Prediction of Fire Spread in Grasslands

Article *in* International Journal of Wildland Fire · March 1998

DOI: 10.1071/WF9980001

James S. Gould
The Commonwealth Scientific and Industrial Research Organisation

Wendy Anderson
Australian Defence Force Academy

Int. J. Wildland Fire 8(1):1-13, 1998

Prediction of Fire Spread in Grasslands

N. P. Cheney[1], J. S. Gould[1], and W. R. Catchpole[2]

[1]*CSIRO Forestry and Forest Products, PO Box E4008, Kingston, ACT, 2604, Australia.*
Tel. +612.6281.8379; Fax +612.6281.8348
Email:phil.cheney@ffp.csiro.au; jim.gould@ffp.csiro.au
[2]*School of Mathematics and Statistics, University College,*
University of New South Wales, Canberra, ACT, 2600, Australia.
Tel. +612.6268.8890; Fax +612.6268.886; Email: w_catchpole@adfa.oz.au

Abstract. This paper describes a model to predict fire spread in grasslands from wind speed at 10 m, dead fuel moisture, and degree of grass curing in three defined pasture types.

The model was developed from spread measurements of experimental fires that were adjusted to their potential rate of spread at wide fronts. Extrapolations of the model were compared with spread data from 20 major wildfires in Australia.

This model uses different functions to describe the relationship between rate of spread and wind speed above and below a critical wind speed of 5 km h^{-1}. A linear relationship is used below 5 km h^{-1} ; above 5 km h^{-1} rate of spread is described by a power function of wind speed with an exponent of less than 1.

Introduction

The McArthur grassland fire danger meters (McArthur 1966, 1977 (a), 1977 (b)) have been widely used in Australia to describe the effect of weather and fuel variables on grass fire spread. The Mk IV meter (McArthur 1973) has been accepted by the Bureau of Meteorology and most State Fire Authorities in Australia as the basis for predicting grassland fire danger (Cheney et al. 1991) and the fire spread equations (Noble et al. 1980) have been incorporated into the grassland fire spread module of the Canadian Fire Danger Rating System (Forestry Canada Fire Danger Group 1992).

The relationship between the rate of spread of the head fire, dead fuel moisture content and wind speed was first published in tabular form (McArthur 1960) and later converted into a circular slide rule (Mk III) with very minor modifications (McArthur 1966). The tables were based on well documented wildfires with some assistance from the results of controlled experimental fires (Luke and McArthur 1978) but the data were not published nor retained on file.

When tested on wildfires that complied with the conditions for predicting fire spread in the field the Mk III meter (or its metric version Mk IV) appeared to predict reasonably well on some wildfires (McArthur 1966, Noble 1991) but not on others (McArthur 1977a, McArthur et al. 1982).

McArthur (1977a) attributed poor predictions to the wind speed function used in the MkIV meter and to the omission of the fuel load as a predictor variable: the wind speed function was changed in the Mk V meter (McArthur 1977b) and a function relating fire spread directly to fuel load was incorporated.

There are conflicting reports on the influence of fuel load on the spread of wildfires in grasslands: on some fires it was considered that fire spread was directly proportional to fuel load (McArthur 1960, 1962, Luke and McArthur 1978, McArthur et al. 1982) while on several large grass fires near Geelong, Victoria it was noted that fires in very fine grasses estimated to be not more than 1 ton per acre ($\simeq$2.5 t ha^{-1}) spread as rapidly as fires in coarser but heavier pastures (McArthur 1964). This observation was attributed to the effects of fuel coarseness and fuel load cancelling each other (Luke and McArthur 1978).

In an extensive field study of the effect of fuel characteristics on fire spread (Cheney et al. 1993) we found that, in continuous pastures, neither fuel load nor grass species (of different coarseness and mean surface-area-to-volume ratio) had a significant effect on rate of spread. We concluded that, for a practical grassland fire spread model for field use, the influence of fuel variables could be accounted for by separating grassland fuels into two types: 1. natural undisturbed pastures; and 2. pastures which have been cut short or grazed.

The aim of this work was to develop a model for fire spread in continuous grasslands and compare the predictions of this model with the spread rates of a number of wildfires. The model was based on data from experimental fires but required a number of logical assumptions to predict fire spread beyond the range of the data.

Wildfire Data

Collection of good data on the spread of wildfires is not easy and rarely are recommended field procedures (eg see Rothermel and Rinehart 1983) possible. We have reviewed data on wildfire spread from the published literature and our own files and have selected 24 spread periods from 20 wildfires to compare predictions of a new fire spread model. Each fire was assessed to ensure the observations complied with the same criteria for applying a model to predict fire spread across the landscape. ie:

- the fuels were predominantly open grasslands with only scattered trees.
- the grasses were continuous
- the grasses were fully cured (with one exception)
- the fire travelled over level or generally undulating terrain
- the headfire burnt freely without obvious checking or restriction in its width.

The fire spread data, prevailing weather conditions and fuel description are set out in Table 1. We assigned the fuels to one of three pasture types: 1 = undisturbed, ungrazed pastures; 2 = cut or grazed pastures, including crop stubble; and, 3 = eaten-out or very heavily grazed and discontinuous pastures. Wherever possible we selected the longest period of fire spread compatible with the average wind speed data.

Information on the pasture type was often sketchy or no details were provided. In most pastoral areas of south-eastern Australia grasslands are normally well grazed by January; where there were no specific details or photographs of the fuel we assigned the fire to pasture type 2 (grazed). The Boonoke fire was the only fire that we could confidently classify as burning through undisturbed, ungrazed pastures. Boonoke station was very lightly stocked (J Noble pers. comm) and natural grazing pressures were low. Three fires were described as burning through eaten-out pastures. Photographs taken after the fires indicated that adjacent unburnt pastures were very heavily grazed and discontinuous. Fire maps indicated that spread on the flanks had been held up by roads and tracks and, in places, the fire had broken into fingers which subsequently went out. These fires were assigned to a third pasture type "eaten-out".

One or other of the authors made direct observations on 3 of the wildfires and recorded wind speeds close to

Table 1. Average rate of spread and weather conditions from major grassland wildfires in south-eastern Australia between 1965 and 1990.

Name of fire	REF([a])	ID	Date	Time Interval	10 m open windspeed km/h	Temp °C	RH %	Curing %	Rate of Spread km/h	Fuel Type	Pasture([b]) Type	Reliability([c]) MET/ROS
Purra-Purra	1	PI	12.02.77	1300-1500	50.5	35	20	100	12.6	Heavy pastures	2	3/4
		P2	12.02.77	1500-1530	43	35	20	100	10.6	Lighter pastures	2	3/4
Tatyoon-Streatham	1	T1	12.02.77	1400-1500	48.5	35	20	100	17.8	Heavy pastures - stubbles	2	3/5
		T2	12.02.77	1500-1600	44	35	20	100	7.5	Lighter pastures	2	4/5
Wallinduc	1	WA	12.02.77	1332-1500	49.5	35	20	100	16.0	Heavy pastures - stubbles	2	3/4
Cresswick	1	CK	12.02.77	1320-1520	42.5	35	20	100	5.0	Eaten out pastures	3	3/4
Strathmore	1	S1	12.02.77	1300-1400	50	35	20	100	10.6	Light pastures	2	3/4
		S2	12.02.77	1400-1500	45	35	20	100	4.5	Eaten out pastures	3	3/5
Penhurst	1	PH	12.02.77	1305-1440	41.3	35	20	100	7.4	Average pastures	2	3/5
Binalong	2	BI	18.12.90	1515-1924	27	37	16	100	4.0	Light pastures	2	1/1
Junee	2	JU	03.01.90	1540-1855	37	40	12	100	11.4	Pasture - stubbles	2	1/1
Hall	2	H1	13.02.79	1551-1645	37	36	13	100	7.7	Light pasture	2	1/1
		H2		1701-1735	33	36	13	100	7.4	Light pasture	2	1/1
Deans Marsh	3/6	DM	16.02.83	1515-1530	50	40	8	100	22	Light pastures	2	5/5
Narraweena	4	NA	16.02.83	1210-1600	53	40	10	100	17	Lighter pastures	2	2/3
Boonoke	5	BO	16.01.87	1320-2100	47	41	7	100	23	Tall pastures	1	2/2
Cudgee	6	CU	16.02.83	1427-1800	45	43	8	100	5.8	Light eaten out pastures	3	3/4
Ballangeich	6	BA	16.02.83	1318-1800	45	43	8	100	8.5	Light pastures	2	3/4
Anakie	7	AL	14.01.85	1310-1410	35	41	8	100	7.9	Average pastures	2	3/4
Melton	7	ME	14.01.85	1812-1830	55	40	7	100	15.5	Pasture - stubbles	2	3/4
Longwood	8	LO	17.01.65	1155-1428	41	34	13	100	8.8	No details	2	1/3
Lara	9/8	LA	09.01.69	0950-1050	78	40	11	80	8.0	Average pasture	2	1/4
Clare	10	CL	21.02.65	1355-1455	32	40	10	100	6.5	No details	2	4/4
Murdinga	10	MU	23.11.69	1100-1200	35	38	8	100	6.7	No details	2	4/4

([a]) 1. McArthur et al. (1982). 2. Direct observation by authors. 3. Rawson et al. (1983). 4. Keeves and Douglas (1983). 5. Noble (1991). 6. Anon. (1983). 7. Maynes and Garvey (1985). 8. McArthur (1966). 9. Finocchiaro et al. (1970). 10. Douglas (1970).

