Turk J Agric For
32 (2008) 121-129

Some Parameters Affecting Fire Behavior in Anatolian Black Pine Slash

Ömer KÜÇÜK[1,*], Ertuğrul BİLGİLİ[2], Bülent SAĞLAM[3], Şağdan BAŞKAYA[2], Bahar DİNÇ DURMAZ[2]

[1]Kastamonu University, Faculty of Forestry, 37200 Kastamonu - TURKEY

[2]Karadeniz Technical University, Faculty of Forestry, 61080 Trabzon - TURKEY

[3]Artvin-Çoruh University, Faculty of Forestry, 08000 Artvin - TURKEY

Received: 13.09.2007

Abstract: This study presents and discusses the results of a fire behavior study conducted in Anatolian black pine (*Pinus nigra* J.F. Arnold subsp. *nigra* var. *caramanica* (Loudon) Rehder) slash. A total of 30 experimental fires were conducted over 3 years under varying weather and fuel loading conditions in aging slash. Relationships between fire behavior and fuel properties and weather conditions were determined with correlation and regression analyses. Spread rate, fuel consumption, and fire intensity were all related to fuel properties and weather, and ranged from 0.2 to 3.1 m min^{-1}, from 0.71 to 6.65 kg m^{-2}, and from 14.05 to 3961.46 kW m^{-1}, respectively. Fuel loading ranged from 1.56 kg m^{-2} to 6.96 kg m^{-2}. Differences in fire behavior were clearly shown to be a function of wind speed, fuel moisture, slash age, and fuel loading. Results obtained in this study should be invaluable in overall fire management practices. However, its use should be restricted to the range of conditions within which the data were gathered.

Key Words: Fire behavior, slash fuel, *Pinus nigra*, Turkey

Bazı Parametrelerin Anadolu Karaçamı Kesim Artıklarında Yangın Davranışına Etkisi

Özet: Bu çalışmada, Anadolu karaçamı (*Pinus nigra* J.F. Arnold subsp. *nigra* var. *caramanica* (Loudon) Rehder) kesim artıklarındaki yangın davranışı sonuçları sunulmuş ve tartışılmıştır. Üç yıl boyunca değişik hava halleri, kesim artıkları yaşı ve yanıcı madde koşullarındaki kesim artıklarında toplam 30 deneme yangını oluşturulmuştur. Yangın davranışı ile yanıcı madde ve hava halleri arasındaki ilişkiler korelasyon ve regresyon analizleri ile belirlenmiştir. Yayılma oranı, yanıcı madde tüketimi ve yangın şiddeti, yanıcı madde özellikleri ve hava halleri ile ilişkili olmuş, sırasıyla 0.2 ile 3.1 m dak^{-1}, 0.71 ile 6.65 kg m^{-2} ve 14.05 ile 3961.46 kW m^{-1} arasında değişmiştir. Yanıcı madde miktarı 1.56 ile 6.96 kg m^{-2} arasında değişmiştir. Yangın davranışındaki farklılıklar açıkça, rüzgar hızı, yanıcı madde nemi, kesim artıklarının yaşı ve yanıcı madde miktarının bir fonksiyonu olarak görülmüştür. Bu çalışmadan elde edilen sonuçlar tüm yangın amenajmanı uygulamaları için çok değerlidir. Fakat sonuçların kullanımı verilerin toplandığı şartlar içinde sınırlandırılmalıdır.

Anahtar Sözcükler: Yangın davranışı, kesim artıkları, Karaçam, Türkiye

Introduction

Each action taken in a forest stand has an effect on fuel properties (Bilgili, 2003). Silvicultural interventions, for example, dramatically alter not only the slash fuel properties but also stand structure parameters, which play an important role in fire behavior.

Slash deposited to the forest floor through harvesting and thinning constitutes a high degree of fire hazard (Fahnestock, 1968; McRae et al., 1979; Vihanek and Ottmar, 1993), a barrier to successful regeneration (Adams, 1966; Heeney, 1977), and is a very important available fuel for fire spread (Andrews, 1986). Treating

* Correspondence to: okucuk@gazi.edu.tr

slash to maintain an acceptable fire hazard is expensive and requires skillful decision-making (Albini and Brown, 1978). Several studies have shown that slash disposal is needed to reduce fuel loads and change fire behavior (Fahnestock, 1960; Fahnestock and Dieterich, 1962; Wagener and Offord, 1972; Roussopoulos and Johnson, 1973; Williams, 1977; Freeman and Roussopoulos, 1983; Wakimoto et al., 1998; Vihanek and Ottmar, 1993). Thus, a great deal of research effort has gone into studying fire behavior (Fahnestock, 1960; Fahnestock and Dieterich, 1962; Stocks and Walker, 1972; McRae, 2001) and fire effects on soil and vegetation dynamics (Trowbridge et al., 1989; Baxter, 2002) in these fuels. As a result, many individual fire behavior studies have contributed to generating fire behavior prediction models in the currently used fire behavior prediction systems (i.e. Australian, American, and Canadian systems). However, the effect of slash age on fire behavior is mostly not accounted for by the models currently in use. Nearly all fire behavior studies conducted in slash fuels involved relatively newly cut slash (i.e. < 1 year old). Given that fuel characteristics play an important role in fire behavior (Bilgili, 2003), aging slash may pose a major problem in predicting fire behavior in silviculturally treated stands where slash fuel characteristics change over time.

