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Fire Development from a Point Source in Surface Fuels of a Mature Anatolian Black Pine Stand

Ömer KÜÇÜK[1,*], Ertuğrul BİLGİLİ[2], İsmail BAYSAL[3]

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

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

[3]Duzce University, Faculty of Forestry, 81320 Düzce - TURKEY

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Abstract: A total of 28 line and 24 point-source fires were ignited under varying weather and fuel loading conditions in Anatolian black pine (*Pinus nigra* J.F.Arnold subsp. *nigra* var. *caramanica* (Loudon) Rehder) stands. Relationships between the rate of fire spread and fuel and weather conditions were determined with correlation and regression analyses. The rate of fire spread ranged from 0.12 to 1.20 m min^{-1} in line fires. In the ignition, transition, and steady state phases of point-source fires, the rate of fire spread ranged from 0.04 to 0.78 m min^{-1}, from 0.11 to 0.59 m min^{-1}, and from 0.08 to 0.99 m min^{-1}, respectively. Surface fuel loading ranged from 1.27 to 2.45 kg m^{-2} for line fire and from 1.56 to 2.67 kg m^{-2} for point-source fire. The results showed that the rate of fire spread was closely related to wind speed and fuel moisture content for line and point-source fires. The linear prediction for wind conditions estimates that equilibrium spread rates may be achieved within 25 min after the ignition of point-source fires.

Key Words: Fire growth, line fire, point fire, litter fuel, black pine

Yaşlı Karaçam Meşceresi Ölü Örtüsünde Bir Noktadan Başlayan Yangının Gelişimi

Özet: Değişik hava halleri ve yanıcı madde koşullarında yaşlı karaçam meşcerelerinde 28 adet hat ve 24 adet nokta kaynaklı yangın gerçekleştirilmiştir. Yangın yayılma oranı ile yanıcı madde özellikleri ve hava halleri arasındaki ilişkiler korelasyon ve regresyon analizleri ile belirlenmiştir. Hat yangınlarında yangın yayılma oranı 0.12 ile 1.20 m/dak arasında değişmiştir. Nokta yangınlarında ise, tutuşma, gelişme ve sabit büyüme safhalarında sırasıyla 0.04 ile 0.78 m/dak, 0.11 ile 0.59 m/dak ve 0.08 ile 0.99 m/dak arasında gerçekleşmiştir. Ölü örtü yanıcı madde miktarı hat yangınlarında 1.27 ile 2.45 kg/m^2 aralığında, nokta yangınlarında ise 1.57 ile 2.67 kg/m^2 arasında değişmiştir. Hem hat hem de nokta yangınlarında yayılma oranı ile rüzgar ve ölü yanıcı madde nemi arasında kuvvetli bir ilişki ortaya konulmuştur. Ayrıca, rüzgara bağlı olarak yapılan yayılma oranı tahminlerinde nokta kaynaklı yangınların 25 dakika içerisinde hat yangınları yayılma oranına ulaşabilecekleri belirlenmiştir.

Anahtar Sözcükler: Yangının büyümesi, hat yangını, nokta yangını, ölü yanıcı madde, Karaçam

Introduction

Forest fires generally start in the surface fuels and, depending on the surface fuel properties and envrionmental conditions, grow in size and intensity, and develop into large fires. The success of fire control is achieved best before fires reach a steady state spread condition under given weather and environmental conditions. Thus, knowledge of fire growth and development is extremely useful in developing fire management decisions concerning presuppression and suppression planning, and prescribed burning.

Most holistic theories of fire growth from a point source divide fire development into 3 phases, each phase releasing more of the total available potential energy (Chandler et al., 1983; Pyne, 1984; Luke and McArthur, 1986). The first stage is the ignition and initial development phase of a point-source fire. The second stage is referred to as the transition phase (Luke and McArthur, 1986) between the ignition stage and the third stage, which is a more steady state condition in which fires steadily grow (Chandler et al., 1983; Pyne, 1984; Luke and McArthur, 1986). Generally, the time periods

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* Correspondence to: okucuk@gazi.edu.tr

for each phase vary in length depending on the type of fuel and loading, and the burning conditions (Brown and Davis, 1973; Chandler et al., 1983; Pyne, 1984).

