A guide to rate of

FIRE SPREAD MODELS

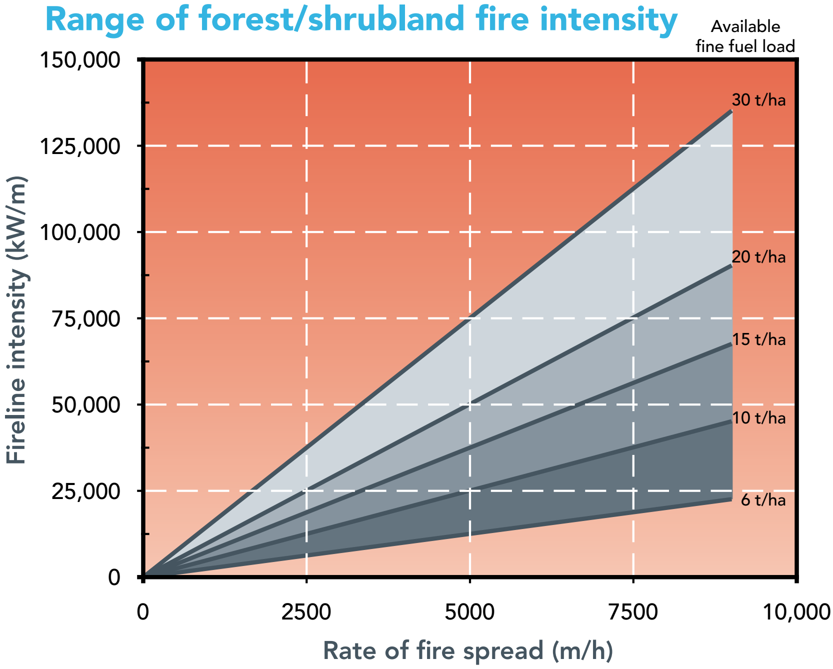
for Australian vegetation

REVISED EDITION

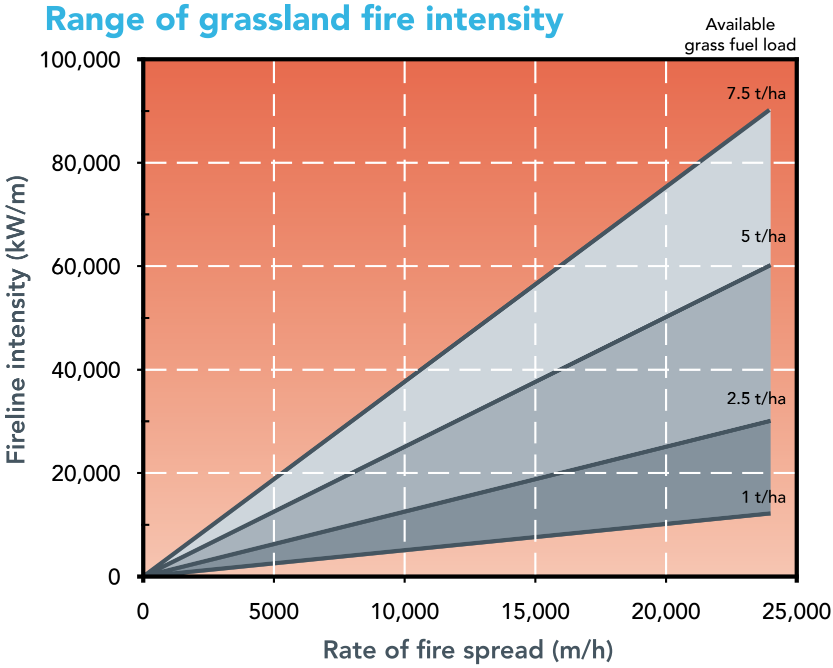
Rate of fire spread unit equivalencies

m/min	m/h
1	60
2	120
3	180
4	240
5	300
10	600
15	900
20	1200
30	1800
40	2400
50	3000
60	3600
70	4200
80	4800
90	5400
100	6000
125	7500
150	9000
175	10,500
200	12,000
250	15,000
300	18,000
350	21,000
400	24,000

Range of forest/shrubland fire intensity



Range of grassland fire intensity



Relative effect of slope steepness on rate of fire spread

	Downslope											Upslope									
Slope angle (°)	-20	-18	-16	-14	-12	-10	-8	-6	-4	-2	0	2	4	6	8	10	12	14	16	18	20
Slope (%)	-36	-32	-29	-25	-21	-18	-14	-11	-7	-3	0	3	7	11	14	18	21	25	29	32	36
Relative effect	0.6	0.6	0.6	0.6	0.6	0.7	0.7	0.7	0.8	0.9	1.0	1.1	1.3	1.5	1.7	2.0	2.3	2.6	3.0	3.5	4.0

A guide to rate of FIRE SPREAD MODELS for Australian vegetation

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Foreword

Predicting the path and speed of a bushfire is critical to public safety. Successful fire suppression strategies, reliable community warnings and effective evacuation planning all hinge on the precision and timeliness of predictions.

There are many rate of fire spread models available in Australia for this task. Developed through about 60 years of scientific research, these models have redefined contemporary approaches to fire and incident management. But they are not black boxes. Different models work in different conditions, and knowing which one to apply is not always straightforward. A range of factors, such as weather, fuel and topographic information, as well as the experience and capability of end users, contribute to the quality and adequacy of predictions.

This publication consolidates, for the first time, all published Australian available models into one resource guide, together with a comprehensive analysis of their potential applications, benefits and limitations. It evaluates applications in different vegetation types and burning conditions, and provides detailed performance appraisals.

This work is the culmination of knowledge from three distinct eras of bushfire rate of spread modelling research: the initial fire research breakthroughs, led by Australia's first fire researcher Alan G. McArthur (1950s to late 1970s); an interim consolidation and refinement period, marked by some preliminary industry-research partnerships (1970s-2002); and the recent past era, characterised by comprehensive research and industry collaboration (2003-2014).

The Bushfire CRC and CSIRO researchers have been at the forefront of this recent applied research period, and this publication is an important research utilisation deliverable from their joint efforts.

A Guide to Rate of Fire Spread Models for Australian Vegetation is not prescriptive, nor a blueprint. It is a practical reference guide to help users select models and formulate predictions for the best outcomes in different bushfire conditions. The publication does not cover prediction systems that integrate spread models into a simulator platform. It also does not include emerging advances in this field, which factor the atmospheric drivers of extreme fire behaviour into modelling. These developments have taken us to a new 3D generation of fire behaviour modelling, and we look forward to using the outcomes of this next exciting era of science in future.

In the meantime, fire behaviour analysts and practitioners – from those starting out to multi-decade veterans – will be able to refer to this invaluable resource for many years to come.

We congratulate the authors for this thorough and comprehensive publication.

Gary Morgan
Chief Executive Officer
Former Bushfire Cooperative Research Centre
2007 to 2014

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We would like recognise the inspirational work of former fire behaviour researchers, in particular A.G. McArthur, G.B. Peet, R.J. Sneeuwjagt, N.P. Cheney, N.D. Burrows, T.E. Just and D.R. Douglas. Without their efforts, we would likely not have attained the fire behaviour prediction capacity we have in Australia today. We also recognise the cast of unnamed hundreds who participated in the collection of experimental fire data over the past six decades that made it all possible. The statistical prowess of W.R. Anderson (formerly Catchpole) in much of the fire behaviour modelling work is also acknowledged.

We thank Al Beaver for the original idea of collating our knowledge on bushfire spread models. We would also like to acknowledge Phil Polglase and Peter Stone of the CSIRO Land and Water for supporting this work, Gary Morgan and Lyndsey Wright from the Bushfire Cooperative Research Centre, and Noreen Krusel and Brenda Leahy from the Australasian Fire and Emergency Service Authorities Council for enabling this work to be completed in a timely manner. We thank Roger Underwood and Neil Burrows for the summary on George Peet's career. Thanks to Kelsey Gibos and Matt Plucinski for critical reviews of earlier versions of this book. And thanks to Fullpoint Media's Brian Diamond and Kathryn Steel for design and production of this book.

We also gratefully acknowledge the following individuals for permission to reproduce their photographs in the present work: Neil Burrows, Department of Parks and Wildlife, WA; Owen Donovan, Department of Parks and Wildlife, WA; Chris Hadfield, NASA, USA; Jen Hollis; Susan Kidnie, Country Fire Authority, Vic; Vijay Koul, CSIRO, ACT; Peter Leeson, Queensland Parks and Wildlife Services, Qld; Jon Marsden-Smedley, University of Tasmania, Tas; Greg Mattingley, Parks Victoria, Vic; Greg McCarthy, Department of Environment and Primary Industries, Vic; Wayne Rigg, Country Fire Authority, Vic; Alan Sewell, Country Fire Authority, Vic; David Vaskess, Department of Environment and Primary Industries, Vic; Peter Venz, HQ Plantations, Qld; Tim Wells, Country Fire Authority, Vic; and Kiwi White.

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Summary

The knowledge of a free-burning fire's potential rate of spread is critical to safe and effective bushfire control and use in Australia. A number of models for predicting the rate of fire spread in various Australian vegetation types have been developed over the past 60 years or so since Alan G. McArthur began his pioneering research into bushfire behaviour.

Most of the major vegetation types in Australia have had more than one rate of fire spread model developed for operational use. A better understanding of these rate of fire spread models and their utility appears warranted in light of recent developments in both bushfire research and management in Australia. This publication presents, reviews and discusses these models and their applicability for operational use in prescribed burning and wildfire suppression in grasslands, shrublands, both dry and wet eucalypt forests, and in pine plantation fuel types.

Background information and in turn a description of each rate of fire spread model is given, including the data used in the model development that constitute their application bounds. The mathematical equations that form each model are presented along with a discussion of model form and behaviour, the main input variables and their influence, and performance evaluation studies undertaken to date. Accompanying graphs, tables and photos are used throughout to illustrate key concepts.

This publication identifies those models that constitute the current state of our knowledge with respect to bushfire behaviour science in Australia. Recommendations are accordingly made on which models should underpin best practices for operational and scientific predictions of rate of fire spread in the near term and those that should now be discounted and the reasons.

Rates of spread vary in a bewildering way. It would be easy to yield to the temptation to throw up our hands and say that it is useless to try for anything but good guesses at the rate a given fire will spread under given conditions of fuel, weather, and topography. The saner attitude is to keep digging away at the effect of this or that factor on rate of spread in the belief that in time the intricate puzzle will be solved by the creation of something that can rightfully be called the science of rate of spread.

– Jemison (1939)

Table of contents

1. The practice of predicting bushfire behaviour*

At its most basic level, given a fire ignition and a specified set of fuel, weather, and topographic conditions, the ultimate goal of bushfire research is to provide relatively simple yet timely answers to the following commonly asked questions about fire behaviour (after Luke and McArthur 1978):

- What will be the fire's forward rate of spread?
- In timed increments, what will be the fire's area, perimeter length, and forward spread distance?
- Will the fire be labelled a high-intensity or low-intensity fire?
- Will the fire be primarily a crown or surface fire?
- How difficult will the fire be to control and extinguish?
- Is the fire burning in such a manner that mechanical equipment and/or air tankers will be required, or can it be handled safely by ground suppression crews?
- Will the fire require more time and effort than normal to mop-up?
- Is there a possibility of the fire "blowing up"? If the fire does blow up, will it produce a towering convection column or have a wind-driven smoke plume?
- What will be the spotting potential – short- or long-range – of the fire?
- Are environmental conditions conducive for the fire to produce fire whirlwinds and/or other types of wildland fire vortexes? If so, when and where might they occur?

The focus of this book are the fire rate of spread models that are available to the fire behaviour analyst (FBAN) or specialist attempting to answer these questions as part of prescribed burning or bushfire suppression operations. While the effects of fire on the environment are dependent in part on fire behaviour (Burrows 1995), the assessment of these impacts is beyond the scope of this work.

Fire behaviour researchers work to codify the relationships between fire behaviour variables and environmental conditions, and out of their effort they produce the tools that enable wildland fire practitioners to answer these questions. This supporting work constitutes the "science" of predicting fire behaviour. In turn, the "art" of fire behaviour prediction represents the artful application of the science (Fig. 1.1), coupled with the meaningful interpretation and communication of the fire behaviour information to different audiences in both written and oral forms (Weick 2002).

While the assessment of fire behaviour potential should be the responsibility of everyone involved in bushfire operations, on larger or more complex fires this responsibility is given to the FBAN or wildland fire behaviour specialist. The U.S. Forest Service was instrumental in

* Refer to Part Four – The Science and Art of Wildland Fire Behaviour Prediction in Scott *et al.* (2014, p. 295-403) for further information and additional readings on the subject.

Alan McArthur

Alan G. McArthur (1923-1978) began his career in forestry and fire control with the Forestry Commission of New South Wales in 1941. In November 1953, he accepted a position with the Commonwealth's Forestry and Timber Bureau as Australia's first professional officer engaged full-time in bushfire research. The next 15 or so years were devoted mainly to research into fire behaviour in a wide range of fuel types, the development of fire danger rating systems for eucalypt forests and grasslands, and the development of prescribed burning guides for eucalypt and conifer forests. In doing so, he became one of the pioneering leaders worldwide in the science of wildland fire behaviour and undertook a number of consultancies outside of Australia for the Food and Agriculture Organisation of the United Nations and other organisations. In 1970, Alan became the Director of the Bureau's Forest Research Institute, an office he performed with ability while still maintaining an active role in fire research. When the research functions of the Bureau were taken over by the newly formed CSIRO Division of Forest Research in July 1975, he continued as a Principal Research Officer until his retirement due to ill health three years later. Alan along with co-author R. Harry Luke published their seminal book on Bushfires in Australia in 1978.*

* Adapted from Australian Forestry (Vol. 41, pp. 189-190, 1978 and Volume 42, pp. 57-62, 1979).

establishing the FBAN position beginning in the late 1950s and early 1960s (Chandler and Countryman 1959; Countryman and Chandler 1963). Australia did not formally recognise the FBAN position in the incident command system or the need for a formal FBAN training course until the mid-2000s, although beginning in the late 1980s selected fire operations staff did work together with fire weather meteorologists from the Bureau of Meteorology on particular incidents.

Barrows (1951) was the first to articulate the basic concepts of fire behaviour prediction as we know them today. As illustrated in Figure 1.2 the process of judging fire behaviour requires the systematic analysis of many factors, involving this five-step process:

- Step 1: Basic knowledge. The foundation for judging probable fire behaviour must rest on basic knowledge of the principles of combustion: What is necessary for combustion to occur? What causes the rate of combustion to increase or decrease? How may combustion be reduced or stopped?
- Step 2: Forest knowledge. Three basic factors in a forest area – weather, topography and fuels – are important indicators of fire behaviour.
- Step 3: Aids and guides. Several aids and guides are available to assist in evaluating the effects of weather, topography, and fuels on fire behaviour.
- Step 4: Estimate of situation. The probabilities for various patterns of fire behaviour are systematically explored through an estimate of the situation based upon the combined effects of weather, fuels, and topography.

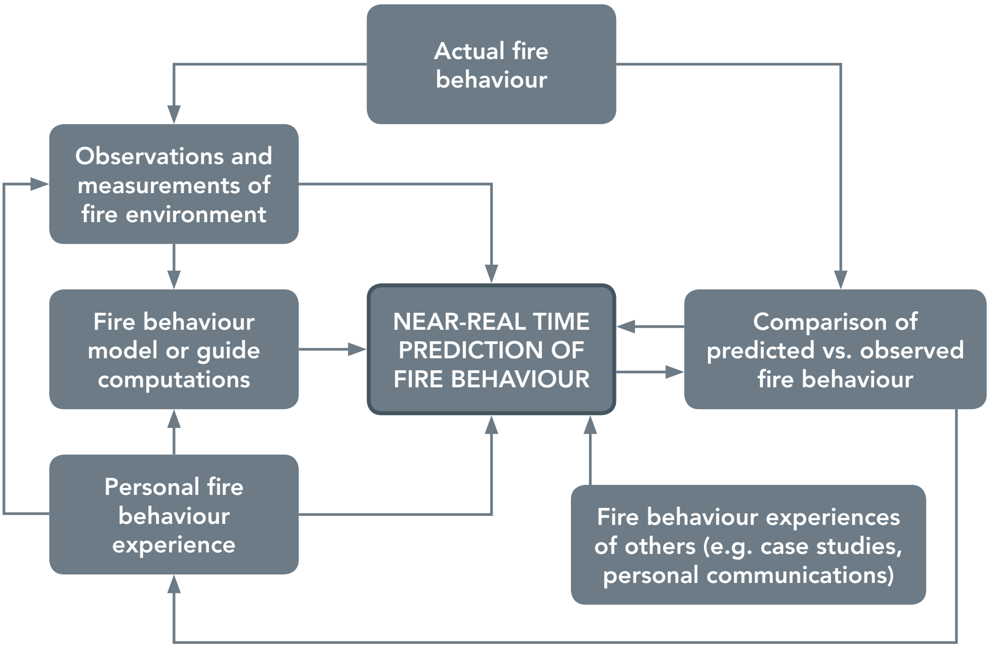


Figure 1.1. The prediction of bushfire behaviour involves the "art and science" of coupling practical knowledge, professional judgment and fire behaviour experiences with the computational tools produced by fire research (from Alexander and Cruz 2013a).

- Step 5: Decision. The end product of the fire behaviour analysis is a decision outlining when, where, and how to control the fire and spelling out any special safety measures required.

These guidelines are applicable to both the control and use of planned or unplanned ignitions in bushfire management. They are also valid in the designing of simulation studies involving the prediction of free-spreading fire behaviour.

Bushfire behaviour predictions involve three sets of assumptions that in turn become the primary limitations in accurately predicting a fire's behaviour. The first set of assumptions include the general simplifying assumptions associated with any of the models or guides used for operationally predicting fire behaviour:

- The model or guide is applicable to the fuel conditions.
- The fuels are uniform and continuous for the period of application of the model.
- The fuel moisture values used are representative of the fire site.
- The topography is simple and homogeneous.
- Wind speed is constant and unidirectional for the period of application of the model.
- The fire is free-burning and unaffected by fire suppression activities.

The second set of assumptions are those that underlie the specific model or guide in question. Ideally, this set of assumptions should include as a minimum the technical basis for the model

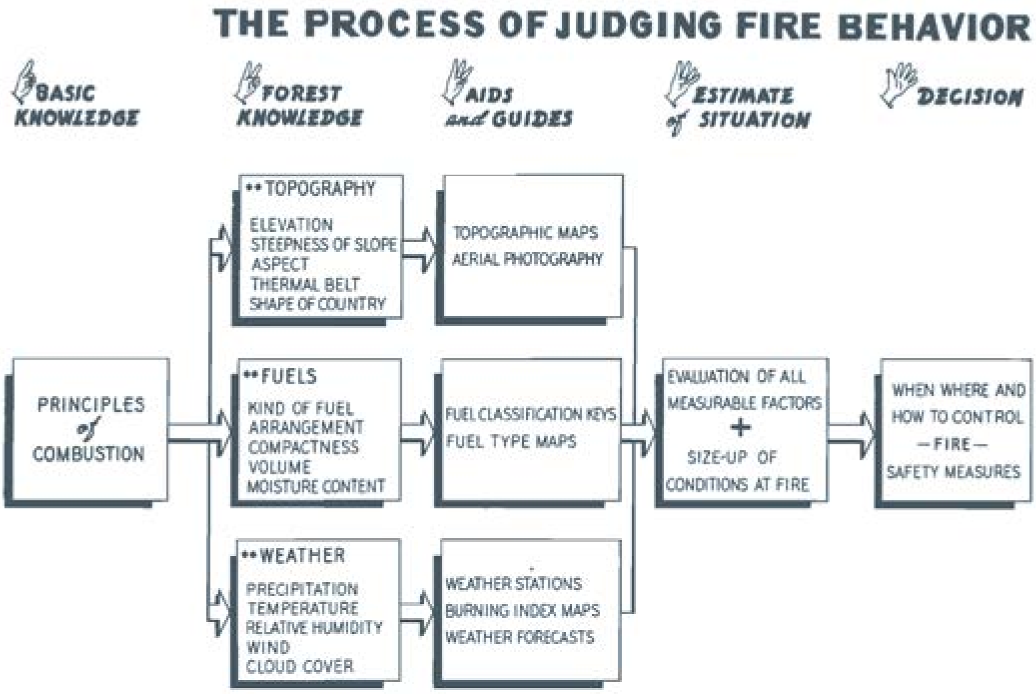


Figure 1.2. Predicting or forecasting fire behaviour requires the systematic analysis of many factors (from Barrows 1951).

or guide development (e.g. experimental fires and/or wildfire observations) and the range in environmental conditions and fire behaviour upon which they are considered valid for. In pointing out the limitation of models for predicting fire behaviour, Brown and Davis (1973) note that:

> *"All fire models simulate reality but fall short of it in varying degrees. In meeting the objective of simplifying relationships, minor factors are neglected and the model is usually based on a single set of idealized conditions. If fire-modelling laws are observed, this will permit approximations close enough for many purposes, but it is easy to forget that they are approximations only. Consequently, there is a strong tendency to apply models beyond their field of usefulness. To avoid this, the assumptions on which they are based and the range of conditions under which the model is valid need to be carefully defined and frequently rechecked."*

The third and final set of assumptions are those specified by the FBAN assigned to produce a forecast of fire behaviour for an actual wildfire incident. This would typically involve such items as (*i*) the date/time of fire perimeter assessment, known or assumed, used to project from, (*ii*) the date and time interval that the fire behaviour forecast is deemed valid for, (*iii*) the weather and topographic conditions applied to the situation at hand and their basis (e.g. from the fire weather forecast, local knowledge), and (*iv*) the model or guide used and why (including the fuel type or model selected) and any adjustment made to the outputs and the rationale for doing so.

Models and modelling are an integral component of modern day fire management practices (Alexander 2009a). Models and guides used for predicting fire behaviour should obviously be sensitive to those parameters known to affect fire behaviour, namely variations in live and dead fuel moistures, wind speed, and slope steepness, amongst other factors, for a given fuel complex. All fire behaviour prediction tools will produce results that do not always agree exactly with observed fire behaviour. As Cheney (1981) points out:

> *"The reality of fire behaviour predictions is that overestimates can be easily readjusted without serious consequences; underestimates of behaviour can be disastrous both to the operations of the fire controller and the credibility of the person making the predictions."*

It is important that all fire practitioners realise that operational models and guides for predicting fire behaviour are mechanical in nature and in all likelihood will not produce an exact answer. Cruz and Alexander (2013) have shown that rate of fire spread predictions frequently vary from observations by at least 30% even when inputs are carefully measured. As Albini (1976) pointed out, there are three principal reasons for disagreement between model predictions and observed fire behaviour, no matter which models are being used (see Alexander and Cruz 2013a for further discussion):

1. The model may not be applicable to the situation.
2. The model's inherent accuracy may be at fault.
3. The input data used in the model may be inaccurate.

With respect to the last category, error can unknowingly be introduced into a prediction as a result, for example, of a lack of adherence to standards for fire weather stations or unrealistic fuel type mapping.

Error statistics

Throughout this book, we use three standard statistical metrics to compare and contrast the performance of each rate of fire spread model. These are explained in the table below.

Statistic	Explanation
MAE	The mean absolute error (MAE) is expressed in the same units as the original data and is a quantity used to measure how close predictions are to the observed value. As the name suggests, the MAE is an average of the absolute error.
MAPE	The mean absolute percent error (MAPE) is a very popular measure of the accuracy of a predictive model or system. It represents the summed differences between the individual predicted versus observed values divided by the observed value; multiplying it by 100 makes it a percentage error. If a perfect fit is obtained then the MAPE is zero. A MAPE of 10% is considered a very good result. A MAPE in the range of 20% to 30% or even higher is quite common.
MBE	The mean bias error (MBE) describes the dispersion or spread of the residual distribution about the estimate of the mean. A positive value indicates an over-prediction trend while a negative is an indication of an under-prediction trend.

On actual wildfire incidents, fire behaviour prediction accuracy is highly dependent upon the skill, knowledge, and experience of the practitioner. To be truly good at predicting fire behaviour, as mentioned earlier, requires applying both the art and science to the task.

Burrows (1984b) observed that most fire operations personnel base their expectations of how a fire will behave largely on experience and, to a lesser extent, on fire behaviour guides. Fire behaviour case study knowledge, coupled with experienced judgment and calculations made using fire behaviour models or guides, is generally considered as the most effective means of predicting fire behaviour. Experienced judgement is certainly needed in any prediction of fire behaviour, but it does have its limitations. In this respect, it is worth reiterating the comments of American forest fire research pioneer Harry T. Gisborne (1948) regarding the subject of experienced judgment:

> *"For what is experienced judgment except opinion based on knowledge acquired by experience? If you have fought forest fires in every different fuel type, under all possible kinds of weather, and if you have remembered exactly what happened in each of these combinations, your experienced judgment is probably very good. But if you have not fought all sizes of fires in all kinds of fuel types under all kinds of weather then your experience does not include knowledge of all the conditions."*

Wildfire case study development should be viewed as a way for bushfire behaviour specialists to formalise their experienced judgment and learn from their successes and failures. The process does have its problems at times (Alexander 2009b).

Predicting bushfire behaviour invariably involves a number of uncertainties. Most people under stress use intuition and other heuristics to deal with uncertainty (Tversky and Kahneman 1974). In addition to evaluating the outcome of a fire behaviour prediction or forecast, it is wise to consider the process itself. Russo and Schoemaker (1989) have, for example, examined the common pitfalls or "decision traps" made by decision-makers that are equally valid for FBANs and others making fire behaviour predictions (Table 1.1).

Can the various characteristics of bushfire behaviour ever really be predicted? That depends on how accurate you expect the prediction to be. Certainly the minute-by-minute movement of a fire will probably never be predictable – especially if that prediction is based on weather conditions forecasted many hours before a fire is expected to make a run. Nevertheless, practice and experienced judgment in assessing a fire and its environment, coupled with a systematic method of calculating bushfire behaviour can yield surprisingly good results. However, judging the quality of fire behaviour predictions solely on the outcome can be hazardous. Just by chance alone, good predictions can have bad outcomes and bad predictions can result in good outcomes (Fig. 1.3). Furthermore, fire suppression actions may mean that a "correct" prediction for a free-burning fire may differ from the actual fire spread rate.

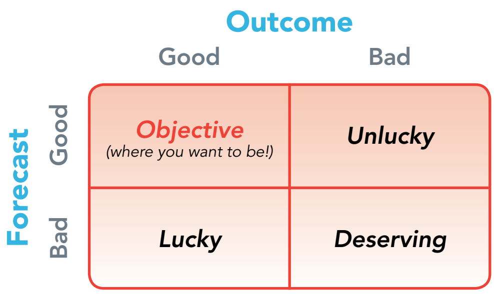


Figure 1.3. The 2-by-2 fire behaviour forecast or prediction matrix illustrates that even good forecasts can sometimes have unlucky outcomes (from Alexander and Thomas 2004). The objective of fire behaviour prediction or forecasting is to produce a good forecast and in turn a good outcome (i.e. prediction or forecast closely matches what actually happened).

Table 1.1. The 10 most dangerous decision traps (from Russo and Schoemaker 1989).

	Decision traps
1	**Plunging in** – Beginning to gather information and reach conclusions without first taking a few minutes to think about the crux of the issue you're facing or to think through how you believe decisions like this one should be made.
2	**Frame blindness** – Setting out to solve the wrong problem because you have created a mental framework for your decision, with little thought, that causes you to overlook the best options or lose sight of important objectives.
3	**Lack of frame control** – Failing to consciously define the problem in more ways than one or being unduly influenced by the frames of others.
4	**Overconfidence in your judgement** – Failing to collect key factual information because you are too sure of your assumptions and opinions.
5	**Short-sighted shortcuts** – Relying inappropriately on "rules of thumb", such as implicitly trusting the most readily available information or anchoring too much on convenient facts.
6	**Shooting from the hip** – Believing you can keep straight in your head all the information you've discovered, and therefore "winging it" rather than following a systematic procedure when making the final choice.
7	**Group failure** – Assuming that with many smart people involved good choices will follow automatically, and therefore failing to manage the group decision-making process.
8	**Fooling yourself about feedback** – Failing to interpret the evidence from past outcomes for what it really says, either because you are protecting your ego or because you are tricked by hindsight.
9	**Not keeping track** – Assuming that experience will make its lessons available automatically, and therefore failing to keep systematic records to track the results of your decisions and failing to analyse these results in ways that reveal their key lessons.
10	**Failure to audit your decision process** – Failing to create an organised approach to understanding your own decision-making, so you remain constantly exposed to all the above mistakes.

2. Historical overview of fire behaviour modelling in Australia

Foley (1947) gave a comprehensive account of the semi-quantitative methods of assessing bushfire potential used in Australia up to the mid to late 1940s. Models of fire behaviour are now widely used operationally to assess current wildfire situations, to assess future scenarios and especially to evaluate alternative bushfire management strategies. The outputs of these models – e.g. rate of fire spread, flame height and fireline intensity (Byram 1959) – are important for both fire and land management and research applications in areas such as suppression strategy planning, public and fire-fighter safety, short- and long-term

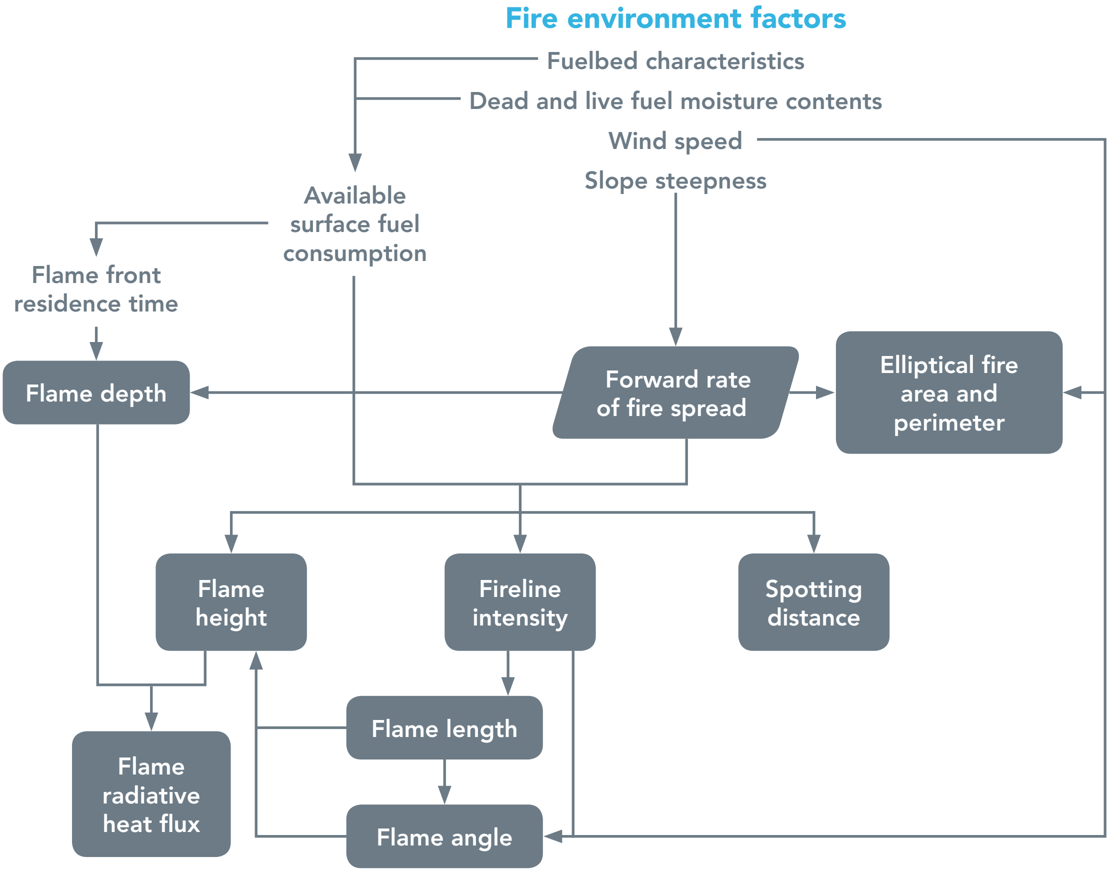


Figure 2.1. Flow chart illustrating the linkages that forward rate of fire spread has to the flame front dimensions and other fire behaviour characteristics (adapted from Cruz and Alexander 2013).

Figure 2.2. Initial stages of the development of a point-source ignition experimental fire in a dry sclerophyll eucalypt forest in the late 1960s, Kowen State Forest, ACT. Fire ignited and monitored by crew from the Forestry and Timber Bureau of the Commonwealth of Australia (photo: CSIRO).

fire ecology issues/fire impacts, smoke emissions, and protection of the wildland-urban interface from unwanted fires. In particular, the knowledge of a free-burning fire's rate of spread is often central to the estimation of other fire behaviour characteristics (Fig. 2.1). As Underwood (1985) notes: "The management or control of forest fires in Australia will never become a reality until the behaviour of fires can be predicted accurately over the many conditions under which they occur."

The development of fire behaviour models has taken on two broad approaches: (*i*) physical or quasi-physical models based on the fundamental processes driving fire propagation, and (*ii*) empirical or quasi-empirical models based on statistical analysis of fire observations. The former have generally taken the form of complex numerical codes and require considerable computing resources. The latter have generally been simple analytical functions relating key dependent variables such as forward rate of fire spread with key independent variables such as wind speed, fuel moisture and slope steepness for a given fuel type.

Both modelling approaches have distinct advantages and disadvantages for various purposes, but due to their relative computational simplicity and ease of use, only the empirical and quasi-empirical approaches have produced working models suitable for operational use (Sullivan 2009b).

Since the pioneering outdoor experimental burning work of Alan G. McArthur and George B. Peet beginning, respectively, in the early 1950s and early 1960s (Fig. 2.2 and 2.3.)*, a considerable number of similar field-based studies carried out in Australia have extended and refined our understanding of fire behaviour in a variety of fuel types. Models have been developed over time with the aim of: (*i*) describing fire behaviour in a fuel type where such knowledge did not previously exist or (*ii*) improving or replacing a model that had been found to not perform adequately under certain conditions.

Unlike the approach taken in the US for fire behaviour model development (Andrews 2007), and similar to that taken in Canada (Stocks *et al*. 2004), Australian fire behaviour models are fuel type specific. That is, models are developed for a particular fuel type and cannot reasonably be applied to another fuel type characterised by a different physical structure. If a model needs to be developed for a new fuel type, then experimental fires are essential to generate the necessary empirical fire behaviour data from which to construct the model.

Over the years, fire behaviour models have been made available to end-users in a number of different forms, ranging from tabulations, linear and circular slide-rules and nomograms through to analytical equations. These often appeared as technical reports or were published in scientific journals. Early versions of models by the likes of McArthur and Peet were presented as tables and slide rules. These were later transformed into equations that then led to development of computer software applications that greatly increased their utility but perhaps with a loss of understanding of how the systems actually worked.

While various summaries have been published (Cheney 1981; Sullivan *et al*. 2012), no single document has yet described the full extent of the fire behaviour modelling knowledge developed to date in Australia. Furthermore, it is observed that, in some instances, outdated and superseded models continue to be used by fire management agencies and researchers. Reasons for such use include lack of adequate training materials with clear information on the deficiencies of the older models and benefits of the newer models or insufficient description of how to obtain input data required for the newer models.

* For further information, consult the writings of McArthur (1958, 1962, 1966a, 1967), McArthur and Luke (1963), and Peet (1965, 1967).

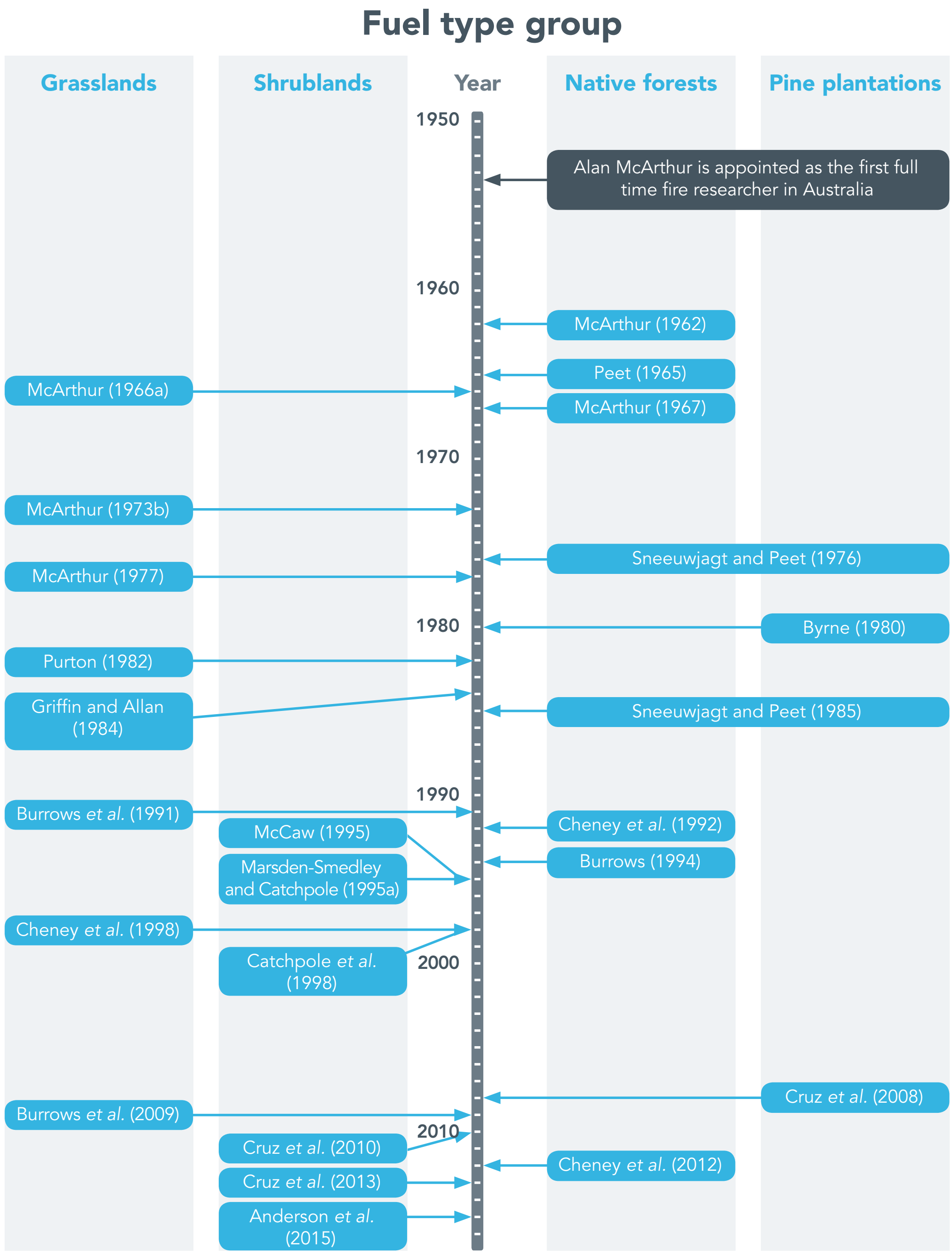


Figure 2.3. Timeline of publications related to bushfire rate of spread models according to broad fuel types found in Australia.

This situation, coupled with the different modelling frameworks used in each model, has created a situation where it is now not clear to practitioners what the underlying assumptions and limitations, and, in particular, what the limits of applicability, are for a given model.

The objective of this book is to provide, in a single document, a description of the models used operationally in Australia to predict bushfire rate of spread and, when applicable, fire sustainability. To give users a better understanding of each model and their application domains, we provide the mathematical equations that form each model and a brief description of data used in model development. We also discuss the main input variables for each model and their influence on model results, and report on known published performance evaluation studies.

The model presentation is divided into four major vegetation groups: grassland, shrubland, eucalypt forest and pine plantation. Within each vegetation group, models are described either by fuel type or application type (i.e. prescribed burning vs. wildfire operations).

The models for pseudo steady state rate of fire spread described in this review are listed in Table 2.1. Collectively, they represent an evolution in bushfire behaviour modelling in Australia over the last 60 or so years (Fig. 2.3). The changes in model forms and the variables used in each model (Table 2.2) reflect the state of the art in the understanding of the fire spread rate processes involved and their drivers at the time of the model development.

In particular, fuel assessment and characterisation methods have evolved to meet the local circumstances, the needs of the times and the level of fire behaviour understanding at the time. As such, the metrics capturing the flammability of the fuel complex are not consistent across models. A similar situation occurs with dead fuel moisture content. This inconsistency also partially reflects the fact that, from an empirical modelling approach, the variables that were identified to determine fire propagation are not the same across fuel types. This may be a function of the perceived differences in propagation processes but has obvious disadvantages in model adoption and can potentially lead to model application errors.

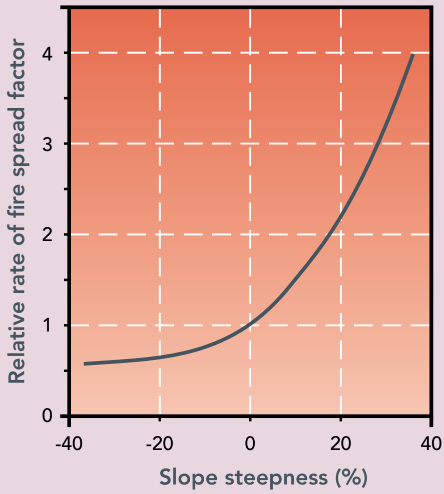
In presenting the various bushfire rate of spread models used in Australia, we chose to introduce their equations in their original formulation (i.e. we did not attempt to change coefficients to homogenise the units of the input variables). Nonetheless, when presenting results we did standardise each model's predictions using the following standard conditions: (*i*) for prescribed fire models for forest stands, the dead fuel moisture content was varied between 7.5 and 17.5% and 10-m open wind speeds between 0 and 20 km/h; (*ii*) for prescribed fire models for open fuel complexes (e.g. spinifex grasslands, shrublands) we varied dead fuel moisture between 7.5 and 30% and wind speed between 0 and 30 km/h; and (*iii*) for models used for wildfire prediction, fuel moisture content was varied between 2.5 and 12.5% and wind speeds between 0 and 70 km/h. Irrespective of the original model output values, rates of fire spread are given in m/min.