([b]) 1 = undisturbed ungrazed pastures; 2 = cut or grazed pastures; 3 = eaten-out pastures.

([c]) See Table 2

the fire. On other fires the information on both the fire spread and wind speed was less reliable. We gave each fire a rating between 1 (very good) and 5 (poor) for the reliability of both wind speed (MET) and fire spread (ROS) observations according to the criteria set out in Table 2.

Data of fire spread from wildfires at high wind speeds were not used in the construction of the fire spread model but were used to compare with extrapolations beyond the range of the experimental data.

Fire Spread Model

Because there is no satisfactory physical model of fire spread (Catchpole and de Mestre 1986) and because a purely statistical treatment of fire spread can be misleading beyond the range of the data we developed an empirical model of grass fire spread for field use based on the field data from the Annabarroo experiments (described in Cheney et al. 1993; Cheney and Gould 1995) and other qualitative and quantitative field observations.

Rate of spread in grasslands depends on the initial growth of the fire, the pasture type, wind speed, and live and dead fuel moisture. A practical model to predict rate of spread after the fire has completed its growth phase[1] can be written:

$$R_{ss} = f(i, U_{10}, M_f, C) \qquad (1)$$

where R_{ss} = the potential quasi-steady rate of spread
i = pasture type
U_{10} = mean wind speed at 10 m in the open - the standard exposure for wind measures in Australia.
M_f = moisture content of dead grass
C = curing stage of the grass.

Table 2. Reliability rating for weather and fire spread observations from grassland wildfire reports.

Rating	Weather (MET)	Fire Spread (ROS)
1.	Nearby meteorological station or direct measurements in the field.	Direct timing of fire spread measurements by authors.
2.	Meteorological station within 50 km of the fire.	Reliable timing of fire spread by a third party.
3.	Meteorological station > 50 km, reconstruction of windspeed for fire site.	Reconstruction of fire spread with numerous cross references to third party observations.
4.	Spot meteorological observation near the fire.	Doubtful reconstruction of fire spread.
5.	Distant metrological observations at locations very different to fire site.	Anecdotal or conflicting reports of fire spread.

[1]For discussion of fire growth see Cheney and Gould (1997).

The steps we used to build the model were to: adjust the experimental data to the potential quasi-steady value; develop wind functions from these data in different pastures at constant M_f and C; and, develop the functions describing the effects of M_f and C.

Adjustment of experimental data

The rate of spread (R) measured on experimental grass fires may be less than the potential quasi-steady rate of spread (R_{ss}) under constant conditions depending on the effective width of the fire front (W) and can be described by the model:

$$R = R_{ss}\, e^{-b/w} \qquad (2)$$

where b is a constant.

Cheney and Gould (1995) found that both R_{ss} and the exponent b were dependent on the wind speed at 2 m (U_2). We plotted the data for open grasslands, given in Table 3 of Cheney and Gould (1995), in Figure 1. If we assume R_{ss} and b to have a linear relationship with U_2 we can rewrite equation 2 as:

$$R = (n + m\, U_2)\ \exp\,[(p + q\, U_2)\,/W] \qquad (3)$$

Where n, m, p and q are constants.

A multiplier for dead fuel moisture of the form exp $(-k\, M_f)$ is included in equation 3 to model the effect of moisture content. This is the same form as the function used to describe the effects of moisture content in Cheney et al. (1993). The constants n, m, p, q and k were estimated by non-linear regression techniques (Meyers 1989, Norusis 1992) using the experimental data described by Cheney et al. (1993) and Cheney and Gould (1995) for open grasslands. Equation 3 including the effect of fuel moisture then becomes.

$$R = (0.165 + 0.534\, U_2)\ \exp\,[(-0.859 - 2.036\, U_2)\ /\ W]\ .\ \exp\,(-0.108\, M_f) \qquad (4)$$

where the units for R, U_2, W and M_f are m s^{-1}, m s^{-1}, m, and percent oven dry weight.

The value for k (-0.108) differs slightly from that obtained by analysis of a sub-set of uncorrected data (eg Cheney et al. 1993).

Equation 4 can provide a general fire growth model to scale the experimental fires to their potential quasi-steady rate of spread for a range of wind speeds, fuel moisture, and effective head fire widths. Thus to correct the field experimental data to potential quasi-steady rate of spread at common fuel moisture content of zero percent we can use the ratio:

$$R_{ss}/R = 1/\{\exp\,[(-0.859 - 2.036\, U_2)\,/W]\ .\ \exp\,(-0.108\, M_f)\} \qquad (5)$$

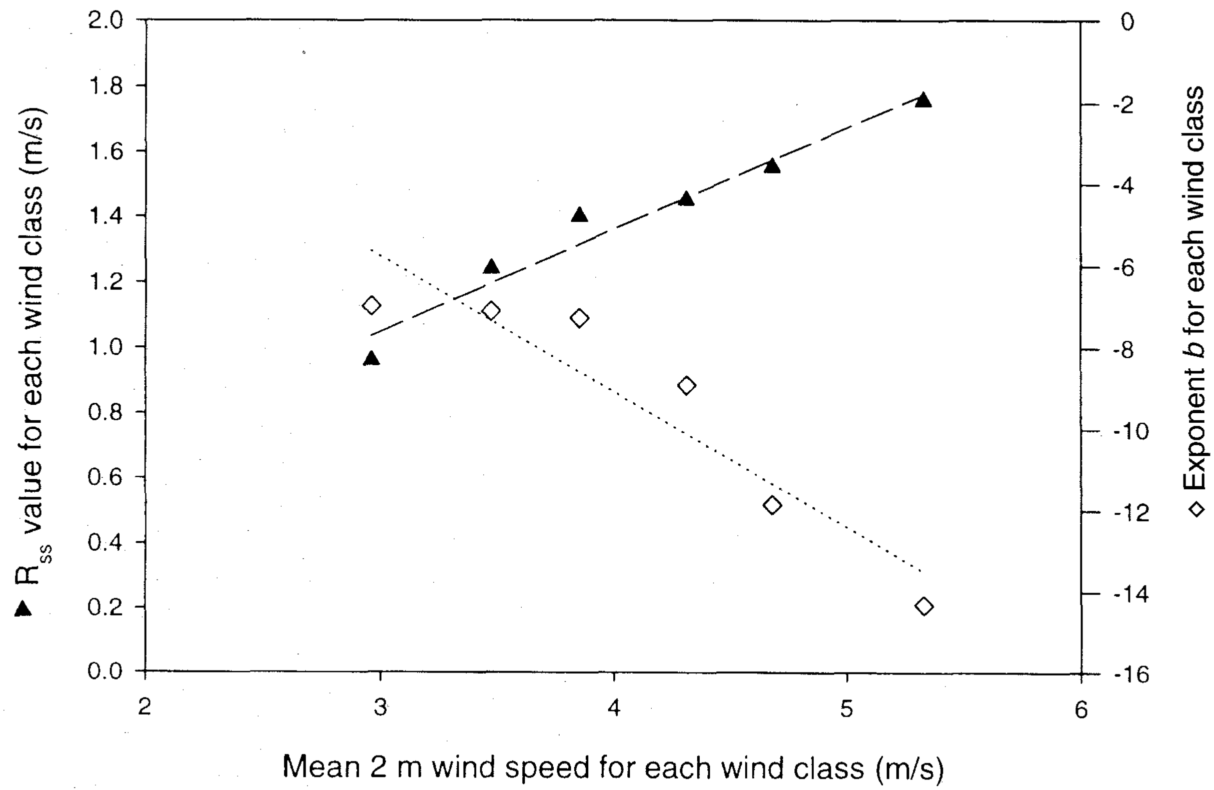


Figure 1. The quasi-steady rate of spread (R_{ss}) at 5.4 percent dead fuel moisture content (▲) and the b value in the exponent function $e^{-b/W}$ (◊) of the fire growth model for each wind class in open grasslands (Cheney and Gould 1995).

