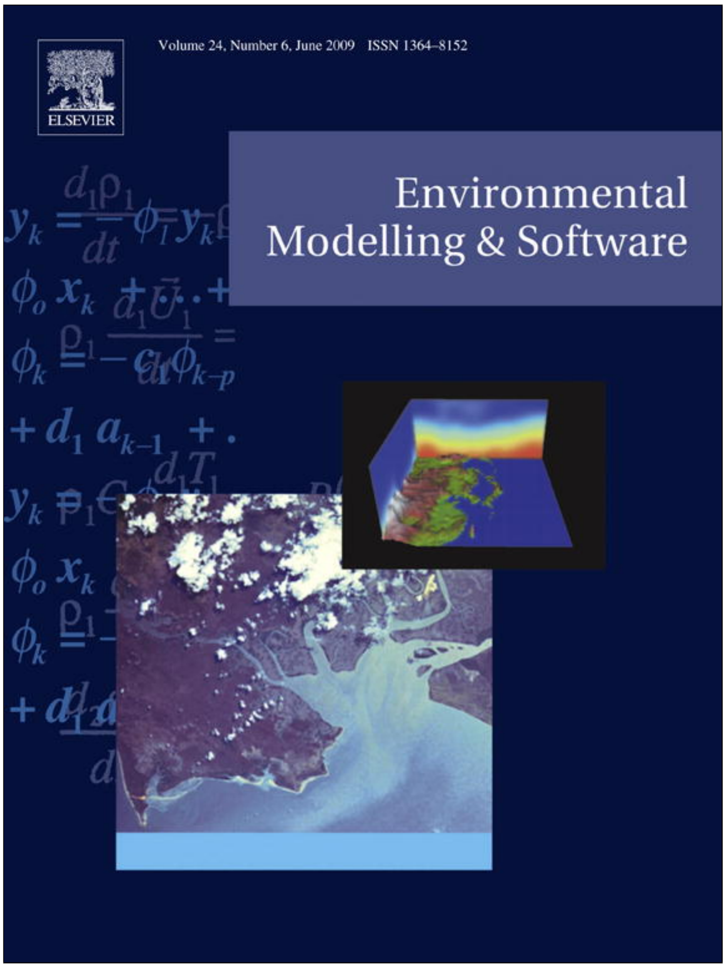
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A simple index for assessing fire danger rating

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ABSTRACT

Fire danger rating systems are used to assess the potential for bushfire occurrence, fire spread and difficulty of fire suppression. Typically, fire danger rating systems combine meteorological information with estimates of the moisture content of the fuel to produce a fire danger index. Fire danger indices are used to declare fire bans and to schedule prescribed burns, among other applications. In this paper a simple fire danger index F that is intuitive and easy to calculate is introduced and compared to a number of fire danger indices pertaining to different fuel types that are used in an operational setting in Australia and the United States. The comparisons suggest that F provides a plausible measure of fire danger rating and that it may be a useful pedagogical tool in the context of fire danger and fire weather.

1. Introduction

Fire danger is a broad concept that incorporates a multitude of factors including well defined physical processes and chance events, which can affect the possibility of a bushfire igniting and then propagating, and the impact it may have on various assets. For example, Beall (1946) describes fire danger as including all the items which determine whether fires will start, spread and do damage, and how difficult they will be to control, while Chandler et al. (1983) define fire danger as the resultant of constant and variable factors that affect the inception, spread and difficulty of control of fires and the damage they cause. These factors include topographic attributes, fuel characteristics and weather variables as well as random factors such as arson. Many of these factors are difficult to quantify numerically, if not completely intangible. Incorporating the totality of these factors into a single numerical index to describe fire danger is therefore a seemingly impossible task (Cheney and Gould, 1995). To assist in fire management, however, fire danger rating systems, which integrate selected quantifiable factors contributing to fire danger, have been developed to provide numerical indices relating to fire protection needs (Chandler et al., 1983). Many of these systems rely on information relating to fire weather, fuel moisture characteristics and drought effects.

In particular, the potential for the occurrence and development of bushfires is dependent upon the interaction of fuels with a number of climatic elements that vary over long and short timescales. Consequently, a number of methods have been devised around the world to combine information on weather, climate and fuels into a fire danger index. Such fire danger indices provide a measure of the chance of a fire starting in a particular fuel, its rate of spread, intensity and difficulty to suppress, through various combinations of temperature, relative humidity, wind speed and drought effects. Examples of fire danger indices include those employed in eastern Australia (McArthur, 1966, 1967; Gill et al., 1987; Cheney and Sullivan, 1997), Western Australia (Sneeuwjagt and Peet, 1985; Beck, 1995), Canada (Van Wagner and Pickett, 1985; Van Wagner, 1987; Forestry Canada Fire Danger Group, 1992) and the United States (Deeming and Lancaster, 1971; Rothermel, 1972; Deeming et al., 1977; Fosberg, 1978; Goodrick, 2002). Fire danger indices are used to declare fire bans, determine readiness levels for fire suppression crews, schedule prescribed burns, allocate resources and inform public awareness of bushfires in addition to assessing fire behaviour potential in an operational setting (Byram, 1959; Gill et al., 1987). For many of these uses fire danger indices are implemented as regional measures. It is important to point out that fire danger indices typically do not involve site specific factors such as terrain and fuel characteristics, which affect a fire's rate of spread. Terrain does nevertheless affect rainfall, soil dryness,

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temperature and relative humidity, but to allow fire danger indices to be used as regional tools these considerations are ignored. Factors such as terrain and fuel structure do, however, play an important role in fire behaviour, which is a local concept.

Typically, indices for assessing fire danger are implemented as meters, which can take the form of tables or circular slide rules. Different meters exist for different climates and fuel types, but all use temperature, relative humidity and wind speed, among other factors, to produce an index that relates to the chance of a fire igniting and then spreading, as well as its difficulty to suppress. In this paper we present a novel, simple and intuitive fire danger index, which can be taken as a rule of thumb. The index we introduce is based on a fuel moisture index (FMI) that was proposed in Sharples et al. (in press). The FMI provides information on fuel moisture content, which is an important factor in determining fire spread and occurrence, and can be calculated easily once dry-bulb temperature and relative humidity are known. Determination of the proposed fire danger index then follows by combining the FMI with a measurement of wind speed. Measurements of dry-bulb temperature, relative humidity and wind speed are all readily obtainable from standard meteorological networks and from hand held weather instruments.

It is interesting to note that some fire danger indices can also be related to fire behaviour characteristics such as flame height and spotting distance. For example, given a constant fuel load, the McArthur fire danger rating system (McArthur, 1967) provides an index that is proportional to the rate of spread of a fire in vegetation similar to that in which it was developed. Spotting distance is then estimated using the derived rate of spread and information on fuel loading (Noble et al., 1980). Cheney and Gould (1995) suggest, however, that fire behaviour prediction and fire danger rating should be considered as separate exercises, as this would allow further development in fire behaviour research without the need for altering fire danger rating systems. As fire danger indices are non-dimensional and not directly measurable, there appears to be little prima facie basis for selecting one over another. Hence if the suggestion of Cheney and Gould (1995) were to be adopted, a simple fire danger index such as the one proposed could prove valuable. However, it must be recognised that any change in a fire danger rating system has significant impacts on the fire management industry and the community at large.

To test the validity of the proposed index, fire danger rating values derived from it are compared with those obtained from four different fire danger indices that feature in the literature and that have been used in operational settings. The fire danger indices used in the comparisons are the McArthur Mark 5 Forest Fire Danger Index (FFDI), the McArthur Mark 4 Grassland Fire Danger Index (GFDI4), the McArthur Mark 5 Grassland Fire Danger Index (GFDI5) and the Fosberg Fire Weather Index (FFWI). Once the effects of drought or grass curing have been accounted for, these models give fire danger rating as a function of wind speed, dry-bulb temperature and relative humidity and so will be directly comparable to the proposed index. We begin by giving a brief account of each of the four models used in the comparison.

2. Models of fire danger rating

In this section a brief account of the four models of fire danger rating, which will be used to assess the validity of the proposed index, is given. Reiterating, the four models are the McArthur Mark 5 Forest Fire Danger Meter, widely used in Australia for dry sclerophyll forest types; the McArthur Mark 4 and Mark 5 Grassland Fire Danger Meters, used in Australia for grassland fuels; and the Fosberg Fire Weather Index, which is used to supplement the U.S. National Fire Danger Rating System (Deeming et al., 1977). Note that the Canadian Fire Behaviour Prediction System (Forestry Canada Fire Danger Group, 1992) and the Western Australian Forest Fire Behaviour Tables (Sneeuwjagt and Peet, 1985; Beck, 1995) also contain indices pertaining to fire danger rating that are used extensively. However, these indices incorporate information on fuel moisture content, which requires additional knowledge of antecedent rainfall, and so will not be directly comparable to the simple index proposed in the next section, which is a function of temperature, relative humidity and wind speed only. For this reason these indices will not be examined here. The Canadian Fire Weather Index and the Forest Fire Behaviour Tables have been treated in a recent study that makes a detailed comparison of these two indices with the McArthur Mark 5 Forest Fire Danger Meter (Matthews, in press). Matthews (in press) concludes that, after rescaling of the Canadian Fire Weather Index, the three fire danger indices provide similar information on fire danger rating. Overall there was no compelling reason to choose one index over another.