Slope steepness effect on bushfire spread rate

Slope is a variable with a dramatic effect on fire propagation. Fires spreading up slopes aligned with the wind are known to increase their rate of spread several fold. All but one of the models described in this book calculate the rate of fire spread for flat ground and then use a slope correction factor to convert this value to a slope-affected rate of spread. McArthur's (1967) rate of fire spread slope function is (Noble *et al.* 1980):

$$R_\theta = R\ exp\ (0.069\ \theta) \qquad [2.1]$$

where R_θ is the rate of fire spread on given slope, θ is the slope angle in degrees and R the calculated rate of fire spread for flat ground. This equation has application bounds $0 < \theta < 20$ degrees (0 to 36%) where the slope is that sensed in the direction of the wind driving the fire.



The effect of slope steepness on the rate of fire spread.

One of the important considerations with the slope effect is that McArthur's function is intended to not only describe the mechanical effect of slope steepness on fire propagation but to also incorporate the broad topographic convergence and interactions associated with terrain in the open (i.e. increased wind speed near ridge tops, drier fuels, etc.). Its use requires a judicious understanding of the local conditions influencing the spreading fire. McArthur (1967) suggested that the function represented by Eq. 2.1 is most applicable to fires burning under milder conditions or still going through the build-up stage. For large wildfires burning across multiple drainages, particularly when spotting is occurring, the effect of slope steepness on the overall rate of fire spread may be regarded as negligible.

For prediction of fire spread down slope, recent work has shown that applying Equation 2.1 to negative angles grossly over-estimates the effect of slope and thus under-predicts potential downslope rates of spread. A new model based on the assumption that increases and decreases in rate of spread over positive and negative slopes will cancel each other out suggests that the negative slope correction factor should not be less than 0.5 of *R* (Sullivan *et al.* 2014). The kataburn model utilises the upslope function to determine the downslope correction factor ($\theta < 0$ degrees):

$$R_\theta = R\ \frac{exp\ (-0.069\ \theta)}{2\ exp\ (-0.069\ \theta)-1} \qquad [2.2]$$

Table 2.1. Summary list of fire spread rate (R) models presented in this book organised by fuel type group, their input variables, equation number(s) and common name.

Model	Inputs (units)	Output (units)	Equations	Common name
Southern grasslands				
McArthur (1966a, 1973b)	10-m open wind speed (km/h) Air temperature (°C) Relative humidity (%) Curing level (%)	*R* (km/h)	3.1 3.2	Mk 3/4 Grassland Fire Danger Meter
McArthur (1977)	10-m open wind speed (km/h) Dead fuel moisture content (%) Curing level (%) Fuel load (t/ha)	*R* (km/h)	3.3	Mk 5 Grassland Fire Danger Meter
Cheney *et al.* (1998)	10-m open wind speed (km/h) Dead fuel moisture content (%) Curing level (%)	*R* (km/h)	3.5 3.6 3.10 3.11	CSIRO Grassland Fire Spread Meter
Grasslands - Hummock spinifex				
Griffin and Allan (1984)	2-m wind speed (m/s) Air temperature (°C) Relative humidity (%) MC (%) live and dead Spinifex cover (%) Bare ground cover (%) Patchiness	*R* (m/s)	3.12 3.13 3.14	Central Australia spinifex model
Burrows *et al.* (1991)	2-m wind speed (km/h) MC (%) live and dead Fuel load (t/ha) Air temperature (°C)	*R* (m/h)	3.15	Spinifex model
Burrows *et al.* (2009)	2-m wind speed (km/h) MC (%) live and dead Fuel load (t/ha) or Fuel cover (%) and height (cm)	Likelihood of fire spread *R* (m/h)	3.16 3.17 3.18 3.19 3.20	WA spinifex model

Model	Inputs (units)	Output (units)	Equations	Common name
Grasslands - Tropical savannas				
Cheney *et al.* (1998)	10-m open wind speed (km/h) Dead fuel moisture content (%) Curing level (%) Overstorey type	*R* (km/h)	3.5 3.6 3.10 3.11	CSIRO Fire Spread Meter for Northern Australia
Shrublands – Buttongrass moorlands				
Marsden-Smedley and Catchpole (1995a)	2-m wind speed (km/h) Dead fuel moisture content (%) Fuel age (years)	*R* (m/min)	4.1	Buttongrass model
Shrublands heathlands				
Catchpole *et al.* (1998)	2-m wind speed (m/s) Fuel height (m)	*R* (m/s)	4.4	Heathland model
Anderson *et al.* (2015)	10-m wind speed (km/h) Dead fuel moisture content (%) Fuel height (m)	*R* (m/min)	4.5	Heathland model
Shrublands Mallee-heath				
McCaw (1995)	2-m wind speed (m/s) Dead fuel moisture content (%)	*R* (m/s)	4.7	WA mallee model
Cruz *et al.* (2010)	10-m open wind speed (km/h) Dead fuel moisture content (%) Near-surface Fuel Percent cover Score (PCS) Elevated Fuel Hazard Score (FHS) Overstorey Height (m)	Likelihood of fire spread Likelihood of crown fire spread *R* (m/min)	4.8 4.10 4.11 4.12 4.13	SA heath SA mallee-heath
Cruz *et al.* (2013)	10-m open wind speed (km/h) Dead fuel moisture content (%) Overstorey Cover (%) Overstorey Height (m)	Likelihood of fire spread Likelihood of crown fire spread *R* (m/min)	4.14 4.16 4.17 4.18 4.19	Mallee-heath

Model	Inputs (units)	Output (units)	Equations	Common name
Dry eucalypt forests – prescribed burning				
McArthur (1962)	1.5-m wind speed (km/h) Dead fuel moisture content (%) Fuel load (t/ha)	*R* (m/min)	5.1 5.2 5.3 5.4	Leaflet 80; Control Burning Guide
Sneeuwjagt and Peet (1985)	1.5-m wind speed (km/h) Dead fuel moisture content (%) Fuel load (t/ha)	*R* (m/h)	5.9 5.10 5.11 5.12 - 5.17	Red Book; Forest Fire Behaviour Tables
Cheney *et al.* (1992)	2-m wind speed (km/h) Dead fuel moisture content (%) Near-surface fuel height (m)	*R* (m/min)	5.18	Young Regrowth Forest Burning Guide
Dry eucalypt forests – wildfire				
McArthur (1967, 1973a)	10-m open wind speed (km/h) Air temperature (°C) Relative humidity (%) Drought factor KBDI (mm) Time since rain (days) Rainfall (mm) Last rain amount (mm) Available litter fuel load (t/ha)	*R* (km/h)	5.19 5.20 5.27	Mk 5 Forest Fire Danger Meter
Cheney *et al.* (2012)	10-m open wind speed (km/h) Dead fuel moisture content (%) Surface Fuel Hazard Score (FHS) Near-surface (Fuel Hazard Score (FHS) Near-surface fuel height (cm) Fuel Hazard Rating (FHR)	*R* (m/h)	5.28 5.29 5.31	Dry Eucalypt Forest Fire model Vesta model

Model	Inputs (units)	Output (units)	Equations	Common name
Wet eucalypt forests – prescribed burning				
Sneeuwjagt and Peet (1985)	1.5-m wind speed (km/h) Dead fuel moisture content (%) Fuel load (t/ha)	*R* (m/h)	6.1 6.2 6.3 6.4 6.9	Red Book; Forest Fire Behaviour Tables
Pine plantations – prescribed burning				
Byrne (1980); Hunt and Crock (1987)	10-m open wind speed (km/h) Relative humidity (%) Available understorey fuel load (t/ha)	*R* (m/h)	7.1	Prescribed burning guide Mk 3
Sneeuwjagt and Peet (1985)	1.5-m wind speed (km/h) Dead fuel moisture content (%) Fuel load (t/ha)	*R* (m/h)	See 5.9 - 5.17 7.2 7.3	Red Book; Forest Fire Behaviour Tables
Pine plantations – wildfire				
Cruz *et al.* (2008)	10-m open wind speed (km/h) Air temperature (°C) Fine dead fuel moisture content (%) Live foliar moisture content (%) Fuel strata gap (m) Surface fuel model Canopy bulk density (kg/m^3) Stand height (m) Stand density (trees/ha)	*R* (m/min) Fire type		PPPY – Pine Plantation Pyrometrics

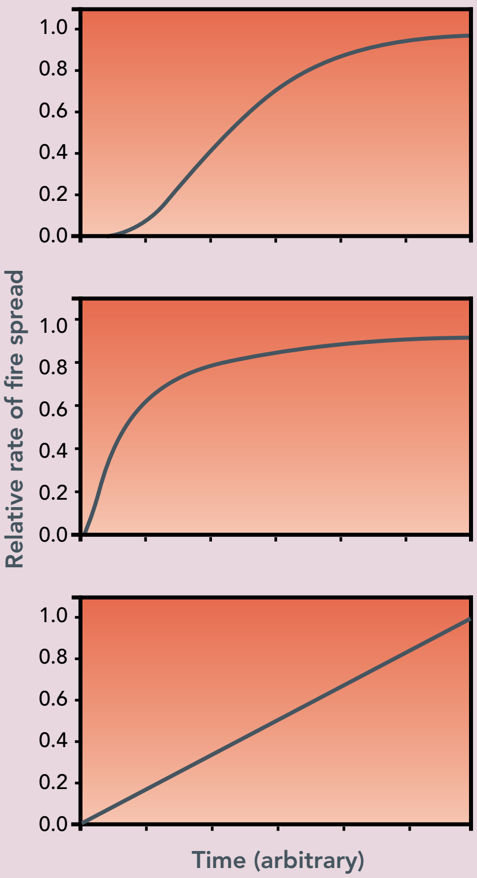
Table 2.2. List of input variables, intermediate model calculations, symbols and units.

Variable	Symbol	Units
Weather		
1.5-m, 2-m wind speed	$U_{1.5}$, U_2	km/h, m/s
10-m open wind speed	U_{10}	km/h
Air temperature	*T*	°C
Relative humidity	*RH*	%
Precipitation	*P*	mm
Days since rain	*N*	days
Fuel moisture		
Dead fuel moisture content	*MC*	% oven-dry weight
Degree of curing	*C*	%
Foliar moisture content	*FMC*	% oven-dry weight
Drought factor	*DF*	Dimensionless (0-10)
Keetch Byram Drought Index	*KBDI*	mm
Fuel structure		
Fuel load	*w*	t/ha, kg/m^2
Fuel bed height	*H*	m, cm
Fuel age	*AGE*	years
Fuel cover	*Cov*	%, fraction
Fuel layer Percent Cover Score (PCS)	*PCS*	dimensionless
Fuel layer Fuel Hazard Score (FHS)	*FHS*	dimensionless
Fuel Hazard Rating (FHR)	*FHR*	dimensionless

For practical purposes wind measured at 1.5-m and 2-m height are considered equivalent.

Rate of spread of a fire originating from a point-source ignition in relation to elapsed time

A fire spreading from a point-source origin will increase its rate of forward spread until such time as a quasi-steady or equilibrium state is reached, or in other words, until it reaches a more or less constant spread rate for the prevailing conditions (Cheney and Gould 1995, 1997). An accelerating fire increases its spread rate and intensity at various rates over a period of time, sometimes quite steadily, at other times in a series of fluctuations. Some of the main factors influencing the accelerations of fire are: the moisture content of fine dead fuels and to a lesser extent of living vegetation and heavy dead fuels; distribution of fuel in the vertical plane; combustion rate and burnout time of fuels; wind speed close to the ground; atmospheric instability; slope and the spotting process (Luke and McArthur, 1978). This acceleration phase is dependent on the fuel type and burning conditions, with the acceleration pattern being determined by the fuel arrangement and its duration being directly proportional to the severity of the burning conditions.



Possible fire acceleration patterns.
Top – burning conditions with slow initial spread potential; **middle** – burning conditions with potential for rapid build-up; **bottom** – simplified linear increase.

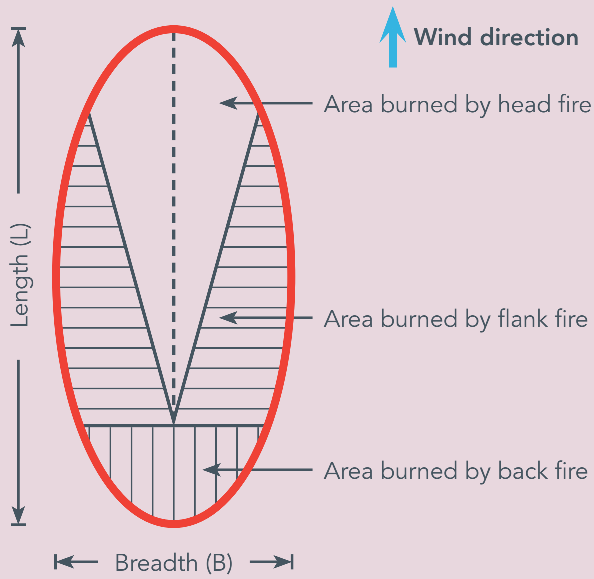
The fire rate of spread models described in this book generally assume that a fire has completed its acceleration and development phase and is spreading at a quasi-steady rate of spread. As the models do not take the acceleration phase into account, their use can lead to over-predictions of forward spread distance, area and perimeter when applied to the initial stages of a fire's development, such as after a point ignition or a breakout from a non-spreading section of a fire perimeter.

As such, the direct application of the rate of spread models described herein assumes that the fire has spread far enough that it is no longer affected by the source of ignition.

Elliptical Fire Shape

The growth pattern or general shape of bushfires originating from a single, point source ignition on level terrain is largely a function of wind speed and fuel complex structure. Provided the wind direction remains unidirectional, wind-driven fires commonly exhibit an elliptical shape. The most fundamental property of an elliptical shaped fire is its length-to-breadth (LB) ratio.

An estimate of the area and perimeter of an elliptically shaped fire can be made on the basis of the LB ratio and the heading and backing rates of fire spread. Provided the fuels are continuous and suppression activities haven't somehow restricted the fire's growth, the prevailing wind speed can often be inferred from the observed LB ratio.



Left: Schematic diagram of a simple elliptical fire growth model (after Van Wagner 1969). Ellipse shown here has a LB ratio of 2.1.

Right: The Cobbler Road Fire near Yass, NSW, Australia, spreading through fully-cured grasslands and open woodland on the afternoon of 8 January 2013 under the influence of strong winds (~50 km/h). Fire was approximately 18 km long (with a LB ratio of 5.3) at the time the photograph was taken (photo: Chris Hadfield/NASA).

3. Grasslands

Grass represents the most widespread fuel type in Australia. The diversity of species and climates where grass fuels are distributed results in a number of different fuel complexes which for fire behaviour prediction purposes are typified as continuous or closed grasslands, tussock grasslands and hummock spinifex grasslands (as per Specht and Specht 1999). In many cases, grasslands are co-located with other vegetation forms, such as in tropical savannah grasslands where an open overstorey is present. In these cases, if grass is the dominant understorey vegetation, it is considered a grassland fuel type (Fig. 3.1).

The continuous or closed grassland formation is the archetypal grassland of short to medium height with individual plant leaf canopies intermingled. Three distinct fuel conditions have been defined for these grasslands (Cheney and Sullivan 2008):

- Undisturbed and/or very lightly grazed natural grassland or improved pasture or unharvested crops, typically more than 50 cm tall (Fig. 3.2).
- Grazed or mown pasture, generally less than 10 cm tall. This is the common condition throughout the agricultural and pastoral zones of southern Australia during summer.
- Heavily grazed and eaten-out pasture, generally less than 3 cm tall,

Figure 3.1. Varied grasslands in Australia: **Top** – continuous grassland, VIC (photo: Country Fire Authority, VIC); **Middle** – spinifex hummock grassland, Lorna Glen, WA (photo: Jen Hollis). **Bottom** – open woodland with grass understorey, King Leopold National Park, WA (photo: Jen Hollis).

with scattered patches of bare ground. This condition may be common in southern Australia during severe drought.

In arid and semi-arid regions of Australia, hummock grasslands dominated by species such as spinifex (*Triodia* spp.) or spear grass (*Aristida* spp.) form a discontinuous grassland that exhibit fire behaviour different from that discussed above for continuous grasslands. Spinifex grasses are drought-resistant perennials that form large hummocks that occupy 10-50% of the ground area with interspaces of normally bare ground but often supporting short grasses and forbs after favourable rains. Hummock diameter will grow with age leaving the centre dead or senescent. Typical heights are around 30 cm. The cover of bare ground patches is a determinant factor in fire propagation.

The lifecycle of annual grassland species controls the combustibility of these grass fuels through the fire season. Once a grass plant has flowered and set seed it begins to die and dry out, or cure. The curing state is expressed as the fraction of dead material in the sward in which the moisture content is dictated by the atmospheric conditions and not moisture of the live cells. Grass curing state changes relatively slowly and it generally takes a plant 6-10 weeks to cure once senescence commences, although in some regions this can be as short as two weeks following onset of warm weather and cessation of spring rains. Once initiated in annual pastures, the process is not affected much by subsequent rainfall, although if the rainfall is sufficient to germinate seed, green shoots may appear beneath the old sward. Curing can be rapidly accelerated, perhaps by as much as a week, by a single day of strong, hot, dry winds (McArthur 1966a).

Perennial grasses cure more slowly than annual grasses. Because perennials do not need to produce seed to continue their life cycle, rainfall will delay the curing process in older leaves and produce new green shoots from the base of the clump that will continue to grow.

Continuous grasslands

McArthur Grassland Fire Danger Meters (McArthur 1966a, 1973b, 1977)

Model description

Alan G. McArthur published the first results of his research into grassland fire behaviour as a set of tables that quantified grassland fire danger and related ranges of expected rate of fire spread (McArthur 1960). He continued development of this knowledge in the form of cardboard slide rules that he called Grassland Fire Danger Meters. These meters combined the effects of weather and fuel conditions into a fire danger index and expected rate of fire spread in grassland pastures. The meters were deemed applicable to annual grasslands of fine structure in the temperate regions of Australia. They were designed to be used in the field and the office by fire managers using actual or forecast weather conditions and observations of fuel state.

At the foundation of the meters were datasets collected from well-documented wildfires and a number of experimental fires. The Commonwealth of Australia's Forestry and Timber Bureau program of experimental burning and wildfire documentation in grasslands lasted for several decades, with new insights into fire behaviour leading to improvements in the meters.

Figure 3.2. Flame front in fast moving experimental fire in fully cured continuous grassland with flames in head fire region averaging 3-4 m tall. Wangaratta, Vic (photo: Vijay Koul, CSIRO).

The meters were originally not developed as equations but published as slide rules, either linear (e.g. Mk 1, Mk 2 and Mk 5) or circular (Mk 3 and 4).

The first version of the grassland fire danger meter incorporated the effects of air temperature, dew point, wind speed, fuel curing, rainfall and fuel amount (quantitatively as height or load or qualitatively by description) which provided an estimate of the forward rate of fire spread, flame height and Grassland Fire Danger Index (GFDI). Rate of fire spread was directly related to the GFDI. A modified version of this meter (Mk 2) was distributed in 1962 (N.P. Cheney, pers. comm.). Both these meters were expressed in imperial units. No equations exist to describe the functional forms embedded in these meters.

The Mk 3 meter, developed for continuous annual and perennial pastures of the southern tablelands of New South Wales, appeared in the form of a circular slide rule and was formally published with a detailed discussion of its design and operation (McArthur 1966a). It does not use fuel amount as an input but instead provides 'average value' estimates of fire behaviour for 'fires in annual and perennial pastures carrying a continuous body of fuel'.

Unlike previous versions, the Mk 3 meter does not explicitly use the moisture content of the fine fuels as an input, but rather relies on an implicit function of air temperature, relative humidity and curing level to infer fine fuel dryness. This fuel moisture content inference assumes clear sky conditions and near equilibrium values for the peak burning period between 1300 and 1600 hours during the fire season between November and March. The use of the meter in the early morning or early evening may tend to over-estimate the fire danger and fire spread rate.

McArthur (1973b) published a metric version of the Mk 3 as the Mk 4 Grassland Fire Danger Meter (Fig. 3.3). In both the Mk 3 and Mk 4 meters there is an inherent assumption that the rate of fire spread is based on a standard fuel quantity between 4 and 5 t/ha.

Luke and McArthur (1978) point out that for this fuel load amount, typical of a good growing season, the fire spread rate in km/h is given by multiplying the GFDI by 0.14. For light grass fuel loads (e.g. 2 t/ha), they suggest an index multiplier of 0.06.

As mentioned earlier, with the advent of easily accessible computing power in the early 1980s, several authors developed equations that attempted to describe the functional forms in the meters. Noble *et al.* (1980) converted the slide rule into mathematical equations by extracting the data from the meters and from hand-drawn graphs provided by Alan G. McArthur. They derived two equations, one to calculate the GFDI and the other to estimate the associated rate of fire spread (Fig. 3.4). The GFDI equation is:

Figure 3.3. A later version of the Mk 4 Grassland Fire Danger Meter.

$$\mathrm{GFDI} = 2\,exp\left(-23.6 + 5.01\,ln(C) + 0.0281\,T - 0.226\sqrt{RH} + 0.633\sqrt{U_{10}}\right) \qquad [3.1]$$

where *C* is degree of curing (%), *T* is air temperature (°C), *RH* is the relative humidity (%) and U_{10} is the wind speed (km/h) as measured/estimated at a height of 10-m in the open.

The headfire rate of spread in km/h is then calculated as:

$$R = 0.13\ \mathrm{GFDI} \qquad [3.2]$$

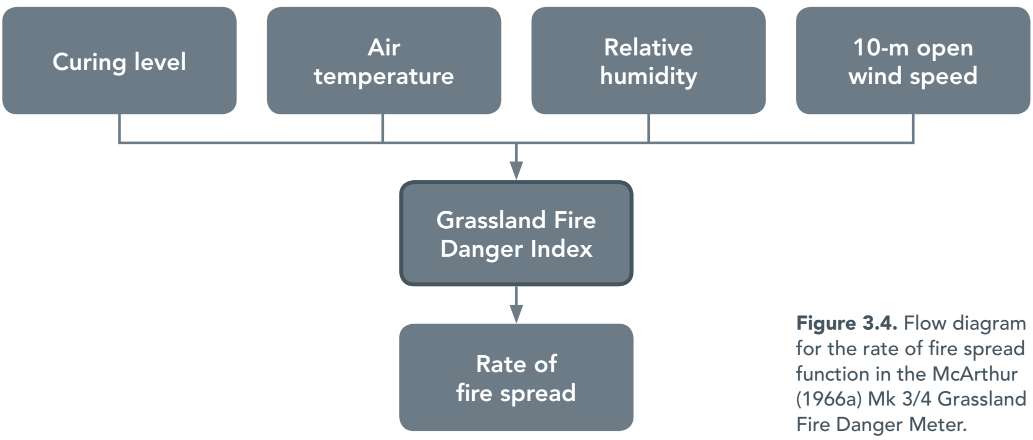


Figure 3.4. Flow diagram for the rate of fire spread function in the McArthur (1966a) Mk 3/4 Grassland Fire Danger Meter.

It is important to note that in the process of deriving the equations from data extracted from the meters there occur slight differences in values read from different meters by different people, normally less than 2% This might explain the slight difference between the 0.13 factor in Eq. 3.2 and the 0.14 factor as suggested by Luke and McArthur (1978).

Observations from the 1977 fires in the Western District of Victoria (McArthur *et al.* 1982) suggested to McArthur the need to reincorporate the explicit fuel load effect in the GFDI and grassfire rate of spread in order to improve the prediction in eaten-out pastures. The Mk 5 meter was published as a rectangular slide rule meter by the Country Fire Authority of Victoria (McArthur 1977). Other changes from the Mk3/Mk4 versions of the grassland fire danger meter include the addition of fuel moisture content as an explicit component predicted from air temperature and relative humidity and a modified wind function (Eq. 3.3). The slide rule meter was formulated to have fuel load input, *w*, varying between 1 and 6 t/ha. Fuel moisture content for partially cured grasslands is considered to be an aggregate of live and dead fuels (Fig. 3.5).

As per the Mk 3/4 grassland fire danger meters, Noble *et al.* (1980) converted the data extracted from the Mk 5 slide rule into an equation. The extracted data suggested a stepwise GFDI equation with the effect of fuel moisture content changing below an 18.8% threshold:

$$\mathrm{GFDI} = \begin{cases} 3.35\, w\, exp(-0.0897\, MC + 0.0403\, U_{10}) & MC < 18.8\% \\ 0.299\, w\, exp(-1.686\, MC + 0.0403\, U_{10})\,(30 - MC) & 18.8 \leq MC < 30.0\% \end{cases} \quad [3.3]$$

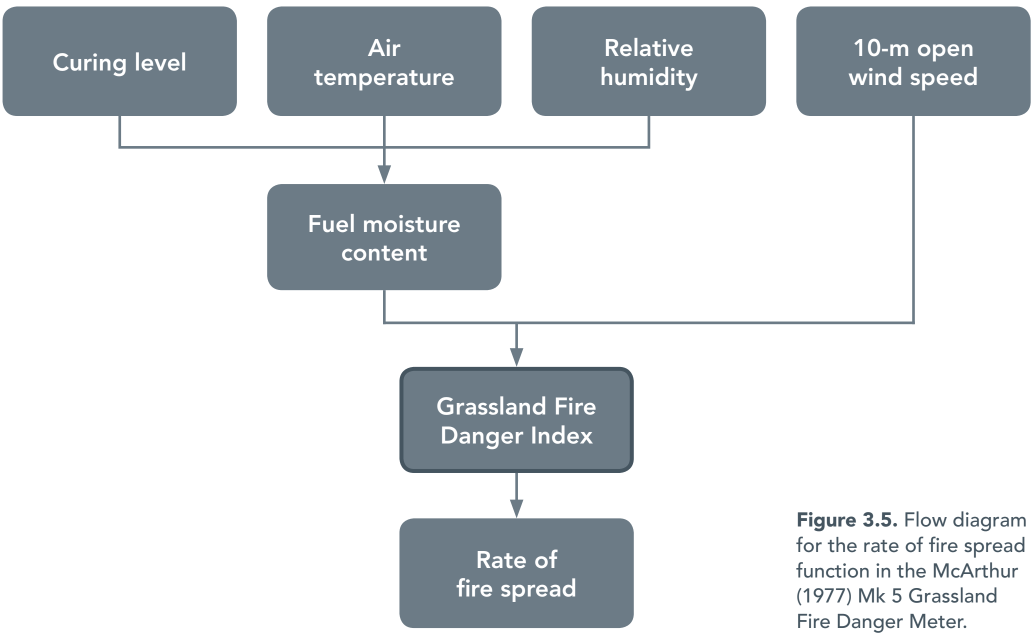


Figure 3.5. Flow diagram for the rate of fire spread function in the McArthur (1977) Mk 5 Grassland Fire Danger Meter.

The moisture content (*MC*) of the grassland fuel is also considered to be an aggregate of live and dead fuels. The *MC* equation was derived as:

$$MC = \frac{(97.7 + 4.06\,RH)}{(T+6)} - 0.00854\,RH + \frac{3000}{C} - 30 \quad [3.4]$$

At a curing level less than approximately 50%, Eq. 3.4 predicts an overall fuel moisture above 30%, the moisture of extinction implicit in Eq. 3.3. For the Mk 5 meter the rate of fire spread is derived from the GFDI in the same way as the Mk 3/4 (Eq. 3.2).

Purton (1982) assumed that the Mk 5 fuel load function could be retrofitted into the Mk 4 meter, which at that time was used operationally for determining the GFDI. He also suggested that the Mk 4 meter was not a direct metric conversion of the Mk 3 meter. By determining the relationship between the angular variation in the meters and the fire danger index value he points out that the Mk 4 meter indices are lower than those obtained in the Mk 3 version of the meter by about 10%. It is likely, however, that these discrepancies arise from the methods used to extract the data from highly variable cardboard meters rather than a reformulation of the GFDI relationship.

Model behaviour and evaluation

Figure 3.6a and b illustrate the effect of wind and fuel moisture on grassfire rate of spread as predicted by the Mk 3/4 and Mk 5 versions of the grassland fire danger meters, respectively. The parameterisation of the exponential function in the Mk 3/4 versions of the meter results in exceedingly high rates of spread for very strong wind speeds. For very dry conditions, (e.g. *MC* = 2.5% given *T* = 40.5 °C and *RH* = 5 %), and average wind speeds above 50 km/h, this model predicts rates of fire spread greater than observed in any previously documented wildfire.

For the same level of fuel dryness, the predicted rate of spread exceeds the wind speed when the latter variable is above approximately 80 km/h. It is unknown if this unreasonable behaviour for extreme conditions is a result of the original McArthur formulation or due to the parameterisation chosen by Noble *et al.* (1980). The Mk 3/4 meters were physically limited to wind speeds of 60 km/h and rates of spread of 217 m/min (13 km/h).

The effect of wind speed in the Mk 5 meter is significantly lower than observed in the Mk 3/4 meters. Fuel moisture content is also observed to be distinctly different in the two meters, with the Mk 3/4 meters showing a higher effect than the Mk 5 meter.

The effect of grassland curing on rate of fire spread is also quite different between the various versions of the grassland fire danger meters, with the Mk 3/4 versions incorporating an exponential function while the Mk 5 function is more linear in nature. The effect of curing is more marked in the Mk 3/4 meters.

The Mk 3/4 meters do not incorporate the effect of fuel load on rate of fire spread as such. However, as mentioned previously, Luke and McArthur (1978) provide two rate of spread factors to convert GFDI into rate of fire spread, namely 0.14 for improved grasslands with a fuel load between 4 and 5 t/ha and 0.06 for lighter load grasslands of approximately 2 t/ha. This suggests a direct fuel load effect – i.e. a doubling of the fuel load will lead to a doubling in the rate of fire spread. This is the function that is implemented in the Mk 5 meter. Nonetheless, this correction factor is considered questionable, as there are confounding effects as a result of fuel particle size (Luke and McArthur 1978). Fine grasses will normally carry lighter fuel loads, although their fineness will contribute to higher spread rates. Later studies (see Cheney *et al.* 1998 below) showed this fuel load effect on the rate of fire spread to be much smaller than that given by the Mk 5.

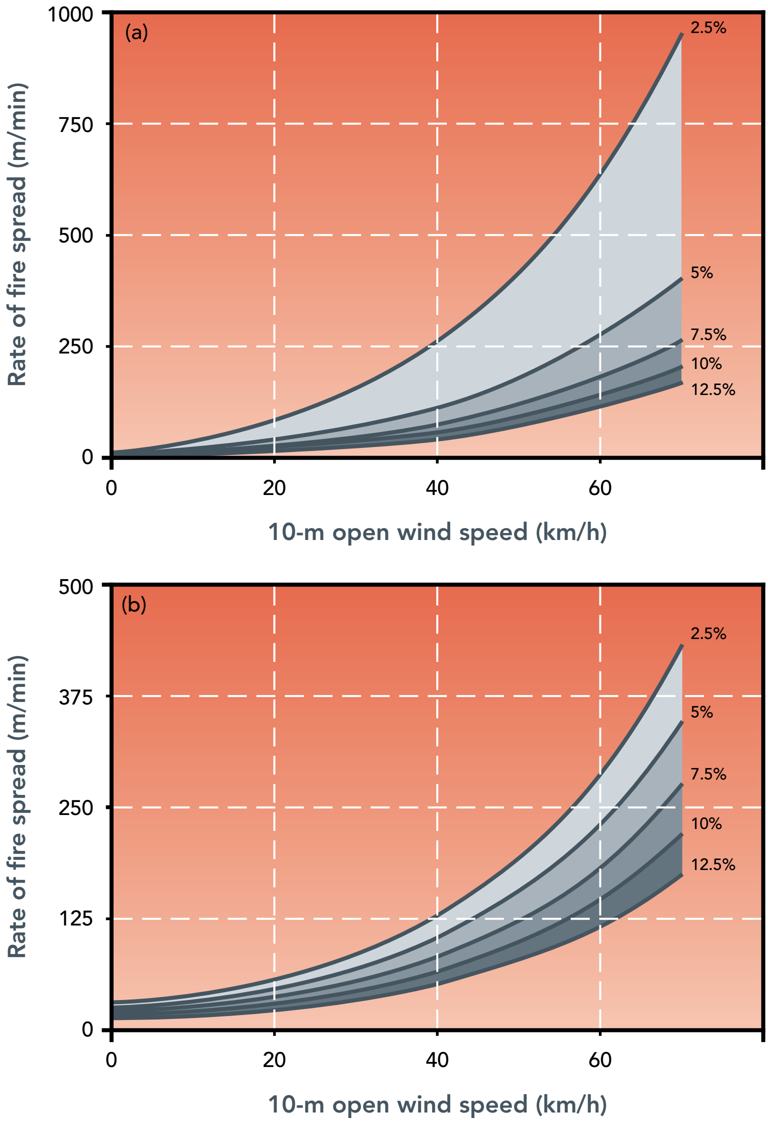


Figure 3.6. Prediction of grassfire rate of spread by (a) McArthur Mk 3/4 and (b) Mk 5 Grassland Fire Danger Meters as a function of 10-m open wind speed and fuel moisture content expected to occur under wildfire conditions. A curing level of 100% and a fuel load of 4.5 t/ha are assumed.

Kilinc *et al.* (in review) evaluated the performance of the Mk 3/4 and Mk 5 meters against wildfire data (n = 187) from southern Australia. This dataset comprised mostly fires in grazed and eaten-out pastures with the fire rate of spread varying between 1.7 to 560 m/min. The Mk 3/4 meters predicted the dataset with an average absolute error of 95 m/min (124% mean error) and an average over-prediction bias of 65 m/min (Table 3.1). The Mk 5 meter on the other hand, assuming an arbitrary standardised fuel load (e.g. 2.5 t/ha for grazed pastures), performed considerably better with an average absolute error of 64 m/min (51% mean error) and an average under-prediction bias of -40 m/min (Table 3.2).

Table 3.1. Statistics and related information associated with the evaluation of McArthur Mk 3 grassland rate of fire spread (ROS) model against independent data derived from wildfire observations.

Number of observations	ROS range (m/min)	MAE (m/min)	MAPE (%)	MBE (m/min)	Study
187	1.7- 560	95	124	65	Kilinc *et al.* (in review)

Table 3.2. Statistics and related information associated with the evaluation of McArthur Mk 5 grassland rate of fire spread (ROS) model against independent data derived from wildfire observations.

Number of observations	ROS range (m/min)	MAE (m/min)	MAPE (%)	MBE (m/min)	Study
187	1.7 - 560	60	51	-40	Kilinc *et al.* (in review)

CSIRO Grassland Fire Spread Model (Cheney et al. 1998)

Model description

Cheney *et al.* (1993) undertook an experimental burning project in the Northern Territory of Australia to determine the relative importance of fuel characteristics and fire size on the rate of spread of grassfires. This work grew out of the confusion seeded by the introduction of the Mk 5 meter prior to Alan McArthur's death in early November 1978 and the different GFDI values calculated by the different meters for the same conditions, and the question of the true effect of fuel load on rate of fire spread.

A total of 121 experimental fires were conducted during a three-week period in July and August of 1986 at the Annaburroo Station in open grassland. Fuels were treated to change fuel load, fuel height and a combination of these. In this dataset the rate of fire spread ranged from 17.4 to 117 m/min, 2-m wind speed between 7 and 25 km/h, air temperatures from 23 to 33°C, and relative humidity from 23 to 45%. Using this dataset and data from wildfire case studies (n = 20), Cheney *et al.* (1998) developed a quasi-empirical model for predicting the rate of spread of grassland fires in undisturbed (R_n, km/h) and cut/grazed (R_{cu}, km/h) pastures (Fig. 3.7):

$$R_n = \begin{cases} (0.054 + 0.269\, U_{10})\, \phi M\, \phi C & , U_{10} \leq 5 \text{ km/h} \\ (1.4 + 0.838(U_{10} - 5)^{0.844})\, \phi M\, \phi C & , U_{10} > 5 \text{ km/h} \end{cases} \quad [3.5]$$

$$R_{cu} = \begin{cases} (0.054 + 0.209\, U_{10})\, \phi M\, \phi C & , U_{10} \leq 5 \text{ km/h} \\ (1.1 + 0.715(U_{10} - 5)^{0.844})\, \phi M\, \phi C & , U_{10} > 5 \text{ km/h} \end{cases} \quad [3.6]$$

Phil Cheney

N.P. (Phil) Cheney graduated from the Australian Forestry School and Melbourne University in 1963 and has been conducting research into bushfires since 1965 when he joined Alan McArthur at the Commonwealth Forestry and Timber Bureau. Phil's research has focussed on fire behaviour to understand how bushfires spread in the natural environment, the development of models to predict the behaviour of fires in important fuel types, and on management systems using fire behaviour knowledge to develop better and safer bushfire management.

Before his retirement in 2005, Phil was Senior Principal Research Scientist with CSIRO's Bushfire Behaviour and Management Group, which he led for over 30 years until 2001. He is a Fellow of the Institute of Foresters of Australia (IFA) and in 2003 was awarded the IFA's highest honour, the NW Jolly Medal. Phil was the recipient of the 2010 International Association of Wildland Fire Ember Award for his outstanding and sustained contribution to wildland fire science.

He has carried out work for the United Nations on fire management in Africa and Turkey and was the selected expert on forest fires on the UN ad hoc group of experts that planned the International Decade for Reduction of Natural Disasters.

Phil was key adviser to the ACT Coroner's enquiry into the ACT January 2003 bushfire deaths and he had input into numerous other inquiries, workshops and research documents released about bushfires throughout Australia. Phil currently lives in Canberra, ACT.

where U_{10} is the 10-m open wind speed (km/h), ϕM is the fuel moisture coefficient and ϕC is the curing coefficient. In turn, ϕM is given by:

$$\phi M = \begin{cases} exp(-0.108\,MC) & , MC < 12\,\% \\ 0.684 - 0.0342\,MC & , MC \geq 12\,\%, \quad U_{10} < 10\text{ km/h} \\ 0.547 - 0.0228\,MC & , MC \geq 12\,\%, \quad U_{10} \geq 10\text{ km/h} \end{cases} \quad [3.7]$$

where MC is the dead fuel moisture content (% oven-dry weight basis) with application bounds of 2 to 24%. A model for MC was not developed but the model for MC used in the Mk 3/4

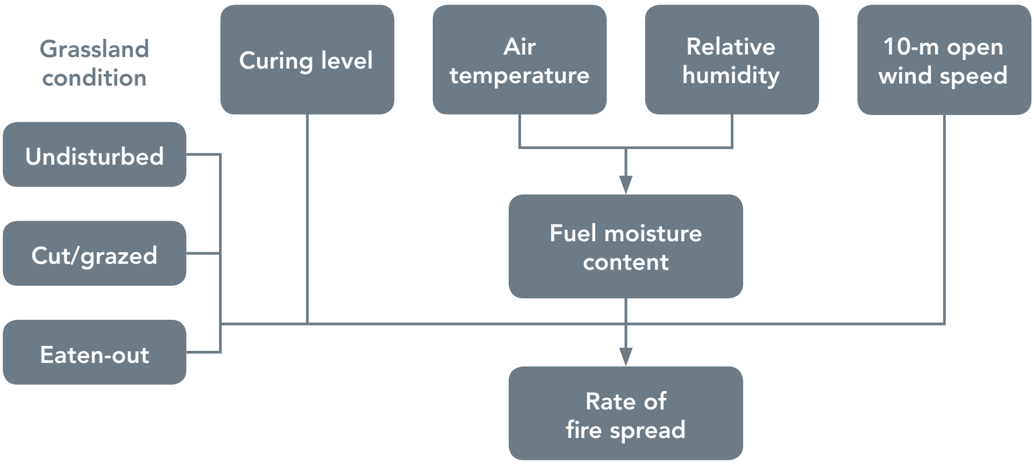


Figure 3.7. Flow diagram for the Cheney *et al.* (1998) grassfire rate of spread model.

meters and published as a graph in McArthur (1966a) was used in the construction of the CSIRO Grassland Fire Spread Meter (Table 3.3):

$$MC = 9.58 - 0.205\,T + 0.138\,RH \qquad [3.8]$$

The curing coefficient proposed by Cheney *et al.* (1998) is:

$$\phi C = \frac{1.12}{1+59.2\,exp\left(-0.124(C-50)\right)} \qquad [3.9]$$

where C is the degree of grass curing (%). This equation embodies the following considerations: (*i*) fire propagation would generally not occur with a degree of curing lower than 50%; (*ii*) the largest rate of change in the curing coefficient occurs when grass curing is between 70% and 90%; and (*iii*) above a curing level of 90% the effect of increases in curing on rate of fire spread is relatively small. Recent experimental work by Cruz *et al.* (2015) showed that grassfire propagation can occur down to curing levels as low as 20% and that the damping effect green fuels is less than suggested in Eq. 3.9. The authors proposed a new curing function as:

$$\phi C = \frac{1.036}{1+103.99\,exp\left(-0.0996(C-20)\right)} \qquad [3.10]$$

with application bounds 20% < *C* <100%.