Point-source ignition requires considerably longer time than line ignition to accelerate to equilibrium spread rates (Cheney, 1981; Cheney et al., 1983; Johansen, 1987), and its growth may depend on several factors such as the moisture content of the fuels, surface fuel loading, fuel distribution, wind speed, and slope (Luke and McArthur, 1986). Studies indicate that point-source fires reach an equilibrium rate of spread within 5 to 10 min for fine grassy fuels and more than 60 min for heavy logging slash (Chandler et al., 1983; Cheney and Gould, 1995), and that the acceleration patterns of fires are extremely variable, but that generally the more severe the burning conditions the longer the time required for a fire to reach equilibrium spread rates (Cheney, 1981). Other accounts of the time to reach equilibrium spread rates (McAlpine and Wakimoto, 1991; Forestry Canada, 1992) showed that the time to reach equilibrium spread rates was constant for each fuel type tested despite different fire weather conditions. The differences among the studies may be attributed to the conditions under which the fires were conducted.

Studies of point-source fire growth have been relatively few (McAlpine, 1988), and most of these studies were conducted under laboratory conditions (e.g., Bilgili and Methven, 1990; Catchpole et al., 1998). There is a lack of detailed research on fire growth from a point-source ignition (Bilgili and Methven, 1990) in Turkey, where forest fires are a major concern.

The principal objective of this study was to examine the development of surface fires of point origin from ignition to steady state of fire spread in a mature Anatolian black pine stand.

Material and Methods

Study area

The study site is located at Merkez Forest District in Kastamonu, northwestern Turkey, at 41°21′N and 33°42′E, and an elevation of 950 m above sea level. The study area was an Anatolian black pine (*Pinus nigra* J.F.Arnold subsp. *nigra* var. *caramanica* (Loudon) Rehder) (commonly referred to as black pine) mature forest situated in the Kastamonu State Forest. The site is mainly level. The region 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 falling mainly from November to April. The fire season generally lasts from late June until mid-September.

The study was conducted in a 45-year-old black pine stand with an average diameter (dbh) of 30 cm, average live crown base height of 6 m, and an average height of 18 m, averaging 700 stem ha^{-1}. No living plants were present in the understorey within the stands and living trees made up 100% of the overstorey. Surface fuels consisted primarily of needle litter along with some branches and cones.

Black pine is the second most widely distributed conifers in Turkey after Calabrian pine (*Pinus brutia* L.), covering a land area of 2,392,079 ha (OGM, 2007). Pure natural stands of black pines are mostly found in fire prone areas and usually originate from high-intensity, stand-replacing fires (Turna and Bilgili, 2006).

Experimental site and fuel loadings

Surface fuel loading measurements were based on 3 fuel samples randomly taken immediately adjacent to each burning plot. Surface fuel material within a sampling frame measuring 30 × 30 cm was removed down to the mineral soil, and then classified as litter (needles, branches) and duff in each sample plot (Rothermel, 1972; Quintilio et al., 1977). Then each fuel component was weighed, placed in nylon bags, and taken to the laboratory to calculate oven dry weights. Total fuel loading for each plot was then calculated based on the oven dry weights.

In early September 2004, a series of 28 line and 24 point burning plots were established on a level terrain. All line fire plots were measured as 3 × 1 m (3 m long and 1 m wide), and laid out, in parallel, in the direction of the prevailing wind. The plots were surrounded by cleared fire lines (0.5 m width) so that each plot would burn free from the influence of other fires.

A complete fire weather station was established at the study site prior to the burnings. Daily observations of the temperature, relative humidity, 1.5 m open wind speed, and precipitation were recorded. The experimental fires were conducted in early September 2004.

Fuel moisture contents

To determine the on-site moisture contents of surface fine fuels (FFMC) and duff (DMC), 3 samples were taken in each plot immediately prior to each burning. Samples were then oven-dried at 100 °C for 24 h. Moisture content determinations were based on the differences between fresh and oven dry weights.

Rate of fire spread

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

The plots were burned under varying temperature, relative humidity, moisture, and wind speed conditions. The preferred time of ignition was late afternoon to capitalize on the daily peak burning conditions. Experimental line fires were ignited as a line fire along the windward edge of each plot, and allowed to spread downwind through the length of the plot in order to simulate a free burning wildfire (Alexander et al., 1991; Bilgili and Saglam, 2003). Experimental point ignited fires were initiated using a single match stick.

