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Wildfire Rates of Spread in Grasslands under Critical Burning Conditions

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Abstract: An analysis of a dataset (n = 58) of high-intensity wildfire observations in cured grasslands from southern Australia revealed a simple relationship suitable for quickly obtaining a first approximation of a fire's spread rate under low dead fuel moisture contents and strong wind speeds. It was found that the forward rate of fire spread is approximately 20% of the average 10-m open wind speed. The data on rate of fire spread and 10 m open wind speed ranged from 1.6 to 17 and 20 to 62 km h^{-1}, respectively. The validity of the resulting rule of thumb was examined across a spectrum of burning conditions and its performance was contrasted against that of established empirical-based fire spread models for three different grassland fuel conditions currently used operationally in Australia. The 20% rule of thumb for grassfires produced error statistics comparable to that of the fire spread rate model for grazed or cut grass fuel conditions as recommended for general use during the summer fire season in southern Australia.

Keywords: fine dead fuel moisture content; fire behaviour; fire danger; fire prediction; fire propagation; fire safety; fire weather; grass fuel condition; model error; wind speed

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Citation: Cruz, M.G.; Alexander, M.E.; Kilinc, M. Wildfire Rates of Spread in Grasslands under Critical Burning Conditions. *Fire* **2022**, *5*, 55. https://doi.org/10.3390/fire5020055

Academic Editors: Russ Parsons and Alistair M. S. Smith

Received: 11 March 2022
Accepted: 12 April 2022
Published: 14 April 2022

1. Introduction

Grass-dominated biomes, ranging from temperate open grasslands and steppes to savanna type shrublands and woodlands, occupy more than 40% of the earth's vegetative cover [1]. Fire, either of natural or anthropogenic origins, and other human activities such as grazing and cultivation are key in maintaining grassland areas.

Most grassland fuels comprise very fine-sized fuel particles with corresponding high surface area-to-volume ratios [2] and light fuel loads compared to other vegetation/fuel types [3]. When fully cured, grass fuel-beds are highly combustible (Figure 1) and grassfires, given their short flame front residence times [4], in turn become exceptionally responsive to wind speed and direction [5–7] in comparison to other wildland fuel complexes such as forests and shrublands [8].

At the extreme end of the fire danger rating scale, grassfires have been observed to propagate over multi-hour periods with sustained rates of spread in excess of 6.0 km h^{-1} (or 100 m min^{-1}) [9–13], easily exceeding the maximums observed in many other wildland fuel types [14]. For example, at 27.3 km h^{-1}, the 1987 Boonoke grassfire in southwestern New South Wales, Australia [15], represents one of the fastest spreading wildfires documented anywhere in the world to date, being observed to advance 25 km over the span of 55 min. Higher rates of spread (i.e., >30 km h^{-1}), often associated with shorter time intervals (e.g., 10 min), have been documented, for example, on the 2005 Wangary Fire in South Australia [8,16] and have been anecdotally described for the 2016 Anderson Creek Fire [17] that occurred in northcentral Oklahoma/southcentral Kansas [18]. Nonetheless, it is unclear if these observations of higher rates of spread can be sustained over long time periods, such as an hour, or if they represent short-term fluctuations that result from occasional peak periods in wind velocity, fire-to-fire and fire-atmosphere interactions or if they are the results of the observation of localised pseudo-flame fronts associated with spotting behaviour that are perceived at times by observers as the main advancing head fire.

Figure 1. A flattened smoke/convection column and a high elliptical fire length-to-breath ratio [19] are hallmarks of a fast-spreading grassfire driven by strong winds. Aerial oblique photos of (**top**) the Cascades fire in Western Australia on 17 November 2015 during its 94 km run as viewed from an airliner (photo courtesy of Australian Broadcasting Corporation); (**lower left**) the Blackford fire in South Australia on 1 November 2021 at 14:31, approximately two hours after ignition; this fire ended up spreading 39 km under the influence of wind speeds averaging 35 km h^{-1} during a single afternoon burning period (photo by Karen Barnes, South Australia Country Fire Service); and (**lower right**) the Parker Creek Fire in Texas on 15 December 2021 during a severe wind event (photo courtesy of Texas A&M Forest Service).

Given their potential rapid rates of spread, wildfires burning in fully cured grasslands under the influence of low relative humidity (<20%) and strong winds (>40 km h^{-1}) can quickly grow to areas of more than 100 km^2 (or 10,000 ha) in a single day [12,15,18–20], as illustrated in the example of the 1983 Narraweena Fire in southeastern South Australia that advanced some 65 km in a single general direction from its point of origin in a little less than four hours, burning an estimated 347 km^2 of grasslands before a change in the wind direction caused the eastern flank to become a wide head with numerous 'fingers' and 'bays' (Figure 2).

