Australian Fire Danger Rating System

Research Prototype

AFDRS

Australian Government

Bureau of Meteorology

Department of Home Affairs

Cover image

Smoke plume from the Beecroft Peninsula Fire. This fire burned in heath fuels on 26 November 2015, travelling at a rate of spread of 1,750 mh^{-1} under a forest fire danger index of 3 (Low-moderate). Photo courtesy NSW Rural Fire Service.

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A note on the name of the system

The Australian Fire Danger Rating System (AFDRS) was known originally as the National Fire Danger Rating System (NFDRS). In June 2019 the new name was adopted to distinguish it from the US NFDRS. This report was prepared prior to the adoption of AFDRS and uses NFDRS throughout.

Citation

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Name	Title	Date
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Jim Gould		14/01/2019

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Name	Title	Date
Rob Rogers, AFSM	Chair, NFDRS Board	31/07/2019

Related documents

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Contents

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Executive summary

This report presents the findings of a 12-month project that developed a Research Prototype for a new National Fire Danger Rating System (NFDRS). The project was run as part of a phased approach to the implementation of the NFDRS. Other components include a requirements gathering project completed in 2016 by Cube Group, development of implementation plans by the AFAC NFDRS Program Management Office, and social research, which is investigating how NFDRS ratings should be communicated. These projects continue a body of work that was initiated in 2009 as an outcome of the Royal Commission into the Black Saturday fires in Victoria.

The purpose of the Research Prototype project was to demonstrate that it is feasible to develop a fire danger rating system based on fire behaviour models that is national, modular, and open to continuous improvement. The aims of the project were to:

1. Define, and build a Research Prototype system
2. Operate the system and demonstrate that the ratings can be applied in a live trial
3. Build a system that is better than the current system
4. Identify knowledge gaps
5. Recommend a path forwards for future development

Aim 1: Define, and build a Research Prototype system

A system of fire danger rating based on fire behaviour calculations was developed incorporating ideas from researchers and operational staff as well as a review of scientific literature and agency training materials. Six rating categories were defined based on the range of possible fire behaviour, prescribed burning potential, suppression opportunities, and potential consequences of a fire. While the categories were tailored to different fuel types, and not all categories were used for some types, the categories can be broadly described as:

1. Mostly self-extinguishing, trouble-free fires
2. Typical prescribed burning conditions, fires generally easy to suppress
3. Most wildfires in this category. Fires typically suppressed with direct, parallel or indirect attack
4. Initial attack success critical to prevent large fire development. Defensive suppression strategies.
5. Defensive suppression strategies. High levels of threat to life/property. Safety of fire fighters and community paramount.
6. Safety of fire fighters and community most important. Without initial attack success, likelihood of very large fire development is very high. High probability of loss of life and property

The system divided the country into eight major fuel types based on the availability of suitable fire behaviour models and the rating category definitions were tailored to each fuel type, with the majority using fire intensity to determine the rating. These major fuel types were sub-divided on the basis of vegetation structure (e.g. wet and dry forest) and classified into several hundred individual fuel types, to differentiate variation in fuel attributes.

Three ‘red flag’ warnings were also defined to identify conditions where fires were likely to be affected by a wind change, long spotting distance or atmospheric instability, which increases the chance a fire thunderstorm will develop. The flags were displayed in the system web pages but were not used to modify the rating categories.

A major component of system build was development of nationally consistent fuel type and fire history maps. These, accompanied by fuel models, matched the requirements of fire behaviour models are an important output of the project. The data sets and models will find wide use beyond calculating fire danger rating.

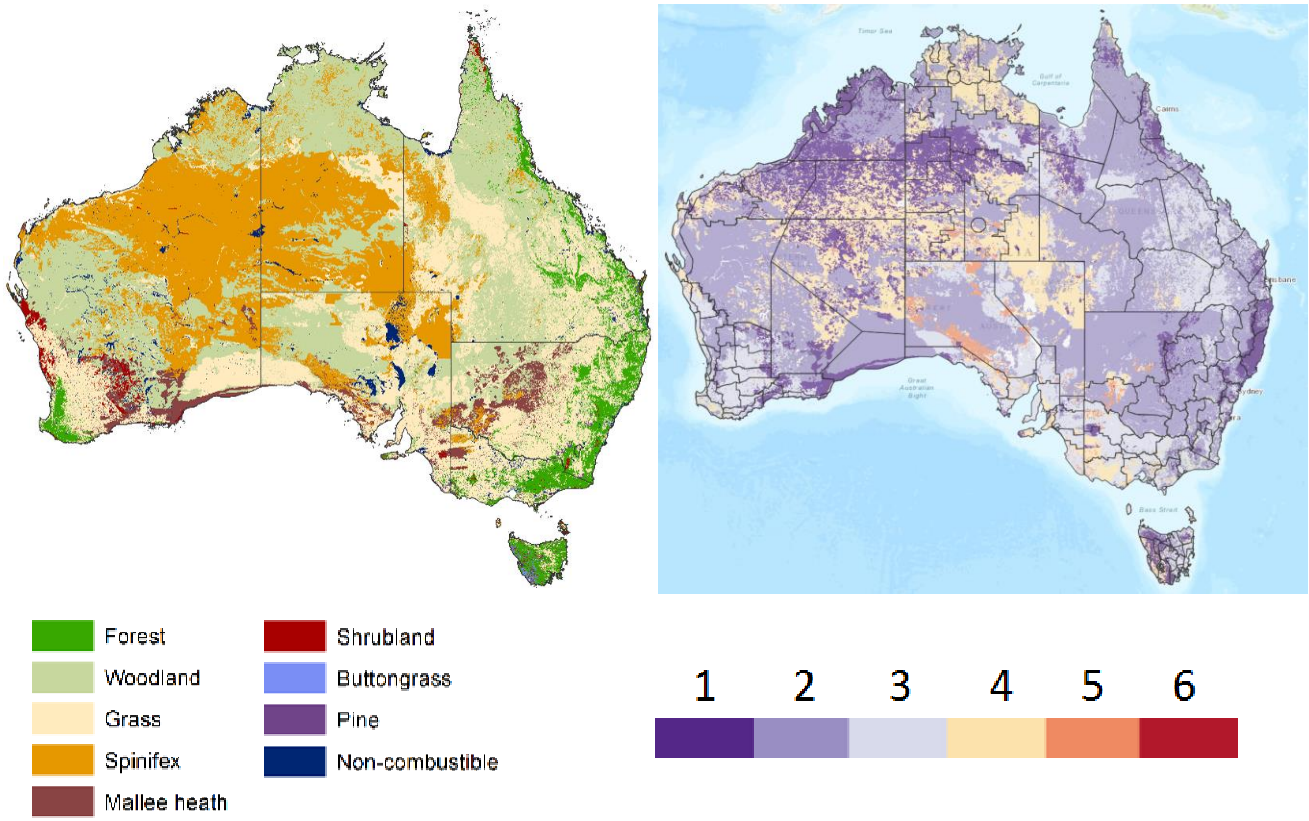

Figure 1 (Left) Major fuel types used to select fire behaviour models. (Right) Sample map of rating categories.

Aim 2: Operate the system and demonstrate that the ratings can be applied in a live trial

A computer system was built to calculate and display ratings. Calculations were performed daily by the Bureau of Meteorology using forecast weather at hourly intervals on a 1.5 x 1.5 km grid across Australia. Each grid cell was assigned to one of the eight major fuel types (Figure 1) and then weather forecasts were used to calculate fire behaviour metrics: rate of spread, intensity, flame height, and spotting distance. The metrics were then classified into rating categories.

In addition to the live trial system, rating calculations were also performed for an initial six-year (2010-2015) tranche of historical weather using outputs from the Bureau of Meteorology's reanalysis project. These historical calculations were used to estimate a climatology for the Research Prototype system.

Two display systems were developed. The first was a static website sorted by each State and Fire Weather Area, updated daily, showing maps and tables of daily maximum ratings and red flag warnings. The second was an interactive website that displayed hourly outputs as maps (Figure 1) and time-series plots.

A national live trial ran from October 2017 to March 2018. 71 participants from all Australian jurisdictions participated in the live trial. After being briefed on the system, participants collected information on the behaviour of, and response to, live incidents then assigned each incident to a rating category based on expert judgement using the detailed fire danger rating tables. They also provided feedback on the accuracy and utility of system outputs. A total of 265 observation reports were received, supplemented by 72 case study reports. Observations were collected covering all jurisdictions and all major fuel types.

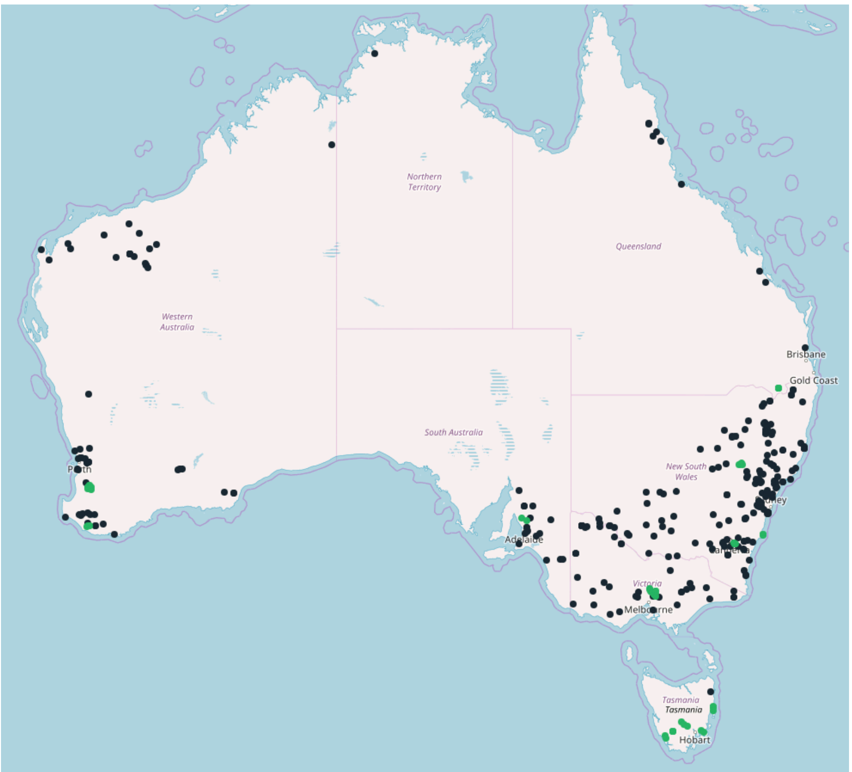

Figure 2 Observations used in the evaluation of the system. The dataset included 264 live trial observations (black) and 72 observations from 9 detailed and 11 other case study fires (green).

Aim 3: Build a system that is better than the current system

We set a target of 30 observations for each major fuel type and category to provide sufficient data to enable statistically confident analyses. This target was met for forest and grass fuels and fires in Categories 1 to 4. While the case studies made up some of the shortfalls, particularly for Category 5 and 6 events, the Research Prototype remains essentially untested for spinifex and buttongrass fuels and the results for pine, mallee-heath, shrubland and savanna are statistically insufficient to be conclusive.

For the live trial data Research Prototype performed better than the current system on several statistical measures, specifically:

- The Research Prototype correctly predicted the observed rating more often than the current system, 56% vs 43% of the time;
- 'Skill scores' for the Research Prototype were 1.5 to 2.0 times higher indicating that the Research Prototype was more accurate overall, including predictions that were not quite correct;
- The ability of the Research Prototype to identify relatively rare severe conditions was much better than the current system; and
- Inspection of the data showed that the Research Prototype had a tendency to over-predict ratings, particularly in spinifex fuels types. This meant that the number of days on which total fire bans would have been issued using the system was higher than expected. This tendency to over-predict needs to be corrected as part of an operational calibration process.

The reported performance of the Research Prototype is based on the system that was launched in October, 2017. With future refinements to the models and input data there is substantial potential to greatly improve performance. The current system is fixed and its performance cannot be improved.

The Research Prototype calculations were also applied to 72 time periods across 9 detailed and 11 other historical case study fires. This included historically significant events, including Black Saturday, as well as major or minor fires in fuel types that were not well represented in the live trial data set, such as the Billo Road pine fire, the Beecroft Peninsula heath fire, and some experimental burns in buttongrass.

For catastrophic fires in the case studies such as Black Saturday, both the Research Prototype and the current system performed well while the Research Prototype performed better for fuel types such as heath that are not well represented as either forest or grass.

An initial period of six years of weather reanalysis data was used to characterise the seasonality and extreme values of the Research Prototype ratings (Figure 4). Extension of the reanalysis to a longer period and deeper analysis of the data will be a valuable part of ensuring the NFDRS performs well and meets end users expectations across the full range of climate variability.

Prototype system

Observed \ Forecast	1	2	3	4	5	6
1	12	6	3	0	1	0
2	7	45	32	9	1	0
3	1	2	48	32	9	0
4	1	4	6	44	17	1
5	0	1	3	4	26	7
6	0	0	0	1	1	12

Current system

Observed \ Forecast	L-M	H	VH	S	E	C
L-M	73	21	7	1	0	0
H	37	21	16	3	0	0
VH	17	29	35	3	0	0
S	4	10	18	5	0	0
E	3	6	7	2	1	2
C	0	1	2	2	1	9

Legend
Correct
Under-predicted
Over-predicted

Figure 3 (Left) A comparison of the number of observed and forecast fires in each rating category for the NFDRS and (Right) curent rating systems.

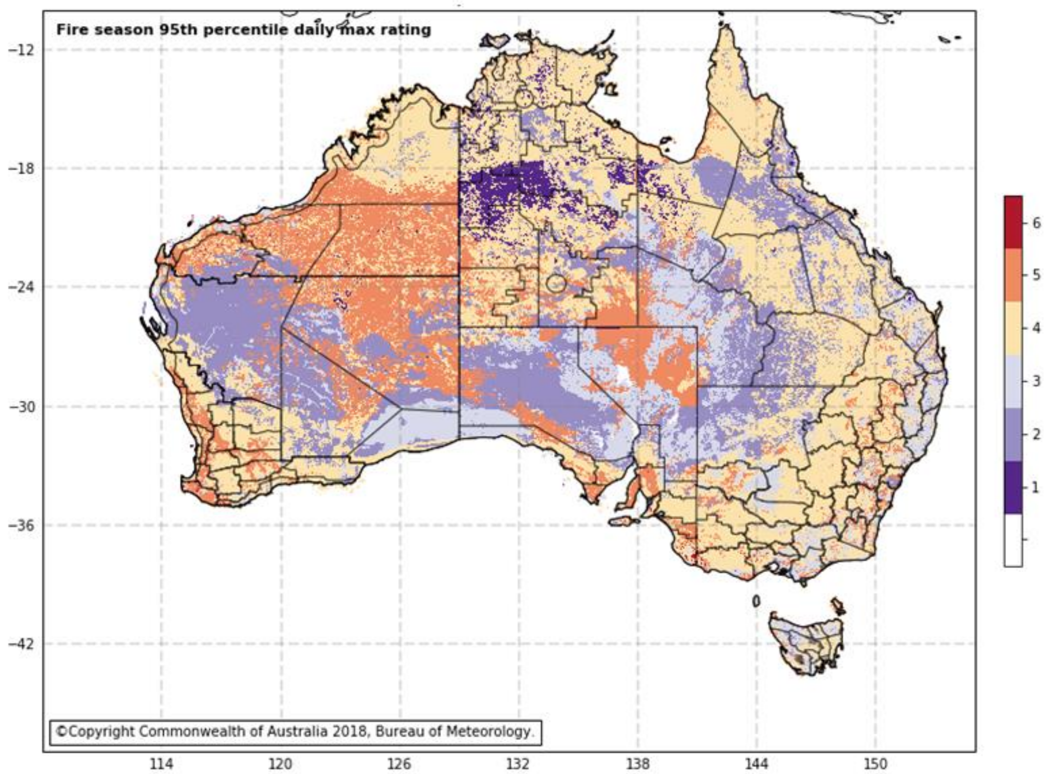

Figure 4 95th percentile daily maximum ratings for the reanalysis period (2010 – 2015).

Aim 4: Identify knowledge gaps

Key knowledge gaps were:

- There are significant gaps in our understanding of application of fire behaviour models to fire danger ratings including: how to best use models designed to predict the spread of fully developed head fires, how to incorporate slope and other terrain effects, how to represent variations in fuel availability across fuel types, how to apply existing fire spread models to fuel types which do not have a specific fire behaviour model;
- How to best incorporate red flag warnings into the system, including use of new products such as pyroconvection and dry lightning forecasts;
- How to include uncertainty and ensemble modelling approaches into the calculation and communication of fire danger rating;
- How to best calculate fire weather area ratings from detailed gridded calculations. We used the existing 90th percentile rule, alternative approaches are possible but were not investigated;
- Climatology calculations were completed for only 6 years of historical weather. This analysis would need to be extended to use the full 25 year dataset when it becomes available to provide reliable statistics; and
- Additional field observations are required to adequately validate models for some fuel types.

A more detailed list of knowledge gaps is provided Chapter 14. Responses to a survey conducted after the completion of the live trial also included many good suggestions for improvements to the system. These will be considered for implementation in the next phase of the Program.

Aim 5: Recommend a path forwards for future development

- Continue the phased implementation of the NFDRS building on the Research Prototype. The next phase should be an 'Operational calibration' of the system which will:
    - Address the observed over-prediction bias of the Research Prototype, particularly identifying problems with application of some fire behaviour models causing over-prediction;
    - Address some identified issues with fuel type classification and fuel parameter inputs, and allow for continual improvement of base data;
    - Identify errors and areas for improvement in the NFDRS rating tables and make necessary revisions to improve their relevance, accuracy, and alignment between descriptors;
    - Conduct a live trial evaluation that addresses data gaps in savanna fuel and represents the dry season in northern Australia;
    - Evaluate the usefulness and accuracy of utilising the NFDRS for prescribed burn planning; and
    - Engage operational decision makers in evaluation of the system.
- Commence a research program to address knowledge gaps identified in this report. The research will be part of a continuous improvement program to support the NFDRS into the future. Key topics for the initial research are:
    - Investigate current options for applying fuel availability modifiers to fire spread models and develop a model of fuel availability for direct application to fire spread models;
    - Develop a better understanding of application of fire spread models to fire danger, including: the build-up phase, topographic effects, the role of spotting, estimation of heat yield, pyroconvective effects and application to less common fuel types; and

  - Develop an understanding of representation of uncertainty in fire danger forecasting including inclusion of uncertainty in weather forecasts, treatment of effectively unknowable quantities (e.g. some fuel parameters), and sensitivity to spatial scale and rating thresholds.
- In the context of community messaging, consider the number and meaning of rating categories, informed by the social research project. These may differ for operational and public facing presentation of the NFDRS.
- Extend the calculation of the NFDRS climatology to use the full weather reanalysis dataset when it is available. If it is feasible, also consider the effects of climate change on fire danger rating.
- Pursue the development of the remaining components of the full NFDRS: ignition, suppression, and impact indices.

The Research Prototype project was completed as part of a suite of projects managed by the NFDRS Program Management Office. Other projects include: social research to design for a fit for purpose community fire danger rating system; revision of the Program Management Plan for implementation of the NFDRS; and development of a sustainable funding model for the delivery of the full project to be agreed by the states and territories. These other projects will be completed in 2018-19.

1 Introduction

Systems for rating fire danger are a key component of proactive fire management, aiding decision making for fire suppression operations. They are also a highly valuable tool in communicating bushfire risk to the community, increasing public awareness and triggering notifications regarding potential threat. In July 2014, Senior Officers and Ministers agreed that the development of a new National Fire Danger Rating System for Australia is a national priority. The current system is based on science and research developed in the 1960s and does not meet the needs of emergency service authorities or the community in achieving the best emergency management outcomes in a bushfire event.

The National Fire Danger Rating System Program (the Program) is intended to implement significant improvements to current national fire danger ratings system. Specifically in areas of fire weather prediction, fire ignition and behaviour potential and the impact on life, assets and the environment, the Program is designed to strengthen the ability of fire authorities to accurately communicate bushfire risk to the community, enhance agency readiness and preparedness and contribute to risk management prevention (including input into building standards and planning controls).

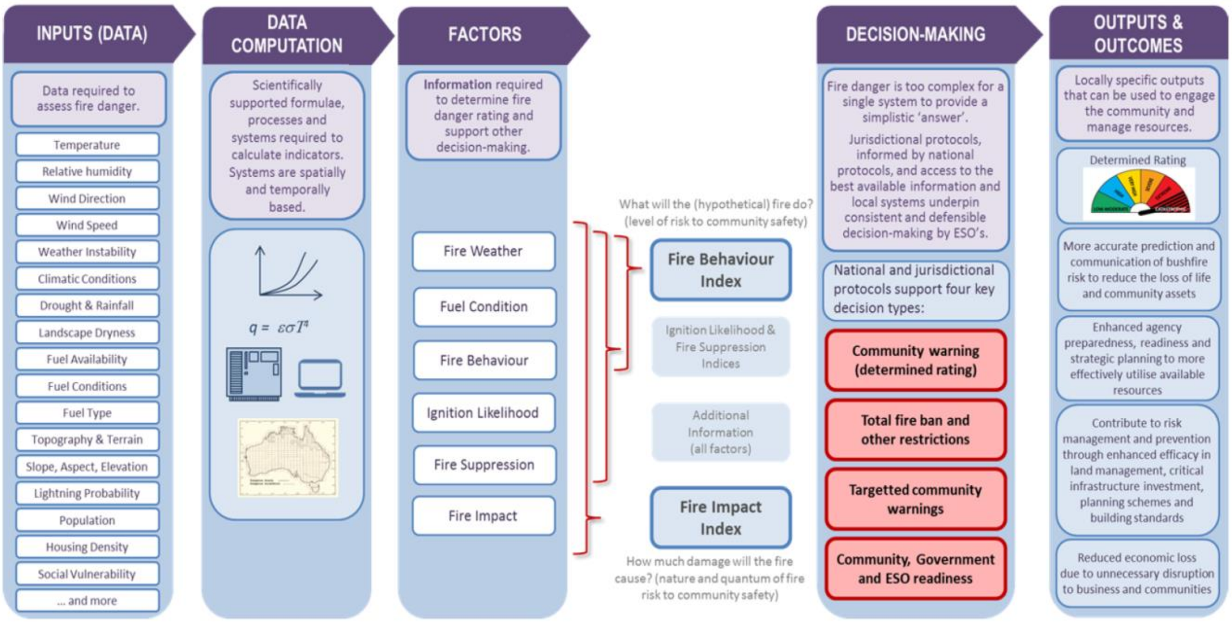

Figure 1.1 Proposed NFDRS structure. Diagram courtesy Cube Group.

Four broad types of decisions are to be supported by the NFDRS:

- Community warning (declared rating): The fire behaviour index supports decision-making for issuing community information and warnings, including the declared rating. Similar to other natural hazard warning systems, including cyclone and floods, it describes the level of risk regardless of whether one or a thousand people would be impacted. The threshold levels are based on a range of community impacts.
- Total fire ban and other restrictions: A total fire ban and other restrictions, such as suspending permits or cease of harvest advice, are based on the fire behaviour index and may be adjusted by additional information including the ignition likelihood indices and fire suppression indices at the jurisdictional level.
- Additional community warnings: The fire impact index informs additional or localised messaging for vulnerable communities and other at risk groups.
- Emergency service organisation readiness: It is a scale of probability of impact that informs community readiness decisions and operational readiness decisions at state, regional and local levels.

Decision-making for the four decision types may occur concurrently or in any order. There is no associated timescale for describing the relationship between the system outputs and decision-making in this context.

At its 8 April 2016 meeting, ANZEMC approved a phased approach to deliver this system, proposed governance arrangements, funding of the first year of work through the Commonwealth's National Emergency Management Projects grant program and state-based co-contributions, and promotion of the fire science research through the Bushfire and Natural Hazards Cooperative Research Centre.

It was agreed the NFDRS would ultimately be a nationally consistent technology solution with a single, integrated data model and a common or unified platform. It also acknowledged that the implementation roadmap for the NFDRS solution will leverage existing jurisdictional investment and computational platforms on the pathway to creating a new, purpose built solution.

After much deliberation on options to progress the implementation of the NFDRS, it was decided to take a phased approach to maintain momentum and provide a better understanding of what needs to be done, and funded, to achieve a new system for Australia. This plan involved the development of a Research Prototype for the next generation NFDRS within 18 months and social research to determine the best way to communicate fire danger.

During 2015 the Cube Group ran a project with fire agencies to determine requirements for a new rating system. The project considered needs within the 6 factors shown in Figure 1: weather, fuel, fire behaviour, ignition, suppression, and impact to produce a large list of requirements which covered both the content and form of the six factors. Summary diagrams for the weather, fuel, and fire behaviour factors are shown in Figure 2. The remaining three factors are out of scope for the Research Prototype project.

Most of the outputs listed are familiar within current fire behaviour research. However, there was no attempt to identify which of the fire behaviour measures should be used as the basis for the fire behaviour index. The trial run by the RFS over the 2015-16 fire season used indices based on rate of spread, intensity, and flame height but no useful conclusions were reached on whether they should be the basis of a rating system because there was no way to assess whether the calculated ratings were correct.