Collection of the fire spread data for line fires 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 metal pins pre-placed 20 cm apart on each side of the burning plot. Fire spread during each fire was monitored from the time the ignition line was fully established to the time fire front reached the edge of the plot. Point-source fires were monitored from the ignition phase to the steady state phase. Rates of spread were determined by recording the time the head fire arrived at the metal pins pre-placed 20 cm apart along the major axis of the fire spread starting from the ignition point. In addition, the progress of all fires was documented by video and photographic records for future evaluation.

The variability in wind speed during the experimental burnings resulted in a problem that precluded the analyses of the measurements for point source fires, as point-source fires accelerate from the time of ignition to the time of steady state phase at a constant wind speed. Unlike the constant wind speed conditions obtainable only under laboratory conditions, variable winds in different phases of fire development result in different rates of fire spread. Thus, to correct this problem, experimental point-source fires were divided into 3 sections based on fire spread measurements to simulate ignition, transition, and steady state phases of fire growth. Each section was then treated as a new fire. Wind speed values were also averaged for each phase.

Statistical analysis

Correlation and regression analyses were performed to determine the relationship between fire spread and weather conditions and fuel properties. Regression analyses considered fuels and weather conditions as the independent variables, and the rate of fire spread as the dependent variable. To analyze the relationships between the rate of fire spread and fuel properties and weather conditions, using linear regression models, rate of fire spread prediction equations were generated. 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 and Discussion

Surface fuel characteristics and line fire spread

Surface fuel loading ranged from 1.27 to 2.45 kg m^{-2}. Fine (litter) surface fuel moisture content ranged from 8% to 13% and duff from 17% to 29% for the line fire plots.

Fire spread was variable across the study plots, primarily due to variation in wind speed, moisture contents of surface fuels, relative humidity, and surface fuel loading. Table 1 summarizes the rate of fire spread and associated surface fuel characteristics and weather parameters recorded on site during each line fire. The fires were burned under a range of weather conditions. During the experimental line fires, the air temperature varied from 19.7 to 32 °C, relative humidity from 15% to 50%, and wind speed from 0.1 to 7.2 km h^{-1}. The rate of spread ranged from 0.12 to 1.20 m min^{-1}.

Table 1. Weather conditions, surface fuel characteristics, and rate of fire spread values associated with the experimental line fires (T, temperature (°C); RH, relative humidity (%); DMC, duff moisture content (%); FFMC, fine fuel moisture content (%); SFL, surface fuel loading (kg m^{-2}); W, wind speed (km h^{-1}); ROS, rate of spread (m min^{-1})).

Line fires	T (°C)	RH (%)	DMC (%)	FFMC (%)	SFL (kg m^{-2})	W (km h^{-1})	ROS (m min^{-1})
1	30	22	18	9	1.44	1.4	0.47
2	30	20	18	8	1.93	5.9	1.13
3	32	19	18	8	1.90	3.8	0.60
4	32	19	18	8	1.65	4.7	0.50
5	30.5	19	18	8	1.82	6.6	1.20
6	21.4	46	22	9	1.83	2.9	0.23
7	21.4	45	22	11	1.81	1.4	0.32
8	20.7	48	17	13	1.33	1.3	0.13
9	20.4	50	22	12	1.59	0.1	0.18
10	21.2	49	18	12	1.31	0.9	0.12
11	21.3	48	18	12	1.31	1.2	0.13
12	27	30	25	13	2.04	7.2	1.05
13	25	33	25	13	1.91	6.0	0.87
14	26	30	28	11	1.86	7.1	0.91
15	26	30	29	11	1.69	4.8	0.84
16	27	32	18	11	1.81	4.7	0.78
17	26	31	18	11	1.94	4.6	0.75
18	26.5	31	22	10	2.45	5.1	0.99
19	26	31	22	10	2.45	7.2	0.89
20	27	22	18	10	1.47	3.7	0.55
21	27	21	18	10	1.56	1.5	0.31
22	30.5	18	19	10	1.53	1.1	0.38
23	32	16	19	10	1.62	1.1	0.56
24	32	15	19	10	1.71	1.2	0.43
25	20	44	19	13	1.40	5.9	0.58
26	22.5	38	19	13	1.45	3.1	0.19
27	19.7	44	18	12	1.27	2.2	0.50
28	19.7	44	18	12	1.27	2.6	0.19

Correlation and regression analyses were undertaken to investigate the relationships between fire spread and associated fuel properties and weather conditions. Table 2 presents the correlation coefficients showing trends and relationships among the independent and dependent variables.

