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A simple method for assessing fuel moisture content and fire danger rating

Sharples, J.J. [1], **R.H.D. McRae** [2, 4], **R.O. Weber** [1, 4] **and A.M. Gill** [3, 4]

[1] *School of Physical Environmental and Mathematical Sciences University of New South Wales at the Australian Defence Force Academy, Australian Capital Territory*
[2] *ACT Emergency Services Agency*
[3] *Fenner School of Environment and Society, The Australian National University*
[4] *Bushfire Cooperative Research Centre*
Email: j.sharples@adfa.edu.au

Abstract: The flammability of wildland vegetation is strongly dependent upon the moisture content of fine dead fuels. Consequently, assessing the moisture content of these fuels to within a reasonable degree of accuracy is an important part of wildland fire management. Estimates of fine fuel moisture content can also be combined with information on wind speed, vegetation type and drought effects to provide a measure of fire potential or fire danger rating. For example, the moisture content of eucalypt litter is an important consideration in determining fire danger rating in the forests of southeastern Australia. This paper describes a simple and intuitive linear index, which provides an equivalent measure of the moisture content of eucalypt litter. Despite its simplicity, the so-called fuel moisture index, defined as $FMI = 10-0.25(T-H)$, where T is temperature and H is relative humidity, is shown to be remarkably effective at reproducing the results of a more sophisticated model for the moisture content of eucalypt litter.

In previous work the fuel moisture index was combined with information on wind speed U to provide a simple fire danger index F. Under the restrictive assumption of constant fuel availability, F was shown to compare favourably with other measures of fire danger rating that feature in the literature. In this paper we extend the definition of F to incorporate the effects of variable fuel availability. This is done very simply by multiplying F by the drought factor to obtain the index F_D. The drought factor, which is determined through knowledge of antecedent rainfall, is used to describe fuel availability in forest fuel types. The utility of the index F_D is tested by comparing its value with the McArthur Mark 5 Forest Fire Danger Index (*FFDI*) using data from two automatic weather stations. Moreover, by converting grass curing, which is used to describe fuel availability in grassland fuels, to an equivalent drought factor the index F_D is also compared with the McArthur Mark 4 Grassland Fire Danger Index (*GFDI*). The comparisons indicate that F_D provides a plausible measure of fire danger rating for forest fuels and grassland fuels in particular.

The structure of the two McArthur indices with respect to the fuel moisture index is also investigated. It is shown that when viewed in terms of the (*FMI*, *U*) phase plane, the McArthur indices have a very simple geometric characterisation: constant *FFDI* corresponds to straight lines and constant *GFDI* corresponds to cubic curves in the (*FMI*, *U*) plane. This confirms that *FMI* is a unifying variable which permits a simpler conceptualisation of fire danger rating, at least as it is treated in the McArthur schemes. Hence, characterising fire danger rating in terms of *FMI* could have a pedagogical advantage over other methods and could provide fire management personnel with a simpler and more intuitive method for assessing fire potential.

Keywords: *Fuel moisture content, fuel moisture index, fire danger rating, fire weather, bushfire, grassfire*

1. INTRODUCTION

Bushfires are a serious environmental problem, and consistently cause loss of life and damage to property and other assets. The potential for the occurrence and development of bushfires is dependent upon the interaction of fuels with variables such as air temperature, atmospheric dryness and wind speed. Other factors such as topographic attributes and random effects such as arson are also important in determining the overall level of fire danger. 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 an intractable task (Cheney and Gould, 1995). However, to assist in fire management 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 the moisture content of fuels, fire weather and drought effects.

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. Fuel moisture content can change in response to various physical processes including latent heat effects, vapour exchange and rainfall (Viney, 1991). The amount of moisture present in fuels is a key factor affecting fire potential and fire behaviour. Assessing fuel moisture content is therefore an important consideration in fire management practices, such as prescribed burning, where fire behaviour within certain thresholds is desired, and in wildfire control and suppression due to the effect that low fuel moisture has on fire intensity and the potential for spot fires to form away from the main fire line. An effective means of estimating fuel moisture content to within a reasonable degree of accuracy is thus an essential tool for fire management.

