A fundamental look at fire spread in California chaparral.

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Abstract: The USDA Forest Service National Fire Plan funded a research program to study fire spread in live fuels of the southwestern United States. In the U.S. current operational fire spread models do not distinguish between live and dead fuels in a sophisticated manner because the study of live fuels has been limited. The program is experimentally examining fire spread at 3 scales – the fuel element, the fuel bed, and field scale. Data from the experimental work is being used to test and improve operational (BEHAVE) and research fire spread models (PAGNI, FIRETEC/HIGRAD). The principal live fuels studied are chamise (Adenostoma fasciculatum), manzanita (Arctostaphylos parryana), ceanothus (Ceanothus crassifolius), and scrub oak (Quercus berberidifolia). The effects of fuel element orientation and moisture content on time to ignition in a convective environment have been studied to date. We have burned 190 single species fuel beds to study the effects of fuel bed density, fuel moisture content, wind speed (0, 2 $m\ s^{-1}$), and fuel bed slope on fire spread success. A thermal imaging technique to estimate velocities in the flame has been developed. Results to date reaffirm the importance of moisture in combustion in live fuels. The importance of wind and slope on fire spread success has been demonstrated and is being described empirically. Wind velocity of 2 $m\ s^{-1}$ has been sufficient to cause fire spread success in live fuel beds with moisture content > 80% dry weight basis. Results of the fuel element, fuel bed, and model testing work will be presented.

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1. INTRODUCTION

In the United States, fire burns large areas in living fuels such as chaparral in California, sagebrush (*Artemisia tridentata*) and pinyon-juniper (*Pinus edulis, Juniperus occidentalis*) woodlands in the interior West, palmetto-gallberry (*Serenoa repens, Ilex glabra*) in the southeastern coastal plain, and coniferous forests annually. Fire spreads in living fuels in many places in the world in Mediterranean-like areas and many types of coniferous forest. Recent work has focussed on modelling fire spread in these fuels (Fernandes 2001, Morvan and Dupuy in press). While these fires are significant events, our ability to predict when and how fire will spread in these fuels is limited by two factors: 1) the fire spread model used in the U.S. (Rothermel 1972, Albini 1976) was not designed primarily for live fuels and 2) a limited set of experimental data to develop and test models exists. In the U.S., limited modelling of fire spread in chaparral fuels has occurred (Albini 1967, Rothermel and Philpot 1973, Albini and Anderson 1982, Cohen 1986). While these various models exist and may be used by fire managers, empirical approaches to predict fire spread in chaparral fuels are also used (Green 1981, Raybould and Roberts 1983, Campbell 1995).

There is currently no resolution to the question "Do live fuels burn differently than dead fuels?" Basic physical and chemical properties of some live fuels in the U.S. have been determined (Countryman and Philpot 1970, Countryman 1982, Susott 1982 a,b). Many of the operational and research fire spread models do not contain sophisticated modelling of the chemical aspects of combustion; heat transfer mechanisms dominate most models. In the Rothermel model, the heat content (kj kg^{-1}) is the principal variable used to distinguish live fuels from dead fuels. Living fuels that have foliage with significant waxy cuticles or that contain volatiles are assigned higher heat content. For example, the heat content for a dead grass is assumed to be 12300 kj kg^{-1} while that for a chaparral fuel bed is 14600 kj kg^{-1}. A limited number of structural studies of various Mediterranean shrub fuels have been conducted (Countryman and Philpot 1970, Papio and Trabaud 1991, Ottmar et al. 2000 Dimitrakopolous and Panov 2001, De Luis et al 2004). Much of this information has not been incorporated into fire spread models. Because of the limited historical emphasis on modelling fire behaviour in chaparral, a study to examine various aspects of combustion in chaparral and other live fuels was established as part of the U.S. National Fire Plan in 2000. This paper presents the research approach being used and some initial results.

