VALIDATION OF BEHAVE FIRE BEHAVIOR PREDICTIONS IN OAK SAVANNAS USING FIVE FUEL MODELS

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Abstract: Prescribed fire is a valuable tool in the restoration and management of oak savannas. BEHAVE, a fire behavior prediction system developed by the United States Forest Service, can be a useful tool when managing oak savannas with prescribed fire. BEHAVE predictions of fire rate-of-spread and flame length were validated using four standardized fuel models: Fuel Model 1 (short grass), Fuel Model 2 (timber and grass), Fuel Model 3 (tall grass), and Fuel Model 9 (hardwood litter). Also, a customized oak savanna fuel model (COSFM) was created and validated. Results indicate that standardized fuel model 2 and the COSFM reliably estimate mean rate-of-spread (MROS). The COSFM did not appreciably reduce MROS variation when compared to fuel model 2. Fuel models 1, 3, and 9 did not reliably predict MROS. Neither the standardized fuel models nor the COSFM adequately predicted flame lengths. We concluded that standardized fuel model 2 should be used with BEHAVE when predicting fire rates-of-spread in established oak savannas.

INTRODUCTION

Historically, Missouri's Ozark forests included an open landscape, containing a thin overstory of trees undergirded with a diverse supply of grasses and wildflowers (Beilmann and Brenner 1951, Ladd 1991, Nigh 1992). It is believed that these savanna-like areas occupied 4.5 to 5.3 million acres throughout the Midwest (Nuzzo 1986) with more than 2 million acres in Missouri (Nelson 1985). There is a renewed interest in reestablishing, restoring, and maintaining oak savannas as part of a diverse forest ecosystem. Land managers are beginning to use large landscape burns for oak savanna restoration.

The use of fire as a restoration and management tool requires managers to develop fire management plans for each savanna. Good fire management plans should include: (1) specific management objectives, (2) control strategies, and 3) methods for assessment of the burn to determine if management objectives were accomplished (Mobely and others 1973).

BEHAVE, a widely accepted fire behavior model developed by the USDA Forest Service, can aid managers in writing fire management plans, since BEHAVE predicts fire behavior such as rate-of-spread, flame length, and fireline intensity (Wilson 1990). The BEHAVE system contains two subsystems: BURN and FUEL (Andrews 1986). BURN contains the programs that predict fire behavior while FUEL is a fuel modeling system. BEHAVE was tested because it can be a valuable planning tool and the model has not been validated in Missouri, although, management experience suggests that BEHAVE does adequately predict fire behavior.

The inputs for BEHAVE are fuel, site, and weather information. The fuel information for BEHAVE comes from a fuel model. This model is a description of the fuel in an area, generally in tons per acre. BEHAVE can use either a standardized or customized fuel model for fuel information (Andrews 1986). There are 13 standardized fuel models which describe average fuel conditions in common fuel types (Anderson 1982). Customized fuel models are developed for fuel conditions that are not adequately described by the standardized fuel models (Burgan and Rothermel 1984). At first glance, fuels in Missouri oak savannas appear to be described by standardized fuel models 1 (short grass), 2 (timber and grass), 3 (tall grass), and 9 (hardwood litter). These standardized fuel models were used to test BEHAVE predictions in established oak savannas.

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The purpose of this project was to validate fuel models 1 (short grass), 2 (timber and grass), 3 (tall grass), and 9 (hardwood litter) for calculating prescribed fire behavior in established oak savannas in Missouri and develop and validate a customized oak savanna fuel model. There were two reasons for creating a customized oak savanna fuel model: (1) To describe the established savanna fuel conditions, and (2) to reduce the variability between predicted and observed fire behavior.

Fire behavior predictions were validated in established savannas because these communities are managed with prescribed fire and there is an increasing interest in restoring this community in Missouri. Established sites were chosen over restoration sites because it was felt that established savannas would maintain a more constant fuel makeup than a site undergoing restoration. For the scope of this project an established savanna is considered any area that has an overstory crown closure between 10 and 80%, a shrub layer is either present or absent, the herbaceous layer contains both prairie and forest species, and the area is managed with fire (Nuzzo 1986).