Wildfires were assumed to be spreading at their potential spread rate (ie $W \rightarrow \infty$) but these data were also corrected to a common fuel moisture using the fuel moisture multiplier given in equation 4.

Rate of spread - wind speed function

Wind speed (U) is the one variable for which the relationship with spread rate must be extrapolated beyond the range of experimental data to produce a model that predicts fire spread under extreme conditions.

A power function has been fitted to rate of spread data derived from laboratory studies of wind driven fires in different fuel arrays but the value of the exponent is quite inconsistent: some studies have an exponent of less than one (e.g. Thomas & Pickford 1961; Wolff et al. 1991) while in others it is suggested that the exponent is greater than one (e.g. Fons 1946; Anderson and Rothermel 1965; Rothermel, 1972) and may be assigned a value as high as 3 (Beer 1993).

A linear relationship between rate of spread (R) and wind speed (U) was recommended for small fires in Ponderosa pine (*P. ponderosa*) needles (Curry and Fons 1938) and for low-intensity prescribed fires in slash pine (*P. elliotii*) needles (Anon 1976). Most Australian fire behaviour guides, however, use a function $R \propto U^n$ where $n > 1$ for both forests and grasslands (e.g. Peet 1965, McArthur 1966, 1967).

Fons (1946) and Beer (1991, 1993, 1995) suggested that different functions should be used to describe the relationship between R and U above and below a critical wind speed (U_c). Fons (1946) suggested that this value was around 2.2. m s^{-1} measured at 0.3 m (1 foot) above the fuel bed, while Beer (1991, 1993) suggested a value around 2.5 m s^{-1}. To develop functions between R and U, we need to define the rate of spread at zero wind speed (R_0), the critical wind speed U_c and the rate of spread at the critical wind speed (R_c) for fires burning in continuous grasslands.

Completely calm conditions rarely exist in the field. When they do, fires are restrained to some degree by the convection behind the leading edge and are circular backing fires. Therefore, we have adopted the backing rate of spread for grass fires (see Figure 2) as the rate of spread at zero wind speed (R_0). In this data set wind speed at 2 m (U_2) was not a significant variable although the range of U_2 was from 0.5 to 4 m s^{-1}.

In the field, the transition from a backing fire to a heading fire is unstable and complicated by thermal activity. When wind speeds at 10 m (U_{10}) are less than 5 km h^{-1} they are aptly described as light and variable and fires progress erratically both in speed and direction as they

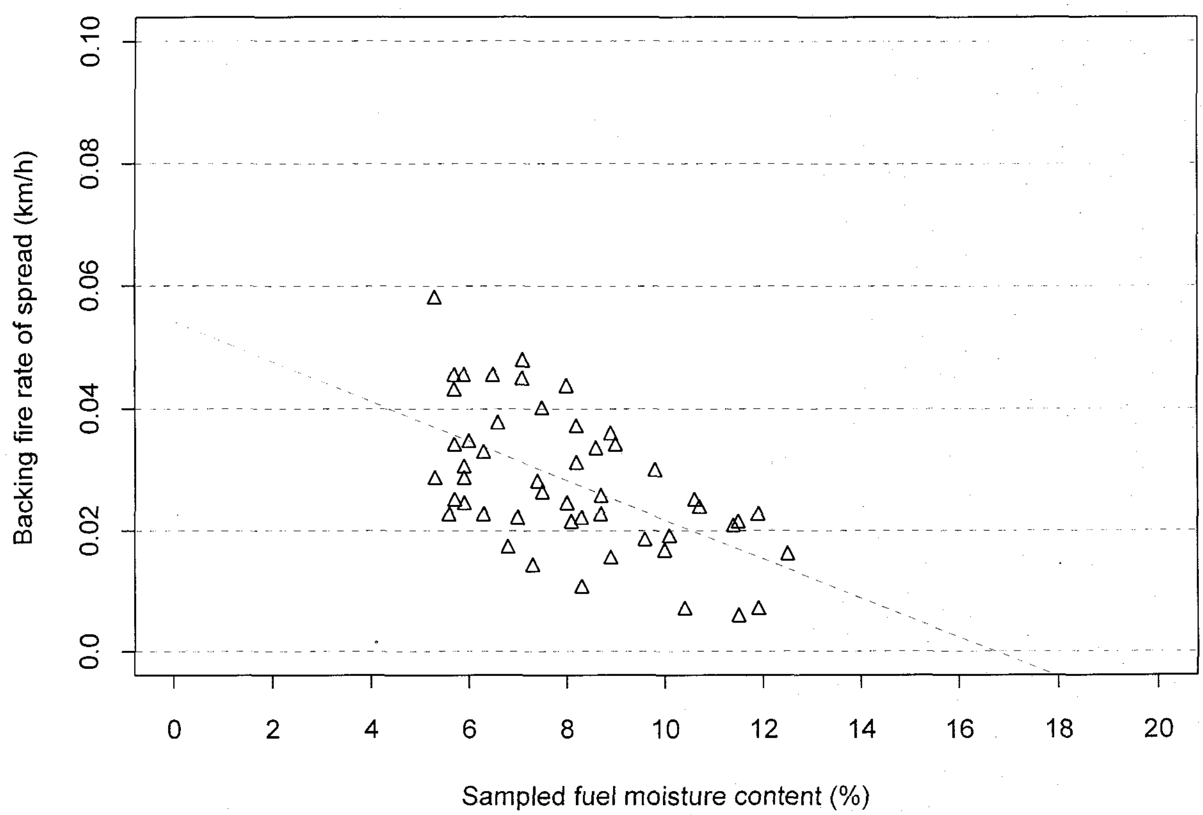


Figure 2. Backing fire rates of spread (R_b) at different fuel moisture contents (M_f). R_b was adopted as the rate of spread at zero wind speed (R_o). (·············R_b= 0.054 - 0.0032M_f).

respond to gusts and lulls caused by thermal activity. Under these conditions we could not obtain reliable correlations between head fire spread and wind speed at 2 m anemometers located near the fire. Often the wind affecting the head fires was quite different from that recorded at the anemometer depending on passage of gusts and lulls over the site. At times a head fire was observed to progress quite rapidly under the influence of a local puff while the wind recorded at the anemometer site was calm or even in the opposite direction to the direction of fire spread.

During our experiments, we obtained consistent head fire spread only when $U_{10} > 5$ km h^{-1}. Similar results were obtained by Sneeuwjagt and Fransden (1977). We adjusted spread measurements to potential rate of spread at M_f = 3% and windspeeds to the value at 10 m (U_{10}). A scattergram of experimental data and wildfire observations is presented in Figure 3.

Experimental data obtained by Sneeuwjagt and Fransden were generally lower than our experimental data and because we were uncertain of the measurement techniques used and the stage of development of the headfire (based on the descriptions of the fires, we assumed W = 20 m for this comparison) we did not use their data in further analysis. Nevertheless these data do suggest that $U_{10} > 5$ km h^{-1} is required for a consistently heading fire and that a power function relationship between R and U would have an exponent < 1 when U_{10} is between 5 and 35 km h^{-1}.

Thus for the development of our model we have defined U_c as 5 km h^{-1} at 10 m. We have assigned R_c the values of 1.4 km h^{-1} in natural pastures and 1.1 km h^{-1} in cut pastures at fuel moisture content of 0 percent after examining alternative functions to fit the data set and the relationships between R and U on individual fires when adjusted to zero moisture. We have defined R_o as 0.054 km h^{-1} for both pasture types by extrapolation of data for backing fires (Figure 2).

