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RESEARCH ARTICLE

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Modeling surface fire rate of spread within a thinned Anatolian black pine stand in Turkey

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Abstract

Aim of the study: To develop regression models for estimating the rate of surface fire spread in a thinned even-aged black pine stand (*Pinus nigra* J.F. Arnold subsp. *nigra* var. *caramanica* (Loudon) Rehder).

Area of the study: The study was carried out within a thinned black pine forest located in the Kastamonu Forest District, northwestern Turkey. The study area is located at 546819, 4577880 UTM.

Material and methods: A total of 33 small scale surface fires were ignited under varying weather and fuel conditions. Line ignition was used during the burnings. Surface fuels consisted generally of thinned material (needle+branches).

Main results: Within the stand, surface fuel loading ranged from 3.0 to 10.2 kg/m^2. Wind speed ranged from 0.3 to 8.4 km/h. Needle moisture content ranged from 8 to 15%. The rate of fire spread ranged from 0.47 to 6.92 m/min. Relationships between the rate of fire spread and fuel and weather conditions were determined through regression analyses.

Research highlights: Wind speed was the most important factor on the rate of fire spread and explained 85% of the observed variation in the surface fire rate of spread within a stand.

Additional keywords: experimental fire; surface fuels; regression models.

Abbreviations used: CC (crown closure, %); FD (fuel depth, cm); FL (fuel load, kg/m^2); FMC (fuel moisture content, %); LIL (length of ignition line, m); MAE (mean absolute error); MAPE (mean absolute percentage error); MBE (mean bias error); RH (relative humidity, %); ROS (rate of spread, m/min); T (air temperature, ºC); TFL (total fuel load, kg/m^2); W (midflame wind speed, km/h).

Authors´ contributions: Field data collection: OK, RU. Statistical analysis: OK, EB. Data interpretation, material support, study design and supervising the work: OK, EB, RU.

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Introduction

Wildland fires are major environmental concerns in many ecosystems. In forest ecosystems, fires usually start in surface fuels, and then further spread and develop into large fires depending on the environmental conditions (Kucuk *et al.*, 2012). In the Mediterranean Basin, fire plays a major role in maquis and pine forests. Surface fuels of Mediterranean pine forests are highly flammable due to their high dead fine fuel loading, aerated litter and chemical volatility (Fernandes *et al.*, 2009; Kucuk & Aktepe, 2017), leading to potentially very high rates of fire spread in pine stands (Fernandes & Rigolot, 2007). Fire spread models have been developed and calculations for surface and crown fuels have been carried out globally (*e.g.* Alexander & Lanoville, 2004; Morvan, 2014), and several studies have provided data and models for surface and crown fire behavior in the Mediterranean Basin (*e.g.*, Dimitrakopoulos, 2002; Bilgili *et al.*, 2006; Kucuk *et al.*, 2007; Fernandes, 2009; Kucuk *et al.*, 2015).

The prediction of surface fire behavior is crucial for fuel and fire management planning. However, it has been one of the most challenging issues in fire behavior modeling as the fuel conditions and stand structure characteristics can be highly variable in various stand types (*e.g.* Sullivan, 2009; Fernandes, 2014), making the successful prediction of fire behavior difficult in these fuel types. The variability in fuel characteristics is usually a result of stand growth and development as well as fuel management. Silvicultural interventions, such as thinning, radically alter the structure and distribution of fuels within a forest stand (Bilgili & Methven, 1994; Bilgili, 2003), thereby resulting in changes in microclimatic conditions. Changes in fuel characteristics and weather conditions greatly influence fire behavior characteristics (Graham *et al.*, 1999; Bilgili, 2003).

Anatolian black pine (*Pinus nigra* J.F. Arnold subsp. *nigra* var. *caramanica* (Loudon) Rehder) (aka black pine) is the second most widely distributed conifer species in Turkey, covering a land area of 4.7 million ha (GDF, 2014). Pure stands of black pine are generally found in fire susceptible environments (Küçük *et al.*, 2008a; Kucuk *et al.*, 2017). Silvicultural interventions (*i.e.*, thinnings) are common practices in black pine stands. However, there has been no study on the prediction of rate of fire spread in thinned black pine forests in Turkey. The main objective of this study was to model the rate of surface fire spread in a thinned, even-aged Anatolian black pine stand. Results of this study can be very useful for fire and fuel management.

