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A laboratory-scale comparison of rate of spread model predictions using chaparral fuel beds – preliminary results

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Abstract
Observed fire spread rates from 240 laboratory fires in horizontally-oriented single-species live fuel beds were compared to predictions from various implementations and modifications of the Rothermel rate of spread model and a physical fire spread model developed by Pagni and Koo. Packing ratio of the laboratory fuel beds was generally greater than that observed in natural stands of chaparral. Fuel bed moisture content was greater than that in Rothermel's or in Wilson's data. Correlation between observed and predicted spread rate was 0 for Rothermel's original model and ranged from 0.07 to 0.49 for the other implementations and modifications of the Rothermel model. Correlation between observed and predicted rate of spread for the Pagni/Koo model was 0.74 and 0.89 in chamise and broadleaf chaparral fuel beds, respectively. Additional comparisons with vertically-oriented live fuel beds and with additional models are planned.

Additional keywords: [Adenostoma fasciculatum, Arctostaphylos, Ceanothus, Quercus]

Introduction

Fire burns 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 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) a limited set of experimental data to develop and test models exists. This problem has been recognized for over 60 years (Buck *et al*. 1941). In the U.S., limited modeling of fire spread in live fuels has occurred (Albini 1967; Rothermel and Philpot 1973; Albini and Anderson 1982; Cohen 1986; Albini and Stocks 1986; Butler *et al*. 2004; Zhou *et al*. 2005, 2007).

The basic formulation of the Rothermel model (eq. 1) assumed that a fire would spread in the absence of wind and slope (Rothermel 1972). Wind and slope terms function as multipliers of rate of spread where φ_w and φ_s are wind and slope multipliers, respectively. If wind or slope is a requirement for spread, the Rothermel model formulation fails (Weise and Biging 1997). This requirement indicates the need for 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. Several sensitivity analyses have been performed to determine the important input variables for the Rothermel model (Sanderlin and Sunderson 1975; Salvador *et al*. 2001; Clark *et al*. 2008; Jimenez *et al*. 2008) and the responsiveness of the model to fluctuating wind velocity was reported (Albini 1982). Jolly (2007) recently evaluated the sensitivity of spread model predictions to live fuel moisture using the thirteen original fuel models (Rothermel 1972) and the recently developed 42 additional fuel models (Scott and Burgan 2005). Recognizing the limitations of the original thirteen fuel models, Hough and Albini (1979) previously formulated a fuel model for the palmetto-gallberry fuel complex of the U.S. southeastern coastal plain.

$$R = \frac{\xi h w_n \Gamma' \eta_M \eta_s \left(1+\varphi_w+\varphi_s\right)}{\rho_b \varepsilon Q_{ig}} \quad (1)$$

where ξ is the propagating flux ratio, h is the fuel heat content (kj kg^{-1}), w_n is the wet fuel loading (kg m^{-2}), Γ' is the reaction velocity (min^{-1}), η_m is the moisture damping coefficient, η_s is the mineral damping coefficient, ρ_b is the fuel bed bulk density (kg m^{-3}), ε is the effective heating number, and Q_{ig} is the heat of preignition (kj kg^{-1}). The moisture damping coefficient is a cubic polynomial function of the ratio of the moisture content m_f to a moisture of extinction m_x. Rothermel (1972, modified in Albini 1976a), implemented a live fuel moisture of extinction based on work of Fosberg and Schroeder (1971) which uses the ratio of the dead to live fine fuel mass (W) as follows: $(m_x)_{Live} = 2.9W\left(1-m_{f,Dead}/(m_x)_{Dead}\right)-0.226$. Using this equation, a fuel bed with dead and live fuel moisture of extinction = 0.2, and dead fine fuel moisture content of 0, requires a dead to live ratio of 0.28. In other words, by setting the minimum live fuel moisture of extinction to 0.2, a mixed fuel bed needs to have at least 28% dead fine fuel that is absolutely dry in order to spread. If the calculated $(m_x)_{live} < (m_x)_{dead}$, then $(m_x)_{live} = (m_x)_{dead}$.