We have assumed a linear relationship between R and U for $U < U_c$ and a power function between R and U for U > Uc. The proposed models for predicting rate of spread below and above the threshold wind speed are:

$$R_{ss} = (R_o + a_i\,U_{10}) \,.\, \phi M \,.\, \phi C \quad \text{when } U_{10} < U_c \qquad (6)$$

and

$$R_{ss} = [R_{ci} + A_i\,(U_{10} - U_c)^b] \,.\, \phi M \,.\, \phi C \quad \text{when } U_{10} > U_c \qquad (7)$$

where

R_{ss} = quasi-steady rate of spread (km h^{-1})

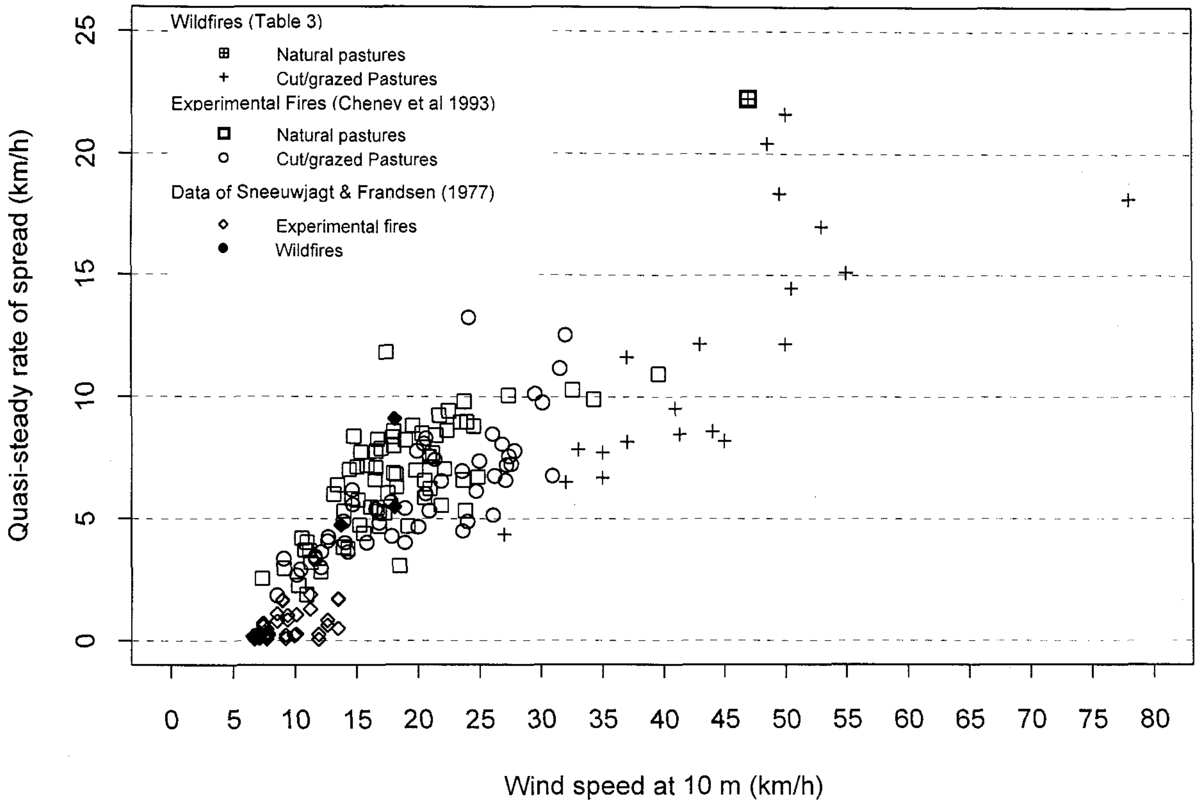


Figure 3. Comparison of the quasi-steady rate of spread and wind speed at 10 m from experimental fires (Cheney et al. 1993 and Sneeuwjagt and Frandsen 1977) with the wildfire data from Table 1. All rates of spread were adjusted to a common fuel moisture content of 3 percent.

R_o = rate of spread when U = 0 (0.054 km h^{-1} in both pasture types) when dead fuel moisture is 0 per cent.

R_{ci} = rate of spread at the critical wind speed of 5 km h^{-1} at dead fuel moisture content of 0 percent (1.1 km h^{-1} in cut/grazed pastures; and 1.4 km h^{-1} in undisturbed natural pastures).

U_{10} = 10 m wind speed (km h^{-1}). The U_{10} correspond ing to the average U_2 of the experimental fires were calculated using vertical wind profiles and atmospheric stability. Durré and Beer (1989) re ported the procedures and results of predicting the " standard" 10 m wind from local 2 m winds.

i = pasture types, 1 for natural undisturbed pasture, and 2 for cut/grazed pastures.

ϕM = fuel moisture coefficient

ϕC = grass curing coefficient

a_i, A_i and b = constants

We corrected the experimental data to a potential quasi-steady rate of spread and zero moisture content (i.e. $\phi M = 1$) using equation 5. The grass was fully cured, so $\phi C = 1$. We used the assigned values of R_{ci} in natural and cut/grazed pastures, for R_{ss} when $U_{10} = 5$ and solved for a_i.

Thus when $U_{10} < 5$ km h^{-1}:

$$R_n = 0.054 + 0.269\, U_{10} \quad (8)$$

$$R_{cu} = 0.054 + 0.209\, U_{10} \quad (9)$$

Where R_n and R_{cu} are the quasi-steady rate of spread for natural and cut/grazed pastures respectively.

For wind speed greater than U_c we obtained the regression constants A_i and b by transforming equation 7 to the following form using a log transformation:

$$\ln (R_{ad} - R_{ci}) = \ln A_i + b \ln (U_{10} - 5) \quad (10)$$

where

R_{ad} = adjusted rate of spread to quasi-steady rate at zero percent fuel moisture in fully cured grass.

The results of fitting this model using S-PLUS (Anon 1993) for the two pasture types are:

$$R_n = 1.4 + 0.838\, (U_{10} - 5)^{.844} \quad (11)$$

$$R_{cu} = 1.1 + 0.715\, (U_{10} - 5)^{.844} \quad (12)$$

where R_n and R_{cu} are quasi-steady rate of spread for natural and cut/grazed pastures respectively at zero percent dead fuel moisture content. The fit had $r^2 = 0.65$.

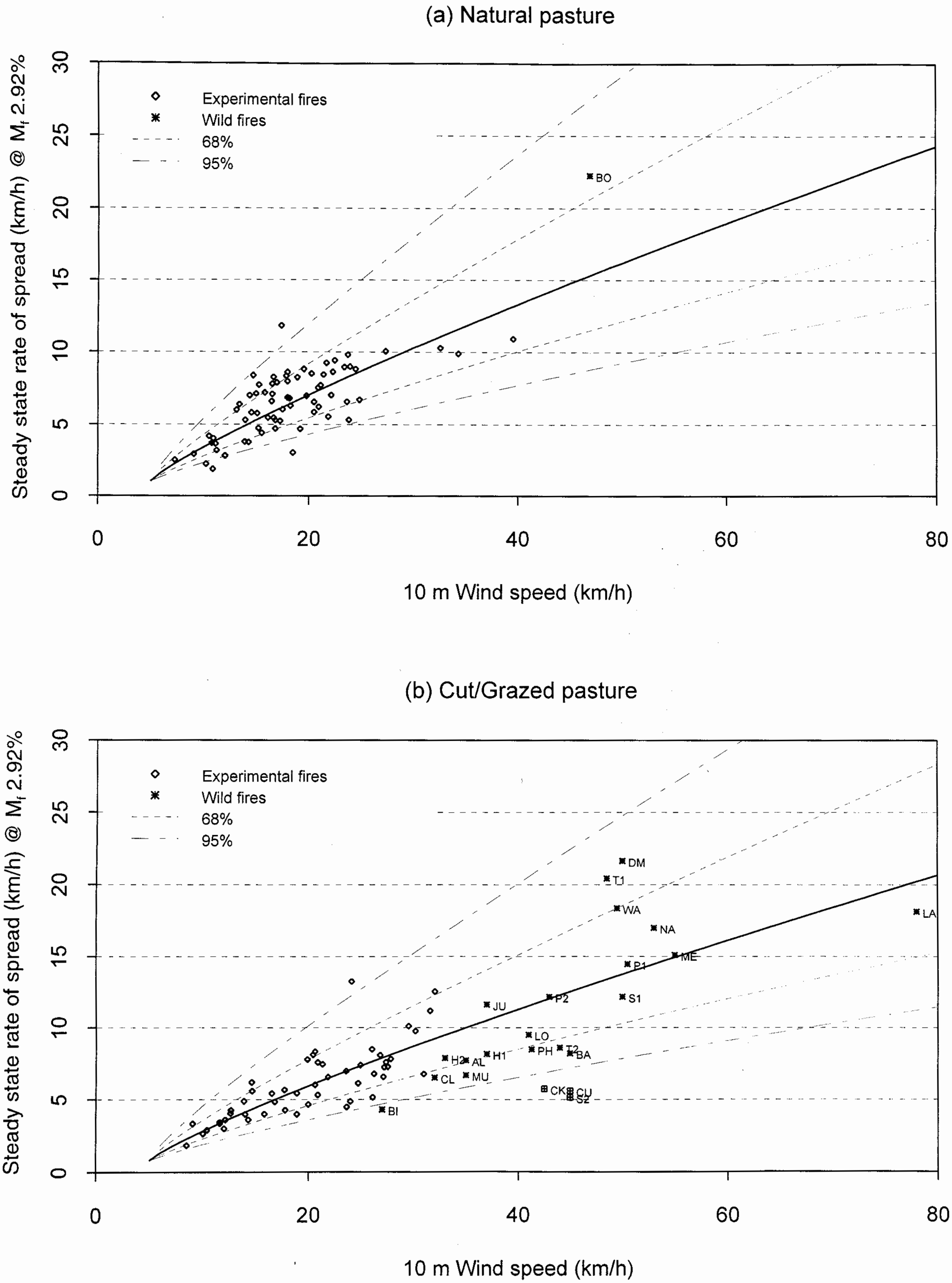


Figure 4. Comparison of equation 11 (a) and equation 12 (b) with the experimental and wildfires data. The 68 % (··········) and 95% (—·—·—·) prediction intervals are shown. See Table (1) for identification of wildfires.