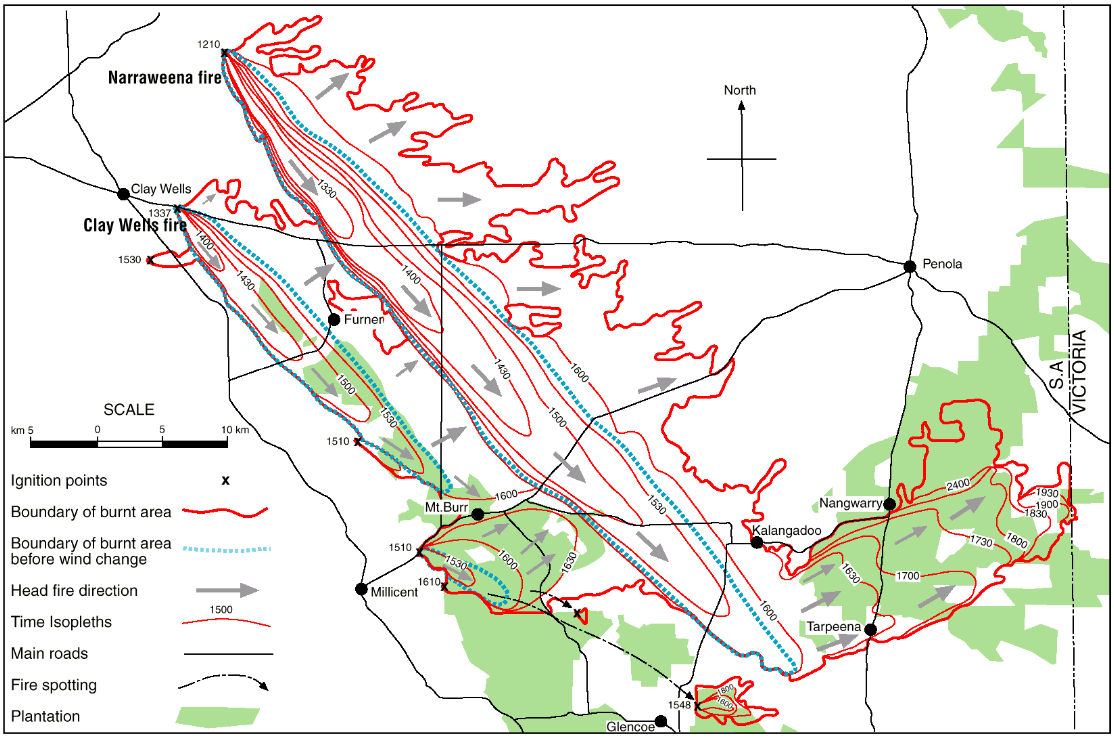

Figure 2. Progress map for the Narraweena and Clay Wells fires in southeastern South Australia on Ash Wednesday, 16 February 1983 (from [8] (p. 93) based on [21]).

It is expected that such examples of extreme wildfire behaviour events are observed throughout grassland areas of the world, which experience a marked dry season and occasional brief occurrences of heightened fire spread potential. However, such grassfires are very seldom described in the scientific literature.

As a result of their rapid spread rate potential at certain times of the year, grassfires are quite often associated with both civilian and firefighter fatalities, particularly in rural areas [12,16,18–20,22–26]. One of the most notable incidents, involving the largest number of grassfire-related human fatalities in Australia (23 in total [27]), occurred on 8 January 1969 near the community of Avalon in southcentral Victoria, in which 17 holiday travelers lost their lives when they became trapped by a grassfire after having exited their cars along the freeway between Geelong and Melbourne [3,28].

Under certain combinations of environmental conditions [19], wildfires and especially those spreading in cured grasslands can quickly impact rural communities with little or no warning. In such cases, traditional predictive fire spread capacity [29–31] may not be capable of issuing timely emergency warnings to the general public in advance of a rapidly spreading grassfire impacting them and the community's values-at-risk [14,32].

Cruz and Alexander [33] have showed that a wildfire's propagation under heightened fire danger conditions in conifer forests, eucalypt forests and shrubland fuel types will have a forward rate of spread that can be approximated as 10% of the average 10 m open wind speed where both values are expressed in the same units. For example, given an average open wind speed of 40 km h^{-1}, the wildfire spread rate would be estimated to be about 4 km h^{-1}. They based this rule of thumb on the analysis of a large wildfire case study dataset (n = 118). Subsequently, they undertook an evaluation study of this rule of thumb that confirmed its validity [14].

The 10% rule of thumb was deemed not applicable to grasslands [33]. The purpose of this paper is to examine the feasibility of devising a simple rule of thumb for estimating the rate of spread of wildfires in cured grasslands from wind speed alone.

2. Materials and Methods

2.1. Data

The data used to evaluate the suitability of a simple relationship between the average 10-m open wind speed (U_{10}, km h^{-1}) and the average forward rate of fire spread (R, km h^{-1}) for grassfires came from the datasets given in [10,34,35], augmented by data from two significant large-scale grassfires in recent times, the 2005 Wangary fire (780 km^2 area burned) in South Australia [16] and the 2015 Cascade fire (1280 km^2) in Western Australia [12]. In addition to information on R and U_{10} for particular fire runs, these datasets included information on the date of the fire, the time interval and, thus, the duration of the fire spread observation; ambient air temperature (T, °C); relative humidity (RH, %), degree of curing (C, %); grass fuel condition (i.e., undisturbed (uncut or very lightly grazed), grazed or cut, and eaten-out (or very heavily grazed)) as per [8,10]; and a reliability rating of the weather and fire spread rate data (Table 1). The values of C were not directly measured in the field but rather estimated visually. All of the fire runs selected for analysis occurred on flat or undulating terrain; thus, slope steepness was not a factor influencing the associated spread rates. All fire runs were also representative of a fire propagating after achieving a pseudo steady-state condition [7,10]. Readers interested in further details should consult the associated publications on the data sources [10,34,35] and case studies [12,16].

Table 1. Reliability rating scheme for weather and fire spread observations for wildfire behaviour case study documentation reported in Australian grasslands (after [10]).

Rating	Weather	Fire Spread
1	Nearby meteorological station or direct observation.	Direct timing from field measurements by authors.
2	Meteorological station within 50 km of the fire site.	Reliable timing by a third party.
3	Meteorological station > 50 km, reconstruction of wind speed for fire site.	Reconstruction based on numerous cross references from third party observations.
4	Spot meteorological observations near the fire site.	Doubtful reconstruction.
5	Distant meteorological observations at locations very different to the fire site.	Anecdotal or conflicting reports.

2.2. Imposed Data Constraints

Criteria were imposed on the data to ensure compatibility with the intended use of the study results to provide approximate predictions of wildfire spread rates in cured grasslands over periods of one hour or more from forecasted weather data. We removed data where the spread observation interval was less than one hour, as we considered small duration wildfire runs to have a high uncertainty and to be poorly correlated with the hourly or half-hourly weather data that is normally recorded at a weather station located tens of kilometres from the headfire region. We also imposed constraints to remove situations with reduced fire spread potential—i.e., we only considered observations with a fine dead fuel moisture content (MC, %) < 10%, a C > 90% and when the Grassland Fire Danger Index ($GFDI$) [19] was >30. To remove data with higher uncertainty, we also did not consider fire spread runs where at least one of the two reliability ratings of 5 was present (Table 1).

2.3. Model Calculations

Several modelled variables were used to support the analysis. *MC*, a variable not typically measured directly during wildfire events, was estimated from an equation developed from McArthur's [36] fuel moisture table. The equation is given in Appendix A (see Equation (A1)). The *GFDI*, a surrogate for fire spread potential incorporating the effects of *C*, *T*, *RH* and U_{10}, was calculated using the Mk 3 equation given in [37]; see Equation (A2). We also contrasted the fit statistics obtained from this analysis with the statistics obtained using the Cheney et al. [10] models currently used operationally in Australia for predicting the rate of spread of wildfires in the following grassland fuel conditions: (1) undisturbed, (2) grazed or cut and (3) eaten-out (see Equations (A3)–(A5), respectively).