Changes in slash fuel loading, its structure, and foliage retention depend on slash age (McRae et al., 1979; Fahnestock and Dieterich, 1962; Kiil, 1968) and environmental factors. Foliage retention quantifies the amount of foliage being retained by branches on slash fuels. The amount of foliage retained greatly affects ignition and fire behavior (Van Wagner, 1966).

The principle objective of this study is to investigate fire behavior in black pine slash under varying weather and fuel conditions, and relate the resulting fire behavior parameters to slash age characterized by fuel loading and foliage retention rates over time. This study should serve to help fill a gap and provide the quantitative data required for developing, validating and calibrating fire behavior prediction models in use.

Material and Methods

Experimental site and design

The species selected for the study was Anatolian black pine (a.k.a. black pine) in Kastamonu. Black pine is the second most widely distributed conifers in Turkey after Calabrian pine (*Pinus brutia* L.), covering an area of 4.2 million ha (OGM, 2007). Pure natural black pine stands are mostly found in fire prone areas and usually originated from high-intensity, stand-replacing fires (Turna and Bilgili, 2006).

The elevation of the site is 950 m above sea level, and the soils in the area are loam and clay loam. The study area has a northwestern Black Sea climate characterized by short hot summers and long cold winters. Mean annual precipitation is approximately 510 mm with most of it occurring mainly from November to April. The fire season generally lasts from late June until mid-September.

In late spring of 2002, a series of 30 burning plots were established on a level terrain using newly cut black pine slash fuels. Fuel was uniformly distributed to the greatest extent possible. Two different fresh fuel loadings (8 kg m^{-2} and 16 kg m^{-2}) were used. Fuels in the burning plots were made up of foliage and branches. Branches > 2.5 cm in diameter were omitted because larger branches have less influence on the rate of fire spread than smaller pieces. All plots measured 3×1 m, and laid out in parallel in the direction of the prevailing wind. The plots were surrounded by cleared, 2-2.5 m wide fire lines so that fire control and access would be facilitated and that each plot would burn free from influence of the other fires.

A complete fire weather station was established at the study site prior to the burnings. Temperature, relative humidity, 1.5-m open wind speed, and precipitation were measured daily. Experimental fires were conducted between mid-July and early September during the summers of 2002, 2003, and 2004.

Preburn fuel sampling

Fuel loading and foliage retention in each plot were determined on the basis of 3 samples that were randomly collected prior to burning. Fuel material within a sampling frame measuring 30×30 cm was removed down to the mineral soil, and then classified as needles and branches. Additionally, fuel depths were measured at 3 points in each plot with a ruler. Fuel depth was measured as the vertical distance from the bottom of the litter layer to the highest slash particle. Branches were later subdivided by size classes as fine (diameter < 0.6 cm), medium (0.6-1.0 cm) and thick (1.0-2.5 cm) (Rothermel, 1972; Quintilio et al., 1977; Stocks, 1980) and weighed. Then, subsamples taken from each fuel component were weighed, placed in nylon bags, and taken to the lab for calculating oven-dry weights. Total fuel loading for each plot was then calculated based on the oven-dry weights. The remaining samples were placed back to where they had been taken from. Foliage retention rates were determined by comparing the amount of foliage remaining on branches sampled to that determined when plots were established.

To determine on-site moisture contents of slash fuels, samples of several fuel components (litter, needle, and fine branch) were collected immediately prior to each burning (Stocks and Walker, 1972; McRae et al., 1979). Samples were then oven-dried at 100 °C for 24 h. Moisture contents were calculated on a dry weight percentage basis.

Fire behavior

During the experimental burns, 1.5 m open wind speed, air temperature and relative humidity were recorded at 15 s intervals using the automatic weather station set up on the edge of the site (Sneeuwjagt and Frandsen, 1977). A hand-held anemometer was also used to record wind speed values for as low as 10 s intervals for control purposes. The wind measurements were averaged over the period during which the fires propagated.

