Preliminary Results of Fire Behavior in Maquis Fuels Under Varying Weather and Slope Conditions in Turkey

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Abstract—*The prediction of fire behavior is of vital importance to all fire management planning and decisionmaking processes including fire prevention, presuppression planning, and fire use. The effect of slope on fire behavior is well acknowledged, yet its effect on fire behavior is not well accounted for. Determining the effects of slope on fire behavior under field conditions can prove invaluable and will allow for the testing of earlier studies conducted under laboratory conditions and help increase the accuracy of fire behavior prediction models. The present study was carried out in Kesan Forest Enterprise in the province of Edirne, Turkey (40°35′ N and 26°31′ E). Although the site was selected for its structural homogeneity, there was an apparent variation in the fuel loadings in different plots. Surface fine fuel (0 to 0.5 cm) loading ranged from 1.07 to 2.10 kg* m^{-2}*, coarse fuel (0.6 to 2.5 cm) loading from 0.97 to 1.75 kg* m^{-2}*, and total fuel loading from 1.52 to 5.67 kg* m^{-2}*. Within the plots burned in this study slope ranged form 1 to 15 percent. Weather conditions during the burns were within the narrow range without wind speed. Air temperature ranged from 25.6 to 33.5 °C, relative humidity from 37 to 62 percent, and wind speed from 5.3 to 17 m* min^{-1}*. Rate of spread ranged from 0.58 to 8.43 m* min^{-1}*, fuel consumption from 1.02 to 2.30 kg* m^{-2}*, and fire intensity from 134 to 2847.6 kW* m^{-1}*. Of the fire behavior characteristics, rate of spread was related to wind speed, slope and moisture contents of live fuels, and fuel consumption was related to fuel loading and moisture contents of live fuels, whereas fire intensity was related to wind speed, slope and moisture contents of live fuels. Results obtained in this study should be invaluable in overall fire management practices, especially in the Mediterranean Region.*

Introduction

Fire is a common feature of Mediterranean landscapes and has a pervasive influence on its forests and their management. An increasingly important requirement of forest and land management in fire-prone ecosystems is the ability to predict fire behavior. Shrublands are one of the most important fire-prone plant communities and have crucial importance for fire management in Turkey. Shrub fuel types are known to be exceptionally flammable and capable of sustaining extreme fire intensity even at moderate fire danger levels (Wouters 1993; Fogarty 1996), thus posing a threat to human life and property (Fernandes 2001). The shrub complexes are known by various names such as fynbos (South Africa), mattoral (Chile), garrique (France), chaparral (California, USA) (Zhou and others 2007), and maquis in Turkey. Maquis grows extensively, neighboring on or adjacent to open forests of oak and pine, and as an understory in these forest types. Thus, determining the effect of varying weather and slope conditions on fire behavior in maquis fuel types has vital importance to all fire management planning and decision making processes.

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The literature review reveals that only a limited number of studies have established the relation between slope and fire behavior (Ward 1971; Rothermel 1972; Hirano and others 1974; Van Wagner 1977; Drysdale and Macmillan 1992; Weise 1993; Weise and Biging 1994; Viegas and others 1994; Dupuy 1995; Van Wagner 1968, 1988; Mendes-Lopes and others 2003; Bilgili and Saglam 2003; Viegas 2004; Zhou and others 2007). Testing slope in fire behavior models is mostly conducted in experimental burns in laboratories, and field burns are conducted on level terrain.

However, results obtained under laboratory conditions do not always reflect the situation under field conditions. Determining the effects of slope on fire behavior under field conditions can prove invaluable and will allow for the testing of earlier studies conducted under laboratory conditions and help increase the accuracy of fire behavior prediction models. The results generated from this study will constitute the basic and fundamental steps toward establishing a fire danger rating system in Turkey and should be invaluable in all phases of fire management planning.