The correlation analyses indicated that the rate of spread was closely related to wind speed ($r = 0.890$; $P < 0.01$). The most pertinent relationships are given in Table 3. Equations are presented with 1 and 2 independent variables, as the second independent variable increased the percent variability explained by the equation.

Wind speed alone explained 73% of the observed variation ($P < 0.01$) in the rate of spread. The relationship between the spread rate and wind speed in the field has been described by Rothermel (1972) and Cheney et al. (1983). It seems that the wind speed alone appears to be the most important element in driving fire spread in this study. The effect of wind on fire behavior, especially on fire spread, has also been addressed in many other studies (e.g., Van Wagner, 1992). In this study, we found similar results. The addition of temperature as the second independent variable considerably improved the percent variability explained ($R^2 = 0.834$; $P < 0.01$) in line fires. Figure 1 shows the predicted vs. observed rate of spread values (ROS model 2 for line fires).

Table 2. Correlation matrix of the variables used in the analyses for line fires (T, temperature (°C); RH, relative humidity (%); DMC, duff moisture content (%); FFMC, fine fuels moisture content (%); FFMC, fine fuel moisture content (%); SFL, surface fuel loading (kg m-2); W, wind speed (km h-1); ROS, rate of spread (m min-1)).

Line fires	T	RH	DMC	FFMC	SFL	W	ROS
T	1						
RH	-0.960**	1					
DMC	-0.794**	0.910**	1				
FFMC	0.249	-0.291	-0.220	1			
SFL	0.489*	-0.605**	-0.587**	-0.167	1		
W	0.055	0.032	0.175	-0.095	-0.019	1	
ROS	0.303	-0.192	-0.092	-0.090	0.114	0.890**	1

* Correlations significant at 5% significance level

** Correlations significant at 1% significance level

Table 3. Regression equations for predicting line fire spread in a mature black pine stand.

Dependent variables	Model form for line fires	Coefficients	Adj. R^2	SEE
ROS	1) Y = a+b.W	a: 0.117; b: 0.123	0.729	0.174
	2) Y= a+b.W + c.T	a: -0.496; b: 0.113; c: 0.025	0.834	0.139

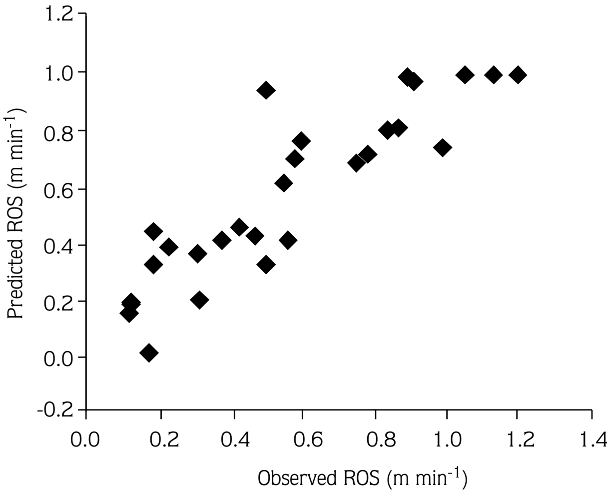

Figure 1. Relationship between predicted and observed rates of fire spread in line fires.

Surface fuel characteristics and point-source fire spread

Surface fuel loading ranged from 1.56 to 2.67 kg m^{-2}. Litter fuel moisture contents ranged from 9.02% to 14.54% and duff from 13.69% to 50.64%. Air temperature varied from 19.2 to 32 °C, relative humidity from 17% to 61%, and wind speed from 0.2 to 9.6 km h^{-1}. The rate of spread ranged from 0.04 to 0.99 m min^{-1}. Surface fuel characteristics and rate of fire spread values for point-source fires are given in Table 4.

Correlation and regression analyses were used to investigate the relationships between fire spread and associated fuel properties and weather conditions for each phase of the point fires. Table 5 presents the correlation coefficients showing trends and relationships among the independent and dependent variables.

Point-source fires showed different spread characteristics in different phases of fire development. The correlation analyses indicated that the rate of fire

Table 4. Weather conditions, surface fuel characteristics, and rate of fire spread values associated with the experimental line fires (T, temperature (°C); RH, relative humidity (%); FFMC, fine fuels moisture content (%); DMC, duff moisture content (%); SFL, surface fuel loading (kg m^{-2}); W, wind speed (km h^{-1}); ROS, rate of spread (m min^{-1})).

