence bands were estimated using *predictNLS* (Spiess 2013) and our fitted models were visually compared with other shrub relationships.

We compared censored empirical cumulative distribution functions (ecdf) of the non-zero actual and predicted ROS. Predicted values smaller than the minimum observed ROS were set to zero; zero values were removed from the empirical distributions. The Cramer–von Mises test compared ecdf using *goftest* (Darling 1957; Faraway *et al.* 2014). Agreement between predicted and observed spread success was analysed with a 2×2 contingency table (Zar 1974) for all models except Pagni because it only used cases that spread. A significant Chi-square statistic (χ^2) indicates a relationship between prediction and outcome. The *stepAIC* and *glm* routines were applied to the model predictions to identify important variables influencing success. Error metrics of mean absolute error (MAE), mean bias (MB), root mean squared error (RMSE), fraction of predictions within a factor of two (FAC2) and normalised mean absolute error NMAE = MAE/$\bar{y}$ where $\bar{y}$ is mean ROS (Mayer and Butler 1993; Carslaw and Ropkins 2012; Cruz and Alexander 2013; Carslaw 2015) were calculated with *modStats*. Mean absolute percentage error (MAPE) was not used because it is undefined when the observed ROS equals zero. Correlation coefficients between actual and predicted spread rates were calculated and tested for significance using *rcorr*.

Results

Experiments

Data for the 240 fires (113 chamise, 127 broadleaf) are available (Weise *et al.* 2015); 123 fires spread (70 chamise, 53 broadleaf). We refer the interested reader to Weise *et al.* (2005) and Zhou *et al.* (2005*a*) for fuel, fuel bed, wind and slope configuration and flame images. ROS ranged from 0.06 to 1.77 m min^{-1}, much slower than field spread rates of 3.5 m min^{-1} (Abell 1940; Chandler *et al.* 1963). Live fuel moisture of the fresh fuels ranged from 0.54 to 1.06 immediately before ignition with oven-dry fuel loadings of 1.1–4.9 kg m^{-2} (Table 1). This moisture content range is typical of chaparral species in this region (Weise *et al.* 2005). Laboratory fuel beds had higher packing ratios than natural chaparral stands (Countryman and Philpot 1970; Rundel and Parsons 1979; Countryman 1982). Correlation between the fuel and environmental variables was generally low (Table 2), suggesting independence. Temperature and relative humidity were correlated, which was expected, and the two derived fuel bed properties ($\sigma\beta\delta, \sigma\lambda$) were highly correlated with depth and bulk density.

Flame data came from chamise fuel beds (59 of 60 fires). Flame length ranged from 0.54 to 2.80 m (mean coefficient of variation (CV) = 11%) and flame depth ranged from 0.15 to 0.73 m (mean CV = 18%). Mean (circular variance) of flame angle (Jammalamadaka and Lund 2006) was 86° (0.006) and 72° (0.008) for the 0 and 2-m s^{-1} wind respectively, indicating that the data were closely grouped. Complete consumption of the fuel beds was observed; fireline intensity ranged from 68 to 2297 kW m^{-1}. Mean intensity using a constant heat content was 104 kW m^{-1} smaller than with variable heat content.

Table 1. Summary of laboratory experimental fires

Type[A]	Wind (m s^{-1})	Slope (%)	n	Fuel mass (kg m^{-2})	Moisture content	Spread success[B]	Spread rate (m min^{-1})
B	0	<0	13	1.77–3.92	0.58–0.74	0.31	0.10–0.18
	0	0	26	1.07–4.86	0.54–1.06	0.15	0.08–0.17
	0	1–30	17	1.92–3.78	0.54–0.74	0.35	0.14–0.60
	0	>30	48	1.65–4.90	0.54–1.04	0.48	0.10–1.36
	2	0	23	1.07–4.86	0.66–1.06	0.70	0.06–0.37
C	0	<0	19	1.78–3.53	0.49–0.60	0.79	0.08–0.21
	0	0	37	1.39–3.53	0.30–0.91	0.43	0.08–0.38
	0	1–30	11	1.28–3.16	0.09–0.66	0.18	0.47–0.64
	0	>30	23	1.39–3.21	0.55–0.80	0.65	0.13–1.77
	2	0	18	1.42–3.41	0.26–0.91	0.94	0.18–0.94
	2	1–30	4	1.28–3.41	0.26–0.64	1.00	0.55–0.88
	2	>30	1	1.44	0.80	1.00	1.45

[A]B, *Ceanothus crassifolius* Torr., *Quercus berberidifolia* Liebm., or *Arctostaphylos glandulosa* Eastw.; C, *Adenostoma fasciculatum* Hook. & Arn.
[B]Proportion of fires that spread entire length of fuel bed.