Materials and Methods

The Study Area

The study is situated in Kesan Forest Enterprise in the province of Edirne, Turkey, at 40°35'N and 26°31'E on various slope conditions, and is 30 m above sea level. The community studied includes maquis formations of the *Quercus-Phillyraea* alliance that occupy areas with different degrees of perturbation and usually have *Q. coccifera* as the dominant species. Soils in the area are generally shallow and loam and sandy loam of limestone origin. The vegetation was an open shrubland with an average height of 1.30 m.

In July 2005, a series of 17 burning plots were established at the experimental burning site. Each plot was more or less 0.04 ha (15×25 m) and was delimited by a 5 m wide firebreak in which vegetation was eliminated through bulldozing to mineral soil. A complete fire weather station was established on the site 10 days prior to the burnings. Air temperature, relative humidity, 2 m open wind speed and precipitation were recorded at 13:00 local standard time.

Preburn Fuel Sampling

Fifteen plots (2×2 m) were randomly selected to determine the fuel loadings. The sampled maquis plots were cleared and categorized by diameter. Regression relationships between fuel loadings, vegetation cover, and mean height were established using the sampling data. Fuels loading in the burning plots were estimated using the relationships generated.

Postburn Fuel Sampling

Postburn fuel loading was estimated after each fire to determine fuel consumption. Remaining fuel in each plot was estimated by clipping, oven drying, and weighing all material from three randomly selected sample plots (2×2 m). Fuel consumption was calculated based on the difference between pre- and postburn fuel loadings.

Fuel Moisture Contents

Moisture content of vegetation was obtained from clipped samples immediately before each burning. Samples were oven-dried at 105 °C for 24 hours, and the fuel moisture was expressed as a percentage of dried weight.

Environmental Variables and Fire Behavior

Wind speed, relative humidity, and air temperature were recorded at 15 second intervals during each fire. Plots were burned over 7 days under varying temperature, relative humidity, moisture, wind speed, and slope conditions. Fires were started with a drip torch to rapidly establish a fire line along the windward edge of each plot. Fire intensity was calculated using Byram's equation, $I=hwr$, where, I is the fire line intensity (kW m^{-1}), h is heat yield of the fuel (kJ kg^{-1}), w is the dry weight of the fuels consumed by the fire (kg m^{-2}), and r is the rate of spread of the flame front (m s^{-1}). In this study, energy contents of 19000 kJ kg^{-1} were used based on the relevant information (Brown and Davis 1973; Alexander 1982).

Results

Preburn fuel characteristics for each plot are presented in table 1. Although the site was selected for its structural homogeneity, there was an apparent variation in the fuel loadings in different plots. Surface fine fuel (0 to 0.5 cm) loading ranged from 1.07 to 2.10 kg m^{-2}, coarse fuel (0.6 to 2.5 cm) loading from 0.97 to 1.75 kg m^{-2}, and total fuel loading from 1.52 to 5.67 kg m^{-2}.

Table 2 displays the observed variations in fire behavior values and fire weather conditions recorded on site during each experimental fire. Weather

Table 1—Preburn fuel characteristics associated with the experimental fires.

