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Improving operational models of fire behaviour

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Abstract: Operational models of fire behaviour—those systems used by rural fire authorities and land management agencies to predict fire spread and behaviour to aid in planning, suppression, issuing of warnings, etc—for the most part are developed through empirical means. These models generally enjoy a high level of confidence and support from firefighters as they are based on real data gathered from real fires. However, the bounds of an empirical model, by its very nature, is limited by the range of conditions in which the experiments used to construct it were conducted; outside this range its applicability may be questioned. It is often impractical, if not impossible, to conduct controlled experiments under the full range of conditions likely to be required (i.e. wildfire conditions) by operational users. In addition, determining the impacts of climate change upon future fire behaviour is not possible using empirical models determined from current conditions.

As the need for determining fire hazard and risk under future climate becomes more and more important, from determination of greenhouse gas emissions to community and land planning, it will be necessary, therefore, to develop and extend the use of physical and quasi-physical models of fire behaviour in order to construct the next generation of operational models that will provide the robust, accurate and useable predictions of fire spread needed in the future. This will involve developing and extending the understanding of the physical and chemical processes involved in the combustion of bushfire fuels and the interactions of these processes with those of climate, weather, fuel and topography that drive the behaviour of a bushfire and will lead to the safe use and suppression of fires in the landscape, to ensuring safe and resilient communities, and sound fire management to support sustainable ecosystems, particularly under likely changed future climate.

While there is a tendency in science to focus on the most extraordinary or potentially dangerous aspect of a phenomena, understanding the more ordinary aspects are just as, if not more, important, particularly where apparent ‘mundane’ behaviour represents the bulk of the phenomena being studied. In the case of bushfires, empirically-based operational fire spread prediction systems rely upon the notion of ‘quasi-steady’ behaviour to predict the medium to long term (0.5-6 hours) mean behaviour and rate of spread of a bushfire based on mean quantities of fuel and weather conditions. This is done with the full understanding that the actual behaviour and spread rate might be considerably different over the shorter term. Short term variation around a mean value (or a degree of ’unpredictability’) is accepted as the norm, given the large number of variables and their potential value ranges.

However, even when variation in many of the variables is controlled or normalised, the variation in fire behaviour can be quite substantial. This paper discusses the issues of accurately predicting a phenomena that exhibits a significant amount of apparent capriciousness in its behaviour; indeed, predictions within a factor of two are considered good. Observations from large-scale field experiments conducted in grassland fuels and the operational fire spread model developed from these are used to show examples of ‘unusual’ (and hence unpredictable by the model) but not extraordinary behaviour. These behaviours are explored and implications for predicting their occurrence as well as possible reasons for their occurrence are discussed.

Keywords: *bushfire spread modeling, prediction, decision support systems, empirical modeling*

1. INTRODUCTION

All current operational fire spread prediction systems aim to predict the mean rate of forward spread of a fire based on estimates of the mean current or forecast meteorological conditions (i.e. wind speed, temperature and relative humidity) and some mean characteristics of the fuel in which the fire is burning. These operational systems were designed to be implemented using simple, straightforward technology widely available at the time of their development.

The US and Canadian systems (BEHAVE (Andrews, 1986) and the Canadian Fire Behaviour Prediction (CFBP) System (Forestry Canada Fire Danger Group, 1992), respectively) initially took the form of nomograms and tables of fire behaviour. The early Australian systems (the McArthur Grassland and Forest Fire Danger Rating Systems (McArthur, 1966, 1967) were implemented as circular cardboard slide rules. With the advent of cheap computing power in the 1970s and 1980s, these systems were soon adapted to run on computers. Even with access to high-tech solutions, Australian fire authorities in the mid-1990s requested the revised grassfire prediction system (the CSIRO Grassland Fire Spread Meter (GFSM)) (CSIRO, 1997) be made available as a circular slide rule; the new interim Australian national forest fire behaviour model (Gould et al., 2007) appears as tables and nomograms.