METHODS

Site Selection

In the spring of 1994, lists of potential savanna study sites were acquired from the Missouri Department of Conservation, Missouri Department of Natural Resources, the United States Forest Service, and The Nature Conservancy. Savanna sites were visited in the summer of 1994 and compared to our definition of an established savanna. Eight established savanna sites were selected (Figure 1).

Data Collection

Required data consisted of BEHAVE input and output data which was broken into pre-burn and burn treatment data. Slope, aspect, and fuel loading data were collected pre-burn, and weather, fuel moisture, and fire behavior data were collected during each prescribed fire.

Pre-burn data were collected from a series of nested transects. Sampling points were randomly located on each study site. A sampling point consisted of a 132 ft fire behavior transect, oriented perpendicular to the slope. Slope and aspect data were collected along this fire behavior transect. Located at the origin and endpoint of each fire behavior transect were four down dead woody (DDW) fuel transects. The DDW fuel transects were orientated at 0°, 90°, 180°, and 270° from the origin and endpoints of the fire behavior transect and were 50-foot long.

Fuel loading was estimated using a technique described by Brown (1984) and Brown and others (1982). Down dead woody fuels that intersected the fuel transect were sampled by timelag class: 1-hr fuels (0 - 0.25 in. diameter), 10-hr fuels (0.25 - 1.0 in. diameter), and 100-hr fuels (1.0 - 3.0 in. diameter). Timelag class is related to the rate which the fuel gain or loses moisture. The woody fuel data were converted to fuel weights using calculations described by Brown (1984).

Herbaceous fuels were sampled using a 1 ft^2 clipping frame located at the end of each fuel transect. Herbaceous fuels were clipped and taken to a laboratory where the fuels were dried and the herbaceous fuel loadings were estimated. Litter weights were estimated from litter depths following procedures described by Burgan and Rothermel (1984).

Burn treatment data were collected during the prescribed burns from the edge of each prescribed fire and the fire behavior transects. Weather data included relative humidity, wind speed, and wind direction. Weather data were collected using a belt weather kit along the fire line at each study site.

Fuel moisture data was estimated from fuel samples collected near the prescribed fire site. 1-hr and 10-hr fuel samples were collected along the fire line during each prescribed fire. These samples were collected hourly, placed in air tight containers, and brought back to the laboratory. Fuel moisture samples were weighed, dried, and fuel moisture content was calculated.

Figure 1. Location of all study sites.

Fire behavior data was collected remotely from the fire behavior transects during each prescribed fire. Fire behavior data collected included fire rate-of-spread and flame height. Rate-of-spread data was collected using a rate-of-spread clock (ROSC) system described by Blank and Simard (1983). The rate-of-spread clocks were modified digital watches, wired to a circuit board, and designed to be activated by a flaming front. Clocks were located at the origins and endpoints of each fire behavior transect, and an additional clock was located at 90^0 and 50 ft from the origin of each transect. Using three clocks to measure rate-of-spread aloud triangulation of the fire's direction of spread and rate-of-spread (Simard and others 1984).

Flame length data was collected using char height as a surrogate. Substituting char height for flame length can be a source of error due to the inherent differences between the two measures. Flame length is the distance from the active flaming zone to the approximate tip of the flaming front. Char height is a measure of flame height, the distance from the ground to the tip of the flaming front. Under burning conditions were there is no wind and the ground is level the flame height can be considered equal to the flame length. If there is wind or a slope tilting the flaming front then the flame length will be greater than the flame height. This difference between flame length and flame height is a source of error when using flame height as a surrogate for flame length. Char height as a measure of flame height can under estimate flame length up to 50% (Cain 1984). The error between char height and flame length was considered acceptable due to logistical and budgetary constraints. A flame length monitoring technique was needed that could monitor multiple fire behavior transects at one time, have a quick setup time, and fit within the budget of this project. Other flame length monitoring schemes were evaluated but char height best met the needs of this project.

Char height was measured on trees surrounding the origin and endpoint of each fire behavior transect. The char height data were used as an estimate of flame length and the potential 50% underestimation was acknowledged.