Fire weather variables include air temperature, relative humidity or dew point temperature and wind speed and direction. Temperature and atmospheric moisture are important fire weather variables due to the effect they have on fuel moisture content: temperature can be thought of as a proxy for solar radiation, which together with relative humidity directly affects the processes of evaporation and transpiration. Wind also has a strong influence on fire potential and the rate and direction of fire spread. It 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.

Drought also has a significant impact of fire occurrence and development due to its effect on the long-term moisture content of wildland fuels. Drought effects, determined through knowledge of antecedent rainfall, are typically considered as giving a measure of the proportion of fuel available to burn. In forests, fuel availability is described by the drought factor (McArthur, 1967) while in grasslands it is described by the degree of grass curing (Cheney and Sullivan, 1997).

To gauge the potential for the occurrence and development of wildfires 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 fuel moisture content, temperature, relative humidity, wind speed and drought effects. 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 (Gill et al., 1987). In southeastern Australia the fire danger indices most commonly used are derived from the McArthur Forest and Grassland Fire Danger Meters (McArthur, 1966; 1967; Noble, 1980; Purton, 1982; Gill et al., 1987; Cheney and Sullivan, 1997), which are given as exponential functions of temperature, relative, humidity, wind speed and fuel availability. Recent work of Matthews (2009) has also related the McArthur Forest Fire Danger Index to an estimate of the moisture content of eucalypt litter as given by a formula derived by Viney (1991).

In this paper we discuss the relationship between a remarkably simple index (*FMI*), which describes fuel moisture, Viney's model for the moisture content of eucalypt litter and McArthur's Fire Danger Indices. The simple index was introduced in Sharples et al. (2009a), where it was compared with existing models of fuel moisture content. The index was also combined with wind speed information to assess fire danger rating in Sharples et al. (2009b), where it was assumed that fuel availability was at a maximum. In the current paper we extend the work of Sharples et al. (2009b) to include the effects of variable fuel availability. We combine the simple index with information on wind speed and drought factor and compare the results with the McArthur Forest Fire Danger Index. Moreover, by converting drought factor to an equivalent degree of curing we also assess the utility of the simple index applied to grassland fuels with various degrees of curing.

2. A SIMPLE INDEX FOR FUEL MOISTURE CONTENT

Sharples et al. (2009a) introduced the following index for assessing the moisture content of fine, dead fuels.

$$FMI = 10 - 0.25(T - H) \tag{1}$$

Here T is the dry-bulb air temperature (^{o}C) and H is the relative humidity (%). *FMI* is a dimensionless index and should not be considered as giving a direct estimate of fuel moisture content, as such. However, as was shown in Sharples et al. (2009a), the values of *FMI* compare remarkably well to predictions of the actual fuel moisture content of eucalypt litter derived from the more sophisticated model of Viney (1991). Viney's model gives an estimate of the fuel moisture content m (%) as follows:

$$m = 5.658 + 0.0465H + 3.151\times10^{-4} H^3 T^{-1} - 0.1854T^{0.77}. \tag{2}$$

Note that (2) is based on data contained in McArthur (1967). Due to the nonlinearities present in equation (2) it is only strictly applicable to temperature and relative humidity values satisfying the following constraints:

$$10 \le T \le 41, \quad 5 \le H \le 70, \quad 42.5 - 1.25T < H < 94.5 - 1.35T.$$

Sharples et al. (2009a) showed that to within a reasonable degree of accuracy, *FMI* values correspond uniquely, and linearly for small values of *FMI*, to values derived from Viney's model (2). The correspondence can be seen in figure 1. Nonlinear correlation between m and *FMI* was 0.9989, while rank correlation was 0.9998. The average and maximum errors from using *FMI* to predict m were 0.07% and 1.21%, respectively. Hence, assuming that Viney's model accurately predicts actual fuel moisture content, *FMI* provides an equivalent measure of actual fuel moisture content that is intuitive and easy to calculate.