2.1. McArthur Mark 5 Forest Fire Danger Meter

The McArthur forest fire danger meters have been widely used in eastern Australia since their initial development in the 1960s by A.G. McArthur. The meters are used to assess fire danger in forest fuel types and are based on (unpublished) observations from over 800 fires. Earlier versions of the meters were presented in tabular form but were subsequently modified and converted into the form of circular slide rules. The forest fire danger meter currently in use in Australia is the Mark 5 Forest Fire Danger Meter, which produces an index referred to as the Forest Fire Danger Rating or Forest Fire Danger Index (FFDI). The FFDI is the basis for the fire danger classification scheme used in eastern Australia, where fire danger conditions are classified as low, medium, high, very high or extreme according to where the FFDI value sits with respect to a number of threshold values. For example, extreme fire danger conditions correspond to a FFDI of 50 or more.

Noble et al. (1980) have expressed the content of the Mark 5 meter as an equation involving an exponential function of dry-bulb temperature, relative humidity, wind speed and drought effects. The equation provides a way of including the forest fire danger meter in computer systems that permit advanced modelling of fire behaviour and spread, among other applications. The equation also facilitates comparison of the forest fire danger rating system with other fire danger prediction systems. The FFDI is given by the following expression, in which T is dry-bulb temperature (°C), H is relative humidity (%), U is the wind speed (km h^{-1}) typically taken at a height of 10 m above the ground surface and DF is the drought factor.

$$\mathrm{FFDI} = 2\exp(-0.45 + 0.987\ln \mathrm{DF} + 0.0338T - 0.0345H + 0.0234U). \tag{1}$$

The drought factor, which ranges from 1 to 10, gives an estimate of the fuel available for combustion. It is a function of the time since last rain, the amount of rain that fell and the dryness of the soil (Keetch and Byram, 1968; Mount, 1972; Griffiths, 1999).

As pointed out by Noble et al. (1980), the dependence of FFDI on the drought factor in equation (1) is very nearly linear. In any case, we may write equation (1) as

$$\mathrm{FFDI} = 2\mathrm{DF}^{0.987}\exp(-0.45 + 0.0338T - 0.0345H + 0.0234U). \tag{2}$$

It is clear in equation (2) that DF enters into the expression as a multiplicative factor. Such a factor will have no real bearing on the methods of comparison employed in the later sections of the paper and so for convenience we assume that DF = 10 in what follows.

2.2. McArthur Mark 4 Grassland Fire Danger Meter

The McArthur grassland fire danger meters were developed to assist in prediction of fire behaviour in grassland fuels, in particular in pastures of the southern tablelands of New South Wales and the Australian Capital Territory. The McArthur Mark 4 Grassland Fire Danger Meter was developed to replace the mark 3 meter (McArthur, 1966) and was presented in the form of a circular slide rule. The mark 4 meter is currently used by the Bureau of Meteorology to assess fire weather conditions relevant to grasslands. As with the forest fire danger meter, the grassfire danger meter produces an index, the Mark 4 Grassland Fire Danger Index (GFDI4), which relates to the expected severity of fire behaviour and difficulty of suppression. Purton (1982) derived an equation that closely replicated the content of the mark 4 meter and also modified the meter to allow for variable fuel quantities. The equation for the modified mark 4 meter is

$$\mathrm{GFDI4} = \exp\Big(-1.523 + 1.027\ln(Q) - 0.009432(100 - C)^{1.536} + 0.02764T - 0.2205\sqrt{H} + 0.6422\sqrt{U}\Big). \qquad (3)$$

Here T is dry-bulb temperature (°C), H is relative humidity (%), U is the wind speed (km h^{-1}) and Q is the quantity of fuel (t ha^{-1}). The degree of grass curing C describes long-term effects on the moisture content of grassland fuels and is determined through the interaction of precipitation and temperature patterns with the growing cycles of individual grass species (McArthur, 1966). Curing is given as a percentage in the range 0–100%. Generally speaking it can be taken as a measure of the proportion of dead grass that is available to burn. Rearranging equation (3) slightly as

$$\mathrm{GFDI4} = Q^{1.027} f(C)\exp\Big(-1.523 + 0.02764T - 0.2205\sqrt{H} + 0.6422\sqrt{U}\Big),$$

it is easy to see that the effects of fuel quantity and curing enter into equation (3) as multiplicative factors that modulate a function of temperature, relative humidity and wind speed. Specifically, the curing factor is given by

$$f(C) = \exp\Big(-0.009432(100 - C)^{1.536}\Big).$$

As mentioned in the last subsection, such factors will have no real bearing on the comparison of the fire danger indices and so for convenience we set $C = 100\%$, for which $f(C) = 1$ and $Q = 4.5$ t ha^{-1}. Using this value for Q amounts to using the original McArthur Mark 4 meter (Purton, 1982).

2.3. McArthur Mark 5 Grassland Fire Danger Meter

Like the mark 4 meter, the McArthur Mark 5 Grassland Fire Danger Meter (McArthur, 1977) was developed to assist in predicting fire danger levels in grassland fuels, but was designed to be more widely applicable than its predecessors (Noble et al., 1980). The associated fire danger index is the mark 5 Grassland Fire Danger Index (GFDI5). An equation for the mark 5 index was also presented in Noble et al. (1980) and is given in terms of dry-bulb temperature (°C), relative humidity (%), wind speed (km h^{-1}) and degree of grass curing (%) as

$$\mathrm{GFDI5} = \begin{cases} 3.35W\exp(-0.0897m + 0.0403U), & m < 18.8, \\ 0.299W\exp(-1.686 + 0.0403U)(30 - m), & 18.8 \le m < 30. \end{cases} \qquad (4)$$

Here W is the fuel weight (t ha^{-1}) and m is the fuel moisture content (%), which is given as a function of dry-bulb temperature, relative humidity and curing as

$$m = \frac{97.7 + 4.06H}{T + 6} - 0.00854H + \frac{3000}{C} - 30.$$

For convenience in the analyses below we will assume a moderate fuel loading of $W = 5$ t ha^{-1}. Altering this value will not affect the correlation analyses presented below. We note here that the inclusion of W in equation (4) is less than desirable as it means the index can no longer be implemented as a regional measure, unless one assumes a constant fuel loading over the region.

In the mark 5 index the effects of curing can no longer be considered as a multiplicative factor, as it was in GFDI4. This means that the results of correlation analyses will differ as the curing factor is varied. For brevity, in the ensuing analyses, we will concentrate on the assumption that $C = 100\%$. Results arising from assuming different curing factors will only be briefly mentioned.

2.4. Fosberg Fire Weather Index

According to Goodrick (2002), the Fosberg Fire Weather Index (FFWI) is a nonlinear filter of dry-bulb temperature, relative humidity and wind speed data, which is designed to provide a linear relationship between the combined meteorological data and fire behaviour characteristics. Essentially, the FFWI is a simple index based upon equilibrium moisture content and wind speed (Fosberg, 1978). Haines et al. (1983) showed that the FFWI was highly correlated with fire occurrence in the north-east United States. Anecdotal evidence also suggests that the FFWI is a good indicator of fire activity in the south-west United States; for example, major fires of the late 1980s and 1990s have been associated with anomalously high occurrences of the FFWI (Roads et al., 1997). The FFWI has been used to supplement the once-daily calculations of fire danger rating delivered by the U.S. National Fire Danger Rating System (Deeming et al., 1974, 1977), as it can be calculated at any time that the required weather inputs are known. The FFWI is given by the equation (Fosberg, 1978; Roads et al., 1991; Goodrick, 2002),

$$\mathrm{FFWI} = a\eta\sqrt{1 + U^2}, \qquad (5)$$

where a is a calibration factor and η is the moisture damping coefficient given by

$$\eta = 1 - 2\left(\frac{m}{30}\right) + 1.5\left(\frac{m}{30}\right)^2 - 0.5\left(\frac{m}{30}\right)^3.$$

Here m is the equilibrium moisture content of the fuel, which is modelled as (Simard, 1968):

$$m = \begin{cases} 0.03 + 0.2626H - 0.00104HT, & H < 10, \\ 1.76 + 0.1601H - 0.0266T, & 10 \le H < 50, \\ 21.06 - 0.4944H + 0.005565H^2 - 0.00063HT, & H \ge 50. \end{cases}$$

In the following sections we will ignore the calibration factor in (5), as it has no bearing on the methods of comparison employed therein.

3. A simple index for fire danger rating

It is interesting to note the common features of each of the three fire danger rating models discussed above. Each model is an increasing function of both temperature and wind speed and a decreasing function of relative humidity, which is in accord with our expectation that hot, dry and windy conditions should lead to increased risk of fire. Wind is the most critical meteorological factor affecting fire potential (Gorski and Farnsworth, 2000), and is one of the main components determining the rate and direction of spread of a fire. Wind aids combustion by causing the flames to lean over closer to unburnt fuel, supplying the fire with oxygen and carrying away moist air which would otherwise restrict the amount of heat available to ignite unburnt fuel. Given the importance of wind in determining fire danger rating, it is worthwhile to further discuss the nature of the wind functions in each of models (1) and (3)–(5). The dependence of fire danger rating on wind speed is essentially linear in (5), but is exponential in (1), (3) and (4). A closer inspection of the functional relationships, however, shows that for wind speeds under 50 km h^{-1} the exponential functions in (1), (3) and (4) may, to a reasonable approximation, be taken as linear functions of wind speed. This assertion is confirmed by considering the linear correlation of data derived from the wind functions in (1) and (3)–(5). The correlation statistics arising from such a consideration are shown in Table 1. It is also interesting to note that more recent experimental studies in Eucalypt forests suggest that the rate of spread of a fire has a power law dependence on wind speed, with an exponent approximately equal to unity (Gould et al., 2007). Cheney and Gould (1995) also found that the rate of spread of grassfires increases linearly with wind speed. However, they advocated the use of an exponential function as it might be more suited to conveying the auxiliary effects of spotting and erratic fire behaviour on grassfire danger levels.