2.4. Statistics

Linear regression analysis was used to develop a statistical relationship between *R* and U_{10}. The results from this analysis were used for deriving a first approximation rule of thumb. Error metrics used to quantify and compare the predictive accuracy of different models were the mean absolute error (MAE), mean bias error (MBE), mean absolute percent error (MAPE) and the root mean square error (RMSE) [38–40]. Statistical analysis was undertaking using the R 4.1.2 software package [41].

3. Results

3.1. Dataset Characteristics

A total of 24 *R* observations were presented in the [10] dataset, 187 in the [34,35] database, 15 in [16] and one run in [12]. After applying the data selection criteria, removing duplicated fire runs and excluding data with a reliability rating (Table 1) of 5 (i.e., the poorest), the dataset for analysis in the present study comprised a total of 58 wildfire observations with a fire run duration of >1.0 h, a $C > 90\%$, an $MC < 10\%$ and a $GFDI > 30$. The fires in the assembled dataset include representation from Australian states of New South Wales, Victoria, South Australia and Western Australia.

Table 2 provides the basic statistics for the analysis dataset. The *R* averaged 6.9 km h^{-1}, varying between 1.6 and 17 km h^{-1}. The fire run duration averaged 1.9 h, with the longest spread distance being that of the 1983 Narraweena fire (Figure 2) that spread approximately 65 km over a period of 3.8 h [21]. The estimated *MC* and U_{10} ranged between 1.5 and 9.6%, and 20 and 62 km h^{-1}, respectively. The *GFDI* averaged 101, with 49 of the 58 observations above a *GFDI* of 50, which is the Extreme Fire Danger Rating Class for grasslands [19]. The wildfires spread in a combination of native grasslands, pastures and winter crops (e.g., wheat, barley and canola). The dataset was characterised by the three grass fuel conditions as described by [8,10] with the following distribution: two fire runs in the undisturbed condition, 38 fire runs in grazed or cut condition and 18 fire runs in an eaten-out condition.

Table 2. Summary of basic statistics for observed rate of fire spread (*R*), 10 m open wind speed (U_{10}), ambient air temperature (*T*), relative humidity (*RH*), estimated fine dead fuel moisture content (*MC*), Grassland Fire Danger Index (*GFDI*) and fire run duration for the grassland wildfires analysed in this study.

Variable	Mean (Standard Deviation)	Range
R (km h^{-1})	6.9 (3.6)	1.6–17.0
U_{10} (km h^{-1})	42.1 (9.3)	20.0–62.0
T (°C)	37.0 (4.5)	23.7–43.0
RH (%)	12.4 (7.2)	3–36
MC (%)	3.7 (1.9)	1.5–9.6
GFDI	101.6 (53.3)	30.3–267.1
Fire run duration (h)	1.9 (1.3)	1.0–5.0

3.2. Modelling

A simple linear regression analysis of R with U_{10} as the sole explanatory variable produced a slope of 0.17122 (p = 0.001) and a y-intercept of −0.2559 (p = 0.89). A similar regression forced through the origin produced a slope of 0.1654 (p < 0.0001). This equation produced an adjusted R^2 of 0.82, an MAE of 2.6 km h^{-1}, an MBE of 0.01 km h^{-1} and an MAPE of 51%.

Assuming the rate of fire spread as being 20% of the wind speed (i.e., an 0.2 multiplier) yielded an MAE of 2.83 km h^{-1}, an MBE of 1.47 (i.e., an over-prediction) and a MAPE of 65.5% (Figure 3). Residuals from the application of this model (Figure 4) were not significantly correlated with *MC* (Pearson r = 0.20; p = 0.13) or *GFDI* (Pearson r = −0.02; p = 0.88). These results suggest that the *MC* values contained in the dataset have no relevance in further explaining the variation in R under the associated heighted fire danger conditions of the dataset. It is noted that all fires with an *MC* above 6% (n = 6) were over-predicted by this model (Figure 4c).

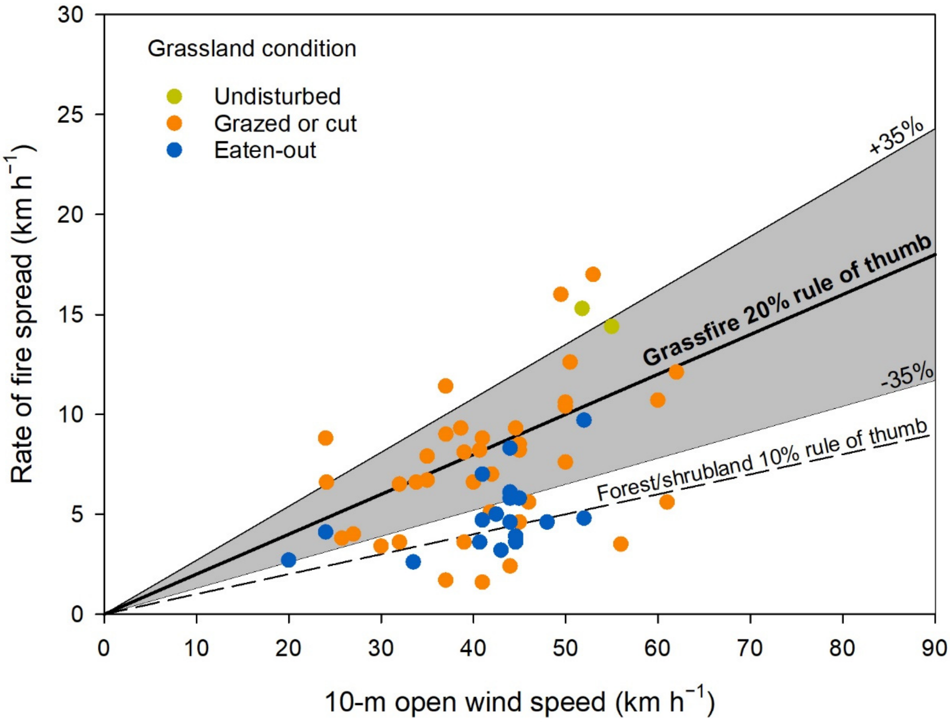

Figure 3. Plot of the 20% rule of thumb line and ±35% error prediction intervals as per the suggestion of [40] against the observations of rate of spread for the 58 wildfires in grasslands used in the present study analysis. The 10% rule of thumb for forests and shrublands of [33] is plotted for contrasting purposes.