Stepwise logistic regression chose all variables but relative humidity to predict spread success (Table 3). All coefficients were significant except the intercept and relative humidity. The AIC for the logistic model was 201. Wind velocity and $\sigma\beta\delta$ accounted for 79% of the deviance reduction. The odds ratio for wind (392) showed the dramatic effect that presence of wind had on fire spread success; fire in chamise was four times more likely to spread. The coefficients and odds ratios for $\sigma\beta\delta$, air temperature and slope indicate that the probability of spread increased as these variables increased and decreased as live fuel moisture content increased. Area under the curve for the logistic regressions was 0.93, 0.87 and 0.91, for chamise, broadleaf and both fuel types combined, suggesting that the chamise model performed better than the broadleaf model.

Relative humidity, air temperature, fuel depth, wind velocity, Tan(θ) where θ is slope angle, LFM, fuel heat content, bulk density, fuel type, $\tan(\theta)^2$, U^2, $\sigma\beta\delta$, *and* e^{LFM} were initially included in the regression equation for ROS. The residuals were heteroscedastic; log-transformation of ROS produced constant variance. The final fitted model (Eqn 2) accounted for 72% of the variation and was highly significant (F-statistic = 50.59, degrees of freedom = 6, 116). All coefficients were significant; however, the effect due to wind was not significant (Table 4). Correlation between most coefficients was generally low except for heat content and the intercept term, suggesting that the selected variables were reasonably independent:

$$\log(\text{ROS}) = 2.740 - 0.017(\textit{air temperature}) + 0.198(\textit{wind velocity}) + 2.202\tan(\theta) - 0.015(\textit{moisture content}) - 0.00008(\textit{heat content}) - 0.120(\textit{bulk density}) \quad (2)$$

Four flame length–fireline intensity relationships for shrub fuels (Alexander and Cruz 2012) were selected for comparison: fynbos (Van Wilgen 1986), Galician shrublands (Vega Hildago *et al.* 2009), Australian and New Zealand heathlands (Catchpole *et al.* 1998*a*), and Mediterranean heathland (Fernandes *et al.* 2000). Variable and fixed heat content yielded similar flame length models $\widehat{\alpha}_0 = 0.20,\ 0.21; \widehat{\alpha}_1 = 0.34,\ 0.35)$ for the variable and fixed heat models respectively. Based on a smaller AIC, the variable heat content model was chosen: $L_f = 0.2I_B^{0.34}$ (Fig. 2). The inverse fitted model, $I_B = 160.8L_f^{2.16}$, was significant ($\alpha = 0.05$); confidence intervals (95%) for $\widehat{\alpha}_2$ and $\widehat{\alpha}_3$ were [98, 239] and [1.62, 2.77] respectively (Fig. 3). Only the Galician shrublands model was statistically similar to the data from the present study.

Table 2. Correlation between fuel and environmental variables for chaparral laboratory fire experiment

RH, relative humidity; T, air temperature; θ, slope angle; LFM, live fuel moisture content; HC, heat content; σ, surface area to volume ratio; β, packing ratio (solid fuel volume to total fuel bed volume); δ, fuel bed depth; λ, fuel bed porosity

	RH	T	Depth	Wind	Tan(θ)	LFM	HC	Bulk density	$\sigma\beta\delta$
T	–0.77								
Depth	0.22	–0.15							
Wind	0.03	–0.15	0.12						
Tan(θ)	0.22	–0.21	–0.22	–0.17					
LFM	–0.20	0.06	0.02	0.16	0.28				
HC	0.51	–0.32	–0.04	–0.03	0.21	–0.44			
Bulk	–0.39	0.38	–0.38	–0.22	0.10	0.04	–0.28		
$\sigma\beta\delta$	0.05	0.03	0.87	0.01	–0.23	–0.07	–0.11	0.06	
$\sigma\lambda$	0.45	–0.45	0.37	0.25	–0.08	–0.03	0.30	–0.96	–0.04

Spread model comparison

The slight differences in packing ratio for the Rothermel variants were of no practical importance to the model predictions. In general, the range of predicted spread rates was similar to observed with the exception of the Rothermel model (Fig. 4). Because 117 fires failed to spread, the actual percentile value for a rate of spread value of zero in the ecdf was 0.488 (117/240); this value is shown on the plots as a dotted horizontal line. Rothermel predicted zero ROS for all but one dry fuel bed (0.09 moisture content). Increasing the live fuel extinction moisture dramatically improved Rothermel2; the ecdfs of Rothermel2 and Cohen did not differ significantly. Cohen predictions were the highest of the models and greater than the actual data. Wilson and Catchpole predictions differed from Cohen but not each other. Balbi and Catchpole predicted fewer cases of no spread (lower probability of zero) (Fig. 4). Wilson, Rothermel2 and

