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The Influence of Fuel, Weather and Fire Shape Variables on Fire-Spread in Grasslands

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Abstract. Fire-spread was measured on 121 grass fires in a 2500 ha experimental site in the Northern Territory, Australia. Selected plots were harvested to alter the height, load and bulk density of the fuel-bed. Fires were lit from a line and allowed to travel up to 400 m downwind. Fire-spread was correlated with fuel, weather and fireshape variables using multiple regression techniques. Wind speed had most effect on fire-spread. The influence of the other variables was examined after a model for wind speed and moisture content had been fitted.

Fuel load did not influence fire-spread. Fires in natural swards burnt 18% faster than fires in cut grass, but this increase could not be fully explained by changes in the height or bulk density of the fuel bed. Grass type characterised either by species group or by surface-area-to-volume ratio of the fuel particle, did not appear to significantly influence fire-spread. Differences in spread rates between the two grasses were attributed to differences in grass curing. The influence of grass curing appeared to be less than indicated by published models. Models of fire-spread in grasslands currently in use need to be revised.

Ignition line length was a significant variable influencing fire-spread and this must be taken into consideration when using experimental fires to validate theoretical models or develop empirical models from field observations.

Keywords: Grassfires; Rate of Spread; Fuel, Weather, Fire shape; Northern Territory.

Introduction

Australia is essentially a pastoral country; more than 50 percent of the land is used for grazing (Moore 1970) and while nearly 75 percent of the country is arid or semi-arid much of this area is subjected to extensive sheep and cattle grazing. After exceptional rainfalls much of the arid lands will carry continuous grass and may be burnt by extensive grass fires. In the 1974-75 fire season more than 117 million ha, or 15 percent of the area of the continent, burned over a period of 8 months (Luke and McArthur 1978).

Although large grass fires are relatively infrequent in the arid and semi-arid interior, they are likely to occur in the more productive pastoral regions in south-eastern Australia at least once every 10 years (Cheney 1976). Under extreme conditions they may travel more than 60 km in a few hours and burn into commercial forests, rural towns, and urban/rural developments on the outskirts of major cities (Keeves and Douglas 1983; Rawson et al. 1983).

Prior to 1960, there were several attempts to relate weather variables to an index of fire danger (e.g. several examples of published and unpublished work are presented in Foley 1947), but it was not until 1960 that A.G. McArthur related an index of fire danger to rate of spread of the head of the fire front (McArthur 1960; Luke 1961). McArthur related a fire danger index between 0 and 100 to dead fuel moisture content (as determined by ambient temperature, relative humidity, grass curing state and recent rainfall), wind speed and fuel quantity (quantified by grass height). He identified six fire danger classes and provided a range of headfire-spread rates and a description of suppression difficulty for each class. These tables were developed and modified over the next 17 years using information from experimental fires and wildfires and reproduced in the form of slide rule type meters - the Grassland Fire Danger Meter Mk IV (McArthur 1966) and the Grassland Fire Danger Meter Mk V (McArthur 1977) - which calculated a grassland fire danger index and the predicted rate of spread of the headfire. One or other of these two meters is used by the Bureau of Meteorology and bushfire authorities in each State to compute grassland fire danger and rate of grass fire-spread.

Fuel load is not used in the Mk IV meter but is included in the Mk V meter. This apparent contradiction has created user confusion. The Mk IV meter was designed for fires in a continuous fuel bed of annual or perennial grasses. The meter does not include a relationship between fuel load, fuel height and rate of spread, but notes that rate of spread will be lower than predicted when fuel is sparse or discontinuous. Luke and McArthur (1978) argued that rate of spread in a specific grass type was directly proportional to fuel load but also that fuel load was a function of grass particle size. In natural grass swards coarse-stemmed grasses carry a higher fuel load than fine-stemmed grasses, and fires in fine materials burn faster than fires in coarse materials (e.g. Rothermel 1972). A wildfire spreading across the country side was likely to encounter both coarse-and fine-stemmed material, and for all practical purposes the two factors would cancel each other.

In the Mk V meter (McArthur 1977), rate of spread is directly proportional to fuel load (see also Noble et al. 1980). The Bureau of Meteorology has included this relationship into programs for calculating fire danger from the Mk IV meter (Purton 1982). Rothermel (1972) measured fire-spread in artificial fuel beds in a wind tunnel and identified the fuel bed characteristics of fuel load, surface-area-to-volume ratio (a measure of fuel fineness) and bulk density as important variables to be included in a model to predict fire-spread.

Several different functional forms have been used to describe the relationship between rate of spread of a grass fire and wind speed. McArthur (1966) stated that rate of spread varied approximately as the square of wind speed; but in the wind relationship fitted to his Mk IV meter, rate of spread (R) varies according to (Noble et al. 1980):

$$R \; \alpha \; exp \; (0.633U_{10}^{0.5}), \qquad (1)$$

while the wind relationship in the Mk V meter is (Noble et al.1980):

$$R \; \alpha \; exp \; (0.04003U_{10}), \qquad (2)$$

where U_{10} is 10-minute average wind speed (km h^{-1}) at 10 metres.

Rothermel (1972) developed a relationship based largely on McArthur's (1968) data for rate of spread of wildfires vs. wind speed, but modified to provide an inter-relationship between a wind correction factor (Φ_w) and the geometrical properties of the fuel particles and the fuel bed. The relationship is a power function of the form:

$$\Phi_w = AU^B, \qquad (3)$$

where U is the wind speed at mid-flame height and A and B are constants depending on the fuel complex (Rothermel 1972). The correction factor is used in the form: $R = R_o (1 + \Phi_w)$ where R_o is the rate of spread at zero wind. The exponent B depends on the surface area to volume ratio of the fuel particle (σ) and could be assigned a value of between 1.56 to 2.22 for natural grass swards in Australia (Gould 1991).

A series of grassland fire behaviour experiments were conducted by the CSIRO Bushfire Research Unit in the Northern Territory (N.T.) to determine the relative importance of fuel characteristics on fire-spread and in particular to resolve the conflicting information about the importance of fuel load.

In this paper we will discuss the methods and results from these experiments and the relative importance of physical fuel factors on the rate of spread in grassland fires. Extension of these results to include wildfire data and an appropriate function for wind speed in order to develop an operational grass fire-spread model will be discussed in a further paper.