Only wind speeds under 50 km h^{-1} have been considered in Table 1 since controlled bushfire experiments are not conducted in excessive winds due to the inherent dangers to researchers, suppression crews and the wider public. As a consequence, the use of the wind functions for excessive winds is not supported by empirical evidence that has been systematically collected, though some information can be inferred from indirect measurement of wildfire characteristics. Nevertheless, it is a rather common practice for wind speeds exceeding 50 km h^{-1} to be used in models (1) and (3)–(5) to calculate fire danger indices.

Temperature and relative humidity mostly influence fire danger through their effect on the moisture content of fuels. The moisture content of a fuel sample is defined as the relative mass of moisture in the sample when compared with the oven-dried mass of the fuel sample, and is expressed as a percentage. Heat that goes into converting the moisture present in the fuel into water vapour is not available to contribute to the combustion process. As a consequence, fuel with lower fuel moisture content will burn more readily and intensely than the same fuel with higher fuel moisture content. Fuel moisture content is affected by various physical processes including latent heat effects, vapour exchange and precipitation (Viney, 1991). Vapour exchange processes are inherently dependent on the ambient temperature and relative humidity and these variables feature significantly in many approaches to modelling fuel moisture content (Viney, 1991; Nelson, 2000). Generally, fuel moisture content is modelled by a function that increases as relative humidity increases and decreases as temperature increases.

Sharples et al. (in press) introduced a dimensionless fuel moisture index (FMI), which was compared to several existing models for determining the moisture content of fine, dead fuels. The results presented there suggest that, up to a small error, the FMI provides a measure of fuel moisture content that is equivalent to that produced by the models. The FMI is given by the simple expression

$$\mathrm{FMI} = 10 - 0.25(T - H), \tag{6}$$

Table 1
Linear correlation statistics arising from data derived from the wind functions of the four fire danger models. Only wind speeds under 50 km h^{-1} have been considered.

Fire danger index	Wind function	Correlation
FFDI	$\exp(0.0234U)$	0.9885
GFDI4	$\exp(0.6422\sqrt{U})$	0.9640
GFDI5	$\exp(0.0403U)$	0.9675
FFWI	$\sqrt{1+U^2}$	0.9999

which embodies the intuitive notion that hotter and drier conditions correspond to lower fuel moisture contents.

Given the considerations above, a fire danger index is a combination of information on wind speed and fuel moisture content, where the latter is derived through consideration of temperature and relative humidity. Intuitively, fire danger decreases as fuel moisture content increases, but increases as wind speed increases. This suggests a simple fire danger index of the form

$$F = \frac{\max(U_0, U)}{\mathrm{FMI}}, \tag{7}$$

where we have used the FMI as a surrogate for fuel moisture content. In equation (7), U denotes wind speed in km h^{-1} and U_0 is some threshold wind speed introduced to ensure that fire danger rating is greater than zero, even for zero wind speed. In what follows we have taken $U_0 = 1$ km h^{-1}. While this may not be the optimal choice for the threshold wind speed it will suffice to facilitate the ensuing comparisons. Moreover, an auxiliary analysis (not reported here) indicated that $U_0 = 1$ km h^{-1} yielded results that were near optimal anyway.

The question of principal interest is how the simple index F compares to the more mathematically involved fire danger indices given by equations (1) and (3)–(5). This question is addressed in the following sections.

4. Data and methods

To facilitate the comparison of F, given in equation (6), with the fire danger indices (1) and (3)–(5) we used data recorded by the Bureau of Meteorology's automatic weather station located at Canberra Airport in the Australian Capital Territory (Station ID: 070014, Long.: 149.20, Lat.: −35.30, Elev.: 578.4 m). In particular, we use half-hourly data recorded between 00:00AEST, 1st November 2006 and 23:30AEST, 31st March 2007, inclusive. The period covered by the data comprises a large majority of the 2006/2007 fire season and therefore includes a broad range of temperature, relative humidity and wind speed values relevant to fire weather considerations. Specifically temperature varied between 1.7 °C and 39.9 °C, relative humidity varied between 8% and 99% and wind speed varied between 0 km h^{-1} and 55.4 km h^{-1}.

In the ensuing comparison only those data that had values for dry-bulb temperature, relative humidity and wind speed were considered. This gave a total of 5720 triples of temperature, relative humidity and wind speed data with which to calculate the index F and the fire danger indices given by equations (1), (3) and (5). Due to the requirement that $m < 30\%$ in equation (4), the fire danger index given by this equation could only be evaluated at 5648 of the data triples, assuming a curing factor of 100%.

Comparisons between fire danger ratings derived from models (1) and (3)–(5) and F were made by calculating FFDI, GFDI4, GFDI5, FFWI and F at each of the valid data points. The results were displayed in the form of scatter-plots and linear and rank correlation and error statistics were calculated. The resulting fire danger values were also compared in time series plots and significant differences were addressed with reference to the prevailing meteorological conditions.

5. Results

The four indices FFDI, GFDI4, GFDI5 and FFWI and F were calculated at each of the valid data triples. Scatter-plots of each of the three model predictions versus the corresponding F values can be seen in Fig. 1. Fig. 1a–d shows a reasonable correlation of F with FFDI, GFDI4, GFDI5 and FFWI, respectively. Linear and rank correlation statistics can be seen in Table 2. We have reported linear correlation statistics despite the fact that, in some cases, the apparent relationship between the data is nonlinear. Fitting a nonlinear function to these data would result in correlation statistics greater than those in Table 2. In any case the correlation statistics, which are all greater than 0.9 even when a linear approximation is assumed, suggest that there is a significant correlation between F and the existing indices. The rank correlation statistics seen in Table 2 are also close to unity, suggesting that there is strong monotonicity in the relationship between F and the existing indices; this is particularly so for GFDI4 and FFWI. The strong monotonicity and correlation between F and the existing indices indicates that F provides a plausible measure of fire danger rating.

Based on the assumption of a linear relationship, the F values were then multiplied by a constant calibration or scaling factor so that the average value of F matched that of the index it was being compared to. The scaled values obtained by this process will be referred to as F^*. The scaling was done so that the values of F^* were of roughly the same size as those obtained from FFDI, GFDI4, GFDI5 and FFWI and so that the scales of F^* and the respective index it was being compared to were roughly consistent. This means that errors between the existing indices and F^* can be discussed in terms of fire danger index points relating to the respective index that F^* is being compared to. The error statistics can be seen in Table 2. It is important to note that it is not meaningful to compare the error statistics between indices, as they relate to different objective scales. The mean absolute differences between F^* and the indices FFDI, GFDI4, GFDI5 and FFWI are relatively low, all being less than 3 fire danger index points. The maximum absolute differences between F^* and the respective indices, on the other hand, are quite high. However, as Fig. 2 shows, large differences between F^* and the existing indices mostly correspond to conditions in which temperature and wind speed are high and relative humidity is low. These conditions typically correspond to relatively high fire danger conditions. For example, Fig. 2 indicates that absolute differences between F^* and FFDI of 20 or more correspond to temperatures over 35 °C, relative humidity less than 10% and wind speeds greater than 25 km h^{-1}. Differences between F^* and GFDI4 greater than 20 correspond to temperatures over 25 °C, relative humidity less than 26% and wind speeds greater than 40 km h^{-1}, while differences between F^* and GFDI5 greater than 20 correspond to temperatures over 29 °C, relative humidity less than 16% and wind speeds greater than 16 km h^{-1}. Differences between F^* and FFWI greater than 20 corresponded to temperatures over 33 °C, relative humidity less than 13% and wind speeds greater than 22 km h^{-1}.