Table 3. Summary of fitted logistic model to predict fire spread success in laboratory fuel beds

All variables had one degree of freedom. s.e., standard error

Variable	Deviance	Coefficient	s.e.	Z^A	Pr > Z^B	Odds ratio
Intercept	332.6	5.90	4.29	1.38	0.169	
Wind velocity	84.1	5.97	0.93	6.40	<0.0001	392.00
$\sigma\beta\delta$	32.5	0.24	0.04	5.95	<0.0001	1.27
Chaparral type	9.9	–1.44	0.51	2.81	0.005	0.24
Air temperature	8.2	0.17	0.04	4.76	<0.0001	1.19
Heat content	5.9	-3.9×10^{-4}	1.4×10^{-4}	–2.75	0.006	1.00
Slope	3.9	0.07	0.01	5.99	<0.0001	1.08
LFM	3.3	–0.11	0.02	–5.18	<0.0001	0.89
Residual (d.f. = 232)	184.8					

[A]Standard normal variate (Zar 1974).
[B]Probability of a greater Z-value.

Table 4. Summary of fit of regression model for log-transformed rate of spread
s.d., standard deviation; MSE, mean squared error; *t*, Student's *t* statistic

Term	Model fit			Coefficient estimates			
	MSE	*F*	Prob > *F*	Estimate	s.d.	*t*	Prob > *t*
Intercept (I)				2.740	0.925	2.96	0.004
Temperature (T)	14.81	87.50	<0.001	–0.017	0.007	–2.57	0.011
Wind velocity (W)	0.24	1.41	0.240	0.198	0.050	3.94	<0.001
Tan(θ)	29.33	173.26	<0.001	2.202	0.164	13.39	<0.001
LFM	2.90	17.14	<0.001	–0.015	0.003	–4.72	<0.001
Heat content (H)	0.33	1.96	0.160	-8×10^{-5}	-3×10^{-5}	–2.87	0.005
Bulk density (B)	3.77	22.25	<0.001	–0.120	0.025	–4.72	<0.001
Residual	0.17						

Correlation of regression coefficients	I	T	W	Tan(θ)	LFM	H
T	–0.24					
W	0.06	0.37				
Tan(θ)	0.43	0.31	0.45			
LFM	–0.63	–0.20	–0.43	–0.62		
H	–0.96	0.12	–0.16	–0.48	0.61	
B	–0.49	–0.14	0.15	–0.19	0.13	0.33

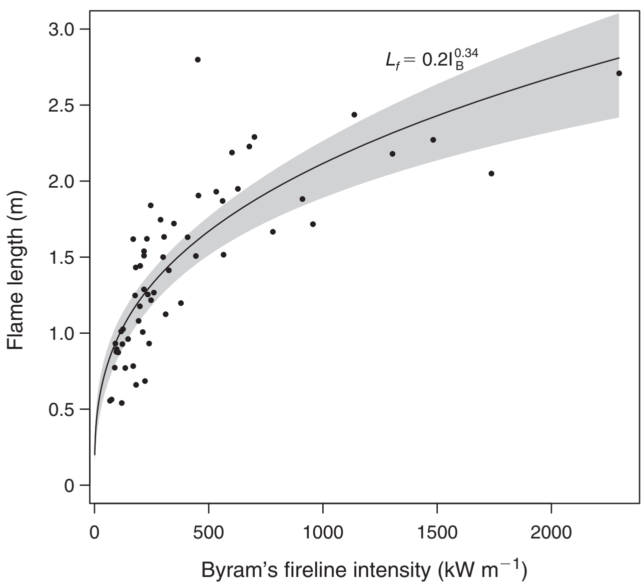

Fig. 2. Observed flame length and calculated Byram's fireline intensity for fire spreading in high-bulk-density fuel beds composed of live chaparral foliage and branches less than 0.63 cm in diameter. Fitted line with 95% confidence band (grey area) estimated.

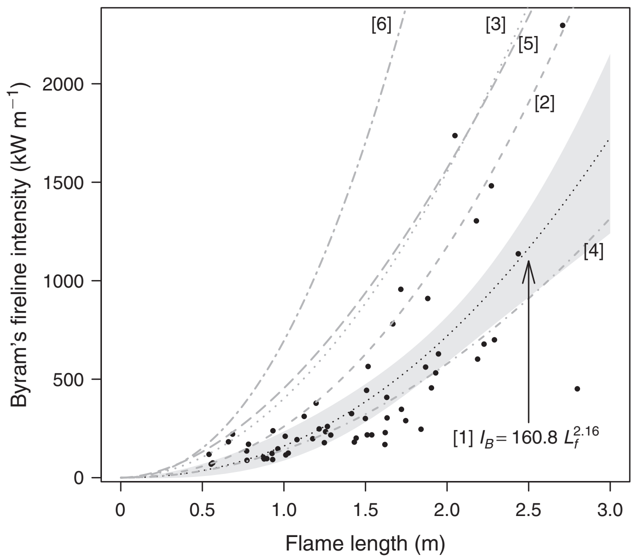

Fig. 3. Comparison of various fireline intensity-flame length relationships developed for shrub fuels. Models are [1] current study; [2] Byram (1959); [3] Van Wilgen (1986); [4] Vega *et al.* (1998); [5] Catchpole *et al.* (1998*a*); and [6] Fernandes *et al.* (2000). Monte-Carlo simulation used to estimate 95% confidence band (grey area).