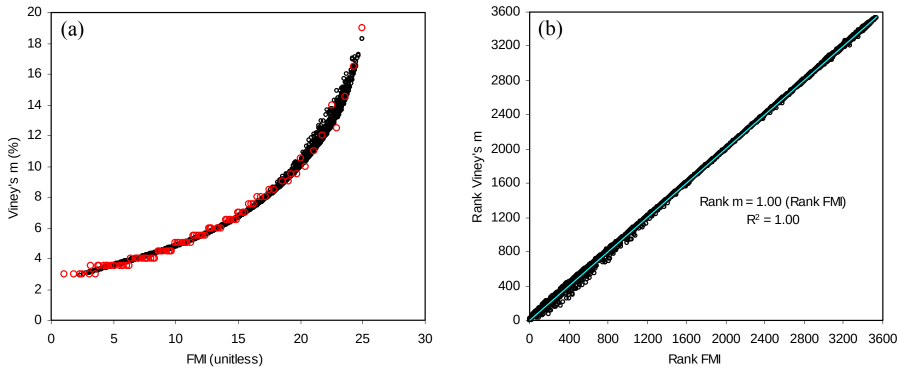


Figure 1. (a) Black circles show predictions arising from Viney's model (2) against *FMI* values derived from equation (1), red circles show fuel moisture values from McArthur (1967) against *FMI* values, (b) Plot of rank of Viney's m against rank of *FMI*. The blue line in (b) is the regression line of best fit. Note that the 'rank' of an *FMI* value is its position in an ordered list of all *FMI* values, likewise for Viney's m. Values of m and *FMI* have been derived from temperature and relative humidity data recorded at Canberra Airport between 1 November 2006 and 28 February 2007.

3. A SIMPLE INDEX FOR FIRE DANGER RATING

Forest and grassland fire danger ratings in southeastern Australia are typically described by the McArthur Mark 5 Forest Fire Danger Index (*FFDI*) and the modified McArthur Mark 4 Grassland Fire Danger Index (*GFDI**), respectively. According to Noble et al. (1980) *FFDI* can be expressed as

$$FFDI = 2\exp\left(-0.45 + 0.987\ln(D) + 0.0338T - 0.0345H + 0.0234U\right) \tag{3}$$

where T and H are temperature and relative humidity as before, U is average wind speed (measured at a height of 10m) and D is the drought factor, which ranges from 0 to 10, where D = 10 indicates maximum fuel availability. It is of interest to note that to a reasonable degree of accuracy, *FFDI* can also be expressed in terms of Viney's m as (Matthews, 2009):

$$FFDI = 33.78D\exp(0.0234U)m^{-2.1}$$

The modified mark 4 grassland index allows for variable fuel quantity, but in what follows we will assume that the fuel quantity is equal to 4.5 t ha^{-1}. This assumption reduces *GFDI** to the original mark 4 grassland index, which we denote as *GFDI*. According to Purton (1982), *GFDI* can be expressed as follows

$$GFDI = \exp\left(0.0217 - 0.009432(100 - C)^{1.536} + 0.02764T - 0.2205\sqrt{H} + 0.6422\sqrt{U}\right) \quad (4)$$

where C is the degree of grass curing, which ranges from 0-100%.

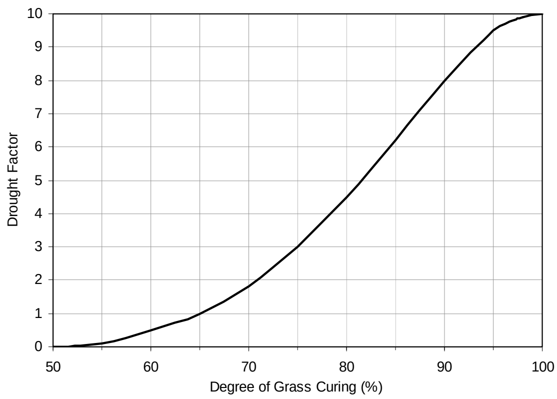
Sharples et al. (2009b) introduced the following simple index for assessing fire danger rating