Methods

The experiments were carried out during July and August, 1986, on a flood plain of the Mary River at Annaburroo Station 120 km southeast of Darwin, N.T. The 2500 ha site was flat and open and protected by a wide burnt buffer around the perimeter which allowed us to burn under a wide range of fire danger conditions with few concerns about fire control. July and August are in the middle of the dry season; grasses are normally fully cured and weather conditions are consistently warm and dry with moderate easterly winds almost every day. The area was subdivided into 170 plots that were 100 m x 100 m, or 200 m x 200 m, or 200 m x 300 m in size by grading tracks 1.5, 3 or 5 m wide (Figure 1). Vertical aerial photographs were taken and the centre points of track intersections were surveyed by theodolite and chain to provide an accurate photo-map of the area.

Fuel Manipulation

The site contained two distinct grass types; *Eriachne burkittii* R.Br. (kerosene grass[1]) and *Themeda australis* R.Br.(Stapf) (kangaroo grass).

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[1] Kerosene grass is a common name used locally in the N.T. for several grasses; Perry (1960) uses this name for the short ephemeral grass *Aristida arenaria* but does not quote a common name for *Eriachne* spp.

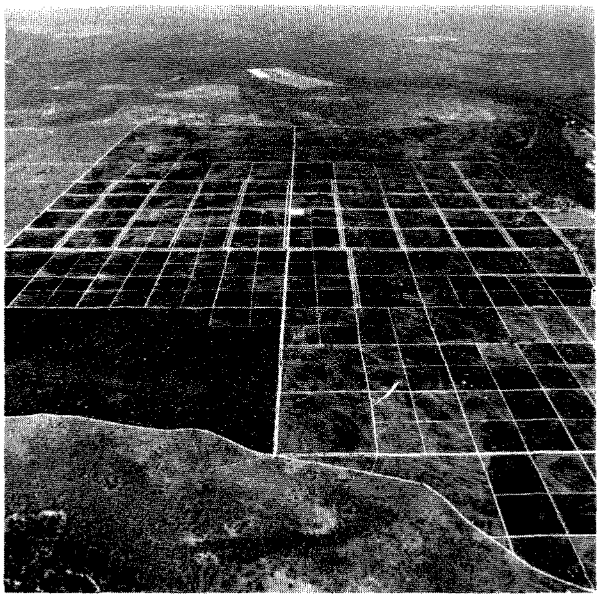

Figure 1. Aerial view of the 2500 ha experimental site Annabaroo, N.T.

1. Kerosene grass grows in dense, almost pure swards on the lower areas and heavy soils in the flood plain. The grass grows up to 2 m during the wet season while the plains are flooded. After floodwaters recede the grass partially collapses and forms a sward with upright lower stems capped with a compact horizontal layer of the upper stems and leaves (Figure 2).

2. Kangaroo grass is a widespread native grass and occurs in many parts of Australia. It is a perennial grass and has a low-basal tussock with higher stems, leaves and seed heads which remain upright after late season rains. (Figure 3).

Figure 2. *Eriachne* grassland: note horizontally layered grass over-topping vertical stems.

Figure 3. *Themeda* grassland: note the bulk of the fuel load is close to the ground.

We examined the aerial photographs and identified plots in each grass type with a uniform and continuous grass sward and without shrubs or tree cover, or with only isolated individuals; treatments were randomly assigned to each plot. Selected plots were cut at 50-25 percent of the natural grass height. On about half the cut plots, the fuels were removed with a forage harvester and on the other half, the cut fuels remained on the plots. A summary of the experimental treatments is given in Table 1. Field examination revealed that some plots were unsuitable for harvesting, and we failed to complete the harvesting program resulting in uneven numbers of treated plots.

Although kerosene grass is restricted to the mid-flood plains in tropical areas we considered it to have some similarities with *Lolium perenne Lam.* (perennial rye grass) which is a common introduced pasture grass in south-east Australia. The two grasses at Annaburroo provided fuel beds which were structurally quite different and, after harvesting, visiting fire control officers (D. Jordan, D. McArthur pers comm.) considered the treatments were not unlike partially grazed pastures or short crop stubble (in the case of *Eriachne*) in southern States of Australia.

Table 1. Summary of the experimental treatments.

Treatment (TR)	No. of Fires	Grass	Treatment
E1	44	*Eriachne* sp.	Natural undisturbed grass.
E2	13	*Eriachne* sp.	Grass cut at 50% of natural grass height and left on site.
E3	14	*Eriachne* sp.	Grass cut at 50% of natural grass height and removed from site.
T1	26	*Themeda australis*	Natural undisturbed grass.
T2	16	*Themeda australis*	Grass cut at 50-25% of natural height and left on site.
T3	8	*Themeda australis*	Grass cut at 50-25% of natural height and removed from site.

Fuel load and fuel height were systematically sampled on a 16 point grid sample in each plot. At each point the mean height of the surrounding grass sward was measured and fuel was gathered from a 30 cm x 60 cm quadrat, oven-dried and weighed. The results of the sixteen samples were averaged to provide a characteristic fuel load and fuel height for each plot. Where there was a large variation in fuel load or discontinuous fuels within the plots, the plots were either excluded from burning or excluded later from analysis.

The fuel sample grid was overlayed on the map of each experimental fire (see next section). Fuel measurements from sample points which fell outside the measured fire area were excluded and the mean fuel load and fuel height for each experimental fire was calculated from the remaining samples.

Surface-area-to-volume ratio was measured on selected whole plants of the two major species. The plants were divided into stalks (cylinders) and leaves (flat plates). The diameters and thicknesses of these components were measured with a micrometer and converted to a surface-area-to-volume ratio using the methods given by Brown (1970). The surface area of the edge of grass leaves was omitted, and we assumed the surface-area-to-volume ratio of grass leaves were adequately estimated by $\sigma = 2/t$ where t is the average thickness of the leaf blade. The mean surface-area-to-volume ratio, σ, for the plant was estimated by weighting the mean σ value of the leaves and stalks by the total length of each component.

Rate of Spread

The fires were lit by two men with drip torches who started at the mid-point of a measured line and moved rapidly to each end. The ignition lines were nominally 50 m long on the 100 x 100 m plots, but there was some variation due to fuel and plot constraints or (occasionally) unfettered enthusiasm of the lighters; longer ignition lines up to 175 m were used on the larger plots. The line was oriented at right-angles to the prevailing wind direction. This technique quickly formed a wide head, and the fire appeared to reach a quasi-steady-state rate of spread soon after ignition. Fire behaviour was recorded by ground observation and from low-oblique aerial photographs (Figure 4).