Cohen models predicted more cases of no fire spread than actually occurred.

The χ^2 tests indicated there was a relationship between actual and predicted spread for Rothermel2, Cohen, Wilson, Catchpole and Balbi in chamise (Table 5) and for all models in broadleaf fuels; the statistic was undefined for Rothermel. The percentage of correctly classified fires ranged from 49% ((43 + 1 + 74 + 0)/240) for Rothermel to 69% for Wilson. In chamise, the range was 39% (Rothermel) to 76% (Balbi); in broadleaf chaparral, the range was 58% (Rothermel) to 64% (Wilson).

The logistic models that identified the variables related to agreement between actual and predicted spread success contained three to seven variables (Table 6). When ranked by deviance reduction, the presence of wind accounted for the largest reductions. It was selected in all models; air temperature, slope ($\tan(\theta)$) and fuel bed surface area ($\sigma\beta\delta$) were selected in four of six equations.

The error metric FAC2 ranged from 0 for Rothermel to 0.86 for Pagni in chamise (Table 7); FAC2 was higher in chamise for

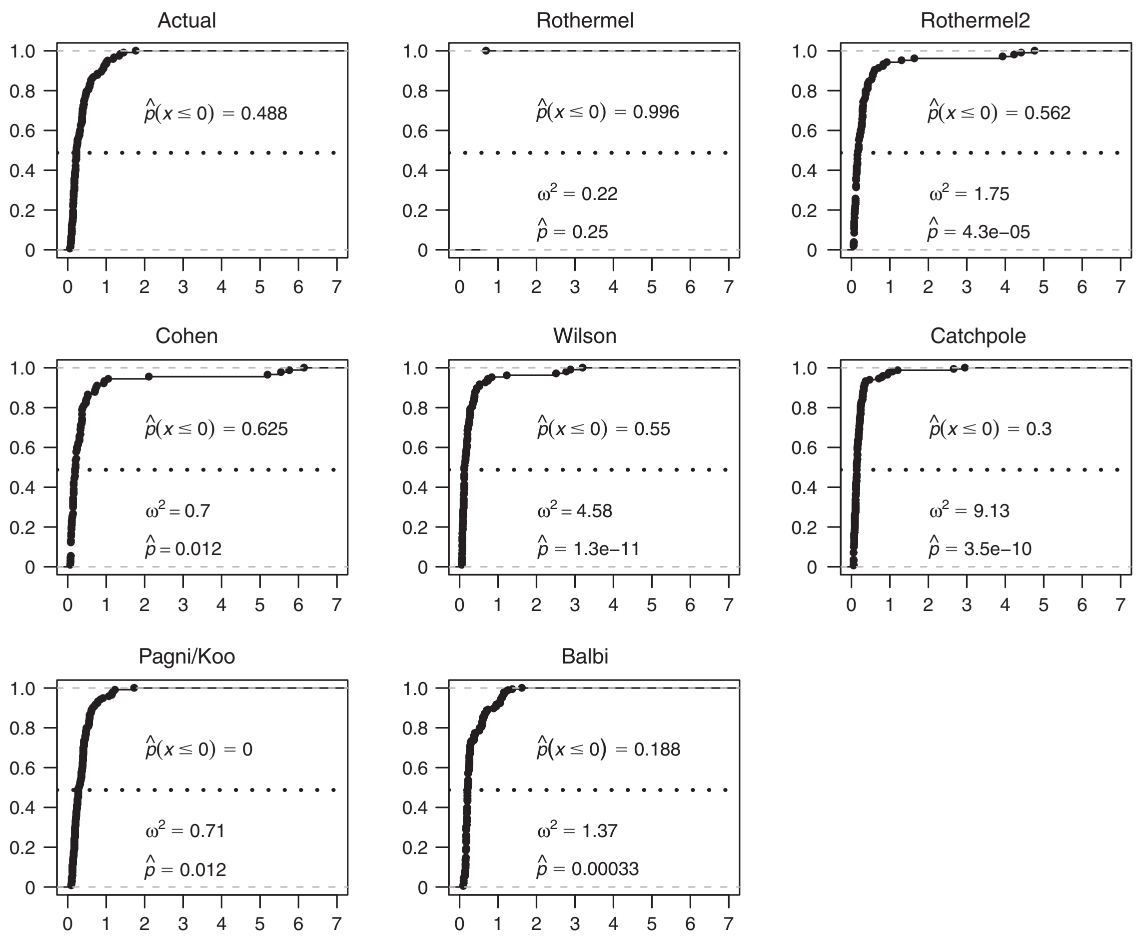

Fig. 4. Empirical cumulative distribution function of actual and predicted rate of spread for laboratory fires in chaparral fuels; ω^2 is the Cramer–von Mises statistic and $\hat{p}$ is the probability of achieving a greater value of ω^2 (Csorgo and Faraway 1996).

