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# FIRE DANGER INDICES: CURRENT LIMITATIONS AND A PATHWAY TO BETTER INDICES

## Setting the agenda for fire danger policy and research into operations

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Cover: A fire front approaches a number of houses near Coonabarabran, NSW. Photo by the New South Wales Rural Fire Service.

## Executive Summary:

*Why does Australia need fire danger indices? Ultimately it is to help protect lives and property from bush fires, and to effectively manage resources. Therefore the foremost necessary characteristic of a fire danger index is that it demonstrably improves the protection of lives and property. The Interim Report of the 2009 Victorian Bushfires Royal Commission presented evidence that the general public and fire agencies found it easier to understand severity in terms of numbers, rather than descriptive indicators. Fire Danger Indices (FDIs) attempt to reduce a complex, multifaceted risk to a single number, or perhaps a few numbers. Inevitably, this reduction will lose or simplify information. The challenge in designing FDIs is to simplify the measure of bushfire risk in this way, without obscuring or overlooking information that might help save life and property, and improve forest management.*

*Fire danger ratings in Australia currently rely heavily on McArthur’s FDIs for forests and grasslands. Advances in both our understanding of fire behaviour and atmospheric science mean that these indices do not adequately reflect current knowledge and recent technological advances. We can now provide information on fire danger at a much greater spatial and temporal resolution than previously, but do not fully utilise this new data. McArthur's indices are used for a wider range of purposes than originally envisaged, and growing societal expectations and changes in communication technology provide both the impetus and opportunity for a more detailed and more accurate service.*

*In response to these pressures and to the 2009 Victorian Bushfires Royal Commission, a research program into the fire danger rating system is underway. As one component of that program, this report examines fire weather indices, with the aims of more accurately capturing the effects of meteorology on fire behaviour, and identifying meteorological factors absent from the current indices. This report also considers fire danger indices, since we found it impossible to meaningfully consider fire weather indices without also considering how they would relate to fire danger indices, and it is unclear to what extent the contribution of fire danger due to weather factors can be separated from the problem of fire danger as a whole.*

*The level of danger posed by a fire depends on a large number of factors, including the type, moisture content, amount and arrangement of fuel; the prevailing weather; the topography; the soil moisture; and the availability, type and quantity of suppression resources. Some of these interact: notably, the fuel characteristics and soil moisture depend on the weather today and over the past hours, days, months and years. In the case of weather, the wind speed, wind changes, wind variability, humidity, temperature, stability and boundary layer depth are known to be important. Where there is no existing fire, fire danger rating must also consider the likelihood of ignition by natural, accidental and deliberate means.*

*The central problem with McArthur's and other indices is that they are based on an arbitrary scale, with the value 100 originally corresponding to the worst conditions then thought possible, Black Friday of 1939. The indices are implicitly predictions of expected fire characteristics, and are defined by the form of the table, slide rule or equations, instead of through physical properties of the fire such as flame heights or forward rates of spread. The effects of fuel and weather element uncertainties, and the sensitivity of the fire danger to these uncertainties, are not explicitly accounted for.*

*We recommend that new indices be defined in terms of physical quantities relevant to the fire hazard. Examples include the fire-line intensity of the head fire, rate of spread, power of the fire, flame height, radiation intensity, and ember density. The advantages of defining indices in such a way include:*

- *The indices are future-proof. New research might change the way the indices are calculated, but will not change their definition. There will be no need to retrain users.*
- *The indices are verifiable. Verification is an essential step towards improvement.*
- *Strong sensitivity to weather, fuel, fire location variables could be addressed with ensembles of predictions and probabilistic methods.*
- *The indices could be calculated using several different methods, depending on computational and data availability.*

*Tools and data used to evaluate the indices should include:*

- *High resolution weather models and eventually fire-atmosphere coupled models as computational capability increases with time.*
- *The three dimensional structure of the atmosphere through stability, mixing depth and vertical wind profile.*
- *Fuel classification and condition for all fuel types.*
- *Landscape soil moisture modelling, utilising all available observations and advanced land surface models.*
- *New remote sensing capability with the Himawari-8 and other satellites.*
- *The interaction between the smoke plume and the atmosphere, including the transport of embers, the development of pyrocumulus, and other effects.*
- *The prediction of lightning ignitions and their likelihood of being sustained.*

*To determine physically based fire indices, we recommend that a suite of methods be used. The use of multiple methods is advantageous because:*

- *Different methods may work better in different situations.*
- *A consensus or average answer will typically be more accurate than any of the individual components.*
- *It may be possible to identify outliers and perhaps omit them, or gain additional information from them.*
- *Advanced computational methods can be used for the most accurate answer when cost is no object, or statistical methods when a quick answer is required or the necessary computation is unavailable or too slow. Each would be trying to determine the same physical quantity (e.g. rate of spread), but by different methods.*
- *Some computational methods will be more accurate, either because they are more sophisticated or because they use more input data. The accuracy should be formally recognised through the use of error bars.*

*The McArthur indices have served Australia well for decades, but this success, together with their definition, has also become an obstacle to progress. This obstacle can be removed by adopting new indices defined in terms of physical characteristics of the fire. This will enable new science to enter operations without needing to re-train users. It will allow for a suite of calculation methods suited to* *the particular problem at hand, and for the use of ensemble and consensus approaches from fire behaviour simulators. In short, it will allow for progress: not just a once-off improvement, but for sustained, scientifically rigorous and measureable progress.*

## Contents

## 1. Introduction

Potter (2012) defines fire danger as the "sum of the constant and variable fire danger factors affecting the inception, spread and resistance to control and subsequent fire damage: often expressed as an index". Fire behaviour is defined as "the manner in which a fire reacts to the influences of fuel, weather and topography". Because rate of spread and resistance to control are part of fire behaviour, there is necessarily an overlap between the factors that increase fire danger and those that influence fire behaviour.

Similarly, Cruz et al. (2015) notes that the level of danger posed by a fire depends on many factors: the initial environmental conditions that could lead to the uncontrollability of a fire, numerous human factors, and resources available for suppression. Where there is no existing fire, fire danger rating must also consider the likelihood of ignition by natural, accidental and deliberate means. The problem, and equally the strength, of the current Fire Danger Indices (FDIs) is the simplification of complex science and human factors. Cruz et al. (op. cit.) define fire danger as “the combination of weather and fuel conditions that indicate essentially how difficult it will be to suppress a fire burning in a standard fuel type, and the propensity for fires to breakout, spread and do damage", while fire behaviour refers to “the manner which fuel ignites, flame develops, fire spreads, and exhibits other phenomena in relation to fuel, weather and topography”. Importantly, they note that “the conditions that affect fire danger do not always affect the behaviour of a fire, including rate of spread, in the same way".

The present report was written for the Bushfire Natural Hazards CRC for the Attorney-General's Department through the National Emergency Management program and investigates the current Australian practice of using McArthur's FDIs as part of the FDR. The aims of this report are to (i) document the relative strengths and weaknesses of these indices (ii) identify meteorological factors absent from the current indices, and (iii) discuss ways to formulate new fire weather indices for purposes including as an input for the FDR. Although the original project scope specified fire weather indices (FWIs), we have necessarily considered fire danger indices also, since (i) we found it impossible to meaningfully consider FWIs without also considering how they would relate to FDIs, and (ii) it is unclear to what extent the problem of fire danger due to weather factors can be separated from the problem of fire danger as a whole.

The Commonwealth's Meteorology Act of 1955 specifies the requirement for the Bureau of Meteorology (henceforth "the Bureau") to issue "warnings for conditions conducive to the spread of bushfires". Around the time of promulgation of the Act, strict limits on staffing enforced by the Public Service Board were relaxed, enabling the Bureau to provide specialised forecasts to State fire authorities and the public, and to engage in fire weather research. In 1964, the comprehensive *Manual of Meteorology - Fire Weather Supplement* was published by the Bureau of Meteorology detailing the understanding of the science at the time, with many concepts back then identified as important, still appearing in papers that are being published today.

Commencing with the Royal Commission into the 1939 Victorian Fires, the Bureau was seen as the authority on fire weather and behaviour. The Bureau, as a Commonwealth body, was setting the policy on fire warnings, leading the research into fire behaviour in Australia and training weather forecasters and forestry personnel on understanding fire behaviour. The 1964 manual, references work by United States and Canadian researchers, as well as Australian scientists. It includes the theory of combustion and fuel types is detailed through the flammability and burning rates of fuel, the combustion of heavy, fine and gaseous fuels (McLaren 1959, Davis 1959). The manual also included discussion of fire behaviour in a theoretical three-dimensional context.

Furthermore, the 1964 Bureau manual details concepts from A. G. McArthur's (Forestry and Timber Bureau, Canberra) report of parameters affecting fire behaviour (McArthur 1962). Parameters such as atmospheric stability were discussed, yet omitted from the present-day rating system. Discussion on the time lag between relative humidity and corresponding changes in fuel moisture, influence of the actual fire, spotting, smoke plume, pyro-thunderstorm, and dry lightning as a contributor to ignition, were all included, but omitted from the eventual rating system as the dynamics of any of these factors were too complex to be included in the eventual FDI.

The 1964 Bureau manual goes on to state that

> "It will be abundantly clear by now that the existing methods of fire danger rating are entirely two dimensional. The third dimension in the wind field, temperature (temperature lapse rate) and humidity (the hydro lapse) have received no consideration".

In closing the paragraph, the manual states that *"work by McArthur is entirely concerned with low intensity forest fire"*. The manual goes on to highlight the need to consider fuel factors:

> "Even assuming that we had in our possession the perfect rating system, the forecaster must bear in mind these important considerations: (a) how accurately is fuel state being estimated? (b) how representative is the reported fuel state of local conditions? Area burnt last season versus one not burnt for years. Different soils carry different amounts and types of vegetation under identical rainfall conditions (compare shaly ridges with river flats) (c) is the fuel state sufficiently representative of the area?"

The use and limitations of the McArthur Fire Danger Tables, and application of the tables prepared by McArthur (1962), put the onus onto the fire weather forecaster to analyse the situation from all angles that include factors such as fuel, the three-dimensional structure of the atmosphere, atmospheric stability, etc., and would require good communication with local fire authorities.

In 1964, the Proceedings of the Productivity Conference (Shields 1964) directed that before a satisfactory bushfire warning system could be developed by the Bureau, a number of steps were necessary, including step "(b) research to determine those weather elements which were most significant to determining fire behaviour" and "(d) development of a quantitative method of combining the forecast elements to determine the degree of fire danger". Further to this statement, the proceedings went on to advise that to do this would involve a *considerable amount of field research* under actual fire conditions on a *joint forestry-meteorological basis*. Once the warning system had been developed it "*would be as essential to constantly test its effectiveness and to continually develop new and improved techniques and methods of providing the warnings*".

McArthur devised the Commonwealth Fire Danger Tables that were based on the results of hundreds of experimental burns and studies of major fires in various parts of the country. McArthur's tables were subsequently revised and in 1963 they were converted into the more convenient circular slide-rule format. The original meters were revised several times over the years, until McArthur's death in 1978. For reference, extensive descriptions of the McArthur system are given in McArthur (1958), Bureau of Meteorology (1964), Luke and McArthur (1978) and Noble et al. (1980).

The Bureau adopted the McArthur Fire Danger Rating System for the calculation of fire danger indices (FDIs) in all States and Territories, originally using the circular slide rules that were manually adjusted by the forecaster to calculate the FDI, and later using the CSIRO versions of the circular meters, the Grasslands Fire Danger Meter Mark 4 (1973) and Forest Fire Danger Meter Mark 5 (1975).

Noble et al. (1980) carried out regression analyses of these meters and engineered equations accordingly to allow for FDIs to be calculated quickly and within computer programs. From the 1980s, the Bureau adopted these equations, then refined by Purton (1982), for calculations of FDIs in operational contexts (see appendix 1 for details of the equations).

