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Fire behaviour in a semi-arid *Baikiaea plurijuga* savanna woodland on Kalahari sands in western Zimbabwe

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Human-induced fires are a major disturbance in *Baikiaea plurijuga* woodland savannas that are economically important for timber production. Most fires occur during the late dry season, when they may severely damage woody plants. Prescribed burning during the early dry season is a management strategy to reduce fuel loads and thus the incidence of intense fires during the late dry season. There is, however, little information on fire behaviour characteristics of early dry season fires. We studied the relationship between experimental fuel conditions and fire behaviour by lighting 15 fires during the early dry season in a *Baikiaea* woodland. Fire intensity ranged from 25 to 1341 kW m^{-1}, while rate of spread of fire varied between 0.01 and 0.35 m s^{-1}. Fire intensity and rate of spread were positively related to flame height, leaf-scorch height and proportion of the area burnt. The relationships suggest that fire characteristics can be retrospectively determined using a variable such as scorch height. The grass fuel load, wind speed, relative humidity and to a lesser extent fuel moisture were important predictors of rate of spread, flame height, leaf-scorch height and proportion of the area burnt, with no impact due to the litter fuel load. The grass fuel load and wind speed had a positive effect on rate of spread, whereas relative humidity and fuel moisture had a negative effect. These findings indicate that managers can predict the likely damage to woody plants during an early dry season burn by assessing the grass fuel load and weather conditions at the time of burning.

Introduction

Fire is a major disturbance factor in many biomes ranging from savannas to tropical rainforests.[1–3] The intensity, season and frequency of fire are key determinants of its impacts on vegetation.[4,5] Frequent fires may reduce species richness and abundance, and change the structure of woody plants.[6–8] Furthermore, the effects of fire on the growth and survival of plants vary both among and within species. It is therefore desirable to obtain information on the characteristics of fire that influence its potential influence on biodiversity in different ecosystems.

Fire has numerous features that affect plants.[9,10] Key attributes are intensity, rate of spread, flame height and leaf-scorch height. Fire intensity is the most important property because it is a measure of the amount of heat released during a conflagration and is thus a useful indicator of its potential impact on plants.[11,12] Moreover, fire intensity influences flame height and the degree of leaf scorch.[13]

The amount and type of fuel and its moisture content directly influence fire behaviour.[9,14,15] The fuel load determines the potential amount of heat that can be released during a burn, whereas the type and distribution of fuel elements affects their combustibility. Fine fuels (diameter <6 mm) burn more readily than coarse ones. The moisture content of fuel affects the completeness of combustion.[15,16] Living tissues have a higher moisture content than dead matter and therefore burn less readily. Fuel characteristics differ among ecosystems, resulting in differences in fire behaviour and hence in damage to plants.[9,15,17] To manage fire, it is therefore important to understand the variability in fire behaviour in different ecosystems.

Weather conditions, including air temperature, relative humidity and wind speed all influence fire behaviour.[11,18] Wind speed affects the rate of spread of fire and flame height.[15,17] For example, strong winds increase the rate of spread and reduce flame height. Air temperature and relative humidity affect fuel moisture.[9] High relative humidity increases the moisture content of cured fuel whereas high temperatures reduce it through enhanced evaporative losses. To understand the potential impacts of fire on plants, it is necessary to study how weather conditions at the time of burning and fuel characteristics influence fire behaviour in different ecosystems.

Weather conditions vary both diurnally and seasonally.[10,13,19] Relative humidity in the morning is generally higher than in the late afternoon, whereas ambient temperature is the opposite. Relative humidity during the late dry season is lower than in the early dry season. In contrast, wind speed during the early dry season is generally lower than in the mid or late dry season in savannas.[13]

Wildfires during the late dry season are a major problem in the economically important timber-producing *Baikiaea plurijuga* woodlands.[20] These fires reduce seedling regeneration and recruitment of saplings to the canopy.[21] Prescribed burning during the early dry season is a common management strategy to reduce fuel loads and thus the incidence of intense fires during the late dry season in savannas.[6] There is, however, limited information on fire behaviour during the early dry season. We studied the behaviour of 15 experimental fires lit at this time in a *Baikiaea* woodland. Our objectives were to answer the following questions. (1) What are the relationships among fire behaviour variables? (2) Which environmental variables best predict fire behaviour?