Plots were burned over 2 years under varying temperature, relative humidity, moisture, and wind speed conditions. The preferred time of ignition was late afternoon to capitalize on daily peak burning conditions. All experimental fires were ignited as a line fire along the windward edge of each plot, and allowed to spread down wind through the length of the plot in order to simulate a free burning wildfire (Alexander et al., 1991). A drip torch was used to establish a successful fire line as quickly as possible. Collection of the fire behavior data started when the fire line had moved about 30 cm from the edge of the plot. Rates of spread were determined by recording the time the head fire front arrived the pre-placed, 1 m apart poles on each side of the burning plot. Fire behavior was monitored during each fire from the time the ignition line was fully established to the time fire front reached the edge of the plots. In addition, the progress of all fires was documented on videos and photographic records for future evaluation. Frontal fire intensity was calculated for each plot using the Byram's equation (Byram, 1959):

$$I = HWR.$$

where I is the fire intensity (kW m^{-1}), H is the net low heat of combustion (kJ kg^{-1}), W is the weight of fuel consumed per unit area in the active flaming zone (kg m^{-2}), and R is the rate of spread (m s^{-1}). In this analysis, an H value of 18,600 was assumed based on the relevant information found in literature (Alexander, 1982; Forestry Canada, 1992; Fernandes et al., 2004). Based on the observation, experience and relevant literature, fuels consumed in the active flaming front were assumed to consist of foliage and branches < 1 cm.

Postburn fuel sampling

Postburn fuel loading was measured immediately after each fire to determine the amount of fuel consumed. All material remaining on the plots were collected. Needles, if any, and branches were placed in bags and taken to the lab to determine oven dry weights. Total fuel consumption was then calculated based on the difference between the pre- and post-burn fuel loadings.

Statistical analysis

Correlation and regression analyses were performed to compare fire behavior characteristics with fuel properties and weather conditions. In regression analyses, fuels and weather conditions were considered as independent variables, and fire behavior characteristics as dependent variables. Before the analyses, the variables were tested for normality and, as a result, a transformation was deemed necessary for some variables (rate of spread and fire intensity). Then, using linear and logarithmic regression models, equations were generated for predicting fire behavior. All selected equations were significant at the 95% significance level. Statistical analyses were performed using SPSS 10.0 for Windows (SPSS, Chicago, IL, USA).

Results

Foliage retention and slash age

Foliage retention was heavily dependent on slash age. On average, 90% of the initial foliage was still remaining on branches after 3 months. Only 25% of the foliage remained on branches after 12 months, and literally no foliage (1%) remained on branches after 24 months (Figure 1).

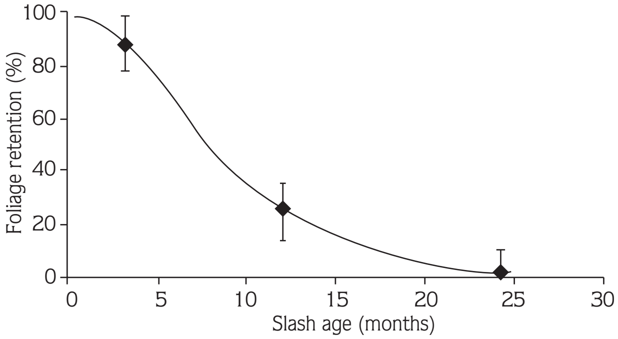

Figure 1. Relationships between foliage retention rates and slash age in Anatolian black pine slash. Data points (◆) with error bars represent the measurements.

Fuel loading and fire behavior characteristics

Preburn fuel characteristics for each plot are presented in Table 1. Although the plots were established for structural homogeneity in fresh weight, mean oven-dry fuel loadings varied somewhat from plot to plot, but the differences were not statistically significant at the $\alpha = 0.05$ level (95% confidence).

Table 2 summarizes fire behavior characteristics and associated weather parameters recorded on site during each fire. Fire behavior was variable across the study plot, primarily due to variable wind speed, differences in moisture contents of the fuels, and variations in litter and

Table 1. Preburn fuel characteristics associated with the experimental fires (Fine branch: branches < 0.6 cm; Medium branch: 0.6-1 cm; Thick branch: 1-2.5 cm; SEE: Standard Error of the Estimate; SD: Standard Deviation; $\bar{X}$: Mean).