Wilson (1982, 1985, 1990) examined fire spread in moist fuel and proposed changes to the moisture content term in the Rothermel model (eq. 2). The original moisture damping coefficient η_M , , was replaced by a new moisture damping coefficient $\langle \eta_m \rangle$, a function of $\exp(-m_f/m_c)$ .where m_c is a characteristic moisture content. An extinction index $P_f(n_x) = \ln\left(\sigma\beta\delta h_v/Q_w\right)/\left(m_f + Q_f/Q_w\right)$ was derived and incorporated into a revised reaction velocity $\langle \Gamma \rangle = 0.34\left(\sigma\beta\delta\right)^{-0.5} \exp\left(-\sigma\beta/3\right) P_f\left(n_x\right)$ and a new propagating flux ratio was developed $\langle \xi \rangle = 1-\exp\left(-0.17\sigma\beta\right)$. σ, β, and δ are the fuel particle surface area to volume ratio (cm^{-1}), fuel bed packing ratio, and fuel bed depth (m^{-1}), h_v is the heat of combustion of pyrolyzate gases, Q_f and Q_w are the heat of pyrolysis and heat of desiccation, respectively.

$$R = \frac{\langle \xi \rangle h_v w_o \langle \Gamma \rangle \langle \eta_m \rangle \left(1+\varphi_w+\varphi_s\right)}{\rho_b \varepsilon \left(Q_f + m_f Q_w\right)} \quad (2)$$

Cohen (1986) incorporated the dynamic fuel model for chaparral proposed by Rothermel and Philpot (1973) into FIRECAST providing 2 basic fuel models for chamise (*Adenostoma fasciculatum*) and broadleaf chaparral such as manzanita (*Arctostaphylos* spp.), ceanothus (*Ceanothus* spp.), and scrub oak (*Quercus berberidifolia*). Fuel loading, depth, and fraction of dead material were modeled as a function of age. The heat content of the fuel changed over the year as a function of time between May 1 and November 30. Fire behavior prediction for the 20 National Fire Danger Rating System fuel models was also implemented. The FIRECAST implementation of Rothermel (1972) did not change the fire model formulation; it only provided additional fuel models for use.

In FIRECAST, σ for both chamise and mixed brush foliage was assumed to be 72 cm^{-1}. We used 58 cm^{-1} for the broadleaf chaparral species by averaging the values for *Arctostaphylos patula*, *Ceanothus velutinous*, and *Castanopsis sempervirens* (Countryman 1982). Countryman and Philpot (1970) reported packing ratios ranging from 0.00068 to 0.00374 for 16 chamise plants sampled near the location fuels were collected for the current study. Others have reported remarkably similar packing ratios for the fine fuels (leaves and stems < 0.64 cm diameter) in various chaparral stands (Table 1). Reported fine fuel loading in various chaparral species mixes ranged from 0.71 to 3.33 kg m^{-2} (Countryman 1964; Ottmar *et al*. 2000).

Catchpole *et al.* (1998) burned 357 fires in a variety of dead fuel beds composed of excelsior and sticks in a wind tunnel. Using these data and building on the work of Frandsen (1971), Wilson (1990), and others, they developed a predictive model similar in formulation to the original Rothermel model (eq. 3). They estimated the three parameters associated with the wind term (*U*) using weighted least squares. Note that this related model does not currently include a slope term as none of the experimental data included slope.

Table 1. Packing ratio estimated in natural chaparral fuel beds.

Source	Species	Sample Location	Sample Size	Packing ratio
Countryman and Philpot (1970)	*Adenostoma fasciculatum*	North Mountain Experimental Area, Riverside, California (NMEA)	16 shrubs	0.0007-0.0040
Unpublished data (Weise)	*Adenostoma fasciculatum*	NMEA	20 1m^2 quadrats	0.0007-0.0013
Rundel and Parsons (1979) [1]	*Adenostoma fasciculatum*	Sequoia National Park, California	3-5 shrubs	0.0005
Countryman (1982) [2]	*Arctostaphylos patula*	Shasta Experimental Forest, Mt. Shasta, California (SEF)	3 4m^2 quadrats	0.0005-0.0014
	Ceanothus velutinus	SEF	3 4m^2 quadrats	0.0007-0.0013
	Ceanothus cordulatus	SEF	2 4m^2 quadrats	0.0009-0.0010
FIRESTOP (1955)	*Adenostoma fasciculatum, Ceanothus cuneatus* [3]		12 4m^2 quadrats	0.0006
	Quercus berberidifolia		12 4m^2 quadrats	0.0008