Considering the distribution of error statistics by grass fuel condition (Table 3), the 20% rule of thumb predicted the grazed or cut grass fuel condition data the best, with the MAE, MBE and MAPE being reduced to 2.54 km h^{-1}, 0.89 km h^{-1} and 51%, respectively. This model under-predicted the two undisturbed or natural grassland condition R observations with an average error of 4.17 km h^{-1} and over-predicted the eaten-out condition observations, with an MAE of 3.30 km h^{-1} and a MAPE of 80%.

Applying the three grassfire rate of spread models of Cheney et al. [10] to the entire dataset resulted in a comparable MAE (2.86 km h^{-1}) and MAPE (60%) and an increase in the over-prediction bias to 2.07 km h^{-1} (Table 3). When contrasting evaluation statistics obtained with the 20% rule of thumb against those yielded by considering the specific grassland fuel conditions, a number of distinct trends were observed. For the grazed or cut fuel condition, the fire spread model produced higher errors than those obtained with the rule of thumb. The MAE was 3.34 km h^{-1} (vs. 2.54 km h^{-1} with rule of thumb), the MBE was 2.68 km h^{-1} (vs. 0.89 km h^{-1}) and the MAPE was 74% (vs. 51%), although the rule of thumb under-predicted the two fastest spreading fires (Figures 3 and 5).

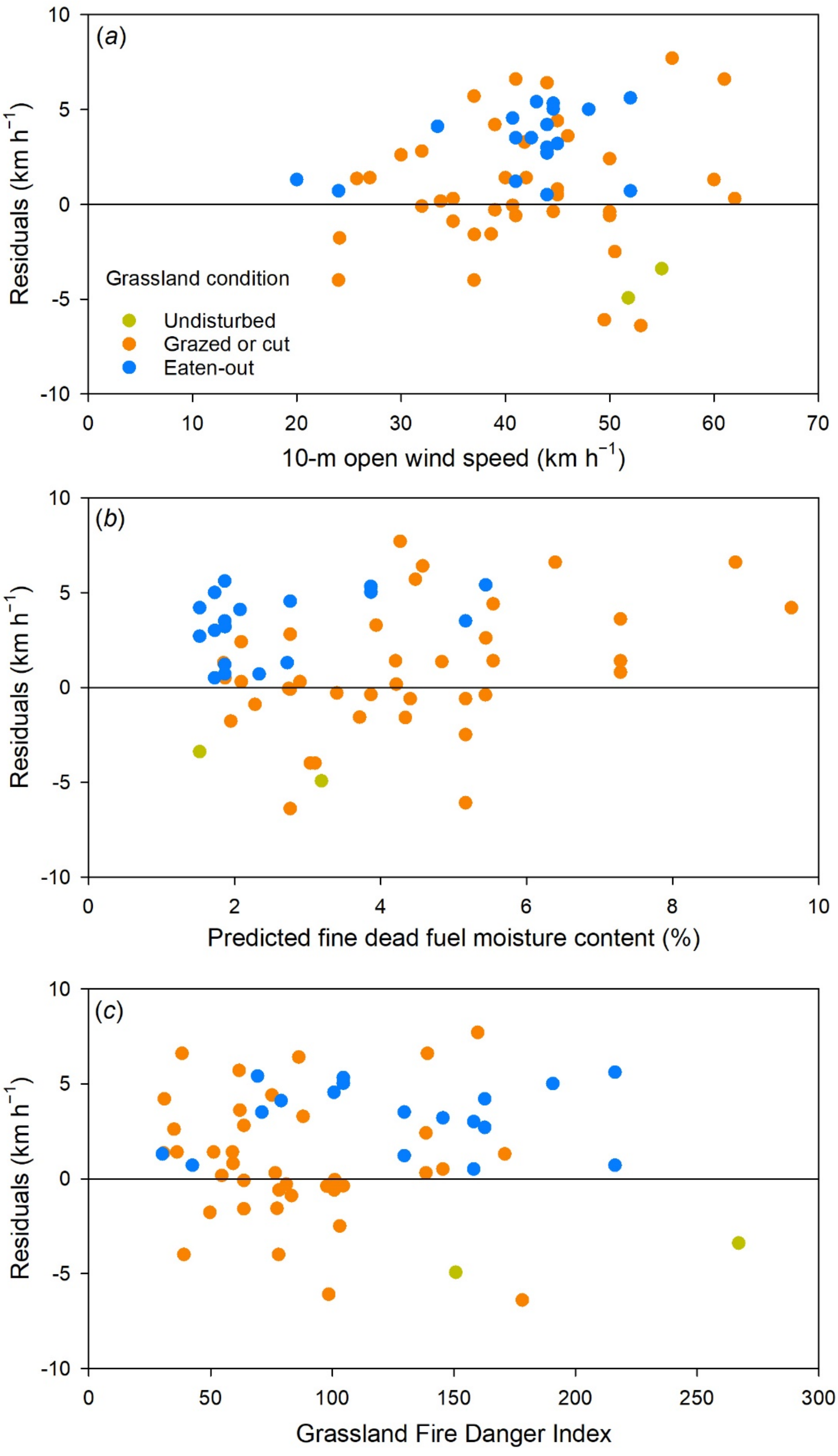

Figure 4. Residuals from the use of the grassfire 20% rule of thumb vs. (**a**) Open wind speed at 10 m (km h^{-1}), (**b**) predicted fine dead fuel moisture content (%) and (**c**) Grassland Fire Danger Index.

Table 3. Summary of evaluation statistics for predicted rate of fire spread by the 20% rule of thumb for grasslands and the Cheney et al. [10] rate of fire spread models for the three Australian grassland fuel conditions.