A customized oak savanna fuel model (COSFM) was created using the mean fuel data from each savanna site. Fuel model construction is not an exact science and variables within a fuel model were adjusted to calibrate the model (Burgan and Rothermel 1984).

Slope, weather, and fuel moisture data were used as inputs for BEHAVE predictions (Table 1). Fuel models 1, 2, 3, 9, and the COSFM were used with BEHAVE to predict fire behavior. All fire behavior predictions were influenced by the assumptions of the BEHAVE model. The assumptions of BEHAVE are that BEHAVE predicts fire behavior in the active flaming front, the fire is advancing in a steady state independent of the ignition source, the fire is spreading through surface fuels, and fuel, fuel moisture, wind, and slope are constant during the prediction period (Rothermel 1983, Andrews 1986). Fire behavior predictions are subjected to increased error when one or more of the assumptions are violated.

Fire behavior predictions were then compared to the actual fire behavior (Table 2) and the models were validated. Model validation is evaluating a model's predictions to see if they are acceptable, validation is not determining if the model is correct or not (Burk 1986, Vanclay 1995). BEHAVE predictions were validated using simple linear regression analysis (Brown 1972, Sneeuwjagt and Frandsen 1977, Andrews 1980, Brown 1982, Norum 1982, Bushey 1985, Hunt and Cook 1987, van Wilgen and Wills 1988, McAlpine and Xanthopoulos 1989). Observed fire behavior was compared to predicted fire behavior and the slope and intercept of the regression equation was analyzed. Given the variation within the data if an equation had a slope equal to one (H_0: $ß_1 = 1$) and an intercept equal to zero (H_0: $ß_0 = 0$), the model predictions could not be distinguished from observed fire behavior, (Smith and Rose 1995). R^2s were compared for each equation to identify how well the line fit the data (Neter and others 1989). Regression analysis was completed on mean fire behavior by site (Table 2) due to the large variability expected between individual observed and predicted fire behavior (Andrews 1985, Bushey 1985).

RESULTS AND DISCUSSION

BEHAVE predictions using fuel models 1, 3, and 9 did not reliably predict prescribed fire MROS, but fuel model 2 did reliably predict fire MROS in established oak savannas (Table 3, Figure 2). Fuel model 2 passed the

Table 1. Input data for fire behavior predictions

Plot	Slope	Aspect	Relative humidity	Wind Speed	Wind Direction	Fuel Moisture 1-Hour	Fuel Moisture 10-Hour	Fuel Moisture 100-Hour
	percent		percent	mph		------------percent-----------		
Knob Noster State Park								
A	3	350°	42	4.0	175°	8.0	9.0	9.0
B	7	333°	42	6.0	183°	8.0	9.0	9.0
C	9	45°	43	4.0	180°	8.0	9.0	9.0
D	2	140°	43	4.0	180°	8.0	9.0	9.0
E	2	353°	42	5.0	180°	8.0	9.0	9.0
Ha Ha Tonka State Park								
A	15	291°	33	3.0	240°	8.5	20	20
B	10	343°	30	2.0	250°	8.5	20	20
C	21	337°	32	3.0	220°	8.5	20	20
D	24	17°	32	2.5	250°	8.5	20	20
E	15	58°	32	2.5	250°	8.5	20	20
Meremac State Park								
A	4	113°	40	3.0	295°	11	14	11
B	20	182°	41	3.0	303°	11	14	11
C	21	194°	39	3.0	295°	11	14	11
D	21	181°	40	3.5	336°	11	14	11
G	12	215°	41	0.0		11	14	11
Taum Sauk State Park								
A	5	7°	54	6.0	200°	8	9	10
B	5	50°	54	6.0	200°	8	9	10
D	5	350°	54	6.0	200°	8	9	10
P-Highway								
B	13	219°	28	2.0	35°	8	20	20
E	8	237°	29	6.0	360°	8	20	20
University State Forest								
A	1	290°	45	1.0	340°	8	12	12
C	1	360°	50	0.0		8	12	12
Peck Ranch Conservation Area								
B	5	306°	35	8.0	210°	4	7	13
C	12	105°	28	1.0	220°	4	7	13
D	15	270°	29	7.0	225°	4	7	13
E	12	104°	28	3.0	220°	4	7	13
F	13	310°	28	3.0	220°	4	7	13
G	16	250°	28	3.0	225°	4	7	13
H	14	232°	28	3.0	230°	4	7	13
I	9	230°	28	3.0	220°	4	7	13
J	8	250°	28	3.0	220°	4	7	13

Table 2. Predicted and observed fire behavior for all sites.