The Mark 4 Grassland Meter assumed a constant fuel loading of 4.5 t $ha^{-1}$. McArthur also prepared a Mark 5 version of the grassland meter in a rectangular slide-rule format in 1978, but this meter was not widely accepted, partly due to McArthur's death before the literature on the meter was completed.

Each meter has a range from 0 to 100, with an index of 1 meaning a fire will not burn, or burn so slowly that control presents little difficulty. An index of 100 means that fires will burn so fast and hot that control is virtually impossible. The meters come with some additional information, including descriptions and data on expected fire behaviour, so the application and the limitations are better understood. The value of 100 was assigned to the worst conditions known at that time, based on weather data recorded during the Black Friday fires in Victoria in 1939. This was a day when fires burned across large parts of the State, destroying everything in their path including townships and bush settlements, killing 71 people, countless livestock and eventually burning almost two million hectares. The value of 100 as the peak fire danger index was assigned and derived from records of the actual observed conditions on that day. While there have been many horrific fire days historically before that tragic day, the records of the conditions were not available. Subsequent observations have shown that the value of 100 can be exceeded. There is also no reason to suppose that the observations on Black Friday captured the worst conditions on the day. The definition of 100 is, therefore, an essentially arbitrary choice.

It is quite likely that from the 1970s, a decade categorised by strong La-Niña years, tropical cyclones and flooding events, that Fire Weather Warning policy in the Bureau of Meteorology reduced in importance as events like Cyclone Tracy occurred. National leadership on fire policy and research no longer was the priority for the Bureau, with fire weather becoming operationally focused within state and territory regions, rather than as a national problem. Fire weather research became ad-hoc and there was no national co-ordination to improve the service through revision of the way the Bureau produced Fire Weather Warnings and ratings using FDI.

From the 1980s, major advances occurred in numerical weather prediction systems (also known as models), for reasons including better science, faster computational capabilities and improved data access, particularly the assimilation of remote sensing data sources. At the same time, improved communication means (such as radio transmissions, voice phone calls, fax then computer to computer systems) did in fact improve the *service* of fire weather forecasting generally over the period from the mid-1980s, by tailoring fire weather forecast products to individual state agency needs. Two select committee reports – one from the 1983 Ash Wednesday Victorian fires, the other from the 1984 Western Australian fires, both include, amongst many other recommendations, that the Bureau's fire weather services needed vast improvement, with funds to be made available for fire weather specialists. The network of forecast sites also increased in this time, augmented by fire agency observations, satellite imagery and ground truthing.

In collaboration with State fire and land management agencies, Bureau regional offices made incremental improvements in improving the fire weather service; however this was not a uniform approach nationally. Increased information, such as lightning activity level, mixing height, wind at upper levels, wind change timing and conditions after a cool change, along with the calculations of FDI, all served as a defacto way of including the “missing” elements to the calculated FDI. In the years after the Ash Wednesday fire event, a wind change chart service was initiated in Victoria (1990) and South Australia (1994) (and later New South Wales) to supplement the text forecast estimation of wind change. A number of internal reports were produced in the Bureau in the 1980s, the most significant of these being the 'Submission for upgrading Fire Weather Services, July 1986'. Some recommendations from this report was implemented, including having specialist trained fire weather meteorologists. Following these recommendations, Severe Weather Sections were formed within the regional offices in the early 1990s, covering fire, storm and tropical cyclone forecasting and research.

The Bureau also initiated a series of fire weather conferences where fire agencies and Bureau staff presented research material relevant to fire danger and behaviour, and contributed to the perennial problem of moving research into operations. Nevertheless, the fixed design of the McArthur FDIs has tended to inhibit the uptake of new research, since it cannot be easily incorporated into that framework. Where there have been improvements over time in FDI forecasts is in the forecast accuracy of the weather elements that are inputs to the McArthur meters. For example, in Victoria the Root Mean Square Error in the next day Maximum Temperature forecasts was about 3.7$^{o}$C in the early 1970’s. By 2011 the error was about 1.9$^{o}$C. This is due to advances in numerical weather modelling, remote sensing and statistical techniques, amongst other factors.

In the 1990s, research organisations such as CSIRO Bushfire Behaviour and Management Group, were innovating potential improvements to the FDI through the fuel component. A new grassland fire danger and fire spread prediction system was developed at the CSIRO by Cheney and Sullivan (1997). The CSIRO system removed the direct link between FDI and Forward Rate of Spread (FROS), which allowed for fuel loads other than the standard fuel load of 4.5 t ha$^{-1}$ and permitted calculated FDI values to exceed the FDI of 100. So now conditions worse than the 1939 Black Friday benchmark could be represented in the scale; however the application of the scale was now different. The use of the equations extrapolated beyond their original domain of fit also brought into use a somewhat open ended scale when it was applied to the rare but very difficult extremely high end Fire Danger days. Assuming that an FDI of 100 means that fires will burn so fast and hot that control is virtually impossible, there is no validation as to the likely impacts of higher FDI values. Further, the grassland FDI is extremely sensitive to wind, to the extent that changes in wind speed that are smaller than current typical forecast uncertainties cause large changes in the GFDI. The CSIRO meter also resulted in higher FDI values than the McArthur Mark 4 meter for those areas where fuel is deemed abundant and lower FDI values in those areas where fuel is deemed sparse.

The Bureau agreed in 1998, through the Australasian Fire Authorities Council (AFAC), to adopt the CSIRO system nationally. As the CSIRO system makes assumptions on fuel load, some State agencies preferred the Bureau to use earlier versions with an assumed standard fuel load. The original meters produced values between 0 and 100, however the equations on which the meters are based, together with the 1997 CSIRO model, permit the calculation of fire indices greater than 100. Another extension of earlier work on fire behaviour in a very different fuel type was conducted by Jon Marsden-Smedley, then of the Parks and Wildlife Service in Tasmania, for the management of button grass moorlands, a dominant vegetation type in the Southwest Tasmanian World Heritage Area, and common in western Tasmania.

The fire weather service in regional severe weather sections did not change greatly through the late 1990s to mid-2000s. The demand on the service, however, had a significant jump in regions such as Victoria, New South Wales and the Australian Capital Territory with the long protracted fire events – continuous uncontrolled fires – in 2002/2003, 2006/2007 and 2009.

A significant change in the fire weather forecasting service and the delivery of FDI and subsequently FDR to the public occurred with the introduction of the new Graphical Forecasting Editor (GFE) in Victoria in 2008, then rolled out State by State, and implemented across Australia by 2014. The GFE allowed for digital production of forecast elements at point locations across a grid, enabling subscribers to use the spatial data in their own Geospatial Information Systems. GFE also enabled a larger number of point location forecasts over a seven day period and new products to be developed utilising the gridded spatial data. One limitation is that these extended ranges are based on an interpolation from numerical weather prediction data with relatively coarse space and time resolution, raising the possibility that peak values are thereby missed.

When first implemented in Victoria, the Fire Weather Estimates (point location forecasts) provided to the agencies mirrored the existing point location forecasts of FDI (grass and/or forest) for conditions at the time of maximum temperature. Area-based forecasts were then created in the following seasons on the calculated values for the grassland FDI (GFDI) and forest FDI (FFDI) using forecast meteorological values for each grid point together with interpolated measures for grassland fuel drying (curing) and a forest dryness calculation known as Drought Factor (DF). Drought Factor is calculated for the FFDI at each grid point as a spatial interpolation of rainfall and the drought indices (Keetch-Byram or Mount Soil Moisture Index). The spatial and temporal limitations of these are explored later in this report. In the New South Wales implementation, a range of spatial measures such as percentage of an area above an FDI threshold was developed. Products such as the percentage of grid points in a district that exceed the thresholds, and the duration of a grid point above the threshold.

The Victorian Bushfire Royal Commission (VBRC) recommendations led to another significant event in the production of FDI forecasts and resulting FDR, namely that the FDR categories were changed within a short space of time. The new categories for FDR were Severe for FDI 50-75; Extreme 75-100 (forest) or 75-150 (grass) and Catastrophic/Code Red for above 100 (forest) or 150 (grass). The Bureau changed its service to accommodate these changes in FDR categories based on FDI. However, in the Bushfire Natural Hazards Cooperative Research Centre (BNHCRC) *Hazard Note* 4 (Feb 2015) a study on community bushfire readiness (McLennan, 2015) stated that since 2009, "there is no evidence of dramatic improvement since Black Saturday in overall levels of bushfire safety planning and preparedness based on the accounts given by those interviewed.” This study was conducted in Victoria, New South Wales, Western Australia and Tasmania with residents that live in bushfire prone areas. This further highlights the social issues with changing the FDR categories, that are independent of the sensitivity of FDI but interrelate on another level by justifying arguments against defined categories based mostly on FDI. The sensitivity of FDI, the use of indices, the problem of using these categories and an alternative solution, are discussed in the body of this report.

## 2. Environmental Influences on Fire: Inputs to Fire Danger Indices

Short term and antecedent weather conditions affect fire behaviour through their direct effect on a fire, and also through the moisture content of the fuel. This section reviews those factors.

### 2.1 Fuel Moisture in Forests

The moisture content of fuels is important in determining likelihood of fire ignition and subsequent fire behaviour. The very short term response (drying or wetting) of dead fine fuel moisture[1] content due to the changes in the current weather conditions, and the longer term response to precursor conditions of the fuels in the deep litter bed, are estimated via the drought factor (DF, see Appendix 1). This estimate of the amount of dead fine fuel available for burning depends on the direct wetting by recent significant rainfall and through wetting from the soil underneath (via soil moisture), plus the amount of drying of the fuel bed by the surrounding air.  In the operational calculation of the DF, the soil moisture deficit (SMD) is calculated first using either the Keetch-Byram Drought Index (KBDI) (Keetch and Byram 1968) or the Soil Dryness Index (SDI) (Mount 1980), then combined with an estimate of recent rainfall (the past 20 days) to calculate the DF. While the DF is calculated from a measure of SMD, in the calculation of a forest fire danger index it is interpreted as a *fuel availability factor*, scaled from 0 to 10 basically representing 10 percentile brackets, with 10 equating to 100% of the dead fine fuel being available to burn.

The assumptions about fuel moisture in existing fire danger calculations are crude by today's standards - they are probably best described as primitive and at times the lack of data with any confidence or enough currency is a major concern in constructing fire danger forecasts. There is some anecdotal evidence of informal ad hoc adjustments to SMD metrics to correct perceived errors, for example when fire behaviour has been observed to be more intense than that predicted by calculated FFDI values. A further issue is in drought affected forests following isolated thunderstorm activity that may have impacted on observed Drought Factors. Fuel moisture content is highly variable, from one place to another and at times from day to day or even from hour to hour.

The DF is now automatically calculated using a formula by Griffiths (1999) to smooth out the steplike increments that sometimes arose from calculations worked on the previously used pocket FDI meters. Apart from that gain, the other limitations remain. For forecasts of the DF, the recent implementation of gridded data by the Bureau has meant that *forecast* daily rainfall is now incorporated into the calculation out to four to seven days. The inherent errors in rainfall forecasts are therefore present in forecasts of DF.

#### 2.1.1 KBDI

The KBDI is widely used in the eastern continental States (Queensland, New South Wales and Victoria). The water balance in the KBDI is expressed in terms of a soil moisture deficit (SMD) which is the amount of water in millimetres necessary to bring the soil moisture content back to saturation. A high SMD means very little water available for soil evaporation or plant transpiration and hence dead fine

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[1] Fine fuel is plant material less than 6 mm in diameter. Fuel moisture content is the proportion of free and absorbed water in the fuel. The fuel fibre saturation point – the upper limit of fuel moisture in the absence of precipitation, is the moisture content reached at 100% relative humidity. When exposed to precipitation, water will also be stored in the cell cavities and on the surfaces of the fuel. Under drying conditions, dead fuels release moisture to the surrounding environment through evaporation until the vapour pressure in the fuel reaches equilibrium moisture content. Rates of wetting and drying are determined by the chemical and physical characteristics of the fuel and by weather conditions (Vinny 1991, Matthews 2007, Slijepcevic 2014).

fuels and decaying organic matter on the soil surface cannot absorb moisture from the soil. Under a high SMD, vegetation becomes drought stressed, although when this occurs depends on the vegetation type. At very high values, such as during a drought, the normally damper areas, such as southerly aspects and gullies, become dry so fire activity could potentially escalate significantly in places that are normally a natural barrier to fire. The KBDI assumes a maximum SMD of 200 mm and a minimum of zero, regardless of the moisture holding capacity of a soil type.