The fact that such large differences between F^* and the respective indices occur for dangerous fire weather conditions is not that much of an issue, given that under these conditions fire danger rating should obviously be high. For example, in the fire danger rating system based on FFDI, fire danger rating is classified as extreme whenever FFDI $\geq$ 50. Inspection of Fig. 1a indicates that FFDI $\geq$ 50 if and only if $F \geq 6.1$. Hence extreme forest fire danger conditions may be equivalently classified as $F \geq 6.1$. Similar thresholds for F could be derived to emulate the classification systems pertaining to the grassland fire danger indices and FFWI. The classification thresholds for F corresponding to those of the FFDI and GFDI4 classification schemes (McArthur, 1967; Cheney and Sullivan, 1997), which are the most relevant to current fire management practices in southeastern Australia, can be seen in

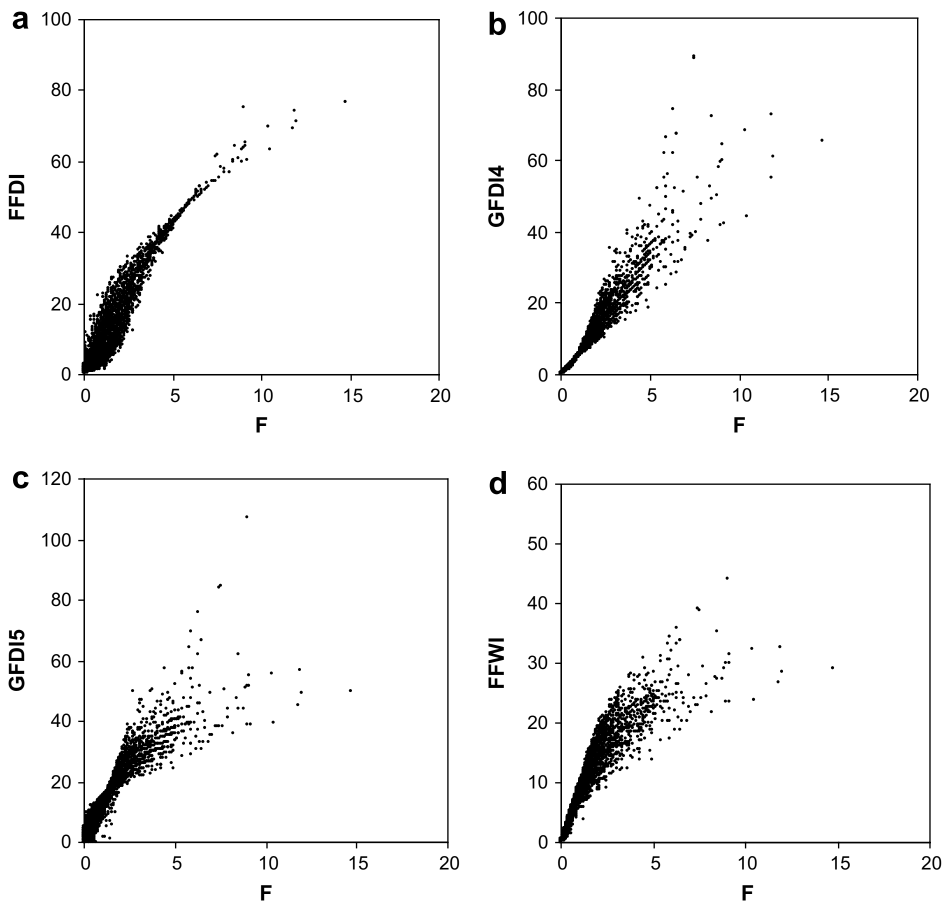

Fig. 1. Scatter-plots of (a) the McArthur Mark 5 Forest Fire Danger Index FFDI, (b) the McArthur Mark 4 Grassland Fire Danger Index GFDI4, (c) the McArthur Mark 5 Grassland Fire Danger Index GFDI5 and (d) the Fosberg Fire Weather Index FFWI, plotted against the index F.

Table 2
Linear and rank correlation and error statistics arising from comparisons of the index F^* with each of the four indices FFDI, GFDI4, GFDI5 and FFWI.

Index	Correlation	Mean abs. error	Max. abs. error	Rank correlation
FFDI	0.9379	2.83	43.49	0.8744
GFDI4	0.9587	1.24	64.88	0.9956
GFDI5	0.9161	2.98	112.34	0.9339
FFWI	0.9053	2.01	59.09	0.9848

Table 3. Table 3 also lists the percentage of values for which a fire danger classification based on the F thresholds differed from that based on the FFDI and GFDI4 classification schemes. The results listed in Table 3 indicate that F emulates the GFDI4 classification scheme very well, with less than 4% of the “Low” fire danger values being misclassified and only 0.2% of the “Extreme” fire danger values being misclassified. The FFDI classification scheme is also emulated quite well, especially for the “Very High” and “Extreme” classes; none of the data classified as extreme using the FFDI scheme are misclassified using F. More will be said about these classification schemes in Section 6.

Time series comparisons of F^* against FFDI, GFDI4, GFDI5 and FFWI for the 60 day period covering 19th November 2006–8th January 2007 can be seen in Figs. 3–6, respectively. The time series indicate that the behaviour of F^* through time is closely linked to that of the indices FFDI, GFDI4, GFDI5 and FFWI. The best agreement appears to be between F^* and GFDI4 (Fig. 4); an observation

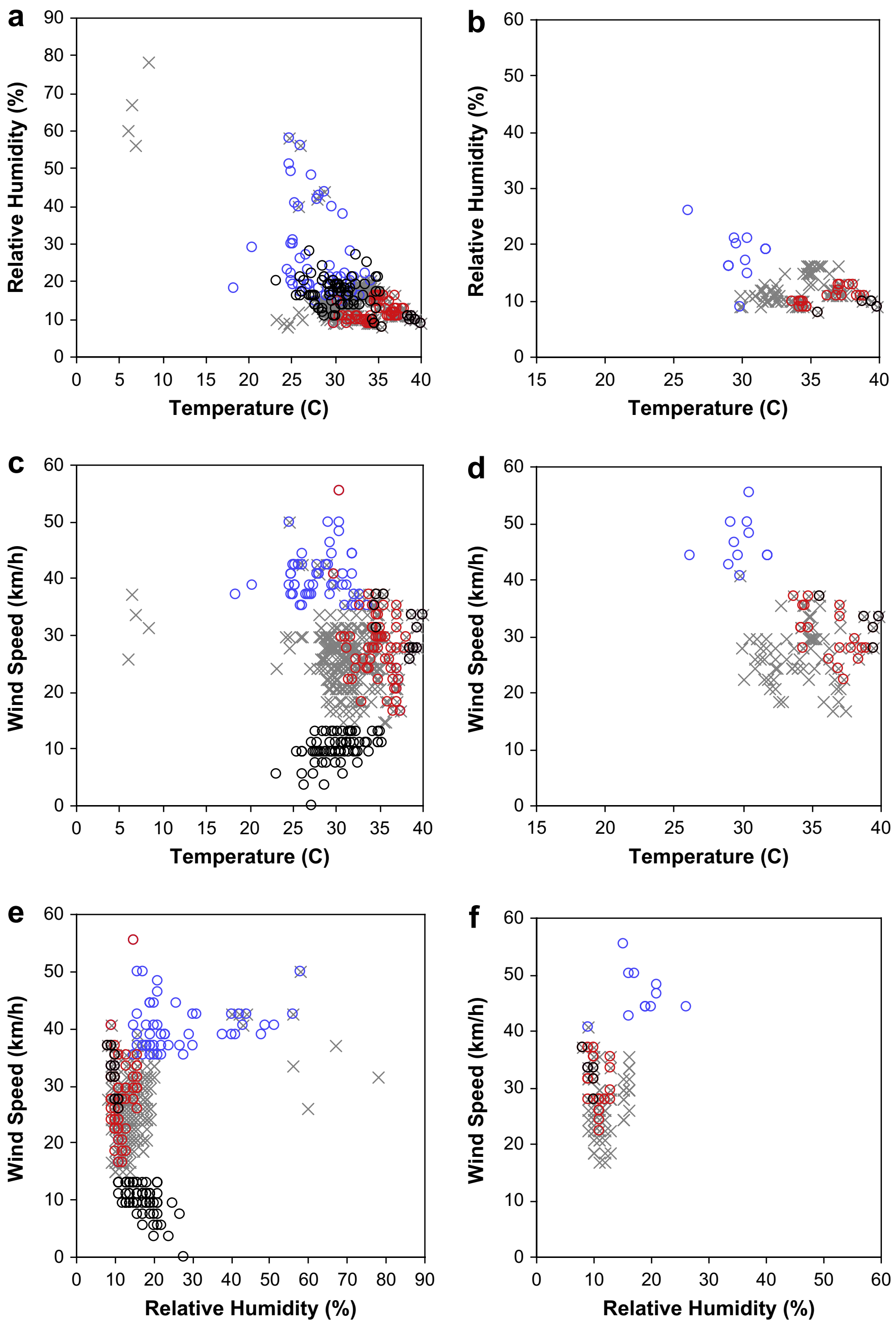

Fig. 2. Plots showing the relationship between dry-bulb temperature, relative humidity and wind speed corresponding to instances when the absolute difference between F^* and the indices FFDI (black circles), GFDI4 (blue circles), GFDI5 (grey crosses) and FFWI (red diamonds) are greater than 10 (panels a, c and e) and 20 (panels b, d and f).

Table 3
Fire danger classification thresholds for FFDI and GFDI4, the approximately corresponding values of F and the percentage of values misclassified based on the listed F values.

Fire danger classification	FFDI	F	% misclassified	GFDI4	F	% misclassified
Low	0–5	0.0–0.7	8.9	0.0–2.5	0.0–0.5	3.6
Moderate	5–12	0.7–1.5	10.1	2.5–7.5	0.5–1.2	2.8
High	12–24	1.5–2.7	7.6	7.5–20	1.2–2.9	1.6
Very high	24–50	2.7–6.1	2.3	20–50	2.9–7.3	1.7
Extreme	50–100	>6.1	0.0	50–200	>7.3	0.2

that is supported by the correlation and mean error statistics in Table 2. However, for F^* to be useful as a fire danger index, it is not critical that the magnitudes of F^* match those of the other indices. As the scales used to describe fire danger are essentially arbitrary, we only require that changes in F^* occur in accord with changes in the other indices. Careful inspection of Figs. 3–6 indicates that F^* does quite a good job of fulfilling this requirement. This again suggests that F is a plausible measure of fire danger rating that can be used as a useful rule of thumb.