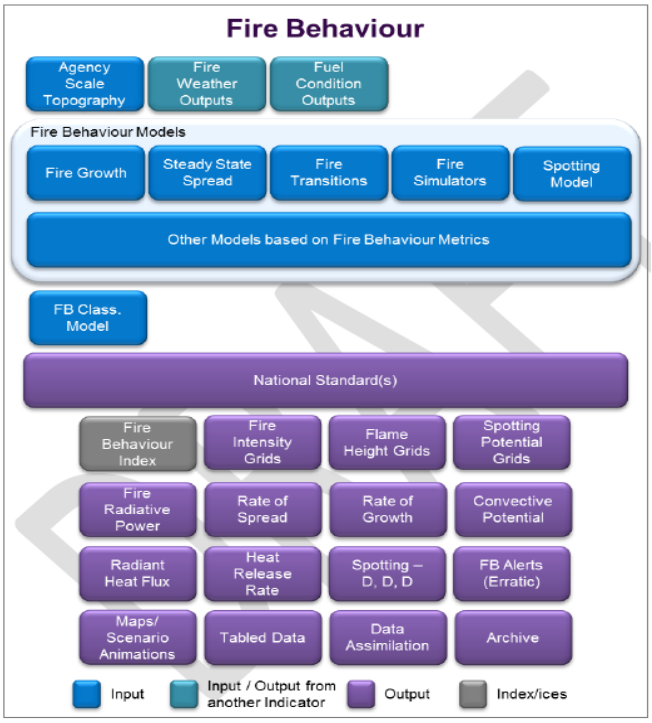

Figure 1.2 Summary of outputs from the fire danger rating system requirements project. Diagram courtesy Cube Group.

The National Fire Danger Rating Working Group found that the current single fire danger rating scale is used for purposes that depend not only fire behaviour but also the number of ignitions, suppression capacity, and values at risk. It recommended splitting fire danger rating into a fire behaviour index and a fire impact index. The Research Prototype project built a new fire behaviour index and ratings scale. Fire impacts will be examined in a later phase.

The project defined rating classes in terms of observable consequences of fires by working with experienced operational fire managers to determine consequences and ratings that are relevant and clear. These definitions were used to assess past and new incidents to construct a set of observed ratings for testing models.

Much has been done in recent years to better understand fire behaviour including development of better spread models and understanding of the roles of drought and atmospheric stability in the development of fires. The Research Prototype included best available science in the fire behaviour index models. The Research Prototype recognised more fuel types and included more appropriate fuel information than the simplistic approach used in the current system.

Because ratings are clearly defined and observable it will be possible to improve prediction skill with new science and experience, setting up the new system to improve as we learn more about fire management. These improvements will happen behind the scenes so ratings become more accurate without needing to change public messaging further after the new system is implemented.

This report describes the work done to develop, implement, and evaluate the Research Prototype for a new fire danger rating system based on fire behaviour metrics. The report is organised as follows:

- Chapter 2 describes the process of developing the rating system and defines the rating categories,
- Chapter 3 defines the fire behaviour models used to calculate the ratings,
- Chapter 4 describes the process of compiling national fuel and fire history data sets. It also describes the fuel models used to select and apply the fire behaviour models to each fuel type,
- Chapter 5: describes the weather inputs used for calculation of ratings for the live trial, historical case studies, and the climatology,
- Chapter 6: describes the computer systems built to implement the system and display outputs for users,
- Chapter 7: describes the methods used to collect observation during a live trial of the system from October 2017 to March 2018,
- Chapter 8: presents the results of the live trial,
- Chapter 9: presents the results of application of the Research Prototype to a number of significant historical fires,
- Chapter 10: presents an analysis of the spatial distribution of fuels and the implications for determining ratings,
- Chapter 11: presents the results of a summary analysis of fire danger ratings and incidents for the whole country over the trial period,
- Chapter 12: presents a preliminary climatology of fire danger ratings based on six years of historical reanalysis weather data
- Chapter 13: presents a sensitivity analysis of the fire behaviour models to help inform investment in future improvements to the models used in the system, and
- Chapter 14: summarises the key findings of the project, discuses opportunities for improvement identified in preceding chapters, and presents recommendations for future work.

The project has also generated several electronic artefacts. These are held by the NSW Rural Fire Service and the Bureau of Meteorology:

- Software implementations of the rating calculations and code for websites to display outputs
- Base data sets for the entire country including fuel mapping, fuel models, and fire history
- An archive of the calculation system outputs
- A collection of fire incident observations and supporting documentation
- A database of fire incident information collected from public information feeds
- Data processing and analysis scripts

2 Fire danger rating definitions

Fire danger rating and the system used to describe it, is a highly valuable tool in communicating bushfire risk to the community. It allows for an increase in public awareness and is a trigger for notifications regarding potential threats and risks. Importantly, because of its foundation on fire weather and behaviour, fire danger rating also provides a tool aiding decision making in planning, preparedness, response of bushfire operations as well as supporting fire and land managers seeking to implement prescribed burns in the landscape.

Developing a suitable framework for fire danger rating, that incorporates current scientific knowledge and a diversity of operational standards and fire suppression requirements for a wide array of fuel (or vegetation) types, has the potential to be particularly challenging (Deeming, 1983; Alexander, 2010). In fact, given the complexity and difficulty representing all aspects of fire danger into just the one defined scheme or index is itself, limiting and problematic (Alexander, 2008).

In order to develop meaningful NFDRS Research Prototype categories with practical outcomes, we sought to identify points in a fires management where fire behaviour, operational responses and strategies are different and/or have different consequences. We considered these thresholds, or transition points, and the possible variables that may be used to signal change in the context of historical application of fire danger rating in Australia and around the world, as well as the current uses and requirements of fire managers throughout Australia. We have endeavoured to do this as thoroughly as possible, but given the time constraints of the project, realise that some things may have been missed, particularly in our understanding of the specific and unique applications of fire danger rating in Australia though time. It is hoped that, together with other recommendations, outlined at the end of this chapter, an extension of our review of both Australian and international literature be completed to better document and inform the work in defining fire danger rating provided here.

In this chapter, we outline some ways in which fire danger rating can be defined. We provide a short history of fire danger rating in Australia and discuss some of the varied applications throughout Australian fire and land management agencies. We provide a brief summary of some of the main fire danger rating practices around the world, discussing some of their strengths and limitations in the context of seeking guidance for development of the Research Prototype. We outline the fire danger rating requirements of Australian fire managers, then discuss and present what was used in the Research Prototype to define, categorise and signal change between categories and provide background to the particular choices that were made. Important, additional components of fire danger rating in Australia as identified within the proposed NFDRS structure, including ignition likelihood, fire suppression and fire impact indices were beyond the scope of this project and so are not addressed here. In the absence of these components, descriptions of suppression difficulty and potential fire impacts (or consequences) have been integrated as definitions and descriptions within the Fire Danger Ratings Tables. Likewise, public warnings and notification policies which vary in their type, usage and application around Australia are also beyond the scope of how we have defined fire danger within the Research Prototype, however we recognise that these will be an integral part of social research and the further development of improved fire danger rating in Australia.

2.1 Defining fire danger rating

Fire danger is a general term with many interpretations but largely representing many constant and variable factors culminating in a fire environment (https://www.nwcg.gov/term/glossary/fire-danger; Douglas, 1957; McArthur, 1958, 1977a; Chandler *et al.*, 1983; Merrill and Alexander, 1987; San-Miguel-Ayanz *et al.*, 2003; Di Giuseppe *et al.*, 2016);

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ignition potential (both probability and potential number of ignition sources)

fire (or fuel) hazard and fuel availability (sustainability of the event),

the likelihood and rate of spread,

difficulty of control,

consequences of fire including impact(s), the potential threat to humans and their welfare (safety), and the vulnerability, or exposure and susceptibility to losses.

How these different elements of fire danger are combined together and what weight each has on the resulting fire danger rating or wildfire threat is complicated (Muller, 1993b). Cheney (1988) suggest that it is next to impossible to adequately embody the total concept of fire danger into a single quantitative index. More simply put, McArthur (1977a) summarised fire danger by stating that 'in a general sense, the rating of fire danger is an expression of probable fire behaviour in relation to a particular set of fuel and weather conditions'.

Cheney *et al.* (1990) preferred to limit fire danger rating to reflect the severity of weather conditions, rather than the combined effects described above with some studies showing that most fire management authorities have found this simplified approach sufficient for representing suppression difficulty and setting readiness levels (Cheney *et al.*, 1990).

Another limitation often considered is that if a fire can start and spread, but there are no values (such as human life and property) at risk, there is no fire danger (Cheney, 1988). Of course, the difficulty in the detail pertains to the definition of 'values', as many variations can be considered.

Estimating risk and the way in which fire danger is rated or classed can be defined as (from Merrill and Alexander, 1987):

'the process of systematically evaluating and integrating the individual and combined factors influencing fire danger represented in the form of indexes'

Merrill and Alexander (1987) go on to define a fire danger class as:

'A segment of fire danger index scale identified by a descriptive term (e.g. Nil or Very Low, Low, Moderate, High, Very High, or Extreme), numerical value (e.g. I, II, III, IV or V), and/or a colour code (e.g. green, blue, yellow, orange or red).

2.2 Fire danger rating in Australia

In Australia, fire danger ratings have evolved from early systems developed for the south-west of WA based on using the moisture content of dowels or ‘hazard sticks’ (Gisborne, 1933) which, when exposed to air, indicate the potential of fire to start and spread (Wallace, 1936; Cromer, 1946). ‘Difficulty of suppression’ tables were later developed in South Australia in which five classes of suppression difficulty are related to the type and amount of fuel, the fire hazard (largely based on hazard stick moisture) and wind velocity (Table 2; Douglas, 1957). In the 1950s and 1960s more comprehensive fire danger ratings were produced based on the predicted rate of spread and the difficulty of suppression of fires burning in grasslands (McArthur, 1960) and dry sclerophyll forest fuels (McArthur, 1958, 1967) under different weather conditions. A.G. McArthur developed these two systems, the Grassland Fire Danger Index (GFDI) and the Forest Fire Danger Index (FFDI) from the analysis of a dataset of over 800 experimental fires, complemented with data from high intensity wildfires. These systems of fire danger rating were designed for general forecasting purposes to be issued by the Bureau of Meteorology and for local application by fire authorities for fire behaviour prediction on the fireline and as a rough control burning guide (Cheney, 1988).

The difficulty of suppression tables were originally presented (McArthur, 1958) based on a rating of ‘difficulty experienced in suppressing the fire perimeter’, against wind speed and relative humidity (for a set range of temperatures) within 89 experimental fires (recorded on a six-point scale where N = fires will not spread, Low= low difficulty of suppression, Moderate= moderate difficulty of suppression, High= high difficulty of suppression, Very High= very high difficulty of suppression and Extreme= extreme difficulty of suppression). Each rating of difficulty of suppression primarily took fuel moisture and wind velocity into account as well as spotting distance and potential, fire intensity and fire instability (McArthur, 1958). Suppression difficulty classes were redefined as fire danger classes and the scale of fire danger was set between 1 and 100, where an index of 100 represented ‘average-bad’ summer conditions of: temperature 35C; relative humidity 10%, mean wind speed 45 km/hr; coupled with average summer drought. These were then related to meteorological variables alone so that fire danger ratings could be based on weather forecasts. Fire danger rating tables for grasslands were also developed (McArthur, 1960) and both systems were modified and published as either linear or circular slide rules with subsequent revisions to incorporate improvements in fire spread predictions (McArthur, 1966, 1967, 1977b). There was little documentation to accompany developments (Cheney, 1988). The grassland fire danger rating system (McArthur, 1960) was initially developed for continuous annual grasslands and has evolved over several years to incorporate the effect of grassland curing and wind (McArthur, 1973b) and most recently (but not being used operationally), fuel load (McArthur, 1977b).

During the same time period, an alternative approach to fire danger rating was developed specific to jarrah and karri forests in Western Australia by Peet (1965). In these forests, five fire danger classes are determined by rate of head-fire spread and are similar to the spread rates predicted by McArthur’s FFDM (Cheney, 1988).

A survey of state rural fire authorities and land management agencies in 1990 by Cheney *et al.* (1990) found that the McArthur based fire danger rating systems were generally satisfactory in meeting needs and applications for bushfire suppression. At that time and after three decades of usage, most states and agencies reported that the McArthur systems provided a sufficient guide to enact appropriate levels of preparedness and public warning and as such the authors suggested that fire authorities continue to use the existing systems.

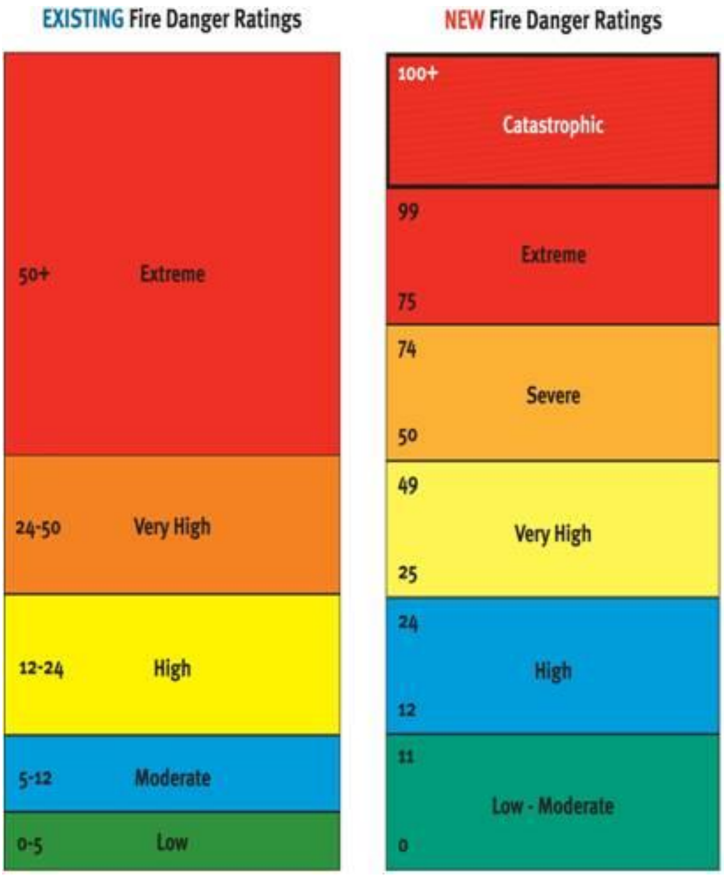

Figure 2.1 Comparisons of the pre-2009 and post-2009 fire danger ratings (Source: NSW Rural Fire Service).

One of the major changes to the fire danger ratings since they were established, was the introduction of additional 'Severe' (in between 'Very High' and 'Extreme') and 'Catastrophic' (above the highest level of 'Extreme') fire danger ratings by the Australian Emergency Management Committee (AEMC) (Figure 2.1) (AEMC - National Bushfire Warnings Taskforce, 2009). These changes came about in direct response to the recommendations by the Royal Commission investigating the causes and responses to the Black Saturday bushfires which swept through Victoria in February, 2009 (Parliament of Victoria, Victorian Bushfires Royal Commission, 2010: in particular Recommendation 5.1).

In addition to adding the 'Catastrophic' category, the existing fire danger ratings were adjusted to correspond to higher index values based on historical events, statistics on loss of life and property and the application of various regulations and codes (AEMC - National Bushfire Warnings Taskforce, 2009). Common descriptors and key messages were then developed for fire management agencies and the public.

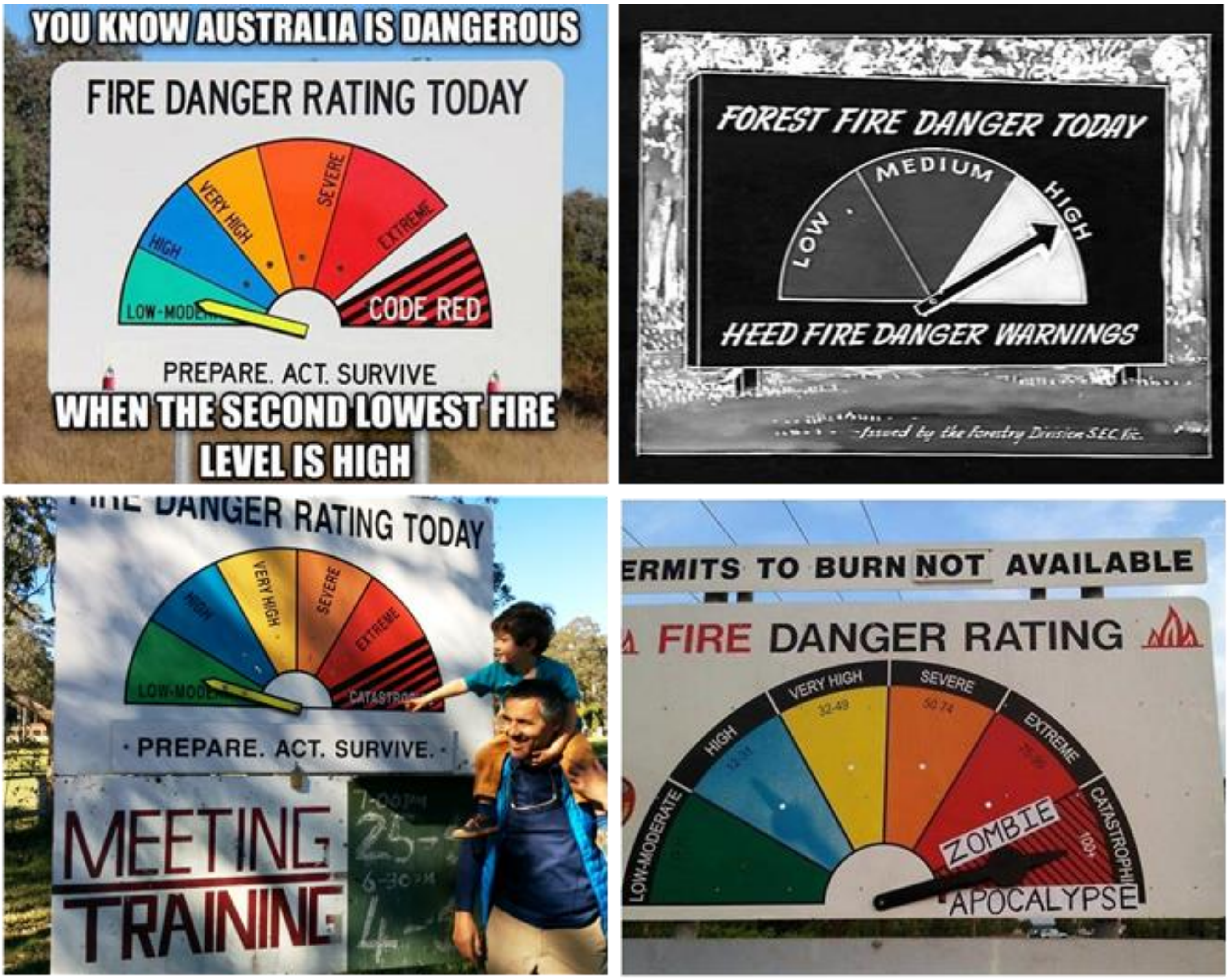

Figure 2.2 Various forms of presentation for fire danger rating around Australia.

Current fire danger ratings throughout Australia are still based on rate of fire spread models for eucalypt forests as presented in Figure 2.3 (FFDI; McArthur, 1967) or grasslands, Figure 2.4 (GDFI; McArthur, 1966) and the simple thresholds that were earlier established by Douglas (1957) and McArthur (1958) are still used in similar formats by many fire agencies and departments to describe the relationship between the fire danger rating, type of fire and difficulty of suppression. In addition, and as new fire behaviour relationships have been established, additional variables have also been used to define thresholds between fire danger ratings including fireline intensity and/or flame height relationships among others (Table 2.1). Various forms of presentation and public signage for fire danger rating in Australia are presented in Figure 2.2, including some interpretations that demonstrate public perception and attitudes to some of the recent changes.

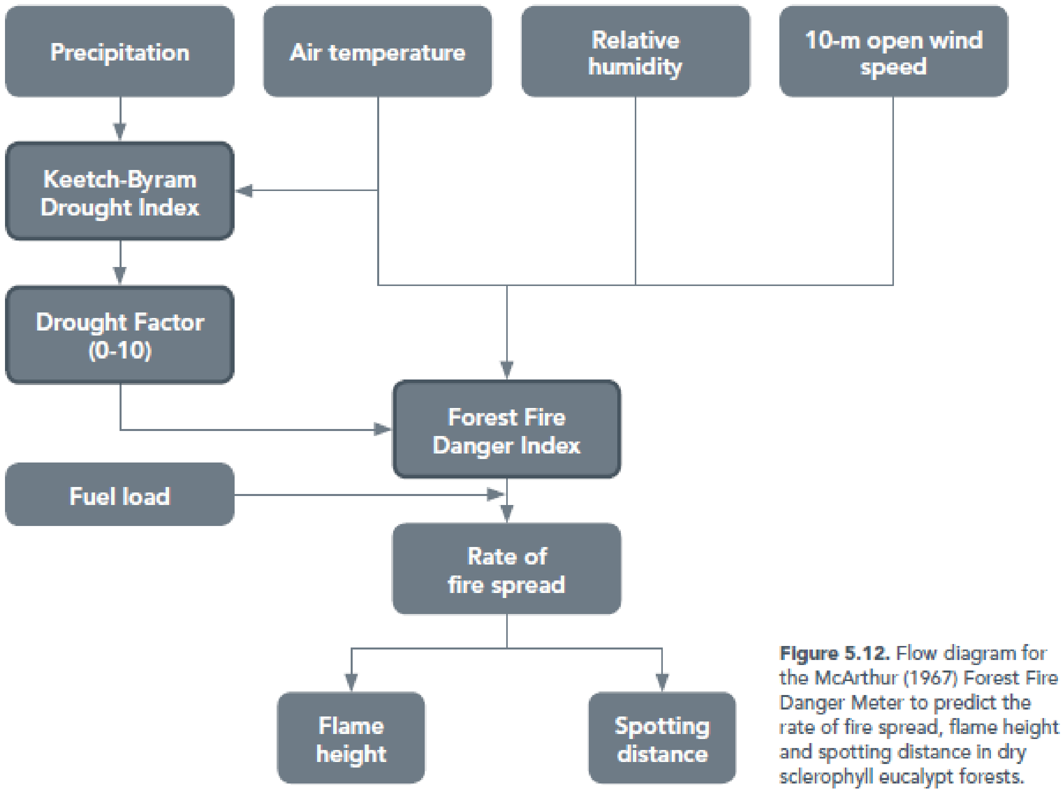

Figure 2.3 McArthur's Forest Fire Danger Index structure and input variables (Source: Figure 5.12 from 5 Cruz *et al.* (2015b)).

McArthur's FFDI determines fuel availability by applying the drought factor (DF) which is determined based on recent rainfall and partly based on the soil moisture deficit, commonly calculated using the Keetch-Byram Drought Index (KBDI; Keetch and Byram, 1968). As the KBDI increases, fuels increasingly become more available due to stress and moisture deficiency.

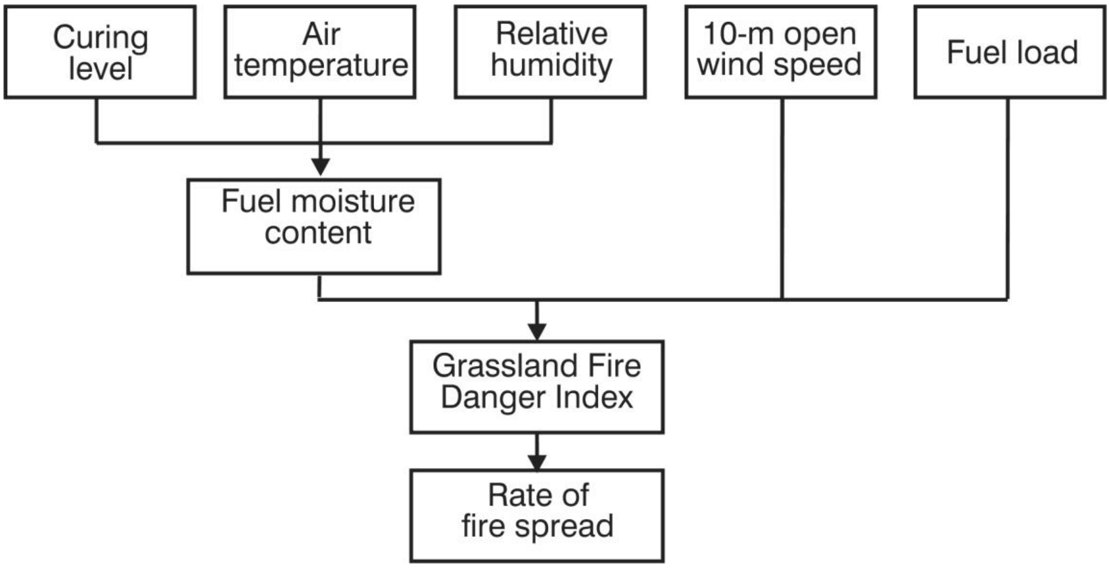

Figure 2.4 McArthur's Grassland Fire Danger Rating System (Mk IV).

The grassland fire danger index (GFDI: Mk 5) is calculated using air temperature, relative humidity, wind speed (10m) and the degree of grassland curing. The index was originally related to the forward rate of spread, the difficulty of suppression, flame height and the maximum potential area for predetermined periods of time (i.e. ½ hr, 1hr, 2hr, 4hr and the average final size) (Table 2.2). The GFDI was originally broken into 8 categories up to the maximum index of 100 and later aligned with 5 categories describing difficulty of suppression.

Table 2.1 Variables used throughout Australia to delineate fire danger ratings and/or prescribed burning conditions.