Plot no.	Slash age (month)	Fresh fuel weight (kg m^{-2})	Oven-dry fuel loading (kg m^{-2}) Litter	Needle	Fine branch	Medium branch	Thick branch	Total fuel	Available fuel for fire intensity	Foliage retention (%)	Fuel depth (cm)
1	12	8	0.072	0.480	0.604	0.679	0.313	2.148	0.753	19.51	18.0
2	12	8	0.086	0.435	0.660	0.725	0.307	2.213	0.741	17.68	20.0
3	12	8	0.092	0.540	0.705	0.738	0.283	2.358	0.867	21.95	20.0
4	12	8	0.105	0.563	0.692	0.771	0.250	2.381	0.899	22.89	22.0
5	12	8	0.088	0.578	0.683	0.883	0.283	2.516	0.894	23.50	20.0
6	12	8	0.108	0.554	0.707	0.807	0.338	2.514	0.898	22.52	22.0
7	12	16	0.192	0.795	1.253	1.288	0.608	4.137	1.404	19.71	35.0
8	12	16	0.205	0.830	1.104	1.150	0.620	3.909	1.403	20.58	35.0
9	12	16	0.185	0.780	1.225	1.225	0.573	3.988	1.374	19.34	35.0
10	12	16	0.217	0.890	1.250	1.158	0.647	4.162	1.523	22.07	37.0
11	12	16	0.188	0.770	1.188	1.213	0.583	3.943	1.354	19.09	35.0
12	12	16	0.210	0.845	1.250	1.263	0.672	4.240	1.472	20.95	37.0
13	3	8	0.000	1.950	0.797	0.729	0.367	3.842	2.216	79.27	22.0
14	3	8	0.000	2.115	0.791	0.741	0.392	4.039	2.379	85.98	22.0
15	3	8	0.000	2.015	0.650	0.732	0.347	3.743	2.232	81.91	22.0
16	3	8	0.000	2.950	0.808	0.785	0.327	4.869	3.219	90.00	22.0
17	3	8	0.000	2.040	0.825	0.804	0.398	4.067	2.315	82.93	22.0
18	3	16	0.000	3.630	1.328	1.324	0.675	6.957	4.073	90.00	38.0
19	3	16	0.000	3.630	1.282	1.317	0.647	6.875	4.057	90.00	38.0
20	3	16	0.000	3.580	1.255	1.305	0.653	6.793	3.998	88.76	38.0
21	3	16	0.000	3.690	1.297	1.233	0.625	6.845	4.122	91.49	38.0
22	3	16	0.000	3.620	1.304	1.290	0.707	6.921	4.055	89.75	38.0
23	24	8	0.025	0.000	0.660	0.668	0.278	1.632	0.245	0.00	15.0
24	24	8	0.017	0.000	0.638	0.705	0.283	1.643	0.229	0.00	12.0
25	24	8	0.017	0.000	0.625	0.703	0.218	1.563	0.225	0.00	12.0
26	24	8	0.017	0.000	0.630	0.750	0.260	1.657	0.227	0.00	10.0
27	24	16	0.045	0.108	1.187	1.240	0.573	3.153	0.549	2.68	28.0
28	24	16	0.050	0.128	1.217	1.227	0.603	3.225	0.584	3.17	30.0
29	24	16	0.050	0.138	1.207	1.247	0.562	3.203	0.590	3.42	30.0
30	24	16	0.047	0.117	1.212	1.253	0.587	3.215	0.568	2.90	27.0
	$\bar{X}$	12.000	0.067	1.259	0.967	0.998	0.460	3.758	1.648	37.735	26.600
	SEE	0.743	0.152	0.238	0.051	0.047	0.030	0.307	0.240	6.645	1.468
	SD	4.068	0.835	1.303	0.281	0.260	0.165	1.683	1.314	36.398	9.026

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

	Meteorological parameters				Fire behavior parameters			
Fire no.	Air temp. (ºC)	Wind speed (km h^{-1})	Relative humidity (%)	Fuel moisture content (%)	Active flame (m)	Rate of spread (m min^{-1})	Fuel consumption (kg m^{-2})	Fire intensity (kW m^{-1})
1	29	2.0	24	10.3	0.3	0.3	1.04	70.04
2	28	4.3	25	8.5	0.5	0.6	1.44	137.85
3	29	5.0	24	11.7	0.5	0.6	1.04	161.20
4	25	7.8	24	7.9	0.8	0.9	2.21	250.70
5	31	4.7	23	7.2	0.7	0.5	2.49	138.59
6	23	8.2	57	8.1	0.7	0.9	2.02	250.51
7	29	4.1	24	7.4	0.3	0.5	3.96	217.69
8	29	6.0	24	8.2	1.0	0.8	3.64	347.94
9	29	5.6	24	8.5	0.8	0.5	3.49	212.90
10	29	9.0	24	8.0	1.3	0.9	3.98	425.01
11	25	3.8	24	7.2	0.4	0.4	3.84	167.95
12	22	7.3	60	8.5	1.2	1.0	3.95	456.22
13	31	9.1	21	14.7	1.5	1.2	3.67	824.23
14	30	11.3	21	16.2	1.2	1.4	3.81	1032.29
15	30	14.9	21	16.6	1.6	2.3	3.47	1591.18
16	30	12.5	21	17.1	1.2	1.8	4.55	1796.33
17	25	11.2	49	15.9	1.8	2.6	3.65	1865.89
18	29	10.2	21	15.6	2.0	1.9	6.65	2398.80
19	29	12.4	21	17.1	2.2	2.7	6.50	3395.90
20	20	6.2	67	17.4	1.5	0.9	6.33	1115.54
21	25	12.4	49	14.9	2.0	3.1	6.48	3961.46
22	25	11.2	49	13.8	1.8	2.6	6.62	3268.06
23	32	12.1	20	9.5	0.2	0.4	0.98	30.39
24	31	9.9	19	9.8	0.2	0.3	0.97	21.34
25	31	9.6	19	10.1	0.2	0.3	0.71	20.93
26	31	7.5	18	10.1	0.1	0.2	0.77	14.05
27	30	7.4	22	7.8	0.7	0.5	1.78	85.03
28	30	7.7	20	7.2	0.8	0.7	2.03	126.63
29	30	9.8	22	7.2	0.8	0.8	2.06	146.38
30	32	7.3	20	7.8	0.6	0.5	1.90	87.97
$\bar{X}$	28.3	8.350	28.5	11.01	0.958	1.070	3.20	820.63
SEE	0.56	0.572	2.56	0.684	0.572	0.152	0.345	205.012
SD	3.09	3.133	14	3.745	0.608	0.835	1.891	1122.897