Eaten-out pastures can at times be a common grassland fuel type in Australia, especially in late summer or during periods of extended drought, and fires in them are recognised to have a lower spread rate than fires in cut/grazed pastures. No experimental fire data exists for this fuel type, but based on the evidence from a few grassfires spreading in the eaten-out pastures it was

Table 3.3. Predicted fine dead fuel moisture content (%) as a function of ambient air temperature and relative humidity for application of the CSIRO Grassland Fire Spread Meter (see Eq. 3.8).

Relative humidity (%)	Air temperature (°C)			
	10	20	30	40
5	8.0	6.0	4.0	2.0
10	9.0	7.0	5.0	3.0
15	9.5	7.5	5.5	3.5
20	10.5	8.0	6.0	4.0
25	11.0	9.0	7.0	5.0
30	11.5	9.5	7.5	5.5
35	12.5	10.5	8.5	6.0
40	13.0	11.0	9.0	7.0
45	13.5	11.5	9.5	7.5
50	14.5	12.5	10.5	8.5
55	15.0	13.0	11.0	9.0
60	16.0	14.0	11.5	9.5
65	16.5	14.5	12.5	10.5
70	17.0	15.0	13.0	11.0
75	18.0	16.0	14.0	11.5
80	18.5	16.5	14.5	12.5
85	19.5	17.0	15.0	13.0
90	20.0	18.0	16.0	14.0

considered that for wildfire conditions the rate of spread in these fuels would be half of that observed in grazed pastures (Eq. 3.6). As such, the model for fire spread rate in eaten-out pastures is:

$$R_e = (0.55 + 0.357\,(U_{10} - 5)^{0.844})\,\phi M\,\phi C \qquad , U_{10} > 5 \text{ km/h} \qquad [3.11]$$

Model behaviour and evaluation

The form of Cheney *et al.* (1998) rate of fire spread model is a significant departure from McArthur's Mk 3/4 and Mk 5 grassland fire danger meter models. The bulk influence of wind follows an almost linear effect (i.e. a power law with an exponent close to 1.0) with a critical threshold of 5 km/h. Below this threshold (when winds are light and variable), fires will not propagate in a consistent manner with a distinct headfire zone. For these conditions, rate of fire spread was modelled as a linear function of wind speed. Above this threshold, fires will develop a headfire that spreads in a consistent direction with the wind (Fig. 3.8). The fuel moisture content function follows an exponential decay with an exponent close to 0.1 (for an *MC* < 12%).

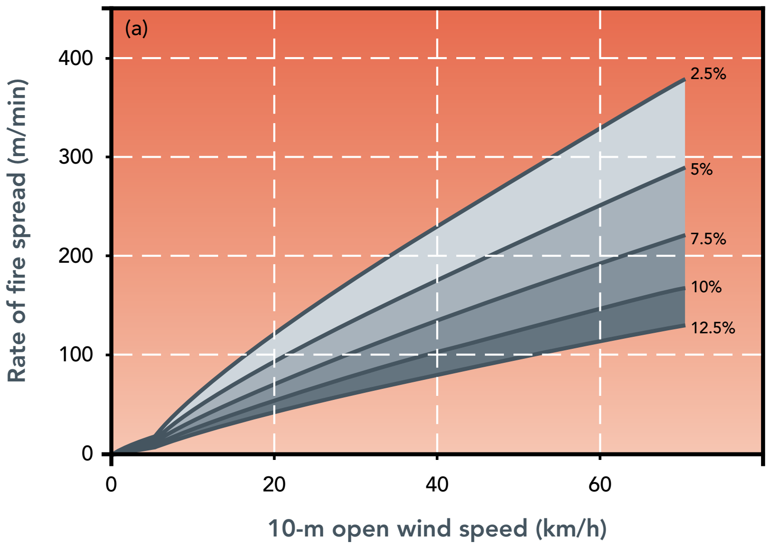
Figure 3.8. Initial fire development in cut grass in southern SA. Note high length-to-breadth ratio due to reduced flank fire activity (photo: Kiwi White).

These effects are consistent with our current understanding of the effect of these variables in fire propagation. Fuel load is not an explicit variable in this model, but the effect of fuel condition and structure (height, load, cover) is captured by the three states of predominant pasture condition: undisturbed, cut/grazed and overgrazed grasslands.

During a typical summer fire season in southern Australia, grassland areas will constitute a mosaic of pasture conditions and agricultural crops (Fig. 3.9). Unless, one fuel condition dominates the landscape it is recommended that the prediction of spread of grassfires be based on the cut/grazed grass model (Cheney and Sullivan 2008).

Fig. 3.10a and b present rate of fire spread for natural and cut/grazed pastures over the range of wind speed and dead fuel moisture content expected to occur under wildfire conditions. As seen by comparing Figure 3.6 with Figure 3.10, the CSIRO Grassland Fire Spread Model's response to wind speed yields distinctly different trajectories compared to those of the Mk 3/4 and 5 meters. For dead fuel moisture contents above 5%, the CSIRO Grassland Fire Spread Model tends to predict faster rates of fire spread for wind speeds up to 50-60 km/h (with the exception of the very dry curves for the Mk 3/4 meters), above which the exponential functions in the McArthur meters yield

Figure 3.9. Typical grassland fuel mosaic observed during summer in southern Australia (photo: Wayne Rigg, Country Fire Authority, VIC).



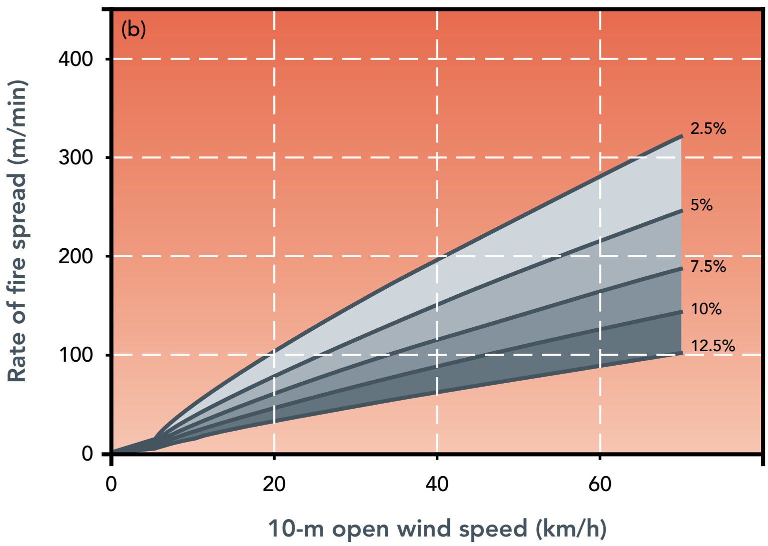


Figure 3.10. Prediction of grassfire rate of spread according to the CSIRO Grassland Fire Spread Meter (Cheney *et al.* 1998) for (a) undisturbed and (b) cut/grazed grasses as a function of 10-m open wind speed and fine fuel moisture content as expected to occur under wildfire conditions. 100% cured state is assumed.

Table 3.4. Statistics and related information associated with the evaluation of Cheney *et al.* (1998) grassland rate of fire spread (ROS) model against independent data derived from wildfire observations.

Number of observations	ROS range (m/min)	MAE (m/min)	MAPE (%)	MBE (m/min)	Study
187	1.7 - 560	56.7	80	15	Kilinc *et al.* (in review)

faster fire spread rates. For fuel moisture contents lower than 5% the Mk 3/4 meter will predict faster rates of fire spread at wind speeds above 30-40 km/h.

The CSIRO Grassland Fire Spread Model predicted well the rate of spread of the wildfires used in its development. Kilinc *et al.* (in review) evaluated the performance of the CSIRO Grassland Fire Spread Model against independent wildfire data from southern Australia (details given above in the McArthur Grassland Fire Danger Meters section). These authors found the CSIRO Grassland Fire Spread Model predicted the dataset with an average absolute error of 57 m/min (80% mean error) and an average over-prediction bias of 15 m/min (Table 3.4). Of the three grass fire spread models tested by Kilinc *et al.* (in review), the CSIRO Grassland Fire Spread Model yielded the most accurate results.

Hummock spinifex grasslands

Griffin and Allan (1984)

Model description

Griffin and Allan (1984) developed a model to predict the rate of fire spread in hummock spinifex grasslands of central Australia. The study aimed to develop a model that could be used to support prescribed burn planning. The base data was collected through an experimental burning program carried out in 1982 in Uluru National Park, in the Northern Territory, over a range of varying seasonal weather conditions and a range of fuel ages (time since fire). The dataset used in model development consisted of a total of 22 fires in spinifex dune fields. Long-term average annual precipitation for the area was 220 mm. Fuel cover varied between 46 and 69%, with spinifex being the most common fuel in the study area (cover ranging between 21 and 65%). Fuel moisture content comprising live and dead components in a hummock varied between 6.1 and 27%. Wind speed measured at 2-m height ranged between 2.3 and 11 km/h. The rate of fire spread varied between a value of zero (i.e. unsustained or "no-go" fires) up to 54 m/min.

Rate of fire spread (*R*, m/s) was modelled as a function of a fuel factor (ϕF) and a weather factor (ϕW) (Fig. 3.11):

$$R = -0.419 + 1.125\ \sqrt[3]{\phi F\ \phi W} \qquad [3.12]$$

This equation explained 57% of the variability in rate of spread in the dataset. The fuel factor was defined as:

$$\phi F = \frac{\sqrt{\frac{Cov}{bare\ ground}}}{\sqrt{MC}}\ \sqrt{Patchiness} \qquad [3.13]$$

where *Cov* is the cover of spinifex hummocks as a fraction of total area, *bare ground* is the fraction of ground not cover by any vegetation, *MC* is the spinifex moisture content (%) taking into account both dead and live fuels in the spinifex cluster, and *Patchiness* is the ratio of variance to mean patch size that attempts to capture the size and distribution of spinifex and

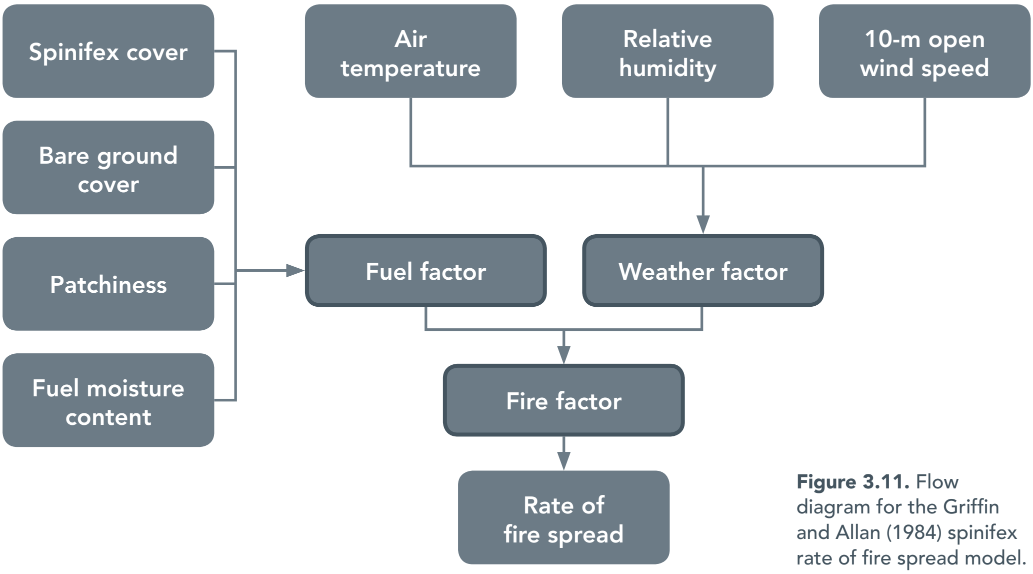


Figure 3.11. Flow diagram for the Griffin and Allan (1984) spinifex rate of fire spread model.

bare patches. A model for *MC* was not developed and the only option is to measure *MC* directly. There is currently no suitable *MC* model for use in spinifex although a trial system is being developed in Western Australia (N.D. Burrows, Department of Parks and Wildlife, pers. comm.). The weather factor was calculated as follows:

$$\phi W = \sqrt{\frac{T\ exp(U_2)}{RH}} \qquad [3.14]$$

where T is the air temperature (°C), U_2 the wind speed measured at 2 m (m/s) and RH is the relative humidity (%).

Model behaviour and evaluation

The use of an exponential function for wind speed makes this variable the most influential one in the model. Figure 3.12 presents the sensitivity of Griffin and Allan (1984) model to wind speed and fuel moisture content. The model is relatively insensitive to changes in wind speed in the lower range of this variable and highly sensitive in the upper range, resulting in exceedingly high rates of spread if the model is used with high wind speeds. The model also shows a relatively small effect of fuel moisture content on the spread rate of the fire.

The adopted model form, without any coefficient directly linked to input variables, means that none of the variables, with the exception of wind speed, show a decisive effect on the rate of spread of the fire. It is uncertain if this is the result of the characteristics of the original dataset or due to the modelling options employed by its authors. Given the model form, it is recommended that the model not be used outside of the bounds of the original dataset (i.e. it should only be used to predict fire behaviour under prescribed burning conditions).

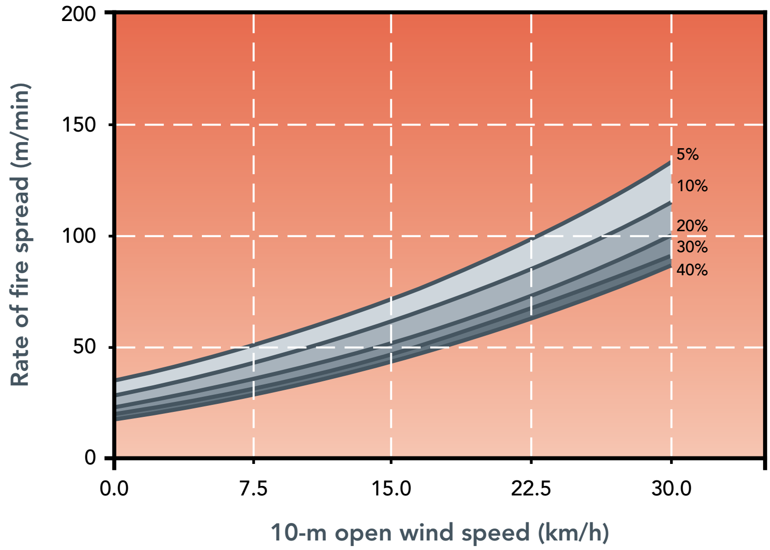


Figure 3.12. Prediction of rate of fire spread in spinifex according to the Griffin and Allan (1984) model as a function of 10-m open wind speed and fine fuel moisture content as expected to occur under prescribed burning conditions. The following conditions are assumed: air temperature 31°C, relative humidity 10%, cover 39%, bare ground 42% and patchiness 0.8. A wind adjustment factor of 0.7 was used to convert 10-m open into 2-m wind speeds.

Table 3.5. Statistics associated with the evaluation of Griffin and Allan (1984) rate of fire spread (ROS) model against independent data derived from experimental fire observations.

Number of observations	ROS range (m/min)	MAE (m/min)	MAPE (%)	MBE (m/min)	Study
58	4.3 - 66.6	43.4	217	43.4	Burrows *et al.* (1991)

Burrows *et al.* (1991) evaluated the Griffin and Allan (1984) model against fire spread rate data (n = 58) collected in experimental prescribed fires in spinifex vegetation in the Gibson Desert Nature Reserve of Western Australia. Rate of fire spread in this dataset varied between 4.3 and 66.6 m/min, a range similar to the Griffin and Allan (1984) dataset. This analysis found that the Griffin and Allan (1984) model largely over predicted Burrows *et al.* dataset, resulting in an average error of 43.4 m/min (217%) (Table 3.5).

Burrows et al. (1991)

Model description

Burrows *et al.* (1991) conducted an experimental burning study in desert spinifex grasslands of Western Australia with the ultimate aim of developing an operational fire spread model for spinifex fuels). The study area lies within the Gibson Desert where annual rainfall averages 220 mm. The fuel complex can be described as predominantly hummock clumps of *Plectrachne* spp. and *Triodia* spp. with scattered low grasses and other shrub vegetation of various species.

The fuel complex at four sites was characterised for patchiness and spatial distribution, fuel load (varying between 0.3 and 13.5 t/ha), fuel height (varying between 0.18 and 0.28 m), compactness and fuel particle size. A total of 41 experimental fires were conducted with rates of spread varying from zero (i.e. self-extinguishing fires) up to 92 m/min with corresponding fireline intensities up to 14,630 kW/m. Relevant weather variables measured included 2-m wind speeds (range: 4 to 36 km/h), air temperature (range: 19 to 50°C) and relative humidity (range: 14 to 48%). Fuel moisture content, a composite of dead and live fuels, varied between 12 and 31%. A model for predicting rate of fire spread (*R*, m/h) was developed from stepwise multiple linear regression analysis:

$$R = 3.9\,U_2^{\,2} - 82.08\,MC + 5826.36\,CovR + 43.5\,T - 4935.3 \quad [3.15]$$

where U_2 is wind speed measured at a 2-m height (km/h), *MC* constitutes the compound fuel moisture content (%) incorporating both dead and live components, *CovR* is the ratio between the spinifex cover (%) and the bare ground cover (%), and *T* the air temperature (°C) (Fig. 3.13). Due to the scattered nature of the hummock fuels, a 12-17 km/h threshold wind speed was deemed necessary for sustained head-fire spread. No back and flank fire propagation was observed in these prescribed fire experiments. No model for estimating *MC* was presented.

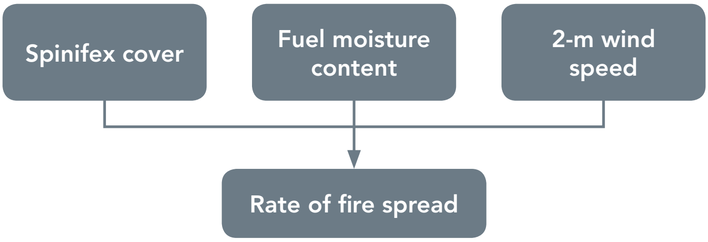


Figure 3.13. Flow diagram for the Burrows *et al.* (1991) spinifex rate of fire spread model.

Model behaviour and evaluation

Figure 3.14 presents the sensitivity of the Burrows *et al.* (1991) rate of fire spread model to wind velocity and fuel moisture content (as an aggregate of live and dead fuels). The patchy fuel distribution that characterises spinifex fuel types makes wind speed the main driver of fire propagation. This is mathematically implied by the power law function of wind speed given in Eq. 3.15. Without the presence of wind to increase heat transfer between burning and unburned clumps, fire will fail to propagate. The effect of fuel moisture content on rate of fire spread is relatively small. The cover ratio (spinifex cover/bare ground cover) is the fuel characteristic describing the fuel complex state and has an approximately linear effect on the fire spread rate. An increase (or reduction) in spinifex cover by 25% will result in a homologous change in the rate of fire spread. Although this fuel variable only considers two aspects of vegetation, in reality it also takes into account

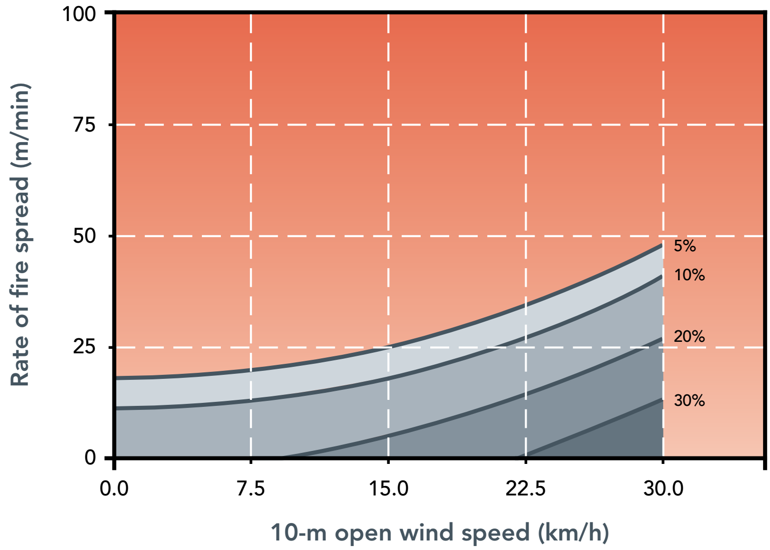


Figure 3.14. Prediction of rate of fire spread in spinifex according to the Burrows *et al.* (1991) model as a function of 10-m open wind speed and fine fuel moisture content as expected to occur under prescribed burning conditions. An air temperature of 31 °C, a spinifex cover of 40%, and bare ground of 45% are assumed. A wind adjustment factor of 0.7 was used to convert 10-m open into 2-m wind speeds.

the effect of other fuel components on rate of fire spread such as ephemeral grasses that occur after periods of high rainfall. As pointed out by Burrows *et al.* (1991), the model represented by Eq. 3.15 is bounded by the intervals in the environmental variables described above.

Burrows et al. (2009)

Model description

Burrows *et al.* (2009) developed a fire spread model for spinifex fuels based on the dataset (n = 41 fires) described above for Burrows *et al.* (1991) and a further 42 experimental fires carried out between 1992 and 1994 at two locations, the Little Sandy Desert and the Great Sandy Desert of Western Australia (Fig. 3.15 and 3.16). The experimental methods used in this second set of experimental fires were similar to those used by Burrows *et al.* (1991). Fuels in the new dataset extended over an age range from 2 to 42 years.

Due to the discontinuous nature of fuels in these arid environments, the application of a fire spread model requires a prior assessment of the likelihood of sustained fire spread. Using the combined datasets, Burrows *et al.* (2009) aimed to develop models to: (*i*) determine threshold conditions for sustained fire spread ("go/no-go") and (*ii*) predict the spread rate of free-burning fires (Fig. 3.17). Two distinct model groups were formulated taking into account the variables used to describe fuel complex structure. The model group that uses fuel load as an input variable will first be described, followed by a description of the second model that uses hummock cover and height as fuel input variables.

Figure 3.15. Flame front spreading in a spinifex hummock grassland, Lorna Glen, WA. Spinifex is 12 years old with a 40-45% cover and 0.3 m height (photo: Neil Burrows, DPaW, WA).

Figure 3.16. Operational prescribed burn in open woodland with spinifex grassland understorey at Lorna Glen, WA (photo: Neil Burrows, DPaW, WA).

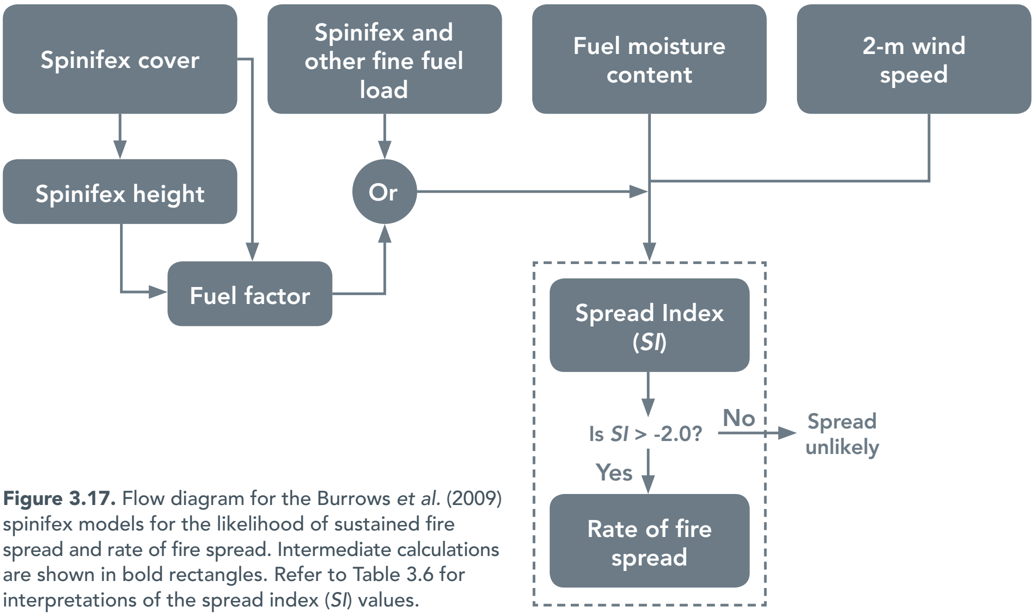


Figure 3.17. Flow diagram for the Burrows *et al.* (2009) spinifex models for the likelihood of sustained fire spread and rate of fire spread. Intermediate calculations are shown in bold rectangles. Refer to Table 3.6 for interpretations of the spread index (*SI*) values.

The model for fire propagation starts with the calculation of a Fire Spread Index (SI_{FL}):

$$SI_{FL} = 0.57\,U_2 + 0.96\,w - 0.42\,MC - 7.42 \qquad [3.16]$$

where U_2 is the average wind speed (km/h) measured over a 5-min period at a height of 2-m, *w* is spinifex and other fine fuel load (t/ha) and *MC* is the compound fuel moisture content (%) incorporating both dead and live fuel components. As with the other spinifex studies, no model for estimating *MC* was developed and measured values or best estimates must be used.

Table 3.6. Interpretation of Burrows *et al.* (2009) fire spread indexes (SI_{FL} and SI_{FF}) in terms of likelihood of sustained fire spread and associated rate of fire spread in spinifex grasslands

SI	Likelihood of fire spread	Potential rate of fire spread (m/h)
SI $\leq$ -2	Fire unlikely to spread	0
-2 < SI $\leq$ 0	Fire may spread	< 500
0 < SI $\leq$ 2	Fire should spread	500 – 900
2 < SI $\leq$ 4	Fire will spread	900 – 1800
4 < SI $\leq$ 6	Fire will spread	1800 – 2700
6 < SI $\leq$ 10	Fire will spread	2700 – 4500
SI >10	Fire will spread	>4500

The SI_{FL} describes the likelihood of a fire to spread. If $SI_{FL} < -2$, then it is unlikely that sustained fire spread will occur. For $SI_{FL} > -2$, higher *SI* values correspond to a higher likelihood that a free-spreading fire will occur. Burrows *et al.* (2009) provide an interpretation guide to the SI_{FL} (Table 3.6). If the SI_{FL} value indicates that a fire is likely to spread, the forward rate of fire spread (R_{FL}, m/h) is then calculated as:

$$R_{FL} = 1581 + 154.9\,U_2 + 140.6\,w - 228.0\,MC \qquad [3.17]$$

The alternative fire spread index model (SI_{FF}) that uses fuel cover and height instead of fuel load is:

$$SI_{FF} = 0.37\,U_2 + 0.78\,FF - 0.31\,MC - 5.23 \qquad [3.18]$$

where *FF* is the fuel factor determined as follows:

$$FF = 0.25\,Cov + 0.04\,H - 3.2 \qquad [3.19]$$

where *Cov* represents the spinifex cover (%) and *H* is the mean hummock height (cm). The interpretations of the SI_{FL} values given in Table 3.6 are also applicable to the SI_{FF}. The model of rate of fire spread calculated using the fuel factor (R_{FF}, m/h) is:

$$ROS_{FF} = 1969 + 142.8\,U_2 + 120.1\,FF - 229.1\,MC \qquad [3.20]$$

Model behaviour and evaluation

The model form adopted by Burrows *et al.* (2009) gives significantly different results compared to the Griffin and Allan (1984) and Burrows *et al.* (1991) models described above. Burrows *et al.* (2009) explicitly considered a function to determine fire spread sustainability after which the rate of fire spread is calculated. Wind speed, fuel moisture content and fuel load (a surrogate of spinifex cover and age) all have a significant effect on the likelihood of fire spread (Fig. 3.18).

The wind function imposes a linear effect on rate of spread that is lower than that found in the other spinifex fire spread rate models. Conversely, the effect of fuel moisture content is observed to have a stronger influence than in previous models. The sensitivity of rate of fire spread to fuel load is lower than found for the two variables described above. A doubling in fuel load will increase rate of spread by about 13%. We are presently unaware of any published evaluation on the performance of the Burrows *et al.* (2009) models against independent datasets.

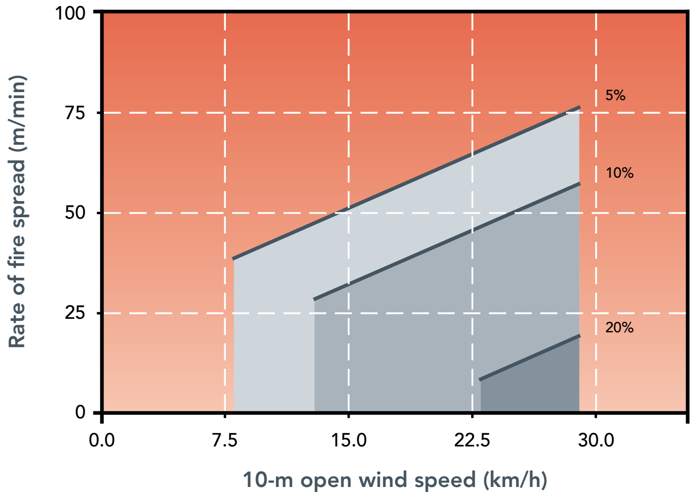


Figure 3.18. Prediction of rate of fire spread in spinifex according to the Burrows *et al.* (2009) model as a function of 10-m open wind speed and fine fuel moisture content as expected to occur under prescribed burning conditions. Fuel load of 7 t/ha is assumed. A wind adjustment factor of 0.7 was used to convert 10-m open into 2-m wind speeds.

Tropical grasslands, woodlands and open forests

CSIRO Fire Spread Meter for Northern Australia

Tropical grassland fuel types can vary from open natural grassland to woodlands and open forests with a dominant grassy fuel understorey (i.e. the sustained shrub and litter components are absent from the understory fuel layer), commonly referred to as savannah. This model is based upon the natural/ungrazed grassland fire spread rate model of Cheney *et al*. (1998) as represented by Eq. 3.5, in which open tropical grassland is considered equivalent to the pasture condition of natural/ungrazed (Sullivan 2010). A rate of spread reduction factor is then used to predict rate of spread in woodlands and open forests. The suggested wind speed reduction factors between 10-m open wind speed and the 2-m wind speed for these vegetation types is given by Cheney and Sullivan (2008) and shown in Table 3.7. It is worthwhile noting that the applicability of this model is not restricted to tropical grasslands. The model can also be applied to structurally similar fuel types occurring elsewhere in Australia.

Table 3.7. Ratio between wind speed at 10-m height in the open and 2-m above ground and relative rate of fire spread in different tropical grassland fuels (from Cheney and Sullivan 2008)

Type of vegetation	Ratio between wind speed at 10 m in the open and at 2-m	Forward rate of fire spread relative to the open (Eq. 3.5)
Open grassland	10:8	1.0
Woodland (canopy cover < 30%)	10:6	0.5
Open forest (10-15 m tall, canopy cover 30–70%)	10:4.2	0.3

4. Shrublands

Shrub vegetation in Australia is found in a wide range of environments, from coastal dunes to arid zones of central Australia, often where soils are either shallow or sandy, and of low nutrient status. Heaths, shrublands and shrubby woodlands comprise a range of structurally very distinct fuel complexes, with heights ranging from 2-8 m in tall mulga shrublands to low (< 25 cm tall) subalpine heathlands, and cover varying between dense (up to 100% foliage cover) coastal shrublands to sparse (10-30% cover) heathlands in arid environments.

Shrubland vegetation is notorious for its high flammability due to a number of intrinsic physical and chemical characteristics, namely a vertically-oriented and well-aerated fuel bed extending from the surface to the top of the canopy, a high proportion of suspended dead fuel and the direct exposure to wind.

Fire behaviour research has focused on four particular fuel types: Tasmanian buttongrass moorlands, temperate heaths and semi-arid heaths and mallee-heaths (Fig. 4.1 and 4.2). Fuel types for which fire spread models do not exist tend to occur in arid regions (annual precipitation typically < 250 mm), namely tall acacia shrublands and chenopod shrublands, such as mulga (*Acacia aneura*) and saltbush (*Atriplex vesicaria*), respectively.

Figure 4.1. Examples of three distinct shrublands types: **Top** – Fuel structure in 21-year-old semi-arid mallee-heath in the Ngarkat Conservation Park, SA. Reference pole is 1 m tall. (photo: CSIRO). **Middle** – 14-year-old coastal sandplain heathland in Southern WA (photo: Lachie McCaw, DPaW, WA). **Bottom** – 10- to 15-year-old wallum heathland in coastal south-east Queensland (photo: Peter Leeson, QPWS, QLD).

Figure 4.2. 25-year-old buttongrass moorlands growing in low productivity site. (photo: Jon Marsden-Smedley, University of Tasmania, TAS).

Buttongrass moorlands

Marsden-Smedley and Catchpole (1995a)

Model description

Marsden-Smedley and Catchpole (1995a) described the fire behaviour modelling component of a study aimed at developing a comprehensive fire danger rating and fire behaviour prediction system for Tasmanian buttongrass moorlands. Buttongrass moorlands, a significant Tasmanian vegetation type, are defined as treeless communities dominated by sedges and low heaths with a significant contribution of buttongrass (*Gymnoschoenus sphaerocephalus*).

Key fuel complex components are the openness of the fuels to wind flow and the substantial quantity of suspended dead fuels within the hummocks. These features make the fuel complex susceptible to sustained fire propagation even when soil and fuel moisture content levels are high.

Fire behaviour measurements were made on 64 fires, comprising experimental fires (Fig. 4.3; n = 44), operational prescribed fires (n = 11) and wildfires (n = 5). Fuel age in the experimental fires varied between four and 25 years. The fire environmental conditions and fire behaviour characteristics associated with the dataset used in model development varied over a wide range. Dead fuel moisture content, wind speed and rate of spread varied between 8.2 and 68%, 0.7 and 36 km/h, and 0.6 and 55 m/min, respectively.

Figure 4.3. Flame front in a buttongrass moorland prescribed burn in Tasmania conducted under light winds (~ 5 km/h) and moist fuels in Tasmania (photo: Jon Marsden-Smedley, University of Tasmania, TAS).

Non-linear regression analysis was used to model the head-fire rate of spread (*R*, m/min):

$$R = 0.678\, U_2^{\;1.312}\, exp(-0.0243\, MC)\, \big(1 - exp(-0.116\, AGE)\big) \qquad [4.1]$$

where U_2 is the wind speed (km/h) measured at a 2-m height, *MC* is the dead fuel moisture content (%) and *AGE* is time since the last fire (years), a surrogate of other fuel characteristics such as fuel load and fraction of dead fuel (Fig. 4.4). Marsden-Smedley and Catchpole (2001) tested several *MC* models of which the best was:

$$MC = exp(1.66 + 0.0214\, RH - 0.0292\, T_{dew}) \qquad [4.2]$$

The unusual combination of dew point temperature (T_{dew}, °C) and relative humidity (RH, %) was chosen because T and RH were correlated in their data set. An alternative model for use after rainfall is (Marsden-Smedley *et al.* 1999):

$$MC = exp(1.66 + 0.0214\, RH - 0.0292\, T_{dew}) + 67.128\, \big(1 - exp(-3.132\, P)\big)\, exp(-0.0858\, t) \qquad [4.3]$$

where *t* is time (hours) since the last rain event and *P* is the precipitation amount (mm). Tables 4.1 and 4.2 present outputs from these two equations.

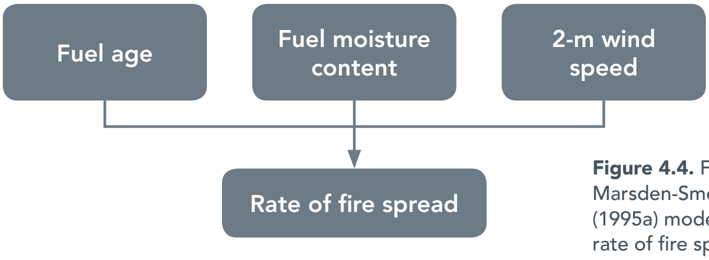


Figure 4.4. Flow diagram for the Marsden-Smedley and Catchpole (1995a) model for predicting the rate of fire spread in buttongrass moorlands.

Table 4.1. Predicted fine dead fuel moisture content (%) as a function of ambient air temperature and relative humidity for application of the buttongrass moorlands fire spread model (see Eq. 4.2).

Relative humidity (%)	Air temperature (°C)			
	10	20	30	40
5	Outside of range of model applicability			
10				
15				
20				
25	11.5	9.0	7.0	5.5
30	12.0	9.5	7.5	5.5
35	13.0	10.0	7.5	6.0
40	13.5	10.5	8.0	6.0
45	14.5	11.0	8.5	6.5
50	15.5	11.5	9.0	7.0
55	16.5	12.5	9.5	7.5
60	17.5	13.5	10.0	7.5
65	19.0	14.5	11.0	8.5
70	20.5	15.5	11.5	9.0
75	22.0	16.5	12.5	9.5
80	24.0	18.0	13.5	10.0
85	26.0	19.5	14.5	11.0
90	28.0	21.0	16.0	12.0

Table 4.2. Fine dead fuel moisture content (%) rainfall correction for application of the buttom grass moorlands fire spread model (see Eq. 4.3). Add the value from this table to the prediction from Table 4.1 if there has been recent rainfall.

Rainfall factor Time since rain (hours)	Amount of rain (mm)				
	0.05	0.1	0.2	0.5	1+
0	9.5	18	31	53	64
3	7.5	14	24	41	49.5
6	6	11	18.5	31.5	38.5
9	4.5	8.5	14.5	24.5	29.5
12	3.5	6.5	11	19	23
24	1	2.5	4	7	8
48	0	0.5	0.5	1	1

Model behaviour and evaluation

Figure 4.5 illustrates the predicted effect of open wind speed and fuel moisture on a 16-year-old buttongrass moorland. The open nature of this fuel complex makes wind the variable with the strongest effect on rate of fire spread. The moisture content of suspended dead fuels has a significant effect on model behaviour, although its effect is much lower than wind. Notably, fire spreads with dead fuel moisture contents that typically would be above the fuel moisture of extinction in other fuel types. This is likely because wind dominates the heat transfer processes at the head of the fire. Wind-driven advective heat transfer in the vertically-oriented fuels of buttongrass moorlands overcomes the damping effect of moisture content, allowing fire propagation under very high dead fuel moisture contents. Not shown in Figure 4.5 is the fuel age (time since disturbance, typically fire) effect. The functional form used results in an approximate 50% increase in spread rate for a doubling in age.

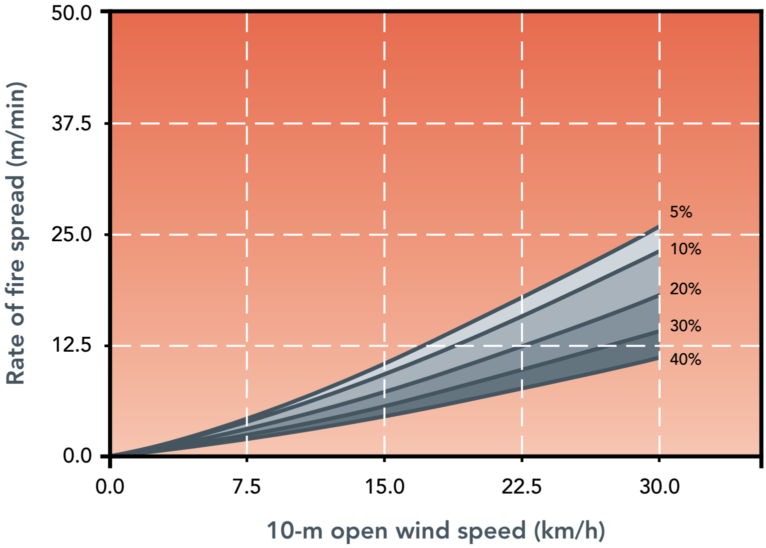


Figure 4.5. Prediction of rate of fire spread for buttongrass moorlands according to Marsden-Smedley and Catchpole (1995a) model as a function of 10-m open wind speed and fine fuel moistures content as expected to occur under prescribed burning conditions. A fuel age of 16 years is assumed. A wind adjustment factor of 0.67 was used to convert 10-m open into 2-m wind speeds.

Table 4.3. Statistics and related information associated with the evaluation of Marsden-Smedley and Catchpole (1995a) buttongrass moorlands rate of fire spread (ROS) model against independent data derived from experimental and wildfire observations.

Number of observations	ROS range (m/min)	MAE (m/min)	MAPE (%)	MBE (m/min)	Study
9	1.1 - 8.7	0.79	27	0.2	Marsden-Smedley and Catchpole (1995a)

The model predictive capacity has been compared against a small number of experimental fires, prescribed fires and wildfires (n = 9). Rates of fire spread in the model evaluation dataset varied between 1.1 and 8.7 m/min (Table 4.3). The model predicted the independent fire spread observations with a mean absolute error of 0.8 m/min (27% error) without any noticeable bias.

Temperate shrublands

Catchpole et al. (1998)

Model description

In the 1990s a group of practitioners and researchers from several Australian states and New Zealand with an interest in fire behaviour modelling in shrublands formed a working group with the aim to: (*i*) develop standardised methods to measure and describe fuels, weather and fire behaviour in shrublands, and (*ii*) to develop models for predicting shrubland fire behaviour. Data collected by this group was pooled to develop an interim fire spread rate model for Australasian shrublands (Catchpole *et al*. 1998).