Point-source fires	T (°C)	RH (%)	FFMC (%)	DMC (%)	SFL (kg m^{-2})	Ignition phase		Transition phase		Steady state phase	
						W (km h^{-1})	ROS (m min^{-1})	W (km h^{-1})	ROS (m min^{-1})	W (km h^{-1})	ROS (m min^{-1})
1	32	20	9.67	18.26	1.84	3.8	0.37	4.2	0.39	5.5	0.98
2	20.6	48	13.97	19.95	1.58	1.1	0.08	2.3	0.22	0.9	0.28
3	25.5	32	12.99	21.42	1.95	3.7	0.16	3.7	0.35	7.6	0.96
4	27.6	33	12.89	18.62	2.23	5.9	0.29	5.7	0.19	7.2	0.60
5	25.6	36	12.54	26.72	1.80	8.4	0.47	7.8	0.59	6.3	0.57
6	26	32	11.00	20.73	2.10	9.6	0.78	8.7	0.31	6.9	0.99
7	32	26	11.37	13.69	2.02	0.7	0.08	3.2	0.41	1.7	0.42
8	30	33	10.57	18.43	1.99	1.4	0.22	0.7	0.19	1.8	0.36
9	29	20	10.57	18.43	2.21	1.8	0.13	1.6	0.28	1.9	0.29
10	32	17	10.27	50.64	1.89	1.5	0.14	1.3	0.18	1.8	0.11
11	28.5	19	9.58	50.64	1.78	0.5	0.19	0.5	0.19	0.9	0.15
12	27.5	22	9.80	19.85	2.38	2.4	0.20	2.0	0.22	1.8	0.27
13	27.5	20	9.02	19.85	2.54	2.3	0.25	2.4	0.35	1.2	0.10
14	28	20	10.06	18.85	2.67	1.6	0.16	0.8	0.13	1.4	0.20
15	29.5	20	9.99	18.06	2.33	0.2	0.14	0.6	0.11	0.8	0.24
16	27	30	10.41	18.27	1.94	3.2	0.20	4.0	0.35	3.5	0.27
17	26	28	10.44	15.38	1.95	1.3	0.09	1.7	0.28	0.7	0.13
18	27	30	11.15	16.15	2.26	3.3	0.38	3.1	0.33	2.9	0.32
19	25	30	11.53	15.76	1.78	3.9	0.29	1.7	0.16	-	-
20	24	40	12.24	16.67	1.79	1.8	0.19	2.0	0.27	0.5	0.08
21	19.2	56	14.54	19.75	1.89	0.7	0.04	-	-	-	-
22	19.3	61	14.54	19.75	1.56	0.9	0.10	3.8	0.13	-	-
23	22	40	12.80	17.30	1.57	3.6	0.11	2.7	0.17	2.8	0.14
24	22	43	12.28	18.64	1.77	0.3	0.09	1.4	0.13	0.9	0.14

spread was closely related to wind speed for all phases of point fires ($P < 0.01$). Similar results exist in the literature (Luke and McArthur, 1986). The effect of dead fine fuel moisture content on the rate of spread was also significant, mainly through its influence on the ignitability and combustion rate (Rothermel, 1972). Regression analyses also revealed that fine fuel moisture content, relative humidity, and temperature were also effective in explaining part of the variability in ROS for different phases of fire development.

Regression equations are presented with 1, 2, and 3 independent variables, as the second and third independent variables increased the percent variability explained by the equation for each phase of the point fires (Table 6).

Ignition phase

Wind speed alone explained 75% of the observed variation ($P < 0.01$) in the rate of spread. The addition of fine fuel moisture content as the second independent variable significantly improved the percent variability explained in the ignition phase ($R^2 = 0.834$; $P < 0.01$). Moreover, the addition of relative humidity as the third independent variable somewhat improved the percent variability explained ($R^2 = 0.872$; $P < 0.01$). Figure 2 shows the predicted vs. observed rate of spread values (ROS model 3 for point fires).

Transition phase

Wind speed alone explained 79% of the observed variation ($P < 0.01$) in the rate of spread. The addition of

Table 5. Correlation matrix of the variables used in the analyses for the 3 phases of point fires (T, temperature (°C); RH, relative humidity (%); FFMC, fine fuels moisture content (%); DMC, duff moisture content (%); SFL, surface fuel loading (kg m^{-2}); W, wind speed (km h^{-1}); ROS, rate of spread (m min^{-1})).