Grassfire Rate of Spread Models by Fuel Condition	MAE (km h^{-1})	MAPE (%)	MBE (km h^{-1})	RMSE (km h^{-1})
		20% Rule of Thumb		
All data (n = 58)	2.83	66	1.47	3.53
Undisturbed (n = 2)	4.17	28	−4.17	4.24
Grazed or cut (n = 38)	2.54	51	0.89	3.39
Eaten-out (n = 18)	3.30	80	3.30	3.72
		Cheney et al. [10] Models		
All data (n = 58)	2.86	60	2.07	3.67
Undisturbed (n = 2)	3.52	24	3.52	4.36
Grazed or cut (n = 38)	3.34	74	2.68	4.16
Eaten-out (n = 18)	1.58	36	1.10	1.80

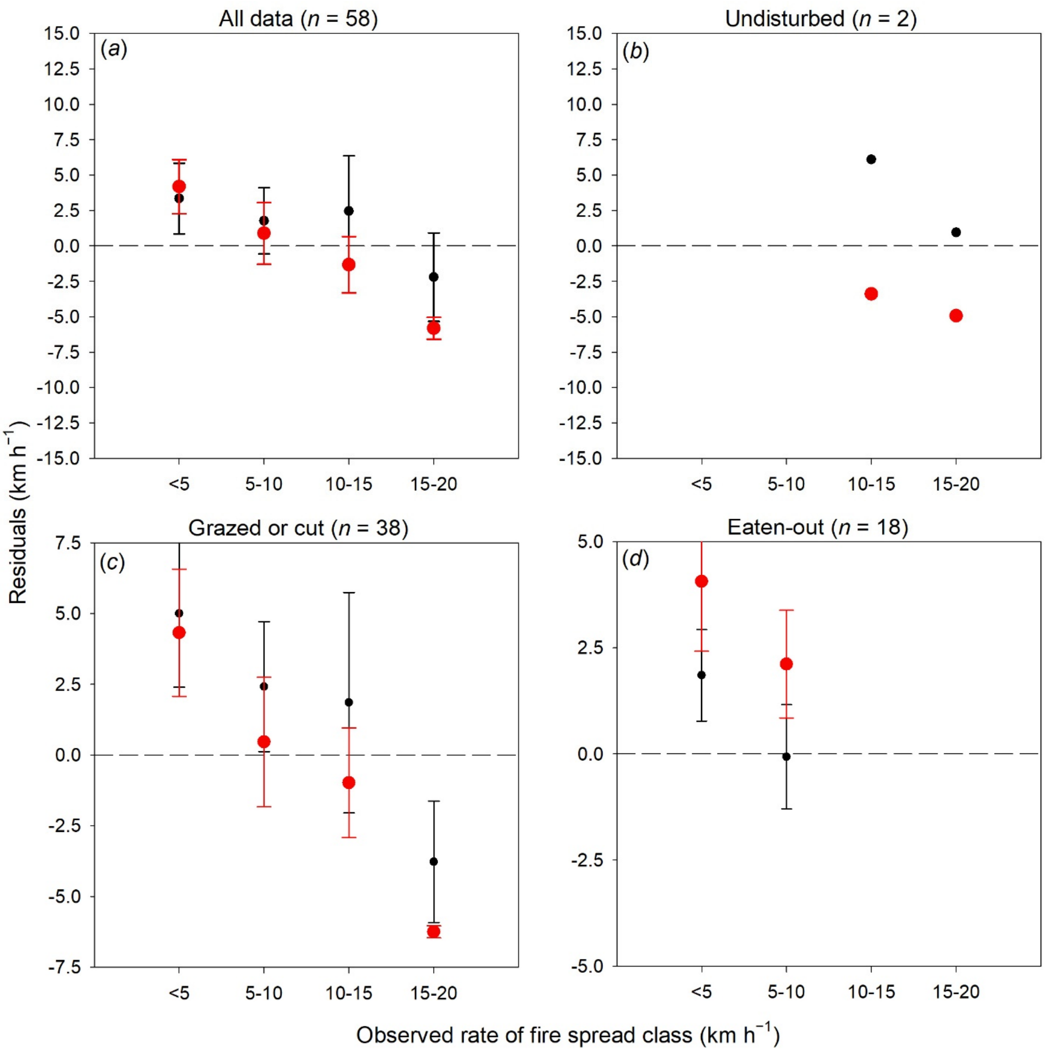

Figure 5. Distribution of mean residuals and standard deviation obtained by the Cheney et al. [10] models (black symbols, •) and the 20% rule of thumb (red symbols, •) across a rate of fire spread spectrum for (**a**) all fires and the three separate grass fuel conditions: (**b**) undisturbed; (**c**) grazed or cut; and (**d**) eaten-out.

In contrast, the fire spread model predictions were more accurate than the rule of thumb for the undisturbed and eaten-out grass conditions, with an MAE of 3.52 and 1.58 km h^{-1} and MAPE of 24% and 36%, respectively (Table 3). For these grassland fuel conditions, the rule of thumb under-predicted all the undisturbed grassfires and over-predicted the eaten-out ones (Figures 4 and 5).

4. Discussion

4.1. General Findings

Our analysis suggests that under critical burning conditions, as defined by high wind speeds, low fine dead fuel moisture content and highly cured fuel-beds, wind speed exerts the dominant effect on the spread rate of grassfires. In such situations, the rate of fire spread in grassland fuel types can very well be approximated as being 20% of the prevailing wind speed. We propose and have, thus, focused our analysis on the 0.2 wind speed multiplier instead of the more precise 0.165 value obtained from regression analyses. We selected this value as it makes computing a grassfire's spread rate from wind speed alone much easier and faster using mental arithmetic.

It is worth pointing out that the 20% wind speed rule of thumb for grassfires results in an approximate 15% over-prediction bias in comparison to use of the statistically derived coefficient. Over-predictions of fire behaviour can be easily adjusted without serious consequences whereas under-predictions can be potentially disastrous [42].

The contrast between our results and those obtained by [33], where it was found that the spread rate of fires in forests and shrublands was well approximated as 10% of the wind speed, reveals that under critical burning conditions, grassfires can spread at about twice the rate of fires occurring in forests and shrublands. Grassfires are, thus, capable of covering the same distance in roughly half the time.

The bulk of the data used in the present study analysis had U_{10} levels > 30 km h^{-1} and estimated MC values < 6%. These thresholds are in close agreement with the findings of [14,33] for the 10% wind speed rule of thumb for fire spread rates in forests and shrublands and should, therefore, be used as the application bounds for the grassfire rule of thumb as well.

4.2. Grassland Fuel Condition and Wildfire Propagation

Any given grassland landscape in southern Australia might very well be represented by a mosaic of varied fuel-bed conditions, composed of native grasslands as well as pastures under different grazing pressures, and winter crops (e.g., wheat, barley and canola) that could be in an unharvested (early in the fire season) or harvested state. From a fire behaviour prediction perspective, there are seasonal changes in the grass fuels across the landscape that determine which of the three Cheney et al. [10] fire spread models (Appendix A) would, for general purposes, be the most appropriate for predicting grassfire propagation. Given the current operational inability to readily map the dynamic nature of the grassland fuel condition mosaic at the landscape scale, Cheney and Sullivan [8] recommended the grazed or cut grass fuel condition model as being the most appropriate for predicting fire spread in typical summer-time situations.