There are five assumptions in the formulation of the KBDI, as discussed by Finkele et al. (2006). A starting value of zero is used during the winter rainfall period. Each day, the KBDI is estimated by the previous day's KBDI, the daily effective rainfall, and the evapotranspiration (ET). The daily effective rainfall is based on the previous day's rainfall amount decreased by the first 5 mm of the rainfall event to allow for interception and runoff. The ET is dependent on the previous day's KBDI, the maximum daily temperature and annual rainfall.

The 'zero' condition of KBDI in winter is a necessary requirement for the index to reset each season. Due to the nature of drought and rainfall patterns across Australia, many areas do not have a period of soil saturation so the index becomes unreliable. KBDI values are not formally adjusted to soil moisture observations, but when saturation does not occur, manual subjective manipulation of the values is practiced in some states, such as Victoria. The absolute value of KBDI (and also SDI) has a different interpretation if it arises from a drying pattern or wetting pattern, particularly at higher levels of the index when the soil is relatively dry. This is because in a wetting cycle scenario, the moisture in the soil is near the surface and hence may easily transfer to the fine fuels, whereas in a drying cycle, the surface of the soil is drier.

### 2.1.2 SDI

The SDI is used in South Australia and Tasmania and for prescribed burning conditions in Western Australia. The SDI is calculated in a similar fashion to the KBDI, however the interception and runoff are treated separately and are vegetation dependent. The SDI requires a vegetation class to be defined, and for each class the canopy and runoff terms are defined. The ET term in the SDI is estimated differently from the KBDI by a linear function of maximum daily temperature, average monthly maximum daily temperature, and monthly evaporation from a capital city location (Finkele et al. 2006).

The ET term in both the KBDI and SDI is treated crudely, where the surface energy balance through radiation, humidity gradients, thermal stability and wind speed are not taken in account. The Finkele et al. (2006) report found the ET for SDI is much higher than KBDI at most locations they analysed. This means that in a drying pattern from a fully saturated soil, the SDI value increases more rapidly than the KBDI, indicating higher fuel availability and hence greater potential fire activity.

Depending on the size of the canopy storage, runoff, frequency and size of a rainfall event, the KBDI and SDI will also have slightly different effective rainfall amounts, although the difference between the two is small when compared to the ET term (Finkele et al. 2006). Hence at warmer inland locations the SDI tends to be significantly higher than the KBDI due to the increased ET there.

### 2.1.3 Further limitations of current measures of forest fuel state

Variations of soil type, topography, latitude, soil moisture conductivity, spatial variation, forest structure and time of year are not included in the SDI and KBDI calculations. Sullivan and Matthews

(2013) comment in their study on the February 2009 Kilmore East fire that effort would be better spent developing spatial models of fuel moisture. Significant development of underlying physical processes would be required to account for the critical components driving fuel moisture content at the landscape level, as well as significant computational resources. Critical landscape components would include understanding the transport of water through soil (Sullivan and Matthews 2013, Roxburgh et al. 2010), the effect of extended drought on soil moisture and the effects of soil moisture on micro-climate and fuel moisture (Samran et al. 1995). Rainfall is a highly spatially variable and point measurements are difficult to extrapolate across a landscape where rainfall from cumuliform cloud (isolated and discrete) and vegetation and terrain may alter rainfall patterns and water transport.

Investigation of the effects of the 2009 heatwave, in the week preceding Black Saturday February 2009, showed that the extreme temperatures had a significant but short-lived impact on modelled fuel moisture content of dead, fine litter fuel compared to a set of hypothetical conditions in which the heatwave did not occur (Cruz et al. 2012, Sullivan and Matthews 2013). It is likely that such extreme sustained temperatures, in conjunction with lack of rainfall, would have had a long-term impact on the moisture content of live fuels (shrubs and other understorey vegetation) as well as on coarser dead medium and large dead fuels such as logs and branches. This would have acted to increase the total amount of fuel available for flaming combustion and increased local and total energy release of the fire (Bureau of Meteorology 1963). Other major fires, including the WA forest fires of 1961 and 2015, similarly followed a period of high temperatures.

Two modified fuel moisture models, the Canadian Fine Fuel Moisture Content (FFMC) and a modified version thereof (Mathews 2006), were evaluated by Slijepcevic et al. (2014). Both verified well for guidance in prescribed burning in southern eucalypt forests, although the Canadian FFMC model could be improved by adjusting for Australian fuel types. However both fuel models do not predict well for extreme dry conditions. There can also be quite wide disagreement between fire spread models for dry forest fuels, and the difference in predicted rates of spread widens as the amount of available fuel increases (McCaw et al. 2008).

Fuel characteristics, such as quantity of various fuel components by size class, live and dead fraction, horizontal and vertical continuity, density and packing ratio and other fuel attributes are important in determining the rate of spread and intensity of bushfires (Gould et al. 2012). Fuel arrangement is also an important factor significantly affecting the resulting fire behaviour, with assessments on fuel hazard also playing an important role in determining a FDR (Hines et al. 2010). A new fuel state assessment that is based on physical models should offer a significant improvement over the current DF system. Additional data sources could include improved observations of rainfall through a denser network using the established hydrology rainfall gauge network currently part of the flood forecasting service and advanced technology such as weather radar. Dharssi (2014) is developing a soil moisture analysis system as a replacement for the KBDI and SDI that uses many different sources of observations including satellite derived soil moisture estimates, land surface models and data assimilation techniques through the BNHCRC, which promises to provide a better-quality spatial resource for this and other purposes.

The work conducted by the CSIRO, based on the structure of the identified fuel types through the National Fuel Classification findings (Gould et al. 2014, Hollis et al. 2015) and the fire behaviour models synthesis work carried out by Cruz et al (2014) will develop linkage guidelines between fire models and fuel types. The fuel moisture, arrangement, load and classification and the work on modelling soil moisture should consider these developments.

## 2.2 Grassland curing and loading

The curing process of annual grasses is that they naturally mature, seed and die. Perennial grasses behave a bit differently and tend to accumulate dry matter over a long period and tend to retain some live parts for most of the year except in a drought. So there is a fairly predictable seasonal pattern of green live grass that is too moist to ignite initially which then undergoes curing to become dead dry grass that burns quickly. Grass may cure very quickly so the focus is to monitor it closely when and where it begins to die. After the grass is fully cured this intense monitoring is not required except if there is a lot of rain which can promote grass growth, giving for example short green grass under dry grass. (Martin et al. 2014).

Many hundreds of grass species grow in Australia, but are classified into broad groups with similar characteristics. For example, tropical, tussock, hummock, improved pastures and grazed/un-grazed pastures. The life cycle of all grasses is dominated by rainfall. A wet spring will produce abundant growth, while an early summer with little rain will accelerate drying. However, if grass is either lying down or cut [e.g. for haymaking], it takes a lot longer to dry and if it is not fully cured, any rain may tend to keep the grass alive for longer. In contrast, standing, fully cured grassy fuels will dry rapidly in a few hours after rain in hot dry sunny conditions. Grass fuel characteristics such as fuel continuity and height affect the fire behaviour. Fuel load by itself will influence flame height, depth and fire intensity[2] (Cheney and Sullivan 1997).

In Australia there are two models that are used for grassland, the McArthur Grassland Mk 5 meter, and the CSIRO grassland fire spread meter which is a modified McArthur Mk 4 (Cheney and Sullivan 1997, 2008). Originally the grassland FDI meter was designed for use in one type of fuel classification, namely relatively fine-textured annual grasslands in the temperate regions of Australia that go through a curing process each spring and summer. The revised CSIRO meter removes the forward rate of spread (FROS) from the calculation, with the FROS being calculated separately in the CSIRO Fire Spread Prediction System.

The CSIRO Grassland Meter was originally designed assuming fairly dense stands of improved pastures carrying a total fuel loading of 4.5 t ha$^{-1}$. A later modification allows for a variable fuel load to enable the grassland meter to be used in either drought affected areas with low fuel loads or in tropical regions where fuel loads often exceed 6.5 t ha$^{-1}$. In areas of the Northern Territory, fuel loads in excess of 11 t ha$^{-1}$ are encountered in Gamba Grass infestations.

The moisture content of dead grasses (100% cured) is not considered independently of the meters, but is built within the meters. Moisture content can range from 2% to 35% of the dry weight, above 35% the grass fibres are saturated and there is free water either on or within the stalks. However, once rain has stopped for example, grassy fuel will dry out within 2 hours on a hot sunny day.

The determination of consistent curing across state borders is problematic. To address this, a project is currently underway by Slijepcevic et al. (2014) to improve understanding of the physical processes

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[2] Here the fire intensity is defined as the available heat of combustion per unit area of ground and the rate of forward spread of the fire.

by which curing state affects fire propagation in different regions. This project will investigate the current predictive equations that define fire propagation thresholds in grassland fuels under marginal burning conditions, and the accuracy of operational grassland fire spread in partly cured grass, to enable development of simple field-oriented decision support tools.

### 2.3 Bushfire fuel classification

Fire cannot exist without fuel, and so fuel state is a major input to fire danger rating. Traditionally, fire danger ratings in Australia have mainly considered two main fuel types, forest and grass, as reflected in the corresponding meters. Exceptions include the calculation for Moorland fuel types in Tasmania, using Marsden-Smedley and Catchpole (1998), and one jurisdiction which uses the McArthur GFDI for forest fuels also.

Fully describing the fuel state is extremely complex, with relevant factors including the total amount, moisture content, relative masses of live and dead, relative amounts of various sizes (e.g. fine through to coarse), vertical arrangement and type. This complexity is recognised in the developing Australian Fuel Classification system (Gould and Cruz 2012), which provides for five fuel layers: over-storey tree bark and canopy, intermediate tree bark and canopy, elevated fuel, near-surface fuel and surface fuel.

Subsequent reports (Hollis et al. 2015, Cruz et al. 2015) further highlight inadequacies in the fuel state prediction using FDIs that reflect only three fuel types. In particular, the current FDI system also does not encompass the fuel characteristics in different regions of Australia and the quantity of fuel at a particular time since the last fire. It also identified that, without an agreed and accepted protocol for defining and assessing fuels, it will be difficult to improve the collective fuel characteristic knowledge. Cruz et al. (2015) provides a comprehensive examination of 22 different fire spread models for various fuel types. Fourteen of these models are recommended as being suitable for use under either prescribed burning conditions, wildfire conditions, or both. Eight models are not recommended.

### 2.4 Wind and wind change

Wind has a complex variation over multiple space and time scales, with a correspondingly variable impact on fire behaviour. Synoptic to local scale environmental winds are components of predicted fire danger, while coupled fire – atmosphere models have indicated that a simulated fire will modify the wind and that this in turn modifies the propagation of the simulated fire (Clark et al. 1996, Peace 2014).

The wind speed used within FDI calculations is averaged over a 10-minute period at a height of 10 m above flat open terrain.  Wind direction is not reflected in the FDI, yet strongly influences the spread of fire so it is also one of the most important factors in evaluating fire danger and resulting behaviour because the fastest and hottest part of a fire spreads, all other factors being equal, in the direction of the wind. Consequently, one of the most dangerous fire risk elements is wind changes because the fire abruptly changes direction, and the flank, which is often much longer than the head, becomes a significantly wider head creating particular danger for fire fighters.