Ignition phase	T	RH	FFMC	DMC	SFL	W	ROS
T	1						
RH	-0.884**	1					
FFMC	-0.794**	0.910**	1				
DMC	0.249	-0.291	-0.220	1			
SFL	0.489*	-0.605**	-0.587**	-0.167	1		
W	0.034	-0.030	0.059	-0.074	0.032	1	
ROS	0.206	-0.190	-0.219	0.003	0.169	0.870**	1
Transition phase							
T	1						
RH	-0.830**	1					
FFMC	-0.728**	0.878**	1				
DMC	-0.153	0.083	0.165	1			
SFL	0.432	-0.633**	-0.639**	-0.025	1		
W	-0.098	0.253	0.343	0.515*	-0.235	1	
ROS	0.161	0.028	0.105	0.372	-0.053	0.892**	1
Steady state phase							
T	1						
RH	-0.827**	1					
FFMC	-0.681**	0.862**	1				
DMC	-0.206	0.105	0.175	1			
SFL	0.411	-0.602**	-0.553**	-0.059	1		
W	0.032	0.120	0.334	0.473*	-0.043	1	
ROS	0.157	0.046	0.209	0.326	-0.014	0.888**	1

* Correlations significant at 5% significance level

** Correlations significant at 1% significance level

Table 6. Regression equations for predicting phase of point fire spread in a mature black pine stand.

Dependent variables	Model form for point fires	Coefficients	R^2	SEE
ROS (Ignition phase)	1a) Y = a+b.W	a: 0.058; b: 0.058	0.756	0.081
	2b) Y= a+b.W + c.FFMC	a: 0.369; b: 0.06; c: -0.027	0.834	0.139
	3c) Y= a+b.W + c.FFMC + d.RH	a: -0.677; b: 0.062; c: 0.074; d: 0.007	0.872	0.062
ROS (Transition phase)	1a) Y = a+b.W	a: 0.114; b: 0.064;	0.796	0.055
	2b) Y = a+b.W+c.T	a: -0.138; b: 0.066; c: 0.009	0.859	0.047
ROS (Steady state phase)	1a) Y = a+b.W	a: 0.045; b: 0.117	0.788	0.148

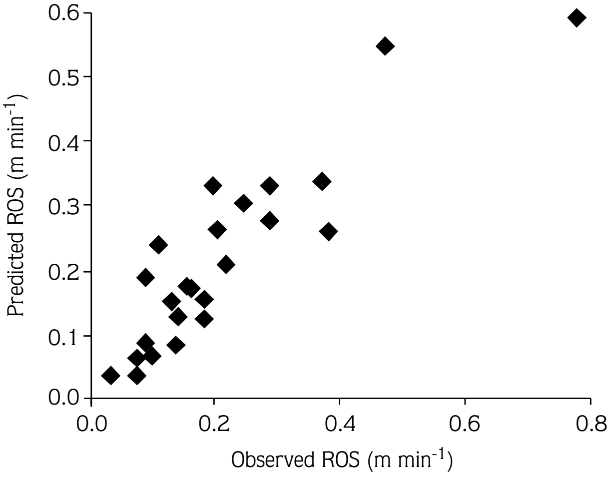

Figure 2. Relationship between predicted and observed rates of fire spread for ignition phase of point fires.

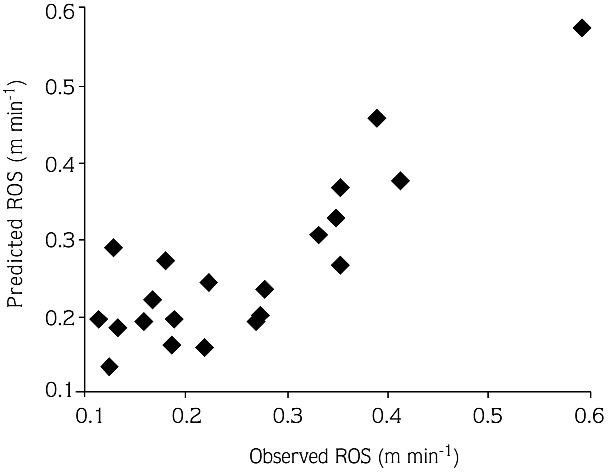

Figure 3. Relationship between predicted and observed rates of fire spread for development phase of point fires.

temperature as the second independent variable slightly improved the percent variability explained ($R^2 = 0.859$; $P < 0.01$) in the transition phase of point fires. Figure 3 shows the predicted vs. observed rate of spread values (ROS model 2 for point fires).