Although the 20% rule of thumb was not developed to serve as a substitute for any one of the Cheney et al. [10] models (Figure 6a), it is worth noting that the fit statistics obtained with the application of the rule of thumb for this dataset were comparable to the fire spread rate model for the grazed or cut condition. The 20% rule of thumb produced smaller average errors for fires spreading with an R up to 15 km h^{-1}, but larger under-predictions resulted for faster spreading fires. During severe drought periods, grasslands might be better characterised by the eaten-out condition for fire behaviour prediction purposes. For this grassland fuel condition, the rule of thumb over-predicted all 18 fires in the dataset. The slower spread rate in this grassland fuel condition is likely to be related to the following: (1) an inherent slower flame spread rate due to the horizontally oriented fuels and limiting fuel quantity; and (2) the inability of the small flames associated with these fuels to breach areas with horizontal fuel discontinuities, such as roads or other non-burnable areas (e.g., firebreak and ploughed field). From these results, it is expected that the rule of thumb will likely over-predict the fire spread potential in this grassland fuel condition.

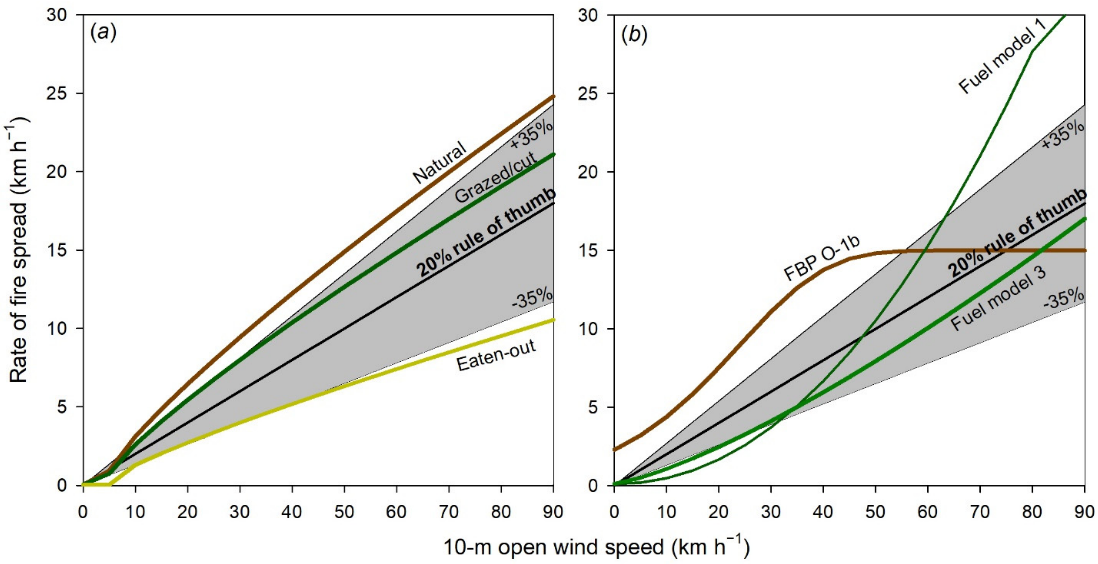

Figure 6. Model predictions of rate of fire spread as a function of 10 m open wind speed on level ground for the 20% rule of thumb in contrast to those fire spread models used operationally in Australia and North America and the ±35% error prediction intervals as per [40]. This includes the following: (**a**) the three grassland fuel condition types (natural, grazed or cut and eaten-out) in southern Australia of [10]; and (**b**) fuel type O-1b (standing grass) in the Canadian Forest Fire Behavior Prediction (FBP) System [43,44] and the Rothermel [45] model as implemented in the US BehavePlus Fire Modeling System [46] for two of the three grass fuel models (1—short grass (0.3 m); 3—tall grass (0.75 m)) found in [47] based on a wind adjustment factor of 0.4 [48]. Simulations assume a 100% degree of curing and a fine dead fuel moisture content of 3.7% (the average in the database used in the present study analysis).

4.3. Main Assumptions of the Grassfire Rule of Thumb

We believe that predictions based on the 20% rule of thumb are likely to represent a worst or near-worst case scenario for fire spread where fine dead fuel moisture contents are low (i.e., <6%); open winds are strong (i.e., >30 km h^{-1}) and gusty; and there are no appreciable barriers to fire spread that would hinder or momentarily limit fire propagation and that fire suppression efforts are not successful in constraining fire spread and size and, hence, reducing the overall propagation. Within this context, the application of the rule of thumb assumes that the landscape is essentially fully cured. The existence of wetter or less than fully cured areas, such as along creek lines and other breaks in landscape fuel continuity (e.g., the presence of irrigated crops), might lead to over-predictions in fire spread across the landscape.

The rule of thumb assumes the fire is spreading at its quasi-steady or pseudo-steady state (i.e., it has already completed its initial growth/acceleration phase). It is expected that this acceleration phase is short, likely under 20–30 min [3,8], given the heightened fire danger conditions to which the rule of thumb is deemed applicable. Incorporating the effect of this acceleration period into the fire spread distance calculations under these burning conditions is likely not to have much practical relevance.

The rule of thumb aims to produce an approximation of the average rate of fire spread over periods of an hour or more, with the best accuracy likely to occur when the prediction period extends over several hours. The rule of thumb does not capture smaller temporal variations in rate of spread which occur in response to peak wind gusts which can cause surges in fire propagation. The rate of fire spread during these surges can be several times faster than the average observed over periods of an hour or more. Short-term peaks in the rate of fire spread have been observed to be three to five times higher than the longer-term average in high-intensity outdoor experimental fires in boreal forest [49] and semi-arid shrubland [50] fuel types. The predictive models of fire spread rate do not capture these fluctuations, but nevertheless, users of these models should be aware of this inherent short-term variability in the speed of a moving flame front. The occurrence of short- to medium-range spotting can also lead to local variations in the short-term movement of the advancing fire edge.

4.4. Error and Uncertainty in Grassfire Rate of Spread Predictions

The rule of thumb predicted the wildfire data that was used in its development to within an average relative error of 66%. This level of error and the degree of scatter visible in Figure 3 is to be expected given the nature of wildfire case study data [10,14,33] resulting from uncertainties in the rate of spread observations and the lack of representativeness of the weather data for the fire location, in addition to the effect of unquantified factors such as fuel discontinuities [51] or suppression effects on fire propagation [52]. For comparison's sake, the fire spread models of Cheney et al. [10] used in the present study analysis estimated the spread rate of experimental fires, which would have involved accurate measurements of the model input variables, to relative errors between 20 and 30% [53].

