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Examination of the wind speed limit function in the Rothermel surface fire spread model

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Abstract. The Rothermel surface fire spread model includes a wind speed limit, above which predicted rate of spread is constant. Complete derivation of the wind limit as a function of reaction intensity is given, along with an alternate result based on a changed assumption. Evidence indicates that both the original and the revised wind limits are too restrictive. Wind limit is based in part on data collected on the 7 February 1967 Tasmanian grassland fires. A reanalysis of the data indicates that these fires might not have been spreading in fully cured continuous grasslands, as assumed. In addition, more recent grassfire data do not support the wind speed limit. The authors recommend that, in place of the current wind limit, rate of spread be limited to effective midflame wind speed. The Rothermel model is the foundation of many wildland fire modelling systems. Imposition of the wind limit can significantly affect results and potentially influence fire and fuel management decisions.

Additional keywords: fire behaviour models, fuel model, grassfire, midflame wind speed, reaction intensity, wind adjustment factor.

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Introduction

Of all the variables affecting the spread of wildland fire, wind speed is among the most studied, under laboratory controlled environments (Rothermel 1972; Wolff et al. 1991; Catchpole et al. 1998), in outdoor experimental fires (Stocks 1987; Cheney et al. 1993; Burrows 1999; Cruz et al. 2005) and on wildfires (Alexander and Lanoville 1987; Cheney et al. 1998). The effect of wind speed on the spread rate of a flame front is complex, integrating interactions among fuelbed characteristics, wind structure, the energy output of the fire and the efficiency of the dominant heat transfer mechanisms. Nelson et al. (2012) found evidence of distinct entrainment and combustion regimes in low- and high-wind-speed free spreading fires. Simplified mathematical descriptions of wind (U) effect on fire propagation (R) assume a bulk power law effect with $R \propto U^{\rm B}$, with values of B at ~1 in outdoor datasets (McCaw 1997; Catchpole et al. 1998; Cheney et al. 1998; Cruz et al. 2005; Cheney et al. 2012; Cruz et al. 2013), irrespective of the fuel type. Exponential functions have also been found to provide an adequate representation of the relationship between wind speed and rate of spread. The use of exponential (e.g. Beck 1995) and power relationships with exponents close to 2 or higher (e.g. Burrows 1994) can result in the unrealistic prediction at high wind speeds of rates of spread exceeding wind speed. The Canadian Forest

Fire Behaviour Prediction System (Forestry Canada Fire Danger Group 1992) considers a sigmoid shaped function integrating the effect of open wind speed and a surrogate of fuel moisture content. The asymptote of this function expresses a maximum assumed rate of fire spread that is fuel-type dependent. The Rothermel (1972) surface fire spread model (the Rothermel model) includes a wind factor of the form AU^B , where A and B are functions of the fuel descriptors and B ranges from ~ 1 to 2. The Sandberg et al. (2007) reformulation of the Rothermel model retains the power function but uses a fixed value of B = 1.2 for all fuel types. It does not include a wind limit function. Understanding the effect of very high wind speeds on fire spread is limited due to the difficulty of conducting field experiments under high winds and of adequately measuring representative wind speeds during wildfire situations (Butler et al. 1998; Taylor et al. 2004; Clements et al. 2007).

One relevant research question regards the effect of high wind speeds on fire propagating in fuel complexes characterised by low fuel load availability, such as grasslands or semiarid shrub communities. An observable effect of the increase of the wind speed upon the flame front in light fuels is the extension of the flame length and the deflection of the flame trajectory towards the unburned fuel, resulting in an increase of heat transfer. Conversely, at some threshold wind speeds local flame extinction has been theorised to occur. Empirical evidence from the 7 February 1967 Hobart fires in Tasmania, Australia, indicated that at very high wind speeds (i.e. $40-45 \text{ km h}^{-1}$) the rate of spread in grassfires decreased with increasing wind speed (McArthur 1969). A possible explanation for this effect put forward by Alan G. McArthur was that as the wind increases above a critical threshold, the flame front in light fuels becomes progressively narrower and fragmented, inducing a decrease in the average rate of fire spread (McArthur 1969; Luke and McArthur 1978). Based on this evidence, Rothermel (1972) modelled an upper wind limit based on the ratio of the energy of the wind and the energy of the fire. Evaluating this ratio for the limiting rates of spread found by McArthur (1969), the threshold condition that defines the upper wind speed value was modelled as a function of reaction intensity, the rate of heat release per unit area of the flaming fire front. The Rothermel model includes calculation of a wind speed limit, above which predicted rate of spread is constant.

