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Improved Formula for the Drought Factor in McArthur's Forest Fire Danger Meter

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Summary

McArthur's Forest Fire Danger Meter (Mark 5) is a key tool for assessing broadscale fire danger throughout eastern Australia. The Drought Factor, an indicator of the fuel availability as calculated by the meter, is a key input in calculating the Forest Fire Danger Index. The currently accepted analytic method for calculating the Drought Factor is reviewed and shown to give significantly different results to that calculated by McArthur's meter. This paper proposes a new formula for calculating the Drought Factor and shows that it fits McArthur's meter to a far better degree than the previously published formula.

Introduction

McArthur's Forest Fire Danger Meter (Mark 5), designed in 1973 and based on the Mark 4 meter designed in 1966, is a key tool in assessing broadscale fire danger throughout eastern Australia. The meter is circular with five dials and is operated manually. For a full description see McArthur (1967) or Luke and McArthur (1977). McArthur's meter calculates the Drought Factor, an indicator of fuel availability, which is used, with meteorological information, to calculate the Forest Fire Danger Index. There are also tables for estimating the rate of spread, the flame height and the spotting distance of fires.

The current investigation was prompted by differences between the Drought Factor calculated using McArthur's meter compared with that calculated using the formula of Noble *et al.* (1980). Crucial decisions about levels of preparation, in the way of personnel and fire fighting equipment on standby, are made by forest authorities based on the Forest Fire Danger Index. Accurate calculation of the index is therefore extremely important. In the most extreme case, the Drought Factor formula of Noble *et al.* leads to assessing a situation as an Extreme Forest Fire Danger while McArthur's meter assesses the same situation as only a High Forest Fire Danger, two categories lower than Extreme.

This paper assesses how the Drought Factor as given by McArthur's meter compares with that predicted by the formula of Noble *et al.* and proposes a new formula which is shown to reproduce the McArthur meter more closely.

The notation of Noble *et al.* is used, namely,

F = Forest Fire Danger Index,

D = Drought Factor,

T = air temperature in degrees Celsius,

H = relative humidity expressed as a percent,

V = 10 minute average wind speed, in km/h, in the open at a height of 10m,

I = soil dryness index in mm equivalent,

P = rainfall in mm during an event,

N = time since the rain event in days.

It is expected that rain is recorded in 24 hour periods to 9am each day. If the rain event is deemed to have occurred in the 24 hours to 9am on the current day then N=1. See the section *Rain Events* for further discussion.

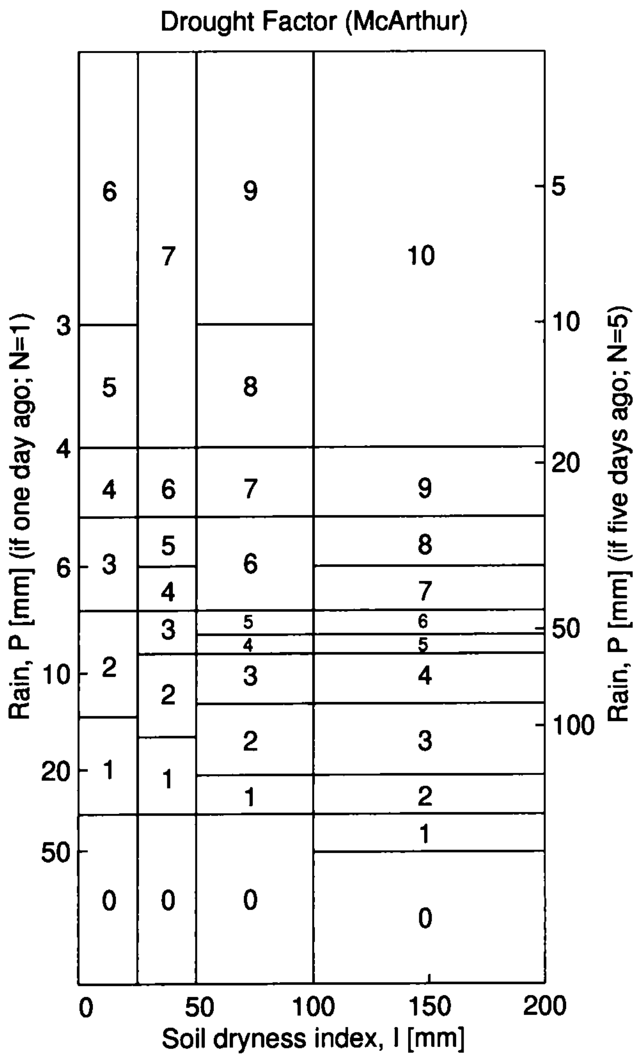

Figure 1. Drought Factor as given by McArthur's Forest Fire Danger Meter. Soil dryness index is shown on the horizontal axis. Scales corresponding to rain events of one and five days ago are shown on the vertical axis.