Fire Danger Rating	Fire behaviour	Soil/Seasonal Dryness
FFDI [g, h, i, j, k, m, b, d, n, e]	Rate of spread [g, i, j, c, o, p,]	SDI [a, b, c, f]
GFDI [i, l, k, m, b, d, e]	Flame height [h, o, k, b, p, q, n,]	KBDI [d, e]
Scrub FDR [b]	Fire intensity [h, r, o, k, m, n]	Drought Factor/ Drought Index [e]
Moorland FDR [b]		
Fuel condition/load/hazard	**Fuel moisture**	**Weather**
Grass curing [g, o, d, e]	Fine fuel moisture content [j, m, b, d, s, f, e]	Wind speed @10m [g, j, b, d, e]
Fine fuel load [j]	Hazard stuck moisture [b,]	Wind speed @ 2m [b]
Other	Surface moisture content (SMC) [c, f, e]	Relative humidity (RH) [g, j, o, m, b, d, e]
Date	Profile moisture content (PMC) [c]	Temperature [g, j, b, d, e,]
Topography [j]	Available fuel factor (AFF) [c]	Days since rain [o, b]
		CHaines [m]

[a] Western Australian Department of Parks and Wildlife (2017)

[b] Marsden-Smedley (2009)

[c] Sneeuwjagt and Peet (1998b)

[d] Department of Environment Land Water and Planning, Victoria (2017)

[e] Victorian Country Fire Authority (2015)

[f] Tolhurst and Cheney (1999)

[g] Western Australian Department of Environment and Conservation (2013)

[h] Western Australian Department of Parks and Wildlife (2016)

[i] Western Australian Department of Parks and Wildlife (2015)

[j] Burrows (1986)

[k] NSW Rural Fire Service (2005)

[l] Cheney and Sullivan (1997)

[m] NSW Rural Fire Service (2014)

[n] Victorian Country Fire Authority (2005)

[o] Queensland Department of National Parks (2012)

[p] Marsden-Smedley *et al.* (1999a)

[q] Alexander (2008)

[r] Fire and Emergency Services Authority of Western Australia (2009)

[s] Victorian Country Fire Authority (2014)

Table 2.2 Fire behaviour characteristics and the Grassland Fire Danger Index. (Source: McArthur (1966))

Fire danger index	Rate of spread (mph)	Difficulty of suppression	Maximum area in acres at various times from start*				Average final size of fire (Acres)	Flame heights in Pasture		
			1/2	1	2	4 (hrs)		Sparse	Average	Heavy
2	0.2	Low. Headfire stopped by roads and tracks	8	50	200	800	7	1	4	9
5	0.4	Moderate. Head attack easy with water	16	100	400	1,600	40	2	6	12
10	0.8	High. Head attack generally successful with water	36	225	900	3,600	160	3	9	18
20	1.6	Very High. Head attack will generally succeed at this index	85	520	2,100	8,500	1,100	6	12	22
40	3.2	Very High. Head attack may fail except in favourable circumstances, and close backburning to the head may be necessary	200	1,200	4,800	19,000	6,000	8	17	29
50	4.0	Extreme. Head attack mostly fails. Backburn from good secure line with adequate manpower and equipment. Flanks must be held at all costs	260	1,600	6,200	25,000	10,000		18	32
70	5.6		425	2,550	10,000	40,000	25,000		21	37
100	8.0		700	4,200	17,000	68,000	80,000		24	42

* This assumes that the headfire burns unchecked. Suppression action which is only partially successful will reduce these areas.

2.3 Strengths and limitations of current fire danger ratings

Probably the biggest strength of the current McArthur based fire danger rating system is its simplicity, resulting in it being used at a variety of levels with ease of computation and interpretation. The significance of simplicity has been pointed out by several authors highlighting the importance of having easily gathered observations as basic model inputs (Cheney, 1988; San-Miguel-Ayanz *et al.*, 2003; Sharples *et al.*, 2009). Nearly 20 years ago, a survey of state rural fire authorities and land management agencies found that the McArthur based fire danger rating systems were generally satisfactory in meeting needs and applications for bushfire suppression (Cheney *et al.*, 1990). At that time and after three decades of usage, most states and agencies reported that the McArthur systems provided a sufficient guide to enact appropriate levels of preparedness and public warning and as such, the authors suggested that fire authorities continue to use the existing systems. Important limitations were later recognised however, in response to the Black Saturday bushfires that swept through Victoria in February, 2009 which lead the Royal Commission investigating the causes of the fire to recommend significant revisions to the system.

While revisions to the fire danger rating in 2009 have improved communications and particularly public warnings as they relate to the top, more dangerous end of the scale, the current system is still being applied well beyond the original design and the scientific variables and computational methods that underpin it require significant review and consideration (Fogarty *et al.*, 2010). It was recognized as part of the review in 2009 that an evaluation of the science driving the fire danger index was needed (AEMC - National Bushfire Warnings Taskforce, 2009), specifically drawing on contemporary knowledge and science such as social and communications implications and requiring a concerted research effort to fill critical knowledge gaps (Fogarty *et al.*, 2010). These suggestions subsequently lead the Australian Government to call for the development of a new fire danger rating system (AEM, 2011).

At Workshop 1 (NSW Rural Fire Service, 2017 (Appendix A)), most participants (n = 9) felt that the most important limitation of the current FFDI/GFDI based FDR was that it was limited to two fuel types and that it does not account for fuel variability (e.g. availability, load, type and structure). Participants (n = 5) also pointed to the large degree of error of current FDR with over and under predictions occurring for specific fuel types and weather conditions. Other important limitations that were raised included; how the current FDR can represent very different fire behaviour in different climatic areas which is not aligned with fire management consideration (n = 2), is sometimes poorly understood (by both practitioners and the public) and without context (n = 3), does not take account of atmospheric stability and potential coupling between fire and the atmosphere (n = 1) and is not suitably targeted toward different audiences with the same FDR use for a broad range of applications (development assessment, suppression difficulty, impact/consequence determination) and audiences (scientists, practitioners, burn planners, general public (n = 1). While many limitations were identified, one participant felt that the current FDR is both valuable and effective for fire management agencies.

Some of the limitations of existing fire danger rating throughout Australia are summarised in Table 2.3.

Table 2.3 Summary of limitations of the current fire danger rating in Australia

1. **Doesn't account for fuel variability**

At Workshop 1 (for operation staff), most participants (*n* = 9) felt that the most important limitation of the current FFDI/GFDI based FDR was that it was limited to two fuel types and that it does not account for fuel variability (e.g. availability, load, type and structure).

2. **Lack of ability to determine accuracy**

Because the current McArthur based fire danger rating systems are largely subjective and have been extrapolated to different specifics and applications around Australia, our ability to assess their accuracy and applicability is limited to general observations.

3. **Scale of forecast**

Some criticism that has characterised fire danger rating in Australia since establishment relates to the scale of forecasted fire danger and where differences may exist due to localised variations in fuel characteristics and weather forecast (Cheney *et al.*, 1990; Dawson, 1988). For example, Cheney (1988) suggests that problems arise when a general fire danger rating is applied to a specific area where the relevant variables depart from the general case and while the author states that these general systems need to be retained, more specific models are also required to predict fire danger at the local level, specific to burning conditions and management operations.

4. **Non-events**

Potentially the biggest criticism that persists still today, relates to when a predicted extreme (or catastrophic) fire danger forecast does not eventuate, either due to changes in weather forecast or lack of ignition to demonstrate fire danger potential (Dawson, 1988). This problem is not limited to Australian fire danger rating. Some of this can be linked to the decision of whether to incorporate 'worst possible' or 'average bad' weather [and fuel] conditions (McArthur, 1977a). Historically in Australia, we've endeavoured to predict fire behaviour under 'worst possible' however in other parts of the world, such as the United States the systems lean more towards 'average bad' weather parameters (McArthur, 1977a).

5. **Degree of error and not based on worst case conditions**

The current Australian fire danger ratings are based on rate of spread of surface fires spreading in a standard fuel type. Because of this, the end of the scale where the most dangerous conditions are represented is based on an eye-fitted curve that was fitted toward the maximum range of the data. Because of this Cheney (1988) suggest that users should treat the system as a guide only and to expect a high degree of error, particularly at the upper end of the fire danger scale, where one could assume that accuracy is needed most. Fogarty *et al.* (2010) also note that while the current forest and grass fire danger rating systems made excellent advances and contributions when they were developed, they do not include some of the worst case conditions that have been experienced since then. This includes: drought and resulting landscape dryness and fuel continuity; atmospheric instability, violent cold front and change conditions; multiple fires in the landscape which rapidly exceed fire control capacity and cause fire interactions; and underpinning heavy forest fuels. The authors also questioned the robustness of the science underpinning the development of the Forest and Grassland fire danger rating systems.

On top of being limited to conditions under which the empirical models were developed (San-Miguel-Ayanz *et al.*, 2003), another criticism, and one that perhaps will always present an issue with the hope of some improvement over time, is the inherent degree of error associated with forecasts that are dependent on model accuracy, both for weather and fire behaviour predictions. Cheney and Gould (1995) suggest that because of this degree of error, we can expect existing McArthur based forecasts to vary by at least one fire danger rating category.

6. **Lack of alignment with consequences**

One of the main limitations of the current McArthur FFDI and GFDI based fire danger ratings is that they are not adequately aligned to community loss or the destructiveness of a fire (Fogarty *et al.*, 2010; Blanchi *et al.*, 2012; Harris *et al.*, 2012; Kilinc *et al.*, 2013). Some work has been done within the last decade to document the characteristics of destructive fires but also to develop and index or scale that relates to loss and much of this work can be directly related to fire danger rating (Blanchi *et al.*, 2012; Harris *et al.*, 2012; Kilinc *et al.*, 2013).

7. **Lack of alignment with fire management**

The current FDR can represent very different fire behaviour in different climatic areas which is not aligned with fire management consideration (Workshop 1, n = 2).

8. **Poor understanding**

The FFDI and GFDI based fire danger ratings are sometimes poorly understood (by both practitioners and the public) and without context (Workshop 1, n = 3).

9. **Limited relationship with fire behaviour**

Our understanding of fire behaviour and specifically what drives rate of spread in different fuel types has evolved over time with many improvements since the FFDI and GFDI were developed (McCaw et al., 2008). Given we are now in a better position to predict fire behaviour demonstrates the limitations and weakness the current fire danger rating has, specifically its association with fire behaviour, which is paramount to fire danger rating (Kilinc *et al.*, 2013).

Kilinc *et al.* (2013) note that because the FFDI and GFDI do not adequately characterise certain aspects of fire behaviour, they are not useful indicators for characterising fire events on a local scale. For example, on an FDI day of 100, individual fire events will have very different characteristics in size and intensity.

10. **Doesn't account for atmospheric instability, potential coupling, overnight air temperature and humidity**

Neither the FFDI or GFDI based fire danger ratings adequately take into account recent advances in understanding of atmospheric stability and potential coupling between fire and the atmosphere (Workshop 1, n = 1). Other important factors that are recognised to be particularly important however are not considered in the current system are overnight air temperature and relative humidity. These determine potential 'blow-up' conditions as well the difficulty of bringing existing fires under control are (Beggs, 1976; McArthur, 1977a).

11. **Not suitably targeted to different audiences**

Fire Danger Rating in Australia is not suitably targeted toward different audiences with the same FDR used for a broad range of applications (development assessment, suppression difficulty, impact/consequence determination) and audiences (scientists, practitioners, burn planners, general public (Workshop 1, n = 1).

12. **Not based on worst case conditions**

While the current forest and grass fire danger rating systems made excellent advances and contributions when they were developed, they were based on conditions experienced then and do not include some of the worst case conditions that have been experienced since then.

2.4 Fire danger rating around the world

Systems for rating fire danger around the world vary a great deal in their complexity. Several publications (e.g. Chandler *et al.* (1983); San-Miguel-Ayanz *et al.* (2003); Fujioka *et al.* (2008); de Groot *et al.* (2015)) present detailed descriptions of the systems, major historical advances, reviews and comparisons of fire danger systems applied around the world. We provide a short summary of these below.

Independent of the fire danger rating system components and mathematical formulation, there are three broad approaches used to categorise or classify fire danger rating around the world (Alexander, 2010):

1. ***Weather-based indices based on frequency distributions*** such as those currently used throughout the majority of Canada (Stocks *et al.*, 1989) whereby predetermined percentiles are used to delineate thresholds on a cumulative frequency distribution based on several seasons of historical fire weather observations;
2. ***Wildfire occurrence data correlated against fire danger indices*** such as the fire danger classes used throughout districts in Portugal which are calibrated against statistical data using the Canadian Fire Weather Index (FWI; Van Wagner, 1987), number of fires and area burnt (Viegas *et al.*, 2004); and
3. ***Using fire behaviour models to yield fire danger assessments*** (e.g. as is current practice in Australia whereby fire danger ratings are determined for fire behaviour and difficulty of suppression thresholds based on rate of fire spread models for eucalypt forests (McArthur, 1967) or grasslands (McArthur, 1966)).

While 1. and 2. above are perhaps the most simplistic of the approaches, both are largely constrained to the fuel and weather conditions upon which the data are based (Taylor and Alexander, 2006; Alexander, 2010) and difficulties arise with 2. because most indices based on wildfire occurrence don't align with expected fire behaviour outcomes making it difficult to accurately define suppression difficulty.

A brief summary of the characteristics of the most prominent international fire danger rating systems is included below, in no particular order.

2.4.1 Canada – Canadian Forest Fire Danger Rating System

Since 1925, various fire danger rating systems have been applied in Canadian forests. With each new system has come increased universal application, evolving with improved science and empirical data (Stocks *et al.*, 1988). The current Canadian Forest Fire Danger Rating System (CFFDRS; Stocks *et al.*, 1989) has two major subsystems: the Canadian Forest Fire Weather Index (FWI) System and the Canadian Forest Fire Behaviour Prediction (FBP) system as well the Fire Occurrence Potential System (FOP) and the Accessory Fuel Moisture System (Figure 2.5). Together, these components enable customised fire danger rating for different regions in Canada that takes into account the likely number of ignition sources and potential fire behaviour in different fuel types.

Like the FFDI in Australia, the FWI systems provide an indication of fire danger based predominantly on meteorological ingredients. The FWI describes the effects of atmospheric variables (temperature, humidity, wind speed, precipitation) on fuel moisture which in turn determines ease of ignition and fire behaviour including the potential spread and relative intensity.

While the addition of the FOP and FBP have made the system less applicable to other vegetation types, many countries currently apply the CFFDRS or FWI and have either tested and/or adapted the system to their own local conditions including: Alaska, Argentina, Chile, Fiji, Mexico, New Zealand (Fogarty *et al.*, 1998), Venezuela, some parts of Europe (e.g. Portugal, Spain and Greece (Dimitrakopoulos *et al.*, 2011)) and to limited extent, here in Australia by Dowdy *et al.* (2009).

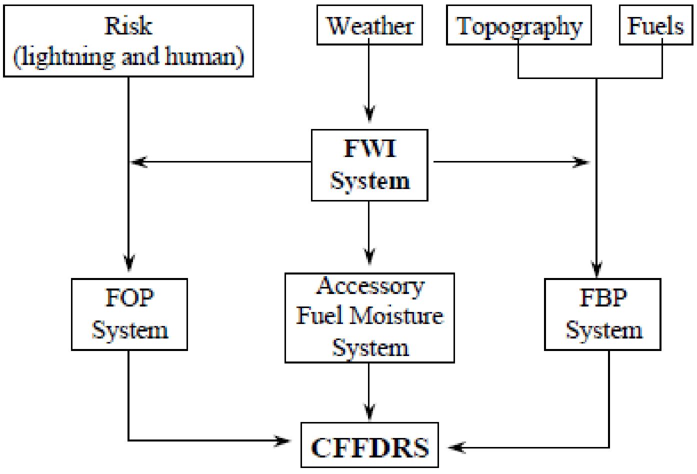

Figure 2.5 Canadian Forest Fire Danger Rating System and its contributing components (Source: Stocks *et al.* (1989)).

Dowdy *et al.* (2009) reported that there are significant differences in sensitivity between the FFDI and FWI values in their representation of some case study events that were studied, specifically that they respond differently to different sets of conditions. In some circumstances, the FFDI and FWI showed potential to provide complementary information for particular fire events. It was also shown that the hourly FWI values and the subcomponents of the FWI System (such as the three separate fuel moisture codes) could add valuable insight into fire conditions.

2.4.2 United States – U.S. National Fire Danger Rating System

The earliest fire danger rating system in the U.S. commenced around the 1930s when Gisbourne produced a Fire Danger Meter based largely on fire weather (McArthur, 1977a). Since 1972, fire danger throughout the United States has been determined using the U.S. National Fire Danger Rating System (NFDRS; Deeming *et al.*, 1972). The U.S. NFDRS (Figure 2.6) was designed around four basic guidelines. It needed to be:

- Scientifically based;
- Adaptable to the needs of local managers;
- Applicable anywhere in the country and
- Reasonably inexpensive to operate.

The NFDRS is largely based on Rothermel's physically based surface fire spread model (Rothermel, 1972) including the spread component (SC) and energy release component (ERC) which combine to formulate the Burning Index which has implications for the fire suppression difficulty under specified conditions (Fujioka *et al.*, 2008). Andrews (2018) provides a detailed description and consolidation of the equations for Rothermel's model and includes those used within the U.S. National Fire Danger Rating System.

The U.S. NFDRS was designed for pre-planning activities (e.g. communicating fire danger to the public, restricting logging activities and setting pre-fire readiness levels) and is used nationwide by all Federal land management agencies and by most of the 50 states.

Fire danger is determined as a function of fuel type, topography and weather with explicit determination of the moisture content of both dead and living vegetation (Bradshaw *et al.*, 1983; Cohen and Deeming, 1985; Burgan, 1988).

The U.S. NFDRS requires selection of specific fuel models as well as some weather parameters (including rainfall duration and cloudiness) that make transfer to other vegetation types without specific fuel models (such as Australian eucalypt forests) and routine access to these weather variables and regions quite difficult. The outputs of the U.S. NFDRS include the six indices shown in Figure 2.6.

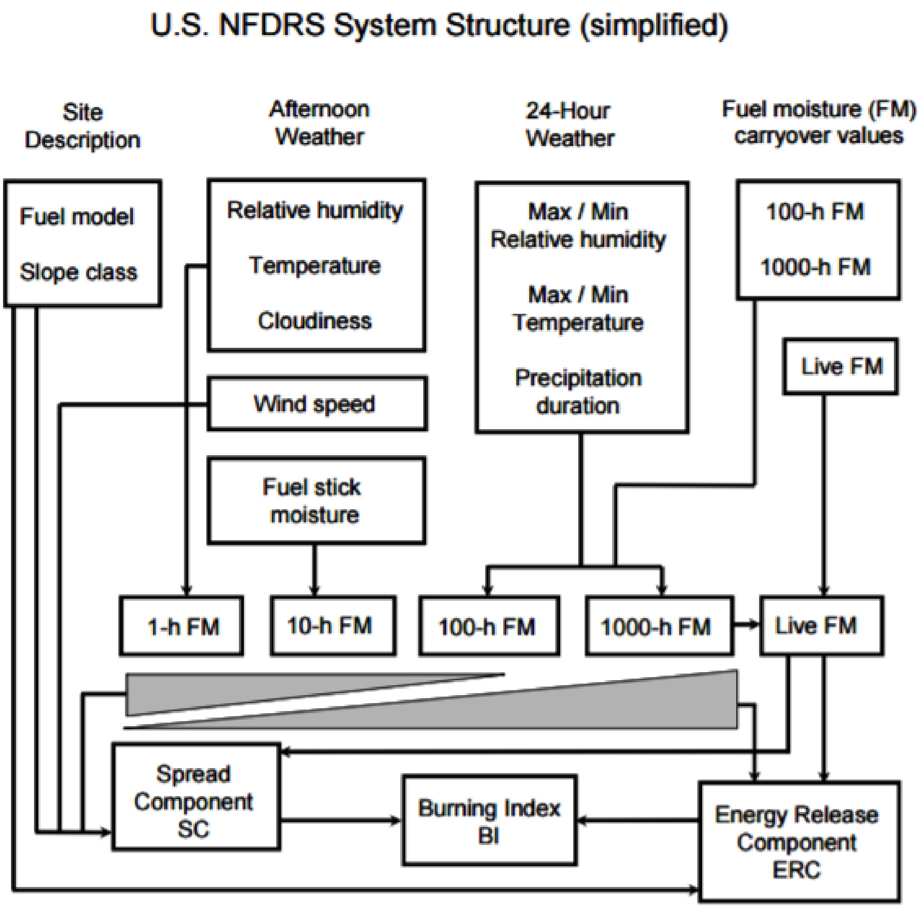

Figure 2.6 Simplified information flow for the U.S. National Fire Danger Rating System. Weather data and site descriptors are used to calculate fuel moisture values, which are used to calculate indices. The wedges indicate the weighting of the dead fuel moisture size classes in the calculation (Source: Andrews (2005)).

Since development of the original systems in the 1970s, some modifications were made in 1978 and 1988 primarily to improve the assessment of live fuels. There have been no changes to the system since this time, however revision and release of a new NFDRS is currently underway focusing on a much simpler and more automated system representing improvements in fire potential assessment capabilities.

There are three main areas where revisions to the U.S. NFDRS are proposed including (National Wildfire Coordinating Group, 2019):

- Incorporating a meteorological based phenology model, the Growing Season Index (GSI: Jolly and Nemani, 2005) to predict seasonal changes to live fuels;
- Incorporating the Nelson Model (Nelson, 2000) to provide a better fine dead fuel moisture that more accurately models diurnal fine DFM using elements from hourly fire weather observations; and
- Reducing the number of fuel models to four fuel types corresponding to the four Fire Behaviour Fuel Model (FBFM) groups: grasses, brush, timber, and slash.

2.4.3 South Africa

In parts of South Africa, the Lowveld Fire Danger System is used, which is an adaptation of the Fire Hazard Index developed by Michael Laing (Laing, 1978) and uses the same inputs as the Australian Forest Fire Danger Index (FFDI; McArthur, 1967). Five categories of fire danger rating were proposed by Willis *et al.* (2001) alongside the descriptive categories of;

- fire behaviour
- fire control
- recommended actions and
- prescribed actions and restrictions.

It is applied widely across the savannas, grasslands, fynbos and arid shrublands in South Africa. In 2009 Jolly (2009) recommended that South Africa adopt the U.S. NFDRS for fire danger rating.

2.4.4 Europe

Throughout Europe, fire danger rating systems range from fairly simple weather based through to more complex indices.

The Angstrom Index used in Sweden (Chandler, 1961) combines relative humidity and temperature while the Russian Ignition Index (Nesterov, 1949) uses temperature and humidity, but also adds on the effect of recent rainfall. Both the Swedish and Russian systems are interpreted into 4 different fire danger rating categories:

- Sweden: (1) fire occurrence unlikely, (2) fire conditions unfavourable, (3) fire conditions favourable and (4) fire occurrence very likely; and
- Russia: (1) Nil, (2) moderate, (3) high and (4) extreme fire danger with class boundaries based on wildfire occurrence against the index (Chandler *et al.*, 1983).

In France, fire danger is rated using Numerical Risk (Sol, 1989; Drouet and Sol, 1990) through the determination of a Drought Index which is then combined with wind speed (Carrega, 1988). The Drought Index itself is calculated using the available water capacity in the soil and potential evapotranspiration.

In Portugal, daily fire danger values are computed on an approximately 1km grid based on the Canadian Fire Weather Index (Stocks *et al.*, 1989) and are calculated using weather forecast data based on weather stations around the country where weather measurements are routinely available and the vegetation status is known. The fire danger rating classification in which the fire danger index threshold separating fire danger classes is currently defined is then a function of potential fireline intensity (and hence fire suppression difficulty) for the worst-case fuel scenario of a typical pine (*Pinus pinaster*) stand (Fernandes, 2017). The weakness with this method is that it doesn't tell you about expected fire behaviour (Fernandes, 2017).

In Spain, the Spanish Forest Fire Index (SFFI) is used, which is an adaptation of the U.S. NFDRS Ignition Component. It includes predicted values of the probability of ignition as well as the final risk value class (classified in four categories). Specific meteorological forecasts are made by the Regional Meteorological Centres of AEMET for fire prevention and suppression purposes which are issued for around 100 zones which cover Spain. Important parameters used in the determination of fire danger and fire spread include: 2m temperature; wind; relative humidity; and the probability of thunderstorms.

2.4.5 Fire danger at the global scale

The availability of global weather models and plant community maps allow for the calculation of fire danger at a global scale. This offers clear advantages to regions of the world with a weak investment and understanding of fire danger rating systems. Such a system would allow the identification of periods of critical fire weather and fire occurrence potential even if a country does not possess a weather forecasting service or a wildfire management agency. Alexander (2010) conducted a feasibility study for the setting up of a Global Wildland Fire Danger Rating System. One of his primary recommendations was that such an endeavour should be based on a sound technical and scientific foundation, with the global fire danger classes defined based on the concept of fireline intensity (which takes into account the effects of weather and fuel conditions on potential fire behaviour).

More recently, fire danger as well as some elements of fire behaviour have been predicted at the global scale. For example Di Giuseppe *et al.* (2016) provided daily predictions of fire danger, determined using weather forecasts (atmospheric model forcing) together with ratings systems such the U.S. NFDRS, the Canadian FWI System and the Australian McArthur (Mark 5) rating system. Using this approach, the authors found the fire danger modelling based on weather forecasts provided reasonable predictions at the global scale. Pettinari and Chuvieco (2017) also produced a large-scale fire danger assessment based on a simulation of surface fire behaviour together with climatic, topographic and a global fuel dataset using the Fuel Characteristic Classification Scheme (Ottmar *et al.*, 2007). In this study, the authors highlighted the limitations of having such coarse resolutions and the importance of including detailed fuel information in fire danger assessments.

Various international presentations forms and signage for fire danger rating are shown in Figure 2.7.

Figure 2.7 Presentation forms of fire danger rating around the world, from top to bottom, left to right (1) Argentina (source: Paulo Fernandes), (2) Canada (source: Kelsey Gibos), (3) Chile (source: Lachie McCaw), (4) United States of America (source: USDA Forest Service), (5) South Africa (Source: Saskia Grootemaat, and (6) Portugal (source: Paulo Fernandes).