The grassland FDI is particularly sensitive to wind speed variation with minor changes to wind speed substantially impacting the resulting FDI, particularly at the higher end of the scale. Thus the calculation of GFDI is sensitive to the temporal and spatial resolution of the input data. Systems such as the Bureau of Meteorology's Next-Generation Forecast System (also known as the graphical forecast editor, GFE) may interpolate less frequent data to an hourly basis[3]. These hourly wind forecasts are available in digital format and are being used within fire simulating systems[4], but may not reflect true wind variation within the hour forecast (Hicks 2013).

Indices such as McArthur's FDIs are based on near-surface meteorological data and neglect three-dimensional environmental interactions. Such three-dimensional environmental interactions include: mechanical mixing of the atmosphere, convection columns interacting with the ambient wind, and the fire interacting with the environment to change wind structure (Peace, 2014). The development of pyro-cumulonimbus clouds (PyroCb) is another complication.

Experimental results from Project Vesta (Gould et al. 2007a,b,c) and simulated fire coupled modelling (e.g., Clark et al. 1996, Badlan et al. 2012, Peace 2014,) have reinforced observations that local scale winds through larger fuels (forest, scrub) may vary significantly from a 10-metre wind in the open that is used in an FDI forecast, because of the effect by complex flow within the canopy and of fire-modified winds. Fire rate of spreads predicted by a Forest Fire Danger Meter (FFDM) were closest to observed values when winds were light (less than 12 km $h^{-1}$) and shrub fuels were sparse, but were vastly under-predicted in anything above this rate. McCaw (2007) noted that FFDMs remain valid for predicting spread during the early stages of fire growth only when fires are developing from a point ignition and the head fire remains narrow. McCaw et al. (2008) demonstrates that empirical models of fire spread are likely to substantially under-predict rate of spread in eucalypt forests under high wind speeds.

Topographical influences on wind in the form of valley funnelling, the acceleration between an inversion layer and mountain (i.e., a mountain gap), mountain waves, are currently too fine detail local weather effects to include explicitly in FDI. A number of authors (Holden et al. 2011, Sharples et al. 2009, Bradstock et al. 2010, Kepert and Fawcett 2013) have investigated the effects of topography on wind on a localised scale. Wind forecasting at this detail will improve with higher resolution weather modelling, and could be included in any new fire weather rating system or fire behaviour simulator.

Results from coupled fire behaviour models show interaction of environmental wind flow and the fire-induced wind (Clark et al. 1996, Cunningham and Reeder 2009, Peace el at. 2014). Clark et al. (1996) found near-surface convergence zones caused by the fire's updraft and low-level inflow moved ahead of the fire; or in simpler terms, increased the wind at the fire and pulled the combustion front forward. Peace (2014) showed a simulated example of the fire causing the inland acceleration of a sea breeze and the descent of elevated air into the surface fire, indicating that the fire changed the arrival time and intensity of the sea breeze wind change.

Fire danger and resulting fire behaviour is modified with a shift in wind direction and speed, be that from a synoptic-scale air mass change such as a cold front or a low pressure trough, or a smaller-scale circulation such as a sea breeze or thunderstorm outflow. Wind changes cause the direction of fire propagation to change, with the flank becoming the head. Often, this leads to a much larger head fire, vastly increased rate of burning, and great danger to those caught in the new path of the fire. Other

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[3] Hourly data is achieved through a linear interpretation of 3 or 6 hourly time steps of weather parameters from numerical weather models. Higher resolution models, and consensus models forecasting out to 48 hours have hourly time steps, but may not always be used, depending on performance on the day.

[4] Fire simulator is a computer program that depicts the development of a fire in space and time based on environmental conditions, fuel characteristics, terrain and interactions amongst these variables. A fire simulator may utilize one or more fire behaviour models or systems to predict fire behaviour as an input to simulating fire spread.

factors to be considered in such cases are the effects of cooler and moister air after the change, and any precipitation that may occur.

Results from high resolution atmospheric modelling (Engel et al. 2012, Fawcett et al. 2013) show small-scale fluctuations in the wind direction on synoptic-scale features such as low pressure trough lines and cold fronts. Features such as density currents, undular bores emanating from a wind change, and pre-wind-change boundary-layer rolls, all create wind speed and direction shifts. The upward motion of air on the wind change and the pre-change features may contribute to rapid plume development and lofting of particulate matter, and be strong enough to allow larger materials such as bark to be supported (Ellis 2011). The vertical wind component from these meteorological features and the fire plume itself may further contribute to spotting, with the changes in wind speed and direction with height being another important factor.

On 7 February 2009, fires that started from spot sources forming a narrow fire front, through the Murrindindi forest area, southeast of Marysville, and the Kilmore gap to Kinglake fire, became larger fire fronts (a 55-km-long head-fire) as the result of the wind change. The area burning increased from approximately 27,000 ha before the wind change to 63,000 ha in the hour after the wind change, while the estimated rate of energy release went from about 2000 GW before the wind change to 8500 GW afterwards. Before the wind change the fire spread occurred were in distinct phases, partially driven by changes in fuel and topography in what would appear to be a fairly constant fire weather condition (i.e. an extremely hot, unstable, dry, deep mixing layer and windy (Cruz et al. 2012).

With the largest fire intensity occurring post wind change, Cruz et al. (2012) comments that the extreme fire behaviour (in terms of rate of energy release) cannot be explained by the prevailing weather conditions shown at the Kilmore Gap or Coldstream weather observations, where the FFDI dropped to values below 20 after the change. This is not surprising, as fuel moisture has a considerable lag[5] after an air-mass moisture change, with the lag being greater for coarser than finer fuels. The size of the new fire front and the strength of the wind post change, are the primary contributors to a larger fire area and therefore a larger energy release and outweigh the change in fuel moisture. Immediately after the change, the danger of this fire was markedly greater than indicated by the FFDI.

## 2.5 Temperature and Relative Humidity

Temperature has a direct thermal effect on materials with which it comes in contact (Potter, 2012). Temperature and relative humidity contribute to the McArthur FDI directly, and also to the evaporation and transpiration terms in the KBDI and SDI.

Temperature and relative humidity influence the equilibrium moisture content (EMC) of fuels. Studies on temperature (Potter 2012) suggest the importance arises from not only the indirect effects on fuel moisture, but also when the sun heats surface fine fuel, and they in turn heat the adjacent air. As fuel temperature increases, moisture on the fuel’s surface evaporates more readily, thus drying the fuel

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[5] Fuel moisture lag refers to the rate a fuel gains or loses moisture, the time necessary for a fuel particle to gain or lose approximately 63% of the difference between its initial moisture content and its Equilibrium Moisture Content (EMC - the vapour pressure of the water in the wood equals that of the atmosphere). The change in moisture content slows as the fuel moisture gets closer to the equilibrium moisture content. In nature, fuel takes five times the lag periods for 95 % of the change to occur. Heavy fuels have a longer time lag. (Utah State University).

and increasing its flammability. The fuel temperature is in turn the result of the overall energy balance of the fuel, driven by sunlight and energy radiated from the fire (Bureau of Meteorology, 1964, Potter 2012).

Consideration of the three-dimensional profile of temperature and moisture is important for understanding fire intensity and behaviour. Hayes (1941) examined temperature, humidity and wind showing the variability with elevation. Incorporating information on temperature inversions can be imperative to forecasting fire behaviour, as inversions form a boundary between air masses above and below that may have very different temperature, humidity and wind characteristics. Stability and temperature inversions will be discussed in the next section, however it is important to note that stability is a function of the vertical distribution of temperature and moisture. Understanding the vertical temperature structure of the atmosphere is another key physical concept that forms part of the analysis of the atmosphere and the interactions between the atmosphere and fire.

## 2.6 Atmospheric Stability and the planetary boundary layer

Atmospheric stability refers to the extent to which vertical motion in the atmosphere is favoured or suppressed by the temperature and moisture structure. Under stable conditions, motion is suppressed, while under less stable conditions it is favoured. Under unstable conditions, it may arise spontaneously. The stability usually varies with height – for instance, a neutral or weakly unstable daytime mixed layer can have a stable inversion layer on top of it.

The FDI meters tend to overestimate fire danger and rate of spread under stable conditions. To address stability, the Haines stability index was developed in 1981, although it is based on only two locations for observations and verification. The Haines Index combines a temperature lapse rate and dewpoint (dryness) component to give an indicative score of ranging between two and six (Haines, 1988).

In the dry Australian climate, the lapse rate and dewpoint depression ingredients exceed the upper bounds considered in the Haines Index. Mills and McCaw (2010) reformulated the Haines Index to use open-ended linear functions of temperature lapse rate and dewpoint depression, leading to a larger range (0 to 13.5), and renamed it the Continuous Haines (C-Haines) index. They state that the "C-HAINES forecast should be used as an alert rather than a simple cause and effect relationship to fire activity. Examining the components of the C-HAINES to understand the drivers of C-HAINES should be the practice". There have been cases of extreme (> 10) C-Haines values associated with sustained night-time fire activity in which the FFDI was low.

The planetary boundary layer[6] (PBL) structure largely determines the near-surface stability and thus may affect fire behaviour. The PBL depth is not reflected in the FDI, but can be considered as another element influencing fire danger. Mills (2008b) showed that environments with deep mixed layers are associated with many of the abrupt surface drying events, and argued that these events were associated with the dry convective mixing of middle atmosphere dry air to the near surface layers (Mills 2005, 2008a, 2008b). As well as the potential for mixing down dry air, deep boundary layers also

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[6] The planetary boundary layer extends upward from the surface to a height that ranges anywhere from 100 to 6000 m: above it is the free atmosphere. The boundary layer is directly influenced by the presence of the Earth's surface, responding to frictional drag, solar heating, surface cooling, and evapotranspiration. A stably stratified PBL is typical at night locations and also occurs in daytime in places where the Earth's surface is colder than the air above.

allow for more vertical plume development, and affect the gustiness of the wind. On days such as Black Saturday, the boundary layer was 5 to 6 kilometres deep by the afternoon. In contrast, a highly stable nocturnal boundary layer may be as shallow as 100 m.

Potter (2005) emphasised the role of convective available potential energy[7] (CAPE) for fire plumes. Although more research is required in understanding and verifying plume dynamics, the body of work all highlights meteorological relationships between stability, wind shear, entrainment of moisture potentially released from fuel to a lifting condensation level and the effect on a fire's plume. Understanding thunderstorm dynamics is helpful for studying the transition of a smoke plume into a thunderstorm, through forecasts of thunderstorm environments and study of radar signatures.

The boundary-layer structure may be important in regions of significant topography. For example, the air above a subsidence inversion is warmer and drier than that below, so when mountains penetrate through the inversion, the fire danger on the ridges and peaks can be very different to that in the valleys. Similarly, nocturnal drainage flows can lead to significant spatial variability in the temperature and humidity overnight, affecting the fire danger. These effects are discussed further in Sharples (2009).

## 2.7 Dry lightning

Dry lightning is the term used to describe lightning with a high probability that significant rain will not fall on the area where the strike has occurred so a fire could potentially be ignited. There are a number of ways in which dry lightning can occur: if a thunderstorm is high-based with relatively dry air at lower levels such that rain evaporates before reaching the ground or if a thunderstorm is fast moving such that the rainfall is spread thinly on the ground, or if lightning occurs outside of the rain shaft of a thunderstorm. The atmospheric conditions for high-based thunderstorm activity have been investigated by Dowdy et al. (2009) in an Australian context. This report investigates atmospheric states that could potentially influence the chance that lightning will cause a fire, including the occurrence of dry lightning. The probability of fuel ignition by lightning has been shown to be relatively independent of fuel moisture, with some fuels igniting even though they may be very wet (e.g. Latham et al. 1997). In contrast to the probability of ignition, the probability that an ignition is sustained *is highly* dependent on fuel moisture (Dowdy et al, 2009). The high dependency of ignition survival on fuel moisture is the reason why the concept of dry lightning is of importance.