The oblique photographs were taken from a helicopter (Bell 47-G) at an elevation that produced a depression angle of approximately 45° to the principal point (approximately the centre of the plot) and 60° to the base of the plot. The photographs were taken with an analog-data-back, 35 mm camera at intervals between 15-30 seconds, depending on the behaviour of the fire.

The oblique photographs of each experimental fire were interpreted for actual ignition line length, fire perimeter, flame depth and ground control points which were compiled into an oblique fire-spread diagram using a photo-enlarger. Ground control points were the centre points of the track intersections and selected features (e.g. trees, patches of bare ground, buffalo wallows) which could be identified on both the oblique photographs and the aerial photo-map. The oblique fire perimeter diagram and planimetric base maps with the same control points were digitised. A computer transformation program selected the best fit for converting the ground control points from the oblique fire perimeter map into a planar map, and then plotted a composite map of time isopleths of fire perimeter and flame depth for each experimental fire (Figure 5).

Rate of forward spread was taken as the maximum distance (D_n) that the head fire advanced between successive time isopleth fire perimeters ($t_n - t_{n-1}$) i.e.

$$R = \frac{D_n}{t_n - t_{n-1}} \tag{4}$$

Rate of spread was plotted against time for the duration of the fire to determine the acceleration period (which was often as short as 15 seconds) and the average rate of spread was then determined over the longest period of spread before a substantial change. This change may have been caused by a sudden lull in wind, a change in fuel, or part of the fire burning out of the plot.

Local wind shifts caused some fires to burn in a direction that was not normal to the ignition line. In these cases an "effective ignition line length" was measured from the fire perimeter maps taking the length of ignition line normal to the mean direction of head-fire spread.

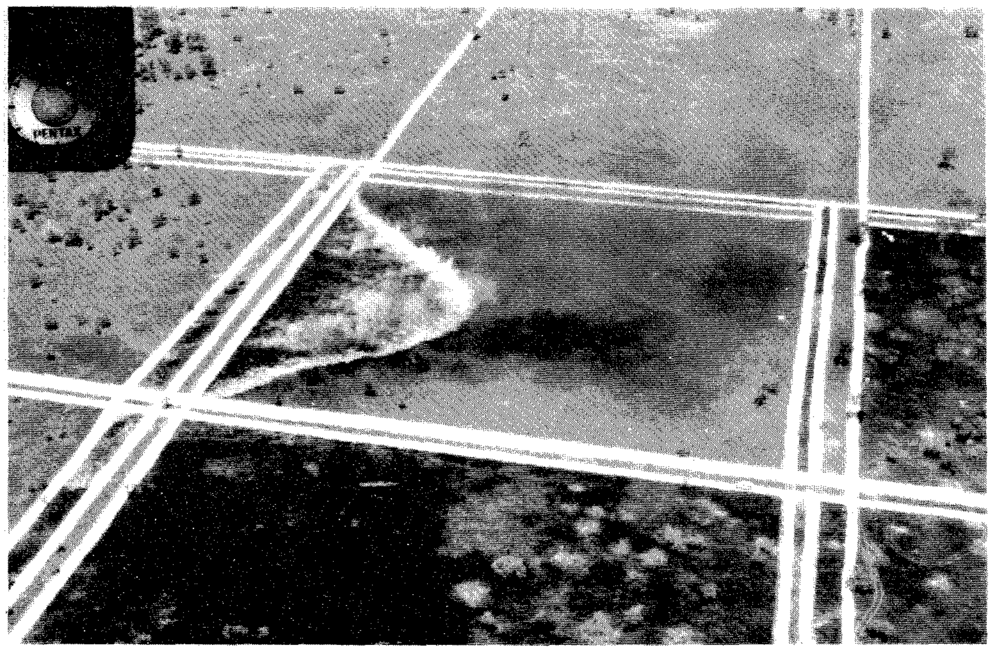

Figure 4. Low oblique aerial photo of experimental fire F19, 48 seconds after ignition. Plot size 200 m x 200 m, ignition line 175 m. Wind speed at 2 m was measured at the four corners of the plot.

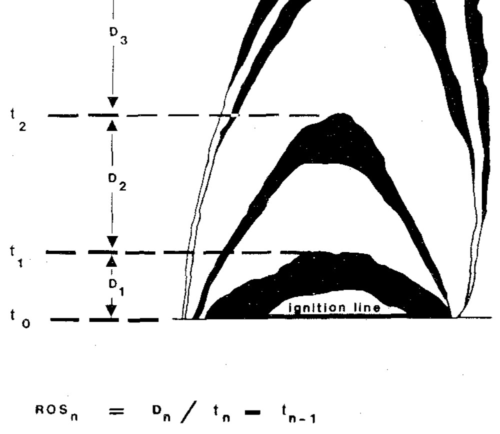

Figure 5. Composite map of time isopleths of fire perimeter and flame depth for experimental fire C064. At time t_2 the fire has developed a pointed front. This shape was not sustained and at time t_3 and t_4 the fire has a typical parabolic front. This fire was classified as 'parabolic' for head fire shape.

Weather Variables

A meteorological station was located near the centre of the study area. Wind speed and air temperature were measured at 10 m and 2 m. Air temperature, relative humidity and solar radiation were measured at 1.4 m. Additional measurements of wind speed at 10 m and 2 m were taken in an open area immediately upwind and within 800 m of the fires that were burnt each day.

During each fire, winds at 2 m were measured with a sensitive cup anemometer at each corner of the experimental plot. The wind speeds were recorded on pre-synchronised data loggers at 5-second intervals. There was considerable spatial and temporal variation of wind speed over the plot during the course of the fire as illustrated in Figure 6.