Plot	Predicted rate-of-spread					Predicted flame height				
	1	2	3	9	observed	1	2	3	9	observed
	chains/hour					feet				
Knob Noster State Park										
A	18.0	7.0	26.0	2.0	7.0	5.2	7.8	13.6	3.1	3.0
B	43.0	18.0	64.0	4.0	13.0	2.7	4.3	8.4	1.8	2.0
C	22.0	9.0	29.0	2.0	30.0	2.3	3.7	6.9	1.5	5.0
D	38.0	16.0	56.0	4.0	30.0	2.2	3.6	7.0	1.5	4.0
E	76.0	36.0	96.0	7.0	40.0	4.0	6.3	11.8	2.6	5.0
Mean	39.4	17.2	54.2	3.8	24.0	3.3	5.1	9.5	2.1	4.0
Ha Ha Tonka State Park										
A	13.0	6.0	21.0	1.0	8.0	0.7	1.4	3.1	0.6	1.0
B	30.0	13.0	53.0	4.0	13.0	0.8	1.7	3.8	0.8	1.0
C	28.0	13.0	52.0	3.0	30.0	1.2	2.5	5.1	1.1	1.0
D	26.0	12.0	50.0	3.0	9.0	1.4	2.8	5.8	1.2	0.5
E	30.0	11.0	33.0	3.0	4.0	1.9	4.0	8.4	1.7	1.0
Mean	25.4	11.0	41.8	2.8	12.8	1.2	2.5	5.2	1.1	1.0
Meremac State Park										
A	8.0	5.0	15.0	1.0	10.0	1.5	2.6	5.0	1.0	0.5
B	10.0	5.0	9.0	1.0	22.0	1.5	2.7	4.1	1.1	1.0
C	11.0	5.0	17.0	1.0	4.0	1.7	2.4	5.3	1.1	1.0
D	11.0	6.0	17.0	1.0	4.0	1.7	2.9	5.3	1.1	0.5
G	6.0	4.0	6.0	1.0	7.0	1.2	2.2	3.3	1.0	1.0
Mean	9.2	5.0	12.8	1.4	11.8	1.5	2.6	4.6	1.1	1.0
Taum Sauk Mountain State Park										
A	18.0	7.0	20.0	2.0	5.0	2.1	2.9	5.7	1.3	4.0
B	30.0	11.0	33.0	3.0	15.0	2.6	3.6	7.2	1.6	5.0
D	11.0	4.0	12.0	1.0	4.0	1.7	2.3	4.6	1.0	6.0
Mean	19.7	7.3	21.7	2.0	8.0	2.1	2.9	5.8	1.3	5.0
P-Highway										
B	6.0	3.0	6.0	1.0	6.0	1.3	2.1	3.4	1.0	3.0
E	20.0	9.0	22.0	2.0	7.0	2.2	3.3	5.9	1.3	5.0
Mean	13.0	6.0	14.0	1.5	6.5	1.8	2.7	4.7	1.2	4.0
University State Forest										
A	0.0	2.0	13.0	1.0	1.0	0.0	1.6	4.6	1.0	0.5
C	0.0	1.0	3.0	0.0	1.0	0.0	0.8	2.4	0.5	1.0
Mean	0.0	1.5	8.0	0.5	1.0	0.0	1.2	3.5	0.8	1.0
Peck Ranch Conservation Area										
B	20.0	7.0	19.0	2.0	5.0	2.3	3.0	6.1	1.4	2.0
C	10.0	5.0	20.0	2.0	4.0	1.7	2.5	6.3	1.4	4.0
D	14.0	4.0	13.0	1.0	28.0	2.3	2.7	5.8	1.3	2.0
E	43.0	18.0	78.0	5.0	13.0	3.3	4.7	11.7	2.4	5.0
F	11.0	5.0	20.0	1.0	5.0	1.8	2.6	6.2	1.3	2.0
G	9.0	4.0	18.0	1.0	1.0	1.6	2.4	6.0	1.2	2.0
H	4.0	2.0	8.0	1.0	2.0	1.1	1.6	4.0	0.8	2.0
I	20.0	8.0	37.0	2.0	2.0	2.3	3.4	8.3	1.7	3.0
J	26.0	11.0	48.0	3.0	9.0	2.6	3.8	9.4	2.0	3.0
Mean	17.4	7.1	29.0	2.0	7.7	2.9	2.9	7.1	1.5	2.8