Rorig and Ferguson (1999) showed that the occurrence of dry lightning in the Pacific Northwest of the United States of America was related to high instability (as represented by a large temperature difference between 850 hPa and 500 hPa, corresponding to approximate heights of 1500 metres and 5.5 km above mean level) combined with low atmospheric moisture levels (as represented by high dewpoint depression at 850 hPa). Their method correctly classified between about 56% and 80% of days on which thunderstorms occurred as either 'dry or wet' as defined by a rainfall threshold of 0.1 inch (i.e. 2.54 mm). Dowdy et al. (2009) investigated the role of fuel moisture and ignition from dry lightning using the Canadian FWI System Fuel Moisture system. It was found using this comparison that an ignition will start, but is less likely *to survive* if the fuel is already wet prior to the occurrence of lightning, regardless of whether the lightning is 'dry' or 'wet'. The dry fine fuels were the best

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[7] The amount of energy a parcel of air would have if lifted a certain distance vertically through the atmosphere. CAPE is effectively the positive buoyancy of an air parcel and is an indicator of atmospheric instability.

indicator of a high chance of fire from lightning, followed by dry fuels of moderate size or depth, with the dry fuels of large size or depth indicating only a slightly higher than average chance of fire per lightning stroke.

Lightning-fire ignitions could smoulder for a number of days before a change in conditions occurs that extinguishes the smouldering fuel (Dowdy et al. 2009). An objective forecast system for lightning would provide another input to FDR, providing an alert where lightning ignitions are sustained are more likely, by combining the fuel state with the chance of dry lightning.

## 3. Sensitivity of McArthur's FDI to wind input

The FDI is less sensitive to input parameters for values less than 50, which represents the FDI range in which most user decisions are made. FDI thresholds are used as a trigger for preparedness. While the effects of small variations in any of these inputs such as wind speed, curing, drought factor, relative humidity or temperature were more likely to be evident when manually calculating FDI using one of the original, 'cardboard' FDI meters, the computer calculation tends to mask this type of sensitivity. Without an understanding of how sensitive the result is to small changes in inputs, particularly at FDIs above 50, there is more likely to be an assumption that the FDI value is accurate to the precision implicit in the derived number. Hicks (2013) provides examples of the range of the uncertainty of FDI calculations where the significance of small variations in inputs is considered thoroughly and goes on to outline the application of derived products, such as a percentage of an area exceeding a specified FDI threshold area.

A single index value may be arrived at by greatly different weather combinations. Table 1 illustrates the range of weather values that will produce FDIs of 50, 75, 100 and 150 for both the FFDI and GFDI. The degree of curing in grasslands and the DF in forests are assumed to be at their maxima).

Table 1. Comparison of Grass and Forest FDI values for a range of weather inputs.

| FDI value | GFDI weather | | | FFDI weather | | |
|---|---|---|---|---|---|---|
| | Temp (°C) | RH (%) | Wind (km h$^{-1}$) | Temp (°C) | RH (%) | Wind (km h$^{-1}$) |
| 50 | 40 | 5 | 24 | 45 | 5 | 2 |
| | 35 | 5 | 26 | 40 | 5 | 9 |
| | 35 | 10 | 30 | 40 | 10 | 16 |
| | 30 | 15 | 36 | 30 | 10 | 31 |
| | 30 | 30 | 43 | 30 | 15 | 38 |
| | 45 | 30 | 34 | 30 | 30 | 60 |
| 75 | 40 | 5 | 32 | 45 | 5 | 19 |
| | 35 | 5 | 35 | 40 | 5 | 27 |
| | 35 | 10 | 39 | 40 | 10 | 34 |
| | 30 | 15 | 45 | 30 | 10 | 49 |
| | 30 | 30 | 53 | 30 | 15 | 56 |
| | 45 | 30 | 44 | 30 | 30 | 78 |
| 100 | 40 | 5 | 37 | 45 | 5 | 32 |
| | 35 | 5 | 40 | 40 | 5 | 39 |
| | 35 | 10 | 44 | 40 | 10 | 46 |
| | 30 | 15 | 50 | 30 | 10 | 60 |
| | 30 | 30 | 59 | 30 | 15 | 68 |
| | 45 | 30 | 49 | 30 | 30 | 90 |
| 150 | 40 | 5 | 45 | 45 | 5 | 49 |
| | 35 | 5 | 48 | 40 | 5 | 56 |
| | 35 | 10 | 52 | 40 | 10 | 63 |
| | 30 | 15 | 60 | 30 | 10 | 78 |
| | 30 | 30 | 69 | 30 | 15 | 86 |
| | 45 | 30 | 58 | 30 | 30 | 108 |

For a given wind speed range, the resulting range in the FFDI is much less than that in the GFDI. The contribution to GFDI and FFDI from wind speed is given by the following equations that are illustrated for a typical case in Figure 1.

$$GFDI \propto \exp\ \{0.633\sqrt{u}\}$$

$$FFDI \propto \exp\{0.024u\}$$

Referring to Figure 1, it can be seen that for that specific example, GFDI can take any value from near-zero to in excess of 150, depending on wind speed, while the FFDI varies over a much smaller, but still substantial, range. It is plausible that grassland fires are more sensitive to wind speed than forest fires, for reasons such as the partial sheltering of the forest floor from wind by the canopy. Nevertheless, the extreme sensitivity of GFDI introduces operational concerns because small changes in the forecast wind speed, of the order of normal weather forecast uncertainties, can shift the fire danger rating from one category to another. This problem could be reduced by using an ensemble of predictions, with outputs including an areal depiction of probability of occurrence estimates. From these outputs, maps of risk and predicted physical fire behaviour measures can be derived. An experimental system along these lines has been developed in the Victorian Department of Environment and Primary Industries.

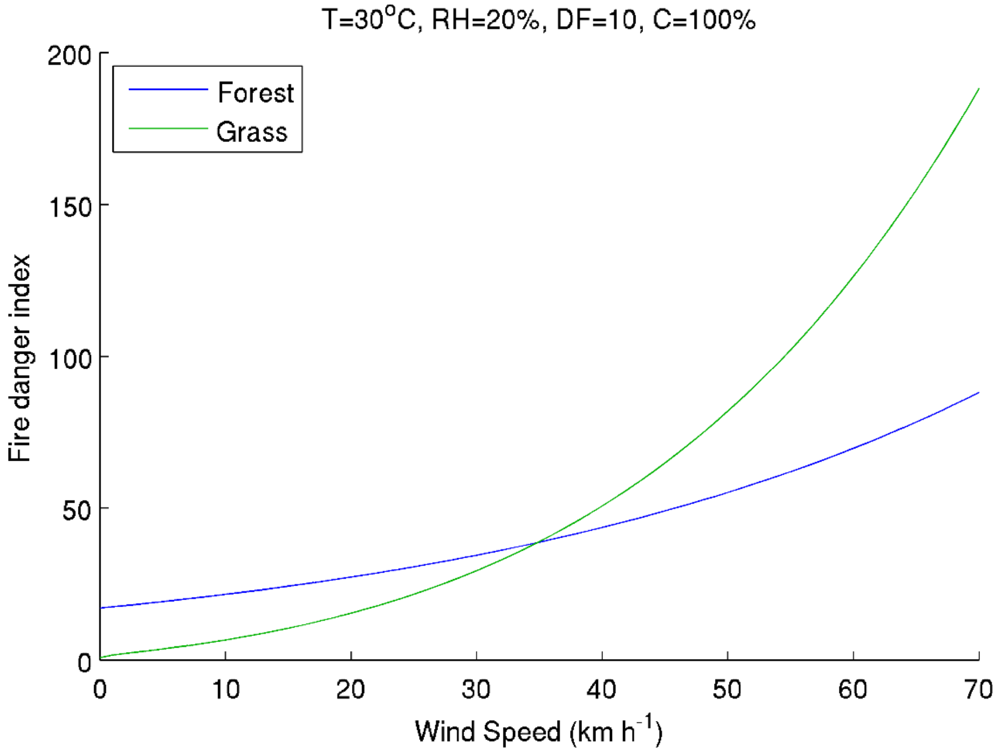

**Figure 1.** Wind speed functions for the grassland fire danger meter (Grass) and the forest fire danger meter (Forest) for wind speeds in km $h^{-1}$.

## 4. Candidate Fire Indices

One option for future operational FDIs would be to adopt, possibly with some local adaptation, an index used in another country, such as the USA or Canada. The Canadian fire weather index (FWI), for instance, is used in a number of other countries around the world. Adopting an established system has the advantage that the benefit of a larger body of relevant research is gained, and that international collaboration can also ensure that further advances made overseas are adopted locally. However, such systems may not meet Australian needs, nor address the full complexity of the problem in the broad Australian context.

Two independent studies have found similar results from the Canadian system and Australian systems. Matthews (2009) performed a comparison between the FFDI (McArthur); the Forest Fire Behaviour Tables (Sneeuwjagt and Peet 1995) and the Canadian FWI (Van Wagner 1987). He showed that all three indices calculate fire danger in a similar manner and provide the same type of information to a fire manager. There were differences in the structure of the indices that for a given wind speed, drought factor and fuel moisture, the indices vary widely in their assessment of fire danger. A limitation is that the indices still are functions of surface variables only. However Matthews (op. cit.) speculates each index could still be applied in Australia with careful consideration of the fuel sub-models.

Dowdy et al. (2009) investigated the effect of weather in Australian conditions comparing the McArthur index to the Canadian FWI system adapted to Australian conditions. They found the relationship between the two indices varied throughout Australia with a standard deviation of 15% of the FWI value. The indices are similar in their sensitivity to wind primarily, with relative humidity and then temperature being less sensitive inputs. On the finer scale there were some differences, with the FFDI being more sensitive to temperature and relative humidity and less sensitive to wind speed and rainfall than the FWI. They concluded, similarly to Matthews (2009), that the differences, in some circumstances, provide complementary information for an event.

The hourly FWI values and subcomponents of the FWI system (i.e. three different fuel moisture codes) can add insight into fire conditions; these would have to be complementary to other components that consider the full three-dimensional atmosphere, the unique fuel types in Australia, and fuel and soil moisture factors. It is emphasised that none of the indices can be considered in isolation, nor as a singular quantity of prediction due to the variability of weather, fuel and topography as discussed in the section on environmental conditions for fire behaviour.

Substantial progress has been made in recent years in improving quantitative predictions of fire behaviour. Simulators such as Phoenix, Aurora, Prometheus and FARSITE have improved in skill, and are used in Australia and internationally for operational prediction of the fire spread. We can confidently expect further improvements into the future. A new fire danger rating system should build upon such growth, otherwise it risks becoming obsolete. However, these simulators may not be available in all circumstances, so a new system should not rely solely upon them. An outstanding benefit of such simulators has been a marked shift towards quantitative, verifiable prediction. While there is still much to be done, the field is moving in the right direction.

The Fire Impact and Risk Evaluation – Decision Support Tool (FIRE-DST) framework (Cechet et al. 2014) incorporates one of these models (Phoenix) into a probabilistic framework, and extends it to also predict the impact of fires. FIRE-DST provides a strong starting point for further research and policy development, but many of the components may need to become more sophisticated, including the use of better fuel models, more comprehensive atmospheric information and fire-atmosphere feedbacks.

The increasing accuracy and resolution of physical atmospheric models, in conjunction with probabilistic fire behaviour and future developments such as coupled fire-atmosphere models, also need to be harnessed.

Fuel models are another area where recent research is yielding substantial progress. The main fuel models used as an input to the current FDR are the McArthur models for grass and forest, with some states also utilising a moorland model. In contrast, recent research by Cruz et al. (2015) gives recommended fuel models for fourteen different fuels or fire conditions (prescribed or wildfire), as well as recommending that eight existing models not be used. Expanding the existing use of fire prediction simulators to use more sophisticated and realistic fuel models would be expected to increase their value.