The 2 m wind measurements were averaged over the period of each fire perimeter time isopleth. These data were examined together with the oblique photographs of the fire-spread to select anemometers that best represented the wind-field driving the fire. Data were not included in the analysis if the wind recorded by an anemometer was influenced by trees, firefighting vehicles (inadvertently parked nearby) or the approaching fire front. On most fires there was no obvious relationship between the average wind speed at individual anemometers and fire-spread between individual time isopleths so the data from all unimpeded anemom-

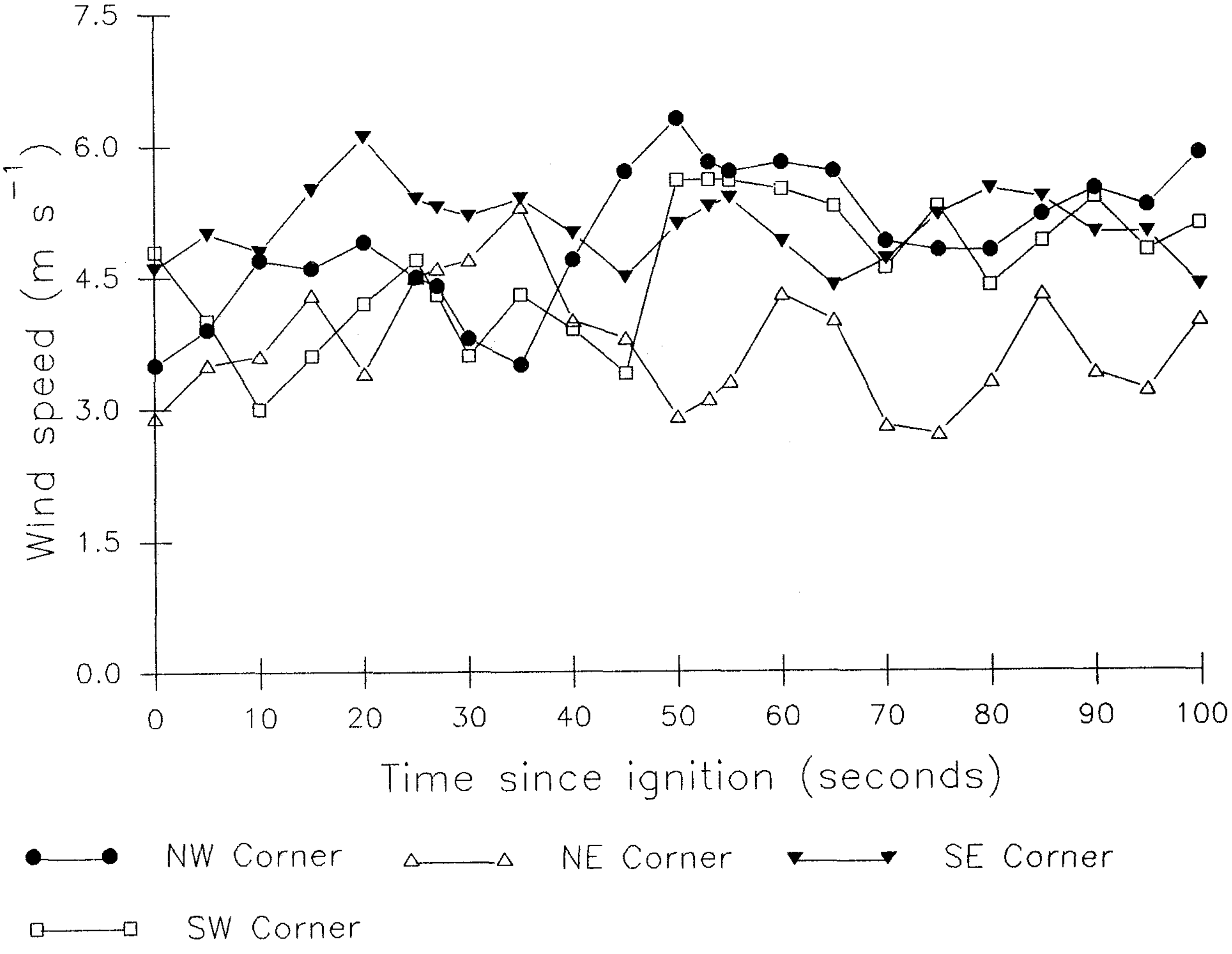

Figure 6. Wind speed measured at the four plot corners over the duration of experimental fire C064.

eters were pooled to provide an average wind speed across the plot for the period used to define the average rate of spread measurement.

Fuel Moisture Content

Two samples of fuel moisture content of fully cured grasses were taken in fuels in, or close to, each experimental plot before and after the fire. Samples were oven dried at 104°C for 24 hours and the fuel moisture expressed as a fraction of oven dried weight. The mean of these four values was calculated to provide a single fuel moisture content value for each experimental fire. Degree of grass curing on each block was determined by ocular estimates.

Results

A list of symbols for variables used in this section is given in Table 2.

More than 30 mm of rain fell on 27 July, 3 days before the scheduled burning program. This rainfall was quite unseasonal (Anon 1986) and added the additional (and unplanned) factor of curing state to the experiments.

Short green shoots appeared below the old fully cured *Eriachne* in the later stages of the experiments. These green shoots did not grow up throughout the body of the grass and were not included in the assessment of curing of the *Eriachne* grass type.

A noticeable amount of green shoot appeared within the tussocks of the perennial Kangaroo grass (*Themeda australis*). This green material was treated by assuming the grass was partially cured (see Luke and McArthur 1978 for discussion on grass curing) and an ocular estimate was made of the fraction of dry material making up the sward.

The surface area-to-volume ratio (σ) for undisturbed pasture was: *Eriachne* 97.7 cm^{-1}; *Themeda* 122.4 cm^{-1}. We did not attempt to measure σ for the treatments where the fuel was harvested and removed

Table 2. Symbols for variables used in analysis of firespread data.

Symbols	Variable
R	Average forward rate of spread (m s^{-1})
U_2	Wind speed at 2 m (m s^{-1})
M_f	Dead fuel moisture content (percent)
M_{fp}	Predicted fuel moisture content (percent)
T	Temperature (°C)
RH	Relative humidity (%)
CC	Cloud cover (percent)
σ	Surface-area-to-volume ratio (cm^{-1})
h	Fuel height (m)
w	Fuel load (t ha^{-1})
ρ	Bulk density (kg m^{-3})
C	Degree of grass curing (percent)
L_{ig}	Effective ignition line length (m)
GT	Grass type: ER - *Eriachne*, TH - *Themeda*
N/C	Natural grass/cut grass
TR	Treatment: Natural, cut and returned and cut and removed
FD	Fire day: number of days since first fire (number of days since rain = FD + 3)
HFS	Head fire shape: Pointed, parabolic

and we assigned these treatments the σ value for the respective species.

The fuel treatments changed the fuel bed characteristics of the two grasses in different ways. Cutting and returning the fuel (E2, T2) reduced the height of the grasses and increased the bulk density. The change of bulk density was greatest in the *Themeda* (Figure 7). Cutting and removing the fuel (E3, T3) reduced the fuel load of the *Eriachne* swards but did not reduce the average or range of fuel loads in the *Themeda* (the average fuel load of the T3 treatments was slightly higher than the T1 treatments). This is a reflection of the variability of the *Themeda* fuel loads through the experimental area, and the structure of the two swards. The *Themeda* has the bulk of the grass near the base and cutting at 25% of the grass height and removing the relatively sparse upper stems and leaves did not remove sufficient fuel from the T3 plots to reduce the average fuel loads, below the lighter T1 plots.