Concerns about the implementation of this wind limit function include its influence on fire behaviour predictions and the lack of physical evidence of a wind speed limit. Concerning fire behaviour prediction, the main issues are: (1) the wind limit function causes no change in rate of spread with increasing wind speed after the threshold condition is attained; (2) the threshold condition is attained at low wind speeds in fuel beds with low fuel loads and (3) a wind limit can be reached for all fuel types at very high moisture contents. The Rothermel model is the foundation of many wildland fire modelling systems in the USA, such as BehavePlus (Andrews 2007), NEXUS (Scott and Reinhardt 2001), FlamMap (Finney 2006), FARSITE (Finney 1998), the Fire and Fuels Extension to the Forest Vegetation Simulator (Reinhardt and Crookston 2003), Fuel Management Analyst (Carlton 2005) and FSPro (Finney et al. 2011). Sullivan (2009) described simulation models that are based on the Rothermel model, including FireStation (Portugal; Lopes et al. 2002), Thrace (Greece; Karafyllidis and Thanailakis 1997), Prolif (France; Plourde et al. 1997), Pyrocart (New Zealand; Perry et al. 1999) and PdM (Italy; Guariso and Baracani 2002). Imposition of the wind limit can significantly affect results under some conditions, and can potentially influence fire and fuel management decisions.

The concept of a decay in rate of fire spread at high wind speeds has been questioned in recent years. The discussion in the Luke and McArthur (1978) textbook, 'Bushfires in Australia,' was changed and an alternative explanation to the observed data was presented in the 1986 reprint. Factors such as partially cured grasses and rapidly increasing relative humidity were believed to explain the 'seemingly paradoxical phenomenon' (Luke and McArthur 1986). Cheney et al. (1998) also discounted the evidence from the Tasmania fires as they were believed to have burnt through a mosaic of dry eucalypt forest and open grasslands. Evidence from very high rates of fire spread observed in fully cured grasslands under strong (sustained $40-50 \text{ km h}^{-1}$) to near-gale (sustained 51–62 km h^{-1}) winds further questions the concept of a wind limit or rate of fire spread decay with increasing wind speeds. Noble (1991) presents weather and rate of spread data for three grassfires in Australia where 10-m open winds between 47 and 53 km h^{-1} result in spread rates between 280 and 380 m min⁻¹. The 2005 Wangary fire in the Eyre Peninsula of South Australia had grassfire runs of 215 and 245 m min⁻¹ driven by average wind speeds between 46 and 61 km h⁻¹ (Gould 2005).

In the present work we examine the original wind limit function of Rothermel (1972) and a revised function based on a changed assumption. This paper begins with an overview of the role of wind in the Rothermel model and a derivation of the wind limit function. The relationship between wind factor and wind limit and definition of 'midflame' wind is discussed. We describe conditions under which the wind limit is reached using both the original and the revised wind limit function. We re-examine the fire spread data used in derivation of the wind limit function and present further empirical evidence that questions the idea that very high wind speeds lead to a decay in rate of fire spread in fuel complexes with light fuel loads.

The units of the source papers (Rothermel and Anderson 1966; McArthur 1969; Rothermel 1972) are retained as the primary units in the following section, which describes wind effect in the Rothermel model including derivation of the wind limit function. Metric units are used for the remainder of the paper.

Wind effect in the Rothermel model

The Rothermel (1972) model is based on a theoretical foundation (Frandsen 1971) combined with laboratory (Rothermel and Anderson 1966; Anderson 1969) and wildfire data (McArthur 1969). Rate of spread for no wind and no slope (R_0) is derived from the ratio of heat source to heat sink, based on fuel descriptors (e.g. fuelbed depth, load, surface-area : volume ratio) and the moisture content of each fuel size component, live and dead.

$$R_0 = \frac{I_R \xi}{\rho_b \varepsilon \mathcal{Q}_{ig}} \tag{1}$$

where I_R is reaction intensity (Btu ft⁻² min⁻¹), ξ is propagating flux ratio (dimensionless), ρ_b is bulk density (lb ft⁻³), ε is effective heating number (dimensionless) and Q_{ig} is heat of pre-ignition (Btu lb⁻¹).

The effect of wind and slope is incorporated into the model through dimensionless wind and slope factors (coefficients) $(\varphi_w \text{ and } \varphi_s)$.

$$R = R_0 (1 + \varphi_w + \varphi_s) \tag{2}$$

Wind factor is a function of midflame wind speed and the geometrical properties of the fuel particles and fuel bed.

$$\varphi_w = A U_f^{\ B} \tag{3}$$

where U_f is midflame wind speed (ft min⁻¹) and A and B are derived from the fuel description.

$$A = 7.47 \exp(-0.133\sigma^{0.55}) \left(\beta/\beta_{op}\right)^{-0.715 \exp(-3.59 \times 10^{-4}\sigma)}$$
(4)

$$B = 0.02526 \,\sigma^{0.54} \tag{5}$$

where σ is the fuelbed characteristic surface-area : volume ratio (SAV) (ft² ft⁻³) and β/β_{op} is the relative packing ratio, which is a



Fig. 1. From McArthur (1969, his fig. 1) as redrafted for Rothermel (1972, his fig. 19). The 15 data points associated with the solid line were used in development of the wind factor. Wind speed at the limit of the increasing spread rate trend line was used to develop the wind limit function.

function of SAV, oven-dry load, fuel bed depth and particle density. Effective wind speed is defined as the combined effect of wind and slope (Albini 1976).