Fire behaviour data originated from experimental fires, prescribed fires (Fig. 4.6) and wildfires across a diverse range of shrubland vegetation types, from semi-arid mallee vegetation in south-western Australia to buttongrass moorlands in Tasmania and Pariki heathlands in New Zealand. The dataset incorporated 133 fires covering fire spread rates and fireline intensities ranging from 0.6 to 60 m/min and 100 to 77,000 kW/m, respectively. A simple fire spread model (R, m/s) was derived from the compiled dataset:

$$R = 0.049\, U_2^{\,1.21}\ H^{0.54} \qquad [4.4]$$

where U_2 is the 2-m wind speed (m/s) and H is the average vegetation height (m), Figure 4.7. This model explained 70% of the variation in rate of spread. Notably, this analysis failed to find a significant effect of dead or live fuel moisture content on rate of fire spread. This could partially be due to the restricted range of dead moisture content in the dataset, with the lowest value at 10%, and the lack of consistency in the methods for determining dead fuel moisture content in the various studies.

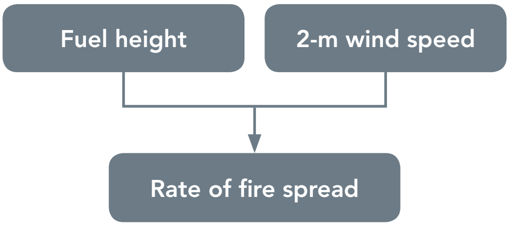


Figure 4.7. Flow diagram for the Catchpole *et al.* (1998) model for predicting the rate of fire spread in shrublands.

Figure 4.6. The potential for high intensity fire propagation in tall coastal shrublands – a prescribed burn in Wilsons Promontory NP, Gippsland, Vic (photo: David Vaskess, Parks Victoria, Vic).

Model behaviour and evaluation

The effect of 10-m open wind speed and shrub height is depicted in Figure 4.8. The effect of wind speed is approximately linear. Special care should be given to the measurement of wind speed, particularly in tall shrub vegetation. The model input is wind at 2-m above the vegetation or bare ground. The model will not work for zero wind speeds.

Fuel height, the variable intended to capture the fuel complex structure, influences the rate of fire spread through an approximate square root effect (i.e. a doubling in the height will cause a 50% increase in the output). The effect of height in the model should be treated with care. It is expected that this effect will hold in the low to medium range of wind speeds, say up to 30-40 km/h. For higher wind speeds the effect of fuel structure should be small due to the overwhelming effect of wind speed masking the effect of other variables. Nonetheless, the multiplicative nature of the fuel effect in the model implies this effect to increase with wind speed.

The lack of the dead fuel moisture effect was considered a serious limitation of the model by its authors. Catchpole (2002) pointed out that the failure to find a fuel moisture content damping effect on rate of fire spread could also be due to the combined effect of the mixture of live and dead fuels. It is expected that the model will under-predict the rate of spread when dead fuel moisture content dips below 7%. Correspondingly, the model might over-predict when the moisture contents of dead and live fuels are high, namely in spring when there is a large quantity of new growth with high fuel moisture content in the shrub canopy.

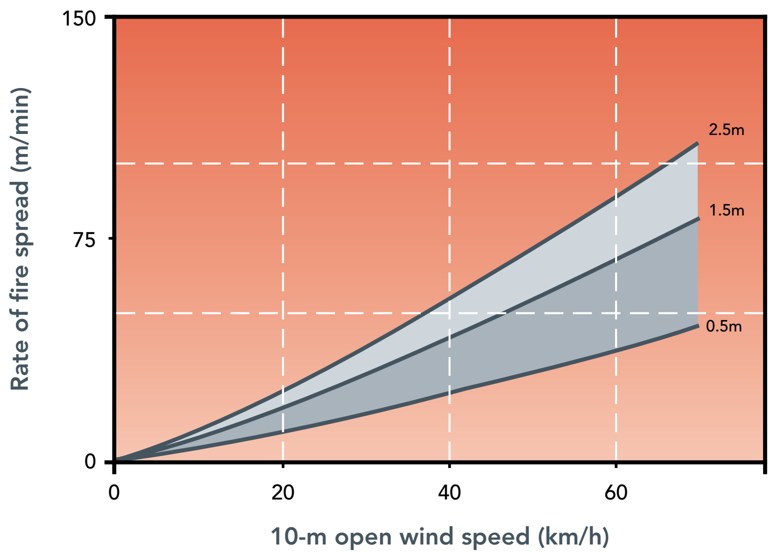


Figure 4.8. Prediction of rate of fire spread in shrublands as a function of 10-m open wind speed and fuel height as expected to occur under wildfire conditions according to the Catchpole *et al.* (1998) model. A wind adjustment factor of 0.67 was used to convert 10-m open into 2-m wind speeds.

The rate of fire spread model represented by Eq. 4.4 was evaluated against the fire spread data from experimental fires in mallee-heath shrublands in Western Australia, experimental fires and wildfires in Tasmanian buttongrass moorlands, and New South Wales Hawkesbury sandstone heathlands burned during the 1994 Sydney wildfires. The model predicted the 1994 Sydney wildfires and the Western Australian mallee-heath data with "reasonable accuracy", but no quantitative error metrics were presented. The model tended to underpredict the rate of spread for the buttongrass moorland fires. This underprediction bias is likely to arise from the fuel height function in the model not capturing well the diminutive fuel structure of the buttongrass moorlands.

Anderson et al. (2015)

Model description

Anderson *et al.* (2015) extended the work of Catchpole *et al.* (1998) by adding further data from Australia, Europe and South Africa. The dataset covered a wider range of heathland and shrubland species associations and vegetation structures, enabling the development of a generic, empirical-based fire spread rate model for shrubland vegetation. Constraints were imposed onto the data that would be used for model development purposes. Fires selected needed to meet the following criteria: (*i*) have a slope steepness < 5 degrees, (*ii*) have an ignition line length > 50 m, and (*iii*) have a measured dead fuel moisture content below 35%. The resulting dataset comprised 79 fires, with the rate of fire spread ranging between 2 and 60 m/min. The 2-m wind speed and dead fuel moisture content in this dataset varied between 4 and 25 km/h and 2 to 30%, respectively. Anderson *et al.* (2015) developed two rate of fire spread models using 10-m open wind speed, elevated dead fuel moisture content, and either

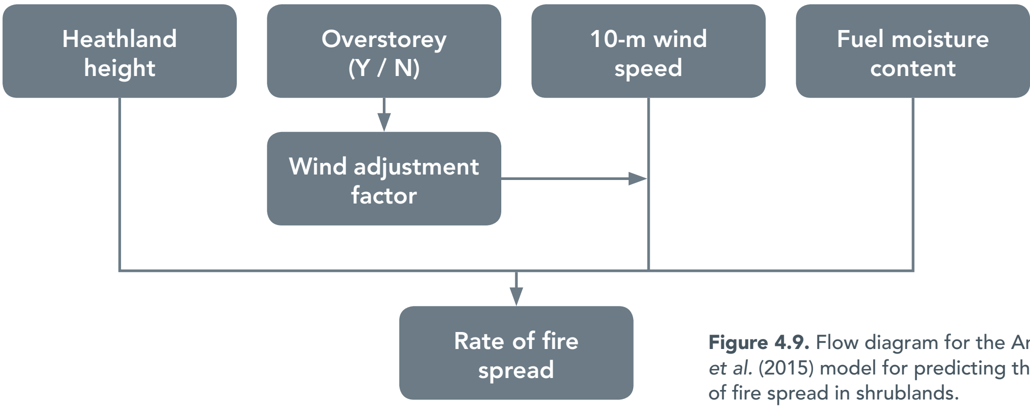


Figure 4.9. Flow diagram for the Anderson *et al.* (2015) model for predicting the rate of fire spread in shrublands.

vegetation height (with or without live fuel moisture content) or bulk density. The rate of fire spread model (R, m/min) with vegetation height and without live fuel moisture content is:

$$R = \begin{cases} [R_0 + 0.2(5.67\,(5\,WF)^{0.91} - R_0)U_{10}]H^{0.22}\exp(-0.076\,MC) & , U_{10} < 5 \\ 5.67\,(WF\,U_{10})^{0.91}H^{0.22}\exp(-0.076\,MC) & , U_{10} \geq 5 \end{cases} \qquad [4.5]$$

where U_{10} is the 10-m open wind speed (km/h), H is the average vegetation height (m) and MC is the dead fuel moisture content (Fig. 4.9). WF is a wind adjustment factor, which for the current parameterisation was set at 0.67 for heath-shrublands and 0.35 for woodlands. R_0 is the rate of fire spread for zero wind taken as 5 m/min. The model predicted the data with an average absolute error of 5.3 m/min. As a percentage, this corresponds to an average error of 40%.

The moisture content of dead suspended fuels (MC, %) can be predicted from ambient air temperature (T, °C) and relative humidity (RH, %) taking into account calendar date and cloud cover:

$$MC = 4.37 + 0.161\;RH - 0.1\;(T - 25) - \Delta\,0.027\;RH \qquad [4.6]$$

where Δ = 1 for sunny days from 12:00-17:00 from October to March (i.e. high solar radiation) and 0 otherwise (Table 4.4).

Model behaviour and evaluation

The effect of 10-m open wind speed and fuel moisture content on rate of fire spread in the model given by Eq. 4.5 is shown in Figure 4.10. The effect of wind speed is approximately linear (driven by a power law with a coefficient just less than 1.0). This coefficient is smaller than the 1.2 exponent used in the Catchpole *et al.* (1998) model. Similarly, the effect of vegetation height is lower than found in Catchpole *et al.* (1998). Overall, this results in lower rates of fire spread, commensurate with expectations (Fig. 4.10). The damping effect of dead fuel moisture content was found within the range of previous fire spread rate modelling studies in shrubland fuels.

Table 4.4. Predicted fine dead fuel moisture content (%) as a function of ambient air temperature, relative humidity and cloud cover for application of the heath fire spread model (see Eq. 4.6).

Relative humidity (%)	Clear sky, peak burning period[1]			Overcast sky, other times		
	Air temperature (°C)			Air temperature (°C)		
	20	30	40	20	30	40
5	5.5	4.5	3.5	5.5	4.5	3.5
10	6.0	5.0	4.0	6.5	5.5	4.5
15	7.0	6.0	5.0	7.5	6.5	5.5
20	7.5	6.5	5.5	8.0	7.0	6.0
25	8.0	7.0	6.0	9.0	8.0	7.0
30	9.0	8.0	7.0	9.5	8.5	7.5
35	9.5	8.5	7.5	10.5	9.5	8.5
40	10.0	9.0	8.0	11.5	10.5	9.5
45	11.0	10.0	9.0	12.0	11.0	10.0
50	11.5	10.5	9.5	13.0	12.0	11.0
55	12.0	11.0	10.0	13.5	12.5	11.5
60	13.0	12.0	11.0	14.5	13.5	12.5
65	13.5	12.5	11.5	15.5	14.5	13.5
70	14.5	13.5	12.5	16.0	15.0	14.0
75	15.0	14.0	13.0	17.0	16.0	15.0
80	15.5	14.5	13.5	18.0	17.0	16.0
85	16.5	15.5	14.5	18.5	17.5	16.5
90	17.0	16.0	15.0	19.5	18.5	17.5

[1] Applicable for clear sky conditions between October and March for the 12:00-17:00 period.

Table 4.5. Statistics and related information associated with the evaluation of Anderson *et al.* (2015) shrubland rate of fire spread (ROS) model against independent data derived from experimental fires (E), operational prescribed burns (P) and wildfire (W) observations.

Number of observations	ROS range (m/min)	MAE (m/min)	MAPE (%)	MBE (m/min)	Study
67 (E, P)	1 - 34	3.5	77	1.9	Anderson *et al.* (2015)
33 (W)	5 - 100	9.1	33	-1.5	Anderson *et al.* (2015)

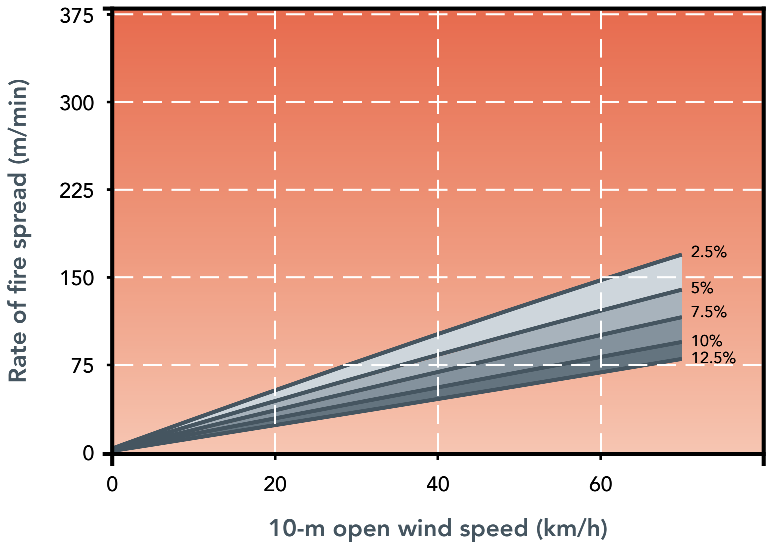


Figure 4.10. Prediction of rate of fire spread in shrublands as a function of 10-m open wind speed and fuel height as expected to occur under wildfire conditions according to Anderson *et al.* (2015) model. A fuel height of 1.5 m is assumed.

The Anderson *et al*. (2015) models were tested against independent data from experimental fires, prescribed fires and wildfires and found to predict fire spread rates within expected accuracy thresholds. Mean absolute errors varied between 3.5 m/min (77%) for the experimental/prescribed burn dataset and 9.1 m/min (33%) for the wildfire dataset (Table 4.5). The mean bias error was 1.9 m/min (over-prediction) for the controlled fire data and -1.5 m/min (~17% under-prediction bias) for the wildfire data.

Semi-arid mallee-heath

WA Mallee-heath (McCaw 1995, 1997)

Model description

McCaw (1995, 1997) presented a model for fire propagation in mallee-heath vegetation of southern Western Australia. Mallee eucalypts are a characteristic vegetation type distributed over extensive areas of semi-arid southern Australia. Typically, mallee-heath comprises a stratum of mallee (a generic term used to describe short, multi-stemmed eucalypts) ranging in height from 3-5 m and cover 20-50 per cent of ground area above a shorter stratum of woody shrubs of variable density.

A total of 18 experimental fires were attempted in 20- to 23-year-old mallee-heath plots in order to obtain fire behaviour data suitable for developing a fire propagation model. These involved a 200-m line ignition with flame fronts typically advancing up to 200 m. The vegetation at the experimental site had an overstorey stratum of *Eucalyptus pleurocarpa* and *E. pachyloma*, an intermediate stratum up to 2.5 m tall of *Xanthorrhoea platyphylla*, *Hakea crassifolia*, *Banksia falcata* and *Banksia sessilis*, and a species-rich layer of dwarf shrubs up to 1 m in height.

The experimental fires spanned a broad range of fire weather conditions: 10-m open wind speeds varied between 5 and 25 km/h, air temperature varied between 20 and 36 °C, and relative humidity ranged from 14 to 63%. The maximum forward rate of fire spread and fireline intensity was 40 m/min and 14,000 kW/m, respectively. Of the 18 experimental line fire ignitions, nine failed to sustained fire spread following ignition (i.e. they were regarded as "no-go" fires). Although the size of the dataset did not allow for factors determining fire sustainability to be modelled, the moisture content of the shallow litter layer beneath the low shrubs was found to have a controlling influence on the likelihood of fire spread. Fires spread freely when the moisture content of the shallow litter was less than 8%, regardless of the prevailing wind speed.

The forward rate of fire spread (R, m/s) was modelled through non-linear regression analysis, with the best fit given by:

$$R = 0.292\, U_2^{\ 1.05}\ exp(-0.11\, MC_{ld}) \qquad [4.7]$$

where U_2 is the wind speed (m/s) measured in the open at a 2-m height, and MC_{ld} is the moisture content of the deep litter beneath mallee clumps (Fig. 4.11). McCaw (1997) found the Nelson (1991) fuel moisture model was the best fitting of several tested, and a guide based on that model using time of day and predetermined values of air temperature and relative humidity for two typical weather patterns, was used operationally until 2008 in Western Australia. Since then the M1 fuel moisture model from the Dry Eucalypt Forest Fire model (Gould *et al.* 2007b; Matthews *et al.* 2010) has been used (see Table 5.6 and 5.7).

The model represented by Eq. 4.7 accounted for 84 per cent of variation in the spread rate of the experimental fires. Experimental fires were conducted in relatively uniform stands of mallee heath, which precluded the investigation of the influence of fuel structure on rate of fire spread. As in other shrubland fire spread studies, no significant live fuel moisture effect was found (see also Alexander and Cruz 2013b).

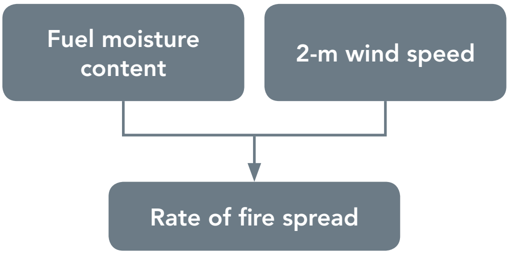


Figure 4.11. Flow diagram for the McCaw (1997) model for predicting the rate of fire spread in WA mallee-heath shrublands.

Model behaviour and evaluation

The general effect of open wind speed and fuel moisture on the McCaw (1997) rate of spread model for mallee-heath shrublands is given in Figure 4.12. The functional form and parameterisation of the wind and fuel moisture effect in this model is similar to that found in studies by Cheney *et al.* (1998) for grasslands and Marsden-Smedley and Catchpole (1995a)

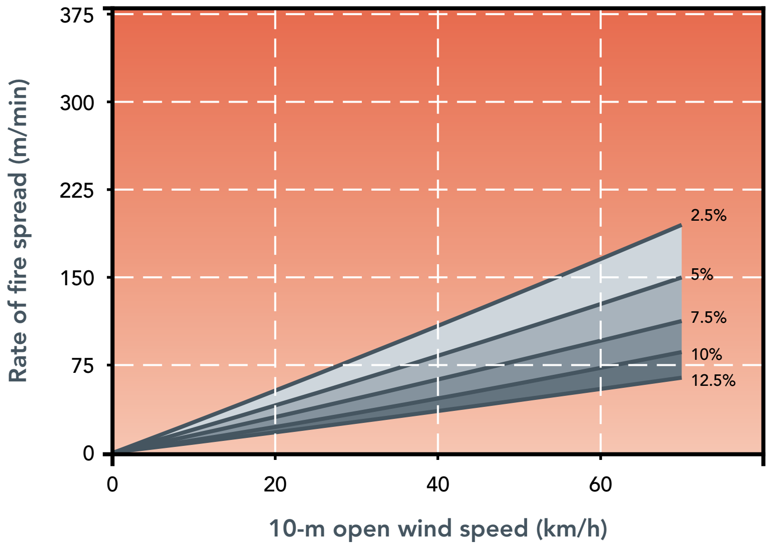


Figure 4.12. Prediction of rate of fire spread in mallee-heath shrublands as a function of 10-m open wind speed and fine fuel moisture content as expected to occur under wildfire conditions as predicted by the McCaw (1997) model. A wind adjustment factor of 0.67 was used to convert 10-m open into 2-m wind speeds.

for buttongrass moorlands. Wind speed has almost a linear effect on rate of fire spread. The effect of fuel moisture content follows an exponential decay function.

It was also found that sustained fire propagation required fuel moisture to drop below 8%. This threshold can be expected to change after a high rainfall period when the increased growth in ephemeral grasses could lead to reduced fuel discontinuities. After such events, the fuel moisture threshold might increase, although it is not expected that the sensitivity in rate of fire spread to the environmental drivers would change.

The predictions of rate of fire spread from the model matched well with observations from a limited number of prescribed fires and wildfires involving spread rates up to 61 m/min.

South Australia semi-arid mallee-heath (Cruz et al. 2010)

Model description

Cruz *et al.* (2010) conducted a experimental fire behaviour study between 2006 and 2008 at the Ngarkat Conservation Park, South Australia (Fig. 4.13). Average annual rainfall in the area is 473 mm. Vegetation was characterised as open woodland with *Eucalyptus calycogona*, *E. diversifolia*, *E. incrassata* and *E. leptophylla* as dominant overstorey species. The vegetation had three age classes as a result of major wildfires in 1958 (48- to 50-year-old fuels), 1986 (20- to 22-year-old fuels) and 1999 (7- to 9-year-old fuels).

A total of 67 experimental fires were conducted in plots ranging from 1 to 8 ha in size under a wide range of burning conditions. A number of plots were burned within a 'Very High' Forest Fire Danger Index (FFDI) class (i.e. 35 < FFDI < 50) (McArthur 1967) in order to capture

Figure 4.13. High intensity fire propagation in nine-year heath fuel complex in Ngarkat Conservation Park, SA. Average fuel height and cover were respectively 0.5 m and 45% (photo: CSIRO).

fire behaviour data representative of wildfires. Dead fuel moisture contents and 10-m open wind speed varied respectively between 2-20% and 2-24 km/h. The type of fire behaviour ranged from self-extinguishing surface fires to fires propagating as sustained active crown fires. The rates of spread in the sustained fires ranged from 3 to 58 m/min.

In developing a system to predict fire behaviour in mallee-heath fuel complexes, Cruz *et al.* (2010) recognised that operational users would require assessments to be made in two distinctly different situations involving different wind speed input variables. Fire behaviour predictions conducted in an office environment are commonly based on weather station data or forecasted weather using wind speeds measured or predicted at a height of 10-m in the open. In a field setting, model usage would rely on local wind measurements made at ~2-m height (i.e. roughly 'eye-level' within a mallee-heath stand).

To minimise the introduction of errors, two distinct model groups were developed, one relying on the 10-m open wind speeds and another based on wind speeds measured at 2-m. To extend the applicability of the mallee-heath models in support of fire management decision-making, alternative models were developed where different input fuel variables were used. Herein we describe the models that have been converted into a field-based prescribed burning guide by Cruz (2010).

The models are integrated into a fire behaviour prediction system most applicable to prescribed fire burning conditions in mallee-heath fuels but extending into 'Very High' to 'Extreme' forest fire danger classes (as defined by McArthur 1973a). The system integrates a series of models aimed at predicting the likelihood of fire propagation, the type of fire and the associated rate of spread (Fig. 4.14).

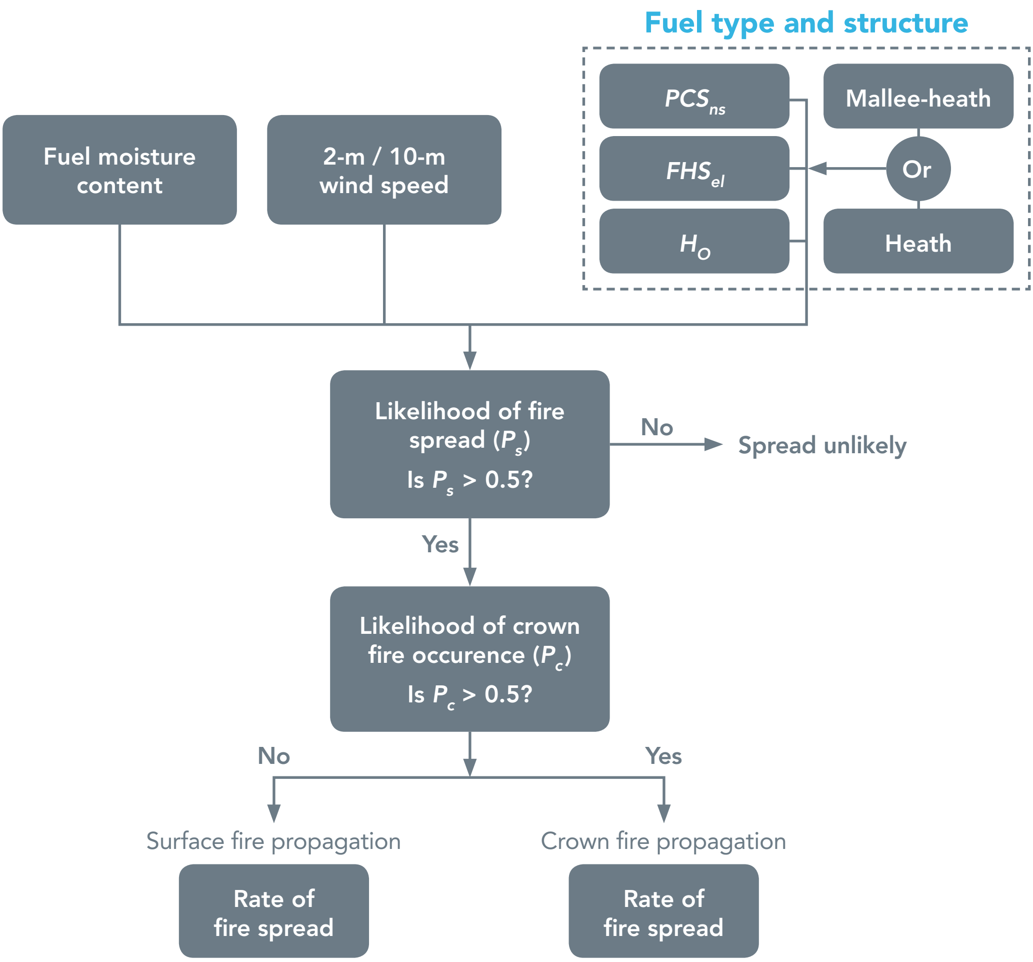


Figure 4.14. Flow diagram for the Cruz *et al.* (2010) model for predicting the rate of fire spread in SA mallee-heath shrublands. PCS_{ns} is the near surface fuel layer percent cover score, FHS_{el} is the elevated fuel hazard score and H_O is the height of the mallee overstorey layer.

The probability of successful fire spread was modelled using logistic regression analysis:

$$P_S(y=1)=\frac{1}{1+\exp[-(2.926+2.132\ U_2-2.32\ MC+5.31\ PCS_{ns})]} \quad [4.8]$$

where $P_S(y = 1)$ is the probability that a self-sustained surface fire will occur, U_2 the 2-m wind speed (km/h), *MC* is the moisture content (%) of dead suspended fuels, and PCS_{ns} is the near-surface fuel layer Percent Cover Score. The threshold P_S value separating non-spreading from spreading fires is 0.5 (i.e. fires are expected to spread if the probability is higher than 50%). Overall, this model correctly predicted 93% of the fires in the modelling dataset.

Nomograms for calculating mallee and heath fuel moisture contents (*MC*, %) from calendar date, cloud cover, air temperature (*T*, °C) and relative humidity (*RH*, %) are included in Cruz *et al.* (2010). For mallee-dominated vegetation this can be approximated as:

$$MC = 4.79 + 0.173\ RH - 0.1\ (T - 25) - \Delta\ 0.027\ RH \quad [4.9]$$

where Δ = 1 for sunny days from 12:00-17:00 from October to March (i.e. high solar radiation) and 0 otherwise (Table 4.6). For heath vegetation, equation 4.6 should be used (Table 4.4).

The probability of crown fire occurrence (P_C), only applicable to the mallee-heath fuel type, was also modelled through logistic regression analysis as a function of 10-m open wind speed (U_{10}, km/h):

$$P_C(y = 1) = \frac{1}{1+exp[-(-13.979+0.878\ U_{10})]} \quad [4.10]$$

As before, the P_C threshold value separating surface from crown fires was set at 0.5 (i.e. crown fires are expected to occur if the probability is higher than 50%). Overall, this model correctly predicted 77% of the fires in the modelling dataset.

Models for surface fire rate of spread were developed separately for pure heath and mallee-heath. For the mallee-heath fuel type, separate surface and crown fire phase models were developed. Model parameterisation relied on non-linear regression analysis. The surface fire rate of spread model for heath fuels (R_{Heath}, m/min) is as follows:

$$R_{Heath} = 2.455\ {U_2}^{1.2}\ exp(-0.11\ MC)\ {FHS_{el}}^{0.90} \quad [4.11]$$

where FHS_{el} is the elevated fuel layer Fuel Hazard Score. This equation explained 82% of the variability in the dataset and predicted the original dataset with a mean absolute error of 51%.

The surface fire rate of spread model for mallee fuels R_{Mallee}, (m/min) is as follows:

$$R_{Mallee} = 6.675\ {U_2}^{1.1}\ exp(-0.11\ MC)\ {FHS_{el}}^{1.28}\ \ {H_O}^{-0.72} \quad [4.12]$$

Table 4.6. Predicted fine dead fuel moisture content (%) as a function of ambient air temperature, relative humidity and cloud cover for application of the mallee-heath fire spread model.

Relative humidity (%)	Clear sky, peak burning period[1]			Overcast sky, other times		
	Air temperature (°C)			Air temperature (°C)		
	20	30	40	20	30	40
5	6.0	5.0	4.0	6.0	5.0	4.0
10	7.0	6.0	5.0	7.0	6.0	5.0
15	7.5	6.5	5.5	8.0	7.0	6.0
20	8.0	7.0	6.0	9.0	8.0	7.0
25	9.0	8.0	7.0	9.5	8.5	7.5
30	9.5	8.5	7.5	10.5	9.5	8.5
35	10.5	9.5	8.5	11.5	10.5	9.5
40	11.0	10.0	9.0	12.0	11.0	10.0
45	12.0	11.0	10.0	13.0	12.0	11.0
50	12.5	11.5	10.5	14.0	13.0	12.0
55	13.5	12.5	11.5	15.0	14.0	13.0
60	14.0	13.0	12.0	15.5	14.5	13.5
65	15.0	14.0	13.0	16.5	15.5	14.5
70	15.5	14.5	13.5	17.5	16.5	15.5
75	16.0	15.0	14.0	18.5	17.5	16.5
80	17.0	16.0	15.0	19.0	18.0	17.0
85	17.5	16.5	15.5	20.0	19.0	18.0
90	18.5	17.5	16.5	21.0	20.0	19.0

[1] Applicable for clear sky conditions between October and March for the 12:00-17:00 period.

where FHS_{el} is the elevated fuel layer Fuel Hazard Score and H_O is the height of the overstorey mallee stand. This equation explained 80% of the variability in the dataset and predicted the original dataset with a mean absolute error of 35%.

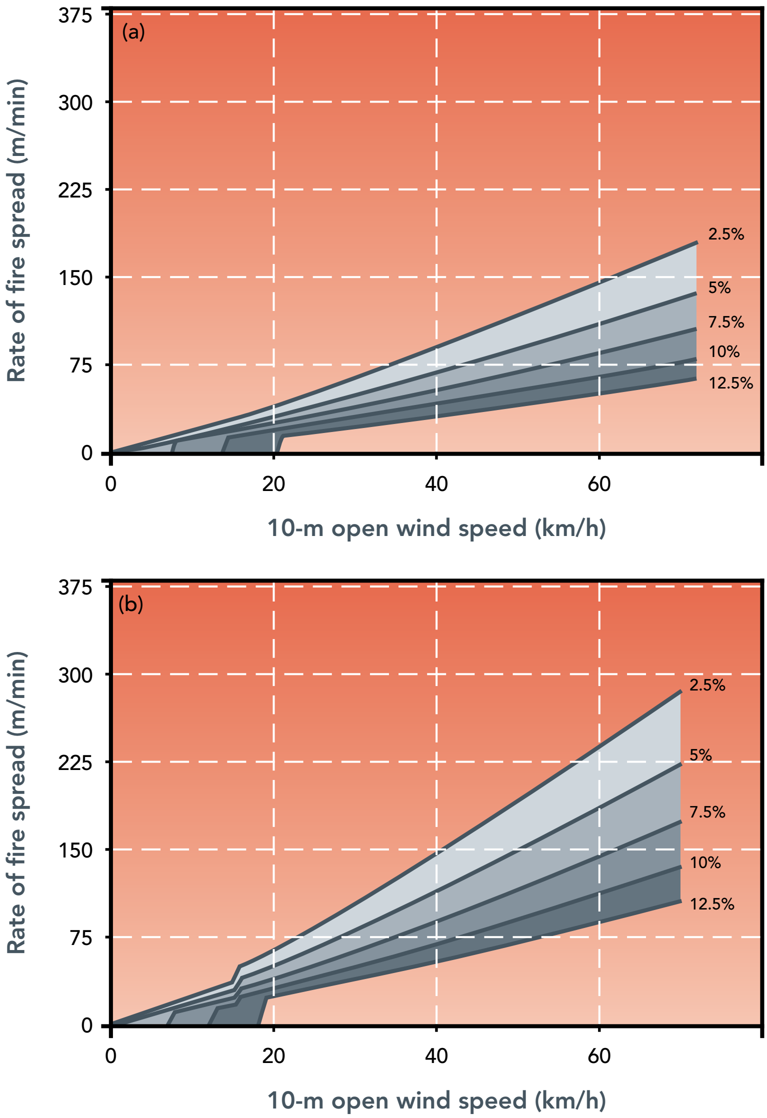
The best model to explain the spread rate of crown fires in mallee stands was:

$$R_C = 2.24\ U_{10}^{1.2}\ exp(-0.10\ MC) \quad [4.13]$$

This equation explained 80% of the variability in the dataset and predicted the original dataset with a mean absolute error of 35%.

Model behaviour and evaluation

Figure 4.15a and b shows the effects of wind speed and litter fuel moisture content on the type of fire and associated rate of spread for heath and mallee-heath shrublands. Both these



variables have a pronounced effect on the likelihood of fire propagation. Although no formal evaluation of these models against independent data has yet been carried out, operational users have reported that the "go/no-go" models perform adequately and that the fire spread models to tend to over-predict the rate of fire spread in prescribed burning conditions (Mike Wouters, DEWNR, Adelaide, 2014 *pers. comm.*).

Figure 4.15. Rate of fire spread in SA (a) heath and (b) mallee-heath shrublands as a function of 10-m open wind speed and fine fuel moistures content as expected to occur under wildfire conditions as predicted by Cruz *et al.* (2010) model. The heath simulation assumes a PCS_{NS} and FHS_{EL} of 1.5 and 1.7 respectively. The mallee-heath simulation assumes a PCS_{NS} of 1.5, a FHS_{EL} of 1.7 and an overstorey height of 3 m. A wind adjustment factor of 0.43 was used to convert 10-m open into 2-m wind speed.

Semi-arid mallee heath (Cruz et al. 2013)

Model description

Cruz *et al.* (2013) merged the datasets of McCaw (1997) and Cruz *et al.* (2010) to develop a model system for semi-arid mallee-heath fuel types in order to predict the likelihood of fire propagation (i.e. "go/no-go"), type of fire (i.e. surface or crown), forward rate of fire spread, and flame height.

The overall dataset comprised 61 experimental fires conducted under the following range of fire weather conditions: 10-m open wind speed varied between 5 and 28 km/h; air temperature varied between 16 and 39°C; and relative humidity ranged from 7 to 80%. The total fuel load comprised litter, understorey shrubs and overstorey canopy fine fuels (i.e. leaves and live twigs < 3 mm in diameter) and varied between 3.8 t/ha in a 7-year-old stand and 14.8 t/ha in a 21-year-old stand. Thirty of the 61 fires failed to propagate following ignition and were classified as "no-go" fires. The average rate of fire spread and fireline intensity for the sustained fires varied between 4 and 55 m/min and 735 and 17,200 kW/m, respectively. Flame height varied between 1 and 8 m, with an average of 3.8 m (Fig. 4.16).

The model system to predict the full range of fire behaviour in mallee-heath shrubland comprises linkages between four models (Fig. 4.18). These include: a model for fire spread sustainability (Eq. 4.14) and if the environmental conditions suggest that a fire will propagate then a model to determine the type of fire – i.e. surface fire or crown fire (Eq. 4.16). Based on the results of these models, the rate of fire spread is then determined for either a surface fire (Eq. 4.17) or a crown fire (Eq. 4.18).

Two model groups were developed, one that required wind measured at 10-m in the open and the other where wind speed is measured at a ~2-m height within a mallee-heath stand. We report here the models based on the 10-m open wind speed. The probability of successful fire spread was modelled using logistic regression analysis:

$$P_S(y=1) = \frac{1}{1+exp[-(14.62+0.207\ U_{10}-1.872\ MC-0.304\ Cov_O)]} \quad [4.14]$$

where $P_s(y = 1)$ is the probability that a self-sustained surface fire will occur, U_{10} is the 10-m open wind speed (km/h), MC is the moisture content (%) of the dead litter fuels, and Cov_o the overstorey mallee cover (%). The P_s threshold value between non-spreading and spreading fires was judged to be 0.5. This model correctly predicted 94% of the fires in the modelling dataset.

The required MC for dead litter fuels can be calculated from calendar date, cloud cover, air temperature (T, °C) and relative humidity (RH, %):

$$MC = 4.74 + 0.108\ RH - 0.1\ (T - 25) - \Delta\ (1.68 + 0.028\ RH) \quad [4.15]$$

where Δ = 1 for sunny days from 12:00-17:00 from October to March (i.e. high solar radiation) and 0 otherwise (Table 4.7).

The probability of crown fire occurrence was modelled through logistic regression analysis:

$$P_C(y=1) = \frac{1}{1+exp[-(-11.138+1.4054\ U_{10}-3.4217\ MC)]} \quad [4.16]$$

where $P_c(y = 1)$ is the probability that a crown fire will occur, with a value of 0.5 separating surface fires from crown fires. This model correctly predicted 78% of the fires in the modelling dataset.

Figure 4.16.
Top: Moderate intensity surface fire propagation in mallee-heath shrubland in Ngarkat Conservation Park, SA. Mallee overstorey is 2.5 - 3 m tall. Right: low intensity propagation in mallee clump litter (photos: CSIRO).

Table 4.7. Predicted fine dead (litter) fuel moisture content as a function of ambient air temperature, relative humidity and cloud cover for application of the Cruz *et al.* (2013) Mallee-heath fire spread model.

Relative humidity (%)	Clear sky, peak burning period[1]			Overcast sky, other times		
	Air temperature (°C)			Air temperature (°C)		
	20	30	40	20	30	40
5	4.0	3.0	2.0	6.0	5.0	4.0
10	4.5	3.5	2.5	6.5	5.5	4.5
15	5.0	4.0	3.0	7.0	6.0	5.0
20	5.0	4.0	3.0	7.5	6.5	5.5
25	5.5	4.5	3.5	8.0	7.0	6.0
30	6.0	5.0	4.0	8.5	7.5	6.5
35	6.5	5.5	4.5	9.0	8.0	7.0
40	7.0	6.0	5.0	9.5	8.5	7.5
45	7.0	6.0	5.0	10.0	9.0	8.0
50	7.5	6.5	5.5	10.5	9.5	8.5
55	8.0	7.0	6.0	11.0	10.0	9.0
60	8.5	7.5	6.5	11.5	10.5	9.5
65	9.0	8.0	7.0	12.5	11.5	10.5
70	9.0	8.0	7.0	13.0	12.0	11.0
75	9.5	8.5	7.5	13.5	12.5	11.5
80	10.0	9.0	8.0	14.0	13.0	12.0
85	10.5	9.5	8.5	14.5	13.5	12.5
90	11.0	10.0	9.0	15.0	14.0	13.0

[1] Applicable for clear sky conditions between October and March for the 12:00-17:00 period.

Models for surface fire and crown fire rates of spread were fitted using both log-linear and non-linear regression analysis. The surface fire rate of spread (R_S, m/min) model is:

$$R_S = 3.337\, {U_{10}}^{1.0}\, exp(-0.1284\, MC)\, {H_O}^{-0.7073} \quad [4.17]$$

where H_O is the mallee overstorey height (m), an age dependent stand characteristic that serves as a surrogate for other fuel characteristics in the model. This equation explained 74% of the variability in the dataset.

The best model to explain the spread rate of crown fires (R_C, m/min) is:

$$R_C = 9.5751\, {U_{10}}^{1.0}\, exp(-0.1795\, MC)\, (Cov_O/100)^{0.3589} \quad [4.18]$$

Figure 4.17. High intensity fire propagation during a prescribed burn in a mallee-heath shrubland in Ngarkat Conservation Park, SA. Mallee overstorey is 2.5 - 3 m tall (photo: CSIRO).