We note that the differences in the sensitivities to the input variables encountered across the four existing models and F^* can produce some inconsistent features in the time series in Figs. 3–6. For example, the peak fire danger rating for F^* and FFDI occurs on the 12th of January 2007, while the peak fire danger according to the other three indices occurs on the 22nd of November 2006. Furthermore, the peaks in FFDI and GFDI4 are nearly matched by F^* on the 21st of November 2006 and the 12th of January 2007, but the peaks of GFDI5 and FFWI are decidedly lower. The peaks on the 22nd of November 2006 corresponded to $T = 30.4$ °C, $H = 15\%$ and $U = 55.4$ km h^{-1}, which was the highest wind speed in the data set. The peaks on the 12th of January 2007 corresponded to $T = 39.9$ °C, $H = 9\%$ and $U = 33.5$ km h^{-1}, which included the highest temperature and the second-to-lowest relative humidity in the data set. The differences in sensitivities to the input variables across the models are also apparent in Fig. 2. In this respect it is interesting to note that while differences exceeding 20 between F^* and FFDI, FFWI and GFDI5 occur only for wind speeds greater than 25, 22 or 16 km h^{-1}, respectively, they also occur only for wind speeds below 40 km h^{-1}. Similarly, differences of greater than 20 between F^* and GFDI4 only occur for temperatures of less than 32 °C.

Changing the degree of curing in GFDI5 only had a small effect on the correlation and error statistics. For example, assuming a curing factor of $C = 90\%$ resulted in a rank correlation of 0.9299, a linear correlation of 0.9137, a mean absolute error of 2.30 and a maximum absolute error of 72.85, while assuming a curing factor of $C = 70\%$ resulted in a rank correlation of 0.8950, a linear correlation of 0.8863, a mean absolute error of 1.64 and a maximum absolute error of 41.93. The maximum absolute errors again occurred under extremely hot, dry and windy conditions.

6. Further analytical remarks

In this section we focus on the differences in structure of F and the McArthur indices FFDI and GFDI4, as these two indices are the most relevant to current fire management practices in southeastern Australia. We begin by considering FFDI and noting the approximate version of equation (1) listed in Noble et al. (1980), which assuming a drought factor of 10 can be written

$$\mathrm{FFDI} \approx 12.5 \exp\left(0.0234U + \frac{1}{30}(T - H)\right). \quad (8)$$

According to Noble et al. (1980) equation (8) reproduces the values of equation (1) to within 2.5 fire danger index points. Substituting

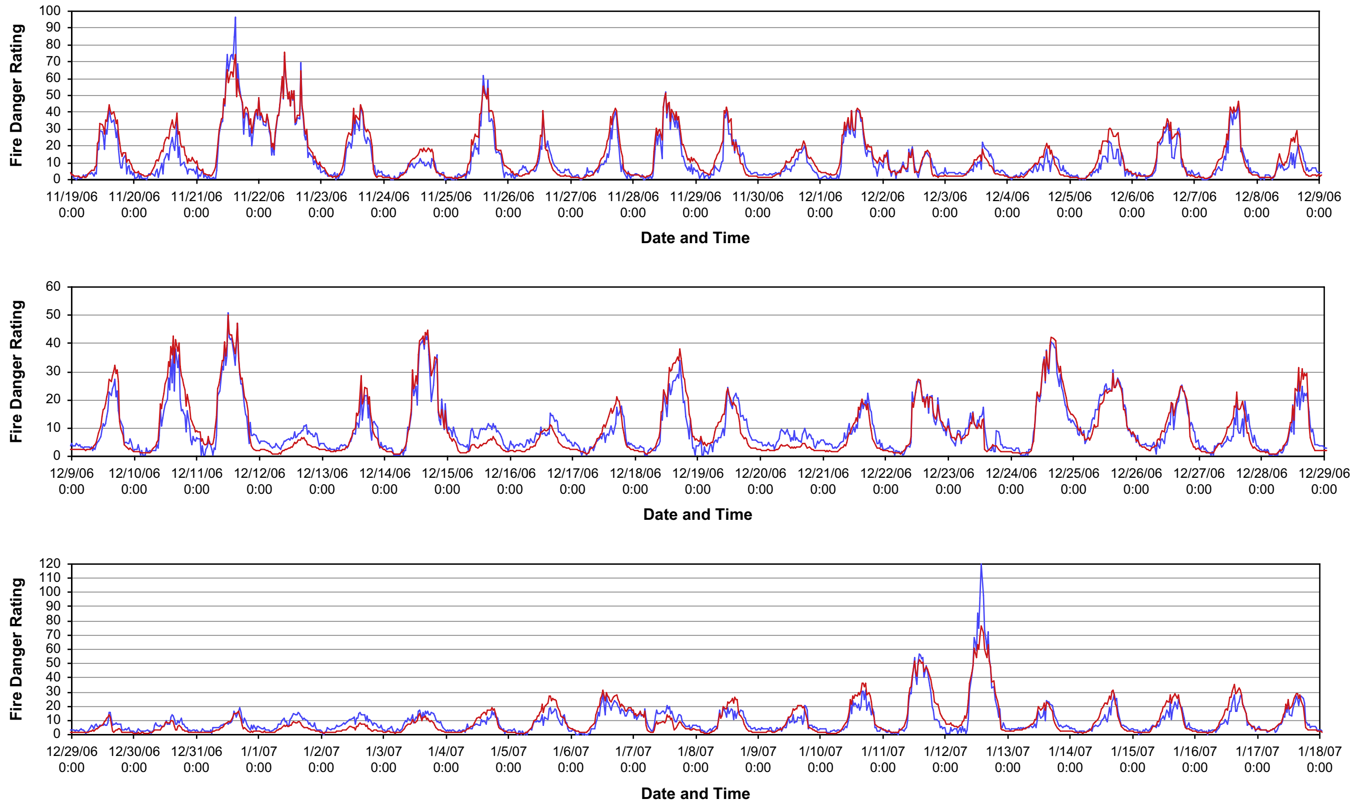

Fig. 3. Time series plots of the McArthur Mark 5 Forest Fire Danger Index FFDI (in red) and the index F^* (in blue) for the period 00:00AEST, 19th November 2006–00:00AEST, 8th January 2007. Note that the vertical scale changes from panel to panel.

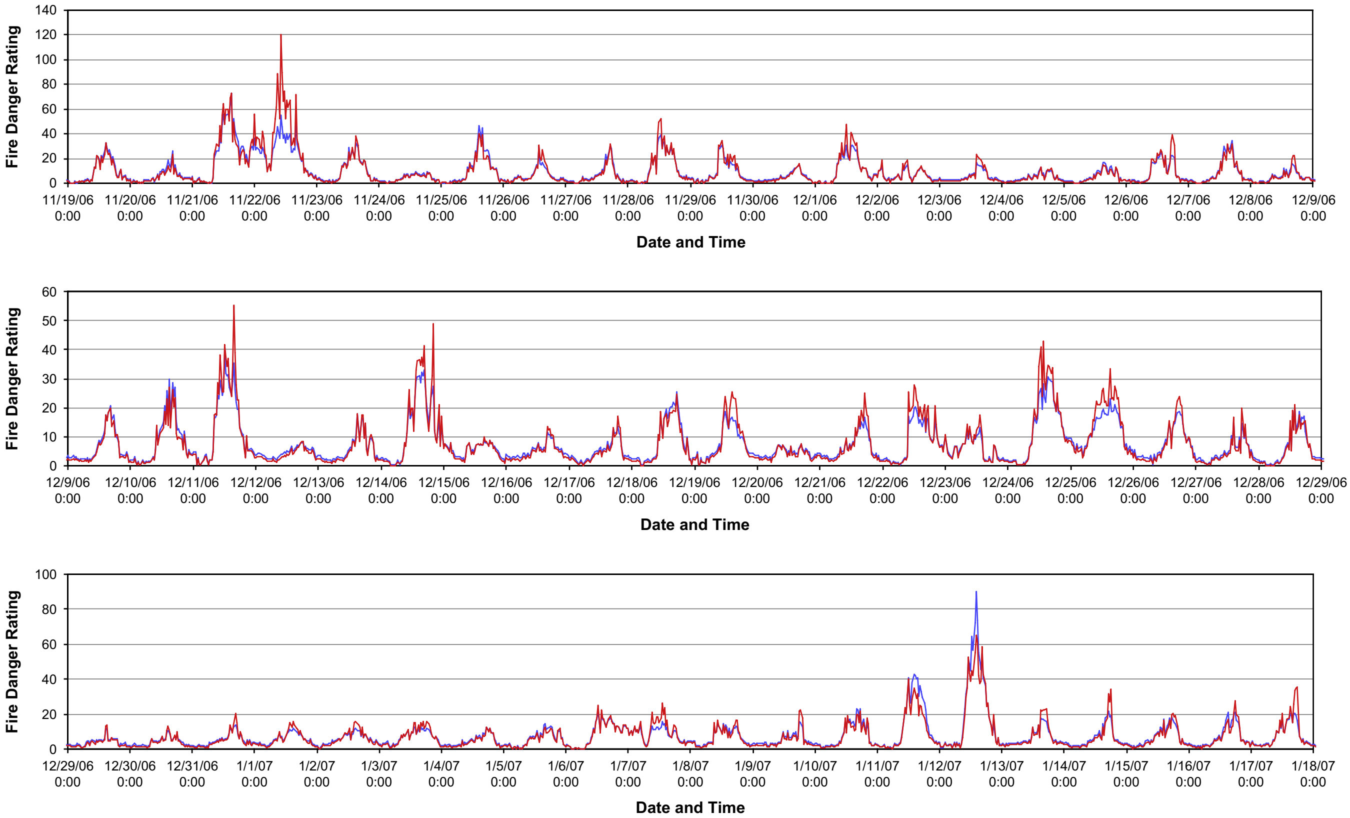

Fig. 4. Time series plots of the McArthur Mark 4 Grassland Fire Danger Index GFDI4 (in red) and the index F^* (in blue) for the period 00:00AEST, 19th November 2006–00:00AEST, 8th January 2007. Note that the vertical scale changes from panel to panel.