The prediction from equations 11 and 12 at a fuel moisture content of 2.92 percent (the fuel moisture predicted for T = 40°C and RH = 10%), are compared with the data from experimental fires in Figure 4 a and b. Data from wildfires, also reduced to the same moisture content are overlaid on the plot. The wildfire data were not used in the development of the model. It can be seen that the wildfire data all fall within 95 percent prediction limits.

Fuel moisture coefficient (ϕM)

The results from equation 3 produced a function for the fuel moisture co-efficient of:

$$\phi M = \exp(-0.108\, M_f) \qquad (13)$$

over a range of fuel moisture content between 2 and 12 percent. The fuel moisture of extinction (M_x - the fuel moisture content at which a fire will not spread) ranges from 20 to 24 percent depending on the wind speed (CSIRO unpublished data). If the moisture function is extrapolated beyond 12 percent the moisture coefficient (ϕM) asymptotes towards zero but does not equal zero when fuel moisture content is greater than 20 percent (moisture of extinction). We had insufficient data to statistically estimate the relationship between R and M_f between moistures of 12 percent and M_x. We assumed that if the wind speed was < 10 km h^{-1}, M_x = 20 percent and if wind speed was > 10 km h^{-1} M_x = 24 percent. To determine the ϕM if the dead fuel moisture content was greater than 12 percent we assumed a linear relationship between ϕM at M_f = 12 and M_x. The moisture coefficients for the different values of M_f and wind conditions are shown in Figure 5 and the equations are:

$$\phi M = \exp(-0.108\, M_f) \qquad \text{if } M_f < 12\% \qquad (14)$$

$$\phi M = 0.684 - 0.0342\, M_f \qquad \text{if } M_f > 12\%,\ U_{10} < 10 \text{ km h}^{-1} \qquad (15)$$

$$\phi M = 0.547 - 0.0228\, M_f \qquad \text{if } M_f > 12\%,\ U_{10} > 10 \text{ km h}^{-1} \qquad (16)$$

where M_f = dead fuel moisture content (%): application bounds 2 - 24%.

Curing coefficient (ϕC)

The degree of curing is known to influence fire spread but there are few reliable data sets relating curing stage to R. The curing function used by McArthur (1966 and 1977) was developed by applying a subjective reduction to the rate of spread in fully cured pastures. That function reduces the rate of spread by around 44 percent when curing is changed from 100 to 85 percent and produces the greatest change in the predicted rate of spread when

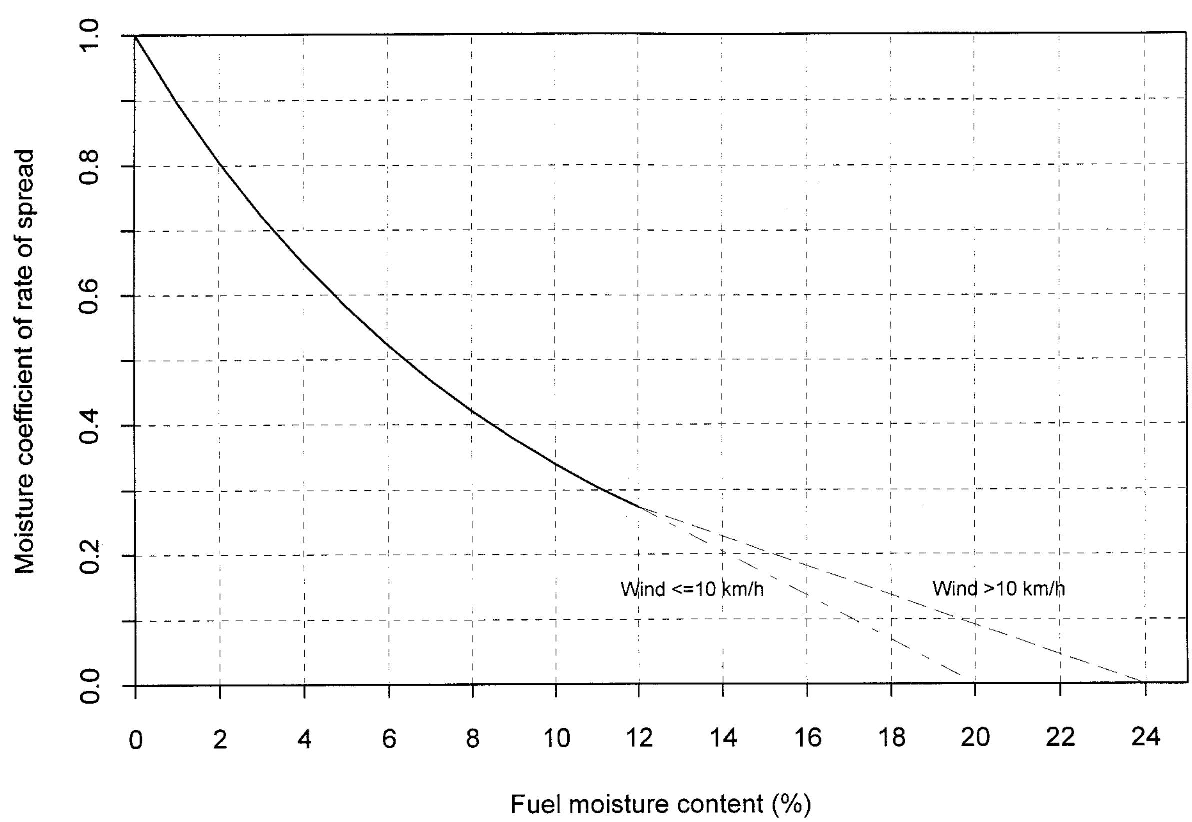


Figure 5. Relationship between the fuel moisture coefficient (ϕM) and dead fuel moisture content (M_f) (Equation 14, 15, and 16).

curing approaches 100 percent. Our field observations in earlier experimental grass fires in the Northern Territory and elsewhere (CSIRO unpublished data) are that grass fires generally will not spread when the grass curing is < 50 percent. There was no significant correlation between R and curing stage when ocular estimates of curing ranged from 85 to 100 percent (Cheney et al. 1993). Therefore, we have assumed a sigmoidal function between 50 and 100 percent curing. This function for the curing coefficient (ϕC) reflects the major influence of grass curing on fire spread which occurs when grasses are between 70 and 90 percent cured (Figure 6). The equation for this curing function is:

$$\phi C = 1.120/[1 + 59.2 \exp(-0.124 (C-50))] \qquad (17)$$

where C is the degree of grass curing (%): application bounds 50 - 100%.

Prediction of forward rate of spread

The general fire spread equations to predict the quasi-steady rate of spread of grass fires in two major pasture types on level ground are:

when $U_{10} < 5$ km h^{-1}

$$R_n = [0.054 + 0.269\ U_{10}]\ .\ \phi M\ .\phi C \qquad (18)$$
$$R_{cu} = [0.054 + 0.209\ U_{10}]\ .\phi M\ .\phi \qquad (19)$$

when $U_{10} > 5$ km h^{-1}

$$R_n = [1.4 + 0.838\ (U_{10} - 5)^{.844}]\ .\ \phi M\ .\ \phi C \qquad (20)$$

$$R_{cu} = [1.1 + 0.715\ (U_{10} - 5)^{.844}]\ .\phi M\ .\phi C \qquad (21)$$

where
R_n = quasi-steady rate of spread in undisturbed natural pastures (km h^{-1}).
R_{cu} = quasi-steady rate of spread in cut, grazed, or par tially trampled pastures (km h^{-1})
U_{10} = 10 m wind speed in the open (km h^{-1}) application bounds (0-80 km h^{-1}).
ϕM = moisture coefficient (equations 14, 15, 16)
ϕC = curing coefficient (equation 17)

The form of the moisture content coefficient ϕM is illustrated in Figure 5; the curing coefficient is illustrated in Figure 6; and, the relationship between R and U_{10} at different fuel moistures is illustrated in Figure 7.