Fire	H			Fuel loadings (kg m^{-2})					Moisture contents (%)	
no.	(m)	VC	HxC	<0,5 cm	<1 cm	Dead	0,6-2,5 cm	Total	Live fuels	Dead fuels
1	0,63	0,70	0,44	1,11	1,35	0,02	0,98	1,60	77,88	11,07
2	1,00	0,75	0,75	1,35	1,70	0,15	1,19	2,68	102,78	17,99
3	1,50	0,83	1,24	1,86	2,28	0,35	1,51	4,42	102,78	17,99
4	1,30	0,80	1,04	1,64	2,04	0,27	1,38	3,70	109,33	9,40
5	1,15	0,80	0,92	1,55	1,90	0,22	1,30	3,28	100,00	8,26
6	0,60	0,70	0,42	1,10	1,32	0,01	0,97	1,52	100,00	8,26
7	2,00	0,80	1,60	2,05	2,69	0,50	1,75	5,67	98,00	8,26
8	1,05	0,83	0,87	1,56	1,84	0,20	1,26	3,11	100,00	8,26
9	1,50	0,83	1,24	1,86	2,28	0,35	1,51	4,42	89,47	13,86
10	1,70	0,80	1,36	1,87	2,41	0,40	1,59	4,83	69,40	8,73
11	1,50	0,65	0,98	1,26	1,96	0,24	1,34	3,48	69,40	8,73
12	1,75	0,85	1,49	2,10	2,56	0,46	1,68	5,28	89,26	14,34
13	1,35	0,85	1,15	1,82	2,16	0,31	1,45	4,08	89,26	14,34
14	0,75	0,70	0,52	1,15	1,44	0,05	1,03	1,89	79,84	9,76
15	1,15	0,80	0,92	1,55	1,90	0,22	1,30	3,28	81,07	10,49
16	1,55	0,85	1,32	1,96	2,36	0,38	1,56	4,68	75,97	7,58
17	0,75	0,65	0,49	1,07	1,40	0,04	1,01	1,76	75,97	7,58
Mean	1,25	0,78	0,99	1,58	1,98	0,25	1,34	3,51	88,85	10,88
Min.	0,60	0,65	0,42	1,07	1,32	0,01	0,97	1,52	69,40	7,58
Max.	2,00	0,85	1,60	2,10	2,69	0,50	1,75	5,67	109,33	17,99
SD	0,41	0,07	0,37	0,35	0,43	0,15	0,25	1,30	12,79	3,50
SE	0,10	0,02	0,09	0,09	0,10	0,04	0,06	0,32	3,10	0,85
N	17	17	17	17	17	17	17	17	17	17

Table 2—Fire behavior values and fire weather conditions associated with the experimental fires.

Fire no.	T (°C)	RH (%)	W (m min^{-1})	S (%)	ROS (m min^{-1})		FC (kg m^{-2})		FI (kW m^{-1})	
					Observed	Predicted	Observed	Predicted	Observed	Predicted
1	25,6	62	11,2	1	1,94	1,53	1,15	1,28	497,61	657,58
2	32,2	42	7,8	10	2,23	2,36	1,40	1,38	720,69	1022,78
3	33,2	39	8,6	10	2,80	2,60	1,95	1,96	1215,07	1070,61
4	31,8	42	10,9	10	3,30	3,52	1,74	1,64	1279,08	1394,34
5	32,2	41	7,2	8	2,84	1,50	1,62	1,61	1025,24	678,55
6	32,2	41	7,8	8	0,58	2,06	1,02	1,17	134,00	882,02
7	32,2	55	7,7	10	1,56	2,37	2,30	2,12	861,92	978,97
8	33,0	41	7,5	9	3,11	1,86	1,57	1,63	1088,75	823,66
9	33,5	37	5,3	10	1,64	1,30	1,95	1,99	710,45	643,38
10	32,2	42	13,5	3	2,76	3,09	2,18	2,08	1473,53	893,24
11	32,5	46	12,9	4	3,19	2,90	1,52	1,45	1189,58	1062,68
12	32,6	38	10,4	12	2,20	3,90	2,11	2,27	1156,68	1541,47
13	32,6	38	11,6	15	5,95	4,61	2,01	1,94	2847,60	1744,58
14	32,7	41	15,7	13	5,10	6,14	1,44	1,26	1742,65	2399,98
15	31,4	45	16,2	13	5,93	6,21	1,76	1,70	2677,75	2265,03
16	27,7	62	15,2	14	5,10	6,17	2,01	2,21	2288,85	2310,22
17	27,0	60	17,0	14	8,43	6,03	1,19	1,24	2243,23	2647,17
Mean	31,4	45	11,0	10	3,45	3,42	1,70	1,70	1361,92	1353,90
Min.	25,6	37	5,3	1	0,58	1,30	1,02	1,17	134,00	643,38
Max.	33,5	62	17,0	15	8,43	6,21	2,30	2,27	2847,60	2647,17
SD	2,3	9	3,6	4	2,01	1,78	0,38	0,37	764,88	674,45
SE	0,6	2	0,9	1	0,49	0,43	0,09	0,09	185,51	163,58
N	17	17	17	17	17	17	17	17	17	17

conditions during the burns were within the narrow range without wind speed. Air temperature ranged from 25.6 to 33.5 °C, relative humidity from 37 to 62 percent, and wind speed from 5.3 to 17 m min^{-1}. Rate of spread ranged from 0.58 to 8.43 m min^{-1}, fuel consumption from 1.02 to 2.30 kg m^{-2}, and fire intensity from 134 to 2847.6 kW m^{-1} (table 2).