Material and methods

Study area

The study was carried out in an even-aged black pine forest located in the Kastamonu Forest District, in northwestern Turkey. The study area is located at 546819, 4577880 UTM. Average elevation of the study area is 1225 m (Fig. 1). The study area has a northwestern Black Sea climate characterized by short

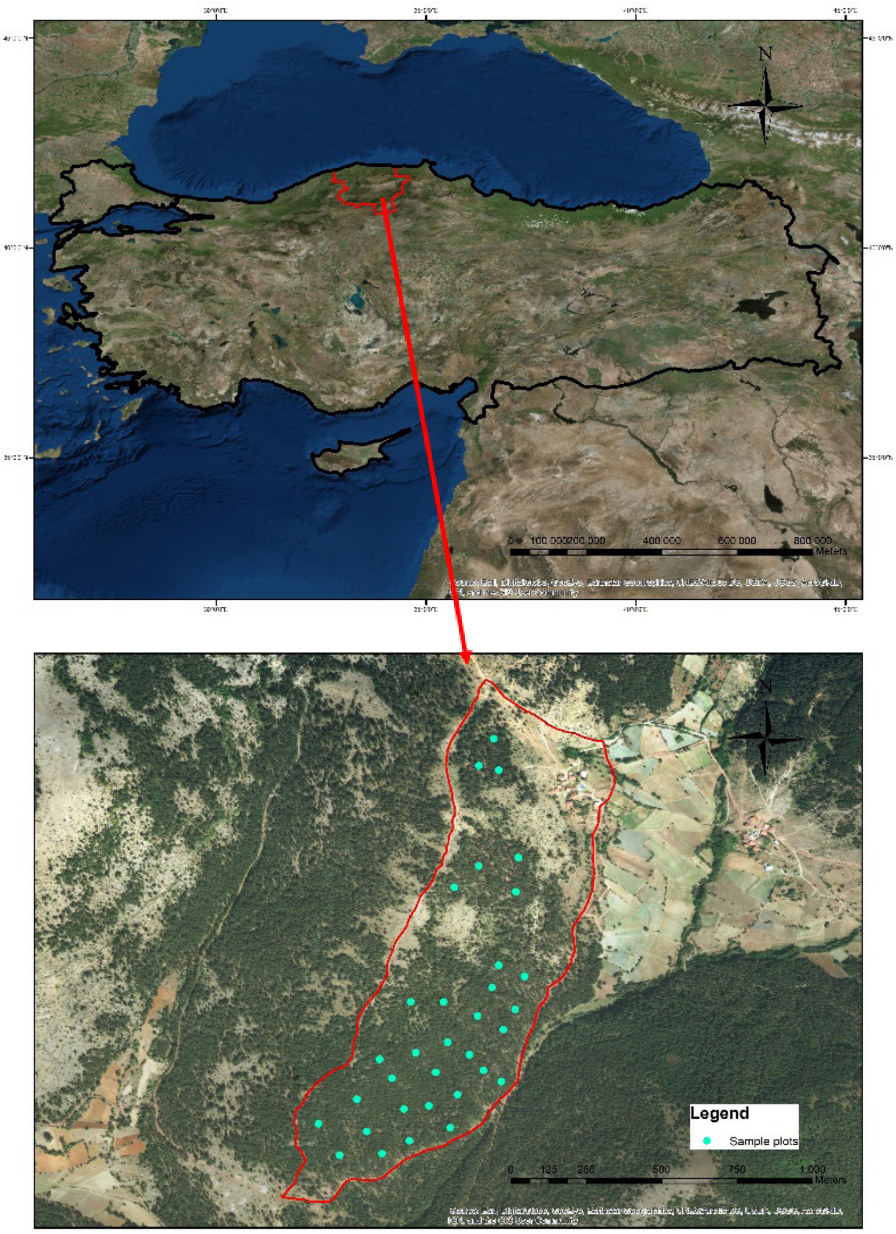

Figure 1. Study area.