needle fuel loading. All fires burned under a reasonably wide range of weather conditions. During the experimental fires, air temperature varied from 20 to 32 °C, relative humidity from 18% to 60%, and wind speed from 2.0 to 14.9 m min^{-1}. Rate of spread ranged from 0.2 to 3.1 m min^{-1}, fuel consumption from 0.713 to 6.647 kg m^{-2}, and fire intensity from 14 to 3961 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 presents the correlation coefficients showing trends and relationships among the independent and dependent variables. The most pertinent relationships are given in equation form in Table 4. Equations are presented with 1, 2, or 3 independent

Table 3. Correlation matrix between the variables used in the analyses (Age, slash age (month); FR, foliage retention (%); AF, available fuel (needle + branches, < 1 cm) loading (kg m^{-2}); TFL, total fuel loading (kg m^{-2}); FD, fuel depth (cm); BD, bulk density (kg m^{-3}); RH, relative humidity (%); MC, fuel moisture content (%); T, temperature (°C); W, wind speed (km h^{-1}); FL, active flame length (m); ROS, rate of spread (m min^{-1}); FC, fuel consumption (kg m^{-2}); FI, fire intensity (kW m^{-1})).

	Age	FR	AF	TFL	FD	BD	RH	MC	T	W	FL	ln ROS	FC	ln FI
Age	1													
FR	-0.860**	1												
AF	-0.779**	0.933**	1											
TFL	-0.625**	0.794**	0.947**	1										
FD	-0.314*	0.364*	0.609**	0.813**	1									
BD	-0.641**	0.876**	0.783**	0.611**	0.063	1								
RH	-0.345*	0.349*	0.421*	0.434**	0.386*	0.186	1							
MC	-0.725**	0.911**	0.802**	0.616**	0.094	0.922**	0.230	1						
T	0.398*	-0.322*	-0.418*	-0.442**	-0.472**	-0.092	-0.896**	-0.158	1					
W	-0.175	0.536**	0.446**	0.335*	-0.021	0.608**	0.023	0.611**	0.117	1				
FL	-0.697**	0.873**	0.890**	0.860**	0.598**	0.669**	0.388*	0.724**	-0.352*	0.568**	1			
ln ROS	-0.704**	0.862**	0.828**	0.765**	0.500**	0.644**	0.385*	0.695**	-0.354*	0.645**	0.935**	1		
FC	-0.672**	0.818**	0.951**	0.981**	0.791**	0.620**	0.435**	0.610**	-0.464**	0.343*	0.860**	0.777**	1	
ln FI	-0.815**	0.912**	0.914**	0.868**	0.629**	0.661**	0.424**	0.709**	-0.438**	0.458**	0.936**	0.953**	0.889**	1

Table 4. Regression equations for predicting fire spread, fuel consumption and fire intensity based on the data obtained in this study (ROS: Rate Of Spread; FC: Fuel Consumption; FI: Fire Intensity).

Dependent Variables	Model Form	Constant	Coefficients				R^2	SEE
		a	b	c	d	e		
ROS	lnY = a + bFR	-0.874	0.018				0.743	0.386
	lnY = a + bFR + cBD	0.209	0.026	-0.156			0.796	0.350
	lnY = a + bFR + cBD + dW	0.209	0.026	-0.156	0.094		0.894	0.257
	lnY = a + bFR + cBD + dW + eMC	0.317	0.031	-0.103	0.104	-0.100	0.920	0.228
FC	Y = a + bTFL	-0.941	1.102				0.962	0.377
	Y = a + bFR + cFD	-1.179	0.032	-0.119			0.951	0.434
FI	lnY = a + bFR	4.171	0.040				0.832	0.665
	lnY = a + bFL	3.324	2.458				0.877	0.570
	lnY = a + bAF	3.851	1.109				0.835	0.659
	lnY = a + bFR + cMC	6.474	0.069	-0.308			0.921	0.465
	lnY = a + bFR + cMC + dBD + eW	7.426	0.073	-0.225	-0.182	0.063	0.947	0.395

variables, as the second, and third independent variables increased the percent variability explained by the equation. Relationships among the independent and dependent variables are the most interesting and meaningful in this study.

Rate of spread was closely related to foliage retention, available fuels, total fuel loading, bulk density, fuel moisture contents, and wind speed ($P < 0.01$). Of these, foliage retention was the most significant predictor of the rate of fire spread, explaining 74% of the variance observed in the rate of spread. The addition of the bulk density as the second independent variable improved the percentage of the variability explained significantly. The addition of the wind speed and fuel moisture content as the third and fourth independent variables also had a significant effect (Table 4). Figure 2 shows the predicted vs. observed rate of spread values.