The harvesting increased the average bulk density of both the grass types but there were only small differences between blocks where the cut fuels were removed and where the cut fuels remained. This was partly due to additional compaction from the wheels of the harvester. In general, the range of bulk densities was greater where the fuels were cut and remained on the block (Figure 7).

The mean values of the observed rate of forward spread and the environmental variables for each fuel treatment are presented in Table 3[2]. Fires were burnt between 1100 hours and 1500 hours to reduce the variation of weather variables. While the mean values of temperature and relative humidity were similar for each treatment the range of weather variables between individual fires was quite large.

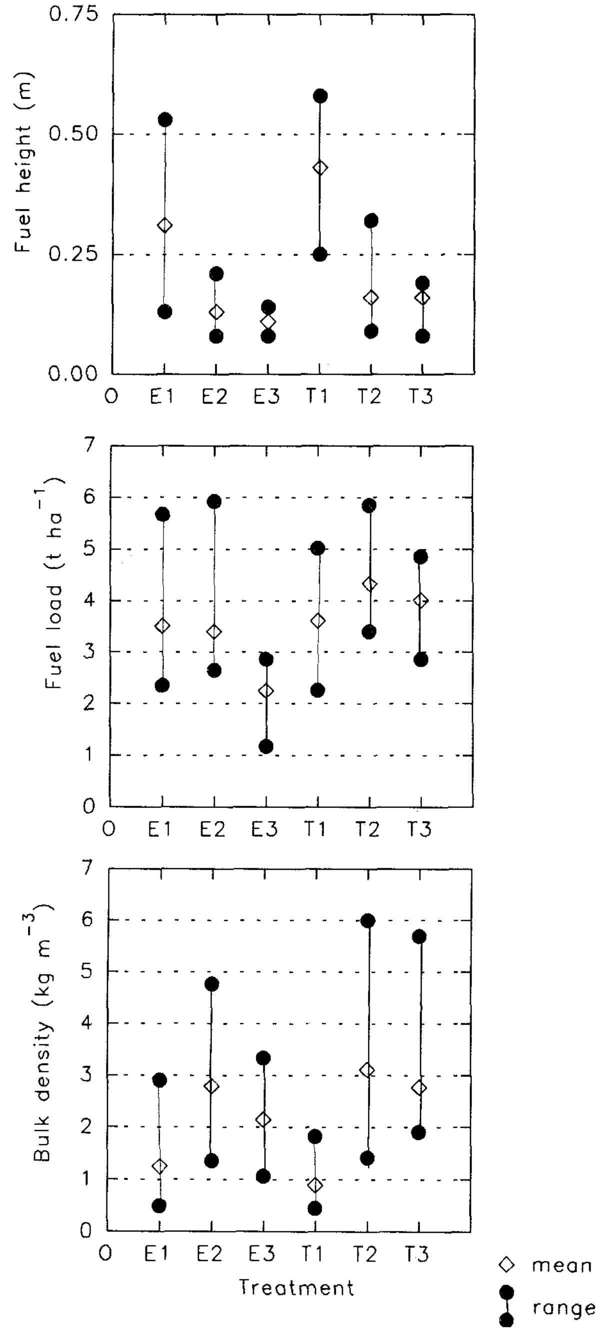

Figure 7. Mean and range of fuel height, load and bulk density for each treatment.

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[2] Access to the complete data set can be negotiated with the senior author.

Table 3. Mean and range of rate of forward spread and environmental variables for each fuel treatment.

Treatment (TR)		R (m s^{-1})	U_2 (m s^{-1})	T (C°)	RH (%)	Curing (%)	Cloud (%)	M_f (%)	h (m)	w (t ha^{-1})	ρ (kg m^{-3})	L_{ig} (m)
E1												
	Mean	**1.29**	**4.2**	**31**	**31**	**100**	**22.2**	**6.8**	**.31**	**3.51**	**1.25**	**97**
	Min	0.32	2.3	24	13	100	0.0	2.7	.13	2.35	0.49	33
	Max	2.07	6.7	38	55	100	87.5	10.2	.53	5.66	2.90	168
E2												
	Mean	**1.06**	**5.2**	**26**	**31**	**100**	**20.2**	**7.5**	**.13**	**3.40**	**2.79**	**52**
	Min	0.62	3.3	23	23	100	0.0	6.3	.08	2.65	1.35	36
	Max	1.66	6.9	32	36	100	75.0	9.1	.21	5.42	4.76	75
E3												
	Mean	**0.95**	**4.6**	**27**	**31**	**100**	**11.6**	**7.6**	**.11**	**2.25**	**2.15**	**50**
	Min	0.49	2.9	24	23	100	0.0	6.2	.08	1.17	1.06	34
	Max	1.32	6.2	32	38	100	62.5	9.4	.14	2.86	3.33	60
T1												
	Mean	**1.05**	**3.7**	**32**	**27**	**90**	**4.8**	**6.1**	**.43**	**3.61**	**0.89**	**69**
	Min	0.41	2.5	23	14	80	0.0	2.8	.25	2.26	0.44	39
	Max	1.88	7.1	36	38	100	37.5	10.8	.58	5.01	1.82	175
T2												
	Mean	**0.82**	**3.8**	**28**	**31**	**89**	**25.8**	**8.3**	**.16**	**4.33**	**3.11**	**48**
	Min	0.41	2.3	24	24	85	0.0	5.3	.09	3.40	1.42	34
	Max	1.95	5.9	33	45	95	75.0	12.1	.32	5.85	6.00	70
T3												
	Mean	**0.84**	**3.9**	**27**	**32**	**89**	**31.3**	**8.2**	**.16**	**4.01**	**2.77**	**50**
	Min	0.29	1.9	23	24	85	0.0	5.3	.08	2.86	1.91	46
	Max	1.34	6.3	31	45	95	75.0	12.1	.19	4.85	5.69	53

See **Table 2** for the explanation of the symbols for the variables.

At the time of the fires we observed that while the flame heights were considerably lower in the cut grass compared with flames in the uncut grass, the effect treatments had on rate of spread was not at all obvious. After ignition the fires developed into either of two distinct headfire shapes:

1. A broad parabolic shaped headfire where the flanks developed to a width that was wider than the ignition line (see Figure 5, t_3).

2. A narrow pointed headfire where the width of the fire along the flanks often did not exceed the width of the ignition line (see Figure 5, t_2).