Steady state phase

The dominant factor influencing the rate of fire spread was the wind speed, explaining 78% ($P < 0.01$) of the observed variation. Unlike the ignition and transition phases, no factors other than the wind speed had any significant influence on the rate of fire spread in the steady state phase, indicating that the effect of wind overrides those of other factors in this phase, at least within the range of the data gathered in the present study. Figure 4 shows the predicted vs. observed rate of spread values (ROS model 1 for point fires).

Overall, as expected, fire spread rates gradually increased from the time of ignition to the time when the rate of spread was relatively constant (i.e. steady state phase). These findings agree well with those reported in the literature (Chandler et al., 1983; Wotton et al., 1999).

Comparison of line and point-source fires

To make the comparison possible, regression models having the wind speed as the independent variable were selected for line fires and for each phase of point fires (Tables 3 and 6). Using 3 different wind speed values (0, 4, and 8 km h^{-1}), rate of spread values were calculated and compared. At 0 km h^{-1} wind speed values, the rate of spread was notably low, and there was no detectable pattern or difference between the 2 fire types (Figure 5a). At 4 km h^{-1} wind speed values, line fires moved, on average, at a rate of 0.6 m min^{-1}. An immediate increase in the rate of fire spread was evident in each phase of fire development, but the final rate of spread reached fell short of that of line fires, indicating that the point-source fires had not yet attained the steady state condition (Figure 5b). Comparable results were also obtained for the 8 km h^{-1} wind speed values. Line fire rate of spread was 1.1 m min^{-1}. Here, as in the 4 km h^{-1} wind fires, an

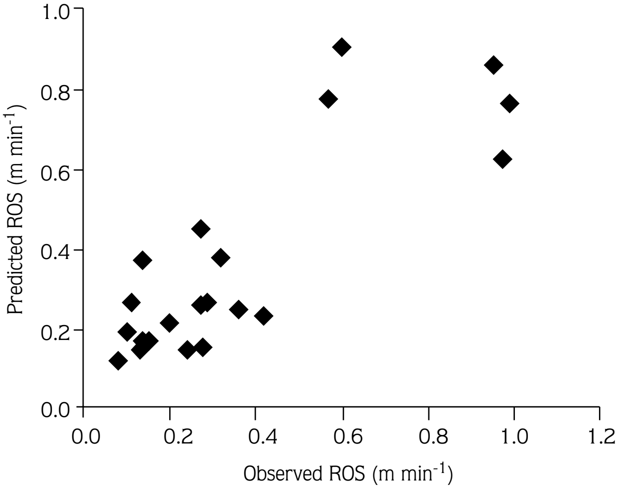

Figure 4. Relationship between predicted and observed rates of fire spread for steady state phase of point fires.