In order to expand the experimental dataset to include conditions not available in the laboratory, Rothermel included McArthur's (1969) dataset of fast spreading grass fires to develop the wind factor (Fig. 1). He used only the portion of the wildfire data for which rate of spread increased with increasing wind speed.

The following is McArthur's (1969) interpretation of the data shown in Fig. 1:

It appears that under conditions of very strong wind the front of a grassfire becomes progressively narrower and frequently peters out. Thus a head fire tends to become fragmented and proceeds in a series of narrow tongues of fire, many of which are self-extinguishing. Under these circumstances the average rate of forward progress progressively decreases as the wind velocity increases above 26–28 miles per hour $[42–45 \text{ km h}^{-1}]$.

Rothermel found evidence of this effect in an aerial photograph of a fire that had burned mixed grass and sage in the US Sheep Experimental Station in Idaho.

Rather than producing a model that predicts decreasing rates of spread with increasing wind speeds, Rothermel derived a wind limit, above which value the rate of spread remains constant. That wind limit is based on the assumption that higher intensity fires can withstand higher wind speeds (have higher wind speed limits) than fires with lower intensities. The maximum reliable wind speed (the wind limit) is described as a function of reaction intensity, which is found from the fuel bed description and fuel moisture. The wind limit is defined as

$$U_f = 0.9 I_R \tag{6}$$

For winds above the wind limit, the wind factor and thus rate of spread are constant. The wind limit is generally applied to effective wind speed.

Wind limit function derivation

A summary of derivation of the wind limit relationship is given by Rothermel (1972, p. 33). Previously unpublished details are given here. In addition, an error in an assumption is corrected and a revised wind limit function is presented.

The analysis is based on a relationship between wind velocity and fire intensity given by Rothermel and Anderson (1966, their fig. 15). They found that the angle of flame tilt could be correlated with a ratio of the energy of the wind and the energy of the fire. The tangent of the flame angle tilt from vertical is related to a dimensionless parameter.

$$\tan \theta \approx \frac{qU_f}{I_R J} \tag{7}$$

where θ is the flame angle tilt, q is dynamic pressure of air stream (lb_f ft⁻², where f represents force), U_f is wind speed or velocity at midflame height (ft min⁻¹), I_R is reaction intensity (Btu ft⁻² min⁻¹) and J = 778 ft lb_f Btu⁻¹ is a proportionality factor to relate units of work to units of heat (778 ft lb_f = 1 Btu).

This correlation was used to determine the relationship of wind velocity to reaction intensity at the limit of spread rate as seen in McArthur's data and then express that limit in a general form for any fire.

Dynamic pressure of the air stream is

$$q = \frac{\rho U_f^2}{2g_0} \tag{8}$$

where ρ is air density (lb_m ft⁻³, where m represents mass), U_f is midflame wind speed (ft min⁻¹) and the conversion coefficient g_0 is 32 ft lb_m lb_f⁻¹ s⁻² or 116 000 ft lb_m lb_f⁻¹ min⁻².

Assuming air temperature of 90°F (32.2°C) at 3000-ft (914.4-m) elevation, ρ is 0.0635 lb_m ft⁻³ (1.012 kg m⁻³).

$$q = \frac{0.0635U_f^2}{232\,000} = (2.74 \times 10^{-7})U_f^2 \tag{9}$$

$$\frac{qU_f}{I_R J} = \frac{(2.74 \times 10^{-7})U_f^3}{778I_R} = (3.52 \times 10^{-10})\frac{U_f^3}{I_R}$$
(10)

Detailed fuel data were not available for McArthur's grass fires. The following assumptions were made: fuel SAV, $\sigma = 3500 \text{ ft}^2 \text{ ft}^{-3}$ (114.8 cm² cm⁻³); fuel bed depth, $\delta = 1.0 \text{ ft}$ (0.305 m); fuel load, $w_0 = 0.0344 \text{ lb ft}^{-2}$ (0.168 kg m⁻²); fuel moisture (fraction), $M_f = 0.04$; heat content, $h = 7500 \text{ Btu lb}^{-1}$ (17 459 kJ kg⁻¹); total mineral content (fraction), $S_T = 0.03$; effective mineral content (fraction), $S_e = 0.01$; fuel particle density, $\rho_p = 25 \text{ lb ft}^{-3}$ (400.5 kg m⁻³). Reaction intensity was calculated using these values in the Rothermel (1972) model to obtain $I_R = 1105 \text{ Btu ft}^{-2} \text{ min}^{-1}$ (209.3 kW m⁻²).

Although Rothermel (1972) did not specify that he multiplied the 33-ft (10-m) wind by 0.4 to get midflame wind speed, that factor can be found from a comparison of his figs 19 and 20.

Although fig. 19 (reproduced as Fig. 1 here) gives wind in miles per hour at 33 ft (10 m), he produced fig. 20 using midflame wind in feet per minute in order to be consistent with the rest of the publication. Consider a data point in fig. 19 associated with a 33-ft (10-m) wind of 19 miles h^{-1} (1672 ft min⁻¹, 30.6 km h^{-1}) that corresponds to the data point in fig. 20 with midflame wind of 670 ft min⁻¹ (12.3 km h^{-1}): 670/1672 = 0.4.