We recognise that fires will spread slower in eaten-out pastures than they will in continuous pastures (see spread rates for the Creswick, Strathmore (S2) and Cudgee fires in Table 1 and Figure 4). We do not have experimental data for fires in eaten-out pastures at low wind speeds. However, for predicting wildfire spread we consider that the eaten-out pastures should be identified and

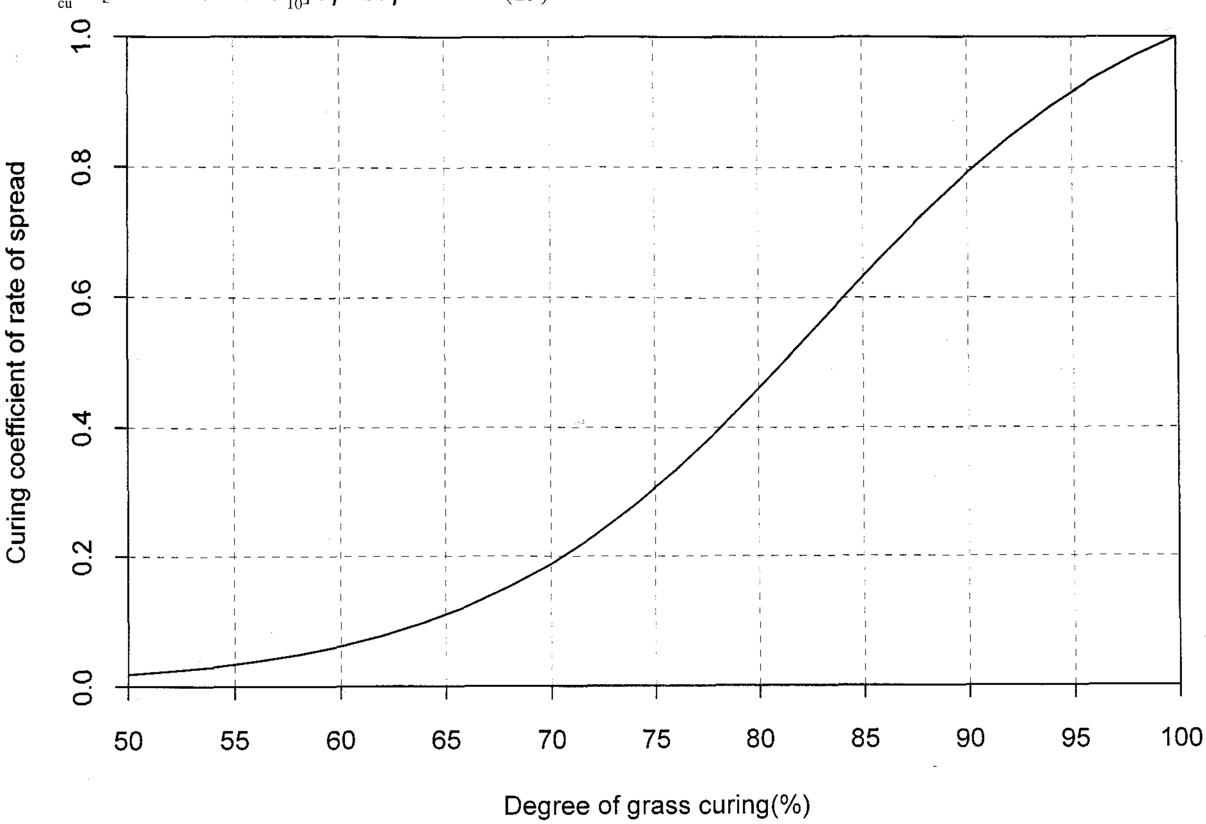
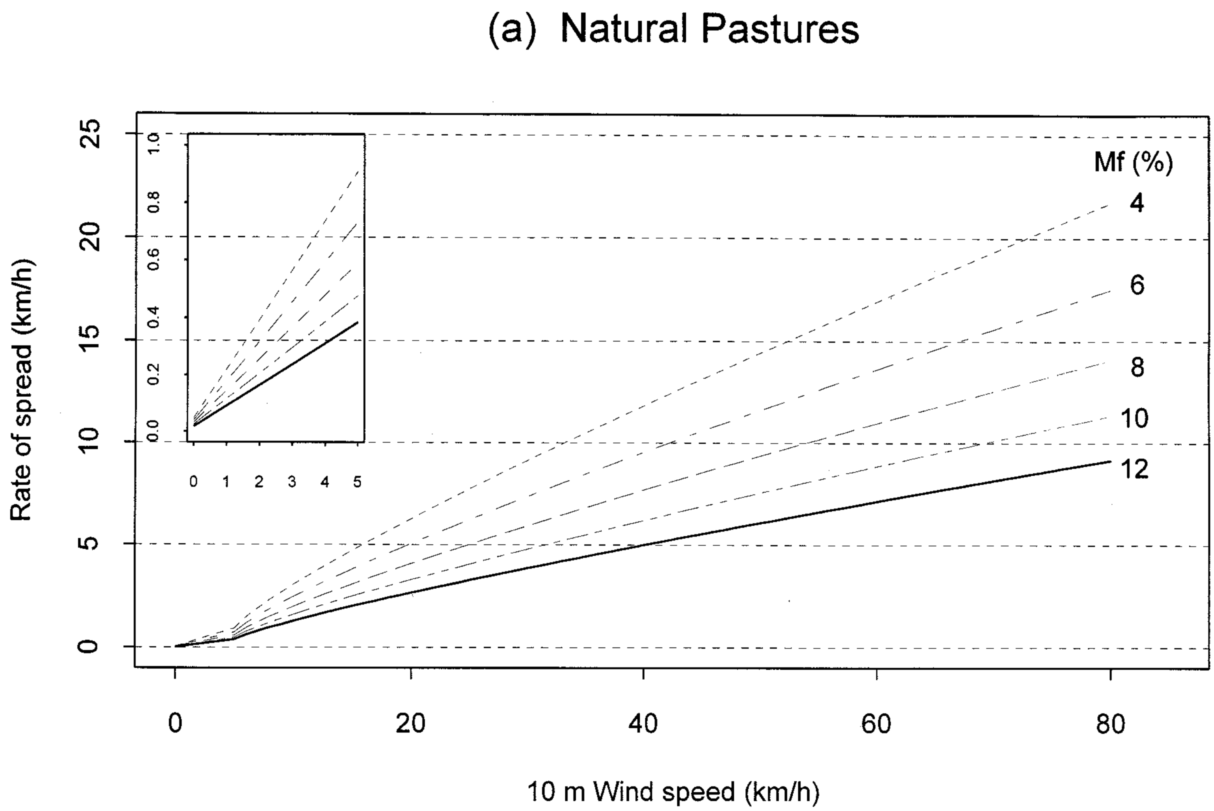


Figure 6. Relationship between curing coefficient (ϕC) and degree of grass curing (C) (Equation 17).