Forest Fire Danger Index

The Forest Fire Danger Index depends on the Drought Factor, the air temperature, relative humidity and wind speed. The Drought Factor is a number between 0 and 10 and gives a broad measure of fuel availability as determined by seasonal severity and recent rain events (McArthur 1967).

The formula for the Forest Fire Danger Index given by Noble *et al.* is

$$F = \exp(\ln 2 - 0.45 + 0.987\ln(D) - 0.0345(H) + 0.0338(T) + 0.0234(V)) \quad (1)$$

and reproduces the results of McArthur's meter very closely. However the value used for the Drought Factor, D, is critical in estimating the Forest Fire Danger Index, F, and the formula offered by Noble *et al.* for the Drought Factor does not reproduce McArthur's meter well. As illustrated in Figures 1, 2 and 3, and discussed in the section *Drought Factor*, the formula offered by Noble *et al.* for the Drought Factor can produce a value of D which differs from the McArthur meter value by a number which can be as large as 5.

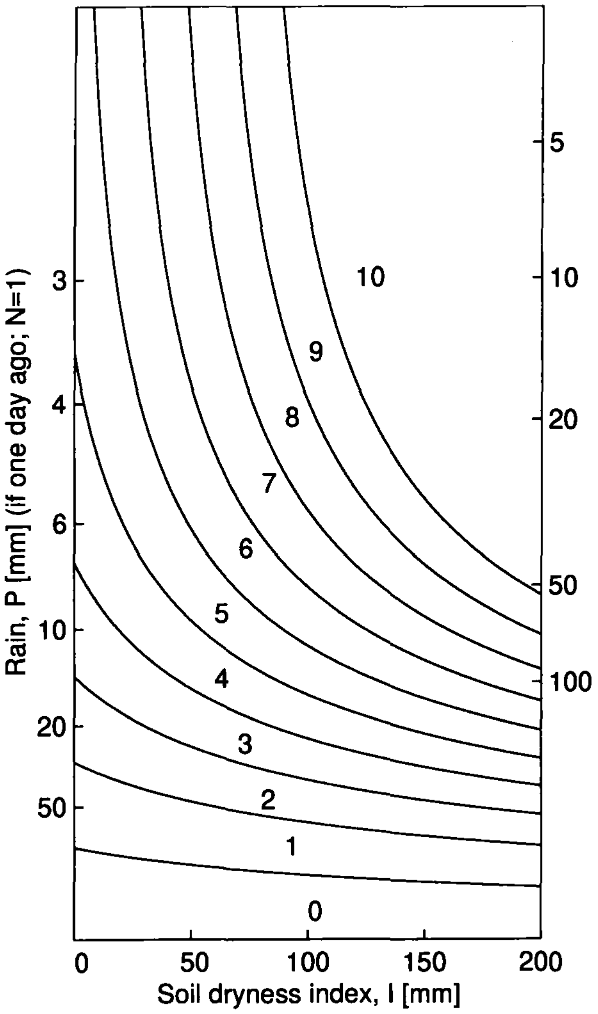

Figure 2. Drought Factor as given by the formula of Noble *et al.* Soil dryness index is shown on the horizontal axis. Scales corresponding to rain events of one and five days ago are shown on the vertical axis.

The Drought Factor is based on the long-term rainfall record as measured by a soil dryness index, and on the most significant recent rainfall. These two quantities are discussed below.

Rain Events

A rain event is denoted (P, N) where P is the amount of rainfall in mm and N is the number of days since the rain occurred. As mentioned in the section *Notation*, it is expected that rain is recorded in 24 hour periods to 9am each day. If the rain event is deemed to have occurred in the 24 hours to 9am on the current day then N=1.