The most dominant factor influencing fuel consumption was the total fuel loading, explaining 96% ($P < 0.01$) of the observed variation. Foliage retention alone explained 67% of the observed variation ($P < 0.01$) in fuel consumption. The addition of fuel depth as the second independent variable significantly improved the percent variability explained ($R^2 = 0.951$; $P < 0.01$). Figure 3 shows the predicted vs. observed fuel consumption values.

Fire intensity was also closely related to fuel, weather, and fire behavior parameters. Foliage retention, flame length, and available fuels each explained 83%, 88%, and 84% of the observed variation in fire intensity, respectively ($P < 0.01$). Along with foliage retention, the addition of the fuel moisture content, bulk density, and wind speed as the second, third, and fourth independent variables significantly improved the percentage of the variability explained ($R^2 = 0.947$; $P < 0.01$). Figure 4 shows the predicted vs. observed fire intensity values.

Discussion

The study focuses on fire behavior (i.e. ROS, FC, and FI) prediction in Anatolian black pine slash under varying weather and fuel conditions. The principle objective of the study was to substantiate the effect of aging (i.e. foliage retention) on fuel characteristics and fire behavior. The results were based on a total of 30 experimental slash fires. Differences in fire behavior were clearly shown to be a function of foliage retention, fuel loading, fuel moisture, and wind speed. Analyses indicated that foliage retention was the most significant single predictor of fire behavior, explaining 74% and 83% of the variance observed in the rate of spread and fire intensity, respectively.

The amount of foliage retained on slash greatly affects fire behavior (Van Wagner, 1966; McRae et al., 1979). This is especially important in intensively managed stands or stands undergoing major changes through silvicultural interventions. The study showed that foliage retention is readily predictable and highly dependent on slash age. These results agree with those found in McRae et al. (1979) with a difference that the rate of litter fall was faster in the present study. This may be ascribed to 2 reasons: i) the environmental conditions to which the slash is subjected, and ii) differences in fuel type characteristics. Within stands, slash tends to retain foliage over a longer time period due to the shelter effect of trees above and around slash.

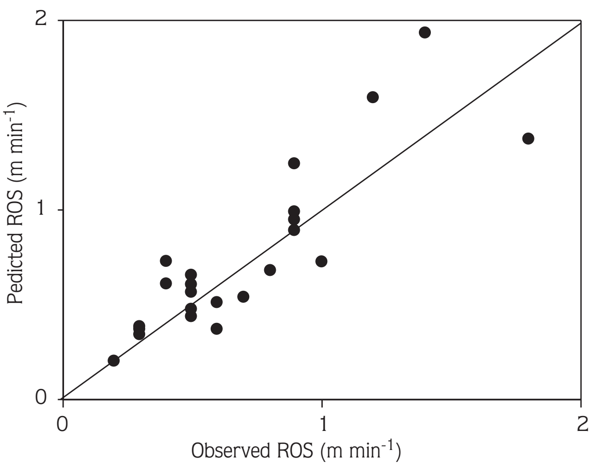

Figure 2. Relationship between predicted and observed rates of spread (ROS). Solid line running through the data points represents the line of perfect agreement.

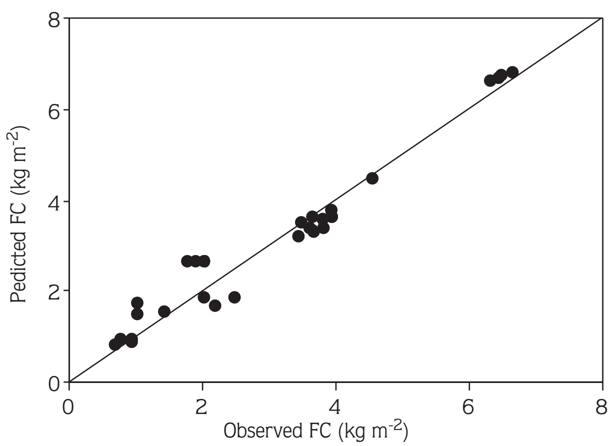

Figure 3. Relationship between predicted and observed fuel consumption (FC). Solid line running through the data points represents the line of perfect agreement.

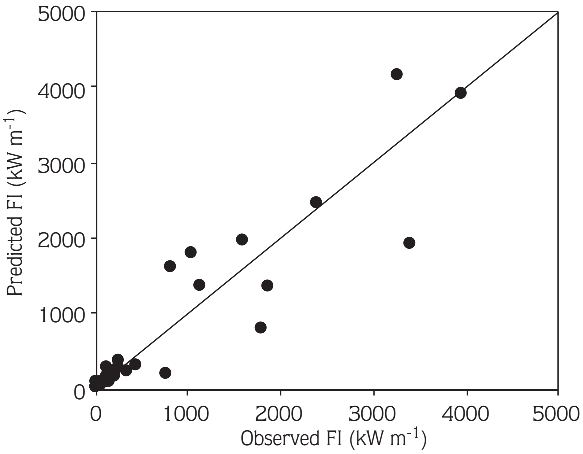

Figure 4. Relationship between predicted and observed fire intensity (FI). Solid line running through the data points represents the line of perfect agreement.