The parabolic headfire appeared to be associated with a down-draft behind the fire front which tended to fan the flames at low angles around the broad front. The pointed head-fires appeared to be associated with an up-draft over the burnt area which restricted the lateral spread of the flanks. When the two head-fire shapes developed on fires burning simultaneously, the parabolic head-fires burnt faster than the pointed head-fires so we classified the fires by head-fire shape (HFS) and included it as a factor in the analysis.

Although we measured the physical characteristics of each treatment we also grouped the treatments as follows:

Grass Type (GT):	*Eriachne* or *Themeda.*
Natural or Cut (N/C):	Natural grass or cut grass (includes both returned and removed).
Treatment Group (TR):	Natural; cut and returned; cut and removed.

We examined the correlations between all variables (Table 4) and plotted the data to examine underlying relationships. The wind speed at 2 m (U_2) accounted for the greatest part of the variation in rate of spread (R), followed by effective ignition line length (L_{ig}).

The correlation between R and dead fuel moisture content (M_f) was not significant. This was attributed to the relatively small range of Mf during the experiments, sampling techniques, difficulties encountered in reliably drying the samples[3] and to the large effect of wind speed masking the effect of moisture content. Because there was a strong negative correlation be-

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[3] The nearest desiccators were 120 km away.

Table 4. Correlation matrix of significant fire spread variables for all fires. (See Table 2 for explanation of the symbols for the variables).

	R	U_2	M_f	T	RH	M_{fp}	GT	N/C	TR
R	1.0	0.56**	-	-	-0.45**	-0.44**	-0.28*	-0.33**	-0.30**
U_2	0.56**	1.00	0.24*	-0.32**	-	-	-0.28*	-	-
M_f	-	0.24*	1.00	-0.70**	0.45**	0.71**	-	-0.33**	0.29*
T	-	-0.32**	-0.70**	1.00	-	-0.70**	-	-0.53**	-0.48**
RH	-0.45**	-	0.45**	-	1.00	0.83**	-	-	-
M_{fp}	-0.44**	-	0.71**	-0.70**	0.83**	1.00	-	0.35**	0.32**
GT	-0.28**	-0.23*	-	-	-	-	1.00	-	-
N/C	-0.33**	-	0.33**	-0.53**	-	0.35**	-	1.00	0.91**
TR	-0.30**	-	0.29*	-0.48**	-	0.32**	-	0.91**	1.00
h	0.25*	-	-0.42**	0.66**	-0.24*	-0.54**	-	-0.78**	-0.73**
w	-	-	-	-	-	0.28*	0.35**	-	-
ρ	-0.30**	-	0.31**	-0.54**	0.27**	0.50**	-	0.68**	0.54**
C	0.24*	0.31**	-	-	-	-	-0.85**	-	-
CC	-0.29*	-	0.28*	-	0.72**	0.53**	-	-	-
L_{ig}	0.49**	-	-0.30**	0.56**	-	-0.38**	-0.27*	-0.51**	-0.47**
HFS	-	-	-0.23*	-	-	-	-	-	-
FD	-	-0.34**	-0.55**	0.90**	-	-0.51**	-	-0.45**	-0.43**

	h	w	ρ	C	CC	L_{ig}	HFS	FD
R	0.23*	-	-0.30**	0.24*	-0.29*	0.49**	-	-
U_2	-	-	-	0.31**	-	-	-	-0.34**
M_f	-0.43**	-	0.31**	-	0.28*	-0.30**	-0.23*	-0.55**
T	0.66**	-	-0.54**	-	-	0.56**	-	0.90**
RH	-0.24*	-	0.27*	-	0.72**	-	-	-
M_{fp}	-0.54**	0.28*	0.50**	-	0.53**	-0.38**	-	-0.51**
GT	-	0.33**	-	-0.85**	-	-0.27*	-	-
N/C	-0.78**	-	0.68**	-	-	-0.51**	-	-0.45**
TR	-0.73**	-	0.54**	-	-	-0.47**	-	-0.43**
h	1.00	-	-0.76**	-	-	0.44**	-	0.60**
w	-	1.00	0.41**	-0.26*	-	-	-	-
ρ	-0.76**	0.42**	1.00	-	-	-0.36**	-	-0.45**
C	-	-0.26*	-	1.00	-	-	-	-
CC	-	-	-	-	1.00	-	-	-
L_{ig}	0.44**	-	-0.36**	-	-	1.00	-	0.48**
HFS	-	-	-	-	-	-	1.00	-
FD	0.60**	-	-0.45**	-	-	0.48**	-	1.00

* Significant at 1%
** Significant at 0.1%

tween R and relative humidity (RH) we calculated a predicted moisture content (M_{fp}) from temperature (T) and RH using the equations fitted to the McArthur Mk V grassland meter (Noble et al. 1980). M_{fp} was significantly linearly correlated with R at the 0.1% level.[4]

To reduce the effect of ignition line length in our analysis we stratified the data into fires with $L_{ig} < 75$ m and fires with $L_{ig} \geq 75$ m. The first group included all fires in the treated fuel types while in the second group all but one fire burnt in undisturbed fuels.

We examined the correlations between R and the remaining variables for all fires with $L_{ig} < 75$ m (Table 5). Now only U_2, RH and fire day (FD) were significant variables. We fitted a model to this reduced data set using logarithmic transformations of R and U_2. The untransformed form of this model is:

$$R = a\ U_2^{\ b} \qquad (5)$$

Table 5. Significant correlation co-efficients of firespread variables and rate of firespread when the effective ignition line length is < 75 m and ≥ 75 m.

Variable[1]	**R** **$L_{ig} < 75$ m**	**R** **$L_{ig} \geq 75$ m**
U_2	0.71**	0.55**
M_f	-	-0.46*
RH	-0.44**	-0.52**
M_{fp}	-	-0.51*
L_{ig}	-	0.47*
FD	-0.28*	-

[1] See Table 2 for explanation of the symbols for the variables.
* Significant at 1%
** Significant at 0.1%

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[4] The correlation matrix also illustrates significant trends as the experiment progressed; for example temperature progressively increased over the 23 day period, fuel moisture content decreased and longer ignition lines were used later in the experiments. Thus "fire day" shows significant correlations with temperature, fuel moisture, ignition line length, etc.

Table 6. The significance, expressed as p-values, of adding different variables to the following models when the effective ignition line length is < 75 m and ≥ 75 m.