2.4.6 Identifying important characteristics and requirements of fire danger rating in Australia

Historically the fire danger rating system in Australia has broadly enabled the calculation and dissemination of timely fire danger forecasts to inform the general public and to identify conditions whereby a total fire ban should be issued. More specifically, the fire danger forecast has been used to represent a measure of the expected fire load in order to plan pre-suppression activities (e.g. detection services, crew placement and park closures) (McArthur, 1958). In addition to this, McArthur (1958) suggested that fire danger rating should assist fire managers to answer the following questions, all of which can be assumed to be just as relevant almost 60 years later;

- What rates of spread could be expected for fires under forecasted conditions?
- What fire area, perimeter and rates of spread could be expected at 1 hour, 2 hours, 3 hours, etc., after ignition?
- How difficult would a fire be to control and will mechanical equipment be required or can it be suppressed affectively by a standard initial attack crew?
- What fire intensity can be expected?
- Would a fire be limited to surface fuels or is there potential for crown fires? Is there a possibility of a fire 'blowing-up'?
- Is there potential for short or long range spotting?

Some fire scientists in Australia have also expressed the need for fire danger rating to remain as simple and easy to operate as possible, making it readily available to the field operator (McArthur, 1977a; Cheney, 1988; Sharples *et al.*, 2009), however simplicity should not come at the expense of improving decision making and practical applications of fire danger ratings. Van Wagner (1971) once suggested that 'if it is complicated, then the complexity should be buried out of sight, as in prepared tables or computer programs'. Cheney (1988) suggest that the best way to keep the fire danger rating simple is to separate out two main functions: (1) providing regional forecasts for fire danger and (2) predicting local fire danger and that the system needs to provide a 'burning index' based on antecedent and prevailing weather conditions (applied to standard fuel conditions). Cheney (1988) also stated that more flammable fuels should be represented by the fire danger rating so that the 'average-worst' conditions are considered. At the time, nearly 30 years prior to this research undertaking, Cheney (1988) stated that improved fire danger rating would require better fire behaviour models within each fuel type, coupled with the use of geographic information systems that aid assessment of other important fire behaviour variables such as slope, fuels and the assets at risk.

More recently, in the United States, a study of historical fire danger rating systems and a synthesis of their common factors was completed. Four guiding characteristics were identified to guide improvements to the U.S. NFDRS. These developments should also be considered during development of the Research Prototype and included;

- Modular: New science can easily be added without altering the major structure of the system.
- Integrative: Fire danger indices integrated over both space (FDRA) and multiple time horizons (today → season → inter-annual). For example, including antecedent weather into today's fire danger values.
- Generalised: Same system performs across a range of climates (i.e. it should work equally well everywhere).
- Standardised: Normalise index scales and apply indices across a spectrum of fire management decisions. Maintain a 'common language' across all agencies.

At Workshop 1 (for operational staff) the majority of participants felt that improved consideration of fuels (type, arrangement, availability etc., n = 6), fire behaviour (usage of appropriate fire behaviour models, n = 6) and/or suppression difficulty (effectiveness, resource availability, n = 4) were paramount to facilitating improved FDR. The difficulty of course is in the detail and participants recognised that improved FDR needs to seek to meet the different needs of each agency and jurisdiction (n = 4). Other considerations that participants thought would facilitate improved FDR included: meeting the changing needs of users (n = 1), capability to adapt with better information and technology (n = 2), better consideration of ignition likelihood (n = 2), fire load (n = 2), being based on quality, verified data (n = 1) and being capable of taking impact/consequence into account (n = 1).

Participants commented that improved FDR, that takes into account the above described considerations, would directly benefit fire management mostly through improved preparedness (and resourcing, n = 7), accuracy (n = 5) and more timely and targeted community notifications (n = 5). It would provide a better quantification of risk (n = 4) and support for decision making (n = 2) as well as improving the alignment with fire behaviour, suppression difficulty and impact (n = 2). Improved FDR would create an environment suitable for better agency and departmental liaison (n = 2) with a greater awareness and improved knowledge of fire practitioners (n = 1). It would also enable better planning for determination of suppression tactics (n = 1).

Fogarty *et al.* (2010) stated that a new fire danger rating systems was required, and specifically it would need 'to link the potential for fires to start, spread and cause damage with the traditional fire agency needs such as prevention and preparedness planning, with end to end knowledge about how threat to communities and their assets'. This included a 'better understanding of the aspects of fire weather and fire behaviour such as fire categorisation, fire and atmospheric interactions, fuel categorisation and better prediction of thresholds that lead to impacts on communities and the things they need and value'.

Ultimately, the system developed needs to enable fire managers by reducing uncertainty, leading to improved decision making in response to fire danger. Roy Headley, the Director of Fire Control for the U.S. Forest Service (1919-1941) said in 1943, 'one of the major needs is for a system that will allow a man in charge of a going fire to be less of a gambler and more of a manager' (Headley, 1943). The usefulness of the system however, will always be limited by the capability and experience of operational fire managers which cannot be replaced. Ralph Nelson later went on to state 'I do not want to leave the impression that I think a good system of danger measurement is the answer to all fire control and management problems. It can be a guide, and a very useful one, but it can never take the place of cool, calculating, and experience judgement (Nelson, 1955). McArthur (1977a) in a similar way said 'a fire danger rating system is not intended to take the place of experience and judgement or the ability of a fire boss to 'size up' a fire situation and estimate fire behaviour'.

2.5 Establishing fire danger categories and the thresholds between categories

During the development of the FFDI and GFDI, the index scale was subdivided into five fire danger categories (i.e. Low, Moderate, High, Very High and Extreme), based mostly on making it as simple as possible (Cheney, 1988). This was subsequently revised to 6 categories in 2009, introducing additional Severe and Catastrophic categories and merging the Low and Moderate categories (AEMC - National Bushfire Warnings Taskforce, 2009). These changes came about in direct response to the recommendations by the Royal Commission investigating the causes and responses to the Black Saturday bushfires which swept through Victoria in February, 2009. In a subsequent review of the grassland fire danger indices Fogarty *et al.* (2010) suggested that significant changes to current thresholds were needed and that the current forest and grassland thresholds do not align adequately when measured in terms of community consequence.

In order to develop meaningful fire danger categories for the Research Prototype, with practical outcomes, we sought to identify points in a fire's management where fire behaviour, operational responses and strategies are different and/or have different consequences. To do this we sought guidance from fire practitioners and fire scientists by way of discussions, workshops (a summary of outcomes from these workshops can be found in Appendices A and B) and consultation, with the question 'at which point/s in a fires management are things (e.g. fire behaviour, responses and strategies) treated or done differently'. Because of the large variation between states and fire managers, and the pre-identified need for social research (part of the broader NFDRS program), we considered these points in the absence of public notifications, communications, warnings and levels of readiness or preparedness.

We considered these points, together with user requirements and the existing thresholds used within each state and agency or department and used them to establish how many categories would best describe fire danger across Australian fuel types, but also how the thresholds between each category could be determined. There were many discrepancies between usage and application of existing thresholds by different states and fire managers (some prominent examples of which are outlined in Tables 2.5-2.9 below) making it difficult to find agreement on any one threshold. For some fuel types, these changes or points were a function within the relevant fire spread model (e.g. identified as probabilities of transitions between self-sustained surface fires or crown fires within the mallee-heath model developed by Cruz *et al.* (2010)). It is important to note here that we assumed that 2 fire danger rating categories would be too few and that 8 would be too many to capture fire danger adequately.

For fuel types where the fire spread model was not indicative of any fire behaviour transitions, we sought the best, most informative and practical threshold to signal changes between NFDRS categories. We considered:

- current relationships that are associated and applied with fire danger rating (presented in Table 2.1, e.g. type of fire, difficulty of suppression, rate of spread and flame height);
- variables suggested by fire practitioners (identified via consultation and workshops);
- those used around the world to distinguish fire danger rating categories;
- possible variables identified throughout literature; as well as
- advice from Australian and International fire scientists.

In 2009, the AEMC - National Bushfire Warnings Taskforce produced a table for Forecast Fire Danger Ratings (Table 2.4). The table contained core descriptors and messages that are available for use by agencies to inform their communities and organised into sections relating to:

- fire behaviour predictions;
- impact assessment – if a fire breaks out; and
- call to action.

Despite being prepared by fire and communications experts and prepared using a 'direct language', the content appears to have not been widely taken up or applied. The table, either in part or entirely, has not been integrated into fire management training publications. This may be due to a lack of awareness that it was developed, or may have been because it wasn't suited to the various uses and requirements of fire management agencies and departments around Australia.

Table 2.4 FORECAST FIRE DANGER – before a fire starts. Sourced from AEMC - National Bushfire Warnings Taskforce (2009) Appendix 3. 'The table below contains core descriptors and messages that are available for use by agencies to inform their communities. They have been crafted by a range of fire and communications experts, taking into account research that suggests more direct language should be used to have a greater chance that people will personalise the risk they face and take appropriate action. The messages are strong, confronting and representative of the gravity of the forecast danger. They can be tailored to suit each State and Territory's community safety policies.'

Fire Danger Rating	Fire Behaviour Predictions	Impact Assessment – If a fire breaks out	Call to Action
CATASTROPHIC (100+) **(CODE RED)**	*Behaviour* Bushfire: • ROS: 10+ km/h, • Spotting: 8-20 km • Intensity: 50,000+ kW/m; • Area growth: 4000 to 8000 ha/h Grass: • ROS: 15-25 km/h, • Intensity: 20,000 to 50,000 kW/m; • Area growth: 20000 to 30,000 ha/h Some fires will be unpredictable, uncontrollable and fast-moving Fires will spread much faster on hills or in thick bush Flames will be much higher than roof tops Thousands of embers blown around and into homes Spot fires will move quickly and could come from many directions – possibly well ahead of the main fire	A fire can threaten suddenly and without warning There is a very high likelihood that people in the path of the fire will die or be injured, and whole communities will be affected Thousands of homes and businesses will be destroyed Well prepared & constructed homes may not be safe during a fire Strong winds will bring down trees and powerlines, blocking roads – this will be well ahead of the fire Strong winds may blow roofs from houses and break windows Power, water, home and mobile phones are likely to fail It will be very hot and windy, and as the fire approaches it will become difficult to see, hear and breathe Petrol-driven cars, pumps and generators may not work Don't expect a fire truck or other emergency workers at your home	- Leaving is the safest option for your survival – finalise your options for relocation – *state 'agency'* recommends that you leave the night before - Prepare to leave – check your kit (state-specific i.e. emergency, survival, recovery, etc.) - Check your bushfire survival plan – Now (state specific message) - Monitor weather and fire situation in any way you can: through website (specific), radio(state specific), TV and newspapers - Call „000" if you see flames (state specific message)
EXTREME **(75-99)**	*Behaviour* Bushfire: • ROS: 3-6 km/h, • Spotting: >6 km • Intensity: 30,000 to 60,000 kW/m; • Area growth: 1000 to 2000 ha/h Grass:	A fire can threaten suddenly and without warning There is a likelihood that people will die or be injured, and whole communities will be affected Hundreds of homes and businesses will be destroyed	- If you plan to leave finalise your options and leave early on the day - Prepare for the emotional, mental and physical impact of defending your property – if in doubt, leave - Only stay if your home is well prepared, constructed and you can actively defend it. - Check your bushfire survival plan - Now

	• ROS: 10-15 km/h, • Intensity: 15,000 to 30,000 kW/m; • Area growth: 10,000 to 20,000 ha/h Some fires will be unpredictable, uncontrollable and fast-moving Fires will spread much faster on hills or in thick bush Flames will be much higher than roof tops Expect thousands of embers to be blown around and into homes Spot fires will move quickly and could come from many directions	Only well prepared, constructed and defended homes are likely to offer safety during a fire Strong winds may bring down trees and powerlines, blocking roads – this may be well ahead of the fire Strong winds may blow roofs from houses and break windows Power, water, home and mobile phones are likely to fail It will be very hot and windy, and as the fire approaches it will become difficult to see, hear and breathe Petrol-driven pumps and generators may not work Don't expect a fire truck or other emergency workers at your home	(state specific message) - Monitor weather and fire situation in any way you can: through website (specific), radio (state specific), TV & Newspapers - Call „000" if you see flames (state specific message)
SEVERE **(50-74)**	*Behaviour* Bushfire: • ROS: 2-3 km/h, • Spotting: >4km • Intensity: 20,000 to 40,000 kW/m; • Area growth: 500 to 1000 ha/h Grass: • ROS: 8-12 km/h, • Intensity: 10,000 to 25,000 kW/m; • Area growth: 9000 to 14000 ha/h Some fires uncontrollable and fast-moving Fires will spread much faster on hills or in thick bush Flames may be higher than roof tops Expect embers to be blown around and into homes Spot fires will move quickly and could come from many directions – possibly ahead of the main fire.	A fire can threaten suddenly and without warning There is a chance people may die and be injured, and communities may be affected Some homes and businesses will be destroyed Well prepared and defended homes can offer safety during a fire Power, water, home and mobile phones may fail It will be very hot and windy, and as the fire approaches it will become increasingly difficult to see, hear and breathe Don't expect a fire truck or other emergency workers at your home	- If you plan to leave finalise your options and leave early on the day - Prepare for the emotional, mental and physical impact of defending your property – if in doubt, leave - Only stay if your home is well prepared and you can actively defend it. - Check your bushfire survival plan – Now (state specific message) - Monitor weather and fire situation in any way you can: through website (specific), radio (state specific), TV & Newspapers - Call „000" if you see flames (state specific message)

VERY HIGH **(25-49)**	*Behaviour* Bushfire: • ROS: 1-2 km/h, • Spotting: >2km • Intensity: 10,000 to 20,000 kW/m; • Area growth: 200 to 400 ha/h Grass: • ROS: 5-10 km/h, • Intensity: 8000 to 2,0000 kW/m; • Area growth: 3000 to 5000 ha/h Fires can be difficult to control Fires will spread faster on hills or in thick bush Embers may be blown ahead of the fire and around your home Spot fires can occur ahead of the main fire	A fire can threaten suddenly and without warning There is a low chance people may die or be injured Some homes and businesses may be damaged or destroyed Well prepared and defended homes can offer safety during a fire Power, water and phones may fail It will be hot and windy, and may become difficult to see, hear and breathe Don’t expect a fire truck or other emergency workers at your home	- If you plan to leave finalise your options and leave early on the day - Only stay if your home is well prepared and you can actively defend it. - Check your bushfire survival plan – Now (state specific message) - Monitor weather and fire situation in any way you can: through website (specific), radio (state specific), TV & Newspapers - Call „000" if you see flames (state specific message)
HIGH **(12-24)**	*Behaviour* Bushfire: • ROS: 0.5-1 km/h, • Spotting: >1km • Intensity: 4,000 to 10,000 kW/m; • Area growth: 50 to 100 ha/h Grass: • ROS: 3-6 km/h, • Intensity: 5000 to 12,000 kW/m; • Area growth: 1500 to 3000 ha/h Fires can be controlled Fires are less likely to burn in the tree-tops Embers may be blown ahead of the fire and around your home Spot fires can occur close to the main fire	A fire can threaten suddenly and without warning Loss of life is highly unlikely, and damage to property will be limited Well prepared and defended homes can offer safety during a fire Don’t expect a fire truck or other emergency workers at your home	- Make sure your family and property are well prepared for the risk of bushfire - Review and practice your bushfire plan for different scenarios (eg kids at school/home, visitors) - Know where to get more information
LOW-MODERATE **(0-11)**	*Behaviour* Bushfire: • ROS: 0.1 to 0.5 km/h,	Little to no risk to life and property	- Make sure your family and property are well prepared for the risk of bushfire

	• Spotting: <1 km • Intensity: 100 to 3000 kW/m; • Area growth: 2 to 30 ha/h Grass: • ROS: 0.1 to 3 km/h, • Intensity: 500 to 5000 kW/m; • Area growth: 100 to 1000 ha/h Fires can be easily controlled		- Review and practice your bushfire plan for different scenarios (e.g. kids at school/home, visitors) - Know where to get more information

Table 2.5 Suppression thresholds and Fire Danger Rating in Forest by the NSW Rural Fire Service (Source: NSW Rural Fire Service (2014)).

FDI	Flame Height (m)	Radiant energy released (fireline intensity, kW/m)	FDR/ Method of attack
0-12	0-0.5	0-50	**Low:** Fire generally self-extinguish or hand tool line will hold the fire
12-15	0.5-1.5	50-500	**Moderate:** Offensive operations usually possible in bush fuels. Most properties usually defendable
12-25	1.5-3.0	500-2,000	**High**: Fire too intense for direct attack. Parallel attack recommended
25-50	3.0-10	2,000+	**Very High:** Crown fire at upper intensities. Indirect attack recommended
50-75	10+	12,000-18,000	**Severe:** The fire may be worse than anything previously experienced. Actions should be focused on safe guarding people and defensive operations. Offensive operations may be possible at night
75-100	12+	18,000-25,000	**Extreme:** As for Severe but crew and public safety becomes a major concern. Safeguarding refuge and defensive operations may be the only safe options
100+	15+	25,000+	**Catastrophic:** Fire behaviour is very dangerous, devastating and difficult to predict. Expect significant ember attack. Actions must focus on safeguarding lives

Based on 20 tha^{-1} fuel load.

Table 2.6 Relationship between fire behaviour and bushfire fighting strategies in forest fuels by the DBCA, Parks and Wildlife in Western Australia (Source: Department of Parks and Wildlife (2017)).

Fire danger	Flame height	Intensity (kW/m)	Significance and comments
Low	<0.5 m	<50	Direct attack recommended. Generally self-extinguish
Mod	0.5-2 m	51-800	Direct attack recommended. Hand tool line should hold. Water support recommended at upper end of range
High	2-5 m	801-2,000	Parallel attack using machines recommended. Direct attack using machines possible although may be difficult at upper end of range
V. High	5-10 m	2,001-3,000	Indirect attack possible provided back burn can be controlled and is sufficiently deep to capture spot fires. Direct attack using machines is dangerous and unlikely to succeed. Crown fire at upper range. Junction zone effect must be considered when determining required back burn depth

Extreme	>10 m	>3,000	Defensive strategies recommended. Crown fire and spotting. Major runs likely. Control efforts probably ineffective

Table 2.7 Levels of suppression difficulty and fire danger rating in grassland by the NSW Rural Fire Service (Source: Cheney and Sullivan (1997) and NSW Rural Fire Service (2014)).

Fire Danger Index (FDI)	Fire Danger Rating (FDR)	Difficulty of suppression (Grassland)
0-2.5	Low	Low. Head fire stopped by roads and tracks
2.5-7.5	Low	Moderate. Head fire easily attacked with water
7.5-20	Moderate to High	High. Head fire attack generally successful with water
20-50	Very High	Very High. Head fire attack may succeed in favourable circumstances
50-200	Extreme to Catastrophic	Extreme. Direct attack will generally fail. Backburns from a good secure line will be difficult to hold because of windblown embers. Suppression should concentrate on flanks and property protection

** 'although it pre-dates the introduction of 'severe' and 'catastrophic' to fire danger ratings, it indicates the increasing suppression difficulty as the index moves beyond 'high''.*

Table 2.8 Head fire behaviour classes used by the Department of Fire and Emergency Services in Western Australia (Source: Muller (1993a), Muller (2008) and Smith (2009)).

Headfire behaviour classes
1. Readily suppressed Intensity <800 kW/m and/or ROS <60 m/hr in all fuels
2. Hand tool attack possible Intensity <800 kW/m and/or ROS <140 m/hr in forest/woodland and shrubland Intensity <800 kW/m and/or ROS <300 m/hr in grassland
3. Direct machine and tanker attack possible Intensity <2000 kW/m and/or ROS <400 m/hr in forest/woodland Intensity <2000 kW/m and/or ROS <1000 m/hr in forest shrubland Intensity <5000 kW/m and/or ROS <6500 m/hr in grassland
4. Direct attack not possible/unlikely to succeed Intensity >2000 kW/m and/or ROS >400 m/hr in forest/woodland Intensity >2000 kW/m and/or ROS >1000 m/hr in forest shrubland Intensity >5000 kW/m and/or ROS >6500 m/hr in grassland
5. Indirect attack likely to fail Intensity >4000 kW/m and/or ROS >800 m/hr in forest/woodland Intensity >8000 kW/m and/or ROS >2000 m/hr in shrubland and/or ROS >10,000 m/hr in grassland

Table 2.9 Fire intensity and readiness level interpretation for the Country Fire Authority in Victoria (Al Beaver pers. comm).

Readiness level	Intensity (kW/m)	Difficulty of suppression / Fire description
1	<500	• Spot ignition sources that cause an ignition to occur are self-extinguishing at the lower end of this intensity-readiness level. • Creeping or gentle surface fire. Direct manual attack at fire's head or flanks by fire fighters with handtools and water is possible. Constructed breaks or firelines should hold (Alexander and deGroot 1989). • These are Head Fire Intensities, ***Planned Burning*** opportunities at the higher end of this Intensity Class depending upon burn objectives.
2	500-2,000	• This is the level of fireline intensity were the majority of planned burning takes place and where ember production and spotting commences. • Very little ember production and spot fire activity at less than 1,000 kW/m (Gould et al. 2007a). • Fires at the upper end of the scale can be challenging if the fuels are prone to ember production and spotting. Hand constructed firelines are likely to be challenged. • ***Planned Burning:*** These are Head Fire Intensities, Risk Manage intensity by Controls of ignition pattern and/or diurnal cycle, control resources.
3	2,000-4,000	• Challenging but achievable fire suppression at lower ends of this fireline intensity-readiness level. Firefighter support with heavy equipment such as dozers, ground tankers and air tankers generally successful. • This is the fire intensity level where automatic dispatch rules for aircraft and heavy equipment support begins in many Canadian agencies. • Very vigorous or extremely intense surface fire (torching common in conifer fuels). Control efforts at head may fail at the upper levels (4,000 kW/m) (Alexander and De Groote 1989). • ***Planned Burning:*** These are Head Fire Intensities, Risk Manage intensity by Controls of ignition pattern and/or diurnal cycle, control resources.
4	4,000-10,000	• 6% house loss category (Harris et al. 2010) • Limit of fireline intensity at the lower end of the level for suppression success in natural grass fires. • 4,000 kW/m is estimated to be the approximate threshold for direct attack on a head fire with dozers, ground tankers and air tankers support. This success is highly dependent upon the degree of ember production and spotting. • Threshold for continuous crown fire (10,000 kW/m). Control is extremely difficult and all efforts at direct control are likely to fail. Direct attack is rarely possible given the fire's probable ferocity except immediately after ignition and should only be attempted with the utmost caution. • Otherwise, any suppression action must be restricted to the flanks and back of the fire. Indirect attack with aerial ignition (i.e. helitorch and/or A.I.D. dispenser), if available, may be effective depending on the fire's forward rate of spread (Alexander and Cole 1995).
5	10,000-30,000	• 24% house loss category (Harris et al. 2010). • 10,000 kW/m threshold for continuous crown fire. This has the potential for a dramatic increase in fire intensity with the addition of the crown fuel consumption. This will produce a related increase in ember production and spotting.
6	>30,000	• 70% house loss category (Harris et al. 2010). • Fireline intensity of greater than 30,000 kW/m is commonly understood as blow-up or conflagration level fire intensity. Intensities exceeding 30,000 kW/m were a defining feature of the 7 February, Black Saturday Fires (Gellie et al, Cruz et al in press). • Wilson (1984) identified that fire intensity was at least 60,000 kW/m for the Belgrave fire during Ash Wednesday 16 February 1983.

Identifying and agreeing on an appropriate threshold variable for the Research Prototype is no simple task and this was highlighted at Workshop 1 (Operations, Appendix A) where there were diverse discussions, constructive debates and broad ranging feedback regarding the setting of thresholds. Any possible contender variable must be able to be linked by fire behaviour or rate of spread (as the Research Prototype is driven by models of rate of spread) by way of a peer reviewed (or widely accepted) function. While this limits the list of possible contenders, we endeavoured to not overlook any variable that may still have potential. While participants at the workshop generally found it possible to agree on general fire danger rating categories, they weren't able to identify or agree on a more specific variable to use the established thresholds. This is captured in the Workshop Outcomes (Appendix A) with some of the variables discussed including rate of spread, flame height, flame length (or variations of flame dimensions) and fireline intensity.

2.5.1 Fireline intensity

Fireline intensity was identified as having many attributes that would make it suitable to signal changes between NFDRS categories. It was for these reasons (outlined below), along with some existing applications against fire danger rating (Table 2.1) that we have applied it to most fuel types (Forest, Grassland, Pine, Savanna and Shrubland), in the absence of a fire spread model that incorporates fire behaviour processes or transitions.

Alexander (2010) notes that because fire danger rating is a general expression of probable fire behaviour under a particular set of fuel and weather conditions, using fire behaviour models to determine fire danger is likely to be the most 'fruitful' method, particularly if based on head fire intensity. In contrast, while examining the consequences of linking fire danger to fire behaviour variables such as rate of spread, Cheney *et al.* (1990) and later, Cheney and Gould (1995) concluded that fire danger rating should be separated from predictions of rate of spread (particularly in grassland), for the main purpose of enabling revision of fire spread equations without impacting fire danger rating systems. The authors also noted that fire danger rating needed to be as simple as possible and that any changes over time by incorporating new fire spread equations would have subsequent impacts on the thresholds set between categories and the number of fires that fall into each category (e.g. increasing the number of fires in the Very High and Extreme categories that trigger total fire bans). In a system where continuous improvement is encouraged, this must always be a consideration and as such, any consequences of implementation of new fire behaviour and spread models would need to be investigated prior to going live. However, if the system is designed so that the thresholds are established between categories based on descriptions of fire behaviour (such as rate of spread), then incorporating improved spread models becomes less of an issue.