Treatment of rain events has not been consistent between agencies. McArthur (1967) stated that "if rain is recorded on a number of successive days the 9am totals should be accumulated and treated as a single fall". The meter as published in Luke and McArthur (1977) gave the instruction "set last rainfall against number of days since rain." Later copies of the meter, as produced by the Tasmania Forestry Commission, stipulated "for successive days with 2mm plus, assume all fell on the wettest day". The requirement for at least 2mm is consistent with the scale on the meter which implies that falls of less than 2mm have no significance with respect to fire danger.

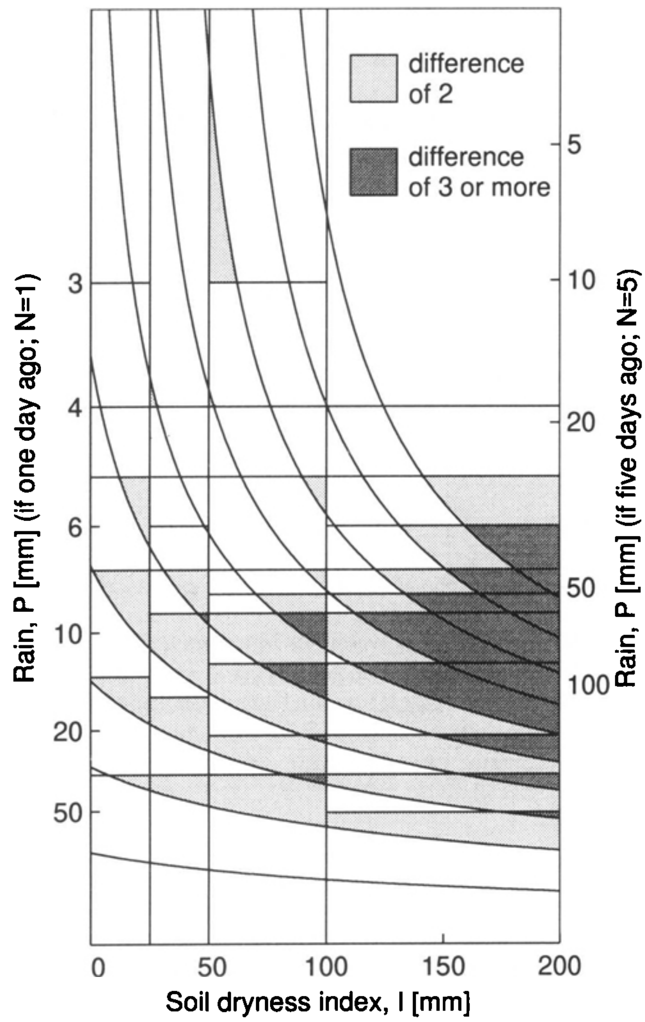

Figure 3. The Drought Factor as calculated by Noble *et al.* overlayed on that given by McArthur's Forest Fire Danger Meter. Regions where the two values differ by two are lightly shaded. Regions where the two values differ by three or more are darkly shaded. Soil dryness index is shown on the horizontal axis. Scales corresponding to rain events of one and five days ago are shown on the vertical axis.

There is precedent and justification for treating a rain event as having occurred on the day of heaviest rainfall or on the day of most recent rainfall. Some situations will be more accurately described by one technique while other situations will be more accurately described by the other technique. Which technique is chosen in a particular location may depend on the climatology or general pattern of rain events.

The Most Significant Rain Event

McArthur's meter requires that all rain events in the last 20 days be considered and the most significant event used, that is, the rain event giving the lowest Drought Factor. Noble *et al.* do not address the issue of how to determine which rain event to use and many algorithms in use follow Luke and McArthur (1977) and Crane (1982) in which only the most recent rain event is used.

In order to analyse the way in which the McArthur meter compares rain events, the following notation is defined:

P = rainfall in mm during an event,

N = time since the rain event in days.

It is expected that rain is recorded in 24 hour periods to 9am each day. If the rain event is deemed to have occurred in the 24 hours to 9am on the current day then N=1.

Analysis of the scales on McArthur's meter for the number of days since rain and for the amount of rain shows that ln(N) and ln(P-2) are in a linear relationship for $N \geq 1$ and $P > 2$, with the most significant rain event (P, N) being that one which maximises

That is, for $N \geq 1$ and $P > 2$, the most significant rain event is that maximising $(P\text{-}2)/N^{1.3}$. The scale on the meter requires that when N=0, that is when there has been rain since 9am, N is to be assigned the significance of 0.8. Rain of less than 2mm is treated as insignificant. Thus the most significant rain event is that maximising y where

$$y = \begin{cases} (P\text{-}2)/N^{1.3}, & \text{if } N \geq 1 \;\&\; P > 2, \\ (P\text{-}2)/0.8^{1.3}, & \text{if } N = 0 \;\&\; P > 2, \\ 0, & \text{if } P \leq 2. \end{cases} \qquad (2)$$

The most significant rain event may be computed by maximising y as above and then the corresponding rain event may be used to calculate the Drought Factor. Alternatively, the Drought Factor can be calculated for each rain event in the last 20 days and the Drought Factor taken to be the minimum of all those calculated.