The level of error obtained with the rule of thumb was lower than that found in other model evaluation studies involving wildfire data where the average error was closer to 100% [33]. This lower level of error is likely to arise from the higher dominance of wind speed on fire propagation in grasslands in contrast to forests or shrublands and the general lack of topographic effects on wind flow and fire behaviour in the grassfire dataset analysed in the present study.

The interpretation of the rule of thumb predictions should consider the uncertainty in the forecasted wind speeds or extrapolation of observed wind speeds at one weather station location to the landscape as a whole. The utilisation of the ± 35 error bands [40] in conjunction with the average prediction is likely to help in the interpretation of the results beyond just a best estimate.

4.5. Practical Application of the Grassfire Rule of Thumb

The practical application of the 20% rule of thumb requires an estimate of the 10 m open wind speed. A weather forecast will be the most obvious source of the wind speed needed to estimate grassfire spread. In cases where a forecast is not available or the forecast is not viewed as representative of the situation, the local observations of average wind speed should be used. If the measurement height and location does not conform to the 10 m open average wind assumption (e.g., wind speed is measured at a different exposure height, the measurement location is sheltered by obstructions such as trees or buildings, or the measurement is averaged over shorter time interval than the 10 min standard), adjustments should be applied [48].

The estimation of a grassfire's rate of spread using the 20% wind speed rule of thumb involves a straightforward mental calculation. In order to extend the application of the rule of thumb even further, we have provided in Appendix B a table of a grassfire's R and elliptical fire length-to-breadth (L:B) ratio as a function of U_{10} [42], in addition to the forward fire spread distance, area burned and perimeter length [54] as a function of elapsed time since ignition (Table A1).

A simple fire spread map can be readily derived from the tabled information in Appendix B through the following steps: (1) estimate R and L:B ratio based on the wind speed; (2) derive the forward fire spread distance from the wind speed and duration of the run (hours); (3) plot a fire spread direction arrow on a map aligned in the direction of the prevailing wind [24] with the length of the arrow, representing the fire's forward spread distance; (4) mark the hourly fire spread increments along this line to determine the fire's expected arrival times at different locations; and finally (5) draw an elliptical shape around the spread vector as a series of 'nested ellipses' based on a common origin given the L:B ratio. The resulting map will represent an approximation of the grassfire's shape and size provided the wind direction remains relatively constant [24].

4.6. Application of the Grassfire Rule of Thumb Outside of Australia

The present analysis was based on wildfire data collected from grasslands in southern Australia. It is pertinent to discuss whether the results obtained here would be applicable to other regions of the world where extreme grassfires are often observed, such as the African savanna regions [25,55,56], the Central Asia grass steppe [57,58] or the North American prairies [11,18,59,60]. This is especially pertinent in countries without an established wildfire behaviour prediction capacity, although it is also relevant to countries with both such a capability as well as an established wildland fire research program.

From a fuel structure perspective, we have not identified any differences that would limit the application of the rule of thumb to just southern Australia grasslands. The variations in grassland fuel structure in the semi-arid, steppe or temperate regions of the world where grassfire outbreaks occur are comparable to the range of grassland fuel conditions found in southern Australia. Grassland fuel types can vary in height from a few centimetres in eaten-out paddocks to about 1–1.5 m tall in undisturbed grasslands after a wet winter. Available fuel quantities in southern Australia grasslands can vary over a range of about 0.05 kg m^{-2} (in heavily grazed pastures) to around 1 kg m^{-2} (or 10 t ha^{-1}) in undisturbed sub-tropical and tropical grasslands, although localised areas with higher fuel quantities can be found in areas dominated by invasive species [53,61]. This range in fuel structure is comparable to what is found in grasslands throughout the world over a range of climates [62–67].

Given the comparable fuel structures, we believe the 20% rule of thumb would be generally applicable to grasslands in regions outside Australia that are prone to the occurrence of extreme grassfires, as long as the environmental conditions meet the assumptions associated with the rule of thumb as described earlier on (i.e., low fine dead fuel moisture, fully cured landscape and strong winds). It should also be noted that in places with an established fire behaviour prediction capacity, the rule of thumb might yield outputs that differ from those obtained with other fire spread rate prediction models. Figure 6b contrasts the different rate of fire spread prediction trajectories as a function of wind speed for fuel type/fuel models found in Canadian [43,44] and US [45,46] fire behaviour modelling systems. Of these, the US fuel model 3-tall grass [47] is the one that best compares with the 20% rule of thumb.

5. Conclusions

Grass, of one species or another, is the most common fuel type found in Australia, covering nearly three-quarters of the country [8]. Australia's climate makes it especially prone to the occurrence of extreme fires, often involving multiple starts of anthropogenic origin [68].

The 20% rule of thumb described here offers fire practitioners a means of quickly assessing the spread potential of grassfires burning under heightened fire danger. The simplicity of the rule of thumb allows its application in situations where trained fire behaviour analysts may not be available or do not have enough time to undertake a detailed fire behaviour prediction. We believe the rule of thumb could be easily applied by experienced fire practitioners that may lack the advanced training in conducting detailed fire spread predictions. In this context, we see the rule of thumb as being valuable in places where an established fire behaviour prediction capacity involving fire spread models may be non-existent.

The findings from the present study also have relevance beyond the operational prediction of fire spread. The results of the data analysis show the dominant control that wind speed exerts on fire spread in grassfires under dry fuel conditions (i.e., low fine dead fuel moisture content of cured grasses). The findings could also provide guidance in future fire spread model development and calibration, namely what kind of behaviour should one expect for grassfires burning under heightened fire danger conditions.

A rule of thumb is, by its own definition, a principle with broad application that does not aim to be strictly accurate in every situation [33]. The 20% rule of thumb was derived from a relatively large (n = 58) and diverse dataset of wildfire rate of spread observations and evaluated against the data used in its development. We aim to continue collecting data on wildfires in grasslands in order to continually evaluate the rule of thumb against independent data. We would be interested in hearing from anyone who might have data on wildfire rates of spread in grasslands and associated fuel and weather conditions that could be used for the purpose of evaluating the 20% rule of thumb, particularly for grassland ecosystems outside Australia.