slope and intercept tests ($\alpha = 0.05$) and inspection of the regression line through the data reveals a good fit between the data and the regression for MROS predictions (Figure 2). MROS predictions by site were less than +/- four chains per hour from the mean observed rate-of-spread data by site. All the standardized fuel models were unreliable for predicting flame heights (Table 3, Figure 3). Fuel models 1, 2, and 3 tended to overpredict mean flame height and fuel model 9 tended to underpredict mean flame heights.

Four standardized fuel models were validated for use in established oak savannas, since BEHAVE users need to be flexible when deciding what fuel model will work best in a fuel type (Norum 1982). Although, a fuel model appears to characterize fuel conditions in an area does not mean that it will produce acceptable fire behavior predictions (Andrews 1986). Four standardized fuel models which appear to at least partially describe savanna fuels were chosen to predict prescribed fire behavior. Fuel models 1 (short grass), 3 (tall grass), and 9 (hardwood litter) did not adequately predict prescribed MROS or mean flame heights. This indicates that these fuel models do not fit established oak savanna fuel conditions. Fire behavior predictions that have large deviations from observed fire behavior indicate that the fuel model used does not adequately represent the fuels in a fuel type (McAlpine and Xanthopoulos 1989).

Fuel model 2 (timber and grass) provided reasonable predictions of MROS but not mean flame height. The mean predictions for fuel model 2 did tend to under predict rate-of-spread but this is expected when working in heterogeneous fuels (Catchpole and others 1993). Comparison of rate-of-spread predictions from fuel model 2 to similar studies shows the results to be consistent with other BEHAVE validation work (Table 4).

A customized oak savanna fuel model (COSFM) was created using the mean fuel loading for all study sites. The fuel weights for the customized fuel model were compared to all the savanna sites to test how well the model represented the sites (Table 5). The fuel weights for P-Highway Savanna in the 10- and 100-hr fuels were statistically different (α=0.05) from the customized fuel model. This site underwent a firewood cutting. Tops from harvested trees increased the fuel loads in the 10- and 100-hr fuels. Taum Sauk Savanna was statistically different (α=0.05) from the customized fuel model in the 1- and 10-hr fuel classes. The area used within Taum Sauk Mountain was at one time a pasture with some widely spaced trees. The savanna at Meremac State Park was statistically different from the customized fuel model in the 100-hr fuel class. This was because this site has the lowest number of trees per acre and basal area of all the study sites. There were fewer trees contributing larger branch material to the 100-hr fuel size class.

Once the fuel weights for the different fuel size classes were calculated, a customized fuel model was developed (Table 6). MROS predictions using the COSFM were reasonable (Table 3, Figure 2). The COSFM passed the slope and intercept test (α=0.05). The error for the MROS predictions for all sites was less than +/- four chains per hour. The mean flame height prediction of the COSFM was not reliable and tended to overpredict mean flame height (Table 3, Figure 3).

A customized oak savanna fuel model (COSFM) was created in an attempt to reduce some of the variability between fire behavior predictions and observations. The COSFM did slightly reduce the variability, making mean fire behavior predictions closer to observed fire behavior. The COSFM reliability was comparable to past validation work (Table 4). However, considering the apparent reliability of fuel model 2 and the amount of time required to collect and analyze fuel data, it was concluded that a COSFM was not needed for the selected established oak savanna sites.

Fuel model 2 was the best standardized fuel model for the established oak savanna sites tested. With good input data and appropriate interpretation of the output, BEHAVE can be a useful management tool (Andrews 1980). Because BEHAVE is computer operated, it is easy to accept its predictions as accurate (Andrews and Latham 1984), but one should keep in mind that BEHAVE is not a substitute for experience (Rothermel 1983). If used carefully BEHAVE can produce acceptable fire behavior predictions and can be a useful tool when managing Missouri's oak savannas with prescribed fire.