hot summers and long cold winters. Monthly average air temperature (*T*) varies from 15 to 20 °C from June to September and average monthly rainfall is between 290 and 320 mm for the same period. The fire season generally lasts from late June until mid-September. At the time of the experiments, average stand age was 50 years. Average stocking density was 560 stems/ha with average tree diameter at breast height 20 cm. Average stand height was 16 m. Crown closure (*CC*) was variable throughout the stand and ranged from 60 to 90%. Crown base height was 5 m, and pre-treatment surface fuel depth (*FD*) was between 2 and 5 cm. After the treatment, depending on the severity of the treatment, there was an increase in the amount of slash, creating a heterogeneous condition in surface fuels. *FD* in the burning plots ranged between 20 and 45 cm. To emulate this condition, sample plots were installed in different locations of the stand.

Experimental plots and pre-burn measurements

A total of 33 small scale burning plots (1×3 m, n=14; 3×3 m, n=14; 5×5 m, n=5) were prepared on relatively flat surfaces in the thinned stand in 2012. Thinnings took place six months prior to the experiments. At the time of the experiments, surface fuels consisted of a litter layer of dead needles, branches and twigs. On average, 60-70% of the initial needle was still remaining on branches 6 months after the thinnings. Needle retention was heavily dependent on the time since thinning (Küçük *et al.*, 2008b).

The plots were located in areas with untreated surface fuels after thinning, consisting mainly of homogeneous (needle + branches + cones) fuels. All burning plots were laid out parallel to the prevailing wind direction. Three length of ignition line (*LIL*) (1, 3 and 5 m) were used. Surface fuel load estimations were based on fuel samples randomly taken from areas immediately adjacent to and representative of each burning plot. During fuel sampling, surface fuel material within a 30×30 cm sampling frame was removed down to the mineral soil. Each fuel component was weighed, placed in nylon bags and taken to the laboratory for the estimation of surface fuel loading after oven-drying. The fuel samples were oven-dried at 105ºC for 24 h. Immediately prior to ignition, fuel samples for each fuel size class (needles, 1 h (<6 mm), 10 h (6-25 mm), 100 h (>25 mm)) were taken from each plot to determine fuel moisture contents (*FMC*). Before the experimental fires, a mobile automatic weather station was setup within the stand. Wind speed (*W*) measurements were taken within the stand at 1.5 m above ground. The location of the anemometer was selected such that wind speed recorded was not influenced by fires. During the experimental fires, midflame *W, T* and *RH* were recorded. A hand-held anemometer was also used to record *W* at 15 second intervals during the burning period.

Experimental fires

Experimental surface fires were carried out in the summer under a relatively narrow range of *T, RH, W* and *FMC* (Table 1). These represent typical weather and fuel conditions in the region in late fire season. Experimental line fires were ignited with a drip torch. No additional fuels were used to establish the fire line. Collection of the fire behavior data started when the fire line had moved about 30 cm from the edge of the plot or when the fuel (from drip torch) used to establish the fireline had lost its effect on the initial phase of fire spread. Rates of spread (*ROS*) were determined by recording the time the head fire front arrived, 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 the fire front reached the edge of the plots (Stocks *et al.*, 2004). In addition, the progress of all fires were documented and evaluated on videos and photographic records.

Data analysis

Correlation analysis was performed to investigate the relationships among fire behavior properties, weather conditions and fuel characteristics. Regression analysis was performed to determine the relationships between fire behavior and environmental conditions. Before the analyses, the variables were tested for normality (Sprugel, 1983) and potential co-linearity among input variables. As a result, a logarithmic transformation was deemed necessary for some variables. To estimate *ROS*, both linear and non-linear regression equations were developed using fuel and weather characteristics as independent variables. Independent variables were initially selected from among the variables that had significant correlations. Less or non-significant variables were also tried as secondary independent variables. In addition, data were also plotted to provide a visual assessment of the relationships between *ROS* and some key independent variables. Linear regression models were developed using the stepwise regression technic with a confidence level of 95%.

Linear relationships between *logROS* and *W*, *logLIL* and *logRH*, and nonlinear relationships between *ROS* and *W*, needle fuel moisture content (*needle FMC*), needle fuel load (*needle FL*) and *LIL* were established.