Slash fuel depth is a critical parameter because it determines bulk density of fuel array for a given fuel loading. Slash age has a significant influence on slash depth. Up to 50% reduction in slash depth was reported to have occurred in 5 years (Fahnestock and Dieterich, 1962; Kiil, 1968). The results of the present study indicated, on average, a 37% reduction in slash depth, and some fine branches were observed breaking up gradually 2 years after cutting.

Rate of spread was very sensitive to foliage retention and bulk density. The gradual shedding of foliage over time was followed by a noticeable reduction in the rate of spread. The rate of spread was also negatively affected by the detachment of twigs from branches. The lowest rate of spread values were observed in 2-year-old slash fuels. Similar results were reported previously (Williams, 1977).

In addition to the fuel characteristics, burning conditions also had significant effects on fire behavior. Highest values of rate of spread, fire intensity, fuel consumption, and flame length were observed under low fuel moisture and high wind speed conditions. Although the variation in fuel moisture contents varied within a relatively narrow range, its effect on both rate of fire spread and fire line intensity was greater than would be expected.

Flammability and ease of combustion of fuels were mostly related to the fuel moisture contents and to the amount of fine branches and foliage hanging on branches. With the newly cut slash (3 months old), the ignition was relatively easy and fuel consumption was complete, resulting in a relatively high fire intensity and fuel consumption. In general, all foliage and branches less than 1.0 cm in diameter were consumed during the experimental fires. Fuels greater than 1.0 cm in diameter were little consumed. With larger fuels, moisture content of the fuels was the determining factor of fuel consumption. Large fuels, when dry, prolonged combustion and added proportionately to heat output. These findings agree well with those of Fahnestock (1968).

It should be noted that the range of slash fuel and weather parameters under which the fires were burned represents the range of open area conditions under which it is possible to use the relationships generated from this study. Thus, the relationships derived to predict fire behavior should be used in areas having similar slash fuel and weather conditions, or after some operational verification. However, the purpose of this study was not only to investigate fire behavior under varying fuel and weather conditions but also to show the differential effect of foliage retention on fire behavior. In this regard, the present study can be considered to have achieved that goal.

The effect of slope on fire behavior has not been addressed in this study. But it is important to address the effect of slope on fire spread as topography has a pronounced effect on fire behavior (Noble et al., 1980; Forestry Canada, 1992).

Given that the study is based on a relatively small number of fires with a relatively narrow range of weather and fuel conditions in open area conditions, more extensive experimentation is required for a comprehensive explanation of fire behavior and the effect of foliage retention on fire behavior for developing fire behavior prediction models in slash fuels. The results of the study should also serve to fill an important gap in fire behavior prediction in silviculturally treated stands.

Acknowledgements

This study was conducted with the cooperation and efforts of many people. The authors greatly acknowledge the assistance of Kastamonu State Forest Enterprise staff and fire crews who cooperated and assisted throughout the study. The continued cooperation and logistical support of General Directorate of Forestry in planning and conducting the study, and the recognition by the directorate staff of the importance of fire research in fire management are greatly acknowledged. This study was partially supported by Gazi University Research Fund (No: 32/2003-05) and by the General Directorate of Forestry.

References

Adams, J.L. 1966. Prescribed burning techniques for site preparation in cut-over jack pine in southeastern Manitoba. Pulp Pap-Canada. 67: 574-584.

Albini, F.A. and J.K. Brown. 1978. Predicting slash depth for fire modeling. USDA Forest Service, Research paper, INT-206, Ogden, Utah, 22 pp.

Alexander, M.E. 1982. Calculating and interpreting forest fire intensities. Can. J. Bot. 60: 349-357.

Alexander, M.E., B.J. Stocks and B.D. Lawson. 1991. Fire behavior in Black spruce-lichen woodland: The Porter Lake Project, Information Report NOR-X-310. (Edmonton, Alberta) 44 pp.

Andrews, P.L. 1986. Behave: Fire behavior prediction and fuel modeling system-burn Subsystem part 1. U.S. Department of Agriculture, General Technical Report INT-194, Ogden, 130 pp.

Baxter, G. 2002. Analysis of the occurrence and cause of fires in slash fuels in Alberta for the period 1961-2000. Wildland Fire Operations Research of Canada, Forest Engineering Research Institute of Canada, Internal Report IR, 20 pp.

Bilgili, E. 2003. Stand development and fire behavior. Forest Ecol. Manag. 179: 333-339.

Byram, G.M. 1959. Combustion of forest fuels, In: Davis, K.P. (Ed.), Forest fire control and use. McGraw-Hill, New York, pp. 61-89.