In a Research Letter, Gill (1998) suggested breaking up a Richter-type fire danger rating scale using the intensity of a fire event as described in Table 2.10.

Fireline intensity has many established relationships that enable it to be used to delineate between NFDRS categories and make it a particularly meaningful threshold. Some of these relationships and their potential application for fire danger rating are outlined in Table 2.11.

At the Workshop 1 (for operational staff) there was a spilt in opinion relating to the appropriateness of using fireline intensity for FDR. While some thought it was the best variable for both agencies and for public warning, other participants expressed concern that fireline intensity may not be the best variable to use for FDR largely because it isn't transferable between vegetation types and because fire practitioners and the public would have difficulty 'measuring' or visualising it. These participants suggested that the variable needs to be measurable and have a meaning that is consistent such as flame height, rate of spread, flame depth, residence time and spotting.

Table 2.10 Suggested break up of a Richter-type fire danger rating scale based in fireline intensity from Gill (1998).

Level	Fireline intensity (kW/m)	Description
1	<100	The lowest step on our scale of fire intensity
2	<350	For this level, Richter would have multiplied the values by 10 but this is too sharp an increase for; an intermediate step is to multiply by the square root of 10 and round off to give us 350 kW/m. This is a convenient number as it is near the upper limit of the prescribed burning range for forests. Cheney (1978) suggested that the "fire intensities recommended for optimum prescribed burning [in forests] range from 60 to 250 kW/m while the maximum intensity recommended ... is 500 kW/m". From 100 to 350 is Level 2 on our scale.
3	<1,000	
4	<3,500	The upper value being about the limit of fire control in eucalypt forests (Luke and McArthur (1977) suggest 4,000).
5	<10,000	
6	<35,000	
7	<100,000	It is doubtful if fire intensities would go over Level 7 (Luke and McArthur, 1977; Gill and Moore, 1990).

Table 2.11 Examples of fireline intensity relationships and their potential application related to fire danger.

Suppression difficulty	Since early ratings of fire danger around the world, fireline intensity has been used to describe and establish thresholds for suppression difficulty (Hodgson, 1968; Burgan, 1979; Andrews and Rothermel, 1982a; Andrews *et al.*, 2011; Werth *et al.*, 2011). More recently, fireline intensity has been used to gauge the effectiveness of aerial suppression (Plucinski et al., 2007) and the likelihood of direct- or intial-attack success (Burrows, 1984; Loane and Gould, 1986; McCarthy and Tolhurst, 1998). These relationships are still used by many fire management agencies around Australia (Table 2.1). Delineating fireline intensity into fire danger classes is considered by Alexander (2008, 2010) as the most objective and quantitative approach in determining suppression difficulty, based on Byram's fireline intensity (Byram, 1959) increasing alongside the suppression difficulty or ability to control a fire. For example, Alexander (2008) sets thresholds for the type of suppression and resources as; ~500kW/m for ground crews using shovels, rake hoes etc., ~2000kW/m for ground crews working with heavy machinery or power tools, ~4000kW/m for single drops from airtankers and helitankers and ~10,000kW/m for indirect attack using back fires from the ground or air. Fireline intensity can also be related to whether or not fuel breaks may be breached (Wilson, 1988; Fogarty, 1996). As part of a cost-benefit study of aerial suppression effectiveness in Victoria, Loane and Gould (1986) indicated that unsupported retardant drops in stringy-bark forest were ineffective at 'holding a fire' when fireline intensity exceeded 2000 kW/m due to heavy spotting across the drop zone (Jim Gould, pers. comm. 2019). If ground crew support the retardant drop within one hour, the effective limit was established to be around 3000 kW/m. In coniferous forests, the effective limit of aerial suppression resources to directly control a fireline has been identified to be higher, at 4,000kW/m (Hirsch and Martell, 1996; Wotton et al., 2017). A study by McCarthy and Tolhurst (1998) of 50 fires in Victoria, found that initial attack was successful at an average of 1247 kW/m whereby fires did not increase by a factor of three and was contained using 'usual' resource availability and within the first eight hours after initial attack). At an average of 3836kW/m, extended first attack was successful whereby fires are likely to be controlled at a reasonable size (< 400 ha) and in a relatively short amount of time (< 24 hrs). At an average of 11,000 kW/m, first attack was unsuccessful whereby fires are likely to increase by more than a factor of three and containment is not possible within 24 hrs.
Firefighter safety	Fireline intensity can be used to approximate radiation intensity levels (kW/m^2) which is important for determining a sufficiently safe separation between firefighters and flame fronts (Fogarty, 1996). Fireline intensity can be indicative of firefighter safety and is used operationally for example in Canada, where diurnal intensity curves have been produced daily in support of British Columbia's Fire Weather and Behavior Advisory and Warning System for both potential and ongoing fires (Beck *et al.*, 2002). These intensity curves are associated with head fire spread rate, a fire intensity class and fire suppression implications to support fire management operations.
Community impact, house and life loss	Fireline intensity has been used to describe and sometimes forecast the consequences of fire such as house survival (Wilson and Ferguson, 1986; Gill, 1998; Wang, 2006; Geoscience Australia, 2007; Harris *et al.*, 2012). Harris *et al.* (2012) describe the fireline intensity variable as a 'possible contender' for predicting house loss with power of fire and FFDI/GFDI (adjusted) variables having a closer fit. However, in the absence of knowing a fire perimeter and fireline length, or making adjustments to FFDI and GFDI (for slope and fuel) fireline intensity was the next best predictor, with better fits than FFDI, GFDI and rate of spread variables.
Fuel consumption and fuel treatment effectiveness	Fireline intensity has been found to have a statistically significant, positive relationship with the proportion of fuel consumed by both controlled fires and wildfires (Hollis *et al.*, 2011; Werth *et al.*, 2011; Cruz *et al.*, 2017b). For woody fuels,

	this has important practical implications related to fuel load reduction as well as impacts on habitat and carbon and climate change management (Hollis *et al.*, 2011). It has also been used to determine the appropriate fire behaviour and associated environmental conditions to meet specific prescribed burn objectives (Andrews and Rothermel, 1982b).
Fire severity, fire impacts and effects	Fireline intensity can be linked and used as a measure of fire severity including damage to vegetation and trees (McArthur, 1962a; McArthur and Cheney, 1966; Van Wagner, 1973; Reinhardt and Ryan, 1988; Taylor and Armitage, 1996) and the height of lethal crown scorching in forests (Van Wagner, 1973; Alexander and Cruz, 2012). More specifically, through it's relationship with fuel consumption, fireline intensity can be used to determine the potential for significant damage to softwood plantation stands (McArthur & Cheney, 1966).
Processes of fire transition	For fuel types where fire spread models do not capture the transitional process between, say, surface, to crowning fires, fireline intensity may be used. For example to indicate crown fire initiation and vertical fire spread (Van Wagner, 1977; Werth *et al.*, 2011).
Fire behaviour	Byram's (1959) fireline intensity has commonly been used as an index of fire behaviour (Beck *et al.*, 2002). It can be directly related to flame height or length (Newman, 1974; Andrews *et al.*, 2011) and the distance spot fires will be transported (Morris, 1987).

While the highest, most intense fireline intensity will be found at the front, or head of the fire, the flanks and rear of the fire are generally lower (Catchpole *et al.*, 1982; Catchpole *et al.*, 1992) which means that the actual fire danger based on other parts of the fire perimeter can be rated differently and depending on the perimeter size. Catchpole *et al.* (1992) provide an excellent example of this, based on an elliptically shaped fire in homogeneous conditions, with a head-fire intensity of 5000 kW/m, a length to breadth ration of 3:1 and a fixed-focus ignition point (Table 2.12).

Table 2.12 Theoretical distribution of fireline intensities for on an elliptically shaped fire with a head-fire intensity of 5000kW/m, a length to breadth ration of 3:1 and a fixed-focus ignition point (source: Catchpole *et al.*, 1992; Alexander, 2008).

	Percentage of total		
Fireline intensity (kW/m)	Perimeter length	Area burned	Perimeter length
<500	25	7	25
500-1000	32	19	59
1000-1500	18	17	
1500-2000	9	13	
2000-2500	5	10	12
2500-3000	3	7	
3000-3500	2	6	
3500-4000	2	5	
4000-4500	2	6	4
4500-5000	2	10	

The main problem associated with applying fireline intensity to delineate NFDRS categories is that fireline intensity cannot be physically, accurately measured and as such, makes it difficult to estimate or 'visualise' by the average fire practitioner. On top of this, of the three variables used to calculate fireline intensity, fuel load can be particularly difficult to estimate, potentially introducing large amounts of error into the delineation of fire danger categories (Cheney, 1990). For fuel types where, fuel load (or hazard) is already used to determine rate of spread (e.g. Vesta: Cheney *et al.* (2012b)), a dubious estimation of fuel load results in the variable being used twice for calculations within the Research Prototype.

For Mallee-heath and Spinifex fuel types, where fire behaviour transitions were adequately captured within the fire spread models, or for the Buttongrass fuel type where there was a strong case for testing existing fire danger rating categories (Marsden-Smedley *et al.*, 1999a), we directly applied these variables as points of change to mark the thresholds between categories (Table 2.13).

Table 2.13 NFDRS Research Prototype fuel types using variables other than fireline intensity to delineate between categories

Fuel type	Fire spread model applied	Variable upon which threshold is established
Mallee-heath	Cruz *et al.* (2010)	Probabilities of transitions between self-sustained surface fires or crown fires
Spinifex	Burrows *et al.* (2018)	Spread index
Buttongrass	Marsden-Smedley *et al.* (1999a)	Rate of spread

2.6 Research Prototype categories and points of transition

Taking the feedback from fire practitioners and fire scientists into account, as well as the historical application of fire danger rating in Australia and throughout the world, we determined that the most suitable transition points for the Research Prototype would reflect transitions in fire behaviour (that result in different strategies for fire management being used), as well as potential changes in possible consequences and impacts. Of course, fire behaviour and the variables that determine fire behaviour vary with fuel type (and the structural characteristics that characterise them). Likewise the consequences and impacts of a fire will vary with fuel type and proximity to assets (e.g. a catastrophic fire within metropolitan forest is unlikely to have the same consequences as a catastrophic fire in remote northern savanna). It therefore makes sense that the points of transition and descriptors that define each fire danger class need to also be specific to each fuel type (Alexander, 2008).

When participants at Workshop 1 (for operational staff), were asked what operational differences existed between an FFDI of 60, compared to an FFDI of greater than 100, most reported differences relating to the level of readiness (or preparedness, with consideration given to pre-deployment of resources to strategic locations to enable rapid response, n = 7). They reported differences in the escalation of notifications including public warnings, fire bans and restrictions to industry (e.g. harvest bans) and public places (e.g. park closures) (n = 8). Participants also noted a decrease in confidence in fire behaviour models but an increase in liaison and integration between state and local governments and industry. No differences in fire behaviour or suppression strategy were identified.

During Workshop 1, operational staff were also asked to agree on and recommend categories and thresholds for the Research Prototype based on thresholds using fireline intensity. These are summarised in Tables 2.14 – 2.16 below for forest, grassland and shrubland together with a comparison with existing categories referred to in agency/departmental training resources. Descriptive summaries for pine, savanna and spinifex fuel types are presented in sections 2.6.4-2.6.6.

2.6.1 Forest

Table 2.14 FDR categories and thresholds recommended by participants at Workshop 1 for eucalypt forest

Fuel type	FDR Category alignment against (lower limit) fireline intensity							Thresholds set by:
	1	2	3	4	5	6	7	
Forest	0	?	?	1000	3000	4000	16,000	Group 1
	0	1000	2000	4000				Participant 1
	100	200	500	1000	4000			Participant 2
	0	500	1,000	2,500	4000	10,000	25,000	Participant 3
	0	500	2,000	4,000	10,000	30,000		Participant 4
	0	500	1,000	3,000	10,000	25,000		Participant 5
	0	100	750	2,000	8,000	36,000		Participant 6
	0	1,000	3,000	4,000	16,000			Participant 7
	0	*50*	*800*	*2,000*	*3,000*			*Department of Parks and Wildlife (2016)*
	0	*800*	*2,000*	*4,000*				*Smith (2009) citing Muller, 2008*
	0	*50*	*500*	*2,000*	*4,000*			*NSW Rural Fire Service (2005)*
	0	*50*	*500*	*2,000*	*12,000*			*NSW Rural Fire Service (2014)*
	0	50	500	2,000	4,000			*Country Fire Authority (2005)*

2.6.2 Grassland

Table 2.15 FDR categories and thresholds that were recommended for grassland

Fuel type	FDR Category alignment against (lower limit) fireline intensity							Thresholds set by:
	1	2	3	4	5	6	7	
Grassland	0	1,000	2,000	4,000				Participant 1
	50	2,000	8,000					Participant 2
	0	600	2,000	5,000	12,000	25,000		Participant 3
	0	200	4,000	8,000	15,000			Participant 4
	0	1,000	3,000	4,000	16,000			Participant 7
	0	*800*	*5000*	*8000*				*Smith (2009) citing Muller, 2008*

2.6.3 Shrubland

Table 2.16 FDR categories and thresholds that were recommended for shrubland

Fuel type	FDR Category alignment against (lower limit) fireline intensity							Thresholds set by:
	1	2	3	4	5	6	7	
Shrubland	0	1,000	2,000	4,000				Participant 1
	0	500	2,000					Participant 2
	0	100	1,250	5,000	10,000	36,000		Participant 6
	0	1,000	3,000	4,000	16,000			Participant 7
	0	*800*	*2,000*	*8,000*				*Smith 2009 (citing Muller, 2008)*

2.6.4 Savanna

At Workshop 1, the group working to set thresholds for savanna fuels recommended four FDR categories be established based on fireline intensity as follows;

- 0-500 kW/m: fires will generally self-extinguish. Too wet, too green;
- 500-1500 kW/m: 50-70% cured, ideal prescribed burning conditions. Rates of spread typically 200-600 m/hr;
- 1500-2000 kW/m: mild wildfire potential. Suspend prescribed burning. Rates of spread >600 m/hr, dewpoint <13% overnight, >70% cured;
- >2000 kW/m: Long flame length and depth. Typically associated with stock and wildlife loss. Kills woody vegetation.

The participants in this group noted how higher intensities can typically be suppressed with offensive suppression strategies compared to eucalypt forests and that perhaps rate of spread or flame length may provide a more useful measure of fire danger instead.

2.6.5 Pine

The group working on establishing categories for pine plantations identified that four FDR categories would suit this fuel type best and aligned these categories with the Forest Fire Danger Index (FFDI: McArthur, 1967):

- Low: FFDI 0-10: older, established fuels won't burn, new weedy fuel may burn. Fires easily controlled with early detection. Low consequences.
- Moderate: FFDI 11-15: fire development depends on level of ladder fuels, weeds, thinning and pruning. Normal detection and response arrangements.
- High: FFDI 16-24: Resources stand up. Reliant on successful initial attack.
- Very High: FFDI >25: Potential for crown fire. Potential loss and recovery rate dependant on age class. Difficult or impossible to suppress. Fall back to major roads. Use heavy plant. Restricted harvest/forest closures.

Because prescribed burning is mostly done in tropical pine, not for southern *Pinus radiata*, the group agreed that including prescribed burning as an FDR category wasn't beneficial. It was also noted that at the upper end of the FDR scale, pine plantation fuels would be comparable to eucalypt forest where consequences and safety are of utmost importance.

2.6.6 Spinifex

Numerical thresholds between categories were not directly discussed during the Workshop 1 for spinifex fuels however one participant did recommend the following FDR categories as part of Exercise 4:

- 0-1000 kW/m: Prescribed burning may be difficult if insufficient wind, fires easily suppressed with direct attack;
- 1000-2000 kW/m: Prescribed burning with experienced crew (complex burns). Fires suppressed with effort. Direct attack;
- 2000-4000 kW/m: Prescribed burning difficult (high intensity burns). Fires suppressed with difficulty. Direct or parallel attack,;
- >4000 kW/m: Prescribed burning not recommended. Fires quickly become unsuppressable. Parallel or indirect attack. Asset protection.

2.6.7 Consequence based transitions

Kilinc *et al.* (2013) found that fireline intensity (by way of a fractional loss model) provided a useful measure for predicting likelihood of community loss. The model developed can be adjusted for settlement type, vegetation class and intensity. To confirm the most appropriate transition points that mark significant differences in potential consequences, Dr Wendy Anderson was kind enough to re-analyse some of the data used in the development of the scale for determining the destructive potential of bushfires (Kilinc *et al.*, 2013). Specifically, Dr Anderson was able to confirm the significance in usage of fireline intensity as a threshold (based on a correlation coefficient) but also provide statistical comparisons testing different thresholds to determine which fireline intensity value would lead to significant differences in potential percent house losses (Figures 2.8-2.10 and Table 2.17). The data used was sourced from 337 fires, including forests, grasslands and mixed vegetation types and was derived from bushfire case studies, reports, aerial imagery (photography and line scans), and newspaper articles with many of the fires occurring prior to the 1980s. A large portion of the dataset used had come from Victoria and Western Australia and this was mostly because of the relatively high frequency of fires occurring in these states, and the fact that many fires had well documented supporting information. It's important to note that Dr Anderson used a heat content of 18,600 kJ/kg in calculations of fireline intensity (Byram, 1959) and that where applicable, the canopy fuel load was included in calculations. An outlier (identified as the Kilmore East fire), was removed from calculations.

Dr Anderson looked at Figure 4.9 in the Kilinc *et al.* (2013) report which suggests a change in slope at an intensity of 50 MW/m on a logarithmic scale. On a linear scale no such cut off is apparent (Figure 2.9).

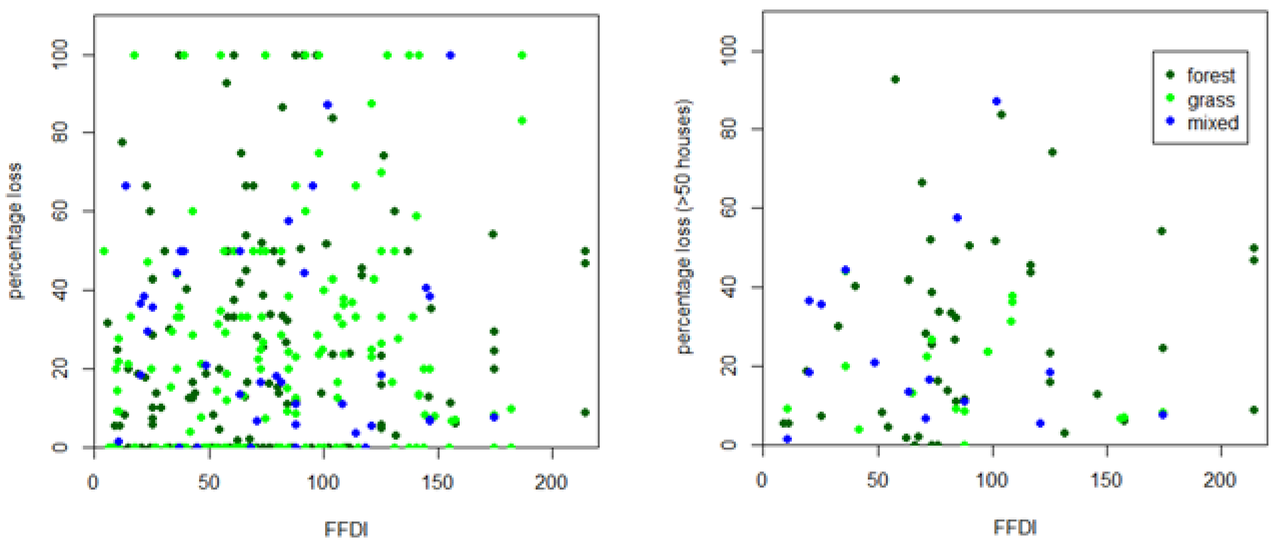

Figure 2.8 (Left) Percentage loss versus FFDI based fire danger rating for all house losses and (Right) for >50 house losses.

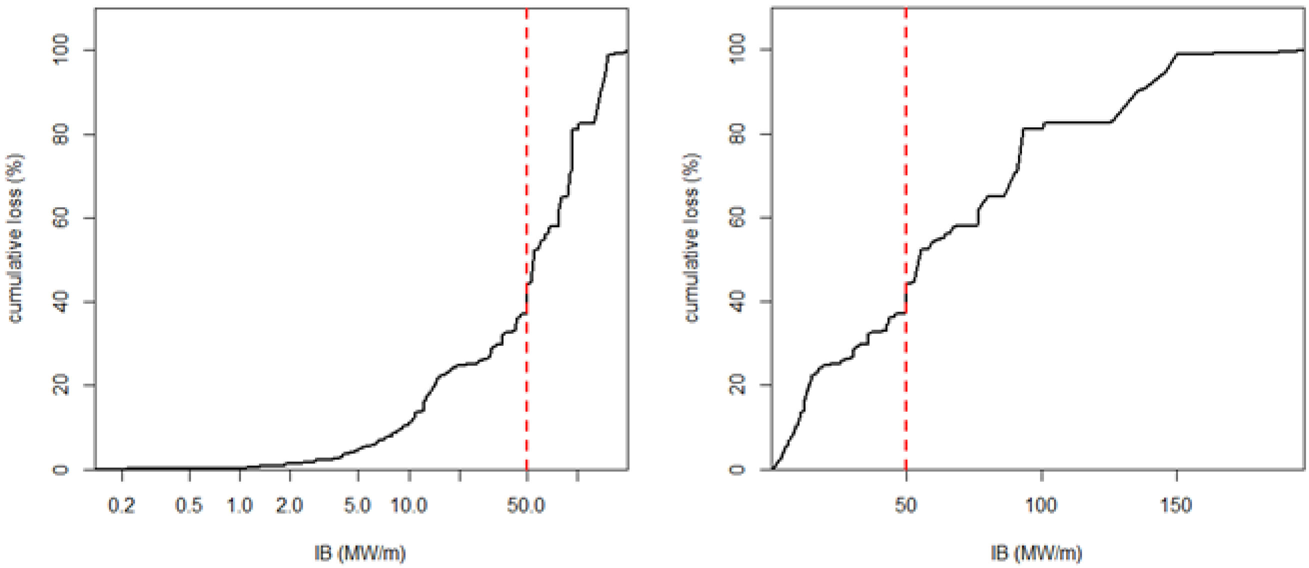

Figure 2.9 Comparisons in cumulative loss (%) of the 50,000 kW/m value on both logarithmic (left) and linear (right) scales.

The correlation between house loss and fireline intensity was 0.34. Note that below 49 MW/m the maximum loss was 124. The problem here is that loss is so dependent on the number of houses exposed. Percentage loss was calculated as: Percentage loss = 100*loss/number of houses exposed. For the percentage loss, the correlation was 0.31. One problem here is that loss of 2 houses out of 2 exposed isn't as significant as loss of 50 houses out of 50 exposed. By restricting to a greater number of houses exposed we get less apparent scatter but lose 2 influential points at the higher intensities.

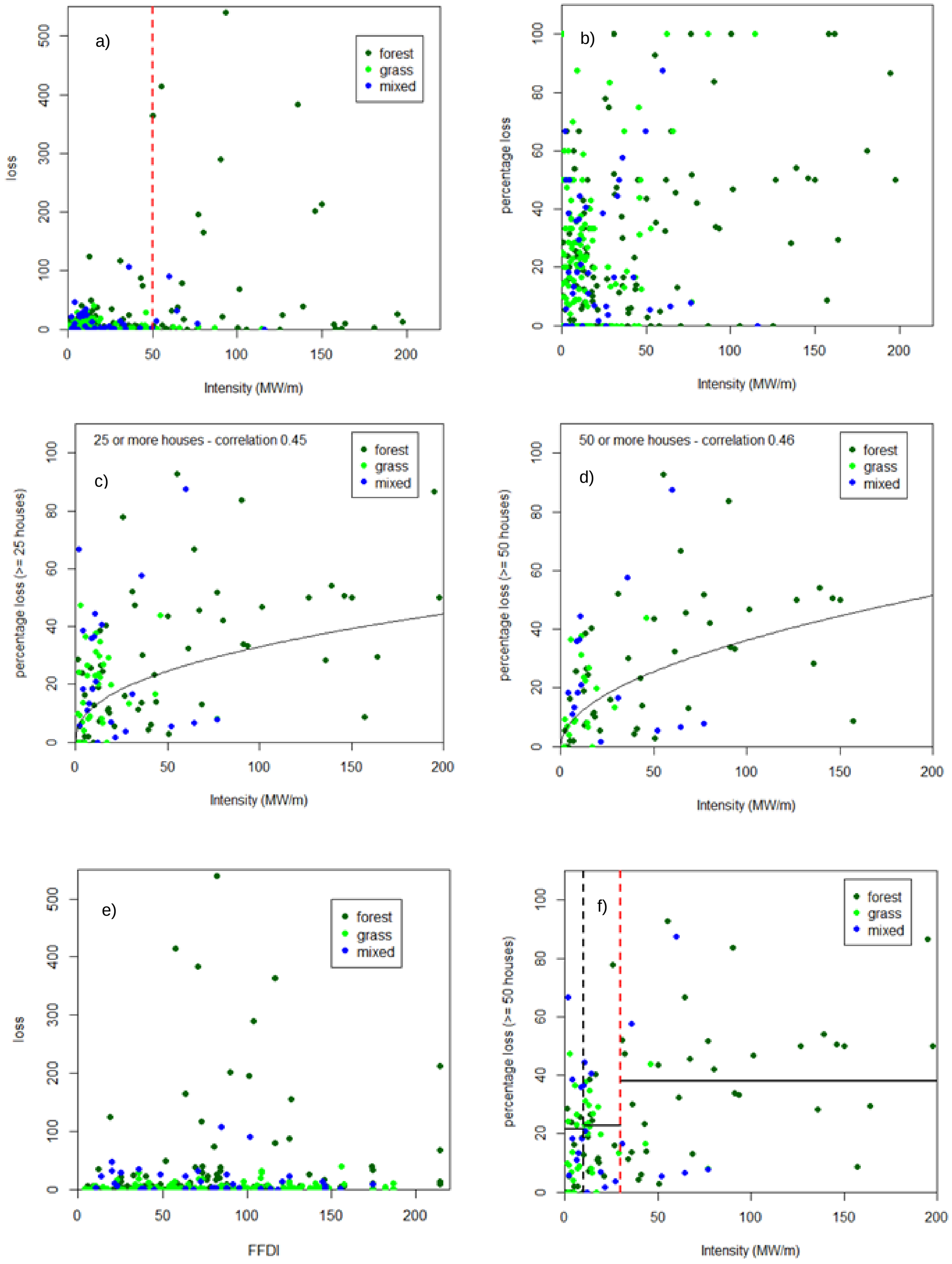

Figure 2.10 a) loss versus fireline intensity b) percentage loss versus fireline intensity c) percentage loss versus fireline intensity (>= 25 houses) d) percentage loss versus fireline intensity (>= 50 houses) e) Loss versus FFDI based fire danger rating and f) percentage loss (> 50 houses) showing the cut-offs of 10 and 30 MW/m with means in the 3 categories. Means and standard deviations for top cut offs of 30, 40 and 50 MW/m are tabulated next.