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

which was found to compare favourably with *FFDI* and *GFDI* when drought factor and curing were assumed to be at their maximum values of D = 10 and C = 100%. Variable fuel availability was not considered, however. To incorporate the effects of variable fuel availability we introduce the following index

$$F_D = D\frac{\max(U_0, U)}{FMI}. \quad (5)$$

As was done in Sharples et al. (2009b) we will take U_0 = 1 km h^{-1}. Given data (T, H, U, D) the indices F_D and *FFDI* will be directly comparable, but F_D will not be directly comparable to *GFDI*. To compare F_D and *GFDI* we will need to convert degree of grass curing to an equivalent drought factor. To do this we use the near linear dependence of *FFDI*, and hence rate of spread (Noble et al., 1980), on drought factor and the relationship between rate of spread and degree of grass curing given in figure 4.9 of Cheney and Sullivan (1997). Considering these factors we arrive at the approximate relationship between drought factor and grass curing seen in figure 2.



C	D
50	0.0
55	0.1
60	0.5
65	1.0
70	1.8
75	3.0
80	4.5
85	6.2
90	8.0
95	9.5
100	10.0

Figure 2. Function used to convert degree of grass curing to an equivalent drought factor. The curve is obtained by smooth interpolation of the values in the table.

The question of principle interest is how the simple index F_D given by equation (5) compares to *FFDI* and *GFDI*.

4. DATA AND METHODS

To facilitate comparison of the index F_D with the McArthur indices *FFDI* and *GFDI* we use half-hourly temperature, relative humidity and wind speed data recorded at Canberra Airport between 1 November 2006 and 28 February 2007. Drought factors for this period were all near 10, so to accommodate more variation in drought factor in the comparisons, daily drought factor data for the same period a year earlier were used. Temperature ranged between 1.7 ^{o}C and 39.9 ^{o}C, relative humidity ranged between 8% and 99%, wind speed ranged between 0 km h^{-1} and 55.4 km h^{-1} and drought factor ranged between 0.13 and 9.03. To test the utility of F_D in a more alpine climate, comparisons were also made using data from Mt Ginini over the same period. At Mt Ginini temperature ranged between -6.0 ^{o}C and 28.5 ^{o}C, relative humidity ranged between 4% and 99%, wind speed ranged between 0 km h^{-1} and 46.4 km h^{-1}. The same drought factor data was used in the calculations for Canberra Airport and Mt Ginini, despite the fact that the drought factors at the two sites will typically be quite different.

Curing data was obtained from the drought factor data by fitting a polynomial function to the data in figure 2. Given a particular drought factor, the polynomial equation was solved numerically using a bisection algorithm to determine the corresponding degree of grass curing.

The indices were compared qualitatively by observing the structure of the respective time series and were quantitatively compared by considering the linear and rank correlation statistics for F_D and the two McArthur indices at the two sites. For the Canberra site 5720 data points were used in the comparison, while at Mt Ginini 5516 data points were used.

5. RESULTS OF INDEX COMPARISONS

Time series of *FFDI* and F_D can be seen for the two sites in figure 3. The time series cover the period 4-18 January 2007. Note that in each panel the F_D time series has been scaled so that its mean is equal to the mean of the *FFDI* time series. The time series indicate that qualitatively, the behaviour of F_D through time is closely linked with that of *FFDI*. It is important to note that for F_D to be useful as a fire danger index it is not critical that the magnitudes of F_D match those of *FFDI*. As the scales used to describe fire danger rating are essentially arbitrary, we only require that changes in F_D occur in accord with changes in *FFDI*. The time series in figure 3 indicate that F_D does a reasonable job in fulfilling this requirement and suggests that F_D is a plausible measure of fire danger rating.