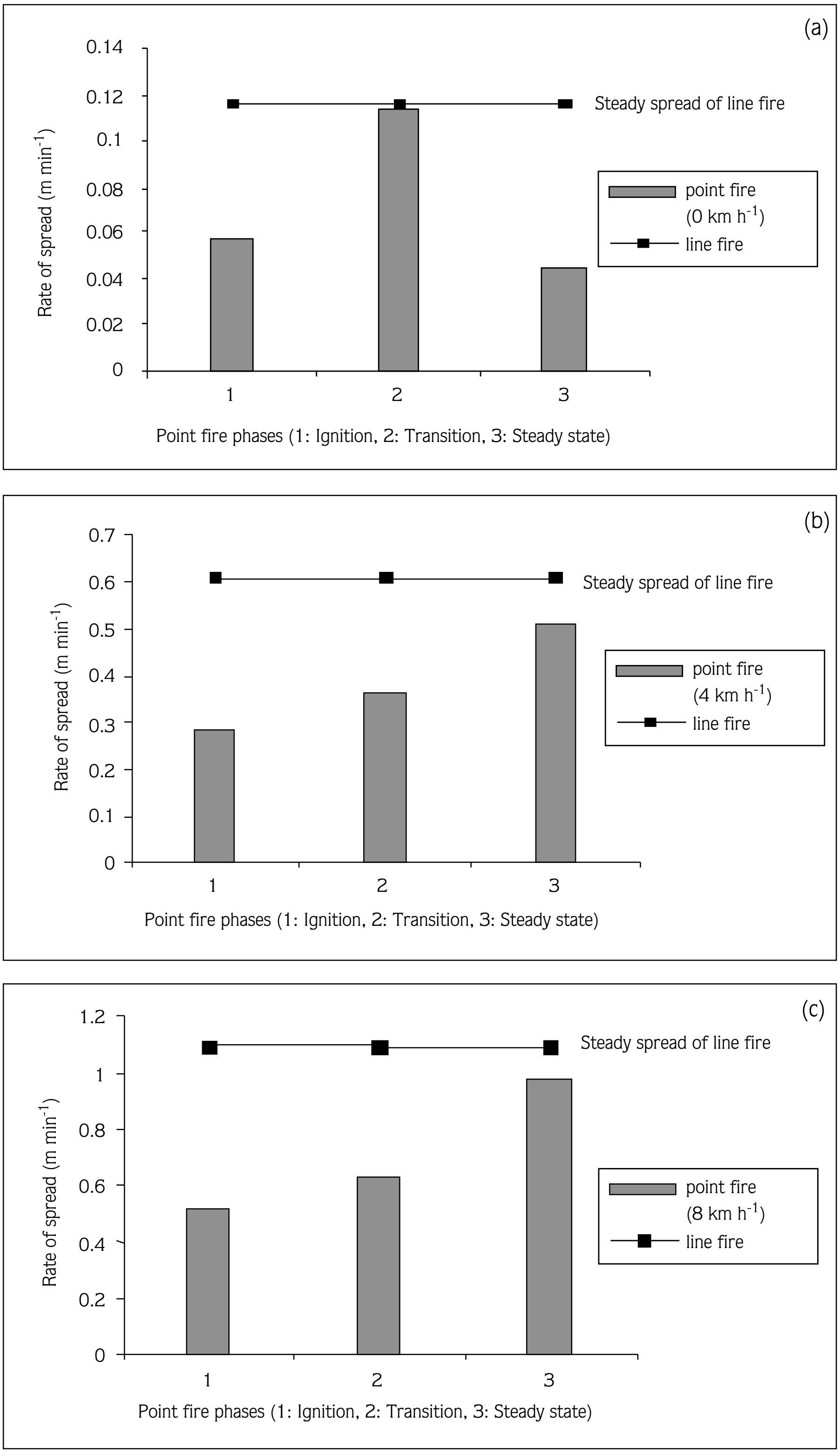

Figure 5. Comparison of line and point-source fire spread values in 3 different wind speed (0, 4, and 8 km h^{-1}) conditions.

immediate increase in the rate of fire spread was obtained in each phase of fire development, but the final rate of spread (1 m min^{-1}) was slightly lower than that of line fires, indicating also that the point-source fires had not yet attained the steady state condition (Figure 5c). On average, point-source fires reached 94% of the line fire rate of spread. The relevant literature suggests that the time required for a point source fire to accelerate to equilibrium (steady state) spread rate in comparable fuels is over 20 min (McAlpine and Wakimoto, 1991; Cheney and Gould, 1995, 1997; McRae, 1999). The durations of the point-source fires in the present study were mostly less than 20 min. This may explain the slight difference between the rate of spread values for line and point-source fires.

The results obtained in the present study can be of great importance in making fire management decisions in that they provide information on fire acceleration from the time of ignition to the time the fire reaches steady state condition. The acceleration phase of the fire is the only time when an initial attack can mostly be successful. Thus, new information on fire development will prove useful in developing guidelines for controlling fires in acceleration and using fires as a management tool in prescribed burns.

The experimental plots were on a level terrain. Thus, the effect of slope on fire spread has not been addressed in this study. However, it is important to address the effect of slope on fire spread as topography has a pronounced effect on fire behavior. Until more research data are available for open fuel types, correction factors developed for forests (Noble et al., 1980; Forestry Canada, 1992) can be used to adjust the predictions for slope.

Given that the study is based on a relatively small number of line and point fires with a relatively narrow range of weather and fuel conditions, more extensive experimentation is required for developing rate of fire spread prediction models for line and point-source fires. Future efforts should, therefore, attempt to cover the broadest possible range in fuel, weather, and topographical conditions to analyze and understand fire spread in these fuels.

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