Dr Anderson's work found that the most significant points were identified as those with a fireline intensity of 10,000 kW/m and 30,000 kW/m and these should provide a suitable starting point from which to base the consequence based fireline intensity thresholds required at the upper end of the fire danger scale.

Table 2.17 Comparison statistics exploring different fireline intensity thresholds.

	means			standard deviations		
	0-10	10-cutoff	>cutoff (number of points)	0-10	10-cutoff	>cutoff
Forest and Grass combined						
30 MW/m	14.2	21.6	37.1	15.2	16.0	25.5
40 MW/m	14.2	22.9	39.1	15.2	16.9	26.4
50 MW/m	14.2	23.1	42.3	15.2	16.7	27.4
Forest only						
30 MW/m	8.4	22.8	39.8	10.7	20.1	24.3
40 MW/m	8.4	23.9	42.8	10.7	19.5	24.5
50 MW/m	8.4	23.6	46.7	10.7	18.7	24.0
Grass only						
30 MW/m	14.1	21.8	22.9 (3)	13.7	10.8	18.7
40 MW/m	14.1	21.8	22.9 (3)	13.7	10.8	18.7
50 MW/m	14.1	22.8	8.2 (1)	13.7	11.5	NA

We established the points of transition that would signal the difference between each fire danger rating category and from these points, the number of NFDRS categories were determined. Once transition points were identified we endeavoured to put a value on the threshold that would signal the change based on a combination of best available science and/or widely agreed value. In the absence of any science based or agreed values, estimates were made in the hope that by testing these points during the live trial evaluation period we might identify incorrect values, and also identify where further work is needed to establish something more concrete. The points of transition, their value and the supporting information for each value are outlined for each fuel type in Table 2.18 below.

Table 2.18 Points of transition, transition value and supporting information identified for each fuel type to signal the difference between NFDRS categories.

1	2	3	4	5
***Forest* – thresholds using fireline intensity**				
The point at which a fire becomes self-sustaining (below which a fire is likely to self-extinguish).	Upper limit for recommended prescribed burn conditions, above which short distance spotting is increasingly likely.	Upper limit for effective 'offensive' fire management strategies above which 'defensive' strategies are increasingly applied. Transition to increased likelihood of medium distance spotting. Upper limit of effective use of aerial suppression to directly control a fire.	Increased likelihood of community loss and significant consequences. Transition to increased likelihood of long distance spotting. Upper limit of effective use of aerial suppression to hold a fire.	Increased likelihood of community loss and significant consequences.
100 kW/m	750 kW/m	4,000 kW/m	10,000 kW/m	30,000 kW/m
Estimated, looking at various experimental burns that weren't self sustaining.	750 kW/m maximum intensity recommended for burning Silvertop Ash Forests (Cheney *et al.*, 1992). At approximately 1200 kW/m, initial attack is likely to be successful whereby fires did not increase by a factor of three and was contained using 'usual' resource availability and within the first eight hours after initial attack (McCarthy and Tolhurst, 1998).	4,000 kW/m is the widely agreed threshold for 'offensive' suppression strategies (Country Fire Authority, 2005; NSW Rural Fire Service, 2005; Smith, 2009: citing Muller 2008). Transition point recommended for CFA (Victoria) by Al Beaver (unpublished research). Above 4,000 kW/m aerial suppression resources are likely to be ineffective at directly controlling a fireline (Hirsch and Martell, 1996; Wotton *et al.*, 2017).	Above 10,000 kW/m aerial resources will not be effective at holding fire (Hirsch and Martell, 1996; Wotton *et al.*, 2017). At approximately 11,000 kW/m, first attack is likely to be unsuccessful whereby fires are likely to increase by more than a factor of three and containment is not possible within 24 hrs (McCarthy and Tolhurst, 1998). Transition point recommended for CFA (Victoria) by Al Beaver (unpublished research).	Relationship between community loss and fireline intensity (see above notes from Wendy Anderson and Kilinc *et al.* (2013).

		At approximately 4,000 kW/m (3836kW/m), extended first attack is likely to be successful whereby fires are likely to be controlled at a reasonable size (< 400 ha) and in a relatively short amount of time (< 24 hrs) (McCarthy and Tolhurst, 1998). Transition point recommended for CFA (Victoria) based on research conducted by Al Beaver (unpublished research). As fireline intensity increases above 2,000 kW/m up to 4,000 kW/m offensive aerial suppression strategies are likely to decrease in their effectiveness at holding a fire, particularly if unsupported effectively by ground crews, but are still likely to impact fire progression and development Loane and Gould (1986).	Relationship between community loss and fireline intensity (see above notes from Wendy Anderson and Kilinc et al. (2013).	

1	2	3	4	5
***Grassland*– thresholds using fireline intensity**				
The point at which a fire becomes self-sustaining (below which a fire is likely to self-extinguish).	Upper limit for recommended prescribed burn conditions.	Upper limit for effective 'offensive' fire management strategies above which 'defensive' strategies are increasingly applied.	Increased likelihood of community loss and significant consequences.	Increased likelihood of community loss and significant consequences.
50 kW/m	2,000 kW/m	8,000 kW/m	15,000 kW/m	25,000 kW/m
Estimated.	In the absence of trees, fires are unlikely (approx. 29%) to breach a small (3m) firebreak under 2,000kW/m (Wilson, 1988). This likelihood is even less (5%) for firebreaks > 5 m.	Estimated. In the absence of trees, fires are approx. 88% and 98% likely to breach a small (3m) firebreak for fires over 5,000kW/m and 10,000kW/m respectively (Wilson, 1988).	Estimated. Relationship between community loss and fireline intensity (see above notes from Wendy Anderson and Kilinc *et al.* (2013).	Relationship between community loss and fireline intensity (see above notes from Wendy Anderson and Kilinc *et al.* (2013).

1	2	3	4	5
***Spinifex*– thresholds using Spread Index**				
The point at which a fire becomes self-sustaining (below which a fire is likely to self-extinguish).	Upper limit for recommended prescribed burn conditions.	Upper limit for containment within established road networks and fuel breaks without the need for additional suppression. Above which fires tend to be damaging and active suppression may be required when in close proximity to assets.		
0	2	10		
Based on the Spread Index threshold below which fire is 'unlikely to spread' (Spread Index ≤ 0) from Burrows *et al.* (2018).	Based on approximations by Neil Burrows and an approx. 2,500 m/hr max ROS for prescribed burning (Pers. Comm. Ryan Butler).	Based on approximations by Neil Burrows. Damaging wildfires with potential to threaten life, structural assets and conservation/cultural assets (Burrows and Butler, 2013).		

1	2	3	4	5
***Pine* – thresholds using fireline intensity**				
The point at which a fire becomes self-sustaining (below which a fire is likely to self-extinguish).	Upper limit for recommended prescribed burn conditions, above which short distance spotting is increasingly likely.	Upper limit for effective 'offensive' fire management strategies above which 'defensive' strategies are increasingly applied. Transition to increased likelihood of medium distance spotting. Upper limit of effective use of aerial suppression to directly control a fire.	Increased likelihood of community loss and significant consequences. Transition to increased likelihood of long distance spotting. Upper limit of effective use of aerial suppression to hold a fire.	Increased likelihood of community loss and significant consequences.
100 kW/m	750 kW/m	4,000 kW/m	10,000 kW/m	30,000 kW/m
Estimated based on the 'Forest' threshold.	Estimated based on the 'Forest' threshold. PPPY surface fires 6-600 m/hr (Cruz *et al.*, 2008). 750 kW/m maximum intensity recommended for burning Silvertop Ash Forests (Cheney *et al.*, 1992).	Estimated based on the 'Forest' threshold. PPPY onset of crowning (Cruz *et al.*, 2008).	Estimated based on the 'Forest' threshold.	Estimated based on the 'Forest' threshold.

1	2	3	4	5
***Savanna*– thresholds using fireline intensity**				
The point at which a fire becomes self-sustaining (below which a fire is likely to self-extinguish).	Upper limit for recommended prescribed burn conditions.	Upper limit for containment within established road networks and fuel breaks without the need for additional suppression. Above which fires tend to be damaging and active suppression may be required when in close proximity to assets.		
100 kW/m	4,000 kW/m	20,000 kW/m		
Fireline intensity <100 kW/m for self-extinguishing fires (Department of National Parks, 2012: adapted from Edwards, A 2009 - Bushfire CRC).	Maximum intensity recommended for burning grasslands is 2,000 kW/m (Department of Parks and Wildlife, 2013). Fireline intensity should be within 100-10,000 kW/m (Department of National Parks, 2012: adapted from Edwards, A 2009 - Bushfire CRC). Fires > 2,000 kW/m create a mosaic of burnt and unburnt patches (Tropical Savannas CRC, 2001) together with the prescribed burn implications from Allan *et al.* (2003). A head fire intensity of 2,000 kW/m seems a little low (Pers.Comm. Trevor Howard & Lachie McCaw, DBCA WA, 2017). When trees are present, fires are unlikely (approx. 35%) to breach a 10 m firebreak under 5,000kW/m (Wilson, 1988).	Scorch & Leaf char height based on curve from Tropical Savannas CRC (2001) with fires > 2,000 kW/m typically burn all available fuel. Conditions >2,000 kW/m best suited for controlling woody plants (Tropical Savannas CRC, 2001). Prescribed burn implications from Allan *et al.* (2003).		

1	2	3	4	5
***Mallee-heath*– thresholds using probabilities determined by Cruz *et al.* (2010)**				
The point at which a fire becomes self-sustaining (below which a fire is likely to self-extinguish).	Surface fires start becoming influenced by intermittent crowning but largely contained within road networks and fuel breaks. Upper limit for recommended prescribed burn conditions.	Fires transition to active crown fires often requiring active suppression around assets with insufficient breaks.	Active crown fires with the potential to be damaging with high levels of threat when in close proximity to people and assets.	
Self-sustained surface fire probability is 50%.	Surface fire propagation probability is 50% and crown fire occurrence probability is 33%.	Crown fire occurrence probability is 66%.	Crown fire occurrence is 100%	
Likelihood of sustained propagation threshold is 50% (Cruz *et al.*, 2015b) below which, fire is unlikely to self-sustain.	Likelihood of crown fire propagation is 33% (Cruz *et al.*, 2015b).	Likelihood of crown fire propagation is 66% (Cruz *et al.*, 2015b).	Crown fire propagation is a certain likelihood (Cruz *et al.*, 2015b).	

1	2	3	4	5
***Shrubland*– thresholds using fireline intensity**				
The point at which a fire becomes self-sustaining (below which a fire is likely to self-extinguish).	Upper limit for recommended prescribed burn conditions, above which fires tend to crown intermittently and active suppression may be required.	Fires transition to active crown fires quickly, often requiring active suppression but mostly contained by established road networks and fuel breaks.	Fires transition to active crown fires quickly, with potentially damaging consequences and requiring wide fuel breaks.	
50 kW/m	500 kW/m	4,000 kW/m	20,000 kW/m	
Estimated.	Prescribed burn conditions based on scrubrolled fuel (Pers. Comm Ryan Butler, 2017).	Estimated.	Estimated.	
***Buttongrass*– thresholds using rate of spread as per Marsden-Smedley *et al.* (1999a)**				
NFDRS Research Prototype points of transition for Buttongrass fuels are based entirely on the thresholds specified by Marsden-Smedley *et al.* (1999a), with no exceptions.				
30 m/hr	450 m/hr	1,020 m/hr	2040 m/hr	4,200 m/hr

Once the transition points and categories were identified for each of the 8 fuel types, we sought to determine what characteristics identified and described them in terms of the following four descriptive categories that are deemed important components for managing fire danger in Australia (outlined in detail in section 2.8 below):

- Suppression difficulty and strategy,
- Fire behaviour and fire weather,
- Prescribed burning opportunities and
- Consequences - rate of fire growth, potential house losses, time to containment, final fire size.

2.7 Development of the Fire Danger Rating Tables

Fire Danger Rating Tables were developed in consultation with fire practitioners and the fire science community to provide a well-defined categorisation of potential fire danger. Through discussions, workshops and consultation it was identified that each Fire Danger Rating category could be defined in terms of four subject areas that are deemed important components for managing fire danger in Australia: fire suppression and containment; fire weather and fire behaviour; prescribed burning; and consequences.

2.7.1 Fire suppression and containment

A description of suppression difficulty and suggested measures of control have been associated with fire danger rating in Australia since early systems were developed in the 1930s and 40s (Gisborne, 1933; Wallace, 1936; Cromer, 1946; Douglas, 1957). The descriptions of suppression difficulty developed by Douglas (1957) are presented in Tables 2.19-2.21 below. Many fire and land management agencies still include similar descriptors within their training manuals and fire danger publications (e.g. AEMC - National Bushfire Warnings Taskforce (2009); Smith (2009); NSW Rural Fire Service (2014); Department of Parks and Wildlife (2016)) and some of these were presented earlier in Tables 2.5-2.9. Development of fire danger ratings for grassland included categories delineated by difficulty of suppression and rate of spread in annual and perennial pastures that carry a continuous fuel and occur on level to undulating ground (Cheney *et al.* (1990) after McArthur (1966); Table 2.25).

Descriptions of suppression difficulty are important to fire managers in assessing fire danger as they are largely indicative of the size and damage potential as well as the work force, or effort needed to contain and mop-up a fire based on its behaviour and persistence (McArthur, 1958; Merrill and Alexander, 1987; Alexander, 2008). Alexander (2008) notes that the fireline intensity, rate of perimeter increase or growth, spotting characteristics and the development of fire whirls determine the difficulty of controlling a fire.

Hodgson (1968) provided two examples aligning fireline intensity with suppression difficulty: (1) a fire burning with an intensity of about 500 BTU/sec/ft (1730 kW/m) will be difficult but not impossible to control; (2) a fire with an intensity of about 2000 BTU/sec/ft (6920 kW/m) will do severe damage and while at that intensity will be impossible to control.

In Workshop 1 (for operational staff) most participants broadly agreed that the current categories describing suppression difficulty reflected current practice in their agency/department with minor, technical suggestions for each category to better reflect current suppression strategies or more appropriately describe local practices. Several participants recommended incorporating aircraft support within operational strategy descriptions as well as reference to initial (or 'first') attack strategies. One participant commented that the suppression component of the FDR should aim to provide a 'suppressability' measure, by taking into account likelihood of ignition, likelihood of initial attack success, extent and duration of campaign fires, likely resource requirements and implications of likely spotting. Another participant noted that consideration should generally be given to a number of factors (not just FDR) when developing operational/suppression strategies including weather outlook, terrain, resource availability (particularly aviation support), accessibility, fire size, cost-effectiveness and on-ground decisions on strength and feasibility of success.

Descriptions of suppression interpretation are also linked to fire danger and fire behaviour within the United States, for example Werth *et al.* (2011) adapted the work of Burgan (1979) to produce a table of fire suppression interpretations based on flame length and fireline intensity (see Table 2.22).

For the development of the Fire Danger Rating Tables (Tables 2.31-2.38) we aimed to capture common themes, language and strategies used to describe fire containment, suppression and potential difficulties observed with fire danger rating across Australian fire management agencies (Tables 2.22-2.30). We also considered that important messages about firefighter safety could be included within the description of fire suppression and containment. Descriptors of fire containment and suppression were aimed at providing sufficient information to aid preparation and readiness setting, but to also be general enough not to limit operational application of possible containment (or delayed containment) strategies.

A short description of approximate, recommended firebreak width was included in descriptions based on the relationships with fireline intensity established by Wilson (1988) in grasslands of the Northern Territory.

Table 2.19 Five classes of difficulty of suppression and type of fire as established by Douglas (1957).

Class		Type of fire
A	Very easy	Creeping and slowly running fire
B	Fairly easy	Running fires (grass, litter or scrub undergrowth)
C	Moderately difficult	Running fires, isolated crowning of rough barked trees
D	Difficult	Grass fires very rapid. Intermittent crown fires in scrub and pines, spotting common.
E	Very difficult, sometimes impossible	Crown fires in pines and scrub. Frequent and continual spotting. Grass fires at times spread so rapidly that powered tankers have difficulty operating effectively.

Table 2.20 Suppression difficulty relationship with fire hazard as established by Douglas (1957) for Pines and Eucalypt Scrub rated against the five classes of suppression difficulty presented in Table 2.19 above.

Fire Hazard	Wind velocity (M.P.H.) Within 15 min. to 20 min. of Start of Fire					
	Calm 0-3	Light 4-7	Gentle 8-12	Moderate 13-18	Fresh 19-24	Strong 25+
10	C	D	D	E	E	E
9	C	D	D	E	E	E
8	B	C	D	D	E	E
7	B	C	C	D	D	E
6	B	B	C	C	D	D
5	A	B	C	C	C	D
4	A	B	B	C	C	C
3	A	A	B	B	C	C
2	A	A	B	B	B	B
1	A	A	A	B	B	B

Table 2.21 Suppression difficulty relationship with fire hazard as established by Douglas (1957) for Grass (dry or less than 20% green).

Fire Hazard	Wind velocity (M.P.H.) Within 15 min. to 20 min. of Start of Fire					
	Calm 0-3	Light 4-7	Gentle 8-12	Moderate 13-18	Fresh 19-24	Strong 25+
10	B	C	D	E	E	E
9	B	C	D	D	E	E
8	B	B	C	D	D	E
7	B	B	C	C	D	D
6	B	B	B	C	C	D
5	A	B	B	C	C	C
4	A	B	B	B	C	C
3	A	A	B	B	B	C
2	A	A	B	B	B	B
1	A	A	A	B	B	B

N.B. Grass 25-45% green, reduce by one class. Grass 50-70% green, reduce by two classes. Grass 75-100% green, reduce by three classes.

Table 2.22 Fire suppression interpretations based on flame length and fireline intensity from Werth *et al.* (2011) and Burgan (1979).

Flame length (m)[a]	Fireline intensity (kW/m)	Fire suppression interpretations
<1.2	<346	Fire can generally be attacked at the head or flanks by persons using hand tools. Handline should hold fire.
1.2-2.4	346-1730	Fires are too intense for direct attack on the head by persons using hand tools. Handline cannot be relied on to hold fire. Equipment such as plows, dozers, pumpers, and retardant aircraft can be effective.
2.4-3.4	1730-3459	Fires may present serious control problems: torching out, crowning, and spotting. Control efforts ate the fire head will probably be ineffective.
>3.4	>3459	Crowning, spotting, and major fire runs are probable. Control efforts at head of fire are ineffective.

[a] based on Byrams' (1959) flame length and fireline intensity relationship

Table 2.23 Fire suppression interpretation of fireline intensity/flame length from Burgan (1979).

Fireline intensity (BTU/sec/ft)	Flame length (ft)	Interpretation
< 100	<4	- fires can generally be attacked at the head or flanks by persons using hand tools - Handline should hold the fire
100 – 500	4 - 8	- fires are too intense for direct attack on head by persons using hand tools - handline cannot be relied on to hold fire - equipment such as dozers, pumpers, and retardant aircraft can be effective - fires are potentially dangerous to personnel and equipment
500 – 1000	8 – 11	- fires may present serious control problems i.e. torching out, crowning and spotting - control efforts at the fire head will probably be ineffective
>1000	>11	- crowning, spotting, and major fire runs are probable - control efforts at head of fire an ineffective

Table 2.24 Fire danger classification for annual grasslands from McArthur (1960).

Fire Danger Class	Fire Danger Index	Fire behaviour and organisational details
Low	0-6	The chances of a fire starting are slight and rate of spread will not exceed 90 chains per hour. Fires are easy to control and the burnt area should not exceed 20-50 acres. No manning details.
Moderate	7-12	The chances of a fire starting increase. Rate of forward progress will vary from 90-200 chains per hour. Fires are relatively easy to control and the area burnt should not exceed 300 acres. Primary lookouts manned. Regular suppression forces available for fires as reported.
High	13-24	Several fires may occur during the day, generally in the afternoon. Rate of forward progress will vary from 160 c.p.h. at low winds to 400 c.p.h at gale force. Fires are relatively hard to control and the burnt area may exceed 1000 acres. All look-outs manned. Suppression forces available for immediate action on fires as reported.
Very High	25-50	Multiple fire outbreaks may occur and can start from 10 a.m. onwards. Rate of forward progress may vary from 280-750 chains per hour and control will be very difficult, necessitating rapid mobilisation or outside suppression forces and mechanical equipment. The burnt area may be as high as 30,000 acres unless suppression action is very efficient. Entire protection force ready for immediate action, patrols on duty, all lookouts manned. Gangs on standby. Total prohibition of the lighting of fires recommended for forecast of Very High or greater.
Extreme	51-75	Emergency conditions. Multiple fire outbreaks are certain in the district and may start from 8 a.m. onwards. Rate of forward progress will vary from 440-940 chains per hour. Control of the headfire is extremely difficult until conditions change. Rapid mobilisation of outside forces for suppression action essential. Work can be carried out efficiently on flanks with head allowed to run until conditions change. The use of backburning under extreme conditions is seldom successful. Burnt area should not exceed 60,000 acres.

Fire Danger Class	Fire Danger Index	Fire behaviour and organisational details
Explosive	76-100	Fires will start and spread rapidly from sunrise onwards and control of the headfire is virtually impossible. If flanks are worked efficiently, burnt area can be kept to within reasonable limits. Burnt area may vary from 100,000 acres to over 500,000 acres unless initial attack is extremely fast and energetic.

Table 2.25 Grassland fire danger classes, rate of spread and difficulty of suppression in annual and perennial pastures that carry a continuous fuel and occur on level to undulating ground from Cheney *et al.* (1990) after McArthur (1966).

Fire Danger Class	Fire Danger Index	ROS at Max FDI in Class (km/hr)	Difficulty of Suppression
Low	0-2.5	0.3	Low: Headfire stopped by roads and tracks
Moderate	3-7.5	1	Moderate: Headfire easily attacked with water
High	8-20	2.6	High: Head attack generally successful with water
Very High	20.5-50	6.4	Very High: Head attack may fail except under favourable circumstances and back burning close to the head may be necessary
Extreme	50.5-100	12.8	Direct attack will generally fail – backburns difficult to hold because of blown embers. Flanks must be held at all costs

Table 2.26 Relationship of surface fire flame length and fireline intensity to suppression interpretations by Andrews and Rothermel (1982b) and Andrews *et al.* (2011).

Flame length		Fireline intensity		Interpretation
(ft)	(m)	(Btu/ft/s)	(kJ/m/s)	
< 4	< 1.2	< 100	< 350	Fires can generally be attacked at the head or flanks by persons using hand tools. Hand line should hold fire.
4-8	1.2-2.4	100-500	350-1,700	Fires are too intense for direct attack on the head by persons using hand tools. Hand line cannot be relied on to hold the fire. Equipment such as dozers, pumpers, and retardant aircraft can be effective.
8-11	2.4-3.4	500-1000	1,700-3,500	Fire may present serious control problems – torching out, crowning, and spotting. Control efforts at the fire head will probably be ineffective.
> 11	> 3.4	> 1000	> 3,500	Crowning, spotting, and major fire runs are probable. Control efforts at head of fire are ineffective.

Table 2.27 Selected fire suppression interpretations for Canada (Hirsch and Martell, 1996).

Deeming *et al.* (1977)			(Andrews and Rothermel, 1982b) and (Rothermel, 1983)		
Fireline intensity (Bti/s/ft) [kW/m]	Flame length (ft) [m]	Narrative	Fireline intensity (Bti/s/ft) [kW/m]	Flame length (ft) [m]	Interpretation
0-50 [0-173]	2.8 [0.9]	Most prescribed burns are conducted in this range	<100 [<346]	<4 [<1.2]	Fire can generally be attacked at the head or flanks by persons using handtools. Handline should hold the fire.
100 [346]	3.8 [1.2]	Generally represents the limit of control for manual attack methods.	100-500 [346-1730]	4-8 [1.2-2.4]	Fires are too intense for direct attack on the head by persons using handtools. Handline cannot be relied on to hold fire. Equipment such as plows, dozers, pumpers, and retardant aircraft can be effective.
500 [1730]	7.8 [2.4]	The prospects for control by any means are poor above this intensity	500-1000 [1730-3460]	8-11 [2.4-3.4]	Fires may present serious control problems - torching out, crowning, and spotting. Control efforts at fire head will probably be ineffective.
700 [2422]	9.2 [2.8]	The heat load on people within 30 feet of the fire is dangerous.			
1000 [3460]	10.8 [3.3]	Above this intensity, spotting, fire whirls, and crowning should be expected	>1000 [>3460]	>11 [>3.4]	Crowning, spotting, and major fire runs are probable. Control efforts at head of fire are ineffective.