While the development of geographical information systems (GIS) in the late 1980s and early 1990s led to the inevitable linking of spatial data with bushfire spread prediction models (e.g. Beer (1990)), these, for the most part, are based on geometrical perimeter expansion approximations (e.g. Anderson et al. (1982)). Simulation models based on physical models of perimeter spread (e.g. Mell et al. (2007)) are generally not compatible with existing operational fire spread models and are yet to be deployed for operational fire spread prediction due to high computational requirements and lack of validation; they are, however, finding use in pre-fire planning, post-fire effects modelling, and general fire dynamics research.

The purpose of this paper is to discuss issues surrounding the operational prediction of fire behaviour, particularly the expectations placed on such systems to predict fire behaviour outside the bounds of the construction of the model or 'unusual' fire behaviour, and possible ways of improving system robustness to conditions and behaviour that while, not necessarily unusual, are generally considered unpredictable.

2. UNUSUAL BUSHFIRE BEHAVIOUR

2.1. Quasi-steady behaviour

The primary aim of operational fire behaviour prediction systems is to provide an estimate of the medium term (i.e. 0.5–6 hours) mean behaviour and rate of forward spread (ROS) of a bushfire based on mean quantities of fuel and weather conditions with the full understanding that the actual behaviour and spread rate might be considerably different over the shorter term. This long term average represents a quasi-steady value for rate of spread (Cheney and Gould, 1997) and allows the developers of empirical fire spread models to incorporate several factors that may act to vary the rate of spread of a fire over the shorter term. These factors include the short term variation in rate of spread that results from the spatial and temporal changes in fuel, topography and wind affecting the fire.

It is because of the high degree of spatial and temporal variation of the primary independent variables that mean values are used in the development of operational fire behaviour prediction systems. Even if the system development itself was based on exactly measured laboratory experiments, the nature of these variables in the field has meant that methodologies for determining the mean field values of those variables for predictive purposes had to be developed (e.g. Albini and Baughman (1979); Rothermel (1983)). For meteorological variables such as wind speed, temperature, relative humidity, standardised meteorological measurement procedures (World Meteorological Organisation, 1988) have become the default standard for operational fire meteorology observations and thus most operational fire behaviour prediction systems are based on such measures.

2.2. Unexpected changes in behaviour

Changes in the quantities of fuel, topography and wind from those used to carry out a fire behaviour prediction will, of course, result in variation from the predicted value. Observations of periods or areas less than that required for a meaningful average value will also result in erroneous predictions. The use of long-term averages (wind, terrain, fuel, ROS) allows the rate of spread over the landscape to be made with some degree of confidence (e.g. over the long-term, fire spread over undulating topography is said to approach that of flat ground (Cheney, 1968)). Detailed measurements of short-term (5 s) wind speed and rate of spread were found to be poorly correlated in both grassfires (Cheney et al., 1993) and northern jack pine/black spruce forest fires (Taylor et al., 2004). The spatial separation of the wind measurement site/s and the fire also introduces possible error (Sullivan and Knight, 2001).

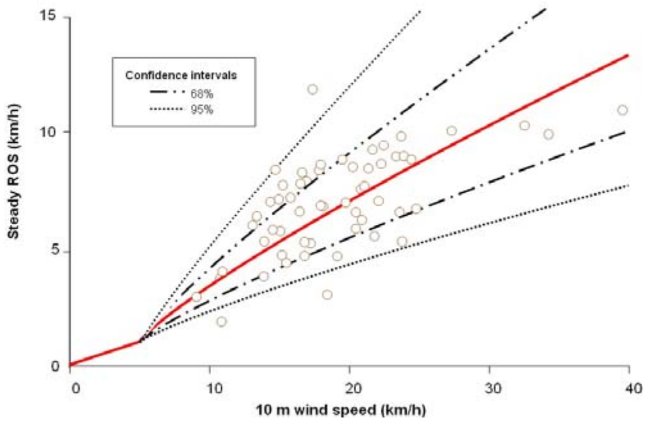

Figure 1. Comparison of the CSIRO grassland fire spread model (red line) for grazed pasture and the data (normalised for FMC and curing and using 10-minute averaged wind speed) on which it was based. (Source: Cheney et al. (1998))

However, even using the highest quality observations of input variables within the range of conditions in which the prediction system was developed will not necessarily result in an accurate prediction of the actual fire behaviour. Detailed measurements of strictly controlled laboratory experiments (e.g. Catchpole et al. (1998)) found considerable variation in fire ROS despite constant wind, fuel and slope conditions. This capricious nature of fire—seemingly chaotic behaviour around some mean value—is widely accepted in both the research and operational bushfire communities as part of the nature of bushfire; predictions within a factor of two are considered good (Albini, 1976). Indeed, both the developers and users of operational fire spread prediction systems do not expect such systems to be perfectly accurate but to provide only a practical prediction upon which planning may be based.