1. Used foliage and < 0.5 cm branch mass for 37 year old stand (Rundel and Parsons, Table 4). Assumed depth of 1.2 m and 737 kg m^{-3} for fuel density.
2. Estimated foliage and < 0.63 cm branch mass by assuming 65% of foliage and 24% of branch mass in upper half of shrub (0.91 m). Multiplied these percentages by percent of total mass of quadrat that was foliage and branches (Countryman, Table 6).
3. Assumed same vertical distribution as in 2 and depth = 1.2 m. Use values for typical plot.

$$R = \frac{(495.5 + 1934U^{0.91})e^{-347/\sigma}\beta^{-0.499}e^{-km_f}}{\rho_p\left(Q_f + MQ_w\right)} \quad (3)$$

where k is a fuel bed dependent constant, and ρ_p is the fuel particle density (kg m^{-3}), respectively.

Recognizing that the fuel models presented in Albini (1976b) and Scott and Burgan (2005) are idealized simplifications of natural fuel beds that contain the necessary information to predict a fire's rate of spread, Sandberg *et al.* (2007) reformulated Rothermel (1972) to allow the direct use of inventoried fuel properties in place of the stylized fuel models. This reformulation, which preserved the basic form of the Rothermel model, is part of the Fuel Characteristic Classification System (Ottmar *et al.* 2007) and contains data for several hundred different “natural” fuel beds. The “heat sink” term of Rothermel’s model (the denominator) was decomposed into four components of a “natural” fuel bed—shrub, woody, non-woody, and litter-lichen-moss strata.

At approximately the same time as the Rothermel parameterization of Frandsen’s (1971) rate of spread model formulation was presented, Pagni and Peterson (1973) presented a rate of spread model for litter-like fuel beds based on solution of the conservation of energy, mass and momentum equations. The model explicitly contained terms for radiative, convective, and conductive heat transfer. The model requires flame length as an input in addition to the usual fuel and environmental variables. This is noticeably different from the Rothermel-type models which require only fuel and environmental variables for input. The Pagni model predicted rate of spread reasonably well in litter-like fuel beds (Rothermel and Anderson 1966) and grass and chaparral stands in northern California (Pagni *et al.* 1971; Peterson 1972). Koo *et al.* (2005) modified the original formulation in light of additional sets of data for litter-like fuels. This modified model is referred to as the Pagni/Koo model in this paper.

There are several different models and modeling systems which can be used to predict fire behavior in wildland fuels. Several reviews of existing models have been performed over the past 20 years (Pastor *et al.* 2003; Sullivan 2009a, 2009b, 2009c; Weber 1991) focusing on different aspects of the models. While some of these models could also be used in the present study, we chose to focus on Rothermel-type models and a simple physical model. In future work, we plan to include the Sandberg variant and the Albini (1967) physical model.

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 240 experimental fires. Fuel beds (2 m long x 1.0 m wide x various depths) were constructed of live branch and foliage material collected from chaparral growing at an elevation of 1160 m in the North Mountain Experimental Area 50 km east of Riverside, California. Branches < 0.64 cm diameter from manzanita (*Arctostaphylos glauca*), chamise (*Adenostoma fasciculatum*), hoaryleaf ceanothus (*Ceanothus crassifolius*), and scrub oak (*Quercus berberidifolia*) plants comprised 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 bed; 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 and burned in the afternoon of the same day to minimize moisture loss. Dead fuel was removed to the extent possible; for all practical purposes, no dead fuel was present in the fuel bed. The fuels were bagged and transported to the burn facility at the USDA Forest Service PSW Research Station’s Forest Fire Laboratory in Riverside, CA. Moisture content of a 5-10 g sample was determined using a Computrac[1] moisture analyzer immediately prior to ignition. Fuel temperature was assumed in equilibrium with air temperature since air temperature at the collection site was generally only a few degrees different from the laboratory temperature. Five fuel beds constructed 24 hours after collection using refrigerated fuels were allowed a few hours to come to equilibrium with ambient air temperature prior to ignition. 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. Further details are available in Weise *et al.* (2005).