2. METHODS

Fire spread in chaparral fuels is being examined at 3 scales – the fuel element, the fuel bed, and in the field through a combination of experimentation and modelling by USDA Forest Service and university scientists. Four species which represent the dominant genera in chaparral in southern California are being studied: manzanita (*Arctostaphylos parryana*), chamise (*Adenostoma fasciculatum*), hoaryleaf ceanothus (*Ceanothus crassifolius*), and scrub oak (*Quercus berberidifolia*). Branches and foliage < 0.64 cm in diameter comprised the fuel used in the fuel element and fuel bed studies. Materials are collected from living plants and burned within 6 hours in the fuel bed study or shipped and burned the subsequent day for the fuel element study to minimize the loss of moisture from the samples.

2.1. Fuel Element Study

The experimental apparatus was described in detail by Engstrom et al. (in press), and is designed to closely resemble the conditions of a wildland flame front. Temperatures in wildland fires are thought to be about 1200 K, with heating rates of approximately 100 K/s. To simulate this condition the fuel sample was attached to a stationary horizontal rod connected to a cantilever-type mass balance. A flat-flame burner was positioned on a moveable platform to simulate the flame front. The post-flame gases from the flat-flame burner simulated heat transfer by convection. The experimental apparatus is shown in Fig. 1. Engstrom and coworkers determined from infrared video images that the optimal location for samples in this experiment was 5 cm above the burner, where the post-flame temperature was 987°C ± 12°C, with about 10 mol% O_2.

Leaf surface temperature data were obtained at 60Hz using 127 μm diameter type K thermocouples. The thermocouple was embedded in a pinhole in the leaf edge near the ignition point for the manzanita (*Arctostaphylos parryana*) and scrub oak (*Quercus berberidifolia*) samples. Thermocouple data were not taken for the chamise (*Adenostoma fasciculatum*) samples due to the small dimension of the needles. All of the mass, video, and temperature data were time stamped for quick and accurate comparison.

2.2. Fuel Bed Study

The effects of wind, fuel moisture content, fuel bed height and slope on flame propagation in live fuels were investigated in a series of 190 experimental fires burned between 1/2003 and 7/2004. Fuel beds (2 *m* long x 1.0 *m* wide x various depths) were constructed of live branch and foliage material collected from living chaparral 50 *km* east of Riverside, CA (Fig. 2). Plant material was collected in the morning so as to minimize moisture loss through transpiration. Dead fuel was removed to the extent possible. The fuels were then bagged and transported to the burn facility at the Forest Fire Laboratory. With the exception of the 1st 9 fuel beds, fuels were burned on the day of collection to reduce moisture loss.

The fuel beds were elevated above the surface of a tilting platform by 40 *cm* to simulate an aerial fuel (Fig. 3). Air could be entrained from the ends of fuel bed; metal sheeting prevented air entrainment from the sides.

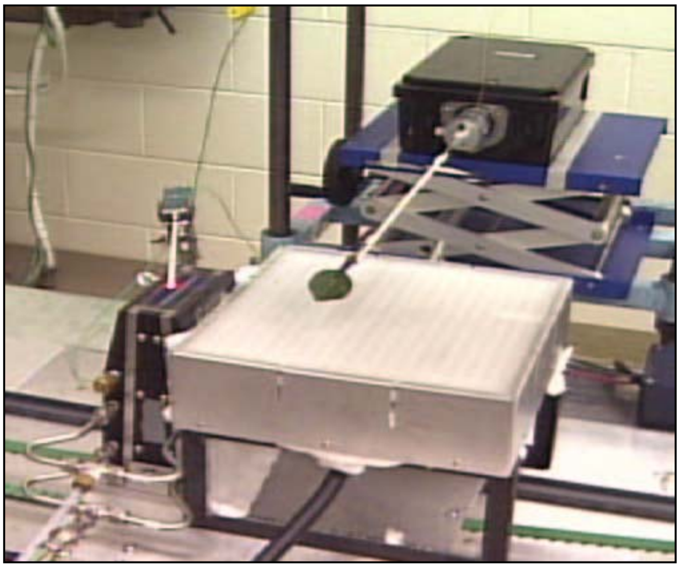

Figure 1. Experimental apparatus used to test ignition characteristics and mass loss of single chaparral fuel elements. A manzanita leaf is attached to the mass balance over a radiant panel. The flat flame burner is the black box to the left of the radiant panel.