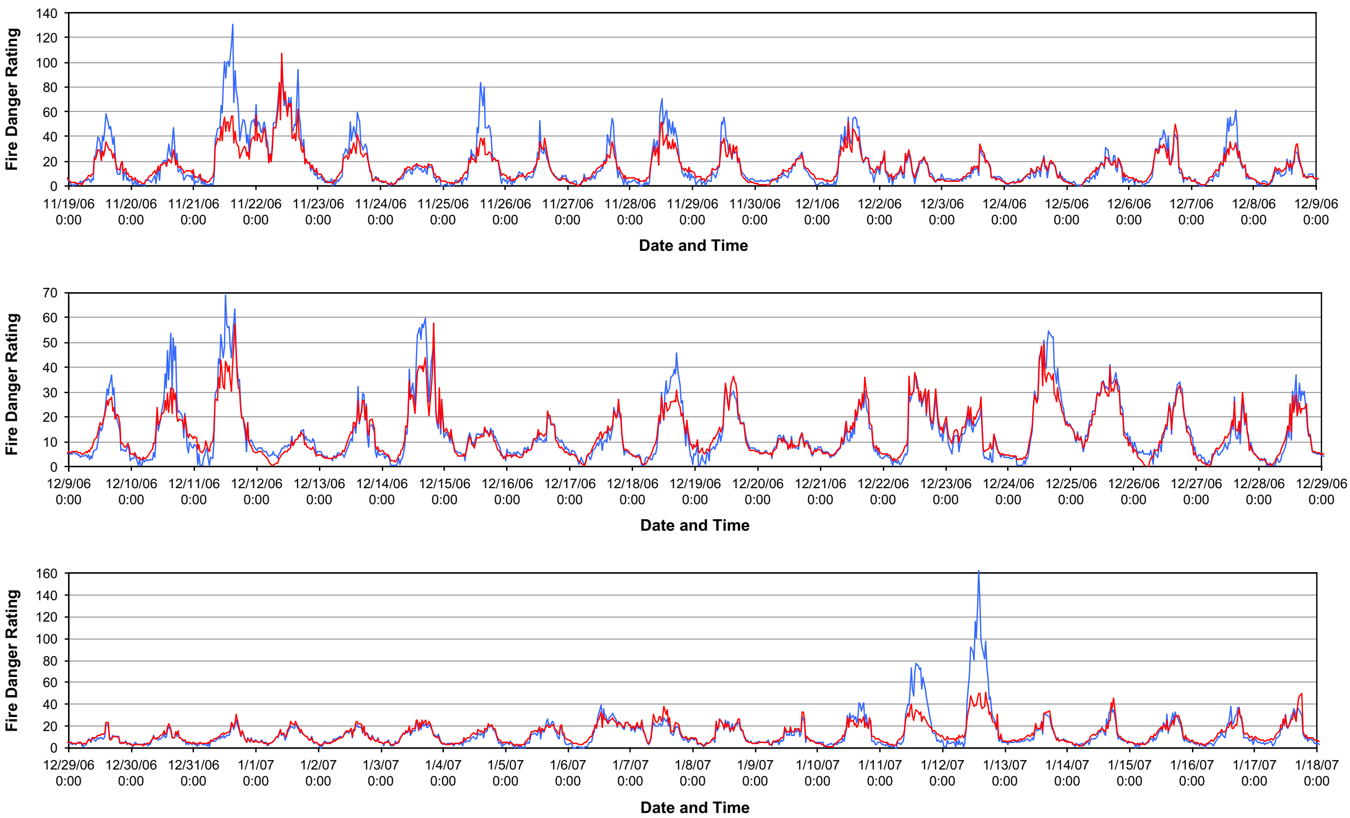

Fig. 5. Time series plots of the McArthur Mark 5 Grassland Fire Danger Index GFDI5 (in red) and the index F^* (in blue) for the period 00:00AEST, 19th November 2006–00:00AEST, 8th January 2007. Note that the vertical scale changes form panel to panel.

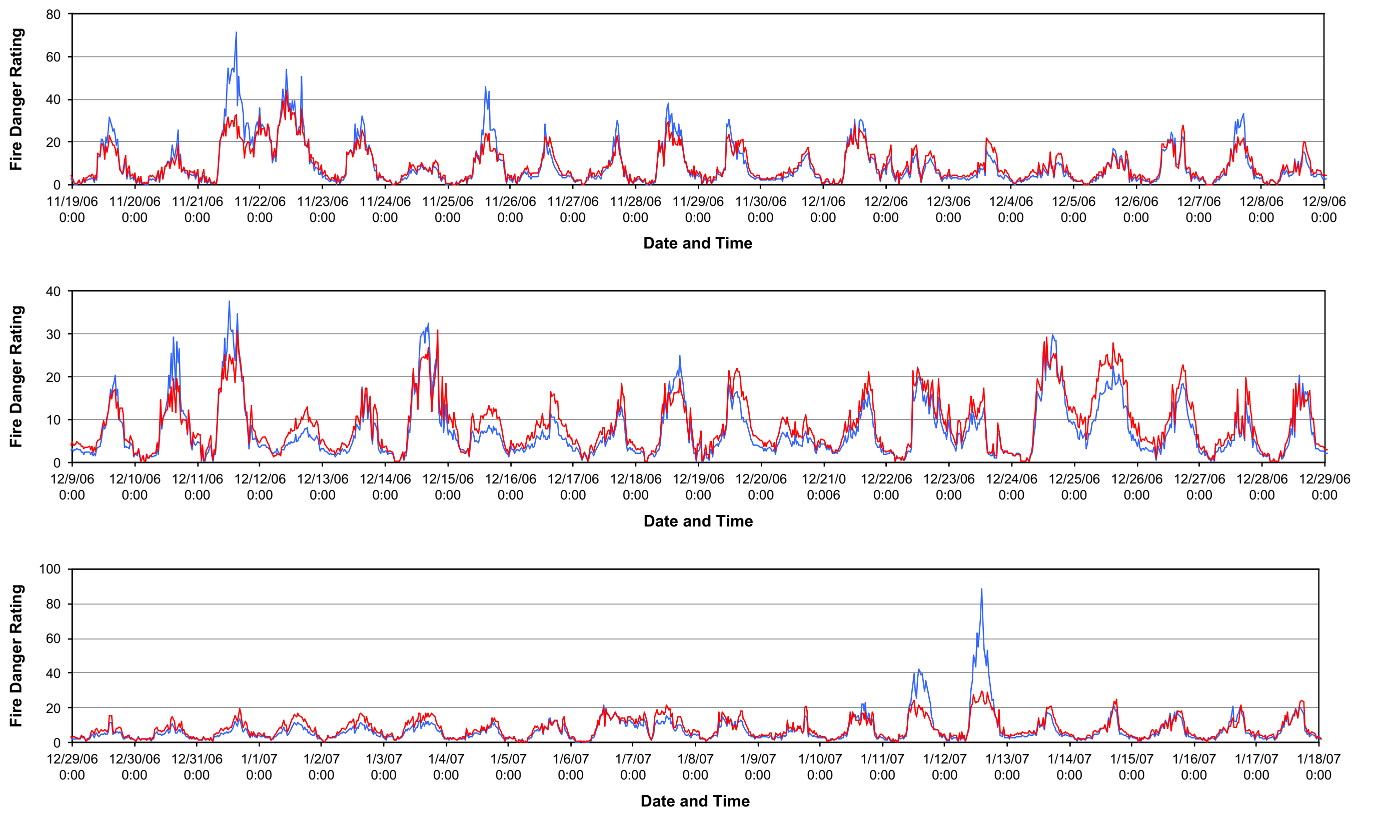

Fig. 6. Time series plots of the Fosberg Fire Weather Index FFWI (in red) and the index F^* (in blue) for the period 00:00AEST, 19th November 2006–00:00AEST, 8th January 2007. Note that the vertical scale changes form panel to panel.

FMI using equation (6), into equation (8) and rearranging then yields

$$U \approx \frac{1}{0.0234}\left\{\frac{4\mathrm{FMI}}{30} + \ln\left(\frac{\mathrm{FFDI}}{12.5}\right) - \frac{4}{3}\right\}. \tag{9}$$

Equation (9) implies that, up to a reasonable approximation, constant FFDI values correspond to straight lines in the (FMI, U) phase plane. According to equation (7) constant F values also correspond to straight lines in the (FMI, U) phase plane, at least for $U \geq 1$ km h^{-1}. The lines in the (FMI, U) phase plane corresponding to the classification threshold values for FFDI and F can be seen in Fig. 7a, along with points derived from the T, H and U data. As can be seen, the lines corresponding to FFDI = 50 and F = 6.1 are almost the same; this is the reason why no data classified as extreme using the FFDI scheme were misclassified using F.