Table 5. Classification of fire spread success in chaparral fuel beds by various rate of spread models
Pagni model not included because only predictions exist if fire spread successfully. AUC is area under curve of the classification

Model		Actual								AUC		Rate
		Chamise (C)				Broadleaf (B)				C	B	
		No	Yes	χ^{2A}	P^B	No	Yes	χ^2	P			
Rothermel	No	43	69	0.00	1.000	74	53			0.507	0.500	0.49
	Yes	0	1			0	0					
Rothermel2	No	29	25	9.51	0.002	53	28	3.94	0.050	0.659	0.608	0.63
	Yes	14	45			21	25					
Cohen	No	29	25	9.51	0.002	58	38	0.43	0.510	0.659	0.533	0.61
	Yes	14	45			16	15					
Wilson	No	20	7	17.57	2×10^{-5}	67	38	6.40	0.010	0.694	0.585	0.69
	Yes	23	63			7	15					
Catchpole	No	20	14	7.68	0.006	31	7	10.79	0.001	0.625	0.645	0.64
	Yes	23	56			43	46					
Balbi	No	21	5	23.84	1×10^{-6}	19	0	14.05	2×10^{-4}	0.709	0.628	0.66
	Yes	22	65			55	53					

[A]Calculated Chi-square statistic.
[B]P is probability of a greater χ^2.

Table 6. Variables selected by logistic regression to predict agreement between model prediction and observed fire spread success

Numbers indicate the order of the variables by descending deviance (1 denotes largest deviance) and the variables are listed in the table in decreasing order based on the number of times the variable was selected

Variable	Rothermel	Rothermel2	Cohen	Wilson	Catchpole	Balbi	Mean
Wind velocity	1	1	1	2	1	2	1.33
Temperature	3	2	2			5	3
$\tan(\theta)$	6	3	3	1			3.25
$\sigma\beta\delta$	2		6		2	3	3.25
Heat content	5		4				4.5
$\log(\sigma\beta\delta)$			5			4	4.5
Chaparral type	4					1	2.5
LFM	7						7
Relative humidity				3			3
Bulk density							

Table 7. Error measures associated with observed and predicted rate of spread in laboratory fires in chaparral fuel beds

Error measures associated with observed and predicted rate of spread in laboratory fires in chaparral fuel beds. FAC2, factor of two; MB, mean bias; MAE, mean absolute error; NMAE, normalised mean absolute error; RMSE, root mean squared error

Model	Fuel type	FAC2[A]	MB[B]	MAE[C]	NMAE[D]	RMSE[E]
Rothermel	Broadleaf (B)	0.00	–0.15	0.15	1.00	0.29
	Chamise (C)	0.01	–0.23	0.23	0.98	0.40
Rothermel2	B	0.19	–0.07	0.16	1.10	0.30
	C	0.32	0.06	0.33	1.42	0.77
Cohen	B	0.14	–0.10	0.15	1.05	0.29
	C	0.32	0.13	0.39	1.66	1.01
Wilson	B	0.07	–0.13	0.14	0.97	0.29
	C	0.29	0.03	0.24	1.03	0.50
Catchpole	B	0.15	–0.06	0.15	1.01	0.25
	C	0.41	–0.01	0.19	0.81	0.39
Pagni	B	0.86	–0.05	0.15	0.43	0.22
	C	0.86	0.05	0.18	0.49	0.30
Balbi	B	0.40	0.16	0.21	1.43	0.33
	C	0.63	0.03	0.14	0.61	0.25
Rothermel	All	0.01	–0.19	0.19	0.99	0.35
Rothermel2	All	0.26	–0.01	0.24	1.29	0.57
Cohen	All	0.24	0.01	0.27	1.41	0.72
Wilson	All	0.20	–0.05	0.19	1.00	0.40
Catchpole	All	0.28	–0.03	0.17	0.89	0.32
Pagni	All	0.86	0.01	0.17	0.47	0.27
Balbi	All	0.51	0.10	0.18	0.95	0.30