[1] Tradenames are provided for informational purposes only and do not constitute endorsement by the U.S. Department of Agriculture.

Three 50.8 cm rotary box fans (Air King Model 9700) induced airflow 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. 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. If the fire propagated the entire length of the fuel bed, a rate of spread was calculated 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).

Fire spread predictions by our implementations of the Rothermel-type models (Original, Cohen, Wilson, Catchpole), and the Pagni/Koo model were made using data from the chaparral fuel beds. Parameters describing two fuel bed types were used – the original static chaparral fuel model 4 (Albini 1976) adjusted for depth and loading and the dynamic models developed by Philpot and Rothermel (1973) for chamise and broad-leaved chaparral (Table 2). The original Rothermel and FIRECAST calculations produce slightly different fuel bed packing ratios. The percentage difference between the two calculations was 4.4% and 11.8% for chamise and broadleaved species, respectively. These did not have an appreciable effect on the rate of spread calculation.

Rothermel's weighting of fuel bed properties requires a moisture of extinction for both live and dead fuels. The minimum moisture of extinction for the live fuel components of a fuel bed in FIRECAST was 0.3 which we used for the static chaparral fuel model instead of the original 0.2. For this experiment, we chose to estimate the extinction moisture from our data for the dynamic chaparral fuel models. The maximum moisture content at which a fire spread successfully under no-wind and no-slope conditions was determined from the 16 chamise, 3 ceanothus, and 1 manzanita fuel beds with successful fire spread. The maximum moisture contents for these three species were 0.65, 0.66, and 0.74, respectively. Live moisture of extinction was set at 0.65 and 0.74 for chamise and broad-leaved chaparral, respectively. Calculation of moisture of extinction for live fuels in Rothermel's original formulation was unchanged (Table 3).

As described previously, the fuel beds consisted of green foliage and branches < 0.625 cm diameter. In order to partition the fuel bed loading between foliage and branches, a small sample of branches with foliage was selected to determine the proportional mass within these two categories. As a result, we used the following proportions for foliage and branches, respectively: chamise – 0.10 and 0.90, broad-leaved chaparral – 0.27 and 0.73.

Table 2. Physical and chemical constants for chaparral fuel beds by fuel particle size class.

Species	Size class (cm)	Surface area to volume ratio (σ, cm^{-1})	Silica-free mineral content (η_s)	Particle density (ρ_p)
Chamise	Foliage	72.0	0.035	513
	Live < 0.63	21.0	0.015	737
	Live 0.64-1.26	4.2	0.015	737
	Live 1.27-2.54	2.1	0.015	737
	Live 2.54-7.64	0.9	0.015	737
Broadleaf	Foliage	58.0	0.035	513
	Live < 0.63	10.5	0.015	737
	Live 0.64-1.26	4.4	0.015	737
	Live 1.27-2.54	2.3	0.015	737
	Live 2.54-7.64	1.2	0.015	737

Table 3. Fuel bed bulk properties.

Species	Surface area to volume ratio (σ, cm^{-1})		Mass fraction		Heat of combustion of volatiles (kJ kg^{-1})	Moisture of extinction	
	Rothermel	Others	Foliage	Woody		Rothermel (dead)	FIRECAST (live)
Chamise	35	21	0.10	0.90	12960	0.30	0.65
Broadleaf	43	12	0.27	0.73	11790	0.30	0.74

The amount of energy in the fuel beds was modelled differently by the various implementations of the Rothermel model. The low heat of combustion was used in the Rothermel and FIRECAST variants; the Wilson and Catchpole variants use the heat of combustion of the pyrolyzed gases. For the static fuel model, low heat of combustion of the fuel bed (h) was 18608 kj kg^{-1} and the low heat of combustion of the pyrolyzed gases was 12960 and 11790 kj kg^{-1} for chamise and broad-leaved chaparral, respectively (Susott 1982). The low heat of combustion for the dynamic fuel model (Rothermel and Philpot 1973) was calculated originally using the number of days (D) from May 1 for the time period May 1 to October 30. Cohen (1986) modified the calculation to cover the entire year.