Table 3. Simple linear regression ANOVA table for mean fire behavior predictions

Fuel model	Rate-of-spread Source of variation	SS	df.	MS	Flame height Source of variation	SS	df.	MS
1 (Short Grass)	Regression	185.88	1	185.88	Regression	5.45	1	5.45
	Error	43.05	5	8.61	Error	11.70	6	2.34
	Total	228.93	6		Total	17.15	7	
	$R^2 = 0.81$	Y = 1.855 + 0.350(X)			$R^2 = 0.32$	Y = 0.587 + 0.916(X)*		
2 (Timber and Grass)	Regression	193.12	1	193.12	Regression	4.87	1	4.87
	Error	35.81	5	7.16	Error	12.29	6	2.46
	Total	228.93	6		Total	17.15	7	
	$R^2 = 0.84$	Y = 0.975 + 0.928(X)			$R^2 = 0.28$	Y = -0.096 + 0.828(X)*		
3 (Tall Grass)	Regression	204.27	1	204.27	Regression	2.29	1	2.29
	Error	24.66	5	4.93	Error	14.87	6	2.97
	Total	228.93	6		Total	17.15	7	
	$R^2 = 0.89$	Y = 0.104 + 0.293(X)			$R^2 = 0.13$	Y = 0.405 + 0.304(X)*		
9 (Hardwood Litter)	Regression	179.33	1	179.33	Regression	4.17	1	4.17
	Error	49.59	5	9.92	Error	12.99	6	2.60
	Total	228.93	6		Total	17.15	7	
	$R^2 = 0.78$	Y = 0.592 + 3.876(X)			$R^2 = 0.24$	Y = -0.224 + 1.850(X)*		
Customized Fuel Model	Regression	194.02	1	194.02	Regression	3.82	1	3.82
	Error	34.91	5	34.91	Error	13.34	6	2.67
	Total	228.93	6		Total	17.15	7	
	$R^2 = 0.85$	Y = 0.651 + 1.064(X)			$R^2 = 0.22$	Y= -0.068 + 0.773(X)*		

Y = Observed fire behavior
X = Predicted fire behavior
* = No relationship between Y and X (α=0.05)