Author Contributions: Conceptualization, M.G.C. and M.E.A.; methodology, M.G.C.; validation, M.G.C.; formal analysis, M.G.C.; investigation, M.G.C. and M.E.A.; resources, M.G.C. and M.E.A.; data curation, M.G.C. and M.K.; writing—original draft preparation, M.G.C. and M.E.A.; writing—review and editing, M.G.C. and M.E.A.; visualization, M.G.C. and M.E.A.; supervision, M.G.C.; project administration, M.G.C.; funding acquisition, M.E.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The dataset assembled for the present study is available upon request from the corresponding author provided a proposal for its intended use is included.

Acknowledgments: Thanks to Andrew Sullivan, Todd Lindley and J.D. Carlson for their comments on a draft of this article. The authors would like to gratefully acknowledge the various practitioners and researchers over the years who have made the data available for this study all possible.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Appendix A.1 Calculating the Estimated Fine Dead Fuel Moisture Content in Grasslands

The moisture content of fine dead grass fuels (MC, %) was calculated from an equation developed by [69] describing McArthur's [36] fuel moisture table:

$$MC = 9.58 - 0.205\ T + 0.138\ RH \tag{A1}$$

where T is air temperature (°C), and RH is relative humidity (%).

Appendix A.2 Calculating the Grassland Fire Danger Index

The Grassland Fire Danger Index ($GFDI$) was calculated from the parameterization by [37] of the McArthur [19] Mk 3 grassland fire danger meter:

$$GFDI = 2\ \exp\left(-23.6 + 5.01\ \ln(C) + 0.0281\ T - 0.226\ \sqrt{RH} + 0.633\ \sqrt{U_{10}}\right) \tag{A2}$$

where C is the degree of curing (%), T is the ambient air temperature (°C), RH is the relative humidity (%) and U_{10} is the 10 m open wind speed (km h^{-1}). The $GFDI$ is "a relative number denoting an evaluation of rate of spread or suppression difficulty for specific combinations of fuel, fuel moisture content and wind speed" [8].

Appendix A.3 Calculating Rate of Fire Spread in Australian Grasslands

Cheney et al. [10] proposed models for predicting the rate of spread of Australian wildfires in undisturbed (R_n, km h^{-1}), grazed or cut (R_{cu}, km h^{-1}) and eaten-out (R_e, km h^{-1}) grassland fuel conditions from an analysis of outdoor experimental fire and wildfire data:

$$R_n = \begin{cases} (0.054 + 0.269\ U_{10})\ \phi M\ \phi C & U_{10} < 5\ \text{km h}^{-1} \\ \left(1.4 + 0.838(\ U_{10} - 5)^{0.844}\right)\ \phi M\ \phi C & U_{10} \geq 5\ \text{km h}^{-1} \end{cases} \tag{A3}$$

$$R_{cu} = \begin{cases} (0.054 + 0.209\ U_{10})\ \phi M\ \phi C & U_{10} < 5\ \text{km h}^{-1} \\ \left(1.1 + 0.705(\ U_{10} - 5)^{0.844}\right)\ \phi M\ \phi C & U_{10} \geq 5\ \text{km h}^{-1} \end{cases} \quad \text{(A4)}$$

$$R_e = \left(0.55 + 0.357\ (\ U_{10} - 5)^{0.844}\right)\ \phi M\ \phi C \qquad U_{10} \geq 5\ \text{km h}^{-1} \quad \text{(A5)}$$

where U_{10} is the 10 m open wind speed (km h^{-1}), ϕM is the fuel moisture coefficient and ϕC is the curing coefficient. The fuel moisture coefficient is calculated as follows:

$$\Phi M = \begin{cases} exp(-0.108\ MC) & MC < 12\% \\ 0.684 - 0.0342\ MC & MC \geq 12\%,\ U_{10} < 10\ \text{km h}^{-1} \\ 0.547 - 0.0228\ MC & MC \geq 12\%,\ U_{10} \geq 10\ \text{km h}^{-1} \end{cases} \quad \text{(A6)}$$

where MC is the fine dead fuel moisture content (% oven-dry weight basis) with application bounds of 2–24%. Model parameterization relied on the use of Equation (A1). The curing coefficient is given as follows [30]:

$$\Phi C = \frac{1.036}{1 + 103.99\ exp(-0.0996(C - 20))} \quad \text{(A7)}$$

where C is the degree of grass curing (%) with application bounds of 20% < C < 100%. If C is <20%, fires are assumed not to spread at all.

Appendix B

Table A1. Fire behaviour and elliptical fire characteristics as a function of wind speed and elapsed time based on the 20% rule of thumb for grassfires.

10-m Open Wind Speed (km h^{-1})									
30	**35**	**40**	**45**	**50**	**55**	**60**	**65**	**70**	**75**
Forward Rate of Fire Spread (km h^{-1})									
6	7	8	9	10	11	12	13	14	15
Elliptical Fire Length-to-Breadth Ratio									
5.3	5.7	6.1	6.4	6.8	7.1	7.4	7.6	7.9	8.2
Forward Fire Spread Distance (km) Elliptical Fire Area (ha) Elliptical Fire Perimeter (km)									
1 h Since Ignition									
6 530 13	7 672 15	8 825 17	9 989 19	10 1162 21	11 1346 23	12 1538 25	13 1739 27	14 1949 28	15 2167 30
2 h Since Ignition									
12 2122 25	14 2688 29	16 3301 33	18 3955 37	20 4650 41	22 5383 45	24 6153 49	26 6957 53	28 7796 57	30 8668 61
3 h Since Ignition									
18 4774 38	21 6049 44	24 7426 50	27 8899 56	30 10 462 62	33 12 111 68	36 13 843 74	39 15 654 80	42 17 542 85	45 19 503 91
4 h Since Ignition									
24 8486 50	28 10 754 58	32 13 202 66	36 15 820 74	40 18 599 82	44 21 531 90	48 24 610 98	52 27 830 106	56 31 185 114	60 34 671 122
5 h Since Ignition									
30 13 260 63	35 16 803 73	40 20 628 83	45 24 719 93	50 29 061 103	55 33 643 113	60 38 454 123	65 43 484 133	70 48 727 142	75 54 174 152
6 h Since Ignition									
36 19 095 75	42 24 196 87	48 29 705 99	54 35 595 111	60 41 848 123	66 48 446 135	72 55 373 147	78 62 617 159	84 70 167 171	90 78 011 183

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