The adjusted coefficient of determination (R^2), standard error of the estimates (*SE*), mean bias error (*MBE*), mean absolute error (*MAE*) and mean absolute percentage error (*MAPE*) were used to evaluate the goodness of fit of the models to the development data. Statistical analyses were carried out with SPSS© software 22.0 for Windows (SPSS, 2016).

Table 1. Descriptive statistics for weather, fuel and fire behavior variables associated with surface fuel characteristics (*n=33*).

Variables	Min.	Max.	Mean	SD
Fuel variables				
Needle fuel loading (kg/m^2)	0.26	2.72	1.04	0.637
Fuel loading 1h$_{fl}$ (kg/m^2)	1.03	5.40	2.52	1.195
Fuel loading 10h$_{fl}$ (kg/m^2)	1.33	4.32	2.62	0.768
Fuel loading 100h$_{fl}$ (kg/m^2)	0.00	2.41	1.06	0.581
Total fuel load (TFL, kg/m^2)	3.00	10.20	6.20	1.970
Needle FMC (%)	8.00	15.00	11.70	1.375
1h FMC (%)	10.00	21.00	14.40	2.092
10h FMC (%)	13.00	34.00	17.00	5.177
100h FMC (%)	15.00	56.00	31.00	14.915
Fuel depth (FD, cm)	20.00	45.00	30.80	7.152
Weather variables				
Air temperature (T,^{o}C)	18.00	26.00	22.70	1.794
Relative humidity (RH, %)	23.00	43.00	35.08	5.053
Midflame wind speed (W, km/h)	0.30	8.40	3.63	2.117
Fire behavior variables				
Length of ignition line (LIL, m)	1.00	5.00	2.45	1.438
Rate of spread (ROS, m/min)	0.47	6.92	1.98	1.768

Results and discussion

Summary of surface fuel, weather and fire behavior parameters is given in Table 1. The correlation analysis indicated that wind speed and some fuel properties were correlated with *ROS* (Table 2). The regression models that best explained the relationships between *ROS* and fuel and weather variables are given in Table 3.

ROS was closely related to wind speed, length of ignition line, moisture content of fine fuels and fine fuel load (needle and 1h fuels). Wind speed alone explained 85% of the observed variation in the rate of fire spread (Table 3; R^2 = 0.854; p < 0.01, *log ROS* model 1). The results obtained are in agreement with many studies conducted under field conditions (*e.g.*, Van Wagner, 1993; Fernandes *et al.*, 2009). The addition of length of ignition line as the second independent variable improved slightly the percent variability explained (R^2 = 0.866; p < 0.01, *log ROS* model 2). Although the *MAPE* decreased from 42.99% to 31.08%, a tendency towards under prediction of *ROS* at high values was confirmed by the *MBE*. For all measured *ROS* values, the *MBE* changed from -0.093% to -15.699% (Table 3). The effect of *LIL* on fire rate of spread have also been reported by other researches (*e.g.*, Wotton *et al.*, 1999; Dupuy *et al.*, 2011; Morandini *et al.*, 2001; Fernandes, 2014). However, the potential use of *LIL* in a model or in practice can be limited from a practical point of view except for prescribed burns for which the length of ignition lines is determined by a practitioner; and

Table 2. Correlation matrix of the variables used in the surface fire analyses.

	Needle FL	1 h FL	TFL	Needle FMC	FD	LIL	W	ROS
Needle FL	1							
1h FL	0.913**	1						
TFL	0.696**	0.826**	1					
Needle FMC	0.012	-0.014	-0.057	1				
FD	0.638**	0.699**	0.768**	-0.015	1			
LIL	-0.229	-0.436*	-0.418*	0.365*	-0.210	1		
W	0.689**	0.698**	0.450**	-0.026	0.458**	-0.250	1	
ROS	0.729**	0.662**	0.379*	0.200	0.475**	0.072	0.873**	1

*: Correlation is significant at the 0.05 level (2-tailed). **: Correlation is significant at the 0.01 level (2-tailed).

Table 3. Regression equations for ROS in the Anatolian black pine surface fuels. The goodness-of-fit statistics for the log linear models represent values calculated after transforming the predicted values using the exponential function multiplied by a correction factor.