Figure 1 shows the performance of the CSIRO GFSM (CSIRO, 1997) against the data (normalised for fuel moisture content, degree of curing and using 10-minute mean wind speed) used to develop it (Cheney et al., 1998). Even with the effects of fuel moisture content, curing, and fuel condition removed from the data, the variation in ROS is considerable. At one standard deviation (i.e. 68% confidence interval), the range of ROS at a mean wind speed of 20 km h^{-1} is 4 km h^{-1} around a mean speed of 7 km h^{-1}.

As a result, while operational fire spread prediction systems are useful for determining mean rate of spread over long periods (such as required for suppression planning and public warning purposes), they do not provide any insight into the short term behaviour and ROS for firefighters on the ground. Short term behaviour that may lie within a standard deviation or two of the mean behaviour may be allowable in the prediction of spread over an hour or two but means that to all intents and purposes the behaviour is unusual and thus unpredictable by the operational fire spread prediction system. Such short term behaviour can include rapid increases or decreases in rate of spread that may mislead observers and catch firefighters unaware. In the most severe situation, particularly where firefighters are undertaking indirect suppression, unexpected changes in fire behaviour can result in firefighters being overrun by the fire.

Byram (1954) identified the situation where the behaviour of a fire (rate of spread and intensity) increased dramatically with no forewarning and no apparent change in burning conditions. This dramatic increase in fire behaviour has been termed variously ‘blow-up’, ‘boil-up’, ‘eruption’, ‘extreme’ or ‘erratic’, amongst others. Many attempts to address this unusual fire behaviour have focussed on the interaction between the fire and the atmosphere.

Non-dimensional analysis primarily based on the Froude number (e.g. Byram (1954) suggested that the interaction of these forces would identify critical behaviour of bushfires. However, not all extreme fire events could be correlated with particular critical Froude number values (Byram, 1959) and no correlation between Froude number and the behaviour of large experimental grassland fires could be found (Sullivan, 2007b).

3. NON-LINEAR BUSHFIRE BEHAVIOUR

While the focus of unusual fire behaviour has been on ‘blow-up’ behaviour (i.e. dramatic or sudden increases in fire behaviour leading to dangerous conditions), unusual fire behaviour can also include decreases in fire behaviour. ‘Non-linear’ is used here in the sense that the progress of the behaviour of a system from one stage to the next is not sequential, to describe the behaviour of a bushfire which increases or decreases its intensity or speed as a result of some seemingly innocuous, or even unnoticeable, change in conditions.

Figure 2 shows a set of simultaneous experimental fires carried out in the grasslands of the Northern Territory (Cheney et al., 1993). These fires were lit with different ignition lengths: 100 m, 50 m and a point ignition. The 100-m fire spread the fastest with an average speed of 1.25 m s^{-1}. Initially, the 50-m fire spread much faster than the point ignition fire (Fig.2a and b) but after 2.5 minutes of spread (Fig. 2c), the point ignition fire was spreading at the same speed as the 50-m fire. Differences in the initial widths of the fires affected their speed, but also so did the shape of the head-fire (Cheney et al., 1998).