Correlation and regression analyses were undertaken to investigate the relationships between fire behavior characteristics and associated fuel properties and weather conditions. Table 3 displays the correlation coefficients showing trends and relationships among the independent and dependent variables. The most fitted relationships are given in table 4. Equations are presented with one or two independent variables as the second independent variable increased the percent variability explained by the equation.

Rate of spread of fire was highly correlated with wind speed (r= 0.791; P=0.001) and slope (r= 0.597; P=0.01). Wind speed alone explained 63 percent of the observed variation (P<0.001) in the rate of fire spread. Slope as the second independent variable improved the rate of spread prediction significantly (R^2=0.791; P<0.0001). Rate of spread observed by these experimental fires was poorly related to the slope alone (R^2=0.357; P<0.01). The addition of moisture contents of live fuels as the second independent variables significantly improved the percent variability explained (R^2=0.657; P<0.001). Wind speed and slope had a positive effect on rate of spread fire and fire intensity, while live fuel moisture content had a negative effect (table 3). The expectation of critical effect of live fuel moisture content on fire behavior would be significant; mainly its influence on ignitability (for example, Wilson 1985) and combustion rate (for example, Rothermel 1972; Catchpole and others 1998) was established in this study, while the effect of dead fuel moisture content, because of too few fuels, was not determined. Figure 1a shows the predicted versus observed rate of spread values.

Table 3—Correlation matrix between the variables used in the analyses.

	T	RH	ROS	FI	FC	W	S	MC_l	MC_d	H	VC	H×C	FL_f	FL_t
T	1													
RH	–,897(**)	1												
ROS	–,367	,298	1											
FI	–,163	,132	,890(**)	1										
FC	,383	–,199	–,068	,290	1									
W	–,487(*)	,436	,791(**)	,736(**)	–,093	1								
S	,105	–,089	,597(*)	,634(**)	,221	,260	1							
MC_l	,424	–,432	–,412	–,400	–,024	–,715(**)	,208	1						
MC_d	,299	–,468	–,183	–,073	,129	–,320	,152	,268	1					
H	,383	–,137	–,198	,113	,933(**)	–,165	,058	–,059	,071	1				
VC	,365	–,350	–,140	,205	,778(**)	–,331	,333	,361	,286	,608(**)	1			
HxC	,380	–,173	–,194	,143	,968(**)	–,204	,140	,024	,123	,982(**)	,741(**)	1		
FL_f	,356	–,217	–,182	,170	,956(**)	–,252	,246	,144	,194	,893(**)	,882(**)	,962(**)	1	
FL_t	,382	–,175	–,196	,141	,968(**)	–,206	,139	,025	,125	,981(**)	,742(**)	1,000(**)	,963(**)	1

** Correlation is significant at the 0.01 level (2-tailed).
* Correlation is significant at the 0.05 level (2-tailed).
☺T, air temperature (°C); RH, relative humidity (%); ROS, rate of spread (m min^{-1}); FI, fire intensity (kW m^{-1}); FC, fuel consumption (kg m^{-2}); W, wind speed (kph), S, slope (%); MCl, moisture contents of live fuels (%); MCd, moisture contents of dead fuels (%); H, mean vegetation height (cm); VC, vegetation cover (%); H×C, (mean vegetation height × vegetation cover)/10000; FLf, fine fuel loading (<0.6cm; kg m^{-2}); FLt, total fuel loading (kg m^{-2}).