Soil dryness index

As well as recent rainfall, the Drought Factor is based on the soil dryness index which is an indication of the amount of rainfall required to saturate the soil. The soil dryness index, I, is typically calculated as the Keetch-Byram Drought Index (Keetch & Byram 1968) or the Mount Soil Dryness Index (Mount 1972).

Drought Factor

The relationship between rain events, the soil dryness index, I, and the Drought Factor, D, as given by McArthur's meter, is the step function shown in Figure 1. In figures 1 to 5 the measure of significance of rain events has been converted to a number between 0 and 1 by using $1/\sqrt{(1+y)}$ where y is defined by Equation 2. More meaningfully, the axes in the figures are labelled with the corresponding rainfall for events of one and five days ago.

The step function nature of the Drought Factor as given by McArthur makes it clear that the function is less amenable than the Forest Fire Danger Index to reproduction by a formula. However the use of the Drought Factor to indicate the fuel availability justifies replacing the step function by a smooth function.

The smooth function suggested by Noble *et al.*, limited to 10 as per Sirakoff (1985), is shown in Figure 2. The comparison of the function of Noble *et al.* with the numbers dervied from McArthur's meter is shown in Figure 3. As may be seen, the most significant discrepancies between the meter and the formula occur when there has been recent rain of at least 5mm, particularly if the soil dryness index, I, is high. In extreme cases the Drought Factor as calculated by McArthur's meter and the formula of Noble *et al.* can vary by up to 5, and this difference can have a dramatic effect on the calculated Forest Fire Danger Index.

A new formula for the Drought Factor is proposed here which is more elegant than that of Noble *et al.* in that it asymptotes or flattens as the soil dryness index, I, increases, having a natural upper bound of 10.5 which is approached in dry situations. These properties fit McArthur's definition of the Drought Factor except that using a natural upper bound of 10 was found to skew the function. The proposed function is given by

$$D = \max\left[10.5\left(1\text{-}\exp\frac{-(I+30)}{40}\right)\frac{y+42}{y^2+3y+42},\ 10\right] \qquad (3)$$

where y is defined by Equation 2 above. The function is shown in Figure 4 with its comparison to McArthur's meter shown in Figure 5. The largest discrepancies between the proposed formula and McArthur's meter occur at lower values of the soil dryness index. The Drought Factor as calculated by Equation 3 is always within 3 of that calculated by the meter, with only very few differences of 2 or more.