Figure 2. Oblique aerial photos 3 experimental fires lit simultaneously (from left to right: 100-m ignition, 50-m ignition, and point ignition). (a) 40 s since ignition: The 50 m and 100 m fires have spread a similar distance; the point ignition is barely discernible. (b) 100 s since ignition: The 100-m fire is spreading faster than the 50-m fire;.the point ignition fire is now visible. (c) 160 s since ignition: The 100-m fire has reached the end of the block; the 50 m and the point ignition fires are now spreading at roughly the same speed. (Source: Cheney and Gould (1995))

Figure 3 is a series of infra-red line scans that show the progress at irregular times of an experimental fire conducted in dry eucalypt forest of southeast Victoria (Gould et al., 1996). This fire was lit from a 200-m ignition line and allowed to burn unimpeded for some time. Figure 3(a) shows the fire 48 minutes after ignition. The fire has just reached a 30 m bare-earth firebreak not visible along the right hand side of the image. Figure 3(b) shows that 7 minutes later the fire has ceased its forward spread due to the break and has begun to throw spotfires a short distance over the break. Figure 3(c) shows the spot fires across the break beginning to coalesce. In Figure 3(d), 40 minutes after the fire hit the firebreak, the spots have coalesced, reforming the shape of the fire prior to hitting the break, and the fire continues to actively spread, despite the presence of the firebreak and a backburn put in along the windward side of the break (the vertical line running through the head fire). The fire eventually burns out all of the neighbouring plot.

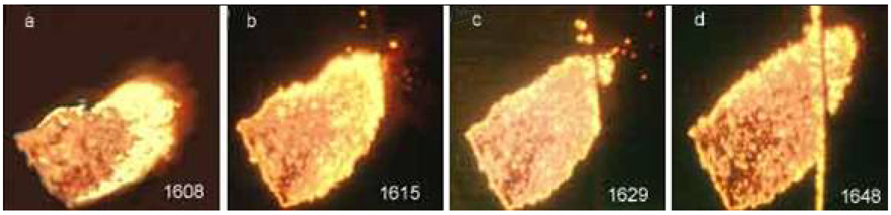

Figure 3. Infra-red line scans of experimental fire in dry eucalypt forest. (a) The fire, lit from a 200-m-long ignition line, has burnt for 48 mins and has just reached a 30-m-wide bare-earth fuel break. (b) The fire's forward spread has been halted and has begun to throw spot fires over the break. (c) 1629 hours: The spot fires have begun to coalesce. (d) The spots have coalesced and reformed the shape of the head fire prior to hitting the break and continues to spread as though unimpeded. (Source: CSIRO Sustainable Ecosystems unpublished data)

While these examples of bushfire behaviour cannot be described as blow-up or erratic, the behaviour is not linear with the prevailing conditions and is indicative of the complex nature of bushfire behaviour. Such non-linearity in behaviour is generally beyond any empirical system of fire behaviour prediction (indeed, such behaviour almost defines the word 'outlier' in statistical analysis and is removed from consideration) and can lead to deaths where such behaviour is not expected. However, while even the most advanced physically-based numerical models still struggle with achieving complete, non-simplified, solvable formulations for all processes involved in the spread of bushfires, it may be possible to provide for such behaviour in operational models if such aspects are considered not only in the construction of the model but also in the execution of the experiments from which it will be built.

4. IMPROVING OPERATIONAL SPREAD PREDICTION

Non-linear behaviours in bushfires have been described in the general literature without actually being defined as such and have been accepted as part of the erratic nature of the phenomenon. These include the examples given above but others may include the shift in dominant fuel strata carrying the fire, establishment of active convection, firebrands and spotting, or even topographic effects. Many of these behaviours may be generalised to be an effect of scaling—as a fire increases in intensity, the processes driving the fire change or interact differently. Inclusion of such effects into an operational prediction system may in some cases be problematic, particularly where input information necessary for the onset of such behaviour is not available, but knowledge of such behaviours may lead to improved experimental design, methods of analysis and models of prediction (or define choice between multi-modal models). The challenge is to include the capacity without making the system too cumbersome for operational use.

The following section briefly highlights some of these non-linearities and discusses how they may be, or in some cases have been, incorporated in an operational model to improve its capability.

4.1. Head fire width and shape

Inclusion of the scaling effects of fire size and shape is important for the prediction of the growth of fire, particularly in the early stages. Figure 4 illustrates the relationship Cheney *et al.* (1998) established for grassfires showing the attainment of the potential maximum rate of spread for a particular wind speed only after the width of the fire has reached some minimum value. However, they recognised that an easily implemented operational system must be suitable predominantly for long term behaviour and so determined that the CSIRO GFSM would only be applicable for fully developed fires. As a result it over-predicts in the early stages or if growth is restricted.