For fuel models that incorporate rainfall (or drought indicators) measurements into the equation (see Cruz et al. (2015) for a recent review), accuracy could be improved by using more rainfall observations. For example, the 79 rainfall observations used in Victoria cannot reflect the true rainfall variability in the landscape, and capture the difference between dry ridges and wet gullies, nor the effect of isolated showers. Additional rainfall observations are available, and incorporating this information into the rainfall grids would be beneficial.

Further benefit could arise from the use of more sophisticated soil moisture models than KBDI or SDI, that incorporate the variations of soil type, topography, latitude and field capacity of the soil. More advanced soil moisture models that include these factors and feature reasonable spatial resolution (Dharssi, 2014) are currently being developed.

Fire is a sufficiently complex and multi-faceted hazard that to present a single replacement index will necessarily not convey the full range of information. Instead a replacement system is needed, of which indices will form an important part. This project provides the opportunity to create a fire danger rating system based on quantitative indices that are verifiable. By identifying the desired characteristics that make an index a “good” index, should help guide the development of future indices. In a sense these are aspirational goals, as they may be hard to reach. However, even partial fulfilment will represent substantial progress on the current situation. We now list desirable characteristics of fire danger indices.

### *Physically meaningful*

An index that is directly related to fire behaviour is more useful than one that is simply an arbitrary number. For example, the tropical cyclone category scale is defined in terms of the peak wind gust within the storm. A category-4 cyclone has peak gusts between 225 and 279 km $hr^{-1}$, providing a clear physical meaning that directly relates to the wind risk that the storm presents. In contrast, the McArthur FFDI is an arbitrary number with limited physical meaning, although the spread tables on the back of the meter alleviate this to some degree by relating the index to the physical quantity of FROS.

We are aware that some will question our description of the McArthur scales as arbitrary, and note that 100 on the FFDI scale is defined in terms of the weather conditions of Black Friday, 1939. However, that is precisely our point. What does this definition mean in terms of fire behaviour, beyond the belief at one time that it was the worst possible? That definition does not describe how to interpolate within that range, nor extrapolate beyond it – what does 50, or 150, correspond to? Moreover, our knowledge of the weather on Black Friday relies on observations that are spatially and temporally sparse compared to those available today – we have gone from manual 3-hourly observations supplemented by a very few autographic chart recorders, to the widespread use of electronic monitoring at 1-minute intervals.

Basing future indices on physical characteristics of the fire is the key point. Other desirable properties of a good index, listed below, largely follow from this basis.

### *Verifiable*

At present, fire indices are verified largely by verifying their "ingredients" (i.e. wind speed, humidity, temperature, etc.). Verifying the FFDI then becomes a rather convoluted method of verifying meteorology, when it would make more sense to separately verify temperature, humidity and wind. Rather than verifying the "ingredients" of the index we strongly recommend verifying against quantities that actually affect the user; that is, a measure of fire behaviour such as intensity, rate of spread and flame height. Naturally, this requires that the index be defined in such terms.

### *Accurate (50 means 50)*

There are many sets of meteorological conditions that will lead to an index value of, say, 50. To the maximum extent possible, the fire behaviour should be the same under all of these conditions. That is, the index or indices should weight the different meteorological and other factors appropriately. This should apply across fuel types, geographic regions and so forth, as far as is practicable.

### *Reasonably uniform response across its range*

A fixed increment in the index value when the index is low should have similar meaning to the same increment for high index values. For example, the expected increment in fire behaviour between an FFDI of 10 and 20 should be similar to that going from 70 to 80. As a corollary to this, it should not "saturate", or lose sensitivity, at either the high or low end of the scale. It should not be hypersensitive to input parameters in any part of its range, and should behave sensibly when extrapolated outside the range of the developmental data set.

### *Incorporate all relevant data*

Stability, wind changes, fuels, insolation and other matters discussed in the environmental factors section should be incorporated.

### *Relevant to Australian conditions*

The indices should be relevant to the full diversity of Australian climate and fuels.

### *Applicable at different time and space scales.*

Provide useful information both for tomorrow for a district, but also at a point location at frequent intervals for either a going fire or planned prescribed burn. It should be able, if required, to discern the differences between, say, north-facing and south-facing slopes. This point may require care with the definition – e.g. is the index for a given time period a measure of the worst conditions during that period, or the average across that period? Ideally, that definition should be consistent for short periods (1 hour) and long periods (1 day).

### *Consistent and precise definition of all inputs*

The input fields need to be defined properly. For example, is the wind speed the instantaneous value on the hour, the maximum value during the hour, the hourly average value, or something else? What is the wind speed averaging period? What is the measurement height and exposure of the measurement?

## 5. Candidate Indices for Communicating and Assessing Fire Danger

Fire is a hazard with many dimensions. Operationally important characteristics of fire include the fire-line intensity of the head fire, rate of fire spread, flame height, radiation intensity, and ember density. If concerned with the initial growth of a fire, measures such as the time to reach a certain area are important. Less easily quantified but still important measures include the suppression difficulty. These fire characteristics depend, sometimes quite sensitively, on input data including fuel characteristics and moisture, topography, atmospheric conditions, availability and effectiveness of suppression, and so on. In practice, we have reduced this vast complexity to either a single number (index) or word (rating).

It is useful to consider the tropical cyclone (TC) experience at this point. Like fires, TCs are a multi-dimensional hazard, with wind, storm surge and fresh-water flooding representing different hazards that are part of the storm. One dimension of wind risk is communicated via the category scale, which is an index based on the peak gust within the storm. Defining the category in terms of a measureable quantity means the definition is fixed. Future advances in scientific knowledge or measurement technology won't change the definition, but they will reduce the error bars on intensity estimates and therefore the chance that a category 4 TC will be incorrectly assigned as a category 3.

Tropical cyclones also present a hazard through storm surge and fresh-water flooding (from heavy rainfall). Neither of these hazards is well correlated with wind intensity, and different locations are vulnerable to different hazards within a TC. For example, houses on top of a hill are invulnerable to storm surge, but especially exposed to wind. Therefore, the category scale refers only to the wind risk, and not to storm surge or rainfall. Storm surge and rainfall are warned for, again, in physical units.

In discussing the qualities of a "good index" above, it was suggested that it should be physically based and verifiable. Current fire indices aim to provide a number which is meaningful information to the user, but the number has no intrinsic meaning on its own. All currently used indices – the FFDI, GFDI, C-Haines, and Canadian FWI – have this limitation. If we define an alternative index in terms of physical quantities, we separate the problem of trying to find a meaningful number into two, more tractable, sub-problems: (i) what properties of the fire are most useful to this user group and (ii) how can we best estimate those properties.  In this context, "physical property" could include any of those listed in the first paragraph of this section (fire-line intensity, rate of spread, flame height, radiation intensity, ember density, time to grow to a certain area), or perhaps even combinations of them (e.g. fire-line intensity multiplied by ember density). It might also be scaled to make it a conveniently sized number[8]. Once that definition is settled, it is fixed and subsequent work can focus on improving the accuracy with which it is measured and predicted. The user will (hopefully) notice that the data supplied are becoming more accurate with time, but will not have to change their understanding of what an index of 50 means.

The expectation of the indices improving with time is a key advantage of making them physically based, which is absent from present systems. Being physically based, they can be measured and

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[8] For example, the Bureau's UV index is defined as the UV energy in the biologically-active frequency range, multiplied by 10. Typical values are 0 to 1.5 mW $m^{-2}$, the scaling ensures that the index takes values of 0 to 15 rather than 0 to 1.5, thereby improving communication.

verified. Weaknesses can be identified and research directed to address them. Stakeholders can be presented with hard data showing how much of an advance they can expect from an updated system.

However, ***we should not expect a single fire index to meet all user needs.***

To determine these physically based indices, a suite of methods will be necessary, and the easier path, of adopting one single method, should be avoided. A suite of methods carries the following strong advantages:

- Different methods may work better in different situations
- A consensus or average answer may be more accurate than any of the individual components therein, however user judgement is required in this choice.
- It may be possible to identify outliers and perhaps omit them, or gain additional information from them.
- One could use advanced computational methods for an accurate answer when cost is no object, but statistical methods when a quick answer is required or the necessary computation is unavailable or too slow. Each would calculate the same physical quantity, but by different methods.

In meteorology, the use of multiple methods and consensus forecasts has a long history, high level of success, and strong user acceptance. “Spaghetti” plots of various model forecast TC tracks are used in determining an average position, as well as the possibility of alternate scenarios that may pose a risk to particular locations. These concepts could be used in the less complex fire behaviour simulators for the simplified two dimensional parameters – surface wind, temperature and dewpoint for example, as these simulators are already being used in some operational environments.

Most of the parameters listed in the first paragraph of section five are either direct outputs of, or can be derived from, fire behaviour prediction simulators such as Phoenix (Tolhurst et al. 2007, Chong et al. 2013), Prometheus, FARSITE and Aurora. Running multiple instances of such a simulator on a suitable grid is expected to be a way of the proposed calculating of physically based indices. This would include the use of multiple weather model outputs, as well as encompassing the work by CSIRO on the variability of fuel data.

As highlighted in earlier chapters, recent work using weather models at very high resolution, down to the sub-kilometre grid scale (e.g., Engel et al. 2012, Fawcett et al. 2013), have provided new insight into detail of weather variables not previously seen in coarser resolution data (e.g. 6 km x 6 km grids). The continuous refinement of future weather models as input into fire behaviour models will improve the fire behaviour model output, however fire prediction could be further improved with an ensemble approach. In the longer term, we expect that coupled fire-weather models will provide a further source of operationally useful predictions.

We advocate the use of several fire prediction models, rather than just one, driven by an ensemble of weather models, including state of the art high resolution weather models. As the models are upgraded or superseded, the accuracy (but not the definition) of the available indices should improve. Indeed, we expect this application to provide a major impetus for improvements in fire modelling.

Fire simulator output and display are as important as the inner workings of the model. The Victorian Department of Environment and Primary Industries (DEPI) Planning and Knowledge team) have developed maps displaying physical fire predictions that are practical means of conveying threat levels and supporting readiness actions (Al Beaver, personal communication, 2014). Fire intensity, an assigned readiness level, the time for a new ignition to grow to 5 ha, and potential threat areas have been developed, with the Phoenix fire prediction simulator used currently for predictive output (Tolhurst et al. 2007). Using an ensemble of fire simulator results from Phoenix as an example, similar maps could be produced depicting a spread of possible outcomes.

Understanding the limitations, improving, verifying and communicating the output of ensembles of fire behaviour models will require multi-faceted collaboration between fire ecologists, natural resource management specialists, fire, fuel and weather research/modellers, fire meteorologists, and science communicators. Training of fire personnel to better understand fire forecasts is important. Ideally a centre for fire prediction would encompass operational practitioners from the fire agencies, working in conjunction with organisations such as the Bureau (e.g. for operational weather specialist, weather research, infrastructure, technology and computational experience), CSIRO and fire agency research (e.g. fire dynamics and fuel moisture specialists), and research work from universities (e.g. fire ecology, behaviour specialists) on a continuing basis.

## Weather indices for risk management

Underlying these needs for fire danger indices, simple weather indices may, under some circumstances, be useful for situational awareness and quick evaluation in the absence of more advanced technology. Such measures will inherently lose accuracy because the factors being ignored, such as fuel, profoundly influence fire behaviour. We now discuss how weather-only indices could be formulated to explicitly recognise this limitation. We note that it will be necessary to ensure that users are fully aware of the limitations of weather-only indices, just as with fuel-only or surface-only indices.

Weather indices alone do not make a complete index. Nonetheless, they should still be defined in terms of physically meaningful, measureable, and hence verifiable, characteristics of the potential fire. The problem of defining the meaning of the index should be separated from the problem of calculating its value. In considering fire weather indices, there is an additional advantage to taking this approach. If a range of indices are in use, each with different meanings, then the user is required to memorise and apply a wide range of significant values. For instance, McArthur FFDI of over 100 is climatologically an exceptionally high value which will seldom be experienced in most locations and calls for strong mitigation measures. But a C-Haines value of 13 is similarly exceptional. With a small number of indices, users can reasonably be expected to interpret them appropriately, but this becomes more difficult as the number of indices grows.