Table 2.28 Fire suppression interpretations for two Canadian fuel types from Hirsch and Martell (1996)

Mature Jack or Lodgepole Pine[a]			Spruce-Lichen Woodland[b]	
Frontal fire intensity (kW/m) [Btu/ft/s]	Flame length (m) [ft]	Type of fire and suppression difficulty	Frontal fire intensity (kW/m) [Btu/ft/s]	Fire suppression interpretations
<10 [<3]	<0.2 [<0.7]	Firebrands that cause an ignition to occur are self-extinguishing (i.e. fire fails to spread). Going fires remain of the smouldering ground or subsurface variety, provided	<500 [<145]	Direct attack at fire's head or flanks by firefighters with hand tools and backpack pumps possible. 'Light' helicopters with helibucket also effective. Constructed fireguard should hold.

		there is a forest floor layer of significant depth and a general level of dryness*. Extensive mop-up is generally required. *Drought Code >300 and or Buildup Index >40.		
10-500 {3-145]	0.2-1.4 [0.7-4.6]	Creeping or gentle surface fire. Direct manual attack at fire's head or flanks by firefighters with had tools and water is possible. Constructed fireguard should hold.		
500-2,000 [145-578]	1.4-2.6 [4.6-8.5]	Low vigor to moderately or highly vigorous surface fire. Hand-constructed fireguards likely to be challenged. Heavy equipment (bulldozers, pumpers, retardant aircraft, skimmers, helicopters with bucket) generally successful in controlling fire.	500-2,000 [145-578]	Hand-constructed fireguards likely to be challenged. Ground suppression crews with water under pressure (i.e. fire pumps and hose-lays) can work along with fire's flanks and possibly "hot spot" the head. Heavy equipment (e.g. 'medium' helicopter with helibucket, skimmer aircraft, or muskeg tanker) generally successful in controlling fire.
2,000-4,000 [578-1156]	2.6-3.5 [8.5-11.5]	Very vigorous or extremely intense surface fire. (torching common). Control efforts at fire's head may fail.	2,000-4,000 [578-1156]	Any attempt to contain the fire's head limited to the use of airtankers applying chemical fire retardants. Control efforts may fail.
>4,000 [>1156]	>3.5 [>11.5]	Intermittent crown fire to active crown fire development (at >10000kW/m)*. Very difficult to control. Suppression action must be restricted to fire's flanks. Indirect attack with aerial ignition (i.e. helitorch or A.I.D. dispenser) may be effective. *Violent physical behavior probable at frontal fire intensities greater than 30000 kW/m (i.e. blow-up or conflagration type fire run); suppression actions should not be attempted until burning conditions ameliorate.	4,000-10,000 [1156-2,890]	Suppression action must be restricted to back and flanks of the fire. All efforts at direct control of the fire likely to fail. Indirect attack with aerial ignition, if available, may be effective.
			>10,000 [>2,890]	Extreme fire behaviour. Fires present serious control problems. An escaped fire is a very distinct possibility. Suppression activities should be curtailed until burning conditions ameliorate.

[a] From Alexander and DeGroot (1988), [b] From Alexander *et al.* (1987)

Table 2.29 New Zealand fire danger classes, fireline intensity and minimum fire suppression resources for direct head fire attack from SCION Rural Fire Research Group (2008).

Fire Danger Class	Fire Intensity (kW/m)	Minimum fire suppression resources for direct head fire attack
Low	0-10	Ground crew with hand tools.
Moderate	10-500	Ground crew with back-pack pumps.
High	500-2,000	Water under pressure and heavy machinery.

Very High	2,000-4,000	Head fire attack using aircraft and long-term retardants may be effective, but it may be too dangerous for ground crews.
Extreme	>4,000	Head fire attack not likely to be effective, and it will be too dangerous for ground crews.

Caution: Flame heights at the fire's head will be greater than 2.5 metres. Under NO circumstances should direct attack be mounted on the head fire. Any containment action must begin from a secured anchor point and progress along the flanks toward the head as the fire edge or perimeter is "knocked down".

Table 2.30 A simple field guide for estimating the behaviour and suppression requirements of fires driven by wind coming from a constant direction, in open, fully cured grasslands at low fuel moisture (Source: Fogarty and Alexander (1999))

Beaufort Wind Force[a]	Forward spread distance/perimeter length/maximum breadth versus elapsed time since ignition (kilometres)				Head fire intensity (kW/m)	Head fire flame length (m)	Minimum firebreak width required to stop head fire[b] (m)	
	0.5 hour	1 hour	1.5 hours	2 hours			Trees absent	Trees present
0-1	0.7/2.4/0.4	1.3/4.9/0.7	2.0/7.3/1.1	2.6/9.8/1.4	2300	2.7	5	12
2	1.0/2.7/0.4	2.0/5.5/0.7	2.9/8.2/1.1	3.9/10.9/1.5	3450	3.3	6	13
3	1.6/3.7/0.4	3.2/7.4/0.8	4.8/11.1/1.2	6.3/14.8/1.6	5550	4.1	7	15
4	2.7/5.7/0.6	5.3/11.5/1.1	8.0/17.2/1.7	10.7/22.9/2.2	9350	5.2	8	30+
5	4.4/9.1/0.8	8.7/18.2/1.5	13.1/27.3/2.3	17.5/36.4/3.1	15,300	6.5	10	30+
6	6.1/12.5/1.0	12.2/25.0/1.9	18.2/37.5/2.9	24.3/50.0/3.8	21,300	7.6	12	30+
7	7.2/14.8/1.0	14.5/29.5/2.0	21.7/44.3/3.1	28.9/59.1/4.1	25,300	8.2	13	30+
8 & higher	7.5/15.2/1.0	15.0/30.5/2.1	22.5/45.7/3.1	30.0/60.9/4.1	26,200+	8.4+	14+	30+

[a] See reverse side for details on the Beaufort Wind Scale.

[b] The "Trees absent" and "Trees present" classes refer to the absence or presence of trees/scrub within 20 metres of the windward side of the firebreak. The presence of trees or scrub has a significant influence on firebreak effectiveness because they supply woody material for firebrands which can spot across the break.

2.7.2 Indicative fire behaviour and fire weather

Suppression difficulty is linked intrinsically with fire behaviour and persistence, with fire intensity and spotting potential being the primary fire behaviour factors influencing the ability of fire suppression resources to contain a fire (Merrill and Alexander, 1987; Alexander, 2008). As such, many training manuals and fire danger publications have categorised fire danger by fire behaviour, often described as flame height, rate of spread or fireline intensity or combinations of each (presented in Tables 2.2-2.9, 2.22-2.29). Australia's revised arrangements for bushfire advice and alerts (AEMC - National Bushfire Warnings Taskforce, 2009) also associated spotting potential and area growth with fire danger categories (Table 2.4).

At Workshop 1 (for operational staff) most participants broadly agreed with the break-up of fire behaviour categories and there were many technical suggestions relating to descriptors or fire behaviour to improve each category (e.g. descriptions of spotting distance, fuel moisture content, crowning behaviour, rate of spread, flame height and fire propagation). Participants generally found it more difficult (some hesitant) to align fire weather descriptors with the fire behaviour and suppression difficulty descriptors stating difficulties associated with such large variation in fire weather leading to variations in fire behaviour and being dependent on fuel type, arrangement and terrain. Those that attempted the exercise, aligned weather descriptors such as wind speed, C-Haines and descriptions of convective column formation and atmospheric stability, relative humidity, temperature, forecasted wind changes and overnight conditions.

We sought to provide descriptions of indicative fire behaviour for each of the FDR categories specific to each fuel type. We aimed to provide a general description as well as the fire behaviour variables currently used by fire practitioners around Australia (e.g. rate of spread, flame height, potential spotting; Tables 2.31-2.38) and applied established methodology to identify values for these variables, based on a range of fuel conditions. For example, we determined flame heights for forest fuels using the equation documented by Noble *et al.* (1980), while rates of spread were mostly back-calculated from fireline intensity (Byram, 1959) using a range for fuel load varying between 10-20 t/ha. Where possible, rates of spread and descriptions of fire behaviour were checked against documented examples and case study examples, particularly in fuel types where calculations were determined based on equations suited to other fuel types. For example, fire behaviour from the descriptions documented by Douglas (1964), the Forest Fire Management Group (2007) and the case studies from Douglas (1973) were used to cross-check descriptions of fire behaviour for pine fuels. The range in fuel load for each fuel type was estimated based on best available field data, together with a higher value representing highest average conditions. For each FDR Table the assumptions and methodology used for the fire behaviour descriptors are provided at the bottom of the table, so users can make an informed assessment of conditions in respect to these. It is important to note that these methods and assumptions can be modified for future usage of the FDR Tables, however, any modifications may have a subsequent impact on the thresholds that are applied between NFDRS categories.

2.7.3 Prescribed burn implications

One of the key messages and feedback from operational fire practitioners at Workshop 1 (for operational staff) was that including a category targeting prescribed burning conditions within the Fire Danger Rating would be helpful to identify typical, indicative burning conditions. This was provided that the Fire Danger Rating did not replace the need for practitioners to consult burn prescriptions and the appropriate fire spread model.

During the development of the FDR Tables (Tables 2.31-2.38) we sought to represent prescribed burning conditions in two ways. Firstly, because prescribed burn conditions are typically associated with fire behaviour mostly involving surface, near-surface, elevated and bark fuels, and which can be adequately contained with appropriate planning and sufficient resources, we aimed to capture prescribed burning conditions within one of the NFDRS categories (Category 2 on each FDR Table). This was done by identifying a lower limit, whereby conditions are unlikely to sustain sufficient fire activity and an upper limit where conditions are likely to make containment particularly difficult for each fuel type. We considered this category could potentially be used for general, safe burning purposes such as identifying suitable, safe conditions for public burning. The upper limit was particularly difficult to establish because of the variation between fuel types, but also because there is not a lot of clearly defined, established relationships with fireline intensity other than those described by Cheney (1978) and Cheney *et al.* (1992).

We also allocated a descriptive line within each FDR Table to specifically discuss the implications of conditions on prescribed burning. Because of the unique nature of prescribed burning within each fuel type, we addressed each independently with the aim of providing general, helpful descriptors, rather than rules or a replacement to using appropriate fire behaviour models or prescribed burn planning.

Practitioners at Workshop 1 suggested that it was not necessary to include a description of prescribed burning conditions in pine fuel types. This is likely because none of the workshop attendees were fire managers linked with management of plantations that are routinely subjected to prescribed fire (e.g. maritime pine in Western Australia and southern pines in Queensland). Given the lack of information available prescribed burning was not included within the Pine FDR Table (Table 2.34). However, we sought to capture typical prescribe burning conditions within Category 2, in a similar way to the other fuel types.

2.7.4 Consequences

One of the main limitations of the current McArthur FFDI and GFDI based fire danger ratings is that they are not adequately aligned to community loss or the destructiveness of a fire (Fogarty *et al.*, 2010; Harris *et al.*, 2012; Kilinc *et al.*, 2013). While the revisions to fire danger rating in 2009 have improved communications and particularly public warnings as they relate to the top, more dangerous end of the scale, scientific variables that underpin the fire danger rating were not reviewed or used to inform revisions the fire danger ratings. It was recognised as part of the review that an evaluation of the science driving the fire danger index was needed (AEMC - National Bushfire Warnings Taskforce, 2009).

Undoubtedly, meteorological conditions and fire danger are highly correlated with house and life loss as demonstrated by numerous studies of historical fire events around Australia. Some of these and their findings as they relate to fire danger are described below.

Harris *et al.* (2011); Harris *et al.* (2012) undertook a project to determine whether a link existed between energy release from a fire and community loss. The dataset used included 81 observations from wildfires predominantly from Victoria but also some other southern states. The research confirmed a relationship between the power of fire (a measure describing the energy release rate, dependant on the perimeter of the fire), fireline length and community loss (Harris *et al.*, 2012) however in the absence of knowing fire size, we were unable to directly apply the findings of the work to describe potential consequences against fire danger. Kilinc *et al.* (2013) however found that fireline intensity (by way of a fractional loss model) provided a useful measure for predicting likelihood of community loss, so in the absence of knowing fire size or perimeter, fireline intensity could be used to describe the potential consequences that characterise the fire danger categories.

Blanchi *et al.* (2010) and Blanchi *et al.* (2012) also established an important connection between fire weather, fire danger (particularly the FFDI) and life loss within a dataset consisting of 260 separate fire events since 1901. Blanchi *et al.* (2010) reported that FFDI and wind speed (as an isolated variable) provided the strongest indications of the potential for house loss. Blanchi *et al.* (2012) found fire events involving 5 or more deaths have historically occurred on days where the FFDI at 3pm was over 50 with particular weather thresholds (temperatures above 33°C, wind speeds above 24 km/hr and relative humidity below 16%). Importantly, Blanchi *et al.* (2012) recognised that there was a prominence of life loss associated with the time of a wind change as well proximity to forest fuel types, with over 78% of all fatalities occurring within 30 m of forest. Blanchi *et al.* (2012) also reported that 50% of all civilian fatalities occurred on days where the FFDI at 3pm exceeded 100 and 60% occurred on days that exceeded 40°C. Approximately 70% of all fatalities occurred on days where the relative humidity was below 10% at 3pm. While these weather and fire danger conditions described by Blanchi *et al.* (2010) and Blanchi *et al.* (2012) are indicative of potential fatalities, without direct links to fire behaviour variables (such as rate of spread, fireline intensity or flame height) it was difficult to apply these values or represent them numerically within the Research Prototype or use them to forecast potential consequences. This highlights a particular area where more work would be beneficial, possibly re-visiting these studies and expanding on work to see how it could be aligned with the fire danger rating based on models of forward rate of spread. In the mean time, we have sought to capture these findings in the context of life and house loss through descriptions within the consequence section of the FDR tables and in the case of life loss associated with wind changes, via the red flag warnings.

As noted by Cheney (1988), a large component of fire danger is dependent on the values at risk (such as human life and property). There have been numerous studies linking the influence of environmental circumstances, particularly terrain and spatial relationships on the wildland/urban interface (such as the distance to wildland vegetation) on house loss and fatalities (McArthur and Cheney, 1967; Ramsay *et al.*, 1987; Ahern and Chladil, 1999; Chen and McAneney, 2004; Leonard and Blanchi, 2005; Crompton *et al.*, 2010; Gibbons *et al.*, 2012; Newnham *et al.*, 2012). Some of the studies relate to post bushfire surveys and many establish excellent links with community loss, however as Blanchi *et al.* (2012) points out, most studies do not provide adequate descriptions of fire behaviour, certainly not in a way that would be sufficient to align with a fire behaviour based fire danger rating. Again, it may be beneficial to re-visit some of these studies to investigate data sources that could be used to develop descriptions or forecasts of the effect spatial relationships have on potential life and/or house loss that could be used for fire danger rating.

We were able however, to represent potential community loss in the Research Prototype, by using the fireline intensity relationships established by Wendy Anderson via the Harris *et al.* (2011); Harris *et al.* (2012) and Kilinc *et al.* (2013) datasets as described in section 2.7.7. For fuel types not represented within the datasets (e.g. spinifex, savanna), we aimed to extrapolate general descriptions of consequence in consultation with fire practitioners working within and familiar with the complexities of managing fire within those specific fuel types.

Fogarty *et al.* (2010) point out the relative difference in potential consequences between grass and forest fuel types, suggesting that based on historic precedent 'Catastrophic' grassland fires are unlikely to occur with the same degree of potential threat to life and property. The authors go on to suggest that significant alterations are needed (for example an appropriate level for the determination of Catastrophic conditions would be at a GFDI of at least 200). This highlights the importance of fuel specific fire danger rating approaches.

While each of the studies described above have important links to fire danger in terms of potential community impacts such as life and house loss, they fail to recognise the consequences of fire on natural assets such as biodiversity or threatened and vulnerable species. One way this could be incorporated into the fire danger rating would be through the spatial and categorical identification and valuation of assets at risk such as the Bushfire Threat Analysis project established by Muller (2001) and Department of Environment and Conservation (2010) which combined potential impacts on both infrastructure (including potential fatalities) as well as biodiversity conservation aspects into an index. This index could then be incorporated into the fire danger rating. While extending an index such as this across the extent of Australia presents a level of complexity that we were not able to address in the scope of the Research Prototype, it would be beneficial to investigate opportunities and possibilities to incorporate a fire impact or asset index like this in future developments.

The conditions under which a fire will burn contribute to the potential area and perimeter burnt which we have aimed to capture within the descriptions of consequence within the FDR Tables. To do this, we based the potential fire area and perimeter on a 4 hour fire run with no suppression, under the maximum potential for the FDR category, with a length to breadth ratio (L:B) best suited to the fuel type, wind speeds ranging from 10-40 km/hr (Cruz *et al.*, 2015b) and a variable fuel load as best identified for the fuel type. It's important to note that the potential fire area and perimeter are based on the maximum potential fireline intensity and rate of spread for the category and not the mean, so in many cases the estimates will greatly exaggerate observations of fire area and perimeter. McArthur (1966) tried to capture consequences in terms of fire area in a similar way within the Grassland Fire Danger Index by including the maximum burnt area at various times (1/2 hr, 1 hr, 2 hr and 4 hr) as well as the average final fire size. McArthur based the maximum burnt area on relationships established between wind velocity and the L:B ratio and the distance travelled. It is not known how the average final fire size was determined. Fogarty and Alexander (1999) also provided estimates of forward spread distance, perimeter length and maximum breadth versus four elapsed time periods (0.5 hr, 1 hr, 1.5 hr and 2 hr; Table 2.30) and the minimum firebreak required to stop head fire.

It may be beneficial to provide an estimate of elapsed-time based measures (such as of average fire area) within the FDR tables in a similar way. Alternatively, a description of the potential range of fire area may be helpful however consideration would need to be given to what conditions characterise the range (for example whether to include the effect of suppression). In the absence of appropriate data to support these calculations at this time, we have not included them.

Table 2.31 NFDRS Research Prototype Fire Danger Rating Table for Forest fuels. Version 1_2018.

Forest

	Category	1	2	3	4	5	6
	Relevance:	Mostly self-extinguishing, trouble-free fires	Typical prescribed burning conditions, fires generally easy to suppress	Most wildfires in this category. Fires typically suppressed with direct, parrallel or indirect attack	Initial attack success critical to prevent large fire development. Defensive suppression strategies.	Defensive suppression strategies. High levels of threat to life/property. Safety of firefighters & community paramount	Safety of firefighters and community most important. Without initial attack success, likelihood of very large fire development is very high. High probability of loss of life and property.
	Lower limit of fireline intensity (kW/m)	0	100	750	4,000	10,000	30,000
	Upper limit of fireline intensity (kW/m)	100	750	4,000	10,000	30,000	30,000+
Indicative fire behaviour & fire weather	Description	Fire difficult to ignite and sustain. Fires generally unlikely to spread and likely to self-extinguish.	Slow spreading fires, typically involving surface and near-surface fuels and sometimes bark and elevated fuels. Spotting is sporadic and limited to short-distances.	Actively spreading fires typically involving surface, near-surface, evelvated and bark fuel layers and occassionally canopy fuels. Low-moderate spotting frequency; isolated medium range spotting can occur.	Rapidly spreading fires with potential for development into large burn areas within burning period. Fires typically involving most fuel layers. Short-range spotting is prevalent, with possibilty of medium range and occacional long-range distance spotting	Fires likely to quickly trasition to crowning. Possibility for fire behaviour to become erratic and plume driven. Strong convective column formation. Wind speed and direction likely to be erratic at times.	Fires likely to quickly trasition to crowning. Possibility for fire behaviour to become erratic and plume driven. Strong convective column formation. Wind speed and direction likely to be erratic at times.
	ROS range:	0-40 m/hr	20-110 m/hr	60-600 m/hr	0.3-1 km/hr	0.7-3 km/hr	Rate of spread in excess of 2 km/hr can be expected and possibly >3 km/hr
	Max flame height range:	<1 m	<4 m	2-11 m	8-26 m	15 m - approx. double forest height	>40m (approx. double forest height)
	Spotting potential:	Potential for any spotting is very limited and likely <75 m	Potential for spotting is limited with short distance spotting possible up to 250 m	Short distance spotting occuring with increasing frequency with possible medium distance spotting up to 1.5 km	Short and medium distance spotting occuring with increasing frequency with possible long distance spotting up to 3.5 km	High ember density in short and medium range with possible long distance spotting up to 10 km	High ember density in short and medium range with possible long distance spotting occuring 20-30 km ahead of the main fire front
	Red flag warnings			*C-Haines >95th percentile (approx >10)* *Wind change forecast during the peak of the afternoon*	*C-Haines >95th percentile (approx >10)* *Wind change forecast during the peak of the afternoon*	*C-Haines >95th percentile (approx >10)* *Wind change forecast during the peak of the afternoon*	*C-Haines >95th percentile (approx >10)* *Wind change forecast during the peak of the afternoon*
Prescribed burn implications	*NB. Descriptions here are offered as a general guide and appropriate fire behaviour models should be consulted to achieve burn prescription outcomes.*	Marginal P/B conditions, even at peak of the day. Possible opprtunities may arise where burn objectives target very low intensity, particularly heavy or dry fuels.	Typical prescribed burning conditions. Simple burns with adequate resourcing. Upper limit for public burning provided adequate resourcing, training and necessary approvals.	P/B opportunities exist for complex burn plans and/or special purpose burns with adequate resourcing and well established boundaries/edges. Safe P/B conducted away from the peak of the day when conditions are optimal and lighting techniques are suitable to achieve P/B objectives.	Conditions are likely to be unsuitable for P/B. Potential fireline intensity and spotting activity pose a serious risk for burn escapes and fire intensity may be inconsistent with land management objectives.	Conditions will be unsuitable for P/B. Potential fireline intensity and spotting activity pose a serious risk to firefighter safety and the community.	Forget it!
	Red flag warnings			*Strong wind gusts forecast*	*Strong wind gusts forecast*		
Fire suppression & containment		Fire control relatively simple. Delayed containment possible with suitable conditions. Head-fire readily suppressed with offensive, direct attack techniques. Initial attack success is typically very high.	Fire control mostly simple with sufficent resources and becoming more complex at higher intensities. Offensive, direct attack techniques on head-fire or flanks largely successful in fire control. Delayed containment sometimes possible with suitable conditions.	Fires generally becoming more complex and require more resources to control. Combinations of direct, indirect or parrallel attack may be neccesary for fire control.	Both ground and aerial resources using offensive strategies likely to be unsuccessful during the peak of the day, with focus largely centered on defensive strategies. Fire control is likely to be difficult and require increased resourcing.	Fire control is extremely difficult and unlikely until conditions ease. Focus will be largely based on defensive strategies, ensuring firefighter and community preparedness and safety. Offensive strategies could position crews in danger. Conditions on the fireground are likely to be extremely windy and smokey so restrictions to visibility, aviation and access are possible. Aerial resources are likely to be ineffective at holding fire.	Fire control is extremely difficult and unlikely until conditions ease. Focus will be largely based on defensive strategies, ensuring firefighter and community preparedness and safety. Offensive strategies could position crews in danger. Conditions on the fireground are likely to be extremely windy and smokey so restrictions to, visibility aviation and access are likely. Aerial resources are likely to be ineffective at holding fire.
	Red flag warnings			*Wind change forecast - potential conditions for 'dead man zone'*	*Wind change forecast - potential conditions for 'dead man zone'*	*Wind change forecast - potential conditions for 'dead man zone'*	*Wind change forecast - potential conditions for 'dead man zone'*
Consequences	Community loss (life & house):				6 % of house loss[1]	24% of house loss[1]. Limited visibility due to smoke and dust. High risk to the community related to inappropriate pre-considered plans, inadequate sheltering[2].	70% of house loss[1]. Very limited visibility due to smoke and dust. Very high risk to the community related to inappropriate pre-considered plans, inadequate sheltering[2].
	Impact on infrastructure:					Strong winds are likely to impact infrastructure (e.g. power lines) and fall trees increasing the likelihood of obstructed roads and power outages.	Strong winds are very likely to impact infrastructure (e.g. power lines) and fall trees resulting in a high likelihood of obstructed roads and power outages.
	Firefighter safety:				Increased risk to firefighter safety	Increased risk to firefighter safety	Increased risk to firefighter safety
	Maximum potential fire area (without suppression):	Small fires that are likely <1.5 ha. Fires may be allowed to spread within an extended (time and area) containment objective.	Possible fires up to 20 ha. Fires may be allowed to spread within an extended (time and area) containment objective.	Possible fires up to 500 ha	Possible fires up to 3,000 ha	Large area fires up to 28,000 ha	Large area fires exceeding 7,000 ha and potentially >28,000 ha
	Maximum potential fire perimeter (without suppression):	<0.5 km	Possible fire perimeter up to 1.5 km	Possible fire perimeter up to 8 km	Possible fire perimeter up to 20 km	Large fire perimeters up to 60 km	Large fire perimeters exceeding 30 km and potentially >60 km

Assumptions and methodology

Flame heights are based on McArthur's equation for flame height (Noble, 1980)
Rates of Spread are back-calculated based on Byram's fireline intensity and a range of fuel load varying from 10-20 t/ha
Spotting distances are based on McArthur's spotting equation
Potential fire area and perimeter are based on a 4 hour fire run under max FDR with a range of LB ratio as determined by wind speeds ranging from 10-40 km/hr (as per Cruz et al 2015 (on the back page)) and a fuel load varying from 10-20 t/ha
The lowest (no. 1) category assumes that only 50% of the fuel load is available for burning, and this is represented in flame heights, rates of spread and potential fire size.
Categories 2 & 3 assume an additional 3 t/ha is available (contributed by bark & elevated layers), and categories 5 and 6 assume an additional 8 t/ha is available (contributed by bark, elevated and canopy fuel layers).
[1] Harris etal 2010 [2] Blanchi etal 2010

Table 2.32 NFDRS Research Prototype Fire Danger Rating Table for Grassland fuels. Version 1_2018.