Dependent variables	Model form	Parameter estimates					R^2	Adj R^2	SE	MBE	MAE	MAPE
		a	b	c	d	e						
Log ROS model 1	*Log ROS*= a+b*W*	-0.697	0.297				0.854	0.849	0.686	-0.093	0.578	42.999
Log ROS model 2	*Log ROS*= a+b*W*+c*logLIL*	-1.157	0.331	0.479			0.866	0.861	0.658	-15.699	0.471	31.085
Log ROS model 3	*Log ROS*= +b*W*+c*logLIL*+ d*logRH*	1.327	0.947	0.677	0.708		0.917	0.915	0.516	-0.085	0.3693	24.625
Log ROS model 4	*Log ROS*= a+b*W*+c*LIL*+ d*needleFL*+e*1h FMC*	-4.009	0.671	0.405	0.709	0.120	0.911	0.898	0.564	0.009	0.53	45.750
ROS model 5	*ROS*= a+b*W* ×c*needle FMC* ×d*needle FL*	0.577	1.788	-0.919	0.296		0.830	0.824	0.741	0.060	0.552	38.061
ROS model 6	*ROS*= a×*W*- 5.26×$e^{(b*needle\ FMC)}$+ LIL^c	0.785	-0.068	0.500			0.871	0.867	0.646	0.000	0.530	41.600

given the sizes of the burning plots as compared with the fire lines achievable in larger experiments and in large wildfires, the contribution of this study should be evaluated with respect to the comparative analysis of *ROS* only, and not the actual prediction of *ROS*. A correction factor such as that proposed by Fernandes (2014) may be used to better justify and compare fire spread differences under the same environmental conditions but different ignition line lengths.

The dependence of *ROS* on fuel properties was also evident from the results. Addition of fuel moisture and fine fuel load (*needle FL* and *1h FL*) significantly increased the percent variability explained (*log ROS* model 3 and 4, Table 3). While the inclusion of other fuel and weather parameters to the model did not significantly change the standard error of the estimates, *MBE* decreased significantly, and, except for *log ROS* model 3, *MAE* and *MAPE* values were comparable

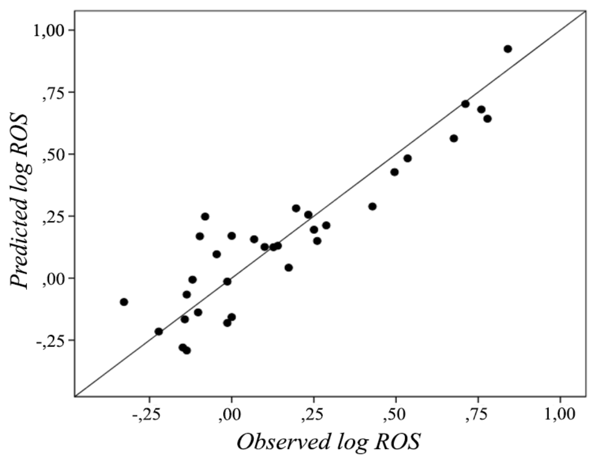

Figure 2. Relationship between predicted and observed *log* rates of fire spread values (*log ROS* model 4).

(Table 3). Differences in fire spread can be ascribed to the considerable heterogeneity in fuel load and fuel moisture content (Table 1). The relationships with fuel moisture content and fuel load in addition to wind (*log ROS* model 4, Fig. 2; *ROS* model 5 and 6, Table 3) indicate that variability and heterogeneity within-stand weather and fuel characteristics greatly influence fire spread.

Conclusions

The results of the study were based on a total of 33 experimental fires in surface fuels under canopy. Regression models were fitted for the estimation of the rate of surface fire spread. Analyses indicated that midflame wind speed was the most significant factor affecting rate of fire spread. Length of ignition line, fine fuel load and fuel moisture characteristics were also influential on fire spread. Although the experimental burns covered a limited range of weather and fuel conditions, the impact of weather and fuel variability within the stand were evident on observed rates of spread. This preliminary results could help managers to plan fire hazard, suppression operations and prescribed burnings in these forests. Nevertheless, further experimentation is required for developing a robust rate of fire spread prediction model for surface fires in thinned Anatolian black pine stands.

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