One possible way to avoid this problem is to normalise the indices with respect to climate. That is, to develop a frequency distribution function of the climate of the index, and instead of reporting its value, report its percentile value within that distribution. In this way, the conditions on Black Saturday might correspond to perhaps to the 99.99th percentile (assuming they occur roughly every 100 years, and the fire season is 100 days long, so the daily probability of such an event is 0.0001). This approach is appealing, but we note the following disadvantages:

- Saturation. The difference in the percentile space between a once-per-year event (99th percentile) and a once-per-century (99.99th percentile) is only 0.99, which does not adequately depict the much greater consequence of the latter event.
- Non-stationary climate. Is it meaningful to normalise against climatology when the climate is changing?
- Determining the climate. Much data is needed, and good quality data may not be available. This problem is especially serious in trying to get well-defined tails to the climatological distribution; that is, understanding the frequency of rare events. Although new products such as reanalyses will greatly assist with this task, it will still be difficult to accurately characterise very infrequent events.
- Time period. The climate would be defined in terms of data at some time period – perhaps daily or hourly. The choice would significantly affect the climatic frequency distribution, as night-time data would be included in one but not the other. Interpreting data, especially sub-daily data, would be affected by the choice.
- The normalised index would have different values in different locations, even if the non-normalised index was the same, because the climate would be different.
- The strong connection to physically meaningful and operationally relevant quantities would be weakened or broken.

Climatological normalisation may thus create more problems than it solves.

Instead, we propose to extend an idea already introduced. Earlier, we noted that a physically defined index could have its value calculated in multiple ways – for example, a statistical calculation could be quick and cheap, whereas a dynamical calculation would be more expensive, slower but more accurate. This last point, the greater accuracy, means that the error bars would be smaller for the more expensive calculation. These ideas can be carried across into the calculation of fire weather indices. Suppose we are trying to estimate some aspect of fire behaviour using only wind, temperature and humidity data. Clearly, the uncertainty in the estimate – the error bars – will be substantially larger, even if a highly reliable calculation method is used. Later, if additional data on, say, stability, becomes available, we can revise that estimate. Likely the mean will change somewhat, and the error bars will shrink to reflect the reduced uncertainty.

Incorporating further additional data will further refine the estimate; in this context, “refine” means that the error bars progressively shrink as more data is added. For example, we have so far said nothing about fuel. To give an extreme case, we might know that the fuel is grass, but not whether it is an eaten-out paddock or a gamba grass infestation, and nor the degree of curing. With this potential uncertainty, the error bars on fire behaviour when there is no information on fuel must be large, but incorporating some information on fuels would reduce the uncertainty.

Figure 2 shows a schematic of this procedure. Note that the successive estimates are consistent with each other, in the sense that each successive set of error bars is contained almost entirely within the previous set, but that the level of uncertainty becomes less and the mean value varies as more data are added.

This procedure can be made rigorous through the use of a statistical law called Bayes’ rule, which describes how an initial estimate, called the prior, is updated through additional data to become a more accurate estimate, the posterior. Bayes' rule has the inherent property that adding data reduces the uncertainty. It also allows for uncertainties in the inputs, and can correctly handle data given as a range, such as the knowledge that the fuel load is between 3 and 4 tonnes/ha. Lastly, while a formal application of Bayes' rule can be difficult, the error bars can be calculated using an ensemble prediction system.

The idea that the uncertainty of the prediction depends on the technique and the input data is very powerful, but also capable of being communicated to users. Indeed, many will intuitively understand that a model calculation using a wide range of detailed data should be more reliable than a simple formula or statistical relationship based only on surface weather and a proxy for soil moisture. This approach makes explicit to users and stakeholders the value of obtaining extra data and using more sophisticated methods, and the trade-offs involved in quicker and dirtier methods. It is, however, likely that a simpler means of communicating the uncertainty than the use of formal error bars will be appropriate in some cases.

Thus, we recommend that if fire weather indices are used, then they, like fire danger indices, should be defined in terms of physically meaningful and verifiable measures of fire behaviour. To facilitate user interpretation, they should have the same definitions in both cases. The fire weather indices will be inherently less accurate than the fire behaviour indices because data on other important factors, such as fuels, has not been used. This loss of accuracy should be formally recognised through the use of error bars, although simpler means will likely be more appropriate for communication in some instances.

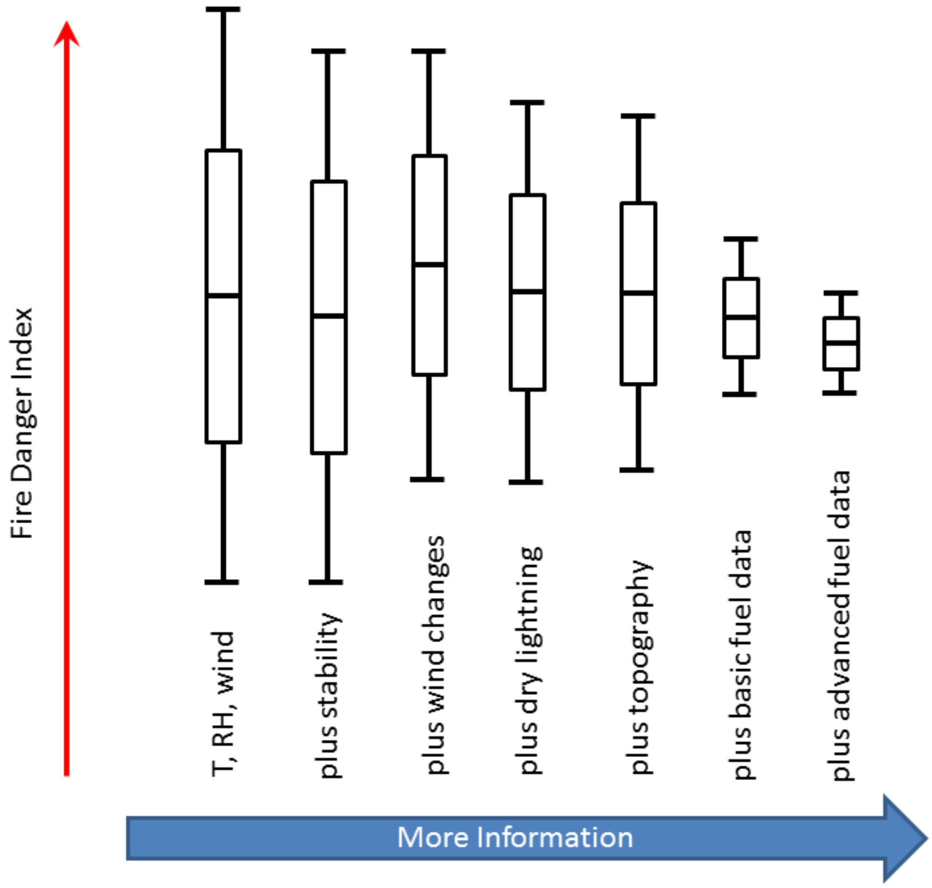

**Figure 2.** A hypothetical example demonstrating the refinement of a fire weather index as information is added progressively. The order of the information versus accuracy is intended as a schematic. The index could be any of the possibilities discussed in the report. The box-and-whisker plots represent the estimated mean value (central bar), 25th and 75th percentiles (the box) and the 5th and 95th percentiles (whiskers). Note that the meaning of an index of, say, 50, is the same in each case. However, as more information is applied, we become increasingly confident that the actual fire behaviour will be consistent with an index of 50.

## 6. Conclusion and summary

Fire danger ratings in Australia are based on McArthur’s indices for forests and grasslands, with the underpinning science dating back several decades. Advances in science and technology mean that those indices do not adequately reflect current knowledge, or make best use of new capabilities such as gridded weather data. While they can now be calculated from equations rather than circular slide rules, and applied to gridded weather data rather than just a few points, the underpinning science has barely changed. Moreover, the use of the equations with values outside the original domains has exposed the extreme sensitivities of the equations for FDI at the higher ends of the scale. Limitations arise because of fuel and weather element uncertainties and the sensitivity of the fire danger meters to some of these uncertainties. In looking for potential new candidate indices, or, a new system, this report began by detailing the ingredients required for fire behaviour prediction and natural ignition, and those specifically used for fire danger indices.

We note that fire danger indices are not the same thing as fire danger ratings. Indeed, the Interim Report of the 2009 Victorian Bushfires Royal Commission presented evidence that indicated the general public and fire agencies found it easier to understand severity in terms of indices, rather than descriptive indicators. The use of indices as a communication tool raises issues, including the complexity of fine-scale variability, the need for a consistent definition, and the sensitivity of the equations above FDI of 50.

The level of danger posed by a fire depends on many factors:  the environmental conditions, (such as weather, fuel and topography) that influence the severity of a fire, human factors, and resources available for suppression (Cruz et al 2015). Where there is no existing fire, fire danger rating must also consider the likelihood of ignition by natural, accidental and deliberate means. However, the focus of this report is narrower, on recommending an approach for fire weather indices, although given the relationship between fuels and weather, and the need to integrate fire weather indices into a broader system, we have necessarily expanded the scope to also consider fuels and other factors that directly affect fire behaviour.

The principal recommendation of this report is that new indices should be defined in terms of physical quantities relevant to the fire hazard. Examples of operationally important characteristics of the fire that could be useable include the fire-line intensity of the head fire, rate of spread, flame height, radiation intensity, and ember density.

This approach has several advantages. It makes it possible to verify the accuracy of the indices, since they have a physical meaning, whereas in the past we could only verify their inputs. Future research which leads to improved means of calculating the index can be incorporated without changing the definition. Calculating the index could use advanced computational methods when the cost is justified (high resolution numerical weather model, fire – atmosphere coupled models, advanced fire behaviour simulators), and statistical methods used when a quick answer is required or the necessary computation is unavailable or too slow. Each would be trying to determine the same physical quantity (e.g. rate of spread), but by different methods.

Once the definitions have been decided, they can be fixed and subsequent work can focus on improving the accuracy with which they are measured and predicted. A key advantage of physically based indices is that their prediction will improve with time as new research is transitioned into operations. Indeed, they provide an additional path to operations for research – as models are upgraded or superseded by better ones, the accuracy (but not the definition) of the available prediction (index) would likewise improve. Indeed, this application will help drive improvements in fire modelling.

Indices defined in terms of physical properties of the fire also open up the possibility of better capturing the effects of variability in the landscape, including addressing the fuel component of the variability. In particular, the recent AFAC and CSIRO reports on recommendations of fuel classification and fire spread models for the many fuel types in the Australian landscape (Hollis et al 2015, Cruz et al 2015) recommend fourteen fuel models for the calculations of forward rate of spread (a physical quantity), enabling a more detailed and more accurate picture of this aspect of fire danger.

Fire weather indices, that provide measures of the inherent fire danger due to meteorological factors alone, and omitting fuel or other data, may also be useful for situational awareness and quick evaluation in the absence of technology. Even fire weather indices that do not incorporate all factors that affect fire behaviour should still be defined in terms of physically meaningful and measureable, and hence verifiable, characteristics of the potential fire.

The fire weather indices would be expected to be substantially less accurate than the full fire danger indices, since that latter use additional data, such as fuel type and condition. This should be explicitly recognised through the use of error bars or other means. Likewise, error bars could also be used to indicate the greater uncertainty expected to result from simpler, rather than more complex, means of calculating the physical parameters that underpin the index.