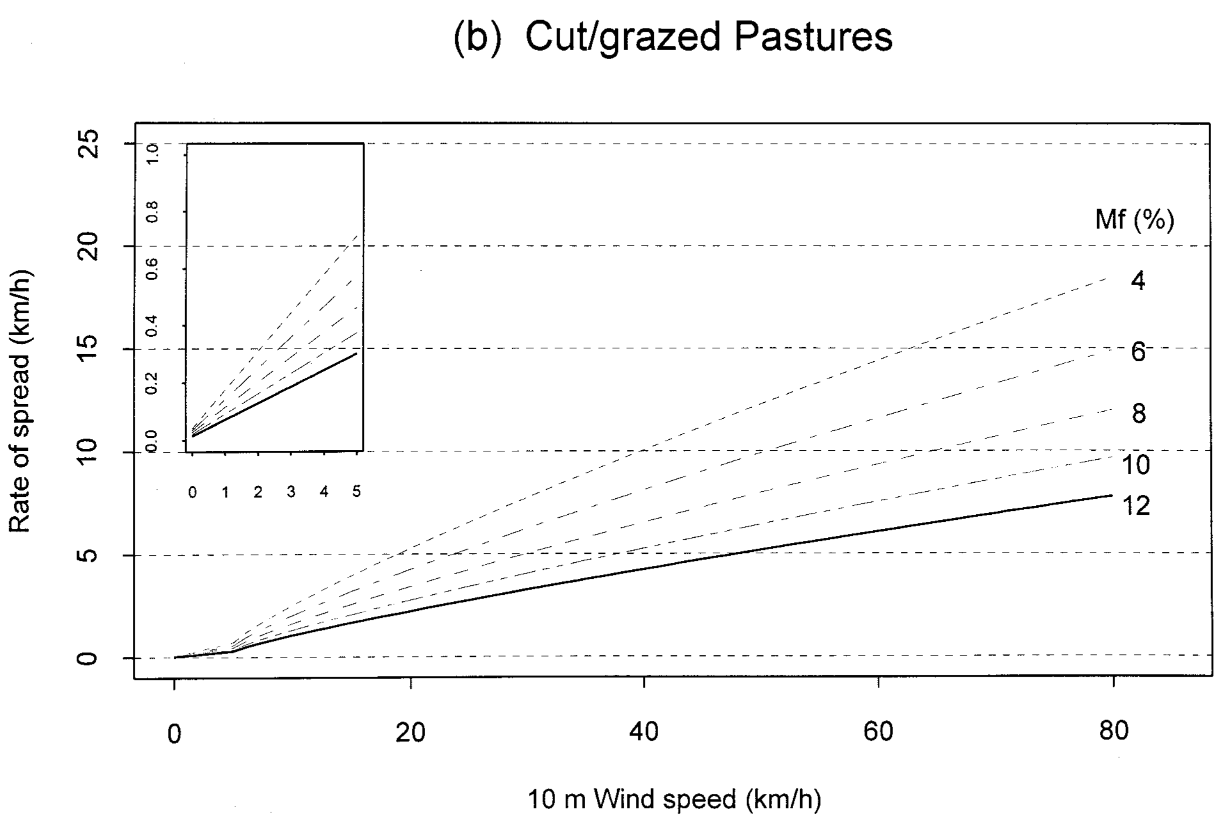


Figure 7. Relationship between natural (a) and cut/grazed (b) pastures rate of spread and wind speed (U_{10}) for fully cured grass at different dead fuel moisture contents.

we have assigned them a spread rate which is half that in the cut/grazed pastures. The equation is:

$$R_e = [0.55 + 0.357 (U_{10} - 5)^{.844}] .\phi M.\phi C \qquad (22)$$

where R_e is quasi-steady rate of spread in eaten out pasture conditions (km h^{-1}).

Discussion

The fire spread model appears to over-predict when compared to wildfires in grazed pastures at moderate (25 - 45 km h^{-1}) wind speeds. This result is not unexpected since the model was built to predict potential quasi-steady spread. Fires spreading across the landscape are likely to encounter barriers (eg roads, creek-lines, firebreaks, etc) which will cause delays and reduce their average rate of spread below the predicted potential rate of spread. Furthermore these barriers will be more effective and cause longer delays at lower wind speeds.

When applying the model it is important to recognise the criteria for which it was designed. Specific features of the model and its application to field prediction of fire behaviour are discussed below.

Critical wind speed

We do not consider that laboratory data and field data can be compared directly without taking account of differences of scale (Cheney and Gould 1995). Considering the differences in fuel beds and the heights of wind speed measurements relative to the fuel bed in laboratory and field studies it seems highly fortuitous that the apparent discontinuity in the relationship between R and U should occur at about the same wind speed. However, we agree with Beer (1995) that it appears unwise to use a simple mathematical function such as a power law to describe rate of spread over a full range of wind speeds. Also rate of spread at zero wind speed (R_o) may not be an appropriate scaling variable for developing a relationship between R and U because there may be a change in the mechanism of fire spread above U_c such as a change from a backing fire to a heading fire.

The concept of a critical wind speed (U_c) is more important for our understanding of fire spread mechanism than it is for practical prediction of R in continuous grasses. Fires under calm conditions on level ground are easy to suppress and suppression agencies have apparently ignored over-predictions (eg at M_f = 3% the McArthur Mk V grassland meter predicts R_o = 2 km h^{-1} in a 6 t ha^{-1} fuel) because they are unimportant.

The value of U_c in continuous pastures is likely to depend on the strength of the convection and thus the weight of fuel consumed. Under stable winds we would expect U_c to be less for fires in light fine pastures than that for fires in heavy pastures. In practice, thermal activity will be a primary factor which determines when fires progress steadily in the direction of the prevailing wind.

The value assigned to R_c will determine whether the value of the exponent of the wind speed function is greater than, less than or equal to 1. The value we have chosen is consistent with observations on individual fires when the apparent linear relationship between R and U is extrapolated to U_c.

In discontinuous fuels fires will not spread at all under light winds. Forward spread occurs when the winds exceed the speed which brings flames from one clump of fuel in contact with the next. The value of this 'threshold' wind speed (U_t) depends on the continuity of the fuel: e.g. for effective forward spread in hummock grasslands U_t at 2 m ranged from 3.5 km h^{-1} (Griffin and Allan 1984) to 17 km h^{-1} (Burrows et al. 1991). Likewise, in discontinuous eaten-out pastures, fires may not spread at low winds and require U_t > 5 km h^{-1} at 10 m, the U_c used in this model, but we have retained the value of 5 km h^{-1} for simplicity.

Relationship between R and U

The experimental data suggests that the relationship between R and U above U_c is a power function with an exponent of less than one. We consider that this relationship is more sensible than one where R continues to increase with increasing wind speed and, theoretically, eventually exceeds it.

Equations 18 and 19 are purely conceptual models to predict R at low wind speeds of < 5 km h^{-1}. Fires burning under these light wind conditions often spread erratically as they respond to gust and lulls caused by the localised thermal activity. The models could under-predict R during a short localised wind gust and over-predict during the lulls.

We have rejected the contention that grass fire spread decreases rapidly with increases in wind speed above 45 km h^{-1} (McArthur 1968). We concluded that the grass fires which burnt in Tasmania on 7 February 1967 used in McArthur's analysis did not meet our criteria for predicting fire spread across the landscape. They burnt through both dry eucalypt forest and open grasslands and across quite divided terrain. We consider both factors would tend to give lower rates of spread than fires in continuous grasslands on level ground independently of the wind speed.

We also have considerable reservations about reports of headfires being blown out at high wind speeds in sparse pastures (McArthur 1968, Van Didden 1978, Luke and McArthur 1978). Aerial photographs of long "fingers" of burnt grass petering out in sparse pastures have been cited as evidence of this phenomena (Anon 1967) but we know of no testing to determine if these pastures would carry fire at lower wind speeds.

Eye witness accounts differ. During the "Cyclone Alby" fires in Western Australia wind speeds exceeded 70 km h^{-1} with gusts recorded to 150 km h^{-1} (Van Didden 1968). Mr Noel Eddy (Personal comment) describes flank fires being blown out in sparse pastures and progress of fire across the paddock by blown smouldering material (mostly sheep droppings) but he considered the paddock would not have burnt at lower wind speeds. The opposite view was expressed by Mr John Twaddle (Personal comment) who described long fingers of fire in sparse fuels being blown out and who felt the fuels would have burnt at lower wind speeds.

Fuel moisture co-efficient

The shape of the relationship between the fuel moisture co-efficient ϕM and M_f may be over-simplified between $M_f = 12$ and M_x. At low wind speeds M_x was difficult to define precisely by field experiments because when extinguishment was occurring fuel moistures were rising rapidly due to rapidly rising humidities and dew formation on the grass. At high wind speeds dew is less likely to form due to better mixing of the air near the grass surface. Therefore $M_x = 20$ at low wind speeds is partly an artefact but reflects the fact that, under low winds, humidities at the grass layer will be higher than humidities at screen level (1.5 m). The practical importance of this is small.

Fuel curing co-efficient

It is difficult to verify any function between curing state and R because of large spatial variation in curing even at an experimental scale. Rate of curing depends on the soil moisture, so that grasses on ridge lines cure more rapidly than grasses in moist depressions or creek lines. Therefore, early in the dry season fires that spread rapidly through fully cured pastures may be stopped by relatively narrow strips of green grasses in the creek lines.

Ocular estimates of curing may also vary substantially between observers so a wide variation between observed and predicted fire behaviour is to be expected until the landscape is more than 90% cured.

The Lara fire (LA) was the one wildfire burning through 80% cured pastures included in the data set. This fire was in good agreement with the prediction for pasture type 2 (Figure 4) although the reliability of the spread measurement was low.

Pasture Type

While natural pastures are extensive in northern Australia and large wildfires are frequent, anemometers are rare. The Boonoke fire was the only documented wildfire that could be reliably classified as in natural pasture. However, pastures in southern Australia are not subjected to uniform grazing pressures and in a run of 40 km or more most fires will inevitably pass through some pastures of each classification. For example the Tatyoon/Stretham Fire (T1) and the Wallinduc Fire (WA) were described as burning in part through heavy pastures and stubbles (Table 1) and may have been better plotted as fires in natural pastures (see Figure 4). The Deans Marsh fire (DM) which also fell outside the 68% confidence limits for the prediction in cut/grazed pastures was rated lowest in reliability of both spread and wind speed estimates.