The use of the model system first requires an estimation of the likelihood of sustained fire spread, P_S (Eq. 4.14). If $P_S < 0.5$, then it is assumed that a line ignition will be self-extinguishing. If $P_S \geq 0.5$, then the line fire ignition is assumed to result in sustained fire spread. For spreading fires, the probability of crown fire propagation is then determined (Eq. 4.16). If $P_C \leq 0.01$, the fire is assumed to be spreading but largely controlled by the surface fuels and surface fire behaviour characteristics are in turn estimated (e.g. Eq. 4.17). If $P_C > 0.99$, fire propagation by crowning is assumed and the crown fire rate of spread model is applied (Eq. 4.18). Recognising the large uncertainty in predicted rate of fire spread around the 0.5 likelihood value, where small errors in the input can lead to substantial output errors, a weighted approach is used when $0.01 < P_C \leq 0.99$. Within this P_C range, a simple ensemble method is used with the final rate of fire spread (R) given by a weighted average of the outputs of the surface fire (R_S) and crown fire (R_C) spread rate models. The weighted factor is the probability or likelihood of crown fire propagation, P_C:

$$R = \begin{cases} R_S, & , P_C \leq 0.01 \\ (1 - P_C) \cdot R_S + P_C \cdot R_C, & , 0.01 < P_C \leq 0.99 \\ R_C, & , P_C > 0.99 \end{cases} \qquad [4.19]$$

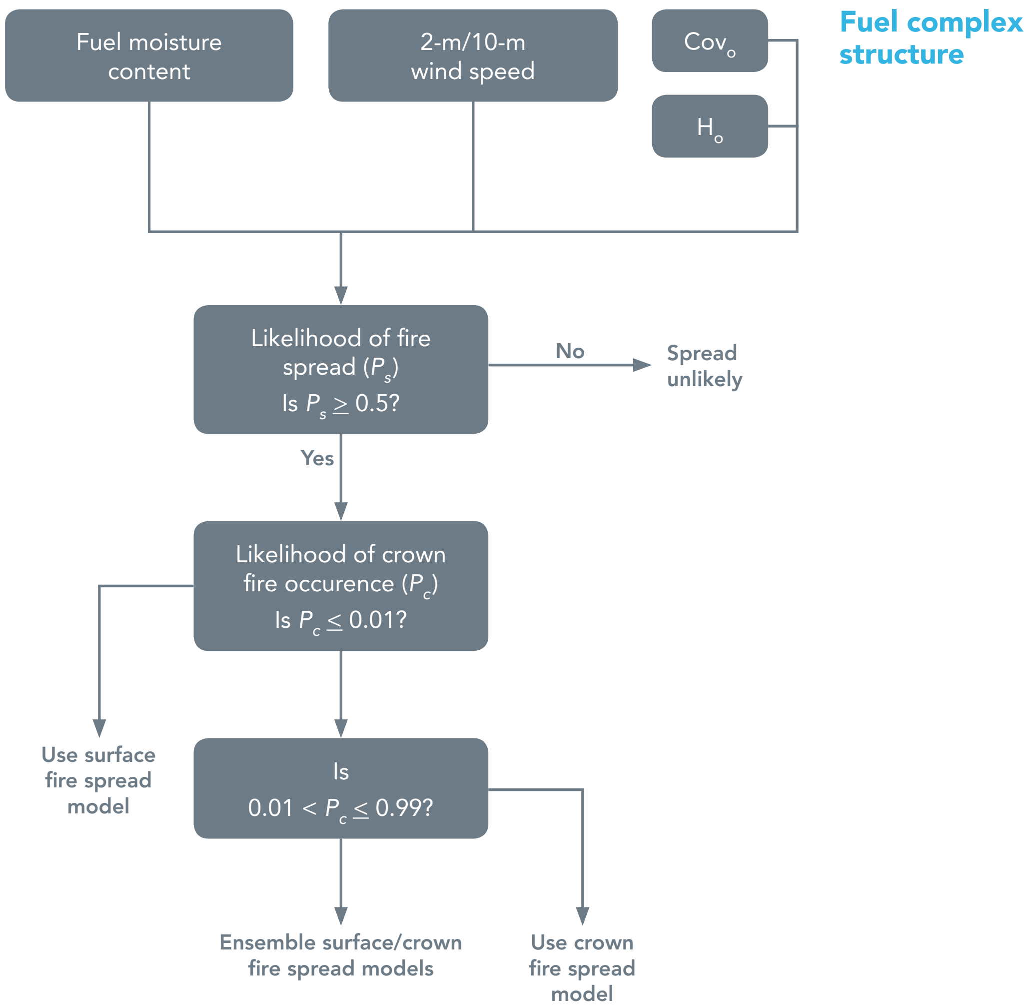


Figure 4.18. Flow diagram for the Cruz *et al.* (2013) model system to predict surface and crown fire rates of spread in semi-arid mallee-heath shrublands.

Model behaviour and evaluation

Figure 4.19 illustrates the effect of wind speed and litter fuel moisture content on the type of fire and associated rate of spread. Both these variables have a pronounced effect on the likelihood of fire propagation. At fuel moisture contents of 5% or less, wind speed is not a necessary factor in maintaining sustained head-fire propagation; active back and flank fire propagation will also occur under these conditions. For fuel moisture contents of 6% or higher, wind *is* a necessary factor to sustain fire propagation. In these fuel moisture conditions and in the absence of wind the fire might still propagate marginally within the litter of mallee clumps.

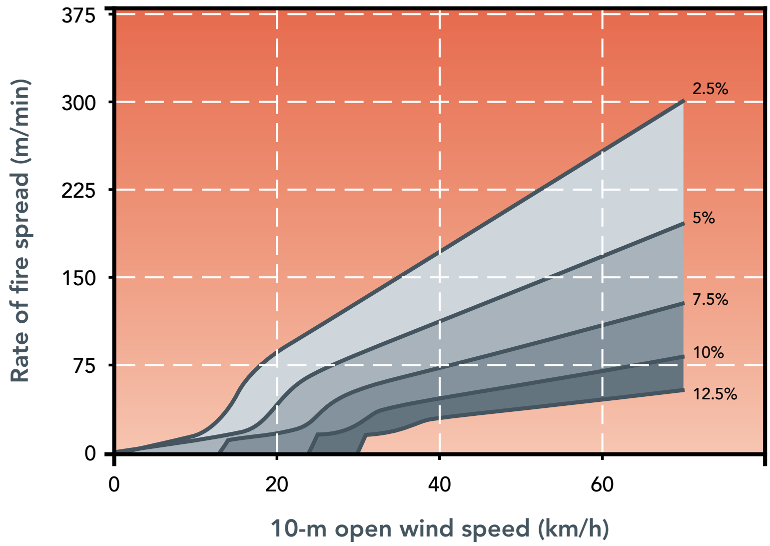


Figure 4.19. Prediction of surface and crown fire rate of spread in mallee-heath shrublands as a function of 10-m open wind speed and fine fuel moisture content as expected to occur under wildfire conditions according to the Cruz *et al.* (2013) model system. Simulation assumes a mallee overstorey cover of 33%.

The model system was evaluated against independent data from experimental fires, large-scale prescribed fires and wildfires with encouraging results. The best models for fire-spread sustainability and crown fire propagation predicted correctly 75% and 79% respectively of the fires in the evaluation dataset. The linked rate of fire spread models represented by Eq. 4.19 produced mean absolute per cent errors between 53% and 58% with only a small bias. Higher errors were associated with the wildfire data, for which larger uncertainty existed in relation to the input variables (Table 4.8). The model system is considered to have direct applicability in planning and conducting prescribed fire operations but can also be extended to produce first order approximations of wildfire behaviour.

Table 4.8. Statistics and related information associated with the evaluation of Cruz *et al.* (2013) mallee-heath rate of fire spread (ROS) model against independent data derived from experimental fires, operational prescribed burns and wildfire observations.

Number of observations	ROS range (m/min)	MAE (m/min)	MAPE (%)	MBE (m/min)	Study
13	7.5-125	18.2	53	3.1	Cruz *et al.* (2013)

5. Dry eucalypt forests

Open eucalypt forests of medium height (10-30 m), commonly referred to as dry sclerophyll eucalypt forests, occur on soils of low to moderate fertility associated with undulating plateaus, rugged escarpments and foothills of the higher ranges. These forests comprise a broad mix of genera (e.g. *Eucalyptus spp., Corymbia spp., Acacia spp.*) but are typically dominated by eucalypts. The open canopy nature of dry eucalypt forests often allows for the development of an understorey layer of dominated trees, shrubs and/or herbaceous vegetation that provide vertical fuel continuity.

Understorey fuels responsible for fire propagation are typically leaf litter, twigs and bark, and the finer components of the understorey herbaceous and shrub layer, which can vary from dense to almost absent depending on site conditions and time since last fire (Fig. 5.1). Coarse woody debris represents the bulk of the available biomass but are mostly consumed after the passage of the flame front. In eucalypt fuel complexes the presence of tree species with fibrous bark (e.g. *Eucalypt obliqua, E. marginata and E. macrorrhyncha*) is a key factor driving fire propagation (Fig. 5.2), namely through prolific spotting that occurs under very dry and windy conditions (See Spotting processes box, page 85). Candlebark and ribbon gums species (e.g. *E. viminalis, E. delegatensis, E. rubida*)

Figure 5.1. Examples of dry eucalypt forest fuel structures: **Top** – Jarrah (Eucalyptus marginata) stand in southwest WA. (photo: Jen Hollis). **Middle** – dry sclerophyll foothill forest in central Victoria of mixed eucalypt species with heights varying between 20 and 25 m (photo: Jen Hollis). **Bottom** – dry sclerophyll forest in eastern Victoria of mixed eucalypt species with heights up to 20 m (photo: CSIRO).

Figure 5.2. Bark fuel combustion during burning out operations for bushfire containment in mixed species dry eucalypt forest *(E. obliqua, E. muellerana, E. cypellocarpa)* in Victoria (photo: Greg McCarthy, DEPI, Vic).

contribute with aerodynamically optimum firebrands that can cause long distance spotting up to tens of kilometers (Cheney and Bary 1969), although it is virtually impossible to accurately quantify these distances.

The relatively open nature of these forests means that understorey dead fuels dry rapidly, often within a few days of rain, and are available to sustain fire propagation over a number of months each fire season. Fire behaviour in dry eucalypt forests may vary from mild surface fires to fully developed crown fires with fireline intensities exceeding 75,000 kW/m.

We have identified five key rate of fire spread models for dry sclerophyll eucalypt forest. For prescribed burning applications, the three main models are the *Leaflet 80* Control Burning Guide (McArthur 1962), the Forest Fire Behaviour Tables (FFBT) for Western Australia (Sneeuwjagt and Peet 1985), and the prescribed burning guide for young regrowth forest of silvertop ash (Cheney *et al.* 1992). For wildfire applications, the two main models are the McArthur (1967, 1973a) Mk 5 Forest Fire Danger Meter (FFDM) and the Dry Eucalypt Forest Fire Model (DEFFM), the result of Project Vesta (Cheney *et al.* 2012). Until recently the FFBT was also used to predict wildfire behaviour in Western Australia. As a note of caution, the following fire behavior guides have been developed for litter and shrub-dominated understories and are likely not adequate for dry sclerophyll forests in sub-tropical environments with a significant grassy understory.

Prescribed burning models

Leaflet 80 Control Burning Guide (McArthur 1962)

Model description

During the late 1950s, A.G. McArthur pioneered the research into the fire behaviour aspects of prescribed burning in dry eucalypt forests of Australia by relating the behaviour of low-intensity surface fires to easily measured fuel and weather variables. His seminal work published as *Control Burning in Eucalypt Forest* (McArthur 1962) presented a burning guide that enabled the predictions of a flame front's forward rate of spread and height from estimates of the amount of fine fuel (< 6 mm in diameter and/or thickness) available for burning, dead fuel moisture content and wind speed in the forest. This burning guide (Fig. 5.3) was based on experimental fires carried out in fuels consisting primarily of leaf, twig and bark litter with a sparse component of herbaceous and low shrub fuels.

The burning guide was originally formulated as tables (in imperial units) that were later converted to a circular slide rule (Ritchie 1970). Gould (1994) used simple linear regression analysis to derive metric equations from the data contained within the tables and graphs given in the original work.

The equations generated by Gould (1994) separate the combined effects of wind speed at 1.5 m ($U_{1.5}$) and fuel moisture content (*MC*) from the effects of fuel load (*w*) and slope steepness (θ). Rate of spread on level ground (*R*, m/min) burning a standardised fuel load of 25 t/ha is given as:

$$R = 5.492 \exp\left(0.158\, U_{1.5} - 0.227\, MC\right) \quad [5.1]$$

The rate of spread is adjusted, R_{rf}, for fuel load by:

$$R_{rf} = 0.04\, w\, R \quad [5.2]$$

Equations 5.1 and 5.2 can be combined and simplified to predict the rate of fire spread:

$$R = 0.22\, w \exp\left(0.158\, U_{1.5} - 0.227\, MC\right) \quad [5.3]$$

Finally, rate of fire spread on sloping ground (R_θ) can be adjusted by:

$$R_\theta = R \exp\left(0.0662\ \theta\right) \quad [5.4]$$

where θ is the slope angle in degrees. Note that this is slightly different from Eq. 2.1. Eq. 5.4 produces values closer to the tabled values in McArthur (1962) for negative slopes whereas Eq. 2.1 is a better approximation for steep, positive slopes. Given the results from Sullivan *et al.* (2014), we suggest Eq. 5.4 not to be used, being replaced by Eq. 2.1 and 2.2.

There was very little difference between the actual values presented in the McArthur (1962) graphs and tables and the derived results from the corresponding equations, with the fit for Eqs. 5.1, 5.2 and

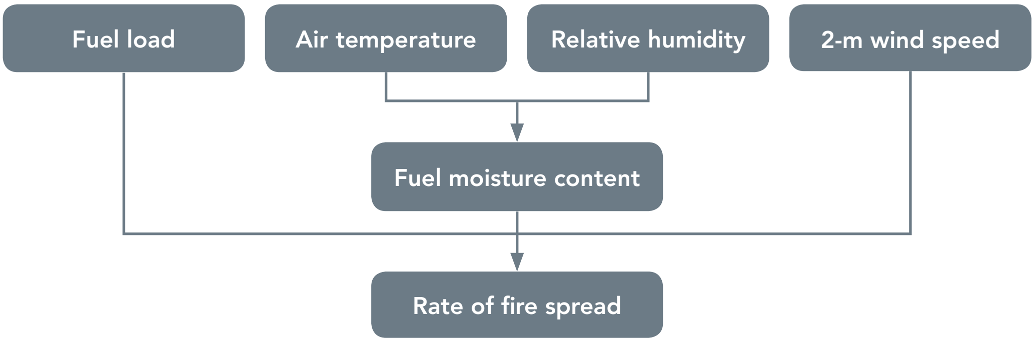


Figure 5.3. Flow diagram for the McArthur (1962) burning guide or model to predict the rate of spread of prescribed fires in dry sclerophyll eucalypt forest.

5.3 producing coefficient of determination (R^2) values ranging from 0.97 to 1.0. Gould (1994) points out that the equations were intended to describe McArthur's graphs and tables as accurately as possible. It is uncertain as to the goodness of fit of the equations to the original data as it is not known what specific fire data was used by A. G. McArthur in developing the burning guide.

Gould (1994) also derived equations from McArthur (1962) for the methods of estimating the inputs required in Eq. 5.3, namely (a) the estimation of wind speed at 1.5 m in the forest from 10-m open wind speed (or range from the Beaufort wind scale number), (b) fuel moisture from air temperature, relative humidity and time of day, (c) fuel load from years since last fire and canopy cover or from litter bed depth, and finally, (d) the fuel available for combustion from total fuel load, daily rainfall and days since last rain.

The wind speed in the forest at a 1.5 m height ($U_{1.5}$, km/h) can be predicted from the 10-m open wind speed (U_{10}, km/h) as follows:

$$U_{1.5} = 1.674 + 0.179\,(U_{10}) \qquad [5.5]$$

The dead fuel moisture content (*MC*, %) of the surface eucalypt litter can be predicted from ambient air temperature (*T*, °C) and relative humidity (*RH*, %) taking into account expected desorption conditions between 6:00 and 12:00 and adsorption conditions after 12:00 and onwards except for two days after a rainfall event of 13 mm or more. For equation for desorption conditions is (see Viney and Hatton 1989 and Gould 1994):

$$MC = 12.519 + 0.112\,RH - 0.282\,T \qquad [5.6]$$

In turn, the equation for adsorption conditions is:

$$MC = 6.783 + 0.133\,RH - 0.170\,T \qquad [5.7]$$

The application bounds for Equations 5.6 and 5.7 are: *T* range 5 – 30 °C and *RH* range 20 – 70%. Tabular outputs from the models are given in Table 5.1.

Table 5.1. Predicted fine dead fuel moisture content (%) as a function of ambient air temperature, relative humidity and wetting/drying phase for application of the *Leaflet 80* prescribed burning guides (see Eq. 5.6 and 5.7). Shaded cells are outside the bounds of the original graph in *Leaflet 80*. Use the desorption model when fuels are drying, typically before 15:00 to 16:00. Use the adsorption model when moisture content is increasing, typically after 15:00 to 16:00 when relative humidity begins to increase.

Relative humidity (%)	Desorption			Adsorption		
	Air temperature (°C)			Air temperature (°C)		
	10	20	30	10	20	30
5	Outside of range of model applicability					
10						
15						
20	12.0	9.0	6.5	7.5	6.0	4.5
25	12.5	9.5	7.0	8.5	6.5	5.0
30	13.0	10.0	7.5	9.0	7.5	5.5
35	13.5	11.0	8.0	9.5	8.0	6.5
40	14.0	11.5	8.5	10.5	8.5	7.0
45	14.5	12.0	9.0	11.0	9.5	7.5
50	15.5	12.5	9.5	11.5	10.0	8.5
55	16.0	13.0	10.0	12.5	10.5	9.0
60	16.5	13.5	11.0	13.0	11.5	9.5
65	17.0	14.0	11.5	13.5	12.0	10.5
70	17.5	14.5	12.0	14.5	12.5	11.0
75	Outside of range of model applicability					
80						
85						
90						

Recent rainfall reduces the amount of fuel available for combustion and this is calculated by multiplying the fuel load (*w*) by a fuel reduction factor (F_{rf}). The fuel reduction factor is calculated according to the number of days since rain (*N*) and the amount of rain in the last event (*P*, mm) as follows:

$$F_{rf} = 0.972 - 0.245\ \ln(P) + \ 0.342 \ln{(N)} \qquad [5.8]$$

Model behaviour and evaluation

The burning guide was developed to assess potential fire behaviour under mild burning conditions typical of low intensity prescribed fires. The guide or model outputs were not intended to reflect the spread of a fully developed, free burning fire, but rather a fire spreading during its built-up phase. This is reflected in the model outputs with relatively slow rates of fire spread even for low fuel moisture contents (< 10%) and high open wind speeds. As illustrated in Figure 5.4, the model has a modest response to wind speed. Model sensitivity to fine dead fuel moisture is similar to that found in other models for fire spread in forests. The model has a directly proportional response to changes in fuel load, with a doubling in fuel load resulting in an equal change in rate of fire spread.

Davis (1976), Tolhurst *et al.* (1992) and Gould (1994) evaluated the predictive capacity of McArthur (1962) burning guide based on a number of operational and experimental prescribed fires (Table 5.2). Davis (1976) compared the burning guide predictions with observed rates of spread in eight prescribed fires in dry sclerophyll forest at the Black Mountain Reserve (ACT). Fuel loads and observed rates of spread varied between 7 and 19 t/ha and 0.1 and 1.43 m/min, respectively. The burning guide predicted the observed rate of spread with a mean absolute error of 0.12 m/min (38%) and -0.12 m/min mean under-prediction bias. Tolhurst *et al.* (1992) used rate of spread data from 41 prescribed fires in messmate-stringybark (*Eucalyptus obliqua*) dominated forest located in the Wombat State Forest, Victoria. The observed rate of fire spread in this dataset varied between 0.1 and 2.5 m/min. The burning guide predictions yielded a mean absolute error of 0.26 m/min (48%) and a small under-prediction mean bias of -0.12 m/min. Gould (1994) used data obtained from 37 experimental prescribed fires in young silvertop ash (*E. sieberi*) regrowth forest in the south-east of New South Wales (Cheney *et al.* 1992). Observed rates of fire spread in this dataset varied between 0.4 and 3.9 m/min. The burning guide under-predicted 89% of cases, yielding a mean absolute error of 0.61 m/min (45%) and a mean bias of -0.6 m/min.

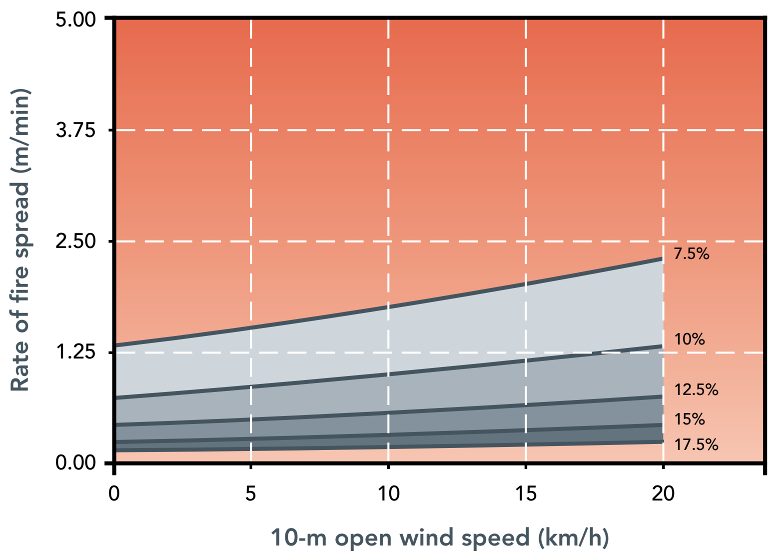


Figure 5.4. Prediction of rate of fire spread in eucalypt forests as a function of 10-m open wind speed and fine fuel moisture content as expected to occur under prescribed burning conditions as predicted by McArthur (1962) guide or model. A fuel load of 25 t/ha is assumed. Wind speed was converted from 10-m open to 1.5-m through Eq. 5.5.

Table 5.2. Statistics and related information associated with the evaluation of McArthur (1962) *Leaflet 80* rate of fire spread (ROS) model against independent data derived from prescribed burning observations.

Number of observations	ROS range (m/min)	MAE (m/min)	MAPE (%)	MBE (m/min)	Study
6	0.1 - 0.33	0.12	44	-0.12	Davis (1976)
41	0.1 - 2.5	0.26	48	-0.12	Tolhurst *et al.* (1992)
37	0.43 - 3.91	0.61	45	-0.6	Gould (1994)

Forest Fire Behaviour Tables for Western Australia – Jarrah fuel type (Sneeuwjagt and Peet 1985)

Model description

The development of formal prescribed burning guides and the practical application of prescribed burning to broad areas of eucalypt forest in south-west Western Australia was initiated in 1962 under the guidance of Forests Department research officer George. B. Peet, who applied techniques similar to those developed by Alan G. McArthur to develop a fuel type-specific prescribed burning guide for northern jarrah forest (Peet 1965, 1967, 1972) (Fig. 5.5). Data came from 130 experimental fires in jarrah (*Eucalyptus marginata*) forest near Dwellingup, WA, during the spring and summer months over three fire seasons, with a further 70 fires conducted during autumn used for evaluation purposes. Experimental fires were lit from a point and allowed to develop for periods of up to 1 hour with the perimeter marked at intervals of 4 minutes (Burrows and Sneeuwjagt 1991).

The operational expression of George Peet's research work was in the form of the Forest Fire Behaviour Tables (FFBT), first issued in 1968 in a distinctive red pocket-book format under the authority of the WA Conservator of Forests (Harris 1968). The tables were fully revised by Sneeuwjagt and Peet (1976) to incorporate a book-keeping system to predict surface and profile litter moisture contents, separate rate of fire spread tables for karri (*Eucalyptus diversicolor*) forest, and aids for estimating fuel quantity in southern forest types. In 1985 a revised rate of fire spread model for jarrah forest was incorporated into the tables (Sneeuwjagt and Peet 1985) based on provisional analysis of the data collected by Neil Burrows from experimental fires conducted under dry summer conditions. While the tables have been re-issued with later dates (e.g. the latest reprinting was carried out in 1998), the underlying models have remained unchanged since 1985.

Beck (1995) fitted equations to the tables and provided a comprehensive description of the structure of the various models, their application bounds, and the range of experimental data used to develop them. The FFBT also provide a range of other decision support guidance for fire management, including canopy scorch height, hours of burning time available, and resource dispatch levels for bushfire suppression. Further information on the development of prescribed burning guides in Western Australia is provided by Burrows and Sneeuwjagt (1991) and McCaw *et al.* (2003).

Figure 5.5. Low intensity prescribed burn in jarrah forest in the south-western WA (photo: Jen Hollis).

In the FFBT, three variables are considered to influence rate of fire spread on flat ground, these being the moisture content of the surface litter fuels (*MC*, %), the quantity of fuel available for burning (*w*, t/ha), and the in-forest wind speed measured at 1.5-2 m above ground ($U_{1.5}$, km/h). These variables are combined to compute a fire danger index for northern jarrah forest. Surface moisture content and wind speed are first used to calculate a forward rate of headfire spread (*R*, m/h), expressed as a fire danger index (*FDI*), for standard fuel and forest stand structural conditions that are typical of five-year-old jarrah fuels (after Beck 1995):

$$FDI_J = Y_J + A_J \, exp\left(U_{1.5} \, N_J\right) \quad [5.9]$$

where the subscript *J* related to the jarrah model. The functions Y_J, A_J and N_J are in turn calculated as:

$$Y_J = 21.37 - 3.42 \, MC + 0.085 \, MC^2 \quad [5.10]$$

$$A_J = 48.09 \, MC \, exp(-0.60 \, MC) + 11.90 \quad [5.11]$$

$$N_J = 0.44 - 0.0096 \, MC^{1.05} \quad [5.12]$$

George Peet

Following graduation from the University of Western Australia and the Australian Forestry School, George B. Peet joined the staff of the Western Australian Forests Department in January 1961. Almost immediately he became embroiled in the great bushfires that swept the forest regions that summer, and was lucky to survive. In their wake, Peet was directed to move to Dwellingup and initiate a program of research into fire behaviour in the jarrah forest. His research culminated in the publication of Western Australia's first prescribed burning guide; this enabled foresters to predict fire behaviour from forecast weather conditions and an understanding of forest fuels, and then to plan and implement fuel reduction burns which met a prescribed standard. Following the success of his work, Peet transferred to Manjimup where, in association with Rick Sneeuwjagt, he initiated the first fire behaviour research in the karri forest. This work also culminated eventually in the development of a burning guide for these southern forests. At the same time, he was instrumental (with others) in the development of fuel reduction burning using aircraft, a technique which later was adopted worldwide, and for which work he was awarded an Order of Australia Medal.

Moving from research to operations in the early 1970s, Peet was appointed state Manager of the Forests Department's Fire Branch, a position he held for the next 12 years. There he was responsible for instituting standards of discipline and professionalism that took the department to the international forefront of forest fire management. George currently lives in Perth, WA.

Further reading:

Peet, George (2011) Bushfire Initiation. In *Tempered by Fire*. York Gum Publishing.
Underwood, Roger (2006) The firefighter: George Peet. In *Old Growth Foresters*. York Gum Publishing.

The *FDI* can then be corrected to allow for cases where fuel load, forest stand structure or slope differ from the standard (Fig. 5.6).

Wind speed can be measured directly in the forest but is more commonly a forecast or observed value indicating conditions at 10-m height in the open or at some tower height above tree canopy. Standard conversion factors representing the ratios of open wind speed to in-forest wind speed are used to determine the fire danger index. In a jarrah forest with 60% crown cover a wind ratio of 5:1 is used with wind measurements from a tower 30 m above the forest canopy. The FFBT provide different wind ratios for situations where the forest is denser or more open, tower heights are lower, or topographic position is different from the standard.

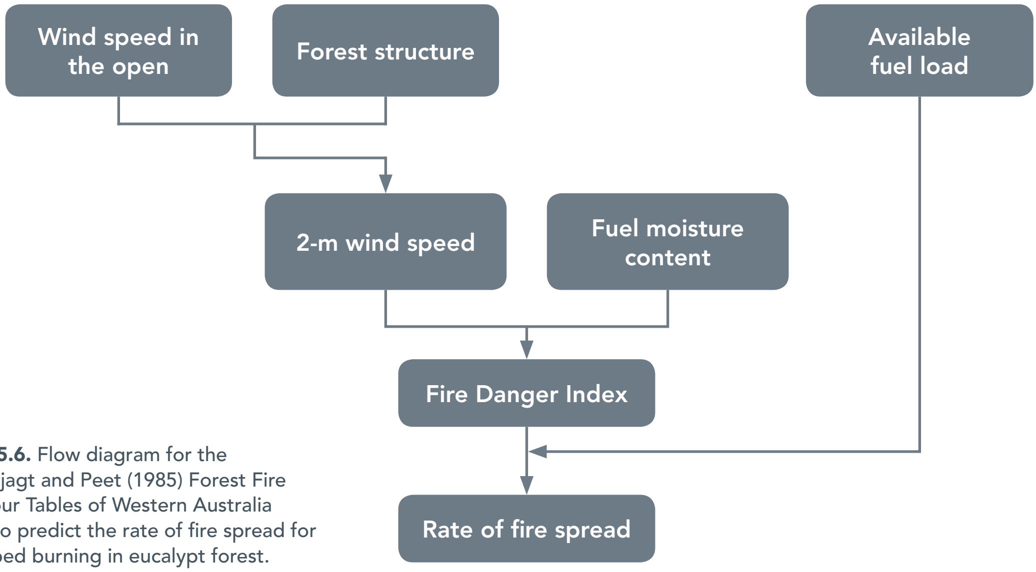


Figure 5.6. Flow diagram for the Sneeuwjagt and Peet (1985) Forest Fire Behaviour Tables of Western Australia model to predict the rate of fire spread for prescribed burning in eucalypt forest.

To predict the forward rate of fire spread in non-standard fuels, the *FDI* must be corrected for the available fuel quantity which can comprise surface litter, suspended twigs and bark (known as "trash fuel") and the available component of the standing shrub layer. Fuel quantity correction factors (*FQCF*) are derived from the available fuel quantity (*AFQ*) and the surface fuel layer *MC*. For jarrah/wandoo (*Eucalyptus wandoo*) fuel quantities between 2.5 and 8.0 t/ha the following equation applies:

$$FQCF_J = 0.1 + \frac{1.02}{1+7266.83\,exp(-1.36\,AFQ_J)} \qquad [5.13]$$

For fuel quantities greater than 8.0 t/ha, the following equations apply:

$$FQCF_J = \frac{6.03+5.81\,AFQ_J}{53.44} \quad , 3\% < \mathrm{MC} < 9\% \qquad [5.14]$$

$$FQCF_J = \frac{11.19+2.92\,AFQ_J}{35.02} \quad , 9.1\% < \mathrm{MC} < 18\% \qquad [5.15]$$

$$FQCF_J = \frac{0.055+0.0023\,AFQ_J}{0.074} \quad , 18.1\% < \mathrm{MC} < 26\% \qquad [5.16]$$

MC is modelled using a bookkeeping method where the morning *MC* is calculated from the previous afternoon's *MC*, rain amount, and the integral of overnight relative humidity above 70%. Afternoon *MC* is calculated from the morning *MC*, air temperature and relative humidity. Equations for the *MC* model were fitted to the tables by Beck (1995). The final rate of spread (*R*, m/h) is given by:

$$R = FQCF_J\ FDI_J \qquad [5.17]$$

Model behaviour and evaluation

Figure 5.7 illustrates the effect of wind speed and fuel moisture on the fire spread rate of the FFBT jarrah model. The exponential form of wind function leads to a steep increase in rate of fire spread for high wind speeds. Similarly, the effect of fuel moisture is strong. The performance of the jarrah rate of fire spread model was evaluated by Burrows (1994, 1999) and McCaw *et al.* (2008) against moderate to high intensity surface fire rate of spread data from experimental fires (Table 5.3). Rates of fire spread for the Burrows (1994) dataset ranged from 0.25 to 9.9 m/min, whereas the data used by McCaw *et al.* (2008) varied between 0.24 to 19.34 m/min. Overall average absolute error was, respectively, 0.84 m/min (54%) and 3.78 m/min (55%).

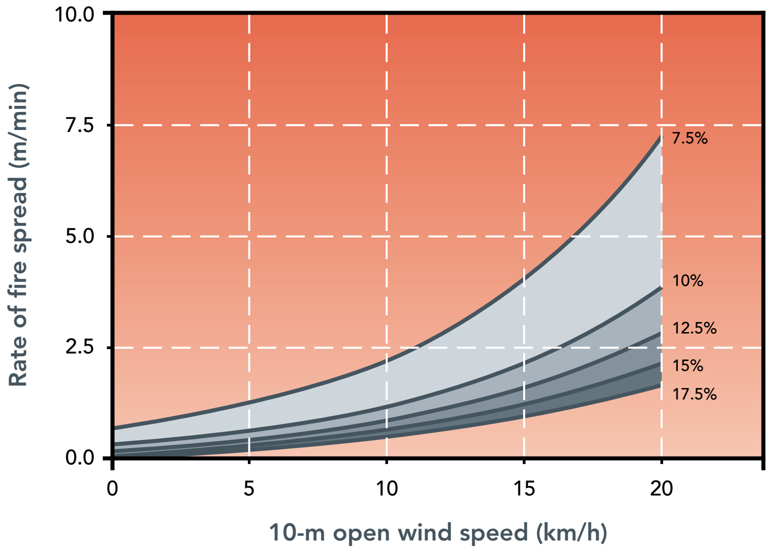


Figure 5.7. Prediction of rate of fire spread in jarrah forest as a function of 10-m open wind speed and fine fuel moisture content as expected to occur under prescribed burning conditions according to Sneeuwjagt and Peet (1985) Forest Fire Behaviour Tables of Western Australia model. A fuel load of 20 t/ha is assumed. A wind adjustment factor of 0.33 was used to convert 10-m open into 1.5-m wind speed (a wind ratio of 3:1, Beck 1995).

Table 5.3. Statistics and related information associated with the evaluation of Sneeuwjagt and Peet (1985) rate of fire spread (ROS) model against independent data derived from experimental fire (E) and wildfire (W) observations.

Number of observations	ROS range (m/min)	MAE (m/min)	MAPE (%)	MBE (m/min)	Study
35 (E)	0.25 - 9.9	0.84	54	-0.39	Burrows (1994, 1999)
97 (E)	0.24 - 19.4	3.78	55	-3.6	McCaw *et al.* (2008)
70 (W)	0.2 - 260	18.3	125	-6.7	Kilinc *et al.* (in review)

In the McCaw *et al.* (2008) study, the FFBT under-predicted rate of fire spread by a factor of two or more, particularly when observed rate of spread was > 10 m/min. A large proportion of the predictions resulted in an under-prediction. Kilinc *et al.* (in review) evaluated the FFBT against wildfire data. The model predicted the rate of fire spread with an average absolute error of 18.3 m/min (125%) and an underprediction bias of -6.7 m/min.

Prescribed burning guide for young regrowth forest of silvertop ash (Cheney et al. 1992)

Model description

Cheney *et al.* (1992) describes a study aimed at developing a prescribed burning guide for regrowth forest of silvertop ash (*E. sieberi*) in south-eastern New South Wales. Data on fuel, weather and fire behaviour were recorded on 56 experimental prescribed fires. The experimental fires were designed to enable measurement of the maximum head-fire rate of spread possible under a range of weather conditions, slope steepness, and understorey vegetation and surface fuel loads. The most significant variables identified to influence the rate of spread were wind speed at a 2-m height (U_2, km/h), which ranged from 0-6 km/h, the dead fine fuel moisture content of the near-surface fuel (*MC*, %), which ranged from 10-24 %), the height of near-surface fuels (*H*, m), which ranged from 0.2-1.2 m, and the slope in the direction of the wind (θ, degrees), which ranged from 0-25 degrees (Fig. 5.8).

The equation to predict the forward rate of fire spread (*R*, m/min) was parameterised through nonlinear regression analysis as:

$$R = -1.554 + 0.652\ U_2^{0.648} + 199.921 \exp(-0.396\ MC) + 1.61\ H + 0.369 \exp(0.062\ \theta) \qquad [5.18]$$

This equation yielded an R^2 value of 0.78. Eq. 5.18 has been coded into a nomogram for field estimation of rate of fire spread (see Figure 31 in Cheney *et al.* 1992). A *MC* model was not developed but the McArthur (1962) burning guide (Eqs. 5.6 and 5.7) or the Dry Eucalypt Forest Fire (Matthews *et al.* 2010) litter models could be used. The Forest Fire Danger Meter *MC* model (see Eq. 5.21 below) is not recommended, as it is most suitable only for dry litter fuels exposed to solar heating in summer.

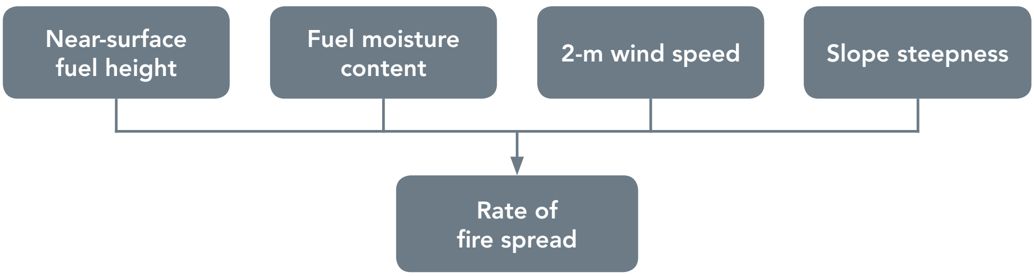


Figure 5.8. Flow diagram for the Cheney *et al.* (1992) model to predict the rate of fire spread in prescribed burns in young regrowth forests of silvertop ash.

Model behaviour and evaluation

The Cheney *et al.* (1992) prescribed burning guide can be seen as an alternative to the McArthur (1962) guide for high productive forest types where near-surface and elevated fuels are the predominant understorey fuels. The wind and moisture content functions in the model suggest that the model should be restricted to the bounds of the original dataset and to similar eucalypt forest types.

The relatively small power coefficient in the wind function yields a low sensitivity to wind speed (Fig. 5.9). Fuel moisture content is the variable with the strongest effect on fire propagation, with the magnitude of the effect increasing with a decrease in fuel moisture below 15%. Near surface fuel height, the surrogate of understorey fuel structure, has a linear and constant effect on rate of spread. This means that for marginal burning conditions (e.g. moisture content around 15% or higher), fuel structure will have a significant effect on fire behaviour. But this effect becomes less critical for drier fuels (e.g. moisture content less than 10%).

It is worth noting that the Cheney *et al.* (1992) prescribed burning guide was designed to predict the rate of fire spread of a well-established linear flame front, spreading under pseudo-steady conditions. The model will not replicate the spread rate of operational prescribed fires ignited using complex line or point source ignition patterns. There has been limited application of the Cheney *et al.* (1992) model represented by Eq. 5.18 to predict the behaviour of prescribed burns in eucalypt forest fuel types other than the original regrowth eucalyptus forest in the southeast region of NSW.

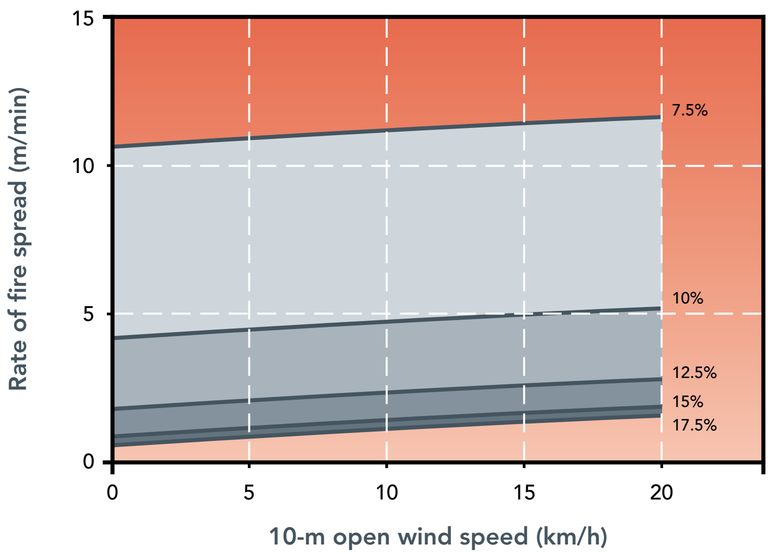


Figure 5.9. Prediction of rate of fire spread in young regrowth forests of silvertop ash as a function of 10-m open wind speed and fine fuel moisture content as expected to occur under prescribed burning conditions according to the Cheney *et al.* (1992) model. Near surface fuel height of 0.4 m is assumed. Wind speed was converted from 10-m open to 1.5m through Eq. 5.5.

Wildfire models

McArthur Mk 5 Forest Fire Danger Meter (FFDM) (McArthur 1967, 1973a)

Model description

The development of McArthur's Forest Fire Danger Meters saw a number of different versions produced beginning in the early 1960s that culminated with the publication of the Mk 4 version (McArthur 1967) and its SI unit variant, the Mk 5 meter, some years later (McArthur 1973a). An important principle in McArthur's approach to fire spread modelling was that fire danger and fire behaviour were intimately linked, with fire spread being directly determined from the fire danger index, a relative numerical scale.

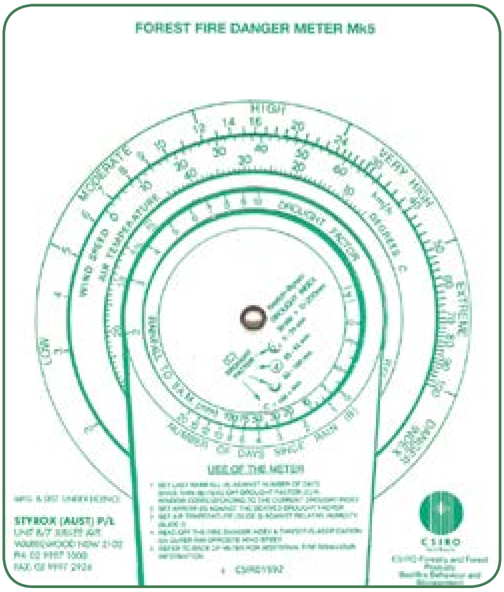


Figure 5.10. A recent reprint of the Mk 5 Forest Fire Danger Meter.

Early development of McArthur's forest fire danger rating system in the late 1950s was based on fire behaviour measurements associated with experimental fires conducted in dry sclerophyll eucalyptus forest (10-20 m tall) carrying continuous surface fuel of leaf, twig and bark litter with some understorey vegetation present at times (McArthur 1958; McArthur and Luke 1963). Fuels were relatively uniform with a characteristic fuel load of approximately 12.5 t/ha (Cheney 1968). Each experimental fire was given a suppression difficulty rating, later redefined as fire danger classes (Cheney 1991). The difficulty-of-suppression/fire danger rating was related to the head-fire rate of spread, the surface moisture content of the fine fuels, wind speed and fuel load.