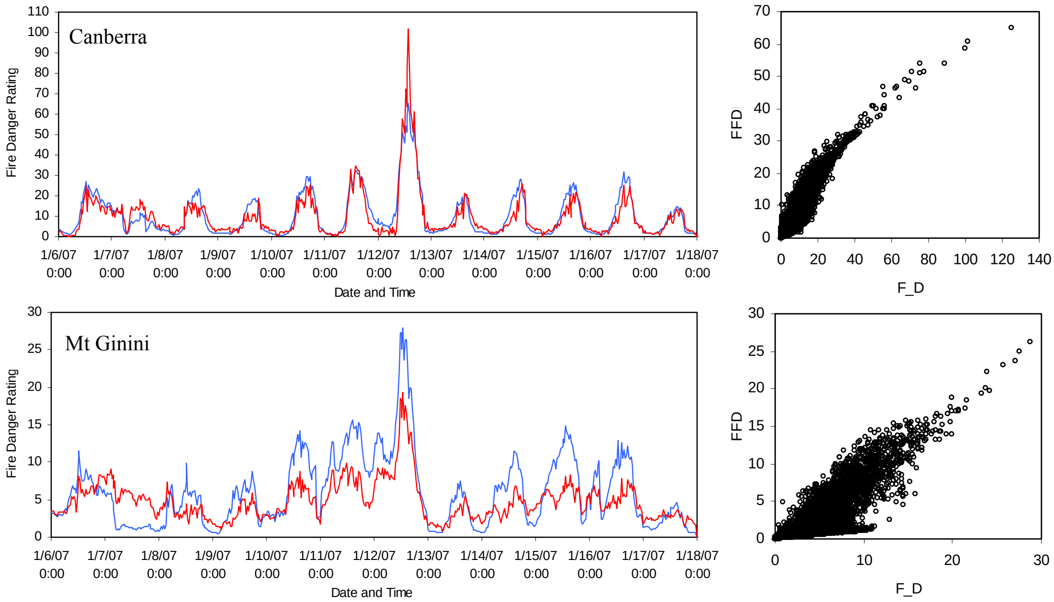


Figure 3. Time series of *FFDI* (blue) and F_D (red) for Canberra and Mt Ginini, 6-18 January 2007, and scatter plots of *FFDI* against F_D for all data for the two stations.

The correlation statistics in table 1 also suggest that there is good quantitative agreement between F_D and *FFDI*, with linear correlations of 0.9364 at Canberra and 0.8309 at Mt Ginini. The lower correlation at Mt Ginini indicates that the indices compare less favourably when fire danger levels are low. This suggests that the index F_D may be less valid when applied at locations such as this subalpine site, where overall fire danger levels are lower. The rank correlation statistics in table 1 are reasonably close to unity suggesting that there is a high degree of monotonicity in the relationship between F_D and *FFDI*. The lower value at Mt Ginini again reflects the reduced validity of the index when fire danger levels are low.

Table 1. Linear and rank correlation statistics arising from the comparisons of F_D with *FFDI* *GFDI* for all data values.

Site	Index	Linear Correlation	Rank Correlation
Canberra	*FFDI*	0.9364	0.9021
	GFDI	0.9593	0.9917
Mt Ginini	*FFDI*	0.8309	0.7865
	GFDI	0.9764	0.9889

The times series of F_D and *GFDI* can be seen in figure 4. The F_D time series has again been scaled so that its mean is equal to the mean of the *GFDI* time series. The behaviour of F_D through time is very closely linked with that of *GFDI*, even when fire danger levels are relatively low. The time series indicate that the simple index F_D conveys information that is closely related to that delivered by the more complicated index *GFDI*. The linear correlation statistics in table 1 are above 0.95 for each of the sites suggesting good quantitative agreement between the indices. The rank correlations statistics are both over 0.98 indicating strong monotonicity in the relationship between F_D and *GFDI*. This suggests that F_D is a plausible measure of grassland fire danger rating.