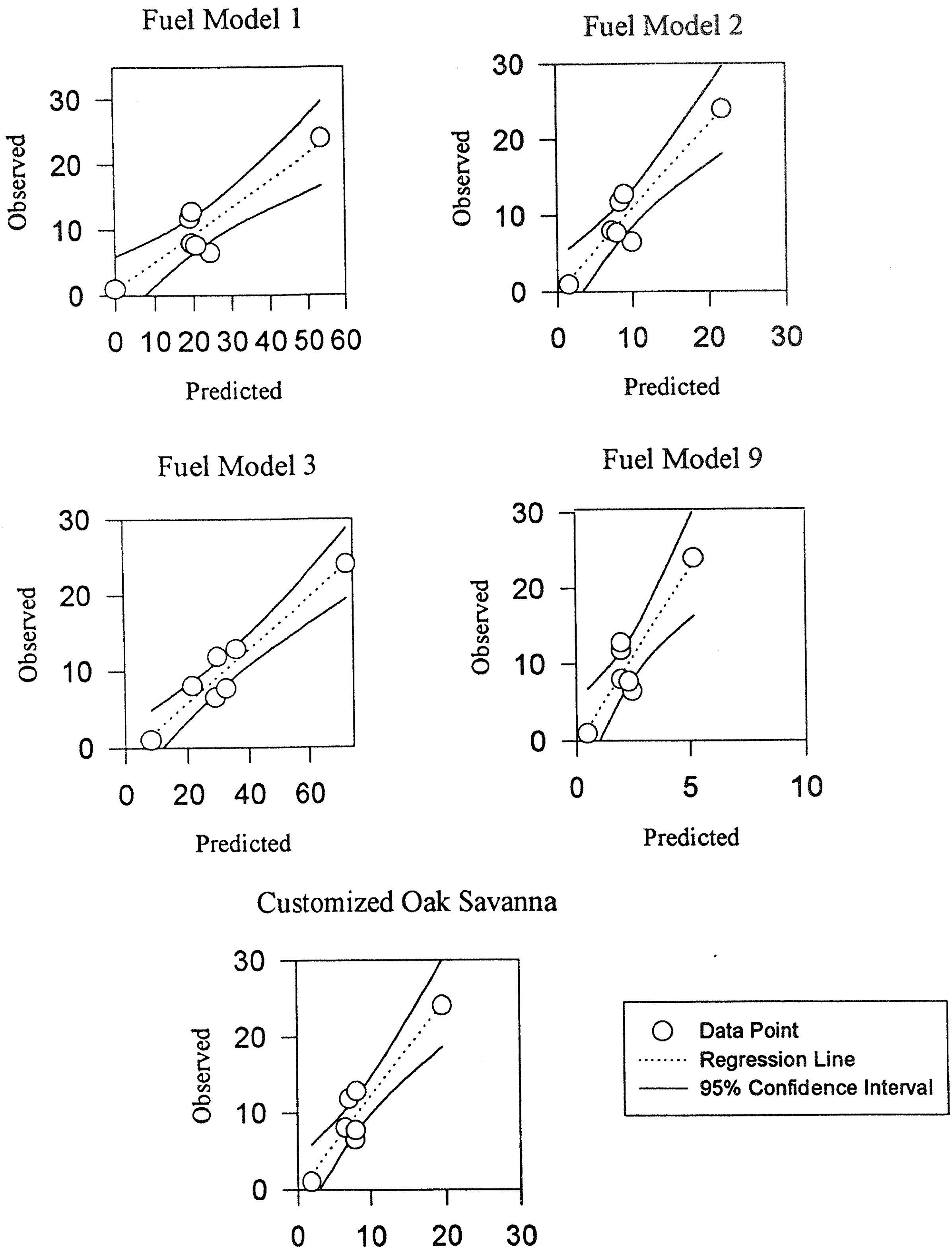

Figure 2. Mean predicted vs. mean observed rates-of-spread for each fuel model.