The wind speed at 33 ft (10 m) at the limit of the increasing spread rate trend line (see Fig. 1) is ~ 28 miles h⁻¹ (2464 ft min⁻¹, 45 km h⁻¹). The corresponding midflame wind speed is therefore 985 ft min⁻¹ (18.0 km h⁻¹), which was rounded to U_f of 1000 ft min⁻¹ (18.3 km h⁻¹).

For the wind speed and reaction intensity values associated with the McArthur data, using Eqns 9 and 10,

$$q = (2.74 \times 10^{-7})1000^2 = 0.274 \tag{11}$$

$$\frac{qU_f}{I_R J} = \frac{(3.52 \times 10^{-10})1000^3}{1105} = 3.19 \times 10^{-4}$$
(12)

Rothermel and Anderson (1966, their fig. 15) presented a plot showing a relationship between tan θ and qU_f/I_RJ . For $qU_f/I_RJ = 3.19 \times 10^{-4}$, the plot shows tan $\theta = 1.7$, so $\theta = 60^{\circ}$. A flame tilt angle of 60° is a reasonable angle for maximum flame tilt. The general case, with $q = 0.274 \,\text{lb}_f \,\text{ft}^{-2}$ (1.34 kg m⁻²) and $J = 778 \,\text{ft} \,\text{lb}_f \,\text{Btu}^{-1}$ is

$$\frac{qU_f}{I_R J} = (3.52 \times 10^{-4}) \frac{U_f}{I_R}$$
(13)

The wind limit is exceeded when the flame tilt for the general case is greater than that determined for the McArthur data.

$$(3.52 \times 10^{-4}) \frac{U_f}{I_R} > 3.19 \times 10^{-4} \tag{14}$$

$$\frac{U_f}{I_R} > 0.9 \tag{15}$$

The original wind limit as given in Rothermel (1972) is therefore

$$U_f = 0.9I_R \tag{16}$$

Wind limit function revision

In doing an examination of the above derivation for this paper, Richard Rothermel found a flaw in his earlier reasoning. The free stream dynamic pressure (q) for the general case was assumed to be the same as that determined for the McArthur data with $U_f = 1000 \text{ ft min}^{-1}$ and $q = 0.274 \text{ lb}_f \text{ ft}^{-2}$ (1.34 kg m⁻²). The correct interpretation is that q varies with the square of wind velocity. The flame angle for the general case using Eqns 7 and 8 is related to

$$\frac{qU_f}{I_R J} = \frac{\rho U_f^3}{2g_0 I_R J} = (3.52 \times 10^{-10}) \frac{U_f^3}{I_R}$$
(17)

For McArthur's data, as shown above,

$$\frac{qU_f}{I_R J} = 3.16 \times 10^{-4} \tag{18}$$

The wind limit is exceeded when the flame tilt for the general case is greater than that determined for the McArthur data.

$$(3.52 \times 10^{-10}) \frac{U_f{}^3}{I_R} > 3.19 \times 10^{-4}$$
(19)

$$\frac{U_f^3}{I_R} > 0.9063 \times 10^6 \tag{20}$$

The revised wind limit is

$$U_f = 96.8 I_R^{1/3} \tag{21}$$

Midflame wind speed

The wind limit function applies to midflame wind speed, the average wind velocity that affects surface fire spread. Although most of our analysis is based on midflame wind, recognition of the relationship of midflame wind to 20-ft, 10-m or 2-m wind is crucial to the evaluation of the wind limit function. The spread model was developed primarily from laboratory data for which the wind speed was essentially uniform in the wind tunnel. The term 'midflame' was coined to differentiate the wind affecting surface fire spread from the free wind at 20 ft (or 10 m) above the top of the vegetation. The fire model was designed to use the fuel and environmental conditions in which the fire is expected to burn; prior knowledge of the fuel's burning characteristics is not required. Flame dimensions are not needed to determine the wind speed for calculating spread rate.

Albini and Baughman (1979) developed wind adjustment factor (WAF) models for sheltered and unsheltered fuel. They defined WAF as the ratio of midflame wind to 20-ft wind. These models were used to develop WAF tables in the Fireline Handbook (NWCG 2006) and are the basis for calculations in fire modelling systems including BehavePlus and FARSITE (Andrews 2012). For fuels unsheltered from the wind by overstorey, the WAF model calculates midflame wind as the average wind from the top of the fuel bed to twice that height, based on a log wind profile. Consider the difference between use of that definition and a fixed 2-m wind. For unsheltered fuel with a depth of 0.3 m, WAF is 0.36. Using the log wind profile, the ratio of 2-m wind to 20-ft wind is 0.72. In this case, 2-m wind is twice the midflame wind.