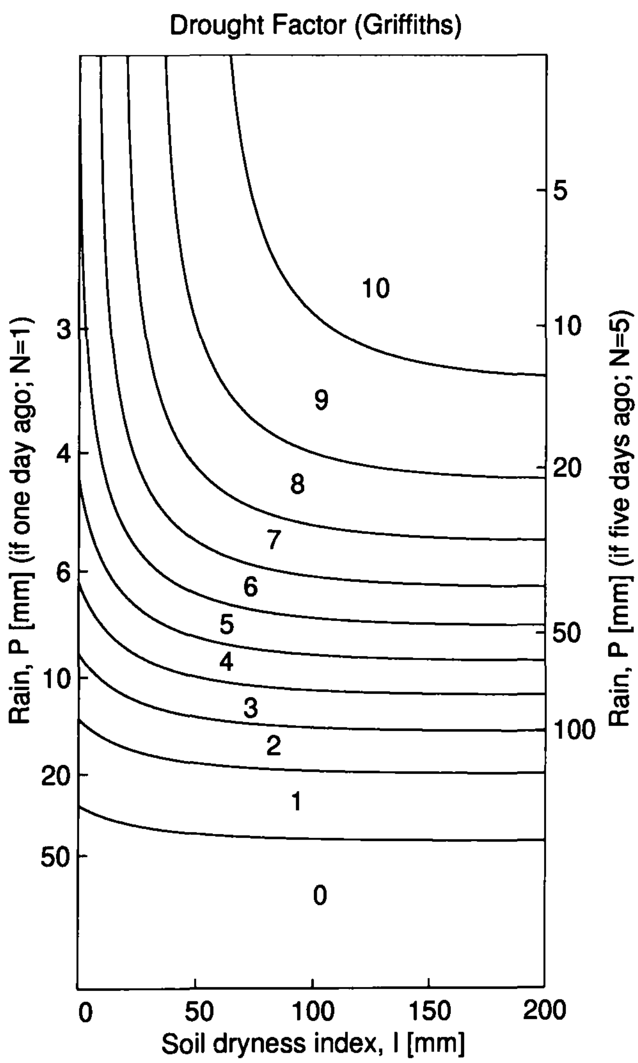

Figure 4. Drought Factor as given by Equation 3. Soil dryness index is shown on the horizontal axis. Scales corresponding to rain events of one and five days ago are shown on the vertical axis.

Comparison of Figures 3 and 5 indicate that the fits of each of the two formulae to McArthur's Drought Factor are of similar quality when the soil dryness index, I, is less than 50. When the soil dryness index is greater than 50 but there has been recent rain, the formula of Noble *et al.* does not match McArthur's Drought Factor at all closely while the new formula presented here is an excellent fit.

The way in which the new formula has been developed is explained in the following section.

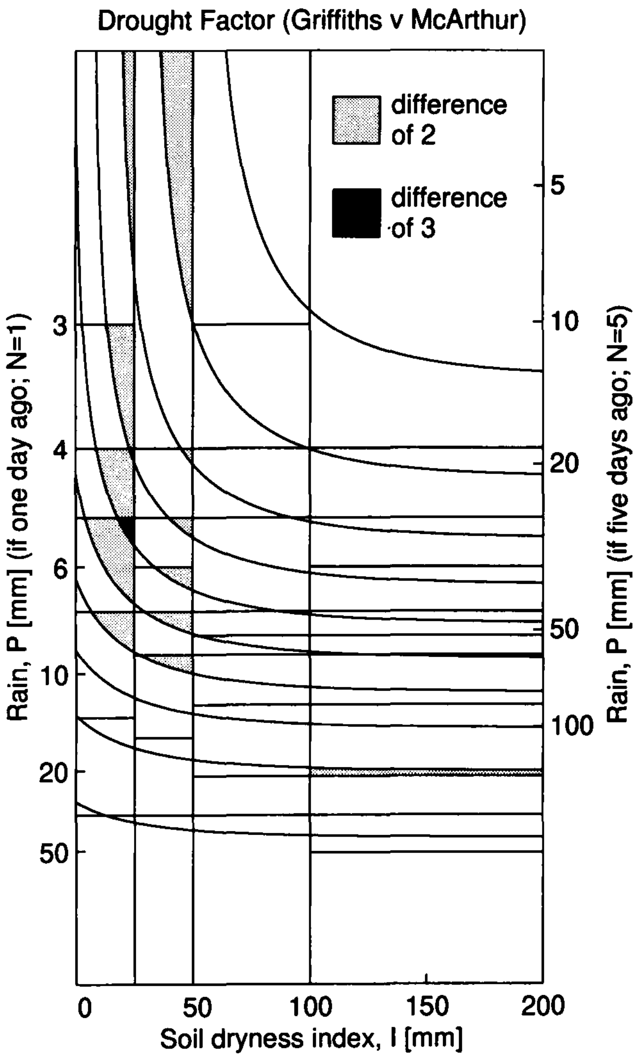

Figure 5. The Drought Factor as calculated by Equation 3 overlayed on that given by McArthur's Forest Fire Danger Meter. Regions where the two values differ by two or more are shaded. Soil dryness index is shown on the horizontal axis. Scales corresponding to rain events of one and five days ago are shown on the vertical axis.

Methodology

Each scale on McArthur's meter was compared to the corresponding angles around the dials of the meter, a method described in detail by Purton (1982). This was done graphically and then tested by a least squares fit. The relationships between each variable and the angles around the dial were mostly found to be linear or logarithmic. The least squares fit for each of $\ln(D)$, T and V gave $r^2 = 1.000$; H gave $r^2 = 0.999$; $\ln(F)$ gave $r^2 = 0.998$. For $N \geq 1$, $\ln(N)$ had $r^2 = 0.997$. For $P>2$, $\ln(P\text{-}2)$ had $r^2 = 0.992$. Relative humidity, H, was the only variable for which a coherent pattern other than linear or logarithmic was found. However the linear fit for H is so good it seems appropriate to use it.