Originally the fire danger rating was presented as a series of tables (McArthur 1958). Periodic updates to the meter aimed to incorporate the latest understanding in fire behaviour garnered from a continuously increasing number of experimental fires and documented wildfires. McArthur (1967) published the Mk 4 version of the meter in circular slide rule form (Fig. 5.10). The front of the meter allowed for the calculation of a Forest Fire Danger Index (FFDI) on the basis of long-term drought, recent rainfall, air temperature, relative humidity, and wind speed. The back of the meter provided tables for estimation of three fire behaviour characteristics related to the FFDI, namely rate of fire spread, flame height, spotting distance and type of fire. (surface or crown, Fig. 5.11). It is worth noting that limited documentation and data accompanied the development of the meter other than what is presented in McArthur (1967).

The tabulated indices and rate of spread values from the FFDM were converted to equations by Noble *et al.* (1980). The equations were derived from data taken either by measuring displacement along the scale, by taking it directly from the table on the back of the meter, or from hand-drawn graphs provided by A.G. McArthur. The FFDI function was parameterised as:

$$\mathrm{FFDI} = 2.0\ exp\ (-0.450 + 0.987\ \ln(D) - 0.0345\ RH + 0.0338\ T + 0.0234\ U_{10}) \quad [5.19]$$

where D is the Drought Factor ($0 < D \leq 10$), RH is the relative humidity (%), T is the air temperature (°C) and U_{10} the average 10-m open wind speed (km/h).

MC is not explicitly included in the equation to calculate the FFDI, instead it is incorporated through T and RH (Fig. 5.12). Matthews (2009) reformulated Eq. 5.19 to enable MC to be explicitly included:

$$\mathrm{FFDI} = 34.81\ exp^{0.987\ ln(D)}\ MC^{-2.1}\ exp^{0.0234\ U_{10}} \quad [5.20]$$

As a result, any suitable MC model for dry eucalypt litter can be utilised. McArthur (1967) included a table for predicting MC from T and RH (see Table 5.4), which was approximated by Viney (1992) as:

$$MC = 5.658 + 0.04651\ RH + 0.0003151\ RH^3\ T^{-1} - 0.184\ \mathrm{T}^{0.77} \quad [5.21]$$

Table 5.4. Predicted fine dead fuel moisture content as a function of ambient air temperature and relative humidity for application of the Mk 5 Forest Fire Danger Meter model (see Eq. 5.21). Shaded cells are outside the bounds of the original table in *Leaflet 107*.

Relative humidity (%)	Air temperature (°C)			
	10	20	30	40
5	5.0	4.0	3.5	2.5
10	5.0	4.5	3.5	3.0
15	5.5	4.5	4.0	3.0
20	6.0	5.0	4.0	3.5
25	6.0	5.0	4.5	4.0
30	7.0	5.5	5.0	4.0
35	7.5	6.0	5.0	4.5
40	8.5	6.5	5.5	5.0
45	9.5	7.5	6.0	5.5
50	11.0	8.0	7.0	6.0
55	12.5	9.0	7.5	6.5
60	14.0	10.0	8.0	7.0
65	16.0	11.0	9.0	7.5
70	18.5	12.5	10.0	8.5

The drought factor (D), a measure of fuel availability for consumption at a landscape level, can be estimated as:

$$D = \frac{0.191\,(KBDI+104)\,(N+1)^{1.5}}{3.52\,(N+1)^{1.5} + P - 1} \quad [5.22]$$

where $KBDI$ (mm) is the Keetch-Byram Drought Index (Keetch and Byram 1968) as advocated by McArthur (1966b), N is the number of days since rain, and P is the amount of precipitation (mm) in the last rain event.

D is bound to a maximum value of 10, i.e., if the calculated value is higher than 10, the input into Equation 58 and 59 is 10.0. Although the drought factor calculation can potentially yield a value of 0, the form of Equation 58 and 59 require a value higher than 0.

Noble *et al.* (1980) admitted that the equation for calculating D (Eq. 5.22) does not produce an exact fit to McArthur's discontinuous (step) function used in the FFDM. No assessment of its performance was provided but it was considered to be suitable "for most purposes".

Sirakoff (1985) and Griffiths (1999) found that the values of D calculated by Noble *et al.* (1980) and the value determine from the FFDM for the same conditions could result in marked differences in the FFDI calculations. Griffiths found that the difference could be as much as two fire danger class ratings (e.g. Extreme vs. High). In order to provide a smooth transition of D across soil moisture deficiency boundaries, Griffiths (1999) derived a new equation for D:

$$D = min\left[10.5\left(1 - exp\frac{-(I+30)}{40}\right)\frac{y+42}{y^2+3y+42}, 10\right] \quad [5.23]$$

where y is a function calculated as follows:

$$y = (P-2)/N^{1.3} \qquad \text{, if } N \geq 1 \text{ and } P > 2, \quad [5.24]$$

$$y = (P-2)/0.8^{1.3} \qquad \text{, if } N = 0 \text{ and } P > 2, \quad [5.25]$$

$$y = 0 \qquad \text{, if } P \leq 2. \quad [5.26]$$

Figure 5.11. Transition between surface and crown fire spread in dry sclerophyll jarrah (*E. marginata*) forest in south-western WA. Image illustrates the importance of understorey shrub vegetation and bark fuels on the onset of crowning (photo: CSIRO).

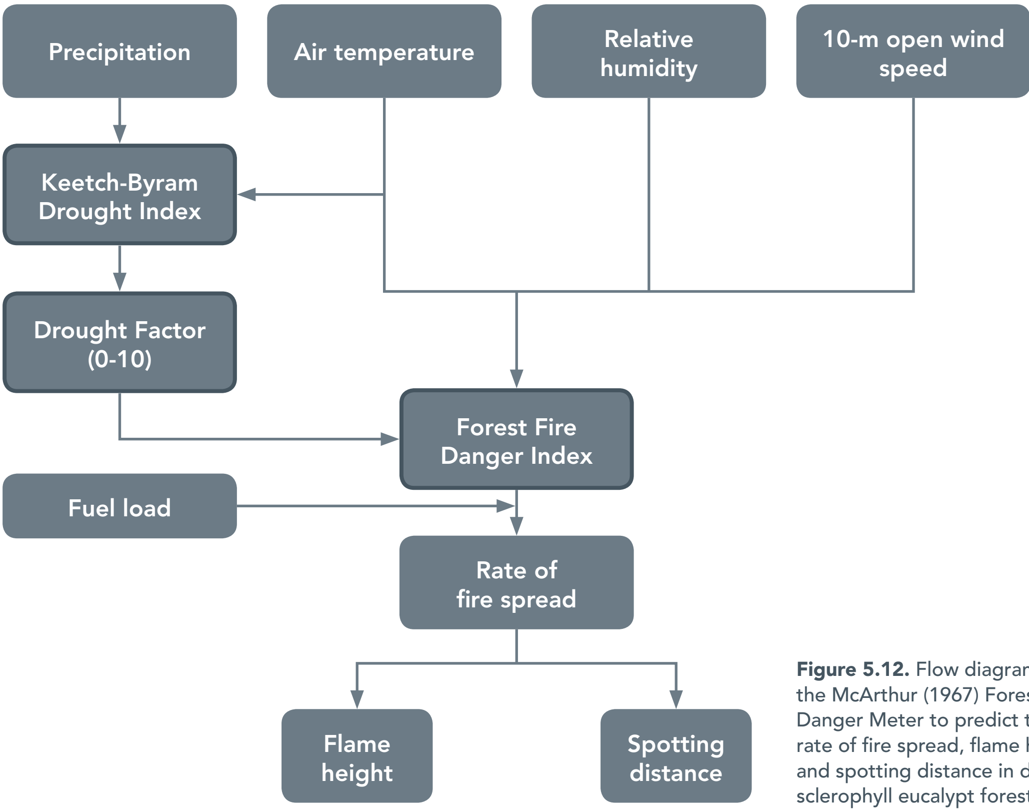


Figure 5.12. Flow diagram for the McArthur (1967) Forest Fire Danger Meter to predict the rate of fire spread, flame height and spotting distance in dry sclerophyll eucalypt forests.

Finkele *et al.* (2006) extended this approach to develop a nationally applicable gridded forecast tool for *D*, comparing the effects of choice of model for the soil moisture deficiency value. They found that use of Mount's Soil Dryness Index (Mount 1972) instead of the *KBDI* generally led to higher soil moisture deficits, which results in a higher *D* value, primarily due to the difference in the treatment of evapotranspiration. The review of Sullivan (2001) discussed these differences and impacts on the calculation of *D* in some detail.

The equation for predicting rate of fire spread on flat ground (*R*, km/h) derived by Noble et al. (1980) from McArthur's (1973a) Mk 5 FFDM is:

$$R = 0.0012 \text{ FFDI } w \quad [5.27]$$

where *w* is the fuel load (t/ha). Equations 5.19 through 5.27 are accepted as providing good estimates of the original circular FFDM slide rule values, and have been incorporated into a number of automated systems for calculating FFDI and predicting fire behaviour such as Australis (Johnston *et al.* 2008), PHOENIX RapidFire (Tolhurst *et al.* 2008), SiroFire (Coleman and Sullivan 1996) and Amicus (Sullivan *et al.* 2013b).

Model behaviour and evaluation

The rate of fire spread component in the McArthur (1967) FFDM has been subject to a number of reviews and evaluations (Burrows and Sneeuwjagt 1991; Cheney 1991; McCaw *et al*. 2008). It is commonly agreed that under dry conditions the model will under-predict the spread rate of a wildfire propagating with a well-established flame front (Burrows 1994). Cheney (1985) and later Cheney and Gould (1996) determined this under-prediction bias to be by a factor of three or more. This is likely due to the wind function that results in a conservative response under moderate to high wind speeds (Fig. 5.13). This might be a result of the model being parameterised based on fires propagating in litter fuel beds where the wind effect is lower than observed in fuel complexes with a understorey dominated by near-surface and or elevated fuels. The model has a strong dead fuel moisture content effect, particularly when the moisture level drops below about 6-7% (McArthur 1967). This strong effect aims to capture the contribution of profuse short-range spotting that occurs at lower fuel moisture contents levels, leading to a step-change increase in rate of fire spread (Cheney and Bary 1969).

The significance of fuel structure is incorporated into the model through the effect of fuel load. As previously discussed with respect to McArthur's (1962) prescribed burning guide, in the FFDM model fuel load has a directly proportional effect on rate of spread (i.e. a doubling in fuel load results in doubling in rate of fire spread). Recent research has shown that the effect of fuel load on rate of fire spread is dependent on weather conditions driving the fire propagation process. McCaw *et al.* (2012) found that for dry fuel conditions, fuel load was a significant factor under low wind speeds but less significant under strong wind speed conditions. This might explain the fuel load effect found by A. G. McArthur in his early experimental work under mild burning conditions.

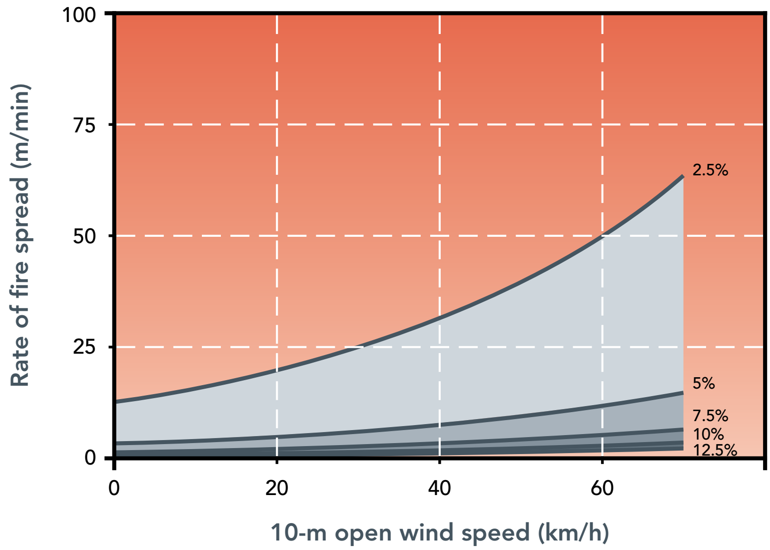


Figure 5.13. Prediction of rate of fire spread in dry sclerophyll eucalypt forests as a function of the 10-m open wind speed and fine fuel moistures content as expected to occur under wildfire conditions according to the McArthur (1967) Forest Fire Danger Meter. A fuel load of 25 t/ha and a *D* of 10 are assumed.

The predictive capacity of the FFDM has been reported in a number of studies. We restrict our analysis to studies with a substantial number of fires, enabling the calculation of robust error statistics. Studies where the FFDM outputs were compared with only a few spread rate observations are not discussed here. We also only report on studies that compared the FFDM with fires burning under moderate or higher fire danger conditions (Table 5.5), leaving out comparisons of model output against prescribed fire data (e.g. Tolhurst *et al.* 1992).

Burrows (1994, 1999) evaluated the predictive capacity of the FFDM against data from 35 experimental fires in jarrah (*Eucalyptus marginata*) forest of the south-western region of Western Australia (Table 5.5). Rates of fire spread varied between 0.25 and 9.9 m/min in this dataset. The McArthur (1973a) Mk 5 meter predictions had an associated mean absolute error of 1.13 m/min (56%). 66% of the data was found to be under-predicted, resulting in an under-prediction mean bias of -0.9 m/min.

McCaw *et al.* (2008) evaluated the performance of the rate of fire spread component of the Mk 5 FFDM against head-fire spread rate data from Project Vesta (Gould *et al.* 2007a) (Table 5.5). Data were divided into two jarrah forest types with distinct understorey fuel structures (sparse shrub layer vs. and tall shrub layer). Rates of fire spread for this dataset ranged from 0.24 to 19.34 m/min. Overall absolute error was 4.0 m/min (65%). The Mk 5 FFDM under-predicted the rate of fire spread by a factor of two or more, particularly when the observed rate of fire spread was > 10 m/min. 81% of the predictions resulted in an under-prediction. The error statistics indicated better agreement between the predicted and observed rates of spread in the sparse shrub understorey than in the tall shrub understorey fuel layer. The rates of fire spread predicted by the Mk 5 FFDM were closest to observed values when 10-m open winds were less than 12 km/h in the sparse shrub understorey fuel type.

Kilinc *et al.* (in review) evaluated the performance of the Mk 5 FFDM against data from 181 wildfire spread rate observations obtained from southern Australia (Table 5.5). The main fuel types in this dataset were dry sclerophyll forest with and without understorey vegetation and a few fires in more productive wet/mixed forests (n = 7). Rates of fire spread in this dataset varied between 0.2 and 260 m/min. The use of the Mk 5 FFDM with fuel load being restricted to the original McArthur formulation (i.e. only considering litter and near surface fuels) resulted in an average absolute error of 38 m/min (86% mean error) and an average under-prediction bias of -37 m/min.

Table 5.5. Statistics and related information associated with the evaluation of McArthur (1967) *FFDM Mk 5* rate of fire spread (ROS) model against independent data derived from experimental fires (E) and wildfire (W) observations.

Number of observations	ROS range (m/min)	MAE (m/min)	MAPE (%)	MBE (m/min)	Study
35 (E)	0.25 - 9.9	1.13	56	-0.89	Burrows (1994, 1999)
97 (E)	0.24 - 19.4	3.78	55	-3.6	McCaw *et al.* (2008)
181 (W)	0.2 - 260	38	86	-37	Kilinc *et al.* (in review)

Spotting and high intensity fire propagation in eucalypt forests

Spotting is an important, at times dominant, fire propagation process in high intensity fires in eucalypt forests. The type of tree bark will determine the size, shape and number of firebrands, which with the prevailing weather conditions will dictate the spotting distances and density of ignitions.

Fibrous bark, present in species such as *Eucalypt obliqua*, *E. marginata* and *E. macrorrhyncha*, is easily ignited and dislodged from the trunk, allowing simultaneously for vertical fire propagation into the overstorey and profuse short- to medium-range spot fire ignitions. Species with smooth decorticating bark (e.g. *E. viminalis*, *E. globulus*, *E. delegatensis*) provide aerodynamically efficient, firebrand material that can remain alight for long periods and be transported over considerable distances.

Spotting can be classed into three categories based on distance and density distribution.

Short-range spotting

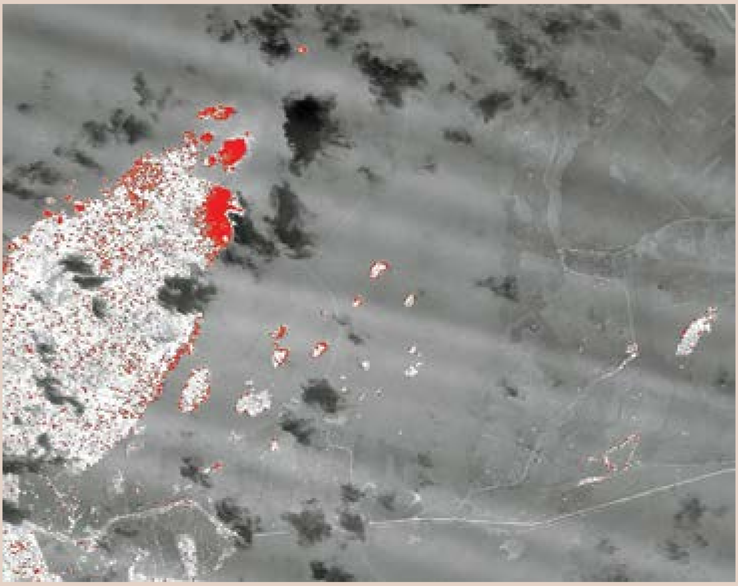
Short-distance spotting (including ember showers) includes all spotfires up to 500-750 m from a fire front and is generally the result of embers and firebrands blown directly ahead of the fire with little to no lofting. Short-range spotting density tends to decrease with distance from the fire front. Under drier and windier burning conditions higher spotting densities are expected as litter fuels are more susceptible to ignition from smaller embers and more firebrands are transported in flatter trajectories.

The coalescence of multiple short-range spotfires results in the development of deep flaming zones, crowning and further generation and transport of burning embers. McArthur (1967) describes this process as key to how a fire maintains overall rates of spread much higher than expected in the absence of spotting. Key components for the maintenance of this process are the presence of high surface fuel loads, long unburnt eucalypt forest with a significant number of species with fibrous bark, high wind speeds and low fuel moisture contents. With fuel moisture contents <4% and in the presence of wind, the likelihood of spotfire ignitions increase significantly as the heat requirements for ignition are reduced. In this situation even tiny glowing particles have sufficient energy to start new spot fires (Ellis 2011).

A quantitative understanding of short range spotting dynamics, namely firebrand density distribution with distance from the fire front, and how distinct fires coalesce in a highly turbulent environment, is lacking.

Medium-range spotting

Medium-distance spotting (1000-5000 m) results from embers and firebrands that are lofted briefly in the convection column, blown directly out of tree tops from an elevated position such as a ridge without being lofted or from the collapse of the convection column at a break in fuel or topography. In the absence of any break in fuel or topography, isolated medium-range spot



Infra-red scan image showing short- and medium-range spotting during the 2012 Tostaree fire in Victoria (photo source: Country Fire Authority, VIC).

fires are generally overrun by the main fire front. When a pattern of concentrated medium-range spotting develops, pseudo flame fronts (McArthur 1967) lead to an immediate large increase of the overall rate of fire spread. Concentrated medium-range spotting can produce mass fire or firestorm effects (Luke and McArthur 1978). In this situation a large number of coalescing fires causes strong turbulent inflow circulation that results in high intensity burning.

Long-range spotting

Long-distance spotting (>5000 m) results from extended flight paths associated with significant lofting in a well-developed convection column and long burn-out times of firebrands. This class of spotting generally creates an isolated ignition that develops as a separate fire. Long-range spotting of approximately 30 km has been authenticated on several occasions in eucalypt forests (Hodgson 1967; McArthur 1969; Cruz *et al.* 2012).

The firebrands responsible for long-range spotting are thought to be long streamers of decorticating bark that normally hang from the upper branches in certain smooth-barked eucalypt species such as *E. viminalis*, *E. globulus*, *E. delegatensis* (Cheney and Bary 1969). The bark strips curl into hollow tubes that when ignited at one end can burn for as long as 40 minutes (Hodgson 1967). The long combustion times coupled with their good aerodynamic properties (Luke and McArthur 1978; Ellis 2011) allows these firebrands to be a viable ignition source even when transported over long distances. Long-range spotting also requires an intense fire that maintains a strong upward motion in the buoyant plume to transport relatively large fuel particles several kilometres above the ground and strong winds aloft to transport firebrands for extended distances downwind.

To counter the known under-prediction bias in the Mk 5 FFDM, some authors have suggested the use of total fuel load, defined as the sum of fine surface, elevated and bark fuels (e.g. McCarthy *et al.* 1999), instead of only the surface (i.e. litter) and near-surface fuels as parameterised by McArthur (1973a). This increase in the fuel load causes a proportional increase in the predicted rate of fire spread. Kilinc *et al.* (in review) found that the addition of the shrub and bark fuel components to the fuel load will increase predicted rate of spread but still result in an under-prediction bias. For this scenario, the model predictions resulted in an average absolute error of 33 m/min (100% mean error) and an average under-prediction bias of -28 m/min.

Dry Eucalypt Forest Fire Model (also known as Project Vesta, Cheney et al. 2012)

Model description

Project Vesta aimed to investigate the behaviour of moderate to high-intensity fires in dry eucalypt forest under conditions of moderate to high forest fire danger associated with dry summer conditions (Gould *et al.* 2007a; Cheney *et al.* 2012). The objectives were to address issues arising from observations of poor performance of the FFDM, the apparent lack of effect of fuel load on observed rates of spread (Burrows 1994), and to develop a new nationally applicable model for fire behaviour in dry eucalypt forest for summer conditions. This project was conducted in south-western Western Australia during the summers of 1998, 1999 and 2001 at two sites in eucalypt forest comprised of jarrah (*Eucalyptus marginata*) and marri (*Corymbia calophylla*) with top heights of 25-30 m in which prescribed burning had been used to manipulate fuel age from 2 to 22 years. The two sites had contrasting understorey fuel structures of tall and low shrubs that had developed since the last fire. These were intended to be representative of most dry eucalypt forests found around the country. The design and execution of these experiments are described in Gould *et al.* (2007a). The methods of fuel sampling and numerical ratings to describe the structure of the fuel complex at different ages are presented in Gould *et al.* (2011); and the significance of fuel and wind variables in describing fire behaviour are presented in McCaw *et al.* (2012).

Experimental fires (Fig. 5.14) were lit as a 120 m line along the upwind side of each plot and intended to enable the fires to spread almost immediately at close to their potential rate of fire spread for the prevailing conditions (i.e. there was no development phase to the fires *per se*). A total of 116 experimental fires were carried out, with 98 of these being used for data analysis and model development. The following range in fire weather variables was obtained for model development purposes: 10-m open wind speed: 7.3 to 26 km/h; air temperature: 21 - 32.5°C; relative humidity: 17 - 54%. Fine dead fuel moisture content in turn ranged from 5.6 to 9.6%. The ensuing fire behaviour varied from non-self sustaining fires to high intensity fires with some degree of canopy fuel involvement. Considering only the self-sustaining fires, observed forward rates of fire spread and flame heights varied between 0.3 and 22.7 m/min and 0.3 and 14.2 m, respectively.

Analysis of the effects of fuel characteristics on rate of fire spread in the dataset revealed that: (*i*) the dependence on surface fuel load was not as strong as assumed by the Mk 5

FFDM or the FFBT, (*ii*) the near-surface fuel layer had the strongest effect, and (*iii*) the visual hazard scores that reflect the quantity and arrangement of fuel were found to be the fuel variables that best explained the variation in fire behaviour.

Following the work of Gould *et al.* (2007a), where rate of fire spread was modelled using fuel hazard scores as surrogate variables of fuel structure, Cheney *et al.* (2012) proposed two fire spread rate variants of the Dry Eucalypt Forest Fire Model (DEFFM), one based on the fuel hazard score (*FHS*) concept, where a numerical value is used to classify fuels, and the other based on the fuel hazard rating (*FHR*) concept, where nominal rating classes are used as per Tolhurst *et al.* (1996), McCarthy *et al.* (1999) and Hines et al. (2010) (Fig. 5.15).

Figure 5.14. Simultaneous experimental fires burning in four fuel ages on Dee Vee Block during Project Vesta, WA (photo: CSIRO).

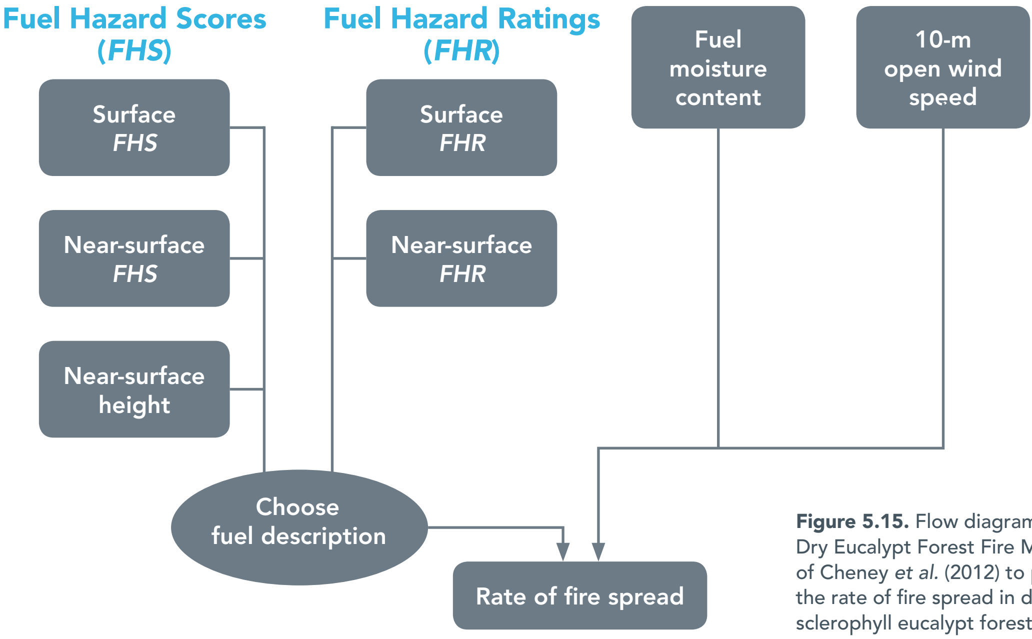


Figure 5.15. Flow diagram for the Dry Eucalypt Forest Fire Model of Cheney *et al.* (2012) to predict the rate of fire spread in dry sclerophyll eucalypt forest.

Fuel hazard score version

Fuel hazard score (*FHS*) is a numeric value from zero to 4.0 based on visual assessment of per cent cover and fuel hazard of different fuel strata (Gould *et al.* 2011). The *FHS* represents a subjective assessment of the flammability of each strata based on the morphological development of vegetation, bulk density, continuity, accumulation of litter fuel and type of bark.

Cheney *et al.* (2012) fitted the relationship between wind speed and rate of fire spread as a power function, and then tested for the effect of different fuel variables by stepwise regression analyses. Fuel variables that provided the best fit were surface and near-surface fuel hazard scores (FHS_s, FHS_{ns}) and near-surface fuel height (H_{ns}) in cm. After incorporating these variables, the *FHS* version of the DEFFM (Cheney *et al.* 2012) for predicting rate of fire spread (*R*, m/h) was formulated as:

$$R = \begin{cases} 30 \;\; \Phi M_f & , U_{10} \leq 5\text{km/h} \\ [30 + 1.531\,(U_{10} - 5)^{0.858}\; FHS_s^{0.93}\; (FHS_{ns}\, H_{ns})^{0.637}\, B_1]\; \Phi M_f & , U_{10} > 5\text{km/h} \end{cases} \quad [5.28]$$

where U_{10} is the average 10-m open wind speed (km/h), B_1 is a model correction for bias (1.03), and ϕMf is the fuel moisture function.

The ϕMf function was based on the relationship between fuel moisture content and rate of fire spread established for jarrah forest fuels by Burrows (1999). This relationship was developed primarily from data collected under dry summer burning conditions with the surface fuel moisture contents less than 10%. Burrows (1999) suggested a power function best described the damping effect of dead fuel moisture on the fire spread rate:

$$\Phi M_f = 18.35\, MC^{-1.495} \quad [5.29]$$

MC is taken from tables in Gould *et al.* (2007b) and Matthews *et al.* (2010), which can be approximated from air temperature (*T*, °C) and relative humidity (*RH*, %) by:

$$MC = \begin{cases} 2.76 + 0.124\, RH - 0.0187\, T & , \text{Period 1} \\ 3.60 + 0.169\, RH - 0.0450\, T & , \text{Period 2} \\ 3.08 + 0.198\, RH - 0.0483\, T & , \text{Period 3} \end{cases} \quad [5.30]$$

where Period 1 extends from 12:00 - 17:00 for sunny afternoons from October to March, Period 2 is used otherwise for daylight hours (Table 5.6), and Period 3 is applicable for night-time hours (Table 5.7).

Fuel hazard rating version

A number of field guides have been developed to provide a systematic method for assessing a fuel hazard rating (*FHR*) and suppression difficulty in dry eucalypt forest (Wilson 1993; Hines *et al.* 2010). These guides provide a description for each fuel stratum and attributes to assess the fuel hazard into five rating classes (Low, Moderate, High, Very High and Extreme) according to what is commonly known as the Overall Fuel Hazard Guide (McCarthy *et al.* 1999; Hines *et al.* 2010).

Table 5.6. Predicted daytime fine dead fuel moisture content (%) as a function of ambient air temperature, relative humidity and cloud cover for application of the Dry Eucalypt Forest Fire Model (see Eq. 5.30, period 1 and 2). Shaded cells are outside the bounds of validation data.

Relative humidity (%)	Clear sky, peak burning period[1]				Overcast sky, other daytime period			
	Air temperature (°C)				Air temperature (°C)			
	10	20	30	40	10	20	30	40
5	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
10	4.0	3.0	3.0	3.5	4.5	4.5	4.0	3.5
15	4.5	4.0	4.0	3.5	5.5	5.5	5.0	4.5
20	5.0	4.5	4.5	4.5	6.5	6.5	6.0	5.5
25	6.0	5.5	5.5	5.0	7.5	7.0	6.5	6.5
30	6.5	6.0	6.0	6.0	8.5	8.0	7.5	7.0
35	7.0	7.0	7.0	6.5	9.5	9.0	8.5	8.0
40	8.0	7.5	7.5	7.0	10.0	9.5	9.0	8.5
45	8.5	8.0	8.0	7.5	11.0	10.0	10.0	9.5
50	9.0	8.5	8.5	8.5	11.5	11.0	10.5	10.0
55	9.5	9.5	9.0	9.0	12.5	12.0	11.5	11.0
60	10.0	10.0	9.5	9.5	13.0	12.5	12.0	12.0
65	10.5	10.5	10.5	10.0	14.0	13.5	13.0	12.5
70	11.0	11.0	11.0	10.5	15.0	14.5	14.0	13.5
75	11.5	11.5	11.5	11.0	16.0	15.0	14.5	14.0
80	12.5	12.0	12.0	12.0	17.0	16.0	15.5	15.0
85	Outside range of model applicability				18.0	17.0	16.5	16.0
90					19.0	18.5	18.0	17.5

[1] Applicable for clear sky conditions between October and March for the 12:00-17:00 period.

The surface and near-surface visual fuel hazard scores from the original experimental data from Project Vesta were allocated into five categorical hazard ratings: *FHR* = 1 (Low, *FHS* ≤ 1.5), *FHR* = 2 (Moderate, *FHS* > 1.5 and ≤ 2.5), *FHR* = 3 (High, *FHS* > 2.5 and *FHS* ≤ 3.5), *FHR* = 4 (Very High, *FHS* > 3.5 and ≤ 3.75) and *FHR* = 5 (Extreme, *FHS* > 3.75). The rate of fire spread (*R*, m/h) model using *FHR* values as fuel descriptors took the form:

$$R = \begin{cases} 30 \quad \Phi M_f & , U_{10} \leq 5\text{ km/h} \\ \left[30 + 2.312(U_{10} - 5)^{0.836}\, exp\left(\sum_{i=2}^{5} b_{2,i}(I_s)_i + \sum_{i=1}^{5} b_{3,i}(I_{ns})_i\right) B_2\right] \quad \Phi M_f & , U_{10} > 5\text{ km/h} \end{cases} \qquad [5.31]$$

where I_s and I_{ns} are indicator variables for surface and near-surface fuel categories respectively (so, for example, $(I_s)_i = 1$ if the surface fuel hazard rating is *i*, and zero otherwise). The regression fuel coefficients for this equation are given in Table 5.8. The B_2 value in the model is the correction for bias of 1.02. The ϕMf variable is the fuel moisture function given in Eq. 5.29.

Table 5.7. Predicted night-time fine dead fuel moisture content as a function of ambient air temperature and relative humidity for application of the Dry Eucalypt Forest Fire Model (see Eq. 5.30, period 3). Shaded cells are outside the bounds of validation data.

Relative humidity (%)	Air temperature (°C)		
	10	20	30
5	Outside range of model applicability		
10			
15			
20	6.5	6.5	6.0
25	7.5	7.0	6.5
30	8.5	8.0	7.5
35	9.5	9.0	8.5
40	10.5	10.0	9.5
45	11.5	11.0	10.5
50	12.5	12.0	11.5
55	13.5	13.0	12.5
60	14.5	14.0	13.5
65	15.5	15.0	14.5
70	16.5	16.0	15.5
75	17.5	17.0	16.5
80	18.5	18.0	17.5
85	19.5	19.0	18.5
90	20.5	20.0	19.5

Table 5.8. Surface and near-surface fuel hazard rating regression coefficients for the fuel hazard rating (FHR) version of Dry Eucalypt Forest Fire Model (DEFFM).

Regression constants	Estimate
Surface fuel	
b_{22}	1.5608
b_{23}	2.1412
b_{24}	2.0548
b_{25}	2.3251
Near-surface fuel	
b_{31}	0.4694
b_{32}	0.7070
b_{33}	1.2772
b_{34}	1.7492
b_{35}	1.2446

Model behaviour and evaluation

The functional forms used in the DEFFM reflect the accrued understanding of the effects of environmental and fuel variables on rate of fire spread and fire behaviour in general. The effect of wind speed was modelled using a power law function with an exponent close to but less than 1.0, resulting in an approximately linear effect (Fig. 5.16a and b). The fuel moisture content effect relies on a power function that approaches an exponential decay with a notable higher effect for low fuel moistures. This effect reflects the nonlinear aspect of fire propagation in eucalypt forests, where under dry conditions the onset of mass spotting behaviour results in substantial increases in rate of fire spread.

Fuel structure is incorporated into the model through descriptors of the surface (FHS) and near-surface (FHS and height) fuel layers. The surface FHS has a slightly higher effect on rate of fire spread than the near surface FHS. Variation of surface FHS from 1 to 4 will result in an approximate three-fold increase in the rate of fire spread. The same change in the near-surface FHS will result in a 2.3 increase in rate of spread. The model is also sensitive to the height of the near surface fuel layer. A doubling of the near surface height will result in a 65% increase in the rate of fire spread. Model sensitivity to the near-surface fuel height warrants special care in its estimation. Measurement errors in the definition of this layer can result in significant bias in the model output (e.g. including part of the elevated fuels in the near surface layer; considering top height instead of average height, not sampling enough points).

The DEFFM rate of fire spread models were evaluated against independent fire spread data compiled from experimental fires and from well-documented wildfires in open eucalypt forests in southern Australia (Table 5.9). The wildfire dataset had fires burning under higher wind speeds, lower dead fuel moisture contents and in fuel types other than those of the Project Vesta experimental fires. The experimental fires had spread rates ranging from 2.5 to 16 m/min. Rate of spread in the wildfire dataset varied between 10 and 175 m/min. Overall, the models predicted the experimental fire data with an average absolute error of 2.2 m/min, which equates to a per cent error of 35%. Bias was negligible at -0.03 m/min. For the wildfire dataset the mean absolute error was 26.4 m/min (54%). The increase in error is possibly due to the larger uncertainty regarding the fuel structure and weather conditions at the fire location and difficulties in obtaining accurate measurements of the rate of wildfire propagation. The model tended to over-predict the spread of the wildfires, with 68% of the cases in this class and a mean bias of 6.8 m/min (approximately 25% of the mean error). Overall, the goodness of fit statistics were slightly better with the FHR rate of fire spread model than with FHS model.

Kilinc *et al.* (in review) evaluated the performance of the DEFFM models against wildfire data from southern Australia (Table 5.9). The FHS and FHR versions performed with similar statistics, with average errors between 25 and 23 m/min, respectively. These results are comparable to the Cheney *et al.* (2012) mean absolute error of 26.4 m/min mentioned above. Both models predicted the dataset with residual bias (-0.7 m/min for FHS and -5 m/min for FHR).

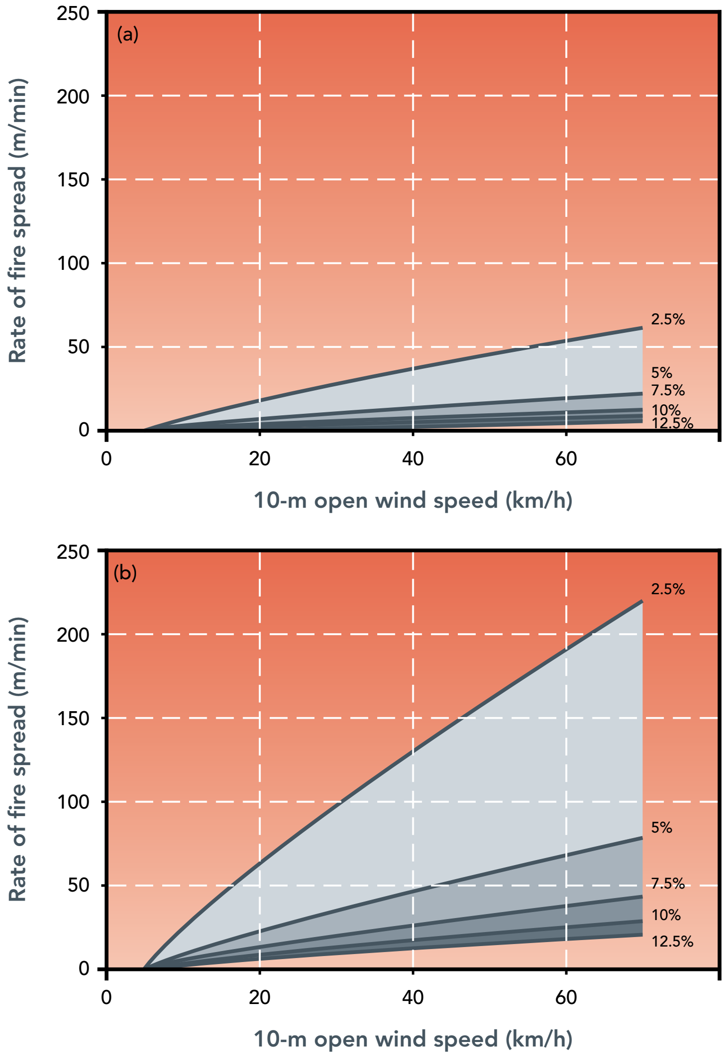


Figure 5.16. Prediction of rate of fire spread in dry sclerophyll eucalypt forests in (a) young and (b) old fuels as a function of 10-m open wind speed and fine fuel moisture content as expected to occur under wildfire conditions according to the *FHS* version of the Dry Eucalypt Forest Fire Model of Cheney *et al.* (2012). Young fuels are described as: Surface *FHS* of 2; Near-surface *FHS* of 1.5; and near-surface fuel height of 15 cm. Old fuels are described as: Surface *FHS* of 3.5; Near-surface *FHS* of 3; near-surface fuel height of 25 cm.

Table 5.9. Statistics and related information associated with the evaluation of Cheney *et al.* (2012) rate of fire spread (ROS) model against independent data derived from experimental fires (E) and wildfire (W) observations.

Number of observations	ROS range (m/min)	MAE (m/min)	MAPE (%)	MBE (m/min)	Study
16 (E)	2.5 - 16	2.16	35	-0.03	Cheney *et al.* (2012)
25 (W)	10 - 175	26.4	54	6.8	Cheney *et al.* (2012)
181 (W)	0.2 - 260	25	122	-0.7	Kilinc *et al.* (in review)
181 (W)	0.2 - 260	23.3	103	-5	Kilinc *et al.* (in review)

6. Wet eucalypt forests

Wet eucalypt forests, also called tall open forests or wet sclerophyll forests, are forests that at maturity are 30 to 50 m tall and present a multi-storey structure, with the dominant overstorey layer cover varying between 30 and 70%. A well-developed understorey stratum might include a layer of sub-dominant and suppressed trees and tall shrubs. The lower section of this layer might have a well-developed shrub layer. Surface fuel quantities are characteristically higher in these forests than observed in dry eucalypt forests, and a well-developed duff layer is often present. The rate at which dead surface fuels dry is restricted by the dense understorey, and so fuels tend to be wetter in these forests than in adjacent dry eucalypt forests. Surface fuels may not dry out until mid-summer, and in the most sheltered locations may only become available to burn following extended drought. However, under these conditions very large quantities of organic material will be available for combustion. The tall and dense stand structure will also limit wind penetration into the lower understorey space. Common wet eucalypt forests are karri forests (*Eucalyptus diversicolor*) in southern Western Australia (Fig. 6.1), mountain ash forests (*E. regnans*) in Victoria (Fig. 6.1) and Tasmania, and blackbutt (*E. pilularis*) in New South Wales.