The fuel was uniformly distributed in the fuel bed to the greatest extent possible. Fires were ignited from one side in a 50 *cm* section along the length of the live fuel bed. Between 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. Three rotary box fans 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 $m\ s^{-1}$. The slope effect was generated by raising the down-wind end of the tilting platform. An experiment was described as successful if the live brush ignited from the burning zone and then propagated the length of the 2 *m* fuel bed. The experiment was unsuccessful if the fire did not propagate. In case of successful fire spread, the resulting rate of spread (ROS) was measured using data from thermocouples buried in the fuel bed and/or direct video image analysis.

Figure 2. Collection of live shrub fuels (< 0.6 cm diameter) for use in fuel bed studies. Photo taken during 2 year drought when abnormal mortality occurred.

2.3. Model Testing Study

Rate of spread data from the fuel bed study are being used in this study. Predictions from 3 rate of spread models are being compared with observed spread rates. The models differ appreciably in formulation. The Rothermel model (Rothermel 1972, Albini 1976) forms the basis for the operational fire prediction systems used in the U.S. and is a well-known empirical spread model. While the modifications Wilson (1990) proposed for the Rothermel model based on a larger experimental data base which included moister fuels are potentially applicable in this study, this version of the Rothermel model was not included. The 2nd model is a physical model that incorporates detailed modeling of heat transfer in a porous fuel bed (Pagni and Peterson 1973). This model includes flame length as an input variable. The reader is referred to the original references or Weise and Biging (1997) for a more detailed listing of the equations used by these models. The 3rd model tested here is the FIRETEC/HIGRAD coupled atmospheric/wildfire behavior model developed at Los Alamos National Lab (Linn et al. 2002). The model formulation is too complex to be presented here. For the model testing reported here, chamise was the only species examined.

Figure 3. Experimental fuel bed constructed of *Ceanothus crassifolius* branches and foliage < 0.6 cm. Fuel bed density is greater than normal density and fuel bed is elevated 40 cm above surface.

3. RESULTS

3.1. Fuel Element Study

Because the study of combustion of live fuels has not been studied for many years, we conducted qualitative work to observe how the fuel was burning. We have also begun quantitative experiments to measure ignition temperatures and mass loss rates.

3.1.1. Qualitative Experiments

Combustion experiments on leaf samples from the 4 species under study were performed in the FFB to determine ignition location as well as shape and orientation effects. Chamise samples were separated from the broad leaf samples (manzanita, ceanothus, and scrub oak) when studying effects of shape and orientation. We found that the leaves ignited in a similar pattern for the broadleaf species when cut in similar shapes. Round shaped samples ignited along the perimeter of the sample then propagated towards the center. Square-shaped samples ignited first at the corners then propagated along the perimeter before burning towards the middle (Engstrom et al. in press).

There was a significant effect of leaf orientation on combustion behavior; broad leaves held horizontally exhibited quite different combustion behavior than broad leaves held vertically. When the leaves were oriented vertically above the flat-flame burner, the leaves ignited at the edge closest to the flame and propagated to the top edge of the leaf regardless of shape differences. In the horizontal configuration of the manzanita leaves, bubbles were observed on the leaf surface prior to ignition, indicating either moisture evaporation or degradation of the waxy layer on the surface of the leaves. At higher moisture content, the bubbles burst on the surface leaving crater like holes on the leaf before burning. Bursting was only observed when moisture content was near 100%. The bursting occurred slightly before ignition.