Such an approach, while not suitable for simulating the development of small fires, provides the operational model with robustness necessary for dealing with large, long-going fires. A similar approach was used by the same authors in the development of forest fire model, dictating the minimum size of experimental fires for study to ensure that the fires immediately achieve the potential ROS.

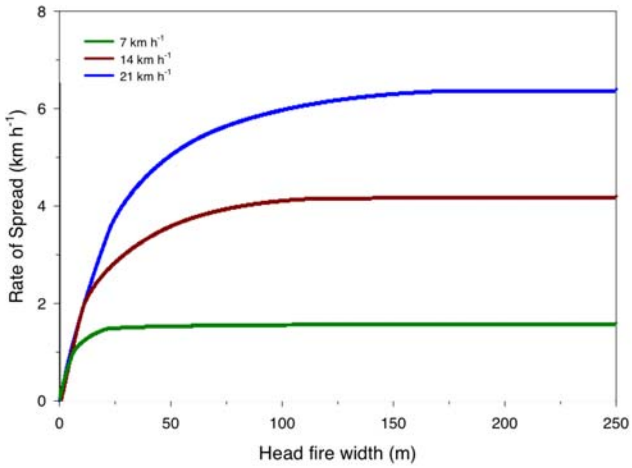

Figure 4. The quasi-steady rate of spread that will be reached for a given wind speed depends on the width of the fire. If the width is constricted, the potential rate of spread will be less than the maximum potential rate of spread. At a wind speed of 7 km h^{-1} a fire must reach a width of 30 m before it reaches its potential rate of spread (1.7 km h^{-1}). At a wind speed of 14 km h^{-1}, the head fire width must exceed 100 m before the fire reaches its potential rate of spread. (Source: Cheney and Sullivan (2008))

4.2. Fuel discontinuities and threshold behaviours

A key non-linear behaviour seen in bushfires is that of a fire overcoming discontinuities in fuel (as seen in Figure 3). Again, this may be generalised to one of scale but may also be considered a threshold behaviour. As a scale behaviour, it is the minimum intensity of fire necessary to bridge a gap in fuel. As a threshold behaviour it is the minimum magnitude of, say, wind speed that dictates the angle of the flame and thus flame breadth (the horizontal length of flame) needed to bridge the gap. In fuel where the discontinuity is a primary characteristic (e.g. spinifex hummocks), threshold wind speeds have been successfully employed (Burrows et al., 1991; Bradstock and Gill, 1993). Similar thresholds have been employed in eaten-out grasslands (Cheney and Sullivan, 2008).

However, where discontinuities are not a general characteristic of the fuel (i.e. it is atypical rather than representative), threshold behaviour may still be applicable but scale behaviour may more properly describe the situation when the fire breaches the fuel gap. Thus, a low intensity fire may be held by a discontinuity which a higher intensity fire will not even see. The simplest operational model will assume correctly that any fire will achieve the minimum intensity necessary to spread continuously, however, as discontinuities of this sort may be of any size (from a 0.25 m wombat track to a kilometre wide river), enabling an operational model to correctly predict the spread across the landscape becomes more problematic. The mechanical processes involved in overcoming fuel discontinuities range from direct flame contact, radiant heat, convective heating, and burning mass transfer (sparks and firebrands responsible for short and long distance spotting). Developing solutions to this problem will entail determining length-scale relationships between the size of the fire, the size of the discontinuity and the distance for successful spotting.

4.3. Fuel strata transitions

Similarly, transitions of the active fuel strata can be considered a scale behaviour with a vertical rather than horizontal orientation. In grass fuels where only one fuel strata is involved this is not an issue. In other fuels, particularly heath and forest fuels, fires will transition from surface to near-surface fuels to elevated and understorey fuels as the scale of the fire increases, involving fuels of different structure and composition with different impacts on fire behaviour. Models of the onset of crown fire spread in conifer forests have been developed (Van Wagner, 1977). Applying these methods to more structurally complex forests such as eucalypts will be a considerable but necessary challenge.