Forest Fire Behaviour Tables for Western Australia – Karri fuel type (Sneeuwjagt and Peet 1985)

Model description

The previous description of the Forest Fire Behaviour Tables (FFBT) of Western Australia focused on the prediction fire spread rate in the northern jarrah forest. Beck (1995) also fitted equations to the karri rate of fire spread tables and provided a comprehensive description of the structure of the various models, their application bounds, and the range of experimental data used to develop them. As per the jarrah rate of fire spread model, four variables are considered to influence rate of spread, namely the moisture content of the surface litter fuels, the quantity of fuel available for burning, the in-forest wind speed measured at 1.5-2 m above ground and slope steepness. The fire danger index (*FDI*) for karri forests assumes a medium-density understorey of shrubs 3.5-5.5 m tall. Surface moisture content and wind speed are first used to calculate a forward head-fire rate of spread (*R*, m/h), expressed as a *FDI*, for a typical forest structure with five-year-old karri fuels (after Beck 1995):

$$FDI_K = Y_K + A_K \, exp(U_{1.5} \, N_K) \quad [6.1]$$

These are in turn calculated by the following equations:

$$Y_K = 4.88 - 263.78 \, MC^{-1.8} \quad [6.2]$$

$$A_K = 163.40 \, MC^{-1.18} \quad [6.3]$$

$$N_K = 0.54 - 0.0059 \, MC \quad [6.4]$$

Figure 6.1. Examples of wet eucalypt forest fuel structures: **Opposite** – karri (*E. diversicolor*) forest, Southwest WA (photo: Lachie McCaw, DPaW, WA). **Right** – mountain ash (*E. regnans*) forest, Vic (photo: Jim Gould, CSIRO).

The resulting fire spread rate/fire danger index value is then corrected to allow for cases where fuel load, forest stand structure or slope steepness differ from the standard. As per the jarrah fire spread rate model, wind speed can be measured directly in the forest but is more commonly a forecast value or observation from a fire weather station representing conditions at a 10-m open height exposure. The standard wind ratio for karri forest is 7:1. Sneeuwjagt and Peet (1985) provide tables for selection of different wind ratios for situations where the forest is denser or more open than the standard.

To predict the forward rate of fire spread in non-standard fuels, the fire danger index must be corrected for the available fuel quantity, which can comprise surface litter, suspended twigs and bark (also known as "trash fuel") and the available component of the standing shrub layer. Fuel quantity correction factors (*FQCF*) are derived from the available fuel quantity (*AFQ*) and the moisture content of the surface fuel layer (*MC*, %). For karri fuel types, the following equation is used for fuel quantities between 5.0 and 17.0 t/ha:

$$FQCF_K = 0.16 + \frac{0.95}{1+957.74\, exp(-0.52\, AFQ_K)} \quad [6.5]$$

In turn, for fuel quantities higher than 17.0 t/ha, use the following:

$$FQCF_K = \frac{5.08+6.26\ AFQ_K}{111.50} \quad , 3\% < MC < 9.9\% \qquad [6.6]$$

$$FQCF_K = \frac{17.35+1.70\ AFQ_K}{46.25} \quad , 10\% < MC < 18.9\% \qquad [6.7]$$

$$FQCF_K = \frac{10.88+0.46\ AFQ_K}{18.7} \quad , 18.9\% < MC < 26\% \qquad [6.8]$$

MC is modelled as described for the jarrah fuel type. The final rate of spread (*R*, m/h) is given by:

$$R = FQCF_K\ \ FDI_K \qquad [6.9]$$

Model behaviour and evaluation

The karri forest fire behaviour predictions from the FFBT relate to surface fires and are intended primarily as a guide to prescribed burning. For the same burning conditions, the karri rate of fire spread model (Fig. 6.2) will predict slower fire spread rates and lower intensity fires than obtained for jarrah forests. The results are comparable to those obtained for the McArthur (1962) burning guide, although with some departures due to the distinct functional forms used in model parameterisation between the two. We are presently unaware of any published evaluation of the performance of the karri fire spread rate model against independent datasets.

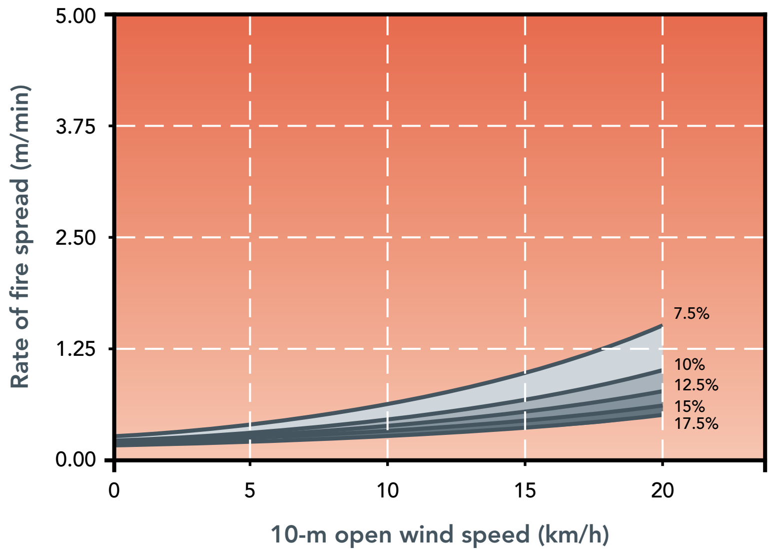


Figure 6.2. Rate of fire spread in karri forests as a function of 10-m open wind speed and fine fuel moistures content as expected to occur under prescribed burning conditions according to Sneeuwjagt and Peet (1985) Forest Fire Behaviour Tables of Western Australia model. Fuel load of 20 t/ha is assumed. A wind adjustment factor of 0.167 was used to convert 10-m open into 2-m wind speed (a wind ratio of 6:1, Beck 1995).

7. Pine plantations

Industrial pine plantations have a significant social and economical role in Australia. The growth characteristics and silvicultural systems that characterise pine plantations established on productive sites result in fuel complexes that can be exceptionally flammable (Williams 1976) but at the same time are amenable to modification through silvicultural management (Fig. 7.1). Key fuel complex characteristics determining fire behaviour are the amount of litter fuel, the amount and density of live foliage, expressed as canopy bulk density, canopy base height, and the presence or absence of ladder fuels (e.g. dead bole branches and dead, suspended needles). Several species are planted throughout Australia, the most common being: (*i*) radiata pine (*Pinus radiata*), predominantly in NSW, VIC, SA, ACT, TAS and WA; (*ii*) maritime pine (*P. pinaster*) primarily in WA; and (*iii*) slash pine (*P. elliottii*) in south-east Queensland and north-eastern NSW. Two rate of fire spread models currently exist for prescribed burning in some of these plantation types, namely the Mk III prescribed burning guide for slash pine (Queensland Department of Forestry 1976) and the Forest Fire Behaviour Tables (FFBT) for maritime pine and radiata pine (Sneeuwjagt and Peet 1985). The FFBT models are also used to predict wildfire propagation in pine plantations in Western Australia (Burrows *et al.* 2000). More recently a model system called the Pine Plantation Pyrometrics (PPPY) was developed to predict the full range of wildfire behaviour (Fig. 7.2) in pine plantations (Cruz *et al.* 2008).

Figure 7.1. Examples of two pine plantation fuel structures: **Top** – seven-year-old unprunned radiata pine plantation after canopy closure, Mt. Gambier, SA. Reference pole is 2 m tall. (photo: CSIRO). **Middle** – 15-year-old high prunned and thinned radiata pine stand, Mt Gambier, SA. Reference pole is 2 m tall (photo: CSIRO). **Bottom** – 15-year-old hybrid (*P. elliottii* x *P. caribaea*) maintained through periodic prescribed burn. Surface fuel comprises litter and bladey grass (*Imperata cylindrica*). Beerburrum State Forest, south-eastern Queensland. (photo: Peter Venz, HQ Plantations, QLD).

Figure 7.2. Top – Post-fire evidence of intermittent and active crown fire propagation in 20-year-old maritime pine plantation, WA. Low intensity fire behaviour in adjoining stands was due to controlled burn in previous years (photo: Owen Donovan, DPaW, WA). **Bottom** – Intermittent crown fire propagation in 20-year-old maritime pine plantation, Gnangara, WA (photo: Owen Donovan, DPaW, WA).

Prescribed burning models

Prescribed burning guide Mk III (Queensland Department of Forestry 1976; Byrne 1980)

Model development

Accompanying the successful application of prescribed burning in south-east Queensland pine plantations in the early 1970s (Just 1972), field guides were developed to support the planning and execution of fuel reduction burns (Fig. 7.3). The Mk III burning guide builds on previous versions (Mk I and II) and provides a series of fuel drying and fire behaviour tables (Queensland Department of Forestry 1976; Byrne 1980). The guide was developed for slash pine plantations carrying an "average fuel condition". This typically consisted of an understorey fuel load ranging from 10 to 20 t/ha, with slash pine needle litter fuels suspended on a layer of grassy fuels such as kangaroo grass (*Themeda australis*) and forming a suspension depth of 0.15 to 0.45 m (Byrne 1980).

Figure 7.3. Prescribed burning in slash pine plantations in south-eastern Queensland: **Top** – Broadcast aerial ignition in slash pine plantations in south-eastern Queensland (photo: Peter Venz, HQ Plantations, Queensland). **Bottom** – Low-intensity prescribed fire in 23-year-old slash pine plantation in south-eastern Queensland. Surface fuels comprise bladey grass and needle litter with an overall fuel load between 15 and 18 t/ha (photo: Peter Venz, HQ Plantations, Queensland).

The rate of fire spread tables in the guide allows for predictions in areas within the plantation and for its edges, where the combined effect of the sun and wind causes a drier environment, leading to higher intensity burning. These tables have three inputs (Fig. 7.4): relative humidity (*RH*, %) in 10% wide classes; wind strength in four Beaufort Force wind (*U*) classes as related to ranges in 10-m open wind speed (U_{10}, km/h) (Force 1: U_{10} = 1 – 5 km/h; Force 2: U_{10} = 6 – 11 km/h; Force 3: U_{10} = 12 – 18 km/h; Force 4: U_{10} = 19 – 29 km/h); and four fuel availability/moisture content (*MC*, %) classes associated with suitable days after rain (Fuel class 1, first day after rain: available fuel 8 t/ha, *MC* 30-35%; Fuel class 2, second day after rain: available fuel 12 t/ha, *MC* 25-30%; Fuel class 3, third day after rain: available fuel 16 t/ha, moisture content 20-25%; Fuel class 4, fourth day after rain: available fuel 18 t/ha; moisture content 15-20%).

Hunt and Crook (1987) used multiple linear regression analysis to derive an equation for predicting rate of fire spread from the tabulated values given in the prescribed burning guide:

$$R = a + b_1\, RH + b_2\, MC(2) + b_3\, MC(3) + b_4\, MC(4) + b_5 \times U(2) + b_6\, U(3) + b_7 \times U(4) + b_8\, RH\, MC(2) + b_9\, RH\, MC(3) + \cdots b_{22}\, MC(4) U(4) \quad [7.1]$$

where *R* is rate of fire spread in m/h, *MC*(*j*) (*j* = 2-4) is the *MC* class of the suspended litter fuels, and *U*(*k*) (*k* = 2-4) the wind speed class. Both *MC*(*j*) and *U*(*k*) are factors with a value of 1 if the variable is at its level and zero otherwise. Coefficients *a* and b_i (*i* = 1-22) are regression coefficients given in Table 7.1. The model fit yielded an R^2 of 0.994 and 0.996, respectively, for the within-stand (interior) and edge regions.

This prescribed burning guide has drying tables that enable the calculation of fuel availability based on rainfall (mm), time since rain event (days) and air temperature (°C). To our knowledge, these tables have yet to be converted into equation form.

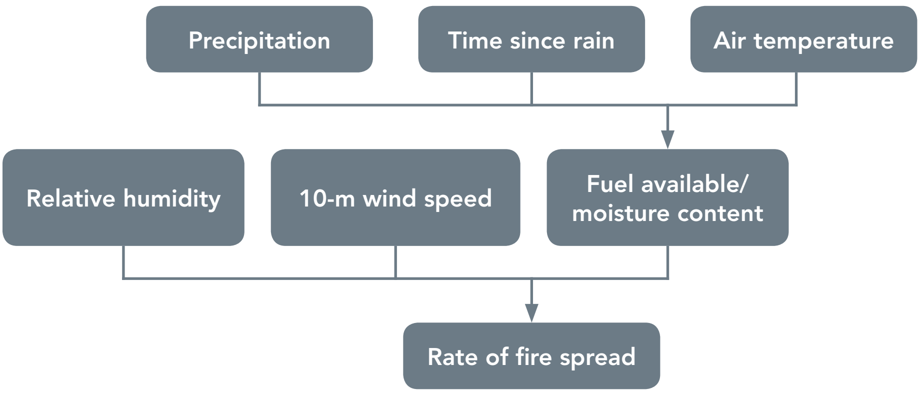


Figure 7.4. Flow diagram for Byrne (1980) model to predict the rate of spread of prescribed fires in slash pine plantations.

Table 7.1. Coefficients for equations describing the fire spread rate tables in the Queensland Mk III burning guide for pine plantations as derived by Hunt and Crock (1987).

Regression constants	R interior	R edge
Constant (a)	35.6	44.3
RH	-0.372	-0.444
MC(2)	6.0	7.6
MC (3)	16.8	20.5
MC(4)	20.6	28.7
U(2)	5.1	10.2
U(3)	17.5	22.2
U(4)	36.2	60.1
RH.MC(2)	-0.052	-0.047
RH.MC(3)	-0.150	-0.185
RH.MC(4)	-0.150	-0.269
RH.U(2)	-0.025	-0.086
RH.U(3)	-0.155	-0.136
RH.U(4)	-0.350	-0.409
MC(2).U(2)	0.5	0.3
MC(2).U(3)	1.6	2.9
MC(2).U(4)	4.4	11.6
MC(3).U(2)	1.5	6.4
MC(3).U(3)	6.6	7.4
MC(3).U(4)	11.5	25.1
MC(4).U(2)	5.1	7.4
MC(4).U(3)	9.4	11.3
MC(4).U(4)	16.0	30.7

Model behaviour and evaluation

The model parameterised by Hunt and Crock (1987) is not a continuous one. It will replicate the tabled values given in the guide, causing step-wise changes when changes in the inputs vary between classes (e.g. from wind class 1 to wind class 2) and will not identify a change in output when the input is varying within the class (e.g. 10-m open wind speed varying between 6 and 11 km/h (Fig. 7.5).

Hunt and Crock (1987) evaluated the Mk III rate of spread output with data from 88 experimental fires where the rates of fire spread varied between 0.2 and 1.3 m/min.

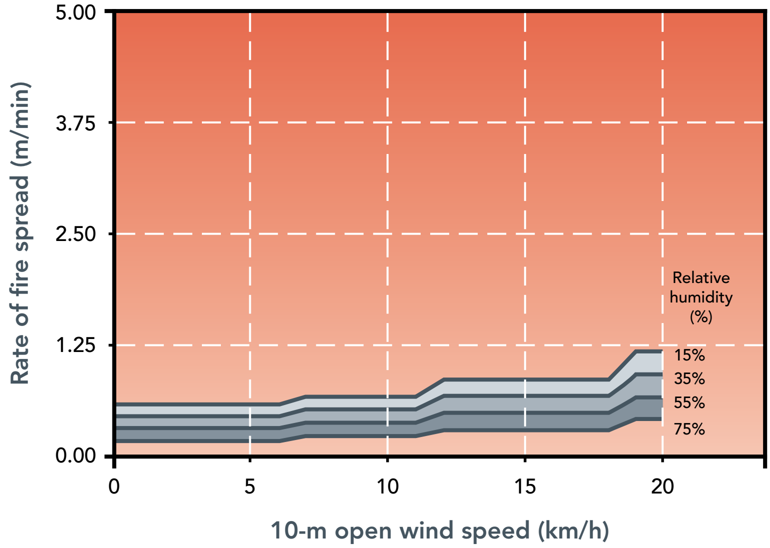


Figure 7.5. Prediction of rate of fire spread in slash pine plantations as a function of 10-m open wind speed and relative humidity as expected to occur under prescribed burning conditions according to the Byrne (1980) model.

The model predicted the evaluation dataset with a mean absolute error of 0.2 m/min (44%), showing a tendency to under-predict the faster rates of spread in the dataset (i.e. > 0.75 m/min). The error was attributed to differences in fuel type between the guide's original model development dataset and the evaluation dataset. The sensitivity analysis of the model (Eq. 7.1) derived by Hunt and Crock (1987) showed a balanced sensitivity to *RH* and *MC* and a weak response to wind speed and interaction parameters.

Forest Fire Behaviour Tables for Western Australia (Sneeuwjagt and Peet 1985)

Model development

The behaviour of surface fires in plantations of radiata pine and maritime pine can be predicted using the Forest Fire Behaviour Tables (FFBT) for Western Australia (Sneeuwjagt and Peet 1985) by drawing upon information collected during an extensive series of fuel drying studies and low to moderate intensity experimental fires undertaken in Western Australia during the 1960s and early 1970s. Beck (1995) fitted equations to the tables that form the basis for the pine plantation fire behaviour prediction portion of the FFBT. Calculations of rate of fire spread in pine plantations fuel types follow the same sequence as for eucalypt fuels, with four variables considered to influence rate of spread: the moisture content of the surface needle litter fuels, the quantity of fuel available for burning, the in-forest wind speed near the ground as measured at a height of 1.5 m and the terrain slope steepness.

Figure 7.6. Low intensity prescribed fire in 23-year-old maritime pine plantation, Gnangara, WA. Surface fuels comprise needle litter with an overall fuel load of 6 t/ha (photo: Owen Donovan, DPaW, WA).

A pine surface moisture content (*SMC*, %) is obtained by simple adjustment of the calculated value of surface moisture content (*MC*, %) for eucalypt litter, by subtracting a value to reflect the more rapid drying rate of the pine needle litter fuels. The adjustment depends on species, fuel moisture content and whether the fuel is surface needle litter fuel bed or elevated needles attached to thinning slash. Calculation of the profile moisture content (*PMC*, %) in deeper needle litter fuel beds follows a similar approach. An available fuel factor (*AFF*) representing the proportion the needle litter fuel bed dry enough for combustion, is calculated from the ratio of *SMC* and *PMC* values. Available fuel quantity (*AFQ*, t/ha) is calculated as the product of the *AFF* and the measured quantity of needle litter and thinning slash, giving a value equal to or less than the total fuel quantity.

A fire danger index is determined using the rate of fire spread model for northern jarrah forest (Eq. 5.9), based on the *SMC* for the pine needle litter fuel bed and the observed or forecast wind speed. Wind ratios recommended for pine stands range from 4:1 to 6:1 depending on the age and silvicultural history (see Table 6.5 in Sneeuwjagt and Peet 1985). Rate of fire spread in a plantation stand is obtained by multiplying the fire danger index by a fuel quantity correction factor (*FQCF*) which depends on the *SMC* and the *AFQ*, with slope steepness correction as required. The *FQCF* is described by an equation which has a common form, but with distinct coefficients, for maritime (*PP*) and radiata pine (*PR*):

$$FQCF_{PP} = AFQ_{PP}\,(-0.0061\,SMC + 0.24) + \left(1.28 - \frac{0.49}{1+38.96\,exp(-0.25\,SMC)}\right) \qquad [7.2]$$

$$FQCF_{PR} = AFQ_{PR}\,(-0.0065\,SMC + 0.21) + \left(1.31 - \frac{0.47}{1+33.99\,exp(-0.36\,SMC)}\right) \qquad [7.3]$$

Model behaviour and evaluation

The pine plantation predictions of rate of fire spread from the FFBT relate to surface fires and are intended primarily as a guide to prescribed burning in commercial plantations of maritime pine (Fig. 7.6). The pine FFBT models do not identify the thresholds for crown fire initiation or the rate of spread of crown fires, but rather just rate of fire spread as illustrated in Figure 7.7. Evaluation of model predictions has been mostly from case studies of independent experimental fires (Burrows *et al.* 1988) and large plantation wildfires (Burrows *et al.* 2000), providing insufficient data for formal evaluation of error statistics. Notwithstanding this, the pine plantation portion of the Sneeuwjagt and Peet (1985) guide has been widely applied in practice and has underpinned an effective program of prescribed burning in the maritime pine plantations on the Swan Coastal Plain around Perth.

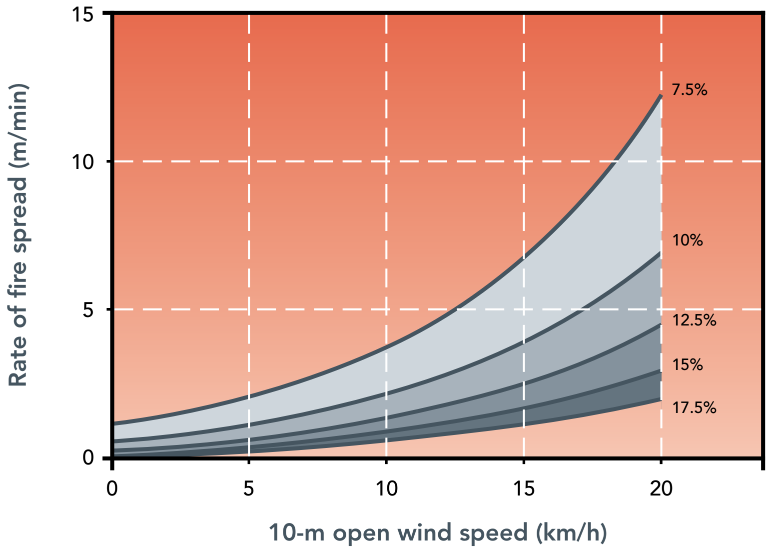


Figure 7.7. Predicted rate of fire spread in pine plantations as a function of 10-m open wind speed and fine fuel moisture content as expected to occur under prescribed burning conditions according to the Sneeuwjagt and Peet (1985) model. A fuel load of 15 t/ha is assumed. A wind adjustment factor of 0.33 was used to convert 10-m open into 1.5-m wind speed (a wind ratio of 3:1, Beck 1995).

Wildfire models

Pine Plantation Pyrometrics model system, PPPY (Cruz et al. 2008)

Model development

The Pine Plantation Pyrometrics (PPPY) model system was developed to predict the rate of spread and type of fire over the full range of fire behaviour in pine plantations, including crown fires (Fig. 7.8), for a variety of fuel complex structures. The system encompasses a suite of fire environment and fire behaviour models that describe the relevant processes occurring within and above a spreading fire. Figure 7.9 illustrates the information flow and some of the key

Figure 7.8.
Extraordinarily high flame heights at the end of an up-slope run in a young pine plantation during the 14 January 1998 Wandong fire in Victoria. (photo: Alan Sewell, Country Fire Authority, Vic).

modelling components of the system. At its core is a model describing the surface fire rate of spread (Rothermel 1972), a model for the temperature increase in canopy fuels and possible ignition (Cruz *et al.* 2006) and models for crown fire rate of spread (Van Wagner 1977; Cruz *et al.* 2005). We do not provide the equations of the PPPY system here as they total more than 100. They can be reviewed in the publications cited above.

The primary inputs into the PPPY model system are: wind speed (either the 10-m open standard or with-in stand measure), weather variables determining dead fuel moisture content (Table 7.2), choice of a surface fuel model, which incorporates surface fuel load and depth (Cruz and Fernandes 2008), fuel strata gap (i.e. the distance between the surface fuel layer and the bottom of the canopy layer, and canopy bulk density. There are a set of inputs that can be seen as secondary due to their minor effect on the model system output (e.g. stand density and basal area, foliar moisture content).

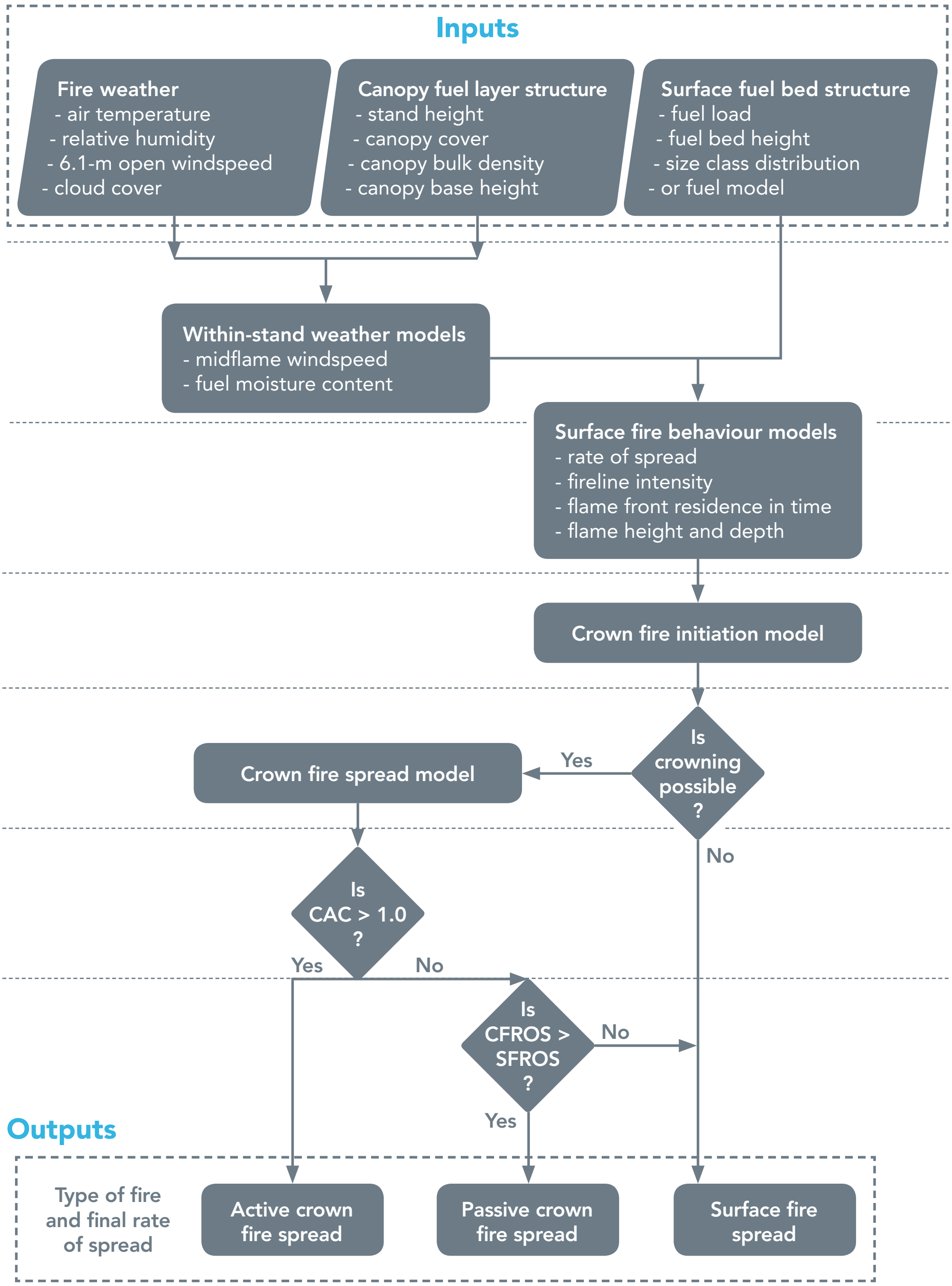


Figure 7.9. Flow diagram for the PPPY model system of Cruz *et al.* (2008) for predicting fire behaviour in pine plantations. CAC is the criteria for active crowning (Van Wagner 1977), CFROS is the crown fire rate of spread, and SFROS the surface fire rate of spread.

Table 7.2. Predicted fine dead fuel moisture content (%) as a function of ambient air temperature and relative humidity assuming a well stocked pine stand (adapted from Rothermel 1983). Tabulated moisture content (%) values are for the period between 12:00 - 16:00 during November-January.

Relative humidity (%)	Air temperature (°C)				
	0 – 9	10 – 20	21 – 31	32 – 42	> 43
0 – 4	4	4	4	4	4
5 – 9	5	5	4	4	4
10 – 14	5	5	5	5	5
15 – 19	6	6	5	5	5
20 – 24	7	7	6	6	6
25 – 29	8	8	7	7	7
30 – 34	8	8	8	7	7
35 – 39	9	9	8	8	8
40 – 44	10	9	9	9	9
45 – 49	10	10	10	10	10
50 – 54	10	10	10	10	10
55 – 59	11	11	11	11	11
60 – 64	12	11	11	11	11
65 – 69	12	12	11	11	11
70 – 74	13	12	12	12	12
75 – 79	14	13	13	13	13

The advantages of this system over other fire spread rate models for pine plantation forests in Australia are: (*i*) applicability over the full spectrum of fire behaviour (i.e. from gentle surface fires to fully-developed, high-intensity crown fires); (*ii*) explicit inclusion of the effects of relevant fuel complex variables influencing the start and spread of crown fires; and (*iii*) adequate quantitative description of fire behaviour factors and processes determining crown fire propagation. This allows the PPPY model system to address questions related to the effects of stand structure, silvicultural operations and/or fuel treatments with respect to influencing fire behaviour potential in pine plantations.

Model behaviour and evaluation

Figure 7.10 shows the effect of wind speed and fuel moisture content on rate of fire spread in the PPPY model system. The predicted sudden jumps in fire spread rates are associated with the transition from a surface fire to a crown fire. When such transitions occur there is a change in the "drivers" of the fire propagation process (e.g. different fuel layer sustaining propagation, increase in wind speed affecting the flame). Within a pine plantation, surface fire rate of spread is a function of the litter layer characteristics, such as fuel load, compactness and moisture content, and within-stand wind speed.

After the onset of crowning, the flame front is subject to stronger winds (3 to 5 times higher), there is a considerable increase in the amount of fuel consumed in flaming combustion, and the fire spreads through a fuel strata characterised by a higher heat transfer efficiency. The pseudo steady-state rate of fire spread in this new situation can be several times higher than that observed prior to crowning, as observed by Burrows *et al*. (1988) and Fernandes *et al*. (2004) in a series of experimental fires in maritime pine plantations in Western Australia and Portugal, respectively. Following crowning, fire spread rates increased by 2 to 5 times. The identification of transition points between the different types of fire propagation is particularly significant to fire suppression operations and fire-fighter safety.

Cruz *et al*. (2008) did not undertake a direct evaluation of the PPPY's model system performance. However, its main components, namely the models describing surface fire spread rate, onset of crowning and rate of crown fire propagation, have been evaluated against independent datasets with acceptable results (Hough and Albini 1978; Cruz *et al*. 2005, Alexander and Cruz 2006; Cruz and Fernandes 2008). Notably, the surface fire rate of spread model was found to underestimate fires burning under marginal burning conditions, namely for high fine dead fuel moisture contents (i.e. >25%). As such this model should not be used to predict fire potential for prescribed burn planning.

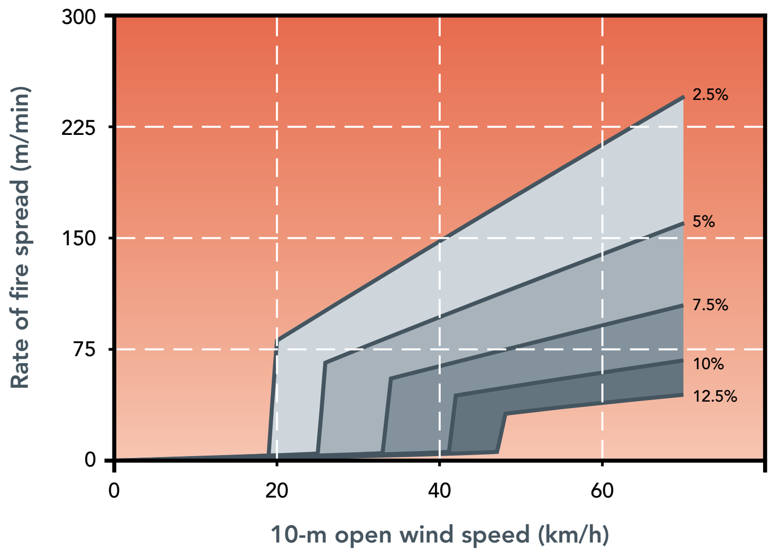


Figure 7.10. Prediction of rate of fire spread in pine plantations as a function of 10-m open wind speed and fine fuel moisture content as expected under wildfire conditions according to the Cruz *et al*. (2008) model system. A stand height of 14 m, a canopy base height of 6 m, and a canopy bulk density of 0.23 kg/m^3 are assumed.

8. Recommendations on model use

A careful examination of the behaviour of the various models presented in this book reveals the evolutionary change in the underlying functional forms used to express the effect of the key environmental and fuel variables on rate of fire spread. These changes in functional forms are the result of years of model use and progressive improvement of our understanding of the physical processes and mechanisms involved in the propagation of flame fronts and the identification and quantification of the driving variables.

The number of different fire spread rate models that currently exist in Australia has caused some confusion amongst the users of such models, including fire practitioners and researchers. The lack of clear information of existent fire spread rate models, fire behaviour knowledge evolution, and identification of model limitations has created a situation where it is unknown which models are outdated and which ones represent the current state of knowledge. This book aims to address this state-of-affairs. Based on prior research results and the reviews undertaken here, we identify a list of models that we consider incorporate the best science and yield the most accurate results (Table 8.1). A contrasting list of models that have been shown to incorporate outdated functional forms and can result in biased results is presented in Table 8.2. We recommend that the use of models in this list should be avoided. But it is recognised that operational constraints, namely the availability of accurate input data, will necessitate the use of models in Table 8.2 to enable timely and functional predictions to be made. However, continued use of these superseded models should be phased out as early as practicable.

Our present review focused on fire spread models that have been or that are currently used operationally to predict fire spread in Australian vegetation types. There are a number of other models that, although not used operationally in Australia, might be seen to have potential to be used in the future in particular settings. It was beyond the scope of the present work to describe these models. Table 8.3 presents a list of models in this category.

Predicting fire behaviour entails combining quantitative and qualitative information, based on experience and scientific principles, to describe the behaviour of fire influenced by topography, weather and fuel, and recognising conditions that lead to extreme fire behaviour. Accurate predictive models of fire behaviour at high spatial and temporal resolutions are the key for effective management action before and during a fire.

However, fire behaviour prediction is much more than the use of a model to carry out a calculation. The process also includes determination of the proper inputs for the calculation and careful interpretation of the results given the underlying model and environment assumptions.

Table 8.1. Summary of recommended models by fuel type group, fuel type applicability, geographical applicability and their targeted fire management situations and comments on limitations.

Model	Fuel type applicability	Geographical applicability	Targeted fire management situations and limitations
Grasslands			
Cheney *et al.* (1998)	Continuous grasslands, pastures and certain crops	Across Australia	Most applicable to wildfire conditions.
Cheney *et al.* (1998)	Grassy woodlands; open forests with grassy understorey	Across Australia	Most applicable to wildfire conditions.
Burrows *et al.* (2009)	Spinifex grasslands	Semi-arid and arid regions of Australia	Most applicable to prescribed burning conditions in arid environments.
Shrublands			
Marsden-Smedley and Catchpole (1995a)	Buttongrass moorlands	Tasmania	Most applicable to prescribed burning conditions; possible use in wildfire conditions (possibly applicable to some areas of Victoria but needs validation).
Anderson *et al.* (2015)	Heaths and other temperate shrublands with height < 2.5 m	Coastal regions across Australia, New Zealand	Wildfire and prescribed burning conditions.
Cruz *et al.* (2010)	Semi-arid heaths	Southern Australia	Prescribed burning conditions.
Cruz *et al.* (2013)	Semi-arid mallee-heath	Southern Australia	Prescribed burning conditions; possible use for wildfire conditions (requires careful extrapolation).

Model	Fuel type applicability	Geographical applicability	Targeted fire management situations and limitations
Eucalypt forests			
McArthur (1962)	Dry eucalypt forest with litter and sparse understory vegetation	Southern Australia	Prescribed burning conditions.
Sneeuwjagt and Peet (1985)	Dry and wet eucalypt forest	Southern Australia	Prescribed burning conditions.
Cheney *et al.* (1992)	Young regrowth forest	Southeast Australia	Prescribed burning conditions
Cheney *et al.* (2012)	Dry eucalypt forest	Southern Australia	Wildfire burning conditions.
Pine plantations			
Byrne (1980); Hunt and Crock (1987)	Slash pine plantations with grassy understorey	Queensland Northern NSW	Prescribed burning conditions.
Sneeuwjagt and Peet (1985)	Maritime pine plantations	Southern Australia	Prescribed burning conditions.
Cruz *et al.* (2008)	Industrial pine plantations with litter understorey	Southern Australia, New Zealand	Wildfire conditions.

Amicus

Amicus is a fire behaviour prediction software tool developed for conducting calculations of fire spread rate, fireline intensity and flame dimensions. The software incorporates the rate of fire models detailed in this book to enable easy determination of expected fire danger and fire behaviour from information on fuels and fire weather conditions. Model outputs can be used to support fire management decision making in a wide number of applications, such as fuel hazard appraisal, prescribed burn planning and bushfire spread prediction.

The use of Amicus assumes knowledge of the assumptions and limitations of the underlying fire spread rate and the other fire behaviour models (as detailed in this book) plus recognition of the uncertainty inherent to accurate assessments of fuel characteristics, weather variables, topography and the fire itself. Users of Amicus should have a sound foundation of bushfire experience and training in fire behaviour prediction.

Amicus can run on PC, Mac or Linux computers and is available for download at: http://research.csiro.au/Amicus.

Table 8.2. List of fire spread rate models not recommended for use in Australia where practicable and the reasons for discontinuation.

Model	Fuel type	Reasoning
Grasslands		
Mk 3/4 Grassland Fire Danger Meter McArthur (1966a, 1973b)	Continuous grasslands, pastures and certain crops	Superseded by Cheney *et al.* (1998). Model form leads to over-prediction under extreme burning conditions (e.g. rate of spread can exceed wind speed).
Mk 5 Grassland Fire Danger Meter McArthur (1977)	Grassy woodlands; open forests with grassy understorey	Superseded by Cheney *et al.* (1998). Model form leads to over-prediction under extreme burning conditions. Fuel load effect found to be exaggerated. Also issue of this effect due to confounding influence of fuel particle size.
Central Australia spinifex model Griffin and Allan (1984)	Spinifex grasslands	Model has been superseded by the more recent work of Burrows *et al.* (2009).
WA Spinifex model Burrows *et al.* (1991)	Spinifex grasslands	Model has been superseded by the more recent work of Burrows *et al.* (2009).
Shrublands		
Shrubland model Catchpole *et al.* (1998)	Temperate shrublands	Model has been superseded by the more recent work of Anderson *et al.* (2015).
WA mallee model McCaw (1994)	Semi-arid mallee-heath	Model has been superseded by the more recent work of Cruz *et al.* (2013). Model applicability restricted to mature fuels in mallee-heath shrublands.
SA mallee-heath model Cruz *et al.* (2010)	Semi-arid mallee-heath	Model has been superseded by the more recent work of Cruz *et al.* (2013).
Eucalypt forests		
Mk 5 Forest Fire Danger Meter McArthur (1967, 1973a)	Dry eucalypt forest with litter and sparse understory vegetation	Model has been superseded by Cheney *et al.* (2012). Model known to underpredict the spread of wildfires by factor of 2 to 3. Model use requires a number of subjective adjustment factors that lack a scientific basis.

Fire danger versus fire behaviour

In Australia, the term "fire danger" refers to a 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. The term "fire behaviour" on the other hand refers to the manner in which fuel ignites, flame develops, fire spreads, and exhibits other phenomena in relation to fuel, weather and topography. The conditions that affect fire danger do not always affect the behaviour of a fire, including rate of fire spread, in the same way.

The difficulty of suppression is related to the type, number and condition of suppression resources available to fight a fire, the number of fire outbreaks that currently, or may soon, need to be suppressed, the type and value of assets that need to be protected from the fire, as well as the behaviour of the fire.

Since the mid-1990s, when a new generation of fire behaviour models were starting to be introduced, there has been a separation of the concept of fire danger and fire behaviour. Previously, fire behaviour was a direct function of a fire danger index value – one simply multiplied the fire danger index value by some constant to determine fire behaviour in useful units (e.g. fire spread rate in kilometres per hour, flame height in metres, spotting distance in kilometres). However, as the rate of fire spread component of these systems was found to be wanting, the link between fire danger and fire behaviour was broken in order to enable more refined (and often more complex) fire behaviour models to be developed and deployed without affecting the calculation of fire danger (which, at the time, suited the needs of many fire authorities as it meant that they would not disrupt organisational arrangements based on fire danger levels, many of which have been in satisfactory use for more than 40 years).

This publication provides recommendations of use for prediction of fire spread only – it does not make any comment on the veracity and fit-for-purpose of the current operational fire danger rating systems. These systems, specifically the McArthur Grassland and Forest Fire Danger Rating systems, are the only ones designed for and suited to Australian conditions and will continue to be employed until replacement systems are developed.

Table 8.3. Listing of models not described in the report that might provide useful fire behaviour predictions to Australian fuel complexes. Note: List is not comprehensive.