Scott and Burgan (2005) compare the 40 fuel models using plots of rate of spread for midflame wind speed from 0 to 20 miles h^{-1} (32 km h^{-1}). The effect of the wind limit is evident in cases where spread rate is constant with increasing wind. Although they provide a consistent basis for fuel model comparison, the plots should be interpreted in terms of winds that are reasonable for sheltering conditions that are common for the fuel model. For fuels that are fully sheltered from the wind, WAF = 0.1; so 20-mile h^{-1} (32-km h^{-1}) midflame wind is equivalent to an unreasonably high 200-mile h^{-1} (322-km h^{-1})



Fig. 2. Fires from Tasmania 1967. Final perimeter and ignition locations are shown. Approximately 226 500 ha burned in a period of 5.5 h on 7 February, causing 62 human fatalities.

20-ft wind (10-m open wind of 370 km h⁻¹). A conifer litter fuel model, TL1, with 9% dead fuel moisture (moderate) shows a wind limit of 4.3 miles h⁻¹ (6.9 km h^{-1}) and a maximum spread rate of 0.6 chains h⁻¹ (0.2 m min^{-1}). The low wind limit seems more reasonable in terms of the equivalent 43-mile h⁻¹ (69-km h⁻¹) 20-ft wind (10-m open wind of 79 km h⁻¹) for fully sheltered fuels.

Methods

Wind limit and wind factor

The BehavePlus fire modelling system (Andrews *et al.* 2008) was used to examine the role of the wind limit function in the Rothermel model. The influence of fuel model and fuel moisture, and the relationship of wind factor and the wind limit function is demonstrated. The effect of no wind limit and the original and the revised limit functions on calculated spread rate is considered. BehavePlus includes the option of imposing the original wind limit or not, and provides intermediate values of fuelbed characteristic SAV, wind factor and wind limit. A BehavePlus export function was used to move values to a spreadsheet where additional calculations were done, including the A and B components of the wind factor and the revised wind limit. Example spread rate calculations using BehavePlus

were compared to wildfire data as a means of assessing the appropriateness of the wind limit function in the Rothermel model.

Wildfire data

In the context of the present work we present evidence that explains the trend exhibited by the 1967 Tasmania fires dataset in Fig. 1 and explore additional grassland wildfire data for evidence or absence of a decay in fire spread rate with exceedingly high wind speeds.

On 7 February 1967 a total of 110 fires, 90 of them already burning on the previous day, spread over extensive areas of southern Tasmania burning a total of ~226 500 ha and causing 62 human fatalities in a period of 5.5 h (Fig. 2). A 2001 fuel map is used to indicate possible fuel types during the fires (Department of the Environment and Water Resources 2001). Reconstruction of the propagation of these fires (McArthur and Cheney 1968; McArthur 1969) provided the data in Fig. 1 that underpin the idea of a decay on rate of fire spread in light fuels at very high wind speeds. Fire rates of spread and other accessory data relative to early 1967 grass curing state throughout southern Tasmania is on file with the CSIRO Bushfire Dynamics and Applications Group and was used in the analysis.



Fig. 3. Original wind limit for fuel model GR1 for dead fuel moisture from 3 to 15% and live fuel moisture 50, 100 and 150%. The wind limit is a function of reaction intensity, which is determined by fuel model and fuel moisture. The wind limit approaches zero as dead fuel moisture approaches the moisture of extinction.

Cheney et al. (1998) present a wildfire dataset based on personal observations and published case studies for free burning fires spreading in open and continuous grasslands in southeastern Australia. The dataset presents data for 23 distinct fire propagation periods relative to 19 fires spanning a period of three decades. Rates of fire spread varied between 67 and $383\,\mathrm{m\,min^{-1}}$ in burning periods with lengths varying from 0.25 to 7.7 h. The 10-m open wind speeds varied from 27 to $78\,km\,h^{-1},$ air temperatures from 34 to $43^\circ\!C$ and relative humidity from 7 to 20%. The dataset covers the high to extreme range of fire weather conditions associated with fast spreading fires. The dataset is accompanied by a reliability rating that characterises the uncertainty associated with the reported weather conditions and rates of fire spread. See Cheney et al. (1998, their table 1) for details of individual fires. Fuel loads or other fuel descriptors were not available for these fires. Fuel loads in southeastern Australia grasslands vary between 0.3 and 0.6 kg m⁻¹ (Luke and McArthur 1978; Sullivan et al. 2012).

As a complement to the Cheney *et al.* (1998) dataset, we examined data from the 18 January 2003 McIntyre Fire run into the Canberra suburbs, ACT (Cheney 2005) and the Wangary Fire, SA, on 10 and 11 January 2005 (Gould 2005; Cheney and Sullivan 2008). In the early afternoon of the 18 January 2003, the McIntyre fire spread in grassland fuels (both ungrazed and sparse pastures) at a rate of 183 m min^{-1} under average wind speeds between 37 and 48 km h^{-1} The fastest sustained rates of spread observed on the Wangary fire varied between 215 and 245 m min^{-1} under average wind speeds ranging from 46 to 61 km h^{-1} . Fine dead fuel moisture content values for these burning periods were estimated to be 2–3% (Cheney *et al.* 1998).