3.1.2. Quantitative Experiments

Quantitative data (i.e., ignition temperature and time to ignition) were gathered for manzanita, oak, and ceanothus. Ignition temperature was defined as the temperature when a flame was first visible. A thermocouple was placed at the point where ignition would first occur. Video data and thermocouple data were recorded simultaneously and had a synchronous time stamp attached to each video frame and thermocouple reading. Ignition temperature was determined for each sample by matching (a) the time stamp of the video frame showing the first visible flame to (b) the temperature time stamp. Average ignition temperatures for the samples ranged between 300 and 500 °C (Tables 1). As moisture content increased from very dry (<5%) to near normal (>70%), measured ignition temperature in oak and manzanita samples increased. The samples with high moisture content were observed to ignite at temperatures that were 80 to 140°C higher than the low moisture samples. Ignition temperature data have not yet been collected for high moisture ceanothus samples. The influence of moisture content on the ignition temperature was more significant than expected, is repeatable, and should be explored further.

Ignition time was based on the amount of time it took for the sample to ignite once the sample was above the flat-flame burner. The start time was defined as the time when the temperature reached 30°C. The ignition time was calculated by subtracting the time stamp of the first thermocouple reading at or above 30°C from the time stamp of the thermocouple reading at the point of ignition. As moisture content of the samples increased, time to ignition increased. A significant change in the average ignition temperature was observed for both species for the samples with moisture content < 5% and for the samples with higher moisture content (>40%).

Table 1. Ignition temperature and time to ignition statistics

Moisture Content	Ignition Temperature		Time to Ignition	
	Mean	S.D.	Mean	S.D.
Scrub oak				
< 5	311	74		
7	343	72	0.91	0.42
43	485	121	1.83	0.73
Manzanita				
< 5	346	61		
19	380	82	2.07	1.17
76	463	71	8.35	1.50

3.2. Fuel Bed Study

To date, 190 fuel beds have been ignited. Of the 190 ignitions, 102 spread the entire length of the fuel bed. The experimental design is currently unbalanced (Table 2). Of the 190 tests, the majority of fuel beds have been chamise. Fuel bed dry mass ranged from 1.09 to 4.90 $kg\ m^{-2}$ (Table 3) and the packing ratio (Rothermel 1972) ranged from 0.008 to 0.024. These packing ratios are greater than those reported for chamise (0.0007 to 0.004, Countryman and Philpot 1970) and are more similar to packing ratios for forest litter beds. The principal orientation of the branches used in the study is horizontal. Chamise is the dominant species at the collection site and has been studied more extensively than the other species given that it is more inflammable (Countryman and Philpot 1970).

Table 2. Fire spread success in fuel beds composed of pure species.

Species	Spread Success in Fuel Bed		
	Yes	No	Total
Ceanothus	19	18	37
Chamise	65	41	106
Manzanita	13	19	32
Oak	5	10	15
Total	102	88	190

Table 3. Fuel bed loading by species.

Species	Oven-dry loading ($kg\ m^{-2}$)		
	Mean	Min	Max
Ceanothus	2.51	1.59	3.89
Chamise	2.49	1.25	3.53
Manzanita	2.99	1.63	4.90
Oak	2.02	1.09	4.40

A substantial number of fires spread successfully at moisture content > 40% (Table 4), the highest extinction used by the standard 13 fuel models in the U.S. 27 of 61 fuel beds with moisture content between 81 and 100% and 69 of 147 fuels with moisture content > 61% spread successfully under the experimental conditions they were subjected to.

Table 4. Fire spread success by species and moisture content class.

Species		Moisture Content (%)					
		10	30	50	70	90	110
Ceanothus	Y	0	0	0	9	10	0
	N	0	0	0	12	6	0
Chamise	Y	1	8	24	25	7	0
	N	0	1	9	22	9	0
Manzanita	Y	0	0	0	3	7	3
	N	0	0	0	1	12	6
Oak	Y	0	0	0	2	3	0
	N	0	0	0	3	7	0
Total	Y	1	8	24	39	27	3
	N	0	1	9	38	34	6

We used logistic regression to identify the set of variables that can best predict fire spread success. In earlier models (Weise et al. 2003, Zhou et al. in press), wind speed was selected as the most important variable to predict spread success. In the current data set, the dry fuel loading was selected as the single variable best related to spread success. Wind velocity, moisture content, slope percent, and air temperature were then subsequently selected.