$$h = 2.326\left(9613 - D + 0.1369D^2 - 0.000365D^3\right) \qquad \text{foliage}$$

$$h = 2.326\left(9509 - 10.74D + 0.1359D^2 - 0.0004055D^3\right) \qquad \text{branches}$$

In the Catchpole formulation, fuel bed values and moisture terms from Wilson's formulation were used. Based on the σ for the fuel beds, a *k* value of 2 was used in eq. 3 (Catchpole *et al.* 1998). Wilson (1990) recommended that the relationship between response times for fine fuels (Anderson 1988) and the characteristic moisture be examined as well as how characteristic moisture is related to moisture diffusion and other physical characteristics. The applicability of this to live fuels is unknown since moisture movement in live fuels is a more complex process than in dead fuels (Nelson 2001) and this type of work has not been carried out for live fuels to our knowledge.

As mentioned above, the Pagni/Koo model requires an independent measure of flame length in order to calculate rate of spread. Currently, flame length data are not available for these experimental fires. For those fires with measured spread rates, we calculated flame length using the average of three different flame length (m) mass loss rate (lb min^{-1}) correlations using Albini's formulations (1981). Mass loss rate was estimated by multiplying the rate of spread by the oven-dry fuel loading and dividing by the length of the fuel bed exclusive of the ignition zone (1.5 m).

$L_f = 0.981\dot{m}^{"0.46}$ Byram 1959

$L_f = 0.954\dot{m}^{"2/3}$ Fons et al 1963

$L_f = 1.201\dot{m}^{"2/3}$ Thomas 1963

where $\dot{m}^{"} = w_0 R/l = 0.67\, w_0 R$

Spread rate success ($R > 0$) was summarized by species in contingency tables for actual and predicted spread rates with the exception of the Pagni/Koo model. Correlation coefficients between actual and predicted spread rates were calculated and scatter plots were made to determine if there were any trends.

Preliminary Results and Discussion

Because a variety of factors influencing rate of spread were examined in an exploratory fashion, the combined data set of 240 fires is not well-balanced experimentally (Table 4). Of the 240 fires (113 chamise, 127 broadleaf), 123 (70 chamise, 53 broadleaf) successfully spread the length of the fuel bed producing a measurable spread rate (Table 4). Fuel from seven of the chamise fuel beds was allowed to dry which resulted in moisture contents of 0.09 – 0.30. Generally moisture content of the fuel beds ranged from 0.54 to 1.06. This range of moisture content resulted in oven-dry fuel loadings of 1.1 – 4.9 kg m^{-2}. The original, Wilson, and Catchpole variants of the Rothermel model use dead fuel particle density while the FIRECAST variant uses both live and dead fuel particle density to calculate packing ratio (fuel bed bulk density/fuel particle density) resulting in slightly higher values; these slight differences are of no practical importance (8-14%). When compared with packing ratios observed in chaparral stands, the chamise fuel beds were generally less porous than naturally occurring chamise shrubs while the packing ratio of the broadleaf fuel beds was of the same order of magnitude as those reported for northern California brush fields (Table 1).

Table 4. Summary of laboratory experimental fires.

Type[1]	Wind (m s^{-1})	Slope (%)	n	Fuel mass (kg m^{-2})	Moisture content	Success[3]	Spread rate (m min^{-1})
Broadleaf	0	< 0	13	1.74-3.89	0.58-0.74	0.31	0.100-0.154
	0	0	26	1.09-4.86	0.54-1.06	0.15	0.079-0.171
	0	<30	17	1.89-3.78	0.54-0.74	0.35	0.136-0.600
	0	>30	49	1.63-4.90	0.54-1.04	0.47	0.099-1.364
	2	0	23	1.09-4.86	0.66-1.06	0.70	0.056-0.368
Chamise	0	< 0	19	1.74-3.53	0.49-0.60	0.79	0.080-0.207
	0	0	37	1.41-3.19	0.30-0.91	0.43	0.078-0.380
	0	<30	11	1.25-3.16	0.09-0.66	0.18	0.474-0.639
	0	>30	23	1.42-3.19	0.55-0.80	0.65	0.130-1.769
	2	0	18	1.41-3.37	0.26-0.91	0.94	0.184-0.940
	2	<30	4	1.25-3.37	0.26-0.64	1.00	0.547-0.883
	2	>30	1	1.42	0.80	1.00	1.451