Table 4—Regression equations for predicting fire spread, fuel consumption, and fire intensity in maquis fuels based on the data in this study.

		Constant	Coefficients		R^2	SEE
No	Model	a	b	c		
1a	ROS=a+b S	0.534	0.302		0.357	1.664
1b	ROS=a+b S+c MCl	14.925	0.361	–0.321	0.657	1.257
1c	ROS=a+b W	–1.357	0.438		0.626	1.268
1d	ROS=a+b W+c S	–2.747	0.378	0.213	0.791	0.982
2a	FC=a+b FLt	0.709	0.283		0.937	0.098
2b	FC=a+b FLf	0.720	1.031		0.914	0.115
2c	FC=a+b FLf+c MCl	0.865	1.056	–0.018	0.941	0.099
3a	FI= a+b S	183.264	122.178		0.402	611.044
3b	FI = a+b S+c MCl	5623.701	144.498	121.189	0.698	449.628
3c	FI =a+b W	–341.268	155.326		0.542	534.456
3c	FI =a+b W+c S	–939.026	129.342	91.497	0.752	406.905
3d	FI =a+b W (2 fire excluded)	–209.409	139.598		0.689	367.365
3e	FI =a+b W+c S (2 fire excluded)	–637.126	127.621	65.608	0.846	268.743

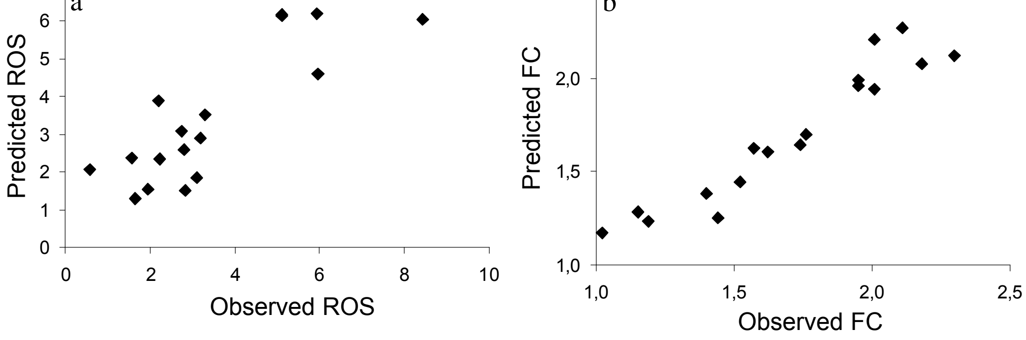

Figure 1—Relationship between predicted and observed rates of fire spread (a), and predicted and observed fuel consumption (b).

Fuel consumption generated by these experimental fires was significantly related to fine fuel loading (<0.6 cm), total fuel loading, and moisture contents of live fuel. Total fuel loading and fine fuel loading alone explained 94 and 91 percent of the observed variation ($P<0.001$) in the fuel consumption, respectively (table 4). The addition of the moisture contents of live fuels as a second independent variable with the fine fuel loading, slightly improved the variability explained (94 percent; $P<0.001$). The relationship between predicted and observed fuel consumption is shown in figure 1b.

Fire intensity was closely related to wind speed (r=0.736; P=0.001) and slope (r=0.634; P=0.001), and slightly related to moisture contents of live fuel (r=-0.400; P=0.001). Slope alone explained 40 percent of the observed variation of fire intensity. The addition of live fuel moisture content as a second independent variables improved the fire intensity prediction significantly ($R^2=0.698$; $P<0.001$). By the same token, wind speed alone explained 54 percent of the observed variation of fire intensity. The addition of slope as a second independent variables improved the fire intensity prediction ($R^2=0.752$; $P<0.0001$). When the minimum and maximum observed fire intensity data (fig. 2a) are excluded from the analyses, wind speed alone explained 69 percent of the observed variation of fire intensity. The addition of slope as a second independent variable improved the fire intensity prediction ($R^2=0.846$; $P<0.0001$; fig. 2b). When this study is completed with a wide range of weather and slope conditions for about 45 experimental fires, these data could be used in the analyses.