Results

Wind limit and wind factor

Wind limit in the Rothermel model is a function of reaction intensity, which is a function of fuel parameters and fuel moisture content. Fuel parameters are generally supplied in the form of fuel models. The original 13 fuel models best represent the severe period of the fire season when wildfires pose greater control problems (Anderson 1982). An additional 40 fuel models were developed to expand the range of conditions and improve fire behaviour predictions for low intensity fires outside of the severe period of the fire season (Scott and Burgan 2005). In total, 17 of the 40 fuel models are dynamic to represent curing; load is transferred from live to dead as a linear function of live fuel moisture. No load is transferred for live moisture over 120%; all live herbaceous fuel is classified as dead at live moisture of 30% (Burgan 1979). The effect of the wind limit is especially pronounced for dynamic fuel models with high live herbaceous fuel moisture (Jolly 2007). For example, fuel model GR1 represents short, sparse dry climate grass. At 150% live moisture, the original midflame wind limit is less than 2 km h⁻ even for very dry (3%) dead fuel (Fig. 3). Reaction intensity approaches zero as the dead fuel moisture increases to the moisture of extinction, resulting in a very low wind limit, even for live fuel moisture of 50%. Although more pronounced for dynamic grass fuel models, the wind limit is reached for all fuel models at very high moisture values.

The revised wind limit (Eqn 21) is higher than the original (Eqn 16) for reaction intensities less than $209 \,\mathrm{kW} \,\mathrm{m}^{-2}$ (1105 Btu ft⁻² min⁻¹) and much lower for high intensity fires (Fig. 4). The revised (corrected) wind limit function produces a higher limit for reaction intensities often associated with sparse grass fuels.

The effect of the original and revised wind limit on spread rate is demonstrated for dynamic grass fuel models GR1 and GR4 with 8% dead and 100% live fuel moisture and for midflame wind speed from 0 to 20 km h^{-1} (Fig. 5, Table 1). The original wind limit for fuel model GR1 is 2.6 km h^{-1} resulting in maximum rate of spread of only 0.2 m min⁻¹. The revised wind limit is 9.6 km h^{-1} with spread rate 1.3 m min^{-1} . Rate of spread for midflame wind of 20 km h^{-1} without imposition of a wind limit is 4.1 m min^{-1} . There is a significant difference in modelled spread rate for 20 km h^{-1} wind for original, revised and no wind limit options (0.2, 1.3 and 4.1 m min^{-1}).

Additional fuel models are used to demonstrate the relationship between wind factor and the wind limit function and to compare the original and the revised wind limits (Table 2). The seven fuel models represent a range of conditions as reflected in their total fuel load (live and dead), characteristic SAV and relative packing ratio. They are sorted by decreasing wind exponent (*B*). Wind factors are given for midflame wind speeds of 10 and 20 km h⁻¹. Reaction intensity and original and revised wind limits are given for each fuel model. Although *B* defines the form of the relationship between U_f and *R*, it is not the determining factor in whether the wind limit is reached. Fuel model GR1 (with B = 1.55) has an original wind limit of 2.6 km h⁻¹, whereas fuel model 2 (with a higher B = 1.83) has a wind limit of 54.7 km h⁻¹. Fuel model 4 (with a lower B = 1.42) has a wind limit of 187.5 km h⁻¹.

Empirical evidence

McArthur (1969) formulated the hypothesis that after a threshold 10-m average wind speed of \sim 45 km h⁻¹, the rates of



Fig. 4. Comparison of the original wind limit (Rothermel 1972) and a revised wind limit based on a changed assumption. The revised limit is higher than the original for reaction intensity $(I_R) < 209 \,\mathrm{kW \, m^{-2}}$ and much lower for high I_R .

spread of grassfires decrease with increasing wind speed. Reexamination of his data, as well as additional evidence from several wildfires, question this idea. In their development of a model to predict fire spread in grasslands, Cheney et al. (1998) 'rejected the contention that grass fire spread decreases rapidly with increases in wind speed ... '. They also stated 'considerable reservations about reports of headfires being blown out at high wind speeds in sparse pastures'. They noted that the Tasmania fires used in the McArthur analysis burnt through a mosaic of open grasslands, woodlands with grassy understorey and dry eucalypt forest, although they did not provide evidence. A current map of fuel types supports this assertion (see Fig. 2). Head fires propagating through a mosaic of fuel types would have slower rates of spread than fires burning in continuous open grassland.

An additional factor that might explain the slower than expected rates of spread observed in the Tasmania 1967 fires is incomplete curing of grassland fuels. On 7 February the Keetch Byram Drought Index (Keetch and Byram 1968) varied between 50 and 76 over the broad area affected by the fires. Although no grass curing samples were taken on this date in Hobart or surrounding areas, grass samples taken in South



Fig. 5. Rate of spread from the Rothermel model for a range of midflame wind speed for fuel models GR1 and GR4 (dead moisture 8%, live moisture 100%). Rate of spread is constant above the wind limit, which is a function of reaction intensity. For these low intensity fires, the revised wind limit is higher than the original limit.