Moreover, equation (9) and Fig. 7a indicate that the FMI can be used to classify forest fire danger in a manner that yields results that are practically identical to the FFDI classification scheme. By considering where a (T, H, U) triple falls in the (FMI, U) phase plane, with respect to the lines corresponding to the threshold values of FFDI, it is possible to classify forest fire danger with near exactitude.

Similarly, rearranging equation (3) with $Q = 4.5$ t ha^{-1} and $C = 100\%$, we find that

$$U \approx \frac{1}{0.6422^2}\left\{\ln\left(\frac{\mathrm{GFDI4}}{4.5^{1.027}}\right) + 1.523 + p(\mathrm{FMI})\right\}^2, \tag{10}$$

where p is some polynomial function such that $p(\mathrm{FMI}) \approx 0.2205\sqrt{H} - 0.02764T$. In what follows we have taken p to be the cubic least squares approximation, which fits the data with $R^2 = 0.994$. Equation (10) then implies that constant values of GFDI4 correspond to curves in the (FMI, U) phase plane. The curves corresponding to the classification threshold values of GFDI4 can be seen in Fig. 7b along with the lines corresponding to the threshold values of F. As can be seen, the curves corresponding to GFDI4 = 2.5 and GFDI4 = 7.5 are very close to the lines corresponding to F = 0.5 and F = 1.2, respectively. The extent of the data in the vicinity of the other curves in Fig. 7b also indicates that only a relatively small proportion of the data would be misclassified.

Equation (10) and Fig. 7b also indicate that the FMI can be used to classify grassland fire danger in a manner that yields results that are practically identical to those derived from the GFDI4 classification scheme. By considering where a (T, H, U) triple falls in the (FMI, U) phase plane, with respect to the curves corresponding to the threshold values of GFDI4, it is possible to classify grassland fire danger with near exactitude.

According to the analysis above, culminating in Fig. 7, it is apparent that the circular slide rules commonly used to calculate forest and grassland fire danger rating in southeastern Australia could be replaced with simple graphs and the FMI formula.

7. Discussion and conclusions

We have presented a simple, intuitive fire danger index F, which produces results that are highly correlated with other fire danger indices employed operationally in Australia and the United States. In many circumstances the proposed index was able to produce results that were similar to those obtained using the other indices. The agreement between F^* and the other indices was worst under extreme fire weather conditions. However, by necessity, fire danger indices based on empirical studies, such as the McArthur indices, were developed in the absence of extreme fire weather (Cheney et al., 1999). This means that their use in these conditions is open to question. Indeed, recent research has found that FFDI is inadequate for predicting the behaviour of moderate to high-intensity wildfires (Cheney et al., 1999; Gould et al., 2001). In any case, if the point of interest is fire danger rating, as opposed to fire behaviour

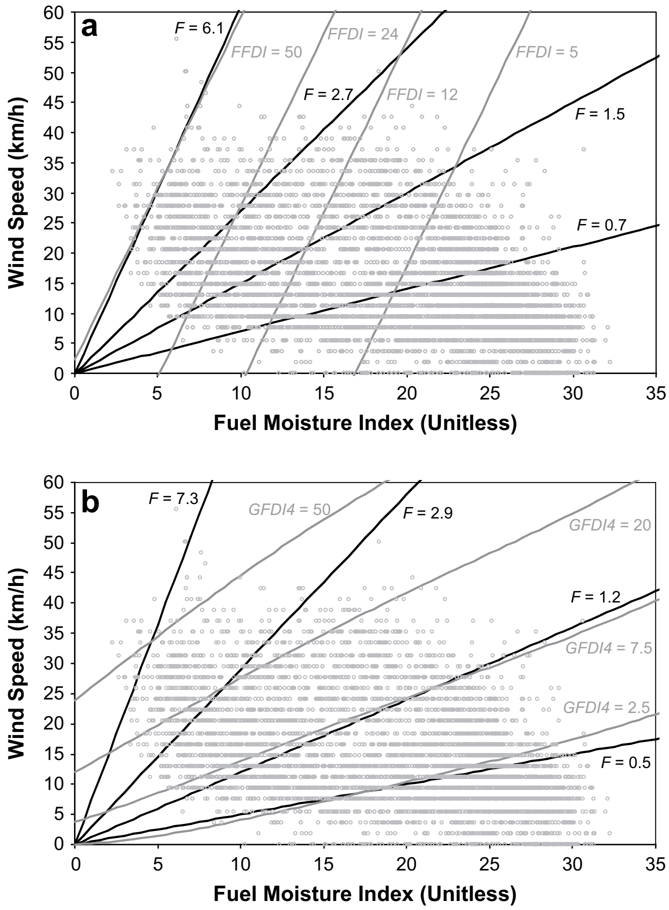

Fig. 7. (a) Plot showing lines corresponding to threshold values of FFDI (grey) and F (black) in the (FMI, U) phase plane. (b) Plot showing lines corresponding to threshold values of GFDI4 (grey) and F (black) in the (FMI, U) phase plane. Points corresponding to the 5721 data points are also shown in each panel.

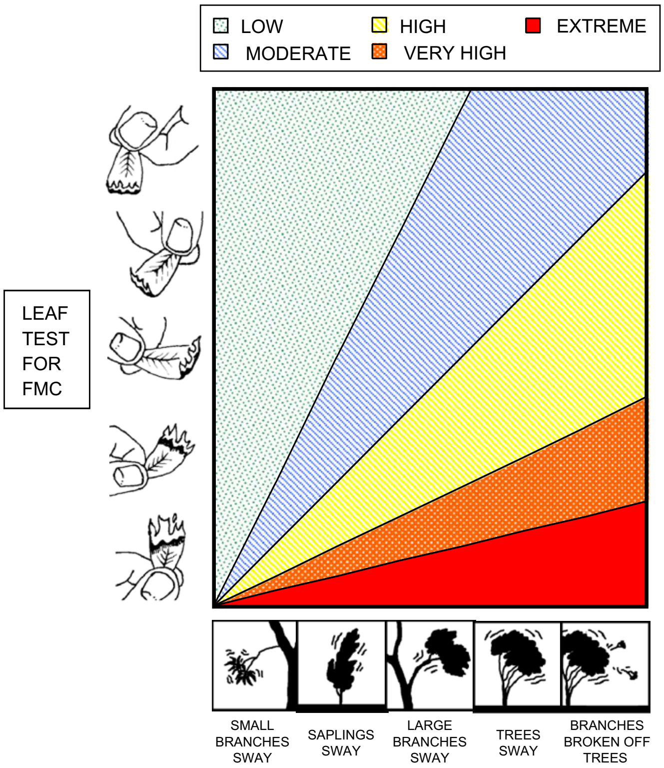

Fig. 8. Fire danger rating nomogram based on the proposed index F.

prediction, the proposed index appears to provide similar guidance to the more complicated indices.

Considering the problem of assessing fire danger intuitively, the proposed approach has considerable merit. Employing the proposed index, fire danger rating can be addressed simply in terms of F, which can be calculated using mental arithmetic. Hence, once enough experience with calculating and interpreting F, in a particular region and/or fuel type, has been gained, fire danger rating could be assessed without the need for tables or circular slide rules. However, if desired, it is also possible to present the proposed system as tables, graphs, nomograms or in very simple forms. For example, the results presented above confirm that fire danger rating can be conceptualised intuitively and simply as 'wind speed divided by fuel moisture content'. This suggests that fire danger rating can be gauged with reasonable accuracy, by appealing to a nomogram like that shown in Fig. 8. This nomogram is indicative only, i.e. it has not been calibrated with any particular fire danger model in mind, but it suggests that fire danger rating can be determined by simple observation of the effect of the wind on foliage (a kind of simplified Beaufort scale) and by conducting a leaf test (Tasmanian Forestry Commission, 1984; Burrows, 1984; Weber, 1990) for fuel moisture content. The leaf test involves lighting a sample leaf and observing at what inclination it ceases to burn. Making such observations is well within the means of anyone in the field that is likely to be concerned with fire danger. Similar nomograms based on the lines of constant FFDI or GFDI4 in Fig. 7a and b are also obvious possibilities. Conceptualising fire danger rating in this way could be a useful pedagogical tool.

The analyses discussed above also indicate that FMI is an extremely useful variable for assessing fire danger rating. The (FMI, U) phase plane approach discussed in Section 6 indicates that fire danger can be classified very nearly exactly in accordance with the classification schemes based on FFDI and GFDI4. This means that the circular slide rules commonly used to calculate forest and grassland fire danger rating in southeastern Australia could be replaced with two simple graphs and the FMI formula. Such graphs could easily be incorporated into operational handbooks, which are routinely carried by personnel on a fire ground.

The comparison with FFDI detailed above assumed a constant drought factor. In reality the drought factor will vary over space and in time. Thus to account for long-term moisture effects with an index like the one proposed, a more suitable option would be

$$F_D = DF\frac{\max(U_0, U)}{\text{FMI}}.$$

Given that the drought factor (DF) enters into FFDI essentially as a multiplicative factor, a comparison between FFDI with variable drought factor and F_D would result in similar statistics to those presented above. In essence the drought factor in F_D accounts for long-term moisture effects or fuel availability, whereas the FMI component describes short-term changes in fuel moisture content. Similar modifications could be made relating to the curing and fuel load components of GFDI4. These ideas will be pursued in further work, though we note that there is no explicit mechanistic connection between drought factor, soil dryness and rate of fire spread.