[A]FAC2 = fraction of predictions satisfying $0.5 \le \hat{y}_i/y_i \le 2.0$

[B]$\mathrm{MB} = \frac{1}{n}\sum_{i=1}^{n}(\hat{y}_i - y_i)$

[C]$\mathrm{MAE} = \frac{1}{n}\sum_{i=1}^{n}|\hat{y}_i - y_i|$

[D]$\mathrm{NMAE} = \mathrm{MAE}/\bar{y}$

[E]$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(\hat{y}_i - y_i)^2}$

where $y_i, \hat{y}_i, \bar{y}, n$ are observed, predicted, and mean rate of spread; n is number of observations.

all models. In broadleaf fuels, all models except Balbi underestimated ROS (MB $<$ 0); bias of Rothermel2, Catchpole, and Pagni was less than 0.1 m min^{-1}. MAE was smaller in the broadleaf fuels except for the Balbi model and ranged from 0.14 to 0.39 m min^{-1}. Relative size of error (NMAE) was greater than one in most cases, indicating that prediction error was generally larger than the actual ROS. Only Pagni had NMAE less than 0.5 for both fuel types. In most cases (exceptions are Rothermel2 and Cohen in chamise), the RMSE values were fairly consistent among the models and ranged from 0.22 to 0.50 m min^{-1}. When fuel type was eliminated, virtually none of the Rothermel predictions fell within a factor of 2 of the actual rate of spread. Twenty to nearly thirty per cent of the other Rothermel models fell within a factor of 2 and more than half of the Pagni and Balbi predictions did. All models except Rothermel and Balbi were generally unbiased and the prediction errors (MAE) ranged from 0.2 to 0.3 m min^{-1}. When normalised, most models had errors equivalent to ROS except Pagni with errors less than 50%. In most cases, RMSE was smallest for Pagni. When all five error measures are considered equally, the Pagni model performed best.

Correlation (Pearson's r) between predicted and actual spread rate ranged from undefined to 0.7 (Fig. 5). Rothermel had the lowest correlation values overall, and r was undefined in broadleaf fuels. Increasing the live extinction moisture improved correlation of Rothermel2 for both fuel types; however, only the correlation for chamise was significantly different from zero. In broadleaf fuels, Rothermel2, Cohen and Wilson predictions were not significantly correlated with actual ROS; however, Catchpole, Pagni and Balbi predictions were. Wilson and Catchpole predictions were not correlated with actual ROS. Pagni and Balbi predictions were significantly correlated with actual ROS. In general, correlation was significant in chamise fuels except for Rothermel. Although correlation was significant for many of the models, only Pagni (both fuels) and Balbi (chamise) had correlations greater than 0.50.

Discussion

Much of the data that have been collected worldwide examining fire spread in live shrub fuels has been field-scale data with limited