1. Broadleaf – *Ceanothus crassifolius, Quercus berberidfolia,* or *Arctostaphylos glauca*; chamise – *Adenostoma fasciculatum*
2. Rothermel (1972), Cohen (1986)
3. Proportion of fires that spread entire length of fuel bed.

Observed rate of spread ranged over two orders of magnitude (0.05-1.77 m min^{-1}). These rates of spread are slow compared to head fire spread rates compiled for chaparral from large fires (Abell 1940 and Chandler *et al.* 1963 reported average fire spread rates of 3.5 m min^{-1}). In general, the predicted spread rates from the various models also ranged over a few orders of magnitude with the exception of Rothermel's original version (Table 5). With the exception of the fuel bed with moisture content of 0.09 (Fig. 1), the original version predicted spread rate = 0 for all other fuel beds. This is due to the moisture of extinction being set at 0.30. All other variants of Rothermel predicted non-zero spread rates because of the higher moisture of extinction assigned (Table 2). Because of the requirement of the Pagni/Koo model to have a flame length used in prediction, the number of fires available to compare spread rates for this model was smaller than for the other models. Predictions from the Pagni/Koo model were of the same magnitude as the Rothermel variants.

There was a wide range of agreement between actual and predicted values for the five models tested (Fig. 1.). In general, the original version of the Rothermel model with moisture of extinction of 0.20 did not predict a non-zero spread rate so the correlation, as measured by the Pearson product-moment correlation *r*, was 0 for broadleaf chaparral fuel beds and low for the chamise chaparral fuel bed (Table 6). The predicted spread rate (0.69 m min^{-1}) for the fuel bed with moisture content of 0.09 was very close to the observed spread rate (0.64 m min^{-1}) which reflects the original data used to parameterize the model very well. In most cases, all other variants of Rothermel exhibited some level of correlation with actual spread rates for the fuel beds with moisture content > 0.30. For the broadleaf fuel beds, the correlation values for the Wilson and Catchpole variants were significantly different from 0 even though very low. For the chamise fuel beds, all three variants of the Rothermel model exhibited correlation coefficients significantly different from 0 and the values of the correlation coefficient were higher than for the broadleaf fuels. Correlations of the Pagni/Koo model for both fuel bed types were significantly different from 0 and the values were the highest of the five models considered.

Table 5. Summary of actual and predicted fire spread rates (m min^{-1}) in chaparral fuel beds in a laboratory.

Type[1]	Wind	Slope	Actual	Rothermel-based[2]				Pagni/Koo
				Original	FIRECAST	Wilson	Catchpole	
Broadleaf	0	< 0	0.00-0.18	0.00	0.005-0.365	0.018-0.115	0.043-0.322	0.120-0.202
	0	0	0.00-0.17	0.00	0.000-0.068	0.001-0.020	0.008-0.040	0.138-0.219
	0	<30	0.00-0.60	0.00	0.000-0.143	0.009-0.043	0.041-0.108	0.178-0.468
	0	>30	0.00-1.36	0.00	0.000-0.761	0.004-0.213	0.032-0.814	0.109-0.951
	2	0	0.00-0.37	0.00	0.000-0.527	0.017-0.215	0.067-0.255	0.132-0.545
Chamise	0	< 0	0.00-0.21	0.00	0.096-0.957	0.072-0.516	0.052-0.454	0.111-0.244
	0	0	0.00-0.38	0.00	0.000-0.382	0.006-0.180	0.019-0.129	0.101-0.635
	0	<30	0.00-0.64	0.00[3]	0.000-1.054	0.057-0.831	0.092-0.711	0.837-1.902
	0	>30	0.00-1.77	0.00	0.000-0.470	0.098-0.271	0.117-0.306	0.199-0.944
	2	0	0.00-0.94	0.00	0.000-5.545	0.089-2.889	0.156-1.203	0.354-1.665
	2	<30	0.55-0.88	0.00	0.181-6.147	0.384-3.200	0.967-2.945	0.918-1.728
	2	>30	1.45	0.00	0.000	0.189	0.930	1.442