It is also of interest to point out the conceptual similarities between F and the FFWI. Of particular significance is the fact that both the FFWI and F assume a linear dependence on wind speed (except for small values). Moreover the moisture damping coefficient in the FFWI is a decreasing function of fuel moisture and so plays an analogous role to the inverse of the FMI in the equation for F. The large differences between F^* and FFWI are entirely due to the divergence of the moisture damping coefficient η and the inverse of

FMI when conditions are very hot and dry. We note, however, that F^* appears to do a better job of discerning these dangerous conditions than the FFWI, as can be seen in the time series in Fig. 6. The peaks on the 22nd of November 2006 and the 12th of January 2007, corresponding to very high wind speeds, very high temperatures and very low relative humidity, are much more pronounced in F^* than they are in FFWI.

Although we have argued that F provides a measure of fire danger rating that is roughly equivalent to that provided by the other indices, implementing F operationally requires some caution. Changes in the way fire danger rating is assessed operationally will, of necessity, alter the thresholds for activities such as hazard reduction burning or readiness for response to wildfires. It will also have an impact on decisions to limit the general use of fire through declarations of days of total fire ban. Separating the functions of resource allocation and public warnings of fire danger from prediction of fire behaviour for specific fuel types could also cause confusion. Implementing F operationally therefore requires further scientific and experimental substantiation of the index, further development of the index in cooperation with relevant fire agencies and broader communication of the index among researchers and stakeholders. On the other hand, the simple rule of thumb provided by the proposed index may be applicable for field guides that assist in determining fire behaviour. Field guides for fire behaviour will provide better information when based on short-term forecasts or adjusted by measurement of local weather and fuel assessment at the fire site (J.S. Gould, pers. comm.).

A more immediate benefit of the proposed index stems from the fact that it provides a simple and intuitive way of conceptualising fire danger rating. As such the index could be incorporated into training materials and may assist in clarifying the notion of fire danger rating.

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References

Beall, H.W., 1946. Forest Fire Danger Tables (Provisional). Forest Fire Research Note 12, Dominion Forest Service, Canada.

Beck, J.A., 1995. Equations for the forest fire behaviour tables for Western Australia. CALMScience 1 (3), 325–348.

Burrows, N.D., 1984. Describing forest fires in Western Australia: a guide for fire managers. Forest Department of Western Australia, Perth. Technical Paper, No. 9.

Byram, G.M., 1959. Forest fire behaviour. In: Davis, K.P. (Ed.), Forest Fire: Control and Use. McGraw-Hill, New York.

Chandler, C., Cheney, P., Thomas, P., Trabaud, L., Williams, D., 1983. Fire in forestry. In: Forest Fire Behaviour and Effects, Vol. I. John Wiley and Sons, New York.

Cheney, N.P., Gould, J.S., 1995. Separating fire spread prediction and fire danger rating. CALMScience Supplement Western Australia Journal of Conservation and Land Management 4, 3–8.

Cheney, N.P., Sullivan, A., 1997. Grassfires: Fuel, Weather and Fire Behaviour. CSIRO Publishing, Australia.

Cheney, N.P., Gould, J.S., McCaw, L., 1999. Project Vesta – predicting the behaviour of summer fires in dry eucalypt forests with fuels of differing ages. In: Proceedings of the Australian Bushfire Conference – Bushfire '99, 7–9 July 1999, Albury (poster paper).

Deeming, J.E., Lancaster, J.W., 1971. Background, philosophy, implementation – national fire danger rating system. USDA Fire Control Notes 32 (2), 4–8.

Deeming, J.E., Lancaster, J.W., Fosberg, M.A., Furman, R.W., Schroeder, M.J., 1974. The National Fire-Danger Rating System. USDA Forest Service Research Paper RM-84, Rocky Mountain Forest and Range Experimental Station. Ft. Collins, Colorado, USA.

Deeming, J.E., Burgan, R.E., Cohen, J.D., 1977. The National Fire-Danger Rating System – 1978. USDA Forest Service General technical Report INT-39. Intermountain Forest and Range Experiment Station. Ogden, Utah, USA.

Forestry Canada Fire Danger Group, 1992. Development and Structure of the Canadian Forest Fire Behaviour Prediction System. Forestry Canada, Science and Sustainable Development Directorate, ST-X-3, Ottawa, Canada.

Fosberg, M.A., 1978. Weather in wildland fire management: the fire weather index. In: Proceedings of the Conference on Sierra Nevada Meteorology, June 19–21, Lake Tahoe, California, USA. American Meteorological Society, Boston, pp. 1–4.

Gill, A.M., Christian, K.R., Moore, P.H.R., Forrester, R.I., 1987. Bushfire incidence, fire hazard and fuel reduction burning. Australian Journal of Ecology 12, 299–306.

Goodrick, S.L., 2002. Modification of the Fosberg fire weather index to include drought. International Journal of Wildland Fire 11, 205–211.

Gorski, C.J., Farnsworth, A., 2000. Fire weather and smoke management. In: Whiteman, C.D. (Ed.), Mountain Meteorology Fundamentals and Applications. Oxford University Press, New York.

Gould, J.S., Cheney, N.P., McCaw, L., 2001. Fire behaviour and fire danger rating: Project Vesta – research into the effects of fuel structure and fuel load on fire behaviour of moderate to high-intensity fires in dry eucalypt forest: progress report. In: Proceedings of Bushfire 2001, Australasian Bushfire Conference 3–6 July 2001, Christchurch, NZ, pp. 13–21.

Gould, J.S., McCaw, W.L., Cheney, N.P., Ellis, P.F., Knight, I.K., Sullivan, A.L., 2007. Project Vesta – Fire in Dry Eucalypt Forest: Fuel Structure, Fire Dynamics and Fire Behaviour. A joint report by Ensis-CSIRO, ACT and Department of Environment and Conservation, Western Australia.

Griffiths, D., 1999. Improved formula for the drought factor in McArthur's Forest Fire Danger Meter. Australian Forestry Journal 62 (2), 210–214.

Haines, D.A., Main, W.A., Frost, J.S., Simard, A.J., 1983. Fire-danger rating and wildfire occurrence in the northeastern United States. Forest Science 66, 159–164.

Keetch, J.J., Byram, G.M., 1968. A Drought Index for Forest Fire Control. USDA Forest Service Research Paper SE-38.

Matthews, S. A comparison of fire danger rating systems for use in Australian forests. Australian Meteorological Magazine, in press.

McArthur, A.G., 1966. Weather and grassland fire behaviour. Department of National Development, Forestry and Timber Bureau Leaflet No. 100. Canberra, Australia.

McArthur, A.G., 1967. Fire behaviour in eucalypt forests. Department of National Development, Forestry and Timber Bureau Leaflet No. 107. Canberra, Australia.

McArthur, A.G., 1977. Grassland Fire Danger Meter, Mk 5. Country Fire Authority of Victoria, Melbourne.

Mount, A.B., 1972. The derivation and testing of a soil dryness index using run-off data. Bulletin 4, Tasmanian Forestry Commission.

Nelson, R.M., 2000. Prediction of diurnal change in 10-h fuel stick moisture content. Canadian Journal of Forest Research 30, 1071–1087.

Noble, I.R., Bary, G.A.V., Gill, A.M., 1980. McArthur's fire-danger meters expressed as equations. Australian Journal of Ecology 5, 201–203.

Purton, C.M., 1982. Equations for the McArthur mark 4 grassland fire danger meters. Meteorological Note 147. Bureau of Meteorology, Melbourne.

Roads, J.O., Ueyoshi, K., Chen, S.-C., Alpert, J., Fujioka, F., 1991. Medium-range fire weather forecasts. International Journal of Wildland Fire 1 (3), 159–176.

Roads, J.O., Chen, S.-C., Fujioka, F.M., Juang, H., Kanamitsu, M., 1997. Global to Regional Fire Weather Forecasts Available from: <http://www.uni-freiburg.de//fwf/ecpc2.htm>.

Rothermel, R.C., 1972. A Mathematical Model for Predicting Fire Spread in Wildland Fuels, INT-115. USDA Forest Service, Intermountain Research Station, Ogden, Utah, USA.

Sharples, J.J., McRae, R.H.D., Weber, R.O., Gill, A.M. A simple index for assessing fuel moisture content. Environmental Modelling and Software. 24(5), 637-646.

Simard, A.J., 1968. The moisture content of forest fuels – 1. A review of the basic concepts. Canadian Department of Forest and Rural Development, Forest Fire Research Institute, Information Report FF-X-14. Ottawa, Ontario. 47pp.

Sneeuwjagt, R.J., Peet, G.B., 1985. Forest Fire Behaviour Tables for Western Australia. Western Australian Department of Conservation and Land Management, Perth, Western Australia.

Tasmanian Forestry Commission, 1984. Guidelines for Fuel Reduction Burning under Dry Forest. Government Printer, Tasmania.

Van Wagner, C.E., Pickett, T.L., 1985. Equations and FORTRAN program for the Canadian forest fire weather index system. Environment Canada, Forestry Service 33 Ottawa, Canada.

Van Wagner, C.E., 1987. Development and structure of the Canadian forest fire weather index system. Canadian Forestry Service 35 Ottawa, Canada.

Viney, N.R., 1991. A review of fine fuel moisture modelling. International Journal of Wildland Fire 1 (4), 215–234.

Weber, R.O., 1990. The moist strand and the burning bed. Canadian Journal of Forest Research 20, 845–848.