Model 5: $R = a\,U_2^{b}$

Model 6: $R = a\,U_2^{b} \exp(c\,M_{fp})$

	$L_{ig} < 75$ m		$L_{ig} \geq 75$ m	
Variable[1]	**Model 5** **p**	**Model 6** **p**	**Model 5** **p**	**Model 6** **p**
M_{fp}	0.0057**	-	0.0002**	-
GT	0.6917	0.9956	0.6561	0.0201*
N/C	0.0006**	0.0035**	-†	-†
TR	0.0027**	0.0142*	-	-
h	0.0018**	0.0221*	0.1557	0.2397
w	0.9968	0.5829	0.0017**	0.0614
ρ	0.0065**	0.0657	0.0071**	0.6637
C	0.6888	0.7896	0.9656	0.1294
CC	0.3480	0.9553	0.0150*	0.2528
L_{ig}	0.1197	0.1391	0.0267*	0.0508
HFS	0.619	0.1217	0.0066**	0.0295*
FD	0.5271	0.4497	0.0109*	0.6715

[1] See Table 2 for the explanation of the symbols for the variables.

* The p-value is the probability of the correlation between the variable and ln(R) (after ln(U_2) in Model 1, and after ln(U_2) and M_{fp} in Model 2 have been allowed for) happening by chance. A p-value of less than 0.05 is equivalent to the variable having a significant effect on ln(R) at the 5% level.

** A p-value of less than 0.01 is equivalent to the variable having a significant effect on R at the 1% level.

† Only one plot had treated grass.

The predicted fuel moisture content (M_{fp}) had a significant effect on R after this model had been fitted, as did fuel height (h), fuel bed bulk density (ρ), the treatment group natural or cut (N/C) and treatment (TR) (Table 6). It is generally accepted that dead fuel moisture is a major factor determining fire-spread, so we fitted a model to the spread rate data using wind speed and predicted fuel moisture content as predictor variables, and examined the significance of the remaining variables using stepwise regression techniques (Draper and Smith 1981).

The resulting model is of the form:

$$R = aU_2^{b} \exp(cM_{fp}), \qquad (6)$$

where the constants a, b and c are 0.4539, 0.951 and -0.0966 respectively after **a** had been corrected for logarithmic transformation (Baskerville, 1971). The correlation between M_{fp} and the fuel variables which is shown in Table 4 (and is also present in the reduced data set) means that it is difficult to assess their relative effects on spread rate. Fitting the model in this way means that we are adopting the conservative approach of giving preference to moisture content in the model, so that clear evidence is needed of any effect of the fuel variables. The coefficient c of M_{fp} is close to that given in Noble et al. (1980), which gives support to this decision. The other variables were added in turn to the model (see equation 6). The significance, expressed as p-values, of adding other variables to the model is shown in Table 6. The effect of the treatments were found to be similar when fitting the TR factor, justifying the use of the N/C group. The N/C group was the most significant variable, but h and ρ also had low p-values.

After the N/C group was added to the model, none of the other variables were significant at the 10% level. The resulting fitted model had different coefficients for the two fuel groups, natural and cut grass. This model explained 66% of the variation in spread rate in the data set. The model fitted to the data for cut and uncut grass is shown in Figure 8. The average spread rate in the cut pastures was 18% less than the rate in the uncut pasture.

Examination of data for fires with $L_{ig} \geq 75$ m show that R was correlated strongly with U_2 and RH (0.1% level) and less strongly M_f, M_{fp} and L_{ig} (1% level) (see Table 5). After fitting model (6) with U_2 and M_{fp} as before, the most significant variables influencing R were the grass types (GT) (fires in *Eriachne* burnt slightly faster than fires in *Themeda*), headfire shape HFS (parabolic >pointed) and effective ignition line length (L_{ig}). The fuel bed characteristics of w,h and ρ were not significant at the 10% level after adding grass type and headfire shape to the model.

Discussion

The results of this experiment suggest there should be substantial changes in models of grassfire spread. There was no evidence that fuel load had a direct influence on spread rate as proposed by McArthur (1977).

Fuel load is easy to define and measure, but may not be a useful variable for predicting fire-spread because it combines the two variables fuel height, and fuel bulk density. Laboratory studies (e.g. Rothermel 1972; Carrier et al. 1991b) suggest that h and ρ may have counter-acting effects when combined as fuel load. When ρ is constant Rothermel (1972) suggests that fire-spread will increase with increasing h and therefore with increasing w; when height is constant fire-spread will decrease with increasing w (ρ), at least within the range of these variables expected in natural fuel beds.

Although fuel height (h) and fuel bed bulk density (ρ) were significant variables affecting R after fitting U_2 and M_{fp} when the fuel bed had been manipulated by cutting and fuel removal (i.e. fires where $L_{ig} < 75$ m), they were not significant when examined in the natural grasses alone (i.e. fires with $L_{ig} \geq 75$ m) even though

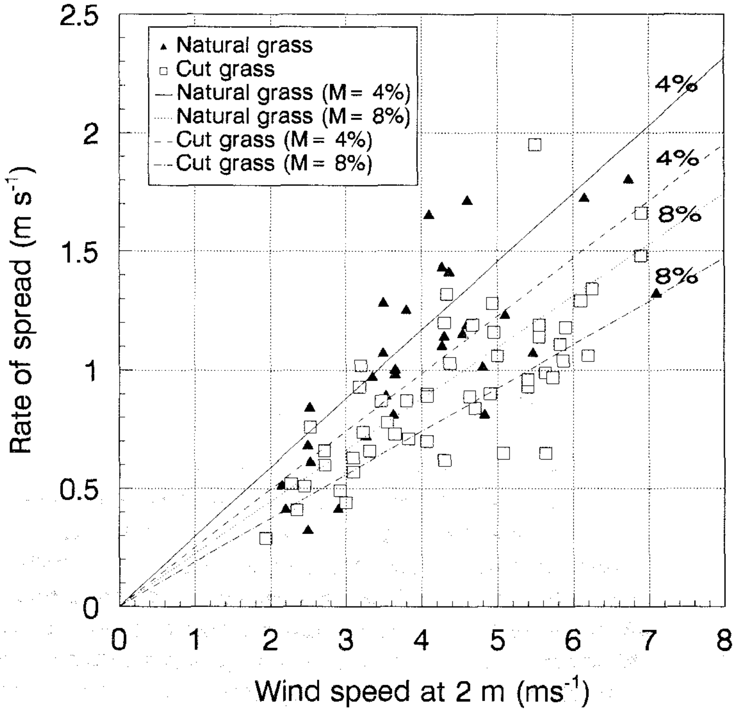

Figure 8. Relationship between rate of spread (R) and wind speed (U_2) for natural and cut grass, at dead fuel moisture content (M_f) of 4% and 8% and ignition line < 75 m.