Midflame wind speed (km h^{-1})

5

0

Tasmania before and after the fire reveal curing levels between 50 and 80% (Fig. 6) in areas with similar drought levels. This evidence contradicts McArthur's (1969) assumption of fully cured fuels for all grasslands in the area.

Fig. 7 shows predictions from the Rothermel model with the original McArthur (1969) data and the wildfire data from Cheney et al. (1998), Cheney (2005) and Gould (2005). Some observed spread rates are well above model results if the wind limits are applied.

Calculations were done with the original, revised and no wind limit using fuel model 1 (fully cured grass; 100% dead), fine dead fuel moisture content 4% and WAF of 0.46. Additional runs used fuel model 1 adjusted to include live fuel (80, 60 and 40% of the total fuel load remained dead). Recall that WAF is defined as the ratio of midflame wind to 20-ft wind and that Rothermel used 0.4 as the ratio of midflame wind to 10-m wind. The ratio of 10-m wind to 20-ft wind is taken to be 1.15 (Lawson and Armitage 2008). Therefore, for this case, $WAF = 0.40 \times 1.15 = 0.46.$

The post-1967 wildfire data invalidates the concept of a decrease in rate of spread with increasing wind speeds in cured grassland fuels. Because the 24 data points from the Tasmania fires in Figs 1 and 7 were derived from a sole burning period, i.e. same fire weather and drought conditions, the trend suggested by these fires needs to be regarded with caution. Uncertainties regarding the mixture of fuel types, curing state and representativeness of the Hobart weather station data (located up to 50 km away from some of the fires) can induce a bias in the analysis. The convergence of these effects possibly caused a reduction in the rate of grassland fire spread and can explain the distinct trends between the Hobart fires and the post-1967 wildfire data. Model results for less than fully cured fuel shows that the presence of live fuel is a plausible influence leading to reduction in spread rates with increasing wind for the Tasmania data.

Table 1. The original and revised midflame wind speed limit for fuel models GR1 and GR4 and rate of spread with imposition of a wind limit and with no wind limit (see Fig. 5)

For I_R , dead fuel moisture 8%, live fuel moisture 100%. For R, midflame wind speed was 20 km h⁻¹

Fuel model	$I_R (\mathrm{kW}\mathrm{m}^{-2})$	Midflame wind sp	beed limit (kmh^{-1})	<i>R</i> with wind limit $(m \min^{-1})$			
		Original	Revised	Original	Revised	None	
GR1 – short, sparse, dry climate grass	30	2.6	9.6	0.2	1.3	4.1	
GR4 - moderate load, dry climate grass	116	10.1	15.0	4.3	7.5	11.3	

Table 2. Comparison of wind factors and midflame wind speed limits for seven of the 53 standard fire behaviour fuel models, sorted by the wind factor exponent (B)

B is a function of characteristic surface-area : volume ratio (SAV). Wind factor is given for midflame wind of 10 and 20 km h⁻¹. Wind limit is based on reaction intensity (I_R), which is found from the fuel description and fuel moisture. The original wind limit is lower than the revised wind limit for $I_R < 209$ kW m⁻². For wind limit calculations, dead fuel moisture is 8% and live fuel moisture is 100%. Fuel models 1, TL9 and 12 do not include live fuel

Fuel model	Fuel model characteristics					Wind factor		Wind limit		
	Total fuel load $(kg m^{-2})$	Characteristic SAV $(m^2 m^{-3})$	Relative packing ratio	А	В	Wind factor $\varphi_w = A U_f^B$		$I_R (kW m^{-2})$	Midflame wind speed limit (km h ⁻¹)	
						$U_f = 10 \mathrm{km}\mathrm{h}^{-1}$	$U_f = 20 \mathrm{km}\mathrm{h}^{-1}$		Original	Revised
1 – short grass	0.17	11 483	0.2534	0.29	2.07	33.6	141.2	145	12.6	16.1
2 - timber grass and understory	0.90	9134	1.1369	0.32	1.83	21.8	77.6	629	54.7	26.3
GR1-short, sparse, dry climate grass	0.09	6738	0.2211	0.92	1.55	32.9	96.4	30	2.6	9.6
4 – chaparral	3.59	5706	0.5156	0.90	1.42	23.6	63.1	2157	187.5	39.7
TL9 – very high load broadleaf litter	3.16	5687	4.5230	0.39	1.42	10.2	27.3	822	71.4	28.8
12 – medium logging slash	7.75	3755	2.0590	0.82	1.13	11.1	24.4	1192	103.6	32.6
SH6 – low load, humid climate shrub	1.29	3754	0.3938	1.80	1.13	24.4	53.5	855	74.3	29.2

Trend of grass curing throughout Tasmania 1966-67



Fig. 6. Curing data indicate that it is likely that not all grasses that burned in the 7 February 1967 Tasmania fires were fully cured (redrafted from a hand drawn plot on file at CSIRO). (See Fig. 2 for sample site locations.)