Grassland

		1	2	3	4	5	6
	Category	1	2	3	4	5	6
	Relevance:	**Mostly self-extinguishing, trouble-free fires**	**Typical prescribed burning conditions, fires generally easily contained within simple road networks and fuel breaks.**	**Most wildfires in this category. Typically controlled within established road networks and fuel breaks together with using direct, indirect or parallel attack suppression strategies.**	**Fires generally escalate very quickly. Defensive suppression strategies.**	**Extremely rapid fire growth. Defensive suppression strategies. High levels of threat to life/property. Safety of firefighters & community paramount**	**Extremely rapid fire growth. Safety of firefighters and community most important. Without initial attack success, likelihood of large area fires and loss of life/property is very high.**
	Lower limit of fireline intensity (kW/m)	0	50	2,000	8,000	15,000	25,000
	Upper limit of fireline intensity (kW/m)	50	2,000	8,000	15,000	25,000	25,000+
Indicative fire behaviour & fire weather	Description	Fire difficult to ignite and sustain. Fires generally unlikely to spread and likely to self-extinguish.	Fire easily sustained. Typically wind driven fires that can spread quickly.	Typically wind driven and rapidly spreading fires with the potential to gain size quickly.	Wind driven, rapidly spreading fires with potential for development into large fire area/size and with the potential for short distance spotting and long flame lengths.	Extremely rapid fire growth and increasing likelihood of large final fire area/size. Possibility for fire behaviour to become erratic and plume driven. Strong convective column formation. Wind speed and direction likely to be erratic at times.	Extremely rapid fire growth and high likelihood of large final fire area/size. Possibility for fire behaviour to become erratic and plume driven. Strong convective column formation. Wind speed and direction likely to be erratic at times.
	ROS range:	0-30 m/hr	<1.3 km/hr	0.6-5 km/hr	2.5-10 km/hr	5-16 km/hr	Rate of spread in excess of 8 km/hr can be expected and possibly >16 km/hr
	Max flame height range:	<0.5 m	<1.5 m	1.5-2.5 m	2-3 m	2.5-3.5 m	flame heights >3 m and possibly >3.5 m
	Spotting potential:	Potential for any spotting is extremely limited	Potential for short distance spotting is limited	Possible short distance spotting occuring	Possible short distance spotting occuring with increasing frequency	Likely short distance spotting occuring with increasing frequency	Likely short distance spotting occuring with increasing frequency
	Red flag warnings			*C-Haines >95th percentile (approx >10)* *Wind change forecast during the peak of the afternoon*	*C-Haines >95th percentile (approx >10)* *Wind change forecast during the peak of the afternoon*	*C-Haines >95th percentile (approx >10)* *Wind change forecast during the peak of the afternoon*	*C-Haines >95th percentile (approx >10)* *Wind change forecast during the peak of the afternoon*
Prescribed burn implications	NB. Descriptions here are offered as a general guide and appropriate fire behaviour models should be consulted to achieve burn prescription outcomes.	Marginal P/B conditions, even at peak of the day.	Typical prescribed burning conditions. Simple burns with adequate resourcing. Upper limit for public burning provided adequate resourcing, training and necessary approvals.	P/B opportunities exist for complex burn plans with adequate resourcing and well established, wide boundaries/edges. Safe P/B conducted away from the peak of the day when conditions are optimal and lighting techniques are suitable to achieve P/B objectives.	Conditions are likely to be unsuitable for P/B. Potential rates of spread, long flame lengths and short distance spotting pose a serious risk of burn escapes and fire intensity may be inconsistent with land management objectives.	Conditions will be unsuitable for P/B. Potential fireline intensity and rates of spread pose a serious risk to firefighter safety and the community.	Forget it!
	Red flag warnings			*Strong wind gusts forecast*	*Strong wind gusts forecast*		
Fire suppression & containment		Fire control relatively simple. Delayed containment possible with suitable conditions. Head-fire readily suppressed with offensive, direct attack techniques. Initial attack success is typically very high.	Fire control mostly simple with sufficent resources and becoming more complex at higher intensities. Offensive, direct attack techniques on head-fire or flanks largely successful in fire control. 3 m wide fuel break is largely successful at holding fire where trees are absent. Delayed containment sometimes possible with suitable conditions.	Fires generally becoming more complex and require more resources to control. Combinations of direct, indirect or parrallel attack may be neccesary for fire control. Requires increased effort and resources to contain fire within existing road networks and fuel break boundaries. Increased likelihood that a 3 m break will be ineffective.	Offensive strategies likely to be unsuccessful during the peak of the day, with focus largely centered on defensive strategies. Fire control is likely to be difficult and require increased resourcing. Typically requires larger fuel breaks >10 m wide, together with increased resourcing and effort to contain.	Fire control is extremely difficult and unlikely until conditions ease. Focus will be largely based on defensive strategies, ensuring firefighter and community preparedness and safety. Offensive strategies could position crews in danger. Conditions on the fireground are likely to be extremely windy.	Fire control is extremely difficult and unlikely until conditions ease. Focus will be largely based on defensive strategies, ensuring firefighter and community preparedness and safety. Offensive strategies could position crews in danger. Conditions on the fireground are likely to be extremely windy. Fuel breaks <100 m are likely to be ineffective at holding head-fires.
	Red flag warnings			*Wind change forecast - potential conditions for 'dead man zone'*	*Wind change forecast - potential conditions for 'dead man zone'*	*Wind change forecast - potential conditions for 'dead man zone'*	*Wind change forecast - potential conditions for 'dead man zone'*
Consequences	Community loss (life & house):				High likelihood of pasture/crop/stock loss together with loss of rural assets such as fencing, machinery and buildings.	Increasingly high likelihood of pasture/crop/stock loss together with loss of rural assets such as fencing, machinery and buildings. Limited visibility due to smoke and dust. High risk to the community related to inappropriate pre-considered plans, inadequate sheltering[2].	Extremely high likelihood of pasture/crop/stock loss together with loss of rural assets such as fencing, machinery and buildings. Very limited visibility due to smoke and dust. Very high risk to the community related to inappropriate pre-considered plans, inadequate sheltering[2].
	Impact on infrastructure:					Strong winds are likely to impact infrastructure (e.g. power lines) and fall trees increasing the likelihood of obstructed roads and power outages.	Strong winds are very likely to impact infrastructure (e.g. power lines) and fall trees resulting in a high likelihood of obstructed roads and power outages.
	Firefighter safety:				Increased risk to firefighter safety	Increased risk to firefighter safety	Increased risk to firefighter safety
	Maximum potential fire area (without suppression):	Small fires that are likely <0.5 ha. Fires may be allowed to spread within an extended (time and area) containment objective.	Possible fires up to 650 ha. Fires may be allowed to spread within an extended (time and area) containment objective.	Large area fires up to 10,500 ha	Large area fires up to 37,000 ha	Large area fires up to 100,000 ha	Large area fires exceeding 54,000 ha and potentially >100,000 ha
	Maximum potential fire perimeter (without suppression):	<0.5 km	Possible fire perimeter up to 11.5 km	Large fire perimeters up to 45 km	Large fire perimeters up to 85 km	Large fire perimeters up to 140 km	Large fire perimeters exceeding 60 km and potentially >140 km

Assumptions and methodology
Flame heights are based on Cheney & Sullivan figure for 'grazed' grassland
Rates of Spread are back-calculated based on Byram's fireline intensity and a range of fuel load varying from 3-6 t/ha (McArthur (1973) assumed max fuel load was between 4-5 t/ha)
Potential fire area and perimeter are based on a 4 hour fire run under max FDR with a range of LB ratio (grassland) as determined by wind speeds ranging from 10-40 km/hr (as per Cruz et al 2015 (on the back page)) and a fuel load varying from 3-6 t/ha
[2] Blanchi etal 2010

Table 2.33 NFDRS Research Prototype Fire Danger Rating Table for Spinifex fuels. Version 1_2018.

Spinifex

	Category	1	2	3	4	5	6
	Relevance:	Fire is unlikely to spread. Spread Index ≤ 0	Typical prescribed burning conditions. Spreading fires, generally easily contained within simple road networks and fuel breaks.		Rapid fire growth typically contained within established road networks and fuel breaks mostly without the need for additional suppression.	Damaging wildfires with extremely rapid fire growth. Active suppression may be required. High levels of threat to the environment and/or when in close proximity to people, assets and property. Safety of visitors and local communites top priority.	
	Lower limit of fireline intensity (kW/m)	0	1,500	10,000		20,000	
	Upper limit of fireline intensity (kW/m)	1,500	10,000	20,000		20,000+	
	Primary threshold limits	Spread Index ≤0	0<SI≤2	2<SI≤10		SI>10	
Indicative fire behaviour & fire weather	Description	Likelihood of spread is largely a function of fuel cover and wind speed (see SI above). If fuel cover <50% and wind speed <12 km/h, flame dimensions are generally insufficient to breach inter-hummock gaps.	Winds speeds (2 m) 12-17 km/hr enabling sustained spread of fire. Largely wind driven head-fires burning in narrow strips and classic 'finger' shapes.	Rapid fire growth, especially when SI >6 or wind speed > 25 km/h. Often reaching 'quasi steady state' within 5-10 mins of ignition. Largely wind-driven head-fires becoming increasingly large with shifts in wind direction. Increased potential for burning hummocks on flanks to develop into smaller fires following changes in wind direction.		Rapid fire growth (<5 mins to steady state), extremely fast moving, wind-driven fires. High potential for large fire areas with complete combustion of fuels and few unburnt patches. Burning hummocks often developing into smaller fires following changes in wind direction.	
	ROS range:	<350 m/hr	0.2-2.5 km/hr	1-5 km/hr		Rates of spread in excess of 2.5 km/hr can be expected and possibly >5 km/hr	
	Max flame height range:	<2 m	<3.5 m	3-4.5 m		>3.5 m	
	Spotting potential:	Potential for any spotting is extremely limited.	Potential for spotting is limited.	Potential for spotting is limited except where eucalypt/mallee trees are present where spotting is likely to be minimal and limited to short distances (<100 m). Any spot fires are typically overrun by the main headfire.		Possible short distance spotting if eucalypt/mallee trees are present (mostly <200 m) with spot fires typically quickly overrun by the main headfire.	
	Red flag warnings			*Wind change forecast during the peak of the afternoon* *C-Haines >95th percentile (approx >10)*		*Wind change forecast during the peak of the afternoon* *C-Haines >95th percentile (approx >10)*	
Prescribed burn implications	NB. Descriptions here are offered as a general guide and appropriate fire behaviour models should be consulted to achieve burn prescription outcomes.	Marginal conditions even at the peak of the day. The probability of sustained spread is minimal.	Typical prescribed burning conditions. Sustained spread likely and largely dependant on wind speed, fuel quantity and fuel moisture content. Head-fires commonly fragment and go out under low wind speeds and diurnal/evening conditions.	P/B opportunities may exist away from assets and with well established, wide (>10 m) boundaries/edges. P/B opportunities may exist away from the peak of the day when conditions are optimal and lighting techniques are suitable to achieve P/B objectives.		Conditions are likely to be unsuitable for P/B however opportunities for P/B may be exist pre immediate storm/rain events or away from the peak of the day when conditions are optimal and lighting techniques are suitable to achieve P/B objectives.	
	Red flag warnings		*Wind change forecast*	*Wind change forecast*		*Wind change forecast*	
Fire containment		Fire containment relatively simple. Mostly contained within simple road networks, fuel breaks and buffers. Suppression generally not neccesary.	Fire containment mostly simple. Fires typically contained within road networks, fuel breaks or buffers >5 m wide (including spinifex *fuel class 1&2: fuel cover <40%*)	Fires generally becoming more complex and requiring wider roads, larger fuel breaks or buffers (including *spinifex fuel class 1&2: fuel cover <40%*) >15 m for containment. Active suppression around assets generally not necessary unless fuel breaks around assets are inadequate.		Fires quickly becoming large, complex and difficult to contain within existing road networks, fuel breaks and buffers (including *spinifex fuel class 1&2: fuel cover <40%*). Fuel breaks typically need to be >200 m to be effective. Conditions are likely to be extremely windy. Active suppression including indirect attack or machines may be required to protect areas of population, high conservation value and on high value built, agricultural and cultural assets.	
	Red flag warnings			*Wind change forecast*		*Wind change forecast*	
Consequences	Community Impact and loss:			Potentially damaging impacts on the environment (threats to fauna, habitat loss, e.g. loss of hollow-bearing trees, hollow logs, shrub cover, mulga groves) as well as potential pasture/crop/stock loss together with loss of rural/structural assets such as fencing, machinery and buildings.		Very high risk of damaging impacts on the environment over large areas (threats to fauna, habitat loss, e.g. loss of hollow-bearing trees, hollow logs, shrub cover, mulga groves) as well as very high likelihood of pasture/crop/stock loss together with loss of rural assets such as fencing, machinery and buildings.	
	Firefighter safety:			Risk to firefighters. Fire behaviour (speed and direction) highly responsive to wind shifts and positive slope		Risk to firefightrers. Fire behaviour (speed and direction) highly responsive to wind shifts and positive slope.	
	Maximum potential fire area (without suppression):	Small fires that are typically <5 ha	Possible fires up to 2,500 ha	Potential for large fires in the absence of significant areas of low fuel cover. Large area fires up to 9,000 ha		Large area fires mostly exceeding 2,000 ha and likely more than 9,000 ha	
	Maximum potential fire perimeter (without suppression):	Small fire perimeters that are typically <1 km	Possible fire perimeters up to 20 km	Large fire perimeters up to 45 km		Large fire perimeters mostly exceeding 10 km and likely more than 45 km	

Assumptions and methodology

Flame heights are based on Neils flame height equation for spinifex (Burrows et al 2017)

Rates of Spread are back-calculated based on Byram's fireline intensity and a range of fuel load varying from 8-16.5 t/ha (Based on a range of fuel loads (3.5-16.5; Burrows et al, 2015) and Griffin & Allan (1984) mean fuel load of 7.5 t/ha (assuming that 8 t/ha is on the heavy end of a light fuel load)

Spread Index ≤0 (SI=0.34(U10)+0.31(Fuel Cover)-0.45(PMC)-7.21

Spotting distances are based on descriptions from Burrows et al 1991, 2006, 2015)

Potential fire area and perimeter are based on a 4 hour fire run under max FDR (without suppression or containment) with a range of LB ratio as determined by wind speeds ranging from 10-40 km/hr (as per Cruz et al 2015 (on the back page)) and a fuel load varying from 3.5-16.5 t/ha

Table 2.34 NFDRS Research Prototype Fire Danger Rating Table for Pine fuels. Version 1_2018.

Pine

	Category	1	2	3	4	5	6
	Relevance:	**Mostly self-extinguishing, trouble-free fires**	**Typically slow moving, surface fires. Fires generally easy to suppress**	**Most wildfires in this category. Fires typically suppressed with direct, parrallel or indirect attack**	**Initial attack success critical to prevent large fire development. Defensive suppression strategies.**	**Defensive suppression strategies. High levels of threat to life/property. Safety of firefigters & community paramount**	**Safety of firefighters and community most important. Without initial attack success, likelihood of very large fire development is very high. High probability of loss of life and property.**
	Lower limit of fireline intensity (kW/m)	0	100	750	4,000	10,000	30,000
	Upper limit of fireline intensity (kW/m)	100	750	4,000	10,000	30,000	30,000+
Indicative fire behaviour & fire weather	Description	Fire difficult to ignite and sustain. Fires generally unlikely to spread and likely to self-extinguish.	Slow spreading fires, typically involving surface and near-surface fuels and sometimes into the elevated, ladder fuels. Spotting is sporadic and limited to short-distances.	Actively spreading fires typically involving surface, near-surface and elevated fuel layers and occassionally canopy fuels. Isolated short range spotting can occur under dry fuel moisture conditions.	Rapidly spreading fires with potential for development into large burn areas within burning period. Fires typically involving most fuel layers. Short-range spotting is prevalent, with possibilty of medium range and occacional long-range distance spotting	Fires likely to quickly trasition to crowning. Possibility for fire behaviour to become erratic and plume driven. Strong convective column formation. Wind speed and direction likely to be erratic at times.	Fires likely to quickly trasition to crowning. Possibility for fire behaviour to become erratic and plume driven. Strong convective column formation. Wind speed and direction likely to be erratic at times.
	ROS range:	0-40 m/hr	20-150 m/hr	70-800 m/hr	400 m -1 km/hr	600 m -3 km/hr	Rate of spread in excess of 2 km/hr can be expected and possibly >3 km/hr
	Max flame height range:	<0.5 m	<4 m	2-10 m	8-12 m	10 m - approx. double forest height	possibly up to 35 m (approx. double forest height)
	Spotting potential:	Potential for any spotting is very limited.	Potential for spotting is limited. Possible isolated spotting up to 60 m under very dry fuel moisture conditions	Potential for isolated spotting is limited to short distances up to around 300 m under dry fuel moisture conditions.	Potential for short distance spotting occuring with increasing frequency with possible spotting up to 400 m	Short and medium range spotting possible up to 1 km	Short and medium range with possible long distance spotting occuring 2-3 km ahead of the main fire front
	Red flag warnings			*C-Haines >95th percentile (approx >10)* *Wind change forecast during the peak of the afternoon*	*C-Haines >95th percentile (approx >10)* *Wind change forecast during the peak of the afternoon*	*C-Haines >95th percentile (approx >10)* *Wind change forecast during the peak of the afternoon*	*C-Haines >95th percentile (approx >10)* *Wind change forecast during the peak of the afternoon*
Fire suppresion and containment		Fire control relatively simple. Head-fire readily suppressed with offensive, direct attack techniques. Initial attack success is typically very high.	Fire control mostly simple with sufficent resources and becoming more complex at higher intensities. Offensive, direct attack techniques on head-fire or flanks largely successful in fire control.	Fires generally becoming more complex and require more resources to control. Combinations of direct, indirect or parrallel attack may be neccesary for fire control.	Offensive strategies likely to be unsuccessful during the peak of the day, with focus largely centered on defensive strategies. Fire control is likely to be difficult and require increased resourcing.	Fire control is extremely difficult and unlikely until conditions ease. Focus will be largely based on defensive strategies, enusuring firefighter and community preparedness and safety. Offensive strategies could position crews in danger. Conditions on the fireground are likely to be extremely windy and smokey so restrictions to visibility, aviation and access are possible.	Fire control is extremely difficult and unlikely until conditions ease. Focus will be largely based on defensive strategies, enusuring firefighter and community preparedness and safety. Offensive strategies could position crews in danger. Conditions on the fireground are likely to be extremely windy and smokey so restrictions to, visibility aviation and access are likely.
	Red flag warnings			*Wind change forecast - potential conditions for 'dead man zone'*	*Wind change forecast - potential conditions for 'dead man zone'*	*Wind change forecast - potential conditions for 'dead man zone'*	*Wind change forecast - potential conditions for 'dead man zone'*
Consequences	Community loss (life & house):				Potential for house loss exists when homes and properties are adjacent to crown fire prone plantations.	High potential for house loss. Limited visibility due to smoke and dust. High risk to the community related to inappropriate pre-considered plans, inadequate sheltering[2].	High potential for house loss. Very limited visibility due to smoke and dust. Very high risk to the community related to inappropriate pre-considered plans, inadequate sheltering[2].
	Impact on infrastructure:					Strong winds are likely to impact infrastructure (e.g. power lines) and fall trees increasing the likelihood of obstructed roads and power outages.	Strong winds are very likely to impact infrastructure (e.g. power lines) and fall trees resulting in a high likelihood of obstructed roads and power outages.
	Firefighter safety:				Increased risk to firefighter safety	Increased risk to firefighter safety	Increased risk to firefighter safety
	Maximum potential fire area (without suppression):	Small fires that are likely <1.5 ha	Possible fires up to 20 ha	Possible fires up to 500 ha	Possible fires up to 700 ha	Large area fires up to 6,500 ha	Large area fires exceeding 1,000ha and potentially >6,500 ha
	Maximum potential fire perimeter (without suppression):	<0.5 km	Possible fire perimeter up to 1.5 km	Possible fire perimeter up to 8 km	Possible fire perimeter up to 10 km	Large fire perimeters up to 30 km	Large fire perimeters exceeding 15 km and potentially >30 km

Assumptions and methodology:

Flame heights are based on McArthur's equation for flame height (Noble, 1980)
Rates of Spread are back-calculated based on Byram's fireline intensity and a range of fuel load varying from 10-20 t/ha (plus an additonal 11 t/ha for cat's 4,5,& 6 for canopy fuel load)
Spotting distances are based on McArthur's spotting equation
Potential fire area and perimeter are based on a 4 hour fire run under max FDR with a range of LB ratio (for FOREST) as determined by wind speeds ranging from 10-40 km/hr (as per Cruz et al 2015 (on the back page)) and a fuel load varying from 10-20 t/ha (plus 11 t/ha canopy fuel load for cat's 4,5 & 6)
The lowest (no. 1) category, assumes that only 50% of the fuel load is available for burning, and this is represented in flame heights, rates of spread and potential fire size.
Categories 4, 5 and 6 assume an additional 11 t/ha is available (contributed by canopy fuel layer)
[2] Blanchi etal 2010

Table 2.35 NFDRS Research Prototype Fire Danger Rating Table for Savanna fuels. Version 1_2018.

Savanna

	Category	1	2	3	4	5	6
	Relevance:	**Mostly self-extinguishing, quickly contained within simple fuel breaks and landscape features**	**Typical prescribed burning conditions whereby a mosaic of burnt and unburnt patches are created. Fires generally easily contained within simple road networks, fuel breaks and recent fire scars**		**Fires generally escalate in size very quickly. Typically consuming all available fuels and controlled within wide fuel breaks and recent fire scars, mostly without the need for additional containment support.**	**Damaging wildfires with extremely rapid fire growth. Additional containment and active suppression may be required. High levels of threat to the environment and/or when in close proximity to people, assets and property. Safety of visitors and local communites top priority.**	
	Lower limit of fireline intensity (kW/m)	0	100	4,000		20,000	
	Upper limit of fireline intensity (kW/m)	100	4,000	20,000		20,000+	
Indicative fire behaviour & fire weather	Description	Fire difficult to ignite and sustain. Fires generally unlikely to spread and likely to self-extinguish.	Fire easily sustained. Typically wind driven fires that can spread quickly. Fires mostly only partially consuming fuels, typically creating a mosaic of burnt and unburnt patches (decreasing patchiness with increasing intensity).	Wind driven, rapidly spreading fires with potential for development into large fire area/size and with the potential for small distance spotting and long flame lengths. Fires typically consuming all available fuel. Increasing scrorch height of tree canopy (up to 20-25m) and char height (up to 3-4m).		Extremely rapid fire growth and increasing likelihood of large final fire area/size. Possibility for fire behaviour to become erratic and plume driven. Strong convective column formation. Wind speed and direction likely to be erratic at times. Fires consuming all available fuel.	
	ROS range:	0-50 m/hr	<1.5 km/hr	1-8 km/hr		Rates of spread > 5km/hr can be expected and possibly >8 km/hr	
	Max flame height range:	<0.5 m	<1.5 m	1.5-2.5 m		>2.5 m	
	Spotting potential:	Potential for any spotting is extremely limited	Potential for short distance spotting is limited	Possible short distance spotting occuring		Likely short distance spotting	
	Red flag warnings			*C-Haines >95th percentile (approx >12)* *Wind change forecast during the peak of the afternoon*		*C-Haines >95th percentile (approx >12)* *Wind change forecast during the peak of the afternoon*	
Prescribed burn implications	NB. Descriptions here are offered as a general guide and appropriate fire behaviour models should be consulted to achieve burn prescription outcomes.	Marginal P/B conditions, even at peak of the day. Consider long line ignitions to increase acceleration.	Typical prescribed burning conditions for hazard reduction and pasture management. At the lower intensity, simple burns with adequate fuel breaks, often going out overnight with higher humidity and fuel moisture. Above 2,000 kW/m, P/B opportunities may exist for burns with adequate resourcing and well established, wide boundaries/edges. P/B opportunities may exist away from the peak of the day when conditions are suitable to achieve P/B objectives. Consider point source ignitions to reduce acceleration. Suitable conditions for controlling woody vegetation structure and exotic weeds.	Conditions are likely to be unsuitable for most P/B objectives although may still be useful in some circumstances. Fires typically burn too large an area and without any internal patchiness. Fires often don't go out overnight and fire intensity is likely to be inconsistent with land management objectives.		Conditions not suitable for prescribed burning to achieve typical P/B objectives.	
	Red flag warnings			*Strong wind gusts forecast*		*Strong wind gusts forecast*	
Fire management and containment		Fire containment relatively simple. Mostly contained within simple road networks, fuel breaks or landscape characteristics. Suppression not neccesary.	Fire containment mostly simple. Fires typically contained within road networks, fuel breaks and recent fire scars (>10 m).	Fires quickly becoming large and generally requiring fuel breaks (or buffers) or recent fire scars (>100 m) for containment. Active suppression around assets generally not necessary with adequate fuel breaks, buffers or recent fire scars. Conditions are likely to be extremely windy. Active suppression including indirect attack and/or machines may be required to protect areas of population, high conservation value and on high value built, agricultural and cultural assets.		Fires quickly becoming large and generally requiring fuel breaks (or buffers) or recent fire scars (>500 m) for containment. Active suppression around assets may be required where fuel breaks are inadequate. Conditions are likely to be extremely windy. Active suppression including indirect attack and/or machines may be required to protect areas of population, high conservation value and on high value built, agricultural and cultural assets.	
	Red flag warnings