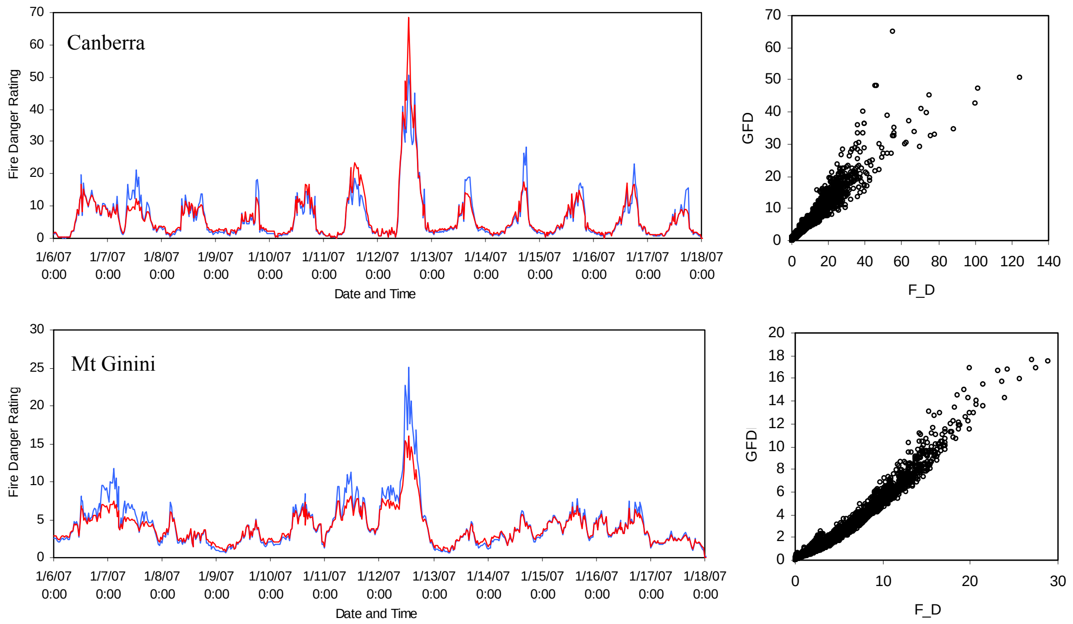


Figure 4. Time series of *GFDI* (blue) and F_D (red) for Canberra and Mt Ginini, 6-18 January 2007, and scatter plots of *FFDI* against F_D for all data for the two stations.

6. ANALYTICAL CONSIDERATIONS

It is of interest to consider how the structure of *FFDI* and *GFDI* relate to the index *FMI*. Rearranging equations (3) and (4), we may write

$$U \approx 42.735\left\{0.45+\ln(FFDI)-\ln(2D^{0.987})+p_1(FMI)\right\}, \quad \text{and}$$
$$U \approx 2.425\left\{-0.0217+\ln(GFDI)+0.009(100-C)^{1.536}+p_2(FMI)\right\}^2$$

where p_1 and p_2 are linear and cubic polynomial functions, respectively, satisfying

$$p_1(FMI) \approx 0.0345H-0.0338T, \quad p_2(FMI) \approx 0.2205\sqrt{H}-0.02764T.$$

In fact, using the temperature and humidity data recorded at Canberra Airport, least-squares approximations of p_1 and p_2 fit the functions of T and H with R^2 values of 0.999994 and 0.994218, respectively. This implies that to a high degree of accuracy, constant *FFDI* corresponds to lines in the (*FMI*, *U*) plane and constant *GFDI* corresponds to sixth-order polynomial curves in the (*FMI*, *U*) plane. This means that the fire danger rating schemes corresponding to *FFDI* and *GFDI* can be simply characterised with near exactitude in terms of *FMI* and *U*. This fact is illustrated in figure 5 where the threshold values of *FFDI* and *GFDI* used for fire danger classification are shown. The structure of *FFDI* evident in figure 5 also gives reason for the discrepancy between *FFDI* and F_D for low values of *FFDI*. In the (*FMI*, *U*) phase plane constant F_D corresponds to straight lines emanating from the origin, which don't align well with the lines corresponding to lower values of *FFDI*.