Fig. 7. Data from McArthur (1969) (Fig. 1) and more recent data compared to results from the Rothermel spread model (fuel model 1 with the original, revised and no wind limit; fuel model 1 adjusted to include live fuel, with no wind limit; WAF = 0.46; 4% dead fuel moisture; 75% live fuel moisture).

Fig. 7 suggests that model predictions with a wind limit, either the original or the revised one, induce an under-prediction bias in fully cured grassland fuels under severe burning conditions.

To show the possible effect of modelling spread of a fire burning grass that is not fully cured, fuel model 1 was adjusted so that 80, 60 and 40% of the total fuel load is categorised as dead and the rest as live fuel with a moisture content of 75%. Based on model results, the presence of live fuel can explain the reduction in spread rate with increasing wind speed.

Fig. 7 does not aim to provide an evaluation of the predictive capacity of the Rothermel (1972) model. Model results are based on constant fuel moisture values and a standard fuel model adjusted for four levels of curing (percentage dead) because specific conditions associated with each data point are not available (curing status, fuel load and depth). The intent is to assess the reasonableness of the wind limit functions and to examine model results for grasslands that are not fully cured, as an alternate explanation of the Tasmania data.

Discussion

It is conceivable that there is a point at which spread rate ceases to increase with increasing winds. We have presented strong evidence that questions both the original and a revised wind limit function in the Rothermel model. The high spread rates reported in the previous sections for high wind speeds were likely a result of short range spotting and rolling debris, violating the model's simplifying assumptions of uniform conditions and quasi-steady-state spread (Gould 2005). As such, if fires spread faster with increasing winds, by whatever mechanism, then we feel that it is not appropriate to impose a wind limit on the model predictions.

Formulation of the Rothermel model is such that, in extreme cases, the rate of spread can exceed midflame wind speed (Beer 1991). Of the 53 fuel models burning under extreme dry conditions (fuel moisture 3% dead, 30% live) on flat ground, only fuel models 1 and GR9 produce $R > U_f$ for $U_f > 0$. Modelled rate of spread for fuel model 1, without imposition of the wind limit, exceeds midflame wind for $U_f > 26 \text{ km h}^{-1}$ (10-m wind 83 km h⁻¹). Although the wind limit is not reached for fuel model GR9 (very high load, humid climate grass), $R > U_f$ for $U_f > 22 \text{ km h}^{-1}$. In the rare cases when calculated rate of spread is greater than non-zero effective midflame wind speed, it is reasonable to reset *R* to the effective wind value.

When models are used to support fire management decisions, under-prediction of fire behaviour is less acceptable than overprediction. In addition to wildfire behaviour prediction, contingency plans in a fire prescription include the potential spread of an escaped fire. Under-prediction would also be undesirable for low intensity fires burning under moist conditions, which are modelled for prescribed fire planning. The wind limit can affect other model predictions. In BehavePlus, for example, rate of spread is used to calculate flame length and fireline intensity, which are in turn used to model transition to crown fire, safety zone size, crown scorch height and tree mortality (Andrews, in press).

Given the wide application and many implementations of the Rothermel model, the effect of a change to the model through removal of the wind limit should include recognition that more is involved than a minor change to computer code. Consistency among the many computer programs and guides that support fire management is a consideration. A change in model results could affect existing plans and reports. Publications, tables and nomographs are not easily changed (Scott and Burgan 2005; NWCG 2006). Although the original nomographs for the 13 fuel models (Albini 1976) include the wind limit by a dashed line with a warning, a recent set of nomographs (Scott 2007) do not produce results beyond the wind limit. Most current fire modelling

systems including FARSITE and FlamMap strictly impose the wind limit. An option of not imposing the wind limit is available in BehavePlus.

Conclusions

The Rothermel model includes a wind limit function that is based on a reasonable assumption that higher intensity fires can withstand higher wind speeds (have higher wind speed limits) than fires with lower intensities. A revised wind limit function, using a corrected assumption, gives what appear to be more reasonable results, with a higher wind limit for low intensity fires and a lower wind limit for high intensity fires. The wind limit function is based in part on McArthur's (1969) presentation of and interpretation of fire spread data that decreased with increasing winds. An analysis of conditions driving the 7 February 1967 Tasmanian grassland fires indicates that these fires might not have been spreading in fully cured continuous grasslands, as assumed. In addition, more recent grassfire data do not support imposition of a wind limit.

Although the wind limit function was included in the Rothermel model to avoid over-prediction of fires burning in sparse fuels under high winds, it also plays a role in low intensity fires resulting from high moisture content. The influence is especially evident for dynamic grass fuel models with high live fuel moisture content (Scott and Burgan 2005; Jolly 2007).

If there is a limit to the speed at which a surface fire can spread under increasing wind speeds, we don't yet have a sufficient understanding of the mechanisms of spread to properly define that limit. Data are not available to develop a new wind limit function in the framework of the Rothermel model. To avoid potential under-prediction of fire behaviour and related fire effects, we recommend that (a) neither the original nor the improved revised wind limit be imposed on the spread rate calculations and (b) that modelled rate of spread not exceed the effective midflame wind speed.

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