Table 5. Fire spread success by species and fuel bed depth.

Species		Depth (*cm*)	
		20	40
Ceanothus	Y	8	11
	N	13	5
Chamise	Y	20	45
	N	26	15
Manzanita	Y	4	9
	N	14	5
Oak	Y	3	2
	N	7	3

Several general trends have been noted in these data. As fuel moisture content increased, the proportion of fires that spread successfully decreased (Table 4). However, several fires spread at relatively high fuel moisture (90, 110%). A greater proportion of fires spread in fuel beds 40 cm deep than 20 cm deep for all species except scrub oak (Table 5).

We have been able to sustain successful ignitions in various chamise fuel beds by increasing the slope or inducing wind (Table 6). For the set of chamise fuel beds burned in March 2003, inducing a wind velocity of 2 m s-1 increased fire spread success from 0 to 75% (3/4) and increasing slope improved spread success by 66% (for 40 % slope) and 86% (for 70% slope).

Table 6. Influence of wind velocity and slope on fire spread success in chamise fuel beds. Fuel moisture content = 80%.

Wind ($m\ s^{-1}$)	Slope (%)		
	0	40	70
0	0 (6)[1]	2 (1)	5 (1)
2	3 (1)	1 (0)	0 (0)

1. Values are Yes (No)

3.3. Model Testing Study

Two replications of two fuel bed depths (20 *cm*, 40 *cm*), three slope angles (0, 21.8, 35º), and two wind velocities (0, 2 $m\ s^{-1}$) were selected from the 190 experimental fires. At the time of this report, rate of spread data were not available for 4 of the 12 fires and model runs for FIRETEC/HIGRAD could not be run due to security issues at Los Alamos. Of the 8 fuel beds ignited, 6 burned the entire length of the fuel bed. The physical characteristics of the chamise fuel beds used were surface to volume ratio (66 cm^{-1}), density (512 $kg\ m^{-3}$), heat content (23400 $kj\ kg^{-1}$), and moisture content – dry weight basis (80%). Other characteristics are listed in Table 7. Fire spread predictions were made with the Pagni model and the Rothermel model as encoded in BehavePlus 2.0 software (Andrews and Bevins 2004). In the Rothermel model, a moisture damping function is used to model the influence of moisture. This function is a cubic function which is constrained to range from 0 to 1. A variable, the moisture of extinction (m_x), is used to scale the function between 0 and 1. The moisture of extinction ranges from 15 to 40% for the standard dead fuel models used in the U.S. Because the chamise fuel beds were live fuel beds with no dead component and moisture content of 80%, 2 different values of m_x were used- 40 and 100%. For the 8 fuel beds listed here, the loading and depth were manipulated to produce the same packing ratio (fuel bed bulk density/fuel particle density, 0.01).

Table 7. Characteristics of chamise (*Adenostoma fasciculatum*) fuel beds used to test fire spread model predictions

Fire	Depth (cm)	Loading ($kg\ m^{-2}$)	Wind ($m\ s^{-1}$)	Slope (º)
1	20	1.42	0	0
2	20	1.42	0	35
3	20	1.42	2	0
4	20	1.42	2	21.8
5	40	2.83	0	0
6	40	2.83	0	21.8
7	40	2.83	0	35
8	40	2.83	2	0

Observed spread rate ranged by an order of magnitude from 0.0022 to 0.0295 $m\ s^{-1}$ (Table 8). These spread rates are for marginal conditions – not the faster spread rates associated with Santa Ana winds and large-scale burning often experienced in chaparral (2003 Cedar Fire – average of 0.81 $m\ s^{-1}$ for 16.5 hours). Performance of the Rothermel model was mixed. When m_x was 40%, BehavePlus predicted 0 $m\ s^{-1}$ because the moisture damping coefficient was 0 (fuel bed moisture content exceeded the moisture of extinction). When m_x was set to 100, BehavePlus predicted spread rates that were generally within an order of magnitude of observed. In general, the Pagni model produced predictions that were similar to observed spread rates, as well. However, the Pagni model currently requires an estimate of flame length in order to predict spread rate.