4.4. Perimeter spread models

Developing a better understanding of the spread of sections of the perimeter other than the head is essential for models of fire perimeter spread across the landscape. While this is an aim of physically-based numerical models, an extension to traditional 1D operational models that do not rely on geometric relationships would be simpler to implement operationally. The competitive pathways in the thermal degradation of cellulosic fuels, essentially between volatile and char forming reactions may provide a key step towards the understanding of the difference between heading and backing fires and thus fire behaviour around the perimeter (Sullivan, 2007a).

In the context of a bushfire burning in the open, the formation of volatiles and char occurs simultaneously at each point around the fire perimeter. However, the extent to which one formation process dominates the other is determined by total heat flux received by the fuel which is moderated by the interaction with the environment. At the rear of the fire, where the reaction zone is open to the ambient-temperature wind, the low activation energy, exothermic formation of char occurs preferentially over the high activation energy, endothermic formation of volatiles, resulting in high residual heat from the solid phase combustion of the char and low flames. At the head of the fire, where the reaction zone is essentially blocked from the effect of ambient-temperature wind, fuel temperatures are higher and volatile formation dominates, resulting in fast heat release in the gas phase and high flames.

Much of the apparent capricious and non-linear behaviour of bushfires may stem from the complexity of the interaction of these thermal degradation pathways with environmental conditions. The competitive processes of charcoal formation and volatilisation of cellulosic fuel provides a source of non-linearity in the combustion of biomass fuel and may provide an explanation for much of the observed behaviour of bushfires, including the formation of parabolic head fire shapes, the variation of rate of spread and residence time for fires under the same conditions, and the formation of different types of ash observed after the fire.

5. CONCLUSIONS

While operational fire spread prediction models have traditionally been statistical in structure and one-dimensional in nature, resulting in easy-to-implement and easy-to-use tools, some degree of knowledge of the physical processes involved has often been used to inform their experimental design and construction. The next generation of operational models, however, must be more robust than the preceding generation and this can only occur through the extended application of physical understanding. Whether is happens through the simplification of current physically-based numerical models or development of hybrid physical/empirical models is not important. What is important is that the increased robustness of these models should not come at the cost of the usability the model.

Inclusion of some of the non-linear behaviours described above will broaden the predictive scope of operational models, enabling them to be used in a broader range of conditions and situations (including those of future changed climate), but will necessarily increase the requirement for input data in order to make a prediction. The challenge for model developers is to incorporate such needs without unnecessarily complicating the implementation of the model.

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REFERENCES

Albini, F. A. (1976). Estimating wildfire behavior and effects. General Technical Report INT-30, USDA Forest Service, Intermountain Forest and Range Experiment Station, Odgen UT.

Albini, F.A. and Baughman, R.G. (1979). Estimating windspeeds for predicting wildland fire behaviour. Research Paper INT-221, USDA Forest Service, Intermountain Forest and Range Experimental Station, Odgen UT.

Anderson, D.H., Catchpole, E.A., de Mestre, N.J., and Parkes, T. (1982). Modelling the spread of grass fires. *J. Aust. Math. Soc. B*, **23**, 451–466.

Andrews, P. (1986). BEHAVE: fire behaviour prediction and fuel modelling system - BURN subsystem, part 1. General Technical Report INT-194, USDA Forest Service, Intermountain Forest and Range Experiment Station, Ogden, UT, Intermountain Forest & Range Experiment Station, Ogden, UT.

Beer, T. (1990). The Australian National Bushfire Model Project. *Math. Comput. Model*, **13**, 49–56.

Bradstock, R. and Gill, A. (1993). Fire in semiarid, mallee shrublands - size of flames from discrete fuel arrays and their role in the spread of fire. *Int. J. Wildland Fire*, **3**, 3–12.

Burrows, N., Ward, B., and Robinson, A. (1991). Fire behaviour in spinifex fuels on the Gibson Desert Nature Reserve, Western Australia. *J. Arid Environ.*, **20**, 189–204.

Byram, G. M. (1954). Atmospheric conditions related to blowup fires. Station Paper No. 35, USDA Forest Service, Southeastern Forest Experiment Station, Asheville NC.

Byram, G. M. (1959). Forest fire behaviour. In Davis, K., editor, *Forest Fire Control and Use*, chapter 4, pages 90–123. McGraw-Hill, New York.