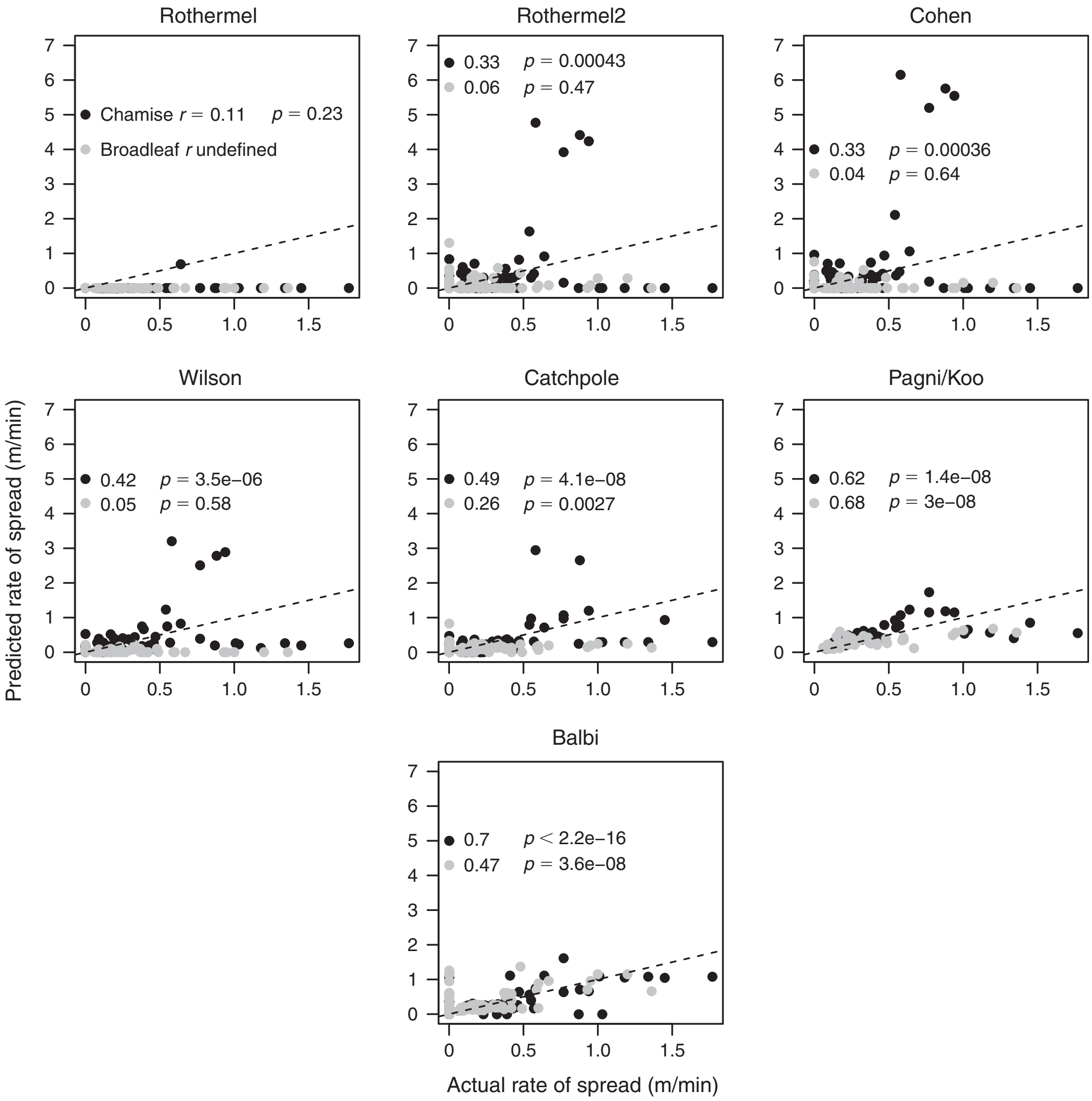

Fig. 5. Predicted vs actual rate of spread of fire in high-bulk-density chaparral fuel beds. Pearson's correlation coefficient (r) calculated for chamise (black dots) and broadleaf (grey dots) fuel types.

replication. These fuel beds contained a mixture of live and dead components, likely producing greater heat release due to the drier dead fuels; the fuel beds in the present study only contain live components. The loading of live material less than 6 mm in diameter in the Galician fuels falls within the range of the present data (1.83 kg m^{-2}). Fuel particles in the Galician fuels were smaller than the chaparral fuels in the present study; however, a higher heat content was measured in the Galician fuels than we assumed. The average wind velocity measured in the field (2.1 m s^{-1}) is similar to the maximum wind velocity in the present experiment (2.0 m s^{-1}). As expected, ROS of the chaparral fires fell in the lower portion of the range for the Galician fuels. The Galician fuels were generally moister, however, wind velocity was greater and the fuel bed contained 8 to 12% dead litter. The fitted fireline intensity–flame length relationship for the Galician fuels predicted lower intensity for a given flame length as a result.

Although many of the physical characteristics of the fuel in fynbos and our live fuel beds were similar, the fynbos fuel beds contained more dead material and finer-sized fuel particles. Measured fire behaviour of the chaparral fuel beds fell in the lower range of the observed fire behaviour in fynbos. Predicted fireline intensity for the fynbos fuels was approximately twice the predicted intensity for chaparral for a given flame height, which may be due to the presence of the dead fuels and finer fuel particles. The range of fuel and environmental conditions in the heathland fuel types (Anderson *et al.* 2015) were comparable with fynbos, which was reflected in the very similar curves (Fig. 3). Similarly, the range of conditions in Fernandes *et al.* (2000) was similar to those in the Galician fuels. The discussion of Alexander and Cruz (2012) regarding the many factors that can affect the statistical fitting of the fireline intensity–flame length relationship is supported by these models; the present study provided support that intensity is a quadratic power of flame length.

When originally proposed, the moisture damping coefficient and the moisture of extinction functioned like a rheostat that moderated the reaction intensity calculation because the role of moisture in fuels is complex (e.g. Nelson 2001; Matthews 2006). Even though the different methods of handling moisture (Rothermel2, Cohen, Wilson, Catchpole) improved the predictions, their similarity of performance suggests that factors other than moisture of extinction are influencing the performance (or lack thereof) of the Rothermel model in these live fuel beds.

Wind presence was found to be the most important variable that influenced the prediction of fire spread success in these live fuel beds. Wind was also the most important variable in determining agreement between model prediction and actual spread success for most of the models. The importance of wind on rate of spread has been recognised from the earliest days of modern organised fire research (Show 1919). Thus, wind affects both fuel particle ignition and propagation of the flame through the fuel bed. It is interesting to note that Lindenmuth and Davis (1973) did not find that wind velocity was as important in their experiments as in these experiments. They concluded that wind was a limiting factor in their experiments because it was required for spread, but its influence once the fire was spreading (without spotting) was not large. Similarly, in the analysis of our experimental data, wind was necessary for spread to occur, but it did not influence rate of spread. A greater range of wind speeds is necessary to determine if our data support Lindenmuth and Davis.