Model	Comment
McArthur (1963)	Fire behaviour and burning guide for Brigalow lands in Queensland. Allows for the calculation of rate of fire spread from a number of tables and graphs. Results not coded into equations.
Rothermel (1972)	Model implemented in US Fire Behaviour Prediction System, such in BehavePlus (Andrews *et al.* 2008) and FARSITE (Finney 2004). Tested in Australian fuel complexes with mixed results. Model performed adequately in grassland (Gould 1991), shrubland fuel complexes (e.g. McCaw 1997) but poorly in Eucalypt forests (Moore 1986; Burrows 1994).
Cheney and Just (1974)	Burning guide for sugar cane plantations. This is not a fire spread model per se, but a burning guide that allows the determination of a Cane Burning Index and associated cane burning operations.
Cheney (1978)	Burning guide for logging slash and open and closed eucalypt forest. Allows for the calculation of rate of fire spread and intensity from a number of tables and graphs. Results not coded into equations.
Forestry Canada Fire Danger Group (1992)	Canadian Forest Fire Behavior Prediction System; implemented in Prometheus fire spread simulator (Tymstra *et al.* 2010) and basis for NZ Fire Behaviour Prediction System. This is a fuel type specific system parameterised for Canadian fuel complexes. Overall most Canadian fuel types have no match to Australian ones with the exception of Fuel Type C-6 (Conifer Plantation), which might be used to predict fire propagation in certain stages of pine plantation rotation (Cruz and Plucinski 2007; Pearce *et al.* 2012). See Wotton *et al.* (2009) for updates to the system.
Buckley (1993)	Burning guide for regrowth forests with wiregrass understory in Victoria.
Lacy (2009)	Burning guide for young tropical eucalypt plantations with dense grassy understorey. Rate of spread model provided in this study restricted to no-wind conditions.
Leonard (2009)	Fire sustainability model for grasslands. Experimental design, namely small burn plots, limits applicability of results to real world situation.
Zylstra (2011)	Fire spread model developed from simplified geometrical considerations and small scale bench-top experiments. Model performance unknown.

9. Bibliography and further reading

Albini, F.A. (1976) Estimating wildland fire behavior and effects. US Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station, General Technical Report INT-30, Ogden, Utah. 92 pp.

Alexander, M.E. (1990) Computer calculation of the Keetch-Byram Drought Index - programmers beware! *Fire Management Notes* **51**(4), 23-25.

Alexander, M.E. (1992) The Keetch-Byram Drought Index: a corrigendum. *Bulletin of the American Meteorological Society* **73**, 61.

Alexander, M.E. (1998) Crown fire thresholds in exotic pine plantations of Australasia. Australian National University, PhD Thesis, Canberra, ACT. 228 pp.

Alexander, M.E. (2009a) Wildland fire behavior and "The Course of Science" flowchart: is there a connection? *Fire Management Today* **69**(3), 44-46.

Alexander, M.E. (2009b) Are we abusing our use of models and modelling in wildland fire and fuel management? *Fire Management Today* **69**(4): 24-27.

Alexander, M.E. and Cruz, M.G. (2006) Evaluating a model for predicting active crown fire rate of spread using wildfire observations. *Canadian Journal of Forest Research* **36**, 3015-3028.

Alexander, M.E. and Cruz, M.G (2013a) Limitations on the accuracy of model predictions of wildland fire behaviour: a state-of-the-knowledge overview. *Forestry Chronicle* **89**, 370-381.

Alexander, M.E. and Cruz, M.G. (2013b) Assessing the effect of foliar moisture on the spread rate of crown fires. *International Journal of Wildland Fire* **22**, 415–427.

Alexander, M.E. and Thomas, D.A. (2004) Forecasting wildland fire behavior: aids and guides, and knowledge-based protocols. *Fire Management Today* **64**(1), 4-11.

Anderson, W.R., Cruz, M.G., Fernandes, P.M., McCaw, W.L., Vega, J.A., Bradstock, R.A., Fogarty, L., Gould, J., McCarthy, G., Marsden-Smedley, J.B., Matthews, S., Mattingley, G., Pearce, G. and van Wilgen, B.W. (2015) A generic, empirical-based model for predicting rate of fire spread in shrublands. *International Journal of Wildland Fire* **24**, 443-460.

Andrews, P.L. (2007) BehavePlus fire modeling system: past, present, and future. In: *Proceedings of 7th Symposium on Fire and Forest Meteorology*, 23-25 October 2007, Bar Harbor, Maine. American Meteorological Society, Boston, Massachusetts. 13 pp.

Andrews, P.L., Bevins, C.D. and Seli, R.C. (2008) BehavePlus fire modeling system, version 4.0: user's guide. US Department of Agriculture, Forest Service, Rocky Mountain Research Station, General Technical Report RMRS-GTR-106WWW Revised. Ogden, Utah. 123 pp.

Barrows, J.S. (1951) Fire behavior in northern Rocky Mountain forests. US Department of Agriculture, Forest Service, Northern Rocky Mountain Forest and Range Experiment Station, Station Paper No. 29, Missoula, Montana. 103 pp. + Appendices.

Beck, J.A. (1995) Equations for the Forest Fire Behaviour Tables for Western Australia. *CALM Science* **1**, 325-348.

Beck, J.A. (2000) Towards an operational geographic information system for fire management in Western Australia. Curtin University of Technology, PhD Thesis, Perth, WA. 212 pp.

Bradstock, R.A. and Gill, A.M. (1993) Fire in semi-arid mallee shrublands: size of flames from discrete fuel arrays and their role in the spread of fire. *International Journal of Wildland* Fire **3**, 3-12.

Brown, A.A. and Davis, K.P. (1973) *Forest fire: control and use*. Second edition. McGraw-Hill, New York, New York. 686 pp.

Buckley, A.J. (1993) Fuel reducing regrowth forests with a wiregrass fuel type: fire behaviour guide and prescriptions. Department of Conservation and Natural Resources, Fire Management Branch, Research Report No. 40, East Melbourne, Vic. 34 pp.

Bureau of Meteorology (2014) Beaufort wind scale, Accessed 5 December 2014, <http://www.bom.gov.au/lam/glossary/beaufort.shtml>

Burrows, N.D. (1984a) Describing forest fires in Western Australia. Forest Department of Western Australia, Technical Paper No. 9, Perth, WA. 29 pp.

Burrows, N.D. (1984b) Predicting blow-up fires in the jarrah forest. Forests Department, Western Australia, Technical Paper No.12, Perth, WA. 27 pp.

Burrows, N.D. (1994) Experimental development of a fire management model for jarrah (*Eucalyptus marginata* Donn ex Sm.) forest. Australian National University, PhD Thesis, Canberra, ACT. 293 pp.

Burrows, N.D. (1995) A framework for assessing acute impacts of fire in jarrah forests for ecological studies. *CALMScience Supplement* **4**, 59-66.

Burrows, N.D. (1999) Fire behaviour in jarrah forest fuels: 2. Field experiments. *CALM Science* **3**, 57-84.

Burrows, N.D. and Sneeuwjagt, R.J. (1991) McArthur's forest fire danger meter and the forest fire behaviour tables for western Australia: derivation, application and limitations. In: N.P. Cheney, and A.M. Gill (eds), *Proceedings of Conference on Bushfire Modeling and Fire Danger Rating Systems*; 11–12 July 1988; Canberra, ACT: CSIRO Division of Forestry, pp. 65-77.

Burrows, N.D., Ward, B. and Robinson, A. (1988) Aspects of fire behaviour and fire suppression in a *Pinus radiata* plantation. Western Australia Department of Conservation and Land Management, Perth, Western Australia. *Landnote* 2(88), 4 pp.

Burrows, N.D., Ward, B. and Robinson, A. (1991) Fire behaviour in spinifex fuels on the Gibson Desert Nature Reserve, Western Australia. *Journal of Arid Environments* **20**, 189-204.

Burrows, N.D., Ward, B. and Robinson, A. (2000) Behaviour and some impacts of a large wildfire in the Gnangara martime pine (*Pinus pinaster*) plantation, Western Australia. *CALM Science* **3**, 251-260.

Burrows, N.D., Ward, B. and Robinson A. (2009) Fuel dynamics and fire spread in spinifex grasslands of the western desert. *Proceedings of the Royal Society of Queensland* 115, 69-76.

Byram, G.M. (1959) Combustion of forest fuels. In: K.P. Davis (ed) *Forest Fire: Control and Use*. McGraw Hill, New York, pp. 61-89.

Byrne, P.J. (1980) Prescribed burning in Queensland exotic pine plantations. Paper prepared for the *Eleventh Commonwealth Forestry Conference*. Queensland Department of Forestry, Brisbane, Qld. 58 pp.

Catchpole, T. and de Mestre, N. (1986) Physical models for a spreading line fire. *Australian Forestry* **49**, 101-111.

Catchpole, W.R. (2002) Fire properties and burn patterns in heterogeneous landscapes. In R.A. Bradstock, J.E. Williams and A.M. Gill (eds), *Flammable Australia: The Fire Regimes and Biodiversity of a Continent*. University Press, Cambridge, UK, pp. 49-75.

Catchpole, W.R., Bradstock, R.A., Choate, J., Fogarty, L.G., Gellie, N., McCarthy, G., McCaw, W.L., Marsden-Smedley, J.B. and Pearce, G. (1998) Cooperative development of equations for heathland fire behaviour. In: D.X. Viegas (ed), *III International Conference on Forest Fire Research/14th Conference on Fire and Forest Meteorology Proceedings, Volume II*, 16-20 November 1998, Luso, Portugal. ADAI, University of Coimbra, Coimbra, Portugal, pp. 631-645.

Chandler, C.C. and Countryman, C.M. (1959) Use of fire behavior specialists can pay off. *Fire Control Notes* **20**,120132.

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

Cheney, N.P. (1978) Guidelines for fire management in forested watersheds, based on Australian experience. In: *Special Readings in Conservation*. Food and Agriculture Organization of the United Nations, FAO Conservation Guide 4, Rome Italy. pp. 1-37.

Cheney, N.P. (1981) Fire behaviour. In: A.M. Gill, R.H. Groves and I.R. Noble (eds), *Fire and the Australian Biota*. Australian Academy of Science, Canberra, ACT, pp. 151-175.

Cheney, N.P. (1985) New approaches to fire danger and fire behaviour. In: *Proceedings of Fire Weather Services Conference*. Commonwealth of Australia, Bureau of Meteorology, Melbourne, Vic. pp 12.1-12.9.

Cheney, N.P. (1991) Models used for fire danger rating in Australia. In: N.P. Cheney and A.M. Gill (eds), *Proceedings of Conference on Bushfire Modelling and Fire Danger Rating Systems*, 11-12 July 1988, CSIRO Division of Forestry, Canberra, ACT. pp.19-28.

Cheney, N.P. and Bary, G.A.V. (1969) The propagation of mass conflagrations in a standing eucalypt forest by the spotting process. In: Collected Papers (Paper A6), *Mass Fire Symposium, Volume I*. Commonwealth of Australia, Defence Standards Laboratory, Maribyrnong, Vic. 18 pp.

Cheney, N.P. and Gould, J.S. (1995) Fire growth in grassland fuels. *International Journal of Wildland Fire* **5**, 237-247.

Cheney, N.P. and Gould, J.S. (1996) Development of fire behaviour models for high-intensity forest fires. In: Heathcote, R.L., Cuttler, C., and Koetz, J (eds), *NDR96 Conference on Natural Disaster Reduction*, 29 September – 2 October 1996, Gold Coast. Queensland.

Cheney, N.P. and Gould, J.S. (1997) Fire growth and acceleration. *International Journal of 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. *International Journal of Wildland Fire* **3**, 31-44.

Cheney, N.P., Gould, J.S. and Catchpole, W.R. (1998) Prediction of fire spread in grasslands. *International Journal of Wildland Fire* **8**, 1-15.

Cheney, N.P., Gould, J.S. and Knight, I. (1992) A prescribed burning guide for young regrowth forest of silvertop ash. Forestry Commission of New South Wales, Research Division, Research Report No. 16, Sydney, NSW. 92 pp.

Cheney, N.P., Gould, J.S., McCaw, W.L. and Anderson, W.R. (2012) Predicting fire behaviour in dry eucalypt forest in southern Australia. *Forest Ecology and Management* **280**, 120-131.

Cheney, N.P. and Just, T.E. (1974) The behaviour and application of fire in sugar cane in Queensland. Australian Department of Agriculture, Forest and Timber Bureau, Leaflet No. 115, Canberra, ACT. 45 pp.

Cheney, P. and Sullivan, A. (2008*) Grassfires: fuel, weather and fire Beha*viour. Second edition. CSIRO Publishing, Collingwood, Vic. 160 pp.

Coleman, J.R. and Sullivan, A.L. (1996) A real-time computer application for the prediction of fire spread across the Australian landscape. *Simulation* **67**, 230-240.

Countryman, C.M. (1972) The fire environment concept. US Department of Agriculture, Forest Service, Pacific Southwest and Range Experiment Station, Berkeley, California, 12 pp.

Countryman, C.M. and Chandler, C.C. (1963) The fire behavior team approach in fire control. *Fire Control Notes* **24**, 56-60.

Crane, W.B. (1982) Computing grassland and forest fire behaviour, relative humidity and drought index by pocket calculator. *Australian Forestry* **45**, 89-97.

Cruz, M.G. (2010) Quick guide for fire behaviour prediction in semi-arid mallee-heath. Bushfire Cooperative Research Centre, Field Guide, East Melbourne, Vic, 2 pp.

Cruz, M.G. and Alexander, M.E. (2013) Uncertainty associated with model predictions of surface and crown fire rates of spread. *Environmental Modelling & Software* **47**, 16-28.

Cruz, M.G., Alexander, M.E. and Fernandes, P. (2008) Development of a model system to predict wildfire behaviour in pine plantations. *Australian Forestry* **71**, 113-121.

Cruz, M.G., Alexander, M.E. and Wakimoto, R.H. (2005) Development and testing of models for predicting crown fire rate of spread in conifer forest stands. *Canadian Journal of Forest Research* **35**, 1626-1639.

Cruz, M.G., Butler, B.W., Alexander, M.E., Forthofer, J.M. and Wakimoto, R.H. (2006) Predicting the ignition of crown fuels above a spreading surface fire. Part I: Model idealization. *International Journal of Wildland Fire* **15**, 47-60.

Cruz, M.G. and Fernandes, P.A.M. (2008) Development of fuel models for fire behaviour prediction in maritime pine (*Pinus pinaster* Ait.) stands. *International Journal of Wildland Fire* **17**, 194-204.

Cruz, M.G., Gould, J., Kidnie, S., Bessel, R., and Nichols, D. (2015) Effects of curing on grassfires – II: The effect of grass senescence on the rate of fire spread. *International Journal of Wildland Fire* **24**, in press.

Cruz, M.G., Matthews, S., Gould, J., Ellis, P. Henderson, M. Knight, I. and Watters, J. (2010) Fire dynamics in mallee-heath: fuel, weather and fire behaviour prediction in south Australian semi-arid shrublands. Bushfire CRC report A.10.01, East Melbourne, Vic. 134 pp.

Cruz, M.G., McCaw, W.L., Anderson, W.R. and Gould, J.S. (2013) Fire behaviour modelling in semi-arid mallee-heath shrublands of southern Australia, *Environmental Modelling & Software* **40**, 21-34.

Cruz, M.G., Sullivan, A.L., Gould, J.S., Sims, N.C., Bannister, A.J., Hollis, J.J. and Hurley, R.J. (2012) Anatomy of a catastrophic wildfire: The Black Saturday Kilmore East fire in Victoria, Australia. *Forest Ecology and Management* **284**, 269-285.

Davis, K.M. (1976) Behaviour and effects of fire during mild weather. CSIRO Division of Forest Research Internal Report 3, Canberra, ACT. 7 pp.

Dell, J.D. (1966) The fire-behavior team in action the Coyote Fire. *Fire Control Notes* **27**(1), 8, 10, 15.

Ellis, P.F. (2011) Fuelbed ignition potential and bark morphology explain the notoriety of the eucalypt messmate 'stringybark' for intense spotting. *International Journal of Wildland Fire* **20**, 897–907.

Fernandes, P.M. (2001) Fire spread prediction in shrub fuels in Portugal. *Forest Ecology and Management* **144,** 67-74.

Fernandes, P.A.M., Loureiro, C. and Botelho, H.S. (2004) Fire behaviour and severity in a maritime pine stand under differing fuel conditions. *Annals of Forest Science* **61**, 537-544.

Finkele, K., Mills, G.A., Beard, G. and Jones, D.A. (2006) National gridded drought factors and comparison of two soil moisture deficit formulations used in prediction of Forest Fire Danger Index in Australia. *Australian Meteorological Magazine* **55**, 183-197.

Finney, M.A. (2004) FARSITE: Fire Area Simulator – model development and evaluation. US Department of Agriculture, Forest Service, Rocky Mountain Research Station, Research Paper RMRS-RP-4 Revised, Ogden, Utah. 47 pp.

Foley, J.C. (1947) A study of meteorological conditions associated with bush and grass fires and fire protection strategy in Australia. Australia Bureau of Meteorology, Bulletin No. 38, Melbourne, Victoria, 234 pp.

Forestry Canada Fire Danger Group. (1992) Development and structure of the Canadian Forest Fire Behavior Prediction System. Forestry Canada, Information Report ST-X-3, Ottawa, Ontario. 63 pp.

Forestry and Timber Bureau (1961) Fire Control. In: Annual Report of the Forestry and Timber Bureau. Commonwealth of Australia, Forestry and Timber Bureau, Canberra, ACT, pp 4-6.

Forestry and Timber Bureau (1970) Fire Protection Section. In: Annual Report of the Forestry and Timber Bureau. Commonwealth of Australia, Forestry and Timber Bureau, Canberra, ACT, pp 14-15.

Gill, A.M., Burrows, N.D. and Bradstock, R.A. (1995) Fire modelling and fire weather in an Australian desert. *CALMScience Supplement* **4**, 29-34.

Gisborne, H.T. (1948) Fundamentals of fire behaviour. *Fire Control Notes* **9**(1),13-24.

Gould, J.S. (1991) Validation of the Rothermel fire spread model and related fuel parameters in grassland fuels. Pages 51-64 in N.P. Cheney and A.M. Gill (eds.). Proc. of Conf. on *Bushfire Modeling and Fire Danger Rating Systems*. 11-12 July, 1988, Canberra, ACT, CSIRO Division of Forestry, pp. 51-64.

Gould, J.S. (1994) Evaluation of McArthur's control burning guide in regrowth *Eucalyptus sieberia* forest. *Australian Forestry* **57**, 86-93.

Gould, J.S., McCaw, W.L. and Cheney, N.P. (2011) Quantifying fine fuel dynamics and structure in dry eucalypt forest (*Eucalyptus marginata*) in Western Australia for fire management. *Forest Ecology and Management* **262**, 531-546.

Gould, J.S., McCaw, W.L., Cheney, N.P., Ellis, P.E., Knight, I.K. and Sullivan, A.L. (2007a) Project Vesta. Fire in dry eucalypt forest: fuel structure, fuel dynamics, and fire behaviour. Ensis-CSIRO, Canberra, ACT and Department of Environment and Conservation, Perth, WA, Australia, 218 pp.

Gould, J.S., McCaw, W.L., Cheney, N.P., Ellis, P.F. and Matthews, S. (2007b) Field guide: Fuel assessment and fire behaviour prediction in dry eucalypt forest. Interim edition, CSIRO Publishing, Collingwood, Vic. 92 pp.

Griffin, G.F. and Allan, G.E. (1984) Fire behaviour. In: E. Saxon (ed.) *Anticipating the inevitable: a patch burn strategy for fire management at Uluru (Ayers Rock-Mt Olga) National Park*, Saxon, E. (ed), CSIRO, Melbourne, Vic. pp. 55-68.

Griffiths, D. (1999) Improved formula for the Drought Factor in McArthur's Forest Fire Danger Meter. *Australian Forestry* **62**, 202-206.

Harris, A. C. (1968) Forest fire danger tables. Forests Department of Western Australia, Perth, WA, 22 pp.

Hines, F., Tolhurst, K.G., Wilson, A.A.G. and McCarthy, G.J. (2010) Overall Fuel Hazard Assessment Guide, fourth edition. Department of Sustainability and Environment. Melbourne, Victoria, 41 pp.

Hodgson, A. (1967) Control burning in eucalypt forests in Victoria, Australia. *Journal of Forestry* **66**, 601-605.

Hough, W.A. and Albini, F.A. (1978) Predicting fire behaviour in palmetto-gallberry fuel complexes. U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station, Research Paper SE-174, Asheville, North Carolina. 49 pp.

Hunt, S.M. and Crock, M.J. (1987) Fire behaviour modelling in exotic pine plantations: testing the Queensland Department of Forestry 'Prescribed Burning Guide Mk III'. *Australian Forest Research* **17**, 179-189.

Jemison, G.M. (1939**)** Determination of the rate of spread of fire in the Southern Appalachians. *Fire Control Notes* **3**(1): 4–7.

Johnston, P., Kelso, J. and Milne, G. J. (2008) Efficient simulation of wildfire spread on an irregular grid. *International Journal of Wildland Fire* **17**, 614–627.

Just, T.E. (1972) Prescribed burning in slash pine plantations. Queensland Department of Forestry, Brisbane, Qld. *Department Notes* **2**, 29-30.

Keetch, J.J. and Byram, G.M. (1968) A drought index for forest fire control. U.S. Department of Agriculture, Forest Service, Southeast Forest Experiment Station, Research Paper SE-38, Asheville, North Carolina. 32 pp. (revised November 1988.)

Kilinc, M., Anderson, W.R. and Price B. (in review) Testing the performance of fire spread models for grassland and forest in Australia. *International Journal of Wildland Fire*.

Knutson, K.K. (1962) The place of the fire behavior officer in the fire suppression organization. *Fire Control Notes* **23**, 81-82.

Lacy, P. (2009). Burning under young eucalypts: a guide for prescribed burning and post-burn assessment. Bushfire Cooperative Research Centre, East Melbourne, Vic. 19 pp.

Leonard, S. (2009) Predicting sustained fire spread in Tasmanian native grasslands. *Environmental Management* **44**, 430–440.

Luke, R.H. (1961) *Bush fire control in Australia.* Hodder and Stoughton, Melbourne, Vic. 136 pp.

Luke, R.H. and McArthur, A.G. (1978) *Bushfires in Australia*. Australian Government Publishing Service, Canberra, ACT, 359 pp.

Marsden-Smedley, J.B. and Catchpole, W.R. (1995a) Fire behaviour modelling in Tasmanian buttongrass moorlands II. Fire behaviour. *International Journal of Wildland Fire* **5**, 215-228.

Marsden-Smedley, J.B. and Catchpole, W.R. (1995b) Fire behaviour modelling in Tasmanian buttongrass moorlands I. Fuel characteristics. *International Journal of Wildland Fire* **5**, 203-214.

Marsden-Smedley, J.B. and Catchpole, W.R. (2001) Fire modelling in Tasmanian buttongrass moorlands. III. Dead fuel moisture. *International Journal of Wildland Fire* **10**, 241-253.

Marsden-Smedley, J.B., Rudman, T., Pyrke, A. and Catchpole, W.R. (1999) Buttongrass moorland fire behaviour prediction and management. *TASFORESTS* **11**, 87-99.

Matthews, S. (2009) A comparison of fire danger rating systems for use in forests. *Australian Meteorological and Oceanographic Journal* **58**, 41-48.

Matthews, S., Gould, J.S. and McCaw, L. (2010) Simple models for predicting dead fuel moisture in eucalyptus forests. *International Journal of Wildland Fire* **19**, 459-467.

McArthur, A.G. (1958) The preparation and use of fire danger tables. In: *Proceedings of the Fire Weather Conference*. Commonwealth of Australian Bureau of Meteorology, Melbourne Vic. 18 pp.

McArthur, A.G. (1960) Fire danger rating tables for annual grasslands. Commonwealth Department of National Development, Forestry and Timber Bureau, Canberra, ACT. 15 pp.

McArthur, A.G. (1962) Control burning in eucalypt forest. Commonwealth of Australia, Forestry and Timber Bureau, Leaflet 80, Canberra, ACT. 31pp.

McArthur, A.G. (1963) Fire behaviour in the brigalow lands of the Fitzroy Basin. Commonwealth of Australia, Forestry and Timber Bureau, Canberra, ACT. 44 pp.

McArthur, A.G. (1966a) Weather and grassland fire behaviour. Commonwealth Department of National Development Forestry and Timber Bureau, Leaflet 100, Canberra, ACT. 23 pp.

McArthur, A.G. (1966b) The application of a drought index system to Australian fire control. Commonwealth of Australia, Forestry and Timber Bureau, Canberra, ACT. 18 pp.

McArthur, A.G. (1967) Fire behaviour in eucalypt forest. Commonwealth Department of National Development. Forestry and Timber Bureau, Leaflet No. 107, Canberra, ACT. 36 pp.

McArthur, A.G. (1968) The effect of time on fire behaviour and fire suppression problems. South Australia Emergency Fire Services, Adelaide, SA. E.F.S. Manual 1968: 3-6, 8, 10-13.

McArthur, A.G. (1969) The Tasmanian bushfires of 7th February, 1967, and associated fire behaviour characteristics. Paper A7 In*: Collected Papers, Mass Fire Symposium, Volume I*. Commonwealth of Australia, Defence Standards Laboratory, Maribyrnong, Vic. 23 pp.

McArthur, A.G. (1973a) Forest Fire Danger Meter Mark V. Commonwealth Department of National Development Forestry and Timber Bureau, Canberra, ACT. (published as a circular slide rule).

McArthur, A.G. (1973b) Grassland Fire Danger Meter Mark IV. Commonwealth Department of National Development Forestry and Timber Bureau, Canberra, ACT. (published as a circular slide rule).

McArthur, A.G. (1977) Grassland Fire Danger Meter Mark V. Country Fire Authority, Melbourne, Vic. (published as a linear slide rule).

McArthur, A.G. (1984) Fire. In: W.E. Hills and A.G. Brown (eds). *Eucalypts for Wood Production*. Academic Press, Sydney, NSW. pp. 169-176.

McArthur, A.G. and Luke, R.H. (1963) Fire behaviour studies in Australia. *Fire Control Notes* **24**(4), 87–92.

McArthur, A.G., Cheney, N.P. and Barber, J. (1982) The fires of 12 February 1977 in the Western District of Victoria. CSIRO Division of Forest Research, Canberra, ACT, and Country Fire Authority, Melbourne, Vic. Joint Report, 73 pp.

McCarthy, G.J., Tolhurst, K.G. and Chatto, K. (1999) Overall fuel hazard guide. Department of Natural Resources and Environment, Victoria. Research Report No 47. Melbourne, Vic. 32 pp.

McCaw, W.L. (1991) Fire spread prediction in mallee-heath shrublands in south-western Australia. In: P.L. Andrews and D.F. Potts (eds), *Proceedings of 11th Conference on Fire and Forest Meteorology*, 16-19 April 1991, Missoula, MT, Society of American Foresters, SAF Publication 91-04, Bethesda, Maryland, pp. 226-233.

McCaw, W.L. (1995) Predicting fire spread in Western Australian mallee-heath. *CALMScience Supplement* **4**, 35-42.

McCaw, W.L. (1997) Predicting fire spread in Western Australian mallee-heath shrubland. University of New South Wales, School of Mathematics and Statistics, PhD Thesis, Canberra, ACT. 240 pp.

McCaw, W.L. (1998) Research as a basis for fire management in mallee-heath shrublands of south-western Australia. In: DX Viegas (ed), *III International Conference on Forest Fire Research/14th Conference on Fire and Forest Meteorology Proceedings, Volume II*, 16-20 November 1998, Luso, Portugal, ADAI, University of Coimbra, Coimbra, Portugal, pp. 2335-2348.

McCaw, W.L., Cheney, N.P. and Sneeuwjagt, R. (2003) Development of a scientific understanding of fire behaviour and use in south-west Western Australia. In: I. Abbott and N. Burrows (eds), *Fire in ecosystems of South-west Western Australia: Impacts and management*. Backhuys Publishers, Leiden, The Netherlands, pp 171-187.

McCaw, W.L., Gould, J.S. and Cheney, N.P. (2008) Existing fire behaviour models under-predict the rate of spread of summer fires in open jarrah (*Eucalyptus marginata*) forest. *Australian Forestry* **71**, 16-26.

McCaw, W.L., Gould, J.S., Cheney, N.P., Ellis, P.M.F and Anderson, W.R. (2012) Changes in behaviour of fire in dry eucalypt forest as fuel increases with age. *Forestry Ecology and* Management **271**, 170–181.

Moore, P.F. (1986) Comparison of the Forest Fire Danger Meter Mk5 and the BEHAVE fire behaviour prediction system in a dry eucalypt forest. University of Montana, Master of Forestry Thesis, Missoula, Montana. 84 pp.

Moore, R.M. (1970) *Australian Grasslands*. Australian National University Press, 455 pp.

Mount, A.B. (1972) The derivation and testing of a soil dryness index using runoff data. Tasmanian Forestry Commission Bulletin No. 4, Hobart, TAS. 31 pp.

Nelson, R.M. (1991) A model of diurnal moisture change in dead forest fuels. In: P.L. Andrews and D.F. Potts (Eds) *Proceedings of 11th Conference on Fire and Forest Meteorology*, 16-19 April 1991, Missoula, Montana. Society of American Foresters, SAF Publication 91-04, Bethesda, Maryland. pp. 109-116.

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

Pastor, E., Zarate, L., Planas, E. and Arnaldos, J. (2003) Mathematical models and calculation systems for the study of wildland fire behaviour. *Progress in Energy and Combustion Science* **29**, 139-153.

Pearce, H.G., Anderson, S.A.J. and Clifford, V.R. (2012) A manual for predicting fire behaviour in New Zealand fuels. Second edition. Scion Rural Fire Research Group, Christchurch, NZ.

Peet, G.B. (1965) A fire danger rating and controlled burning guide for the northern jarrah (*Euc. marginata* Sm) forest of Western Australia. Forests Department of Western Australia, Bulletin 74, Perth, WA, 37 pp.

Peet, G.B. (1967) The shape of mild fires in jarrah forest. *Australian Forestry* **31**, 121-127.

Peet, G.B. (1972) Fire studies in jarrah (*Eucalyptus marginata* Sm.) forest. University of Melbourne, MSc Thesis, Melbourne, Vic. 199 pp.

Purton, C.M. (1982) Equations for the McArthur Mark 4 Grassland Fire Danger Meter. Commonwealth of Australia, Bureau of Meteorology, Meteorological Note 147, Melbourne, Vic. 12 pp.

Queensland Department of Forestry (1976) Operations manual – prescribed burning in exotic pine plantations. Queensland Department of Forestry, Brisbane, QLD. 11 pp.

Ritchie, R. (1970) Control Burning Meter Mark 2. Forest Commission of Victoria, Melbourne, Vic. (published as a circular slide rule).

Rothermel, R.C. (1972) A mathematical model for predicting fire spread in wildland fuels. US Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station, Research Paper INT-115, Ogden, Utah. 40 pp.

Rothermel, R.C. (1983) How to predict the spread and intensity of forest and range fires. US Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station, General Technical Report INT-143, Ogden, Utah. 161 pp.

Rothermel, R.C. (1991) Predicting behavior and size of crown fires in the Northern Rocky Mountains. US Department of Agriculture, Forest Service, Intermountain Research Station. Research Paper INT-438, Ogden, Utah. 46 pp.

Russo, J.E. and Schoemaker, P.J.H. (1989) Decision traps: ten barriers to brilliant decision-making and how to overcome them. Simon and Schuster Incorporated, New York, New York. 280 pp.

Russo, J.E. and Schoemaker, P.J.H. (2002) *Winning decisions: getting it right the first time*. Doubleday, New York, 329 pp.

Scott, A.C., Bowman, D.M.J.S., Bond, W.J., Pyne, S.J. and Alexander, M.E. (2014) *Fire on Earth: An Introduction*. Wiley-Blackwell, Chichester, UK. 413 pp.

Sirakoff, C. (1985) A correction to the equations describing the McArthur forest fire danger meter. *Australian Journal of Ecology* **10**, 481.

Sneeuwjagt, R.J. and Peet, G.B. (1976) Forest fire behaviour tables for Western Australia. Forests Department of Western Australia, Perth, WA.

Sneeuwjagt, R.J. and Peet, G.B. (1985) Forest Fire Behaviour Tables for Western Australia, Third Edition. Department of Conservation and Land Management Perth, WA, 59 pp.

Specht, R.L. (1981) Heathlands. In: R.H. Groves (ed), *Australian Vegetation*. Cambridge University Press, Cambridge, UK. pp. 253-275.

Specht, R.L. and Specht, A. (1999) *Australian plant communities: dynamics of structure, growth and biodiversity*. Oxford University Press, Oxford, UK. 502 pp.

Stocks, B.J., Alexander, M.E. and Lanoville, R.A. (2004) Overview of the International Crown Fire Modelling Experiment (ICFME). *Canadian Journal of Forest Research* **34**, 1543-1547.

Sullivan, A.L. (2001) Review of the operational calculation of McArthur's Drought Factor. CSIRO Forestry and Forest Products, Client Report No. 921, Canberra, ACT. 46 pp.

Sullivan, A.L. (2009a) Wildland surface fire spread modelling, 1990-2007. 1: Physical and quasi-physical models. *International Journal of Wildland Fire* **18**, 349-368.

Sullivan, A.L. (2009b) Wildland surface fire spread modelling, 1990-2007. 2: Empirical and quasi-empirical models. *International Journal of Wildland Fire* **18**, 369-386.

Sullivan, A.L. (2009c) Improving operational models of fire behaviour. In: R.S Anderssen, R.D. Braddock and L.T.H. Newham (eds), *18th World IMACS Congress and MODSIM09 International Congress on Modelling and Simulation*, 13-17 July 2009, Cairns, Australia, pp. 282-288.

Sullivan, A.L. (2010) Grassland fire management in future climate. *Advances in Agronomy* **106**, 173-208.

Sullivan, A.L., Cruz, M.G., Ellis, P.F.M., Gould, J.S., Plucinski, M.P., Hurley, R. and Koul, V. (2013a) Fire Development, Transitions and Suppression final report. Client Report EP1312986. CSIRO Ecosystem Sciences and CSIRO Climate Adaptation Flagship, Canberra, ACT, 197 pp.

Sullivan, A.L., Gould, J.S., Cruz, M.G., Rucinski, C. and Prakash, M. (2013b) Amicus: a national fire behaviour knowledge base for enhanced information management and better decision making. In: J. Piantadosi, R.S. Anderssen and J. Boland (eds), *MODSIM2013, 20th International Congress on Modelling and Simulation*, Adelaide, South Australia, pp. 2068-2074.

Sullivan, A.L., McCaw, W.L., Cruz, M.G., Matthews, S. and Ellis, P.F. (2012) Fuel, fire weather and fire behaviour in Australian ecosystems. In: R.A. Bradstock, A.M. Gill and R.D. Williams (eds.), *Flammable Australia: Fire Regimes, Biodiversity and Ecosystems in a Changing World*, CSIRO Publishing, Collingwood, Vic. pp. 51-77.

Sullivan, A.L., Sharples, J.J., Matthews, S. and Plucinski, M. (2014) Estimating downslope fire spread for landscape fire spread prediction. *Environmental Modelling & Software* **62**,153-163.

Taylor, S.W., Pike, R.G. and Alexander, M.E. (1997) A field guide to the Canadian Forest Fire Behavior Prediction (FBP) System. Natural Resources Canada, Canadian Forest Service, Northern Forestry Centre, Special Report 11, Edmonton, Alberta. 60 pp.

Tolhurst, K.G. (2013) Fire behaviour analysts - saviours or disciples? Presentation made at the CSIRO Bushfire Behaviour Science Symposium, 14-16 October 2013, Canberra, ACT. http://www.youtube.com/watch?v=XHRq0mhqzAc.

Tolhurst, K.G. Kellas, J.D. and Wilson, A.A.G. (1992) Low intensity fire behaviour and fuel dynamics in dry sclerophyll forest, Wombat State Forest. In K.G. Tolhurst and D.W. Flinn (eds), *Ecological Impacts of Fuel Reduction Burning in Dry Sclerophyll Forest: First Progress Report*, Forest Research Report No. 349, Department of Conservation and Environment, Melbourne, Vic, pp. 2.1-2.40.

Tolhurst, K.G., Shields, B. and Chong, D. (2008) Phoenix: development and application of a bushfire risk management tool. *Australian Journal of Emergency Management* **23**(4), 47-54.

Tversky, A. and Kahneman, D. (1974) Judgment under uncertainty: Heuristics and biases. *Science* **185**, 1124-1131.

Tymstra, C., Bryce, R.W., Wotton, B.M., Taylor, S.W., and Armitage, O.B. (2010) Development and structure of Prometheus: the Canadian wildland fire growth simulation model. Natural Resources Canada, Canadian Forest Service, Northern Forestry Centre, Information Report NOR-X-417, Edmonton, Alberta 102 pp..

Underwood, R.J. (1985) Research for forest fire operations in Australia. In: J.J. Landsberg, J.J. and W. Parsons (Eds), *Research for Forest Management*. CSIRO Division of Forest Research, Canberra, ACT. pp. 269-282.

Van Wagner, C.E. (1969) A simple fire growth model. *The Forestry Chronicle*. **45**,103-104.

Van Wagner, C.E. (1971) Two solitudes in forest fire research. Environment Canada, Canadian Forestry Service, Petawawa Forest Experiment Station, Information Report PS-X-29, Chalk River, Ontario. 7 pp.

Van Wagner, C.E. (1977) Conditions for the start and spread of crown fire. *Canadian Journal of Forest Research* **7,** 23-34.

Viney, N.R. (1992) Modelling fine fuel moisture. University of New South Wales, University College, Department of Mathematics, Ph.D. Thesis, Canberra, ACT. 137 pp.

Viney, N. R., and Hatton, T. J. (1989) Assessment of existing fine fuel moisture models applied to Eucalyptus litter. *Australian Forestry*, **52**, 82-93.

Weber, R.O. (1991) Modelling fire spread through fuel beds. *Progress in Energy and Combustion Science* **17**, 67-82.

Weick, K.E. (2002) Human factors in fire behavior analysis: reconstructing the Dude Fire. *Fire Management Today* **62**(4), 815.

Williams, D.F. 1976. Forest fuels in unthinned radiate pine stands. *Australian Forestry* **39**, 238-244.

Willmott, C.J. (1982) Some comments on the evaluation of model performance. *Bulletin of American Meteorological Society* **63**, 1309-1313.

Wilson, A.A.G. (1992) Eucalypt bark hazard guide. Department of Conservation and Natural Resources, Research Report No. 32, Melbourne, Vic. 16 pp.

Wilson, A.A.G. (1993) Elevated fuel guide. Department of Conservation and Natural Resources, Victoria, Research Report No. 35, Melbourne, Vic. 22 pp.

Wotton, B.M., Alexander, M.E., and Taylor, S.W. (2009) Updates and revisions to the 1992 Canadian Forest Fire Behavior Prediction System. Natural Resources Canada, Canadian Forest Service, Great Lakes Forestry Centre, Information Report GLC-X-10E, Sault Ste. Marie, Ontario. 45 pp.

Zylstra, P. (2011). Forest flammability: modelling and managing a complex system. University of New South Wales, Australian Defence Force Academy, PhD Thesis, Canberra, ACT. 435 pp.

Beaufort wind scale

Beaufort scale number	Descriptive term	10-m open wind speed (km/h)	Description on Land
0	Calm	0	Smoke rises vertically.
1	Light air	1 - 5	Smoke drift indicates wind direction. Leaves and wind vanes are stationary.
2	Light winds	6 - 11	Wind felt on exposed skin. Leaves rustle. Wind vanes begin to move.
3	Gentle winds	12 - 19	Leaves and small twigs constantly moving, light flags extended.
4	Moderate winds	20 - 29	Raises dust and loose paper; small branches are moved.
5	Fresh winds	30 - 39	Small trees in leaf begin to sway; crested wavelets form on inland waters.
6	Strong winds	40 - 50	Large branches in motion; whistling heard in telephone wires; umbrellas used with difficulty.
7	Near gale	51 - 62	Whole trees in motion; inconvenience felt when walking against wind.
8	Gale	63 - 75	Twigs break off trees; progress generally impeded.
9	Strong gale	76 - 87	Slight structural damage occurs -roofing dislodged; larger branches break off.
10	Storm	88 - 102	Seldom experienced inland; trees uprooted; considerable structural damage.

(adapted from Bureau of Meteorology, 2014)

Length-to-breadth (LB) ratio for elliptical fire shapes on level terrain

Fuel type	10-m open wind speed (km/h)										
	0	5	10	15	20	25	30	35	40	45	50
	LB										
Forest	1.0	1.1	1.5	2.0	2.6	3.3	3.8	4.4	5.0	5.6	6.1
Grassland	1.0	2.3	3.2	3.5	4.4	4.9	5.3	5.7	6.1	6.4	6.8

Expect +/- 30% variation in the LB ratio due to effects of topography, fuels and wind direction changes.

(adapted from Taylor *et al.* 1997)

"This publication pulls together bushfire spread models so that the best available science can be integrated into incident management forecasts and decision making. The models in this publication will aid decisions that save lives. This is essential reading for all bushfire managers."

– Euan Ferguson AFSM, Chief Officer, Country Fire Authority, Victoria

Scale distances (km)

0 cm	1:10000	1:25000	1:50000
	0.1	0.25	0.5
	0.2	0.50	1.0
	0.3	0.75	1.5
	0.4	1.0	2.0
5 cm	0.5	1.25	2.5
	0.6	1.5	3.0
	0.7	1.75	3.5
	0.8	2.0	4.0
	0.9	2.25	4.5
10 cm	1.0	2.5	5.0
	1.1	2.75	5.5
	1.2	3.0	6.0
	1.3	3.25	6.5
	1.4	3.5	7.0
15 cm	1.5	3.75	7.5

"This book is a valuable resource for students of fire science who wish to understand some of the important drivers of fire behaviour and the development of fire behaviour models during the past 50 years in Australia."

– Associate Professor Kevin Tolhurst, University of Melbourne

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