Fire management is an interesting and challenging problem because of the wide range of disciplines it brings together. Collaboration is required to bring together the expertise of fire ecologists, physical fire behaviour experts, operational fire managers, fuel modellers and mappers, fire modellers, atmospheric modellers, fire meteorologists and soil hydrologists. Operational personnel will need to be trained to interpret specialised advice from advanced systems, as well as to make the best use of probabilistic and uncertainty information. Through organisations such as the Bureau of Meteorology, CSIRO, universities, State fire agencies and Geoscience Australia, and with international collaboration, Australia has a wealth of expertise to direct towards this difficult problem. While the McArthur indices have served us well for 50 years, they are unable to meet the challenges of today, or to make best use of the opportunities provided by technological advances. The challenge is to develop a framework in which to harness the expertise we have and build a fire danger rating system that will serve us for the next half-century and beyond.

# Appendix 1: Fire Danger Index Calculations

## *Drought Factor Calculations*

In 1963, McArthur introduced the concept of Drought Factor that ranged from 0 to 10 with a drought factor of 10 representing the driest conditions. In 1964 McArthur returned from the USA with a version of the Keetch-Byram Drought Index (KBDI, also referred to as the Byram-Keetch Drought Index, or BKDI). In later versions of the Forest Meter, and by Noble et al (1980) there were different approaches to expressing the Drought Factor as functions of the KBDI. See CSIRO (2001) for details. Since 2002 the Bureau has adapted the equation of Griffiths (1999) for operational use. That equation is

$$DF = \min\left(10, 10.5\left(1-\exp\frac{-(I+30)}{40}\right)\times\frac{y+42}{y^2+3y+42}\right)$$

Where y is the function

$\dfrac{(P-3)}{N^{1.3}}$ N ≥ 1 and P > 3

( P = precipitation mm and N is the number of days since the previous rain, *I* is the value of the Keetch-Byram Drought Index.)

$\dfrac{(P-3)}{0.8^{1.3}}$ N = 1 and P > 3 and 0 if P ≤ 3

## Keetch-Byram Drought Index

Keetch and Byram (1968) developed an index to quantify the effect that drought has on fire suppression difficulty and behaviour. The dryness of sub-surface material has a significant effect on fire suppression and less of an influence on fire behaviour. See CSIRO (2001) for the development to that of Crane (1982) of the equation in SI units

$$dQ = \frac{(203.2-Q)(0.968\exp(0.0875T+1.5552)-8.30)d\tau}{1+10.88\exp(-0.001736R)}\times 10^{-3}$$

where dQ is the change in KBDI value from the previous value Q,

T is the maximum temperature in Celsius for the previous period and

R is the mean annual rainfall for that location.

Thus today's value of $Q_n = Q_{n-1} + dQ - r$ where r is the effective rainfall (The Bureau assumes that the first 3mm of rainfall is not effective, other agencies might use different threshold values)

The maximum value the Keetch-Byram Drought index can take is 203.2, corresponding to a totally dry soil layer to 8 inches or 203.2 mm deep The index does not take account of the variations of soil type, topography, latitude, soil moisture conductivity, field capacity of the soil run off or time of year.

### *Mount's Soil Dryness Index*

Mounts soil moisture (SDI) deficit system is a modification to the KBDI. The formula for the value of SDI on a given day is

$$SDI = MAX\,(0, (SDI_{-1} - (R - MIN\,(2, 0.2 \times R) - 0.025R))) + \frac{T}{6 \times 2^{((SDI_{-1} - 25) \times 0.02)}}$$

where $SDI_{-1}$ is the value on the previous day , T is the maximum temperature in degrees Celsius on the day and R is the rainfall in mm since yesterday. Note that between February and May that T should be replaced by T-2

While mathematically there is no theoretical upper limit to the value of SDI, the assumption is made that a value of 200mm corresponds to a completely dry upper soil layer. It would require a prolonged period of low rainfall and persistent high daily maximum temperatures to attain values in excess of 200.

### *Algorithms for McArthur Meters*

By about 1980 the Bureau and other agencies using the circular or linear slide rule McArthur meters found a need for algorithms to enable electronic calculation of fire danger indices. It should be emphasised that all these algorithms are mathematical representations of best fit to the original meters within the domains of the input parameters, and that they are empirical relationships rather than physical models of relationships.

The meters are designed for level or gently undulating ground but fires travel faster upslope with the prevailing wind than on level ground. A 5-degree slope increases the rate of spread by 1/3, a 10-degree slope by a factor of 2, and a 20-degree slope by a factor of 4. In moderate conditions corresponding reductions occur on down slopes, but there have been examples on critical fire events where strong winds interacting with a ridge top fire will result in fast spreading fires down the lee slope.

### *Mk 4 Grass Meter*

The equation derived by Purton (1982) to approximate the GFDI as determined when using the McArthur Mk 4 grassland meter is

$$\log 10\,(GFDI) = 0.009254 - 0.004096 \times (100 - C)^{1.536} + 0.01201 \times T + 0.2789 \times \sqrt{V} - 0.09577 \times \sqrt{RH}$$

C = degree of curing, expressed as a percentage, (100% being fully cured),

T = air temperature, in degrees Celsius,

V = 10 metre, 10 minute mean wind speed, in km/h,

RH = relative humidity, expressed as a percentage..

This can be mathematically rearranged to

$$GFDI = 1.021537 \times 10\left(^{-0.004096 \times (100-C)^{1.536} + 0.01201 \times T + 0.2789 \times \sqrt{V} - 0.09577 \times \sqrt{RH})}\right)$$

Purton noted that these equations gave values 0 to 2 index values higher than those using the original cardboard meter.

A modified algorithm to calculate the grassland fire danger index GFDI was developed (Cheney and Sullivan, 1997) and is commonly referred to as the

### *CSIRO Modified Mk 4 Meter System:*

$$GFDI = Q^{1.027} \times 0.2180567 \exp(^{-0.009432 \times (100-C)\wedge 1.536 + 0.02764 \times T - 0.2205 \times \sqrt{RH} + 0.6422 \times \sqrt{V}})$$

Where Q is the fuel loading in tonnes per hectare,

C = degree of curing, expressed as a percentage, (100% being fully cured),

T = air temperature, in degrees Celsius,

V = 10 metre, 10 minute mean wind speed, in km/h,

RH = relative humidity, expressed as a percentage.

### *MK V Grassland Meter*

Shortly before McArthur retired due to ill health he published the Mk V Grassland Meter, which was notably a rectangular rather than circular slide rule. Noble et al (1980) determined the following algorithms.

Firstly the Fuel Moisture content M in %

$$M = \left[\frac{(97.7 + 4.06 \times H)}{(T + 6.0)}\right] - 0.00854 \times H + 3000.0 / C - 30.0$$

If the moisture content is less than 18.8% then

*GFDI* = 3.35 x W x exp( -0.0897 x M + 0.0403 x V)

Or if the moisture content is between 18.8 and 30%

$$GFDI = 0.299 \times W \times \exp^{(-1.686 + 0.0403 \times V)} \times (30 - M)$$

Where H is the Relative humidity and C the curing percentage and W is the fuel load in tonnes per hectare.

No fire agency has used the Mk 5 Grassland Meter for many years.

## MkV Forest Meter (1973)

The algorithm of Noble et al (1980) has been generally accepted as follows

$$FDI = 2 \times \exp(-0.45 + 0.987\ln(DF) - 0.0345H + 0.0338T + 0.0234U)$$

Alternatively this can be simplified mathematically to

$$FDI = 1.27525630\ \ 3 \times DF^{0.987} \times \exp(-0.0345H + 0.0338T + 0.0234U)$$

Where

DF is the Drought Factor that ranges from 0 to 10 (a dimensionless parameter)

- H is the Relative Humidity (%)
- LN represents the natural logarithm function, that is LN(10) ≈ 2.3026 and exp(1) = e ≈ 2.71827

This meter is designed for use in a well-stocked sclerophyll eucalypt forest 20 m or more in height. Short term drying effects are based on the expected changes in moisture content of surface litter less than 6 mm in diameter assuming a constant drying trend typical of a temperature of 28.2C and relative humidity of 40%. A fuel quantity of 12.5 tonnes per hectare is assumed. Preliminary results from Project Vesta have indicated that the predicted rate of spread of forest fires calculated by the meter significantly underestimate in nearly all conditions. Forests with a developed shrub layer in particular will have a faster rate of spread by up to about a factor of three.

Luke and McArthur (1978) state that the forest meter should not be used in low woodlands or in woodland communities where the ground cover consists of grasses and herbs. In these situations they recommend application of the Grassland meter with some adjustment to account for a lower wind speed relationship.

## Moorland Fire Danger Meter

In Tasmania a moorland fire danger index is also calculated for some areas. Moorland FDI is calculated using a scheme also developed by the Parks and Wildlife Service (Marsden-Smedley et al 1998, 1999).

A Moisture Factor, Mf, is defined as:

Mf = Hf + Rf,

Where Hf, Humidity Factor, is:

Hf = exp(1.660 + 0.0214x(relative humidity) – 0.0292x(dewpoint temperature))

And Rf, Rainfall Factor, is:

Rf = 67.128 x (1- exp(-3.132 x rain )) x exp(-0.0858 x (hours since rain))

Here, Rf is assumed to be:

Rf = Rf_to_9am + Rf_since_9am

For implementation within the fire weather forecast system, the validity time for the forecast is assumed to be 3pm, and (hours since rain) for Rf_to_9am is 6, while (hours since rain) for Rf_since_9am is assumed 0.

This gives:

Rf_to_9am = 40.117 * (1 – exp(-3.132 x (rain 24 hours to 9am)))

Rf_since_9am = 67.128 * (1 – exp(-3.132 x (rain since 9am)))

Wind speed for moorland calculations is the speed 2 metres above ground, assumed to be 2/3 of the standard (forecast) 10 metre wind speed.

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## Glossary

| Abbreviation | Description |
|---|---|
| **Australian Digital Forecast Database (ADFD)**. | The ADFD is a database of official weather forecast elements produced by the Bureau of Meteorology, such as temperature, rainfall and weather types, presented in a gridded format. Elements such as FDI and more complex elements relating FDI values to other elements are also produced and stored in the ADFD. |
| **Fire Weather Season** | The period of time during which weather conditions can climatologically have a reasonable possibility of leading to conditions where Fire Danger Ratings of Very High or above. The dates for the approaching season are established with agencies by mutual agreement. |
| **Controlled Burning**: | The planned use of fire in a pre-determined area to achieve defined land management objectives such as hazard reduction and silviculture. |
| **Curing:** | The change of state of vegetation from a live green condition to a dry condition. Curing is usually expressed as a percentage, with 100% denoting that the vegetation is fully dried. |
| **Drought Factor**: | A measure of the dryness of forest fuels; its calculation is based on the amount of rain needed to fully saturate the soil and the amount of recent rainfall. |
| **Fire Danger**: | A general term encompassing the degree of flammability of fuels, the likely rate of fire spread, and the difficulty of control of fires. Fire danger may be expressed qualitatively as a Fire Danger Rating (FDR); or a numerical rating of the variable fire danger commonly referred to as the Fire Danger Index (FDI). |
| **Fire Danger Indices (FDI).** | An index expressed as a positive integer that uses temperature, wind speed, relative humidity as meteorological inputs. The Grassland Fire Danger Index (GFDI) also uses fuel curing and fuel load information as provided by the agency or potentially from satellite data sets as agreed to on a regional basis. |
| **Fire Danger Ratings**. | The National Fire Danger Rating Scheme is used in determining the appropriate Fire Danger Rating for a specific Fire Danger Index value. These values may be different to District Fire Danger Ratings as determined by the relevant agency. Fire Danger Ratings shown on FWFE and in ADFD grids are based on the corresponding Fire Danger Index values. |
| **Fire Season:** | The period during which wildfires are likely to occur and become dangerous. The incidence of the fire season varies Regionally, depending on climatic conditions and the availability of fuels. In some districts the fire season may be continuous or prolonged in excess of twelve months on some occasions. In some jurisdictions the fire season is determined by legislation, although the dates may be varied in any given year by the state agencies by agreement between the Bureau and the relevant fire authorities. |
| **Fuel State**: | Describes the dryness or degree of curing of fuel. |

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