Fahnestock, G.R. 1960. Logging slash flammability. USDA Forest Service, Intermountain Forest and Range Experiment Station, Research Paper 58, 67 pp.

Fahnestock, G.R. and J.H. Dieterich. 1962. Logging slash flammability after 5 years. USDA Forest Service, Intermountain Forest and Range Experiment Station, Research Paper 70, Ogden, Utah, 15 pp.

Fahnestock, G.R. 1968. Fire hazard from precommercial thinning of ponderosa pine. U.S. forest Service, Research paper PNW-57, Portland, Oregon, 16 pp.

Fernandes, P., C.A. Loureiro and H.N.S. Botelho. 2004. Fire behavior and severity in a maritime pine stand under differing fuel conditions. Ann. Forest Sci. 61: 537-544.

Forestry Canada. 1992. Development and structure of the Canadian forest fire behavior 13 prediction system. Forestry Canada, Information Report ST-X-3, Ottawa, 59 pp.

Freeman, D.R. and P. Roussopoulos. 1983. Tables for predicting the slash weight of shortleaf pine. USDA General Technical Report NC-93, 8 pp.

Heeney, C.J. 1977. Regeneration in Ontario. Paper presented at the Ontario Professional Foresters Association Workshop at Dorset, Woodland Section 58th Annual Meeting, 11 pp.

Kiil, A.D. 1968. Changes in the physical characteristics and moisture of pine and spruce/fir slash during the first 5 years after logging. Forest Research Lab. Internal Report, A-14, Edmonton, Alberta, 49 pp.

McRae, D., M. Alexander and B. Stocks. 1979. Measurement and description of fuels and fire behavior on prescribed burns: A handbook, Canadian Forestry Service, Information report, O-X-287.

McRae, D.J. 2001. Point-source fire growth in Jack pine slash. Int. J. Wildland Fire. 9: 65-77.

Noble, I.R., G.V. Bary and A.M. Gill. 1980. McArthur's fire-danger meters expressed as 39 equations. Aust. J. Ecol. 5: 201-203.

OGM. 2007. Orman Atlası, Orman Genel Müdürlüğü, Ankara, 88 pp.

Quintilio, D., G.R. Fahnestock and D.E. Dubé. 1977. Fire behavior in upland jack pine: the Darwin Lake Project. Canadian Forestry Service, Northern Forestry Research Centre NOR-X- 174.

Roussopoulos, P.J. and V.J. Johnson. 1973. Estimating slash fuel loading for several Lake States tree species. USDA Forest Service, North Central Forest Experiment Station, Research paper NC-88, 7 pp.

Rothermel, R.C. 1972. A mathematical model for predicting fire spread in wildland fuels. USDA Forest Service, Intermountain Forest and Range Experiment Station Research Paper INT-115. (Ogden, UT)

Sneeuwjagt, R.J. and W.H. Frandsen. 1977. Experimental grass fires vs, predictions based on Rothermel's fire model. Can. J. Forest Res. 7: 357-367.

Stocks, B.J. 1980. Black spruce crown fuel weights in northern Ontario. Can. J. Forest Res. 10: 498-501.

Stocks, B.J. and J.D. Walker. 1972. Fire behavior and fuel consumption in jack pine slash in Ontario. Canadian Forest Service. Great Lakes Forestry Center, Inf. Rep. O-X-169.

Turna, I. and E. Bilgili. 2006. Effect of heat on seed germination of *Pinus sylvestris* and *Pinus nigra ssp. Pallasiana.* Int. J. Wildland Fire. 15: 283-286.

Trowbridge, R., B. Hawkes, A. Macadam and J. Parminter. 1989. Field handbook for prescribed fire assessments in British Columbia: logging slash fuels, Forestry, FRDA handbook 001, ISSN 0835 1929, Economic & Regional Development Agreement, p. 339.

Van Wagner, C.A. 1966. Three experimental fires in jack pine slash. Canada Department of Forestry, (Ottowa Ontario), Publication no. 1146.

Vihanek, R.E. and R.D. Ottmar. 1993. When logged units burn in a wildfire, does slash treatment mitigate effects? In: 12th Conference on Fire and Meteorology, Jekyll Island, Georgia, pp. 709-714.

Wagener, W.W. and H.R. Offord. 1972. Logging slash: its breakdown and decay at two forests in northern California. USDA Forest Service, Research paper PSW-83, 11 pp.

Wakimoto, R.H. R.D. Pfister and K.D. Kalabokidis. 1998. Evaluation of alternative fire hazard reduction techniques in high-hazard, high-value, and high-use forests. In: Proceeding? Future forests of the mountain west: a stand culture symposium. USDA Forest Service, General Technical Report INT-243. Ogden, pp. 401-402.

Williams, F.A. 1977. Mechanism of fire spread. In: Sixteenth Symposium (International.) on combustion proceedings, The Combustion Institute, Pittsburg, pp 1281-1294.