1. Broadleaf – *Ceanothus crassifolius, Quercus berberidfolia,* or *Arctostaphylos glauca*; chamise – *Adenostoma fasciculatum*
2. Original – Rothermel 1972, FIRECAST – Cohen 1986, Wilson 1990, Catchpole *et al.* 1998
3. 1 fire with moisture content = 0.09 had predicted spread rate of 0.691 m min^{-1}. All others were 0.00.

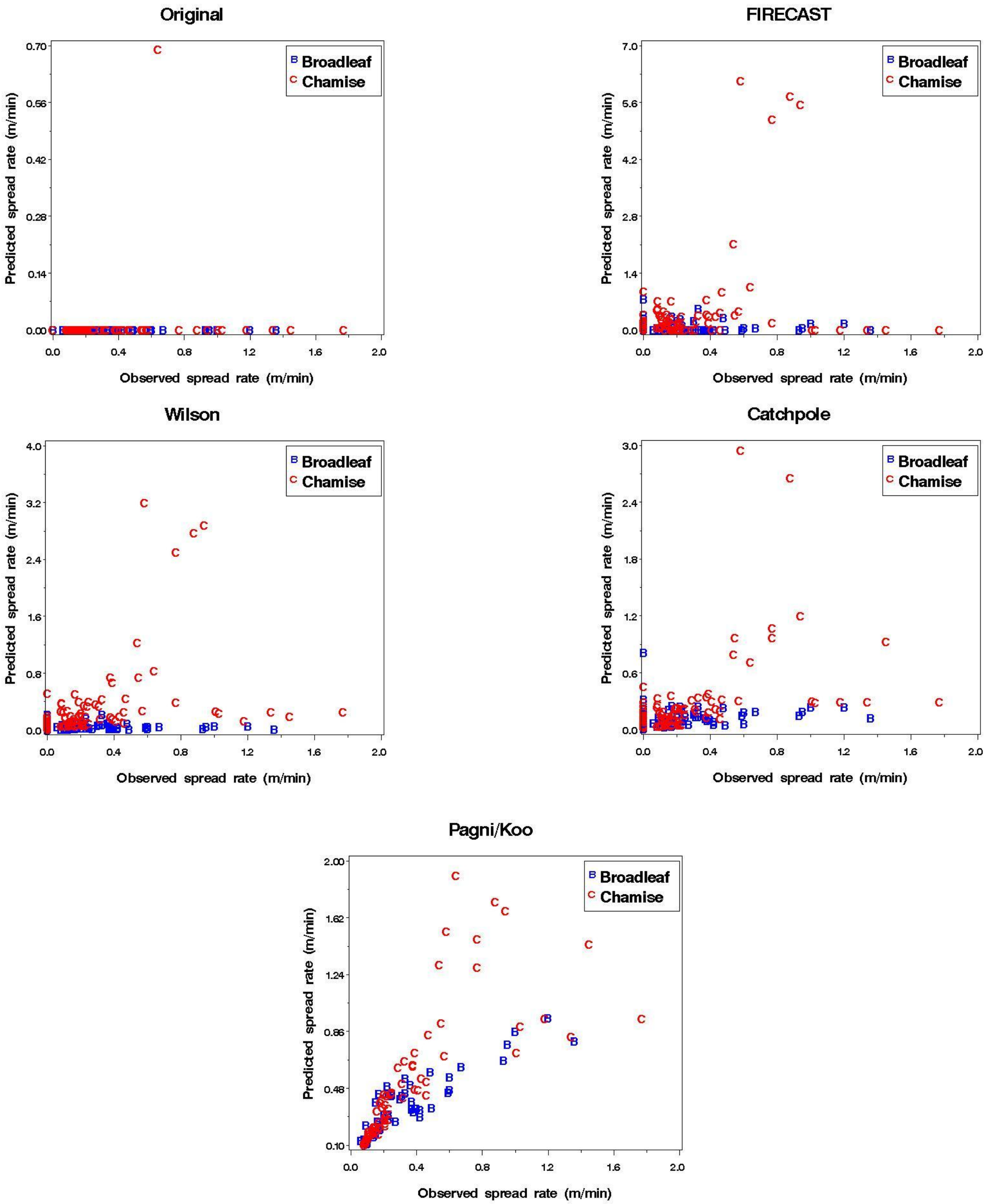

Fig. 1. Comparison of actual fire spread rates with predicted fire spread rates for four variants of the Rothermel model and the Pagni/Koo model in fuel beds of live chamise and broadleaf chaparral fuels.

Table 6. Correlation between actual and predicted fire spread rates in chaparral fuel beds in a laboratory.

Type[1]	Model[2]	r[3]	$Pr > \lvert r \rvert$[4]	n
Broadleaf	Original	0.0		127
	FIRECAST	0.07	0.451	"
	Wilson	0.17	0.053	"
	Catchpole	0.24	0.006	"
	Pagni/Koo	0.89	0.0001	51
Chamise	Original	0.12	0.213	113
	FIRECAST	0.34	0.0002	"
	Wilson	0.42	0.0001	"
	Catchpole	0.49	0.0001	"
	Pagni/Koo	0.74	0.0001	69

1. Broadleaf – *Ceanothus crassifolius, Quercus berberidfolia,* or *Arctostaphylos glauca*; chamise – *Adenostoma fasciculatum*
2. Original – Rothermel 1972, FIRECAST – Cohen 1986, Wilson 1990, Catchpole *et al.* 1998
3. Pearson product-moment correlation.
4. Two-tailed probability associated with test that r=0.

While moisture of extinction is a "user-selectable" variable that can be associated with a fuel model (Burgan 1987), increasing the moisture of extinction only changes the range of the effect of the moisture dampening coefficient. This type of tuning to the fuel model parameters is an example of the "art" of fuel modeling to attempt to improve the agreement between model predictions and observations. It is not something that is readily available to users with the current implementation of the Rothermel model (BEHAVEPlus) unless a user has access to the computer code. Even though the Wilson and Catchpole variants used a different formulation for the effect of moisture on fire spread, predictive capability was improved slightly over the original model. The basic assumption that energy is required to vaporize all of the water in fine fuels prior to ignition may not be appropriate for fine live fuels as has been demonstrated by Pickett and coworkers (2010). As others have demonstrated (Finney *et al.