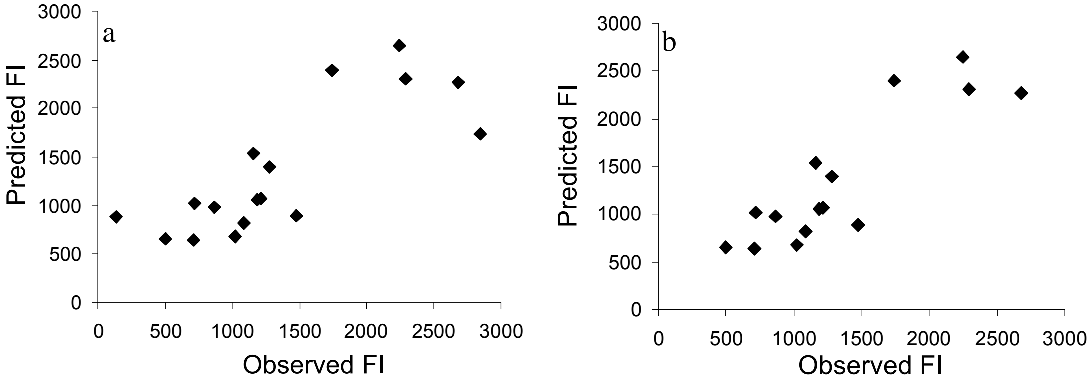

Figure 2—Relationship between predicted and observed fire intensity with whole fire intensity data (a), and (b) without the minimum and maximum fire intensity data.

Discussion and Conclusions

The preliminary results presented in this study come from the first efforts dealing with the prediction of fire behavior under various weather and slope effect in maquis fuels in Turkey. In that respect, the study makes an invaluable contribution to fire behavior analyses in maquis fuels in the Mediterranean Region. The results were based on 17 experimental fires. Differences in fire behavior were clearly shown to be a function of wind speed, slope, moisture contents of live fuels and fuel loading.

Analyses indicated that wind speed was the most significant single predictor of rate of spread of fire and fire intensity, explaining 63 and 69 percent of the variance observed, respectively. Similarly, rate of spread and fire intensity observed by these experimental fires was slightly related to the slope alone ($R^2=0.357$; $R^2=0.402$), respectively. It is important to address the effect of slope on fire spread as topography has a pronounced effect on fire behavior (see for example Noble and others 1980; Forestry Canada 1992; Mendes-Lopes and others 2003; Viegas 2004; Zhou and others 2007). Our results on rate of spread of fire agree with literature (Cheney and others 1993; Johnson and Miyanishi 1995; Burgan and others 1998; Piñol and others 1998; Baeza and others 2002), and support a negative relationship with moisture contents of fuels. On the contrary, because of the little amount of dead fuels, the effect of dead fuel moisture content on fire behavior has not been addressed in this study. Fernandes (2001) indicated that when live fuels are an important fraction of the total fuel load, dead fuel moisture content has a limited influence on the overall moisture content, and consequently, it is logical to expect also a limited effect on fire spread. Fuel consumption generated by these experimental fires was significantly related to fine fuel loading (<0.6 cm), total fuel loading, and moisture contents of live fuel. The addition of the moisture contents of live fuels as a second independent variable with the fine fuel loading explained 94 percent of the observed variation fuel consumption ($P<0.001$). Fire intensity observed in this study (mean 1361.92 kW m^{-1}) agree with those found in Trabaud (1979) in *Quercus coccifera* shrubland (1880 kW m^{-1}).

Given that the study is based on a relatively small number of fires with relatively narrow range of weather, slope, and fuel conditions in open area conditions, more extensive experimentation is required for a comprehensive explanation of fire behavior and the effect of slope and weather parameter on fire behavior for developing fire behavior prediction models in maquis fuels. Future effort will attempt to complete a series of about 45 experimental fires with a wide range of weather and slope conditions to analyze and understand fire behavior in maquis fuels.

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