Practical Prediction of Fire Spread

The distribution of the data on the scattergram (Figure 4) illustrate the practical reality of predicting fire spread: there is likely to be a high degree of variability associated with measures of both fuel and weather variables. A practical field model, such as circular slide rule or similar device, might well be based on a single linear relationship between R_{ss} and U passing through R_o and linked to single functions for ϕM and ϕC.

A conservative approach might also design the model to predict the upper 68% confidence limit. Fire suppression agencies may prefer to plan their logistics on the basis that actual fire spreads are likely to exceed predictions on only 15% of occasions.

References

Anderson, H.E. and Rothermel, R.C. (1965). Influence of moisture and wind upon the characteristics of free-burning fires. Tenth Symposium (International) on Combustion. The Combustion Institute, Pennsylvania, 1009-1019.

Anon. 1967. Wildfire investigations. Commonwealth Forestry and Timber Bureau, Annual Report. page 28.

Anon. 1976. Prescribed burning in exotic pine plantation: Prescribed Burning Guide Mk3, Queensland Forestry Department : Operations Manual. 9 pages.

Anon. 1983. The major fires originating 16th February, 1983. Country Fire Authority Vic Report. 38 pages.

Anon. 1993. S-PLUS for Windows User's Manual, Version 3.1 Statistical Science Inc. Seattle.

Beer, T. 1991. The interaction of wind and fire. Boundary Layer Meteorology 54: 287-308.

Beer, T. 1993. The speed of a fire front and its dependence on wind speed. International Journal of Wildland Fire 3(4) : 193-202.

Beer, T. 1995. Fire propagation in vertical stick arrays: the effects of wind. International Journal of Wildland Fire 5(1) 43 - 49.

Burrows, N., Ward, B. and Robinson, A. 1991. Fire behaviour in spinifex fuels on the Gibson Desert Nature Reserve, Western Australia Journal of Arid Environments 20: 189-204.

Catchpole, T. and de Mestre, N. 1986. Physical models for a spreading line fire Australian Forestry 49(2): 102-111.

Cheney, N.P. and Gould, J.S. 1995. Fire growth to a quasi-steady rate of forward spread. International Journal of Wildland Fire 5(4): 237-247.

Cheney, N.P. and Gould, J.S. 1997. Fire growth and acceleration. International Journal of Wildland Fire 7(1) 1-5.

Cheney, N.P., Gould, J.S. and Catchpole, W.R. 1993. Influence of fuel, weather and fire shape variables on fire spread. International Journal of Wildland Fire 3(1): 31-44.

Cheney, N.P., McCaw, L. and Wilson, A.A.G. 1991. Development of an Australian fire danger rating system. Rural Industries Research and Development, Report, Project No CSF-35A. 24 pages.

Curry, J.R. and Fons, W.L. 1938. Rate of spread of surface fires in the Ponderosa pine type of California. Journal of Agricultural Research 57 (4) : 239 - 267.

Douglas, D.R. 1970. Wind changes and your tactics. EFS Manual. page 7-10.

Durré, A.M. and Beer, T. 1989. Wind information prediction study, Annaburroo Meteorological data analysis. CSIRO Division of Atmospheric Research, Technical Report No 17. 30 pages.

Finocchiaro, N., Lindforth, D.J. and Shields, B.T. 1970. Report on the Meteorological aspects of the extensive grassfires in Victoria on 8 January 1969. Commonwealth Bureau of Meteorology, Melbourne, Working Paper No. 127 17 pages. + App.

Fons, W.L. 1946. Analysis of fire spread in light forest fuels. Journal of Agriculture Research 72: 93-121.

Forestry Canada Fire Danger Group. 1992. Development and structure of the Canadian forest fire behaviour prediction system. Forestry Canada, Ottawa Ontario. Information Report ST-X-3. 63 pp.

Griffin, G.F. and Allan, G.E. 1984. Fire behaviour In, Anticipating the inevitable: a patch burn strategy for fire management at Maru (Ayers Rock - Mt Olga) National Park Saxon, E.C. (ed). Commonwealth Scientific and Industrial Research Organisation, Australia. 55 - 68.

Keeves, A. and Douglas, D.R. 1983. Forest fires in South Australia on 16 February 1983 and consequent future forest management aims. Australian Forestry 46: 148-162.

Luke, R.H. and McArthur, A.G. 1978. Bushfires in Australia. Australian Government Publishing Service. 359 pp.

Maynes, K.J. and Garvey, M.F. (1985). Report on selected major fires in country areas of Victoria on 14th January, 1985. Country Fire Authority of Victoria, Melbourne, Report. 36 pages.

McArthur, A.G. 1960. Fire danger rating tables for annual grasslands. Commonwealth Forestry and Timber Bureau, Canberra. 15 pages.

McArthur, A.G. 1962. Fire behaviour in annual grasslands. Commonwealth Forestry and Timber Bureau Canberra, Annual Report. page 7.

McArthur, A.G. 1964. Fire behaviour studies. (d) Grasslands. Commonwealth Forestry and Timber Bureau, Annual Report. page 17.

McArthur, A.G. 1966. Weather and grassland fire behaviour. Department of National Development, Forestry and Timber Bureau, Canberra. Leaflet 100. 23 pages.

McArthur, A.G. 1967. Fire behaviour in Eucalypt forests. Department of National Development Forestry and timber Bureau. Leaflet 107 36 pp.

McArthur, A.G. 1968. The Tasmanian bushfires of 7th February, 1967, and associated fire behaviour characteristics Conference Papers. Second Australian National Conference on fire Australian Fire Protection Association, Melbourne, Victoria. 25-48.

McArthur, A.G. 1973. Grassland fire danger meter MkIV. Forest Research Institute, Forestry and Timber Bureau, Canberra (published as a circular slide rule).

McArthur, A.G. 1977 (a). Grassland fire danger meter Mk V. CSIRO Division of Forest Research Annual Report 1976-1977. page 58.

McArthur, A.G. 1977(b). Grassland fire danger meter MkV. Country Fire Authority of Victoria, Melbourne (published as a linear slide rule).

McArthur, A.G., Cheney, N.P. and Barber, J. 1982. The fires of 12 February 1977 in the Western District of Victoria. CSIRO Division of Forestry Research, Canberra and Country Fire Authority of Victoria, Melbourne. 73 pages.

Myers, R.H. 1989. Classical and modern regression with applications. Second Edition. PWS-Kent Publishing Company Boston. 488 pages.

Noble, I.R., Bary, G.A.V., and Gill, A.M. 1980. McArthur's fire danger meters expressed as equations. Australian Journal of Ecology 5: 201-3.

Noble, J.C. 1991. Behaviour of a very fast grassland wildfire on the Riverine Plain of south-eastern Australia. International Journal Wildland Fire 1(3): 189-196.

Norusis, M.J. 1992. SPSS for Windows, Advanced Statistics. SPSS Inc, Chicago, USA. 578 pages.

Peet, G.B. 1965. A fire danger rating and controlled burning guide for the northern jarrah (*Euc. marginata Sm.*) forest of Western Australia. Western Australia Forest Department Bulletin 74. 37 pages.

Rawson, R.P., Billing, P.R. and Duncan, S.F. 1983. The 1982-83 forest fires in Victoria. Australian Forestry 46: 163-172.

Rothermel, R.C. 1972. A mathematical model for predicting fire spread in wildland fuels. United States Department of Agriculture, Forest Service Research Paper INT-115. Intermountain Forest and Range Experiment Station Ogden Utah. 40 pages.

Rothermel, R.C. and Rinehart, G.C. 1983. Field procedures for verification and adjustment of fire behaviour predictions. United States Department ofAgriculture Forest Service, General Technical Report INT-142 Intermountain Forest and Range Experiment Station, Ogden, Utah. 25 pages.

Sneeuwjagt, R.J. and Frandsen, W.H. 1977. Behaviour of experimental grass fires vs. Predictions based on Rothermel's fire model. Canadian Journal of Forest Research 7:357-367.

Thomas, P.H. and Pickford, R.W. 1961. Fire spread in forest and heathland material. Fire Research Station, Boreham Wood Hertfordshire. Report on Forest Research. P. 105-109.

Van Didden, G.W. 1978. A review of fire suppression operations resulting from cyclone "Alby" April 1978. Forests Department, Western Australia Internal Report. 21 pages + App.

Wolff, M.F., Carrier, G.F., and Fendell, F.E. 1991. Wind-aided firespread across arrays of discrete fuel elements. II. Experiments. Combustion Science & Technology 75: 261-289.