Catchpole, W.R., Catchpole, E.A., Butler, B.W., Rothermel, R.C., Morris, G.A., and Latham, D.J. (1998). Rate of spread of free-burning fires in woody fuels in a wind tunnel. *Combust. Sci. Technol*, **131**, 1–37.

Cheney, N. P. (1968). Predicting fire behaviour with fire danger tables. *Australian Forestry*, **32**, 71–79.

Cheney, N.P. and Gould, J.S. (1995). Fire growth in grassland fuels. *Int. J. Wildland Fire*, **5,** 237–247.

Cheney, N.P. and Gould, J.S. (1997). Fire growth and acceleration. *Int. J. Wildland Fire*, **7**, 1–5.

Cheney, N.P., Gould, J.S., and Catchpole, W.R. (1993). The influence of fuel, weather and fire shape variables on fire-spread in grasslands. *Int. J. Wildland Fire*, **3**, 31–44.

Cheney, N.P., Gould, J.S., and Catchpole, W.R. (1998). Prediction of fire spread in grasslands. *Int. J. Wildland Fire*, **8,** 1–13.

Cheney, P. and Sullivan, A. (2008). *Grassfires: Fuel, Weather and Fire Behaviour 2nd edition*. CSIRO Publishing, Collingwood, Australia, 150 pp.

CSIRO (1997). CSIRO Grassland Fire Spread Meter. Cardboard meter, Styrox Pty Ltd.

Forestry Canada Fire Danger Group (1992). Development and structure of the Canadian Forest Fire Behavior Prediction System. Information Report ST-X-3, Forestry Canada Science and Sustainable Development Directorate, Ottawa, ON.

Gould, J.S., Cheney, N.P., Hutchings, P.T., and Cheney, S. (1996). Prediction of bushfire spread. Final Report for IDNDR Project: 4/95, CSIRO Forestry and Forest Products, Canberra.

Gould, J.S., McCaw, W.L., Cheney, N.P., Ellis, P.F., Knight, I.K., and Sullivan, A.L. (2007). Project Vesta–Fire in Dry Eucalypt Forest: fuel structure, dynamics and fire behaviour. Ensis-CSIRO, Canberra ACT, and Department of Environment and Conservation, Perth WA.

McArthur, A.G. (1966). Weather and grassland fire behaviour. Forestry and Timber Bureau Leaflet 100, Commonwealth Department of National Development, Canberra.

McArthur, A.G. (1967). Fire behaviour in eucalypt forests. Forestry and Timber Bureau Leaflet 107, Commonwealth Department of National Development, Canberra.

Mell, W., Jenkins, M.A., Gould, J., and Cheney, P. (2007). A physics based approach to modeling grassland fires. *Int. J. Wildland Fire*, **16**, 1–22.

Rothermel, R. C. (1983). How to predict the spread and intensity of forest and range fires. General Technical Report INT-143, USDA Forest Service, Intermountain Forest and Range Experimental Station, Odgen UT.

Sullivan, A.L. (2007a). Competitive Thermokinetics and Non-linear Bushfire Behaviour. PhD thesis, ANU Research School of Physical Sciences and Engineering, Dept. of Theoretical Physics, Canberra, ACT.

Sullivan, A.L. (2007b). Convective Froude number and Byram's energy criterion of Australian experimental grassland fires. *P. Combust. Inst.*, **31,** 2557–2564.

Sullivan, A.L. and Knight, I.K. (2001). Estimating error in wind speed measurements for experimental fires. *Can. J. Forest Res.*, **31**, 401–409.

Taylor, S.W., Wotton, B.M., Alexander, M.E., and Dalrymple, G.N. (2004). Variation in wind and crown fire behaviour in a northern jack pine - black spruce forest. *Can. J. Forest Res.*, **34**, 1561–1576.

Van Wagner, C.E. (1977). Conditions for the start and spread of crown fire. *Can. J. Forest Res.*, **7**, 23–24.

World Meteorological Organisation (1988). World Meterological Organisation Technical Regulations Vol 1: General meterological standards and recommended practices. Number 49. Secretariat of the World Meterological Organisation, Geneva, Switzerland.