Table 8. Observed and predicted fire spread rates in chamise fuel beds.

Fire	Observed ($m\ s^{-1}$)	Rothermel (m_x = 40)	Rothermel (m_x = 100)	Pagni
1	0.0000	0.0000	0.0033	0.0003
2	0.0197	0.0000	0.035	0.0090
3	0.0000	0.0000	0.033	0.0015
4	0.0242	0.0000	0.043	0.0223
5	0.0000	0.0000	0.0067	0.0004
6	0.0022	0.0000	0.027	0.0068
7	0.0295	0.0000	0.068	0.0125
8	0.0052	0.0000	0.067	0.0097

4. DISCUSSION AND SUMMARY

Examination of the ignition of foliage from chaparral species using a flat flame burner has lead to an interesting question – "Does the temperature at which live foliage ignites increase as fuel moisture increases?" The fuel element experiments completed thus far has produced repeatable results; we are performing additional tests to make sure that the thermocouple is measuring the temperature of the leaf sample and not of the hot gasses in the flat flame burner. If the data we have collected are correct, then a new model of preheating, pyrolysis, and ignition of live fuels might be necessary. The Rothermel model (and Wilson's modifications) assumes that prior to ignition, a fuel particle absorbs energy resulting in a temperature increase from ambient to 100ºC, the energy then drives off the water in the fuel particle, and then the fuel particle increases in temperature until ignition occurs. Rothermel applied this model was applied to dead fine fuels. Our data suggest that either this model is incorrect or that live fuel particles do not ignite like dead fuel particles.

The fuel bed study has shown the importance of a variety of variables that govern fire spread in live fuels. The importance of wind and the inadequacy of the Rothermel model formulation of the effects of wind and slope on fire spread are reinforced by our data. This shortcoming has been identified in other studies involving both live and dead fuels (see Weise and Biging 1997). Slope alone may be sufficient to enable successful spread in live fuels. Chaparral occurs in the foothills and mountains of California – often on slopes that are difficult for a person to walk on.

To date we have compared only a few of the 190 fires to spread predictions from operational and research spread models. While moisture of extinction is set to 40% for the standard chaparral fuel model (Albini 1976), we were able to generate non-zero fire spread predictions by increasing the extinction to 100% for our fuel model. The Rothermel model offers flexibility in the tuning of various fuel model parameters to yield reliable predictions; however, the tuning of fuel models to produce these predictions is not necessarily tied to sound physical principles. The performance of the Pagni physical model for these fuels is also promising since it is a fast calculating physical model. Current efforts are underway to improve the operational spread models used in the U.S. by improving the physical modelling. The data generated by the various studies described here should contribute to a better understanding of fire spread in live fuels.

Examination of the ignition of individual leaf samples from common chaparral species suggests that the temperature of ignition may increase with increasing moisture content. Time to ignition also increased with increasing moisture content. Logistic regression identified fuel dry loading, wind speed, moisture content, slope percent and air temperature as variables related to fire spread success in the dense live fuel beds. Under the same environmental and fuel moisture conditions, we have been able to cause successful fire spread by inducing wind or inclining the fuel bed. This indicates an error in the formulation of the Rothermel model. With moisture of extinction set to 100%, the Rothermel model predicted non-zero spread rates for fuel beds at 80% moisture content. Predictions from the Pagni physical model for these same fires came very close to observed spread rates.

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