7. DISCUSSION AND CONCLUSIONS

We have presented two simple and intuitive indices for the fuel moisture content of eucalypt litter and for fire danger rating. The simple fuel moisture index *FMI* was shown to give an equivalent measure of the moisture content of eucalypt litter when compared to the more complicated model of Viney (1991). The simple fire danger index was then derived by combining the *FMI* with information on wind speed and fuel availability (drought effects). In particular, the fire danger index presented in Sharples et al. (2009b) was extended to incorporate fuel availability in a simple manner using the drought factor. Given data (*T*, *H*, *U*, *D*), the resulting index F_D was found to compare favourably, over the range of data used, with the McArthur Mark 5 Forest Fire Danger Index. Converting the degree of grass curing to an equivalent drought factor, the index F_D was also found to compare favourably, over the range of data used, to the McArthur Mark 4 Grassland Fire Danger Index, incorporating a range of curing values. Analyses based on data recorded at a subalpine site and analyses of the structure of *FFDI* with respect to the (*FMI*, *U*) phase plane suggested that the overall discrepancy between F_D and *FFDI* will be greater when overall fire danger levels are lower, however.

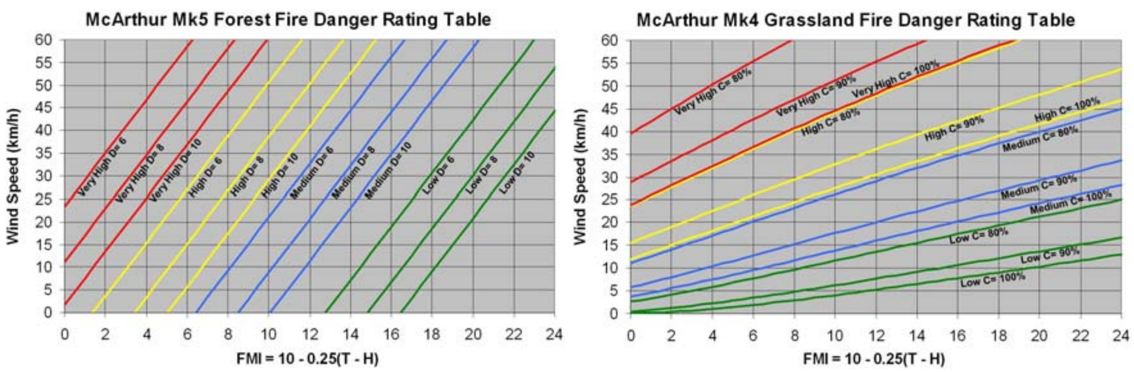


Figure 5. Forest and grassland fire danger rating characterised in terms of *FMI* and *U* for various drought factors and degrees of grass curing.

Correlation statistics obtained from comparisons of F_D with *FFDI* and *GFDI* based on data recorded at Canberra Airport were very similar to those obtained from comparisons of *F* with *FFDI* and *GFDI* in Sharples et al. (2009b). Assuming maximum fuel availability linear and rank correlations relating to *FFDI* were 0.9379 and 0.8744, respectively, compared with 0.9364 and 0.9021 when the effects of fuel availability were included. For *GFDI* the linear and rank correlation statistics changed from 0.9587 and 0.9956, respectively, assuming maximum fuel availability, to 0.9593 and 0.9917, including the effects of variable fuel availability.

The fuel moisture index was also shown to be particularly useful in characterizing the McArthur fire danger rating systems. In particular it was shown that the McArthur Mark 5 Forest Fire Danger Rating system and the McArthur Mark 4 Grassland Fire Danger Rating system could be characterised with near exactitude in terms of the (*FMI*, *U*) phase plane. This indicates that when viewed in terms of *FMI* the McArthur systems are manifestly two-dimensional. Characterising fire danger in terms of *FMI* and *U* could have a pedagogical advantage over other methods; tables such as those in figure 5 could be included in operations handbooks carried by fire fighters, providing them with a simple and intuitive method for field estimation of fire danger levels.

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