None of the models currently consider the effects of wind on ignition explicitly (e.g. Bilbao *et al.* 2001); however, both Balbi and Pagni models account for convective heat transfer due to the flame above and within the fuel bed. Although the wind profiles in our experiments may differ from other experiments and field studies, the experiments demonstrated the importance of wind and convective flux (Zhou *et al.* 2005*b*) on ignition. As numerous authors have stated, fire spread in porous fuel beds is simply a series of successive ignitions, and conditions in the immediate vicinity of a fuel particle are critical to ignition. The high bulk density of our fuel beds and flow of the buoyant flame gases likely reduced any aberrant flow through the fuel bed caused by the rotary fans at the interface between burning and unburnt fuel. Results might be different in more porous fuel beds. Recent work (e.g. Fletcher *et al.* 2007; Schemel *et al.* 2008; Tachajapong *et al.* 2008; Bianchi and Defossé 2015; Finney *et al.* 2015; Butler *et al.* 2016) points to the dual nature of convection and importance of flame contact in fuel particle ignition and propagation.

The effect of moisture on fire spread in the experiments should be representative of what occurs in natural settings; another limitation of the dataset is wind velocity (0, 2 m s^{-1}). There was a step change in fire behaviour over this very small interval. Although we now have a small wind tunnel that has been used successfully to study fire spread transitions with more precise control of wind (Tachajapong *et al.* 2014; Sanpakit *et al.* 2015), these recent experiments with these low wind speeds can produce flame heights of 2 m or more, which are challenging to manage in a laboratory setting, and so our ability to perform laboratory experiments of field-scale fire behaviour in live fuels continues to be restricted.

Although the dataset used in the present study provided an opportunity to gain an understanding of the important variables that influence marginal fire spread in chaparral fuel beds, it is limited in its applicability to field-scale wildland fire spread. With their higher bulk density, these fuel beds are more akin to forest litter fuel beds and the experimental data used to develop and modify the Rothermel model previously described. As such, results of the current study illustrate that empirical fire behaviour relationships derived for low-moisture dead fuels do not perform well in high-fuel-moisture live fuels that will also burn, thus emphasising the need to better describe the physics and chemistry of fire spread in wildland fuels.

Summary and conclusions

Analysis of a series of 240 experimental laboratory-scale fires in high-bulk-density live chaparral fuels demonstrated the importance of wind velocity, slope and fuel bed surface area on fire spread initiation. Comparison of rate of spread predictions with several models produced a wide range of results. The original Rothermel model performed poorly and failed to predict fire spread in nearly all of the experiments. Proposed and generally unimplemented changes to the Rothermel model improved prediction results and wind was found to be the most important experimental variable related to fire spread success.

Physically based models generally performed better, suggesting that improved understanding of the physical and chemical processes associated with ignition and propagation will improve our ability to predict fire spread in fuel beds that are more complex than fuel beds composed of dead, machined wood. Implementation and evaluation of the Pagni model with suitable modification to predict rate of spread from fuel and environmental variables could be a good first step to developing a physical model as the basis for fire spread and fire danger prediction in surface fuels containing a significant shrub component.

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Appendix 1. Summary of fire spread success in marginal burning experiments by fuel type, wind velocity, fuel bed depth and slope

Table also shows distribution of experiments across all possible combinations of fuel type, wind velocity, fuel bed depth and slope percentage. The numbers in each cell of the table are number of successful fires/number of replications

Fuel[A]	Wind[B]	D[C]	Slope percentage																			
			<0									0	>0									
			100	70	60	50	40	30	25	20	10	0	20	27	30	35	40	45	50	55	60	70
B	0	20	0/1[D]	0/2	0/1		0/2			0/2		0/10	3/9		3/6		2/10	0/4	1/8	1/2	9/9	3/4
		40						2/2		2/3		4/16	0/2				5/8				0/1	2/2
	2	20										7/12										
		40										9/11										
C	0	20			0/1	1/1	1/1	1/2		1/2		5/17	0/1	1/2	0/5	0/3	4/5		1/2	1/2	1/1	2/3
		40			1/1	1/1	2/2	2/3	1/1	3/3	1/1	11/20		1/3			3/4					3/3
	2	20										6/7		1/1			1/1					
		40										11/11		3/3								

[A]Fuel type: B = broadleaf chaparral, C = chamise chaparral.
[B]Nominal wind velocity (m s^{-1}).
[C]Fuel bed depth (cm).
[D]0/1 indicates 0 fires out of 1 total fires spread successfully.