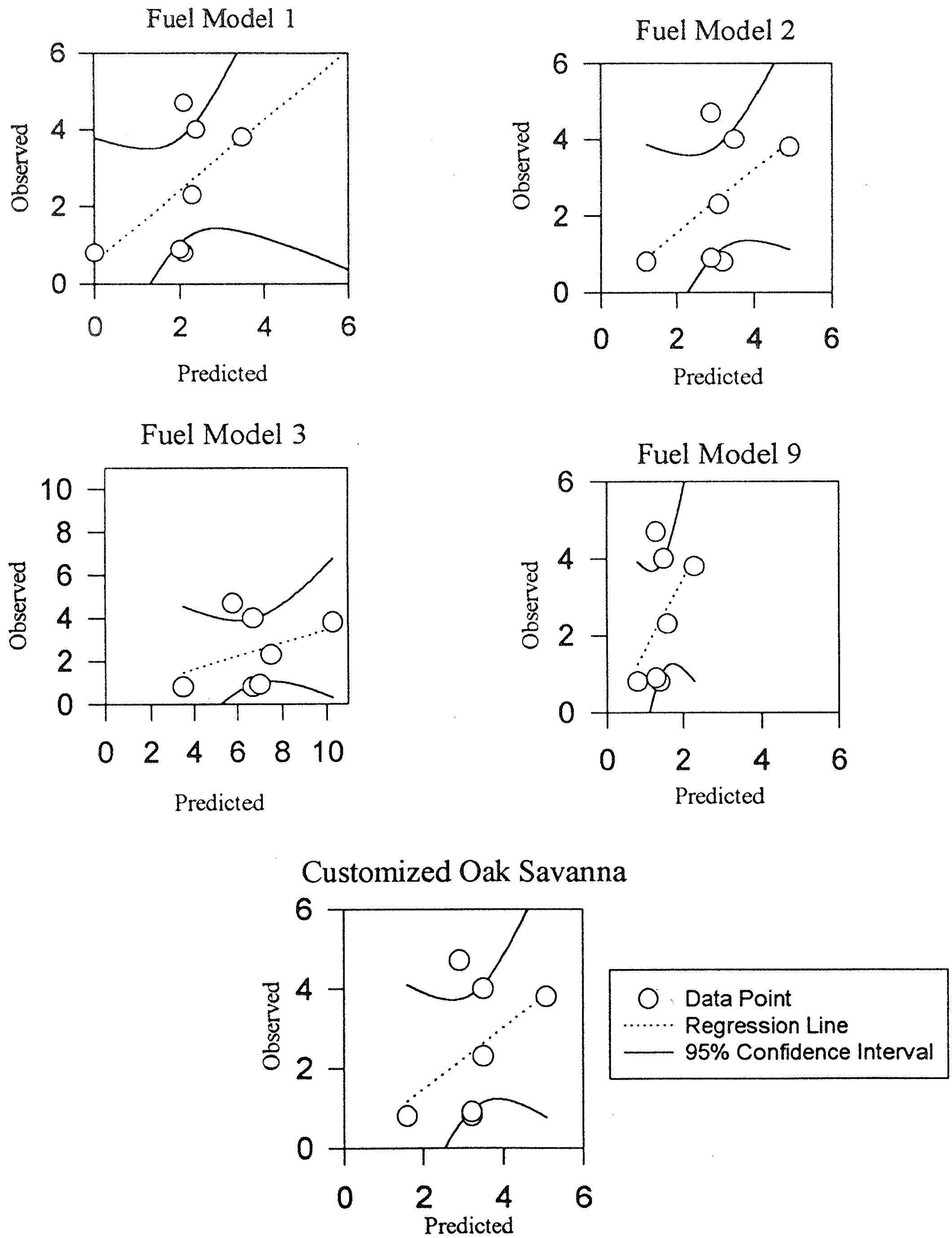

Figure 3. Mean predicted vs. mean observed flame length for each fuel model.

Table 4. Comparison of fuel model 2 validation in oak savannas to other BEHAVE validation work

Fuel type	R^2	Citation
Oak Savanna:		
Predictions using COSFM	0.85	Grabner 1996
Predictions using Fuel Model 2	0.84	Grabner 1996
Grass	0.92	Sneeuwjagt and Frandsen 1977
Western Slash	0.80	Brown 1972
Southern Rough	0.89	Hough and Albini 1978
Sage Brush	0.60	Bushey 1985
Black Spruce	0.94	Norum 1982
Ponderosa Pine	0.78	McAlpine and Xanthopoulos 1989
Synthesis of Validation Research up to 1980	0.89	Andrews 1980
South African Savanna	0.82	van Wilgen and Wills 1988

Table 5. Comparison of fuel weights by site to customized fuel model

Site	Litter	Herbaceous	1-hour	10-hour	100-hour
	-----------------	-----------------	tons/acre	-----------------	-----------------
Knob Noster S.P.	3.02	0.82a	0.044	0.297	1.672
Ha Ha Tonka S.P.	3.12	0.33	0.100	0.364	0.543
Meremac S.P.	2.50	0.48	0.042	0.220	0.253a
Taum Sauk S.P.	2.90	0.51	0.012a	0.159a	0.317
Bennett Spring	2.56	0.35	0.053	0.573	0.709
P-Highway	2.72	0.08a	0.100	0.675a	2.896a
University State Forest	2.18	0.09	0.071	0.425	1.394
Peck Ranch Conservation Area	2.76	0.78	0.053	0.477	2.111
Custom Oak Savanna Fuel Model	2.72	0.43	0.058	0.398	1.236

a = indicates values that are significantly different from the customized fuel model (α=0.05).

Table 6. Structure of customized oak savanna fuel model.

Fuel load		Surface area to volume ratio		Other	
------------tons/acre-------------					
1 Hr	3.21	1 Hr	2800	Depth (ft)	0.63
10 Hr	0.40	Live Herb.	0	Heat Content (BTU/lb.)	8000
100 Hr	1.24	Live Woody	0	Extinction Moisture (%)	30
Live Herb	0.00				
Live Woody	0.00				

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