$R = a\,U_2^{0.987} \exp(-0.0707\,M_f)$ ($r^2 = 0.66$)
For natural grass $a = 0.406$
For cut grass $a = 0.343$

the range of fuel height was comparable between the two groups. This result suggests that measurements of either fuel height or bulk density do not fully account for the change in fire-spread in harvested pasture compared to an undisturbed pasture.

Although the two grasses had very different fuel bed structures and different σ values, grass type was not a significant variable when L_{ig} < 75 m; possibly because of the complicated effect of the treatments. When L_{ig} > 75 m the coarse stemmed *Eriachne sp.* burnt slightly faster than the fine stemmed *Themeda australis*, a result which was in the opposite direction to that suggested by other models (e.g. Rothermel 1972); i.e. that fires in fine stemmed grasses spread faster than fires in coarse stemmed grasses. Although curing was not a significant variable we suggest that this difference in spread rate may be because the *Themeda* was generally less than 100% cured while the *Eriachne* was 100% cured. Observations by the senior author (N.P. Cheney) on fires elsewhere in the N.T. were that there were no obvious changes in fire-spread when fires burned from tall, course annual sorghums (*Sorghum intrans*) to fine-stemmed swamp grasses although there were large differences in flame characteristics. Because there are the practical difficulties in measuring σ for individual pastures, and because the influence of σ on rate of spread of grassfires appears to be negligible under the field conditions, we consider that, in Australia at least, the species type can be ignored when grasses are continuous.

Hummock grasslands which do not form a continuous sward will require a separate model (e.g. Griffin and Allan 1984; Burrows and van Didden 1991) but this is because the fuel bed is discontinuous rather than because of the thickness of the component particles.

There was no evidence to suggest that it is valid to use σ to adjust the exponent of the wind function for different fuel types. The exponent b in the model $R \propto aU^b$ remained just less than 1.0 in all analyses. This is considerably different to the functions proposed by McArthur (1966), where b = 2, or by Rothermel (1972) where b could be assigned a value between 1.56 and 2.22 depending on the surface-area-to-volume ratio of the grass. It is possible that the fastest moving fires had not truly reached a pseudo-steady-state rate of spread in the time available for measurement and that measurements of R at higher wind speeds may be lower than may be achieved on free burning fires. The form of the wind function needs to be verified by comparing our data with data from large fires burning under wind speeds greater than 8 ms^{-1}.

These data suggest that a model to predict fire-spread for annual or perennial short grasslands does not need to include measurements of the fuel bed, which can be difficult to define (e.g. see Sneeuwjagt 1974) and spatially very variable. Rather it should be sufficient to separate the fuel bed into two classes:

1. natural undisturbed pasture, and
2. cut, mown, grazed or trampled pastures where the bulk of fuel is within 10 cm of the surface.

We would expect the rate of spread in cut or grazed pastures to be around 18% slower than the undisturbed pastures. Fires are likely to spread even more slowly in heavily grazed pastures if the fuel bed is discontinuous with bare patches or animal tracks to interrupt fire-spread. This would be consistent with the observations of Davis (1949) who reported that fires spread 3 times faster in a lightly grazed pasture than a heavily grazed pasture but did not specify the precise condition of the fuel bed.

The degree of grass curing is known to have an influence on fire-spread but at no time in the analysis was curing identified as a significant variable even though ocular estimates of curing ranged from 85% to 100%. The relationships used by McArthur (1966, 1977) reduce the rate of spread by around 44% when curing is changed from 100% to 85%, and produce the greatest rate of change in the predicted spread rate when the curing fraction approaches 100%. We have observed elsewhere that several grasses (e.g. *Sorgum intrans*, *Themeda australis*, *Poa sp.*) do not support a moving fire when the curing is around 50%. We suggest that the function relating R to curing be modified to a sigmoid function between 50% and 100% so that the greatest change in predicted spread rate does not occur as pastures approach the fully cured state.

It is worth noting the strong impact of effective ignition line length on rate of spread in relatively large plots. Effective ignition line length was an unplanned variable which changed accidentally and somewhat haphazardly (eg by wind changes) throughout the experiment so that is was coincidently associated with fire day. However, effective ignition line length remained significant after the effect of moisture content had been accounted for and, towards the end of the experiments, we burnt simultaneous fires with different ignition line lengths (point, 50, 100 and 150 m) which produced a similar results to that from data pooled from the overall experiment. Models developed from experimental fires which have not been allowed to burn to a substantial size (headfire width > 100 m) are likely to under predict the spread rates of wildfires, particularly at higher wind speeds.

We also noted that during simultaneous fires, those fires which developed a narrow pointed head burnt slower than those which developed a wide parabolic head under the same wind speed as measured on the perimeter of the block. This feature was not identified as a highly significant variable in the analysis but it does illustrate a major problem of carrying out field verification of fire-spread models. The wind speed influencing the fire is that blowing directly through the flame zone while any measurement of wind speed must be made remotely from the fire. In these experiments we noted considerable spatial and temporal variation of wind speed at the edges of 100 m x 100 m blocks (e.g. Figure 6) which at times did not reflect the winds influencing the fire behaviour in the centre of the block. Fire-spread measurements will thus show considerable variation when related to wind speed from a single, remote anemometer. Measurements of average fire-spread and average wind speed over a longer time interval of 15 to 30 minutes, say on wildfires, may provide a more precise relationship between R and U than can be obtained on small plots provided the anemometer is close enough to give a measurement which is representative of the wind field over fire area.

Conclusions

The rate of fire-spread in fully cured grasslands was primarily dependent on wind speed, dead fuel moisture content and whether or not the pastures had been closely cut. Fires in natural undistrubed pastures spread 18% faster than fires in cut pastures. Fuel load did not influence fire-spread although it may influence other fire behaviour characteristics such as fire intensity. Grass height and fuel bed bulk density had a statistically significant but small influence on spread rate when fires in treated pastures were compared with fires in natural grass. They did not have a significant influence on fires in natural grasses alone, although any influence may have been masked by other variables. These fuel factors do not warrant inclusion in a practical grassland fire-spread model for field use because they can be accounted for by separating continuous grassland fuels into two types: natural undisturbed pastures; and, pastures which have been cut or grazed. These results should be compared with spread rates on wildfires in comparable fuel types.

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