* 2010), flame bathing of fuels may be required for successful ignition and radiant heating may not be sufficient for successful flame propagation through live fuels. Flame bathing is heat transfer by convection. Weise *et al.* (2005) demonstrated that wind velocity (which affects flame angle and flame contact with fuels) is an important (and perhaps required) environmental variable in these laboratory fuel beds.

The relatively good predictions from the Pagni/Koo physical model which explicitly contains heat transfer terms for flame radiation, ember radiation, and convective heating are promising. This simple physical model appears to capture the important mechanisms of heat transfer in live fuel beds; however, the comparison presented here is not completely "fair". Recall that the observed spread rate in fuel beds was used to estimate a flame length which was then used to predict rate of spread. This is not a completely independent test. For fair comparison to be made, we need to derive flame lengths from video of the experiments and then predict spread rate. To be a useful predictive tool, either a correlation that can predict flame length from the environmental and fuel variables which is then used in the spread calculations is needed or a quick iterative solution method to solve for flame length and rate of spread is required to enable the use of this model for fire spread prediction.

Additional comparison of the models is planned using results from over 100 laboratory fires in vertically-oriented live fuels to determine performance. Even though the present comparison is limited in nature, it does indicate that additional work and modeling is needed to improve our ability to predict fire spread in live fuels. A physics-based fire spread model that eliminates some of the art based on improved science is needed.

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