Methods

Study site

The study was carried out in Gwayi State Forest, Zimbabwe (18°45′–19°30′S and 27°40′–28°11′E; altitude 1 060 m), a gazetted indigenous woodland. The main commercial activity in these woodlands has been the harvesting of timber since 1904, when the Bulawayo to Victoria Falls railway line was constructed. Trees of the commercial hardwood timber species (*Baikiaea plurijuga, Guibourtia coleosperma* and *Pterocarpus angolensis*) with a diameter at breast height (1.3 m) greater than 35 cm are harvested on a 40-year rotation. The study site was last logged in December 1992. Cattle (*Bos indicus*) and wild herbivores such as *Loxodonta africana* (elephant), *Taurotragus oryx* (eland) and *Tragelaphus strepsiceros* (kudu) lightly utilize the woodland. Annual rainfall is low and erratic with a mean of 597 mm and a coefficient of variation of 27.4% (over 40 years, 1959 to 1997). The main rainy season extends from November to March. January is the wettest month and June the driest. October is the hottest month, with a mean daily temperature of 33.4°C, and June is the coldest, with a mean daily minimum of 4.5°C. Frost is common during the cool dry season (May to August).

The soils at the study site are deep (>5 m), structureless aeolian sands of uniform texture, coloquially referred to as Kalahari sands.[22] These soils are extremely infertile, and have little organic matter and a low

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water-holding capacity.[23]

White[24] describes the vegetation of the study site as a Zambezian dry deciduous forest and scrub forest. The dominant canopy species is *B. plurijuga.* It is commonly associated with *P. angolensis, Combretum collinum, Schinziophyton rautanenii, Croton gratissimus* and *G. coleosperma.*

The grasses *Heteropogon melanocarpus* and *Panicum maximum* dominate the herb layer. Other common grasses are *Pogonarthria fleckii, Aristida pilgeri, A. stipitata, Triraphis schlerchteri, Tristachya rehmannii, Eragrostis* species and *Digitaria pentzii.*[25] Dicotyledonous herbs such as *Vernonia poskeana, Clerodendrum ternatum* and *Jasminum stenolobum* are also common. The nomenclature of plant species follows that of Arnold and De Wet.[26]

Experimental design

This study was part of a larger experiment that investigated the impact of early dry season fires on the population dynamics of *Baikiaea plurijuga.*[21] We collected data on fire behaviour and environmental variables within this large experiment, which was laid out as a randomized block design.

A uniform area (4 ha) was selected using Walker's[27] procedure. A block of plots was laid out in each of top-, middle- and bottom-slope positions. Each block had three plots each 50 × 50 m and 5 m apart. A fence was erected around the plots to exclude large herbivores. Three early burning treatments were applied in each block annually in mid-May from 1993 to 1997. Treatments were replicated three times and applied to the plots in a randomized block design. The treatments were: (1) burning using a reduced fuel load, (2) burning using the ambient fuel load, and (3) burning using an added grass fuel load. In treatment 1, herbaceous plants were clipped to a stubble height of 5 cm to simulate heavy grazing. Herbaceous biomass clipped from treatment 1 plots and from borders around the experimental plots was spread evenly in plots receiving treatment 3.

Fuel load

Herbaceous fuel loads were measured the day before burning. Five 50-m line transects were systematically laid out 8 m apart in each plot, leaving a border of 9 m at either side. Eight 1.0 × 0.5 m quadrats were chosen randomly on each line. Herbaceous biomass in each quadrat was clipped at ground level. Samples were transported to a laboratory and weighed using an electric balance. Ten samples from each plot were chosen randomly and used to measure moisture content, which was determined by drying samples to constant weight in a forced draught oven at 60°C.

Herbaceous vegetation harvested from treatment 1 plots was placed in hessian bags and weighed in the field using a spring balance. Harvested herbage was spread evenly in plots receiving treatment 3. The weight of the stubble in treatment 1 plots was measured by clipping as described above.

Plant litter was collected by hand from thirty 1.0 × 0.5 m quadrats per plot. Quadrats were chosen randomly from those used to measure herbaceous biomass. Woody litter consisted of woody fragments, leaves, bark, fruit pods and twigs with a diameter less than 6 mm. Samples were placed in khaki bags and transported to a laboratory for weighing. Fine sand was separated from litter using a 2-mm sieve.

Three litter samples were randomly chosen per plot and used to measure moisture content (using the same procedure as above). Herbaceous biomass and litter mass samples were chosen randomly per plot and used to measure moisture content just before burning. Three samples were selected for each fuel type treatment.

Environmental variables and fire behaviour

Wind speed, relative humidity and air temperature were measured three times during each fire. Wind speed was recorded using a portable cup anemometer mounted on a stand (1.5 m high). Relative humidity was measured using a whirling psychrometer.

Fires were started as headfires from one side of a plot. Fire intensity was calculated using Byram's[28] equation, $I = hwr$, where I is the fire line intensity (kW m^{-1}), h is heat yield of the fuel (kJ kg^{-1} DM), w is the dry weight of the grass and litter consumed by the fire (kg DM m^{-2}), and r is the rate of spread of the flame front (m s^{-1}). A combustion factor of 0.95 for grass and 0.85 for litter[29] and energy contents of 16 890 kJ kg^{-1} DM for grass and 18 000 kJ kg^{-1} DM for litter fuel[30] were used.

The rate of spread of fire was calculated by dividing the distance (in m) by the time (in s) taken by the flame front to cover it. Three poles, 5 m apart, were driven into the ground along a straight line. The time taken for the flame front to cover the distance between poles was recorded using a stopwatch. The benefit of using this method for estimating the rate of spread is that it was easy to use and computationally simple. The method required the line of sample points to be consistently at right angles to the fire front that resulted from a line ignition. The method was potentially prone to over-estimating rate of spread if the lines were not at right angles to the fire front, or if the fire shape was an ellipse, as typically occurred after a point ignition. The tendency to overestimate in such cases arose because the method did not take into account slower, lateral movement in directions other than orthogonal to the headfire. However, this was not a major problem in our study because the experimental plots were small (50 × 50 m) and the fires were lit as line ignitions rather than as points. The fires generally travelled in straight lines.

During the fires, flame height was estimated visually. After each fire, the proportion of the plot burnt and leaf-scorch height were estimated visually a day after burning. Leaf-scorch refers to the height of leaves that are scorched brown but not burnt.

Statistical analyses

The relationships between fire behaviour (rate of spread of fire, flame height, leaf-scorch height and proportion of the area burnt) and environmental variables (fuel load, fuel moisture content, wind speed, relative humidity and air temperature) were examined with multiple regression analysis using Statistica 6.0.[31] Data were transformed to meet the assumptions of normality of residuals and homogeneity of variances.[32] Flame height, rate of spread of fire, air temperature, wind speed and fuel moisture content were square root-transformed. Relative humidity, fuel load, fire intensity and leaf-scorch height were log-transformed. The proportion of the area burnt was arcsine-transformed.

The moisture content of litter fuel was positively correlated with moisture content of grass fuel ($r = 0.93$; d.f. = 13, $P < 0.001$) and was therefore excluded from the regression models. Air temperature and grass fuel moisture content were collinear. Principal component analysis (PCA) was therefore carried out to extract uncorrelated factors.[33] The first principal component (axis I) explained 85.4% of the correlated variation in air temperature and grass fuel moisture content; the second principal component (axis II) explained 14.6% of the uncorrelated variation in air temperature and grass moisture content. Principal component axis I scores were positively correlated with air temperature and negatively correlated with grass fuel moisture content.

We used stepwise multiple linear regression with grass fuel, litter fuel, temperature-grass fuel moisture PCA variable, wind speed and relative humidity as predictors of fire behaviour. Forward selection of variables was used and variables where included in the model if their P value was less than 5%.[33] The magnitude of the standardized β coefficients was used to test the relative importance of variables in the multiple regression analysis.[34]

Results

Properties of fire behaviour and environmental variables

Fire intensity, rate of spread of fire, flame height, leaf-scorch height and proportion of the area burnt varied widely. The coefficient of variation ranged between 41% and 101%. The proportion of area burnt had the lowest variability, whereas fire intensity had the highest (Table 1). However, the magnitude of the fire behaviour variables was low during these early season fires.

The coefficient of variation of the fuel load and moisture content ranged between 33% and 80%. The litter fuel load had the lowest variability while the grass fuel load had the highest (Table 1). The mean fuel load was 85.6 g DM m^{-2} for grass and 124 g DM m^{-2} for litter. The fuel moisture content averaged 10.0% for grass and 6.6% for litter.

The coefficient of variation of weather conditions ranged between 17% and 81%. Air temperature had the lowest variability while wind speed had the highest (Table 1). Mean air temperature was 25.7°C, whereas wind speed averaged only 0.5 m s^{-1}. Relative humidity averaged 24.8%.

Table 1. Descriptive statistics of variables measured during 15 experimental fires (three fuel load treatments over five years).

	Mean	Minimum	Maximum	CV (%)
Fire behaviour				
Fire intensity (kW m^{-1})	45 2	25	1341	100.7
Rate of spread of fire (m s^{-1})	0.12	0.01	0.35	85.4
Flame height (m)	1.19	0.10	3.5	88.0
Leaf-scorch height (m)	3.12	0.20	7.3	84.6
Area burnt (%)	73.8	5	100	40.6
Fuel characteristics				
Grass fuel load (g DM m^{-2})	85.6	6.8	260.1	80.2
Grass fuel moisture content (%)	10.0	1.2	22.4	80.0
Litter fuel load (g DM m^{-2})	124.1	56.6	197.9	32.8
Litter fuel moisture content (%)	6.6	2.0	17.8	75.2
Weather conditions				
Relative humidity (%)	24.8	13.7	47.3	46.7
Air temperature (°C)	25.7	18.8	32.7	17.1
Wind speed (m s^{-1})	0.5	0.0	1.1	80.9

Relations between fire behaviour variables

Fire behaviour variables were highly correlated (Table 2). Fire intensity and rate of spread of fire were highly correlated with flame height, leaf-scorch height and proportion of the area burnt. Similarly, flame height was highly correlated with leaf-scorch height and proportion of the area burnt. Leaf-scorch height and proportion of the area burnt were also highly correlated.

Environmental variables influencing fire behaviour

The grass fuel load explained 67% of the variation ($F_{3,11} = 10.7$, $P < 0.001$) in rate of spread of fire (Table 3). In contrast, litter fuel load, relative humidity, wind speed and temperature-grass moisture (PCA axis I) were poor predictors of rate of spread of fire (Table 4).

Flame height was a function of the grass fuel load, wind speed and relative humidity (Table 3). The multiple regression model explained 77% of the variation in flame height ($F_{4,10} = 13.0$, $P < 0.001$). Both the grass fuel load and wind speed had positive effects on flame height, whereas relative humidity had a negative effect (Table 4). The litter fuel load and temperature–grass moisture PCA variable were poor predictors of flame height (Table 4).

Leaf-scorch height was a function of the grass fuel load, wind speed, relative humidity and the temperature-grass moisture variable (Table 3). The four predictor variables explained 94% of the variation in leaf-scorch height ($F_{4,10} = 54.7$, $P < 0.001$). The grass fuel load and wind speed had positive effects on leaf-scorch height, whereas relative humidity and temperature-grass

Table 2. Pearson correlations (r) between variables.[a] Correlation coefficients are for transformed variables. Sample size was 15.

	RH	T	W	G	Gm	L	Lm	FI	ROS	F	S
RH	1										
T	–0.28	1									
W	0.26	0.23	1								
G	–0.25	–0.04	–0.38	1							
Gm	–0.16	–0.71**	–0.09	–0.01	1						
L	0.32	0.56*	0.29	–0.39	–0.35	1					
Lm	–0.17	–0.83***	–0.19	0.05	0.93***	–0.56*	1				
FI	–0.39	0.19	–0.21	–	0.04	–	0.01	1			
ROS	–0.47	0.16	–0.15	0.79***	0.04	–0.27	0.05	–	1		
F	–0.43	–0.03	–0.12	0.81***	0.27	–0.47	0.30	0.86***	0.90***	1	
S	–0.41	0.04	–0.02	0.87***	0.16	–0.38	0.15	0.87***	0.89***	0.93***	1
A	–0.53*	0.23	–0.02	0.66**	0.06	–0.18	0.07	0.83***	0.86***	0.77***	0.85***

[a] RH, relative humidity (%); T, air temperature (°C); W, wind speed (m s^{-1}); G, grass fuel load (g DM m^{-2}); Gm, grass fuel moisture content (%); L, litter fuel load (g DM m^{-2}); Lm, litter fuel moisture content (%); ROS, rate of spread of fire (m s^{-1}); F, flame height (m); S, scorch height (m); A, proportion of area burnt (%). The correlations between FI and ROS, G and L are not given because FI was computed from the three variables.

*Asterisks indicate significant correlations: *$P < 0.05$; **$P < 0.01$; ***$P < 0.001$. All other correlations are not significant ($P > 0.05$).

Table 3. Multiple regression coefficients for the relationships between fire behaviour and environmental variables.[a]

Variable	Slope	s.e.	t	P	r_a^2	F	P
Rate of spread					0.67	10.7	0.001
Intercept	0.179	0.208	0.861	0.408			
Grass fuel load	0.105	0.022	4.75	0.001			
Flame height					0.77	13.0	0.001
Intercept	0.336	0.582	0.576	0.577			
Grass fuel load	0.380	0.0621	6.112	0.001			
Wind speed	0.440	0.187	2.35	0.040			
Relative humidity	–0.368	0.152	–2.42	0.036			
Scorch height					0.94	54.7	0.001
Intercept	–1.86	0.725	–2.57	0.028			
Grass fuel load	1.03	0.077	13.27	0.001			
Wind speed	1.41	0.233	6.05	0.001			
Relative humidity	–0.80	0.189	–4.23	0.002			
Temperature–grass moisture correlation (PCA axis I)	–0.13	0.061	–2.18	0.054			
Proportion of area burnt					0.589	7.68	0.005
Intercept	60.6	34.8	1.74	0.11			
Grass fuel load	13.8	3.71	3.71	0.003			
Relative humidity	–21.5	9.03	–2.38	0.036			

[a] Flame height, rate of spread of fire, air temperature, wind speed and fuel moisture content were square root transformed. Relative humidity, fuel load, fire intensity and leaf-scorch height were log-transformed. The proportion of the area burnt was arcsine-transformed.

The statistics given are the intercept, slope, standard error, coefficient of determination and the probability of the slope being significantly different from zero.

Table 4. Standardized regression (β) coefficients for the multiple regression variables indicating their relative importance in influencing fire behaviour.[a] The probability of the unstandardized coefficient being significantly different from zero is given.

Variable	Grass fuel load (g DM m^{-2})	Relative humidity (%)	Wind speed (m s^{-1})	Litter fuel load (g DM m^{-2})	Temperature–grass moisture correlation (PCA axis I)
Rate of spread (m s^{-1})					
β	0.80	–0.33	0.23	0.039	0.076
t	4.75	–2.05	1.39	0.204	0.434
P	0.001	0.065	0.192	0.842	0.672
Flame height (m)					
β	0.85	–0.32	0.34	–0.19	–0.26
t	6.11	–2.42	2.35	–1.10	–1.97
P	0.001	0.036	0.040	0.294	0.077
Scorch height (m)					
β	0.96	–0.30	0.45	–0.054	–0.15
t	13.3	–4.23	6.05	–0.61	–2.18
P	0.001	0.002	0.001	0.555	0.054
Area burnt (%)					
β	0.70	–0.43	0.37	0.077	0.076
t	3.71	–2.38	1.97	0.33	0.35
P	0.003	0.036	0.075	0.75	0.73

[a] Variables were transformed as described in Table 3.

moisture variable had a negative effect (Table 4). The litter fuel load was a poor predictor of leaf-scorch height.

The grass fuel load and relative humidity explained 59% of the variation ($F_{3,11}$ = 7.68, P < 0.01) in the proportion of the area burnt (Table 3). The grass fuel load and wind speed had a positive effect on the proportion of the area burnt, while relative humidity had a negative effect (Table 4). The effect of wind speed was, however, not significant (t = 1.97, d.f. = 11, P = 0.07). Again, litter fuel load was a poor predictor of the proportion of the area burnt.

The predicted values of fire behaviour variables from the fitted multiple regression models (Table 3) corresponded well with the observed values. The correlations between the predicted and observed values ranged from 0.82 for the proportion of the area burnt to 0.98 for leaf-scorch height (Fig. 1). The models adequately predicted rate of spread within the range 0.04–0.2 m s^{-1}; flame height within the range 0.2–2.0 m; scorch height within the range 0.6–7.0 m; and proportion of the area burnt within the range 45–75%. The predictions of the fire behaviour variables would be unreliable outside these ranges.

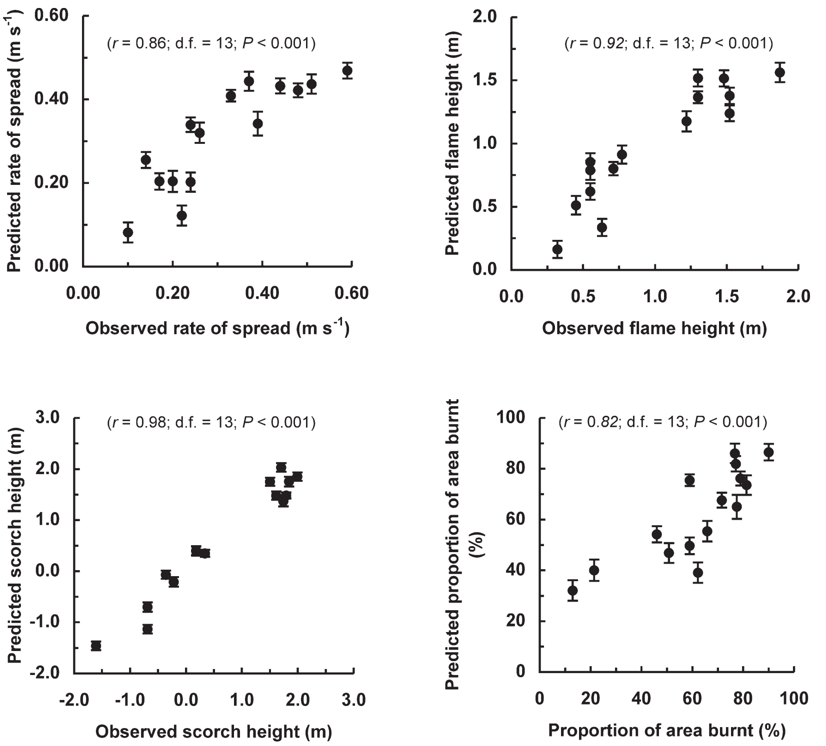

Fig. 1. The relation between the means (±s.e.) of fire behaviour variables predicted by the regression models and observed values. Rate of spread and flame height are on a square root scale, whereas scorch height is on a natural logarithm scale.

Discussion

Relations between fire behaviour variables

Fire behaviour variables were highly correlated. Fire intensity was positively correlated with flame height, leaf-scorch height and proportion of the area burnt as reported by other workers.[9,11,13] Measuring the variables used to calculate fire intensity is laborious. Furthermore, it may not be possible to observe a fire directly to measure its rate of spread. Thus, pre-fire and post-fire indices of fire intensity would greatly improve our understanding of the potential impact of fire on plants.[9,13,35]

Responses of plants to fire are generally explained in terms of season of burning and fire-return interval.[4,5,36] The effects of fire as governed by intensity are equally important.[6,9] Our results show that leaf-scorch height is a potentially useful post-fire index of fire intensity (Table 2). Williams *et al.*[13] also found a positive relation between fire intensity and leaf-scorch height. Fire intensity explained 83% of the variation in leaf-scorch height in their study. These findings have important implications for managing fire-prone biomes because estimates of fire intensity can help to explain the observed changes in plant communities after a fire.[6,37]

The magnitude of the fire behaviour variables are in general agreement with those reported by other workers.[19,29,36] However, they are generally lower than those reported for the late hot dry season when conditions are more conducive to supporting intense fires.[11,13] For example, Williams *et al.*[13] reported that wind speed was 1 m s^{-1} higher, air temperature about 5°C higher and relative humidity 10% lower in the late dry season than in the early dry season. We attribute the low values of fire behaviour variables to the moderate weather conditions during the early dry season (Table 1). Our work was constrained to a narrow subset of possible seasonal fire weather and fuel conditions. The relationships between fire behaviour and the variables measured apply only under conditions of low fire weather danger. It is therefore important to take into account these moderate weather conditions when interpreting the findings of our study.

Determinants of fire behaviour in *Baikiaea woodlands* during the early dry season

The grass fuel load, wind speed and relative humidity were the principal determinants of rate of spread of fire, flame height, leaf-scorch height and proportion of the area burnt as reported by numerous workers.[9,13,15,19] Both the grass fuel load and wind speed consistently contributed to fire damage, whereas relative humidity had the opposite effect (Table 4). Fire intensity was correlated with flame height and leaf-scorch height.[13] Intense fires generally resulted in tall flames and elevated leaf-scorch height.

Simulation studies have shown the importance of the grass fuel load in determining the impacts of fire on the abundance of woody plants in savannas.[38,39] Our results indicated that a grass fuel load as low as about 86 g DM m^{-2} allowed fire to spread. In contrast, other workers have suggested that a grass fuel load of at least 200 g DM m^{-2} is required to support fire in savannas.[16,40] We attribute the ability of fire to spread despite the low grass fuel load to a relatively continuous litter fuel bed. For example, the litter fuel load was 2.4 times less variable and 1.4 times more abundant than the grass fuel load (Table 1). Other workers have also highlighted the importance of a continuous fuel bed in allowing fire to spread.[6,9] The lack of a significant effect of the litter fuel load on fire behaviour during the early dry season was probably due to its incomplete combustion because of moderate weather conditions at the time of burning (Table 1). The completeness of combustion of fuel is influenced by its moisture content and by the weather conditions at the time of burning. However, the average moisture content of litter fuel was low (6.6%) in our study. Unfortunately, we did not assess the amount of litter that was consumed by fire. Frost and Robertson[36] reported that the proportion of litter consumed in a fire was highly variable.

Ambient air temperature was negatively correlated with fuel moisture content as reported by other workers.[9,11,19] Whilst fuel moisture content had no significant effects on rate of spread of fire and proportion of the area burnt, it had a significant negative effect on leaf-scorch height and a nearly significant negative effect on flame height. We attribute the lack of a significant effect of fuel moisture on rate of spread of fire to the narrow range of values (6.6–10%) used in this study. It is clear that moisture content influences the probability of ignition and completeness of combustion of fuel.[9,15,19] For example, Baeza *et al.*[14] found that fuel moisture content explained 49% of the variation in the rate of spread of fire in their study. Trollope[11] suggests that moisture content generally has a significant effect on fire behaviour when it is greater than 40%.

Relative humidity had a negative effect on flame height, leaf-scorch height and proportion of the area burnt. These findings are in agreement with those of other workers.[9,11,19] High relative humidity tends to increase the moisture content of cured fuel, thereby leading to its reduced combustibility. We attribute the lack of a significant effect of relative humidity on rate of spread to the narrow range of values that we used in this study. The non-significant negative correlation between relative humidity and fuel moisture content results from the limited ranges of both variables.

Wind speed had a positive influence on flame height and leaf-scorch height, whereas it had no significant effect on rate of spread of fire and proportion of the area burnt. The positive effects of the generally low wind speed on flame height (Table 1) may be attributed to an enhanced supply of oxygen to the fire, thereby promoting the combustion of fuel.[19] Strong winds reduce flame height by reducing flame angle.[11,13,18] The lack of a significant effect of wind speed on rate of spread is a result of our limited data set. Catchpole[9] reported, however, that a threshold wind speed ranging between 1 m s^{-1} and 2.5 m s^{-1} is required for wind to influence the rate of spread of fire. Generally, we lit fires when wind speed was less than 2 m s^{-1}, so that we could control the fire and for safety reasons.[11]

Conclusions

Fire intensity, rate of spread of fire, flame height, leaf-scorch height and proportion of the area burnt were highly correlated. Leaf-scorch height is therefore a potentially useful index for measuring fire intensity retrospectively.

The grass fuel load was the main determinant of fire behaviour. It had a positive effect on fire behaviour whereas litter fuel had none. Grass fuel moisture had a variable influence. It had negative effects on leaf-scorch height and no significant influence on rate of spread, flame height and proportion of the area burnt. We attribute the lack of significant effects of fuel moisture on fire behaviour to the narrow range of values that we used in our study. Although litter fuel had no significant effects on fire behaviour, it is probably a key determinant of the ability of fire to spread where the grass fuel load is as low as 86 g DM m^{-2}.

Wind speed and relative humidity influenced flame height, leaf-scorch height and proportion of the area burnt. Air temperature influenced fire behaviour through its negative effect on fuel moisture. Wind speed consistently had a positive influence on fire behaviour whereas relative humidity had an adverse effect. However, wind speed and relative humidity had no significant effects on the rate of spread of fire. We attribute this finding to the moderate weather conditions during the early dry season. For example, wind speed ranged between zero and only 1.1 m s^{-1}. This is well below the threshold speed for wind to have a significant impact on rate of spread of fire.

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1. Cochrane M.A. (2003). Fire science for rain forests. *Nature* **421**, 913–919.
2. Andersen A.N., Cook A.D. and Williams R.J. (eds) (2003). *Fire in Tropical Savannas: The Kapalga Experiment*. Springer-Verlag, New York.
3. Laurance W.F. (2003). Slow burn: the insidious effects of surface fires on tropical forests. *Tr. Ecol. Evol.* **18**, 209–212.
4. Bradstock R.A., Williams J.E. and Gill M.A. (eds) (2002). *Flammable Australia: The Fire Regimes and Biodiversity of a Continent.* Cambridge University Press, Cambridge.
5. Goldammer J.G. and de Ronde C. (eds) (2004). *Wildland Fire Management Handbook for Sub-Saharan Africa.* Global Fire Monitoring Center, Freiburg.
6. Bond W.J. and van Wilgen W. (1996). *Fire and Plants*. Chapman and Hall, London.
7. Moreira A.G. (2000). Effects of fire protection on savanna structure in Central Brazil. *J. Biogeogr.* **27**, 1021–1029.
8. Hoffmann W.A. and Solbrig O.T. (2003). The role of topkill in the differential response of savanna woody species to fire. *For. Ecol. Mngmnt* **180**, 273–286.
9. Catchpole W. (2002). Fire properties and burn patterns in heterogeneous landscapes. In *Flammable Australia: The Fire Regime and Biodiversity of a Continent,* eds R.A. Bradstock, J.E. Williams and M.A. Gill, pp. 49–75. Cambridge University Press, Cambridge.

10. Cheney N.P. and Sullivan A. (1997). *Grassfires, Fuel, Weather and Fire Behaviour.* CSIRO, Melbourne.
11. Trollope W.S.W. (1984). Fire behaviour. In *Ecological Effects of Fire in South African Ecosystems,* eds P. de V. Booysen and N.M. Tainton, pp. 199–217. Springer-Verlag, Berlin.
12. Alexander M.E. (1982). Calculating and interpreting forest fire intensities. *Can. J. Bot.* **60**, 349–357.
13. Williams R.J., Gill A.M. and Moore P.H.R. (2003). Fire behavior. In *Fire in Tropical Savannas: The Kapalga Experiment,* eds A.N. Andersen, G.D. Cook and R.J. Williams, pp. 33–46. Springer-Verlag, New York.
14. Baeza M.J., De Luis M., Raventos J. and Escarre A. (2002). Factors influencing fire behaviour in shrublands of different stand ages and the implications for using prescribed burning to reduce wildfire risk. *J. Environ. Mngmnt* **65**, 199–208.
15. Bilgili E. and Saglam B. (2003). Fire behaviour in marquis fuels in Turkey. *For. Ecol. Mngmnt* **184**, 201–207.
16. Hely C., Alleaume S., Swap R.J., Shugart H.H. and Justice C.O. (2003). SAFARI-2000 characterisation of fuels, fire behavior, combustion completeness, and emissions from experimental burns in infertile grass savannas in western Zambia. *J. Arid Environ.* **54**, 381–394.
17. Fernandes P.A.M. (2001). Fire spread prediction in shrub fuels in Portugal. *For. Ecol. Mngmnt* **144**, 67–74.
18. Bessie W.C. and Johnson E.A. (1995). The relative importance of fuels and weather on fire behavior in subalpine forests. *Ecology* **76**, 747–762.
19. Trollope, W.S.W., de Ronde, C. and Geldenhuys, C.J. (2004). Fire behaviour. In *Wildland Fire Management Handbook for Sub-Saharan Africa,* eds J.G. Goldammer and C. de Ronde, pp. 27–59. Global Fire Monitoring Center, Freiburg.
20. Piearce G.D. (1986). How to save the Zambezi teak forests. *Unasylva* **152**, 29–36.
21. Gambiza J. (2001). *The regeneration of Zambezi teak forests after logging: influence of fire and herbivory.* Ph.D. thesis, University of Zimbabwe, Harare.
22. Nyamapfene K. (1991). *Soils of Zimbabwe.* Nehanda Press, Harare.
23. Childes S.L. and Walker B.H. (1987). Ecology and dynamics of the woody vegetation on the Kalahari Sands in Hwange National Park, Zimbabwe. *Vegetatio* **72**, 111–128.
24. White F. (1983). *The Vegetation of Africa.* UNESCO, Paris.
25. Rattray J.M. (1957). The grasses and grass associations of Southern Rhodesia. *Rhod. Agric. J.* **54**, 197–234.
26. Arnold T.H. and De Wet B.C. (1993). *Plants of Southern Africa: Names and Distribution.* National Botanical Institute, Pretoria.
27. Walker B.H. (1976). An approach to the monitoring of changes in the composition and utilisation of woodland and savanna vegetation. *S. Afr. J. Wildl. Res.* **6**, 1–32.
28. Byram G.M. (1959). Combustion of forest fuels. In *Forest Fire: Control and Use,* eds A.A. Brown and K.P. Davis, pp. 61–89. McGraw-Hill, New York.
29. Shea R.W., Shea B.W., Kauffman J.B., Ward D.E., Haskins C.I. and Scholes M.C. (1996). Fuel biomass and combustion factors associated with fires in savanna ecosystems in South Africa and Zambia. *J. Geophys. Res.* **101**, 23551–23568.
30. Trollope W.S.W., Trollope L.A., Potgieter A.L.F. and Zambatis N. (1996). SAFARI-92 characterisation of biomass and fire behaviour in small experimental burns in the Kruger National Park. *J. Geophys. Res.* **101**, 23531–23539.
31. StatSoft, Inc. (2002). STATISTICA, version 6; http://www.statsoft.com.
32. Sokal R.R. and Rohlf F.J. (1995). *Biometry.* W.H. Freeman, San Francisco.
33. Draper N.R. and Smith H. (1981). *Applied Regression Analysis.* Blackwell Scientific Publications, Oxford.
34. Zar J.H. (1996). *Biostatistical Analysis.* Prentice Hall, Upper Saddle River, NJ.
35. Stronach N.R.H. and McNaughton S.J. (1989). Grassland fire dynamics in the Serengeti ecosystem, and a potential method of retrospectively estimating fire energy. *J. Appl. Ecol.* **26**, 1025–1033.
36. Frost P.G.H. and Robertson F. (1987). The ecological effects of fire in savannas. In *Determinants of Tropical Savannas,* ed. B.H. Walker, pp. 93–140. IRL Press, Oxford.
37. Williams R.J., Muller J.W., Wahren C., Setterfield S.A. and Cusack J. (2003). Vegetation. In *Fire in Tropical Savannas: The Kapalga Experiment,* eds A.N. Andersen, G.D. Cook and R.J. Williams, pp. 79–106. Springer-Verlag, New York.
38. Gambiza J., Bond W., Frost P.G.H. and Higgins S. (2000). A simulation model of miombo woodland dynamics under different management regimes. *Ecol. Econ.* **33**, 353–368.
39. Higgins S.I., Bond W.J. and Trollope W.S.W. (2000). Fire, resprouting and variability: a recipe for grass–tree coexistence in savanna. *J. Ecol.* **88**, 213–229.
40. van Wilgen B.W. and Scholes R.J. (1997). The vegetation and fire regimes of the southern hemisphere Africa. In *Fire in Southern African Savannas: Ecological and Atmospheric Perspectives,* eds B.W. van Wilgen, M.O. Andreae, J.G. Goldammer and J.A. Lindesay, pp. 27–46. Witwatersrand University Press, Johannesburg.

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