Establishing the formula for F was routine and the formula for the Forest Fire Danger Index (Equation 1) was verified. Establishing the relationship between N and P was also routine. The ratio of the gradients of the straight lines in Figure 6 is 1.296 and it is from this that $(P\text{-}2)/N^{1.3}$ was found to be a measure of the significance of a rain event.

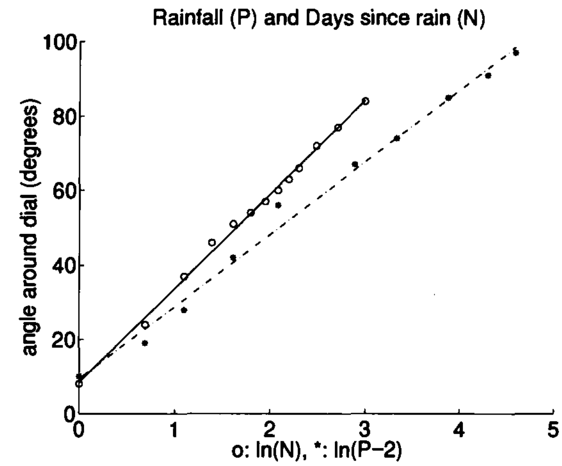

Figure 6. The angle for N (number of days since rain) as measured on the dial of McArthur's Forest Fire Danger Meter is graphed against $\ln(N)$ and shown as open circles. The angle for P-2 (rainfall over 2mm) as measured on the dial of McArthur's Forest Fire Danger Meter is graphed against $\ln(P\text{-}2)$ and shown as asterisks. Least squares lines of best fit for each set of measurements are shown.

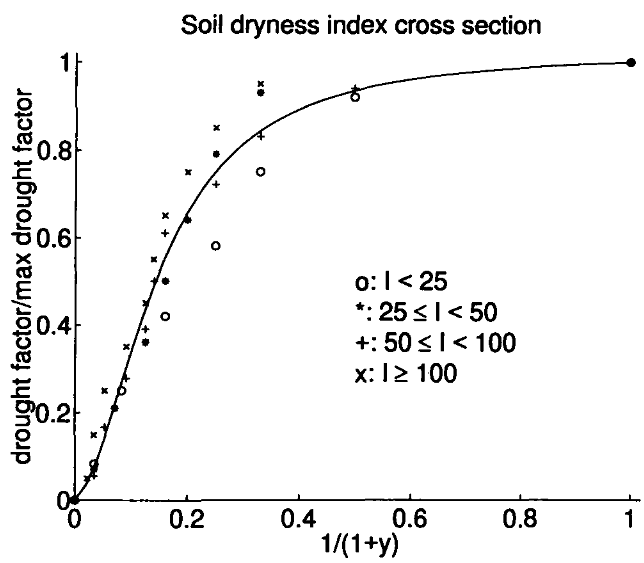

Figure 7. The function $(y+42)/(y^2+3y+42)$ is shown as a solid line. The Drought Factor (McArthur), as a proportion of maximum Drought Factor (McArthur), is plotted for the four categories of soil dryness index, I, and for various rain events. The scale on the horizontal axis is $1/(1+y)$ where y is the significance of a rain event as given by Equation 2.

Designing a formula for D to approximate the step function of McArthur was not routine and the formula may well be improved. As a function of I the Drought Factor asymptotes, or flattens, as I increases. An exponential function was tried and found to be suitable. Figure 7 shows the Drought Factor as a proportion of the maximum Drought Factor plotted against $1/(1+y)$ for the four categories of soil dryness index, I. As a function of y the Drought Factor asymptotes or flattens as $1/(1+y)$ increases, however an exponential function in y was not of the desired shape and so rational functions were tried. The rational function $(y+42)/(y^2+3y+42)$ is shown as a solid line in Figure 7 and compared to points derived from McArthur's meter. The final formula for the Drought Factor, Equation 3, is justified by the good fit it provides.

Conclusion

An improved method for calculating the Drought Factor, one of the variables used to calculate the Forest Fire Danger Index, is presented. The formula provides a smooth function for the Drought Factor that is closer than any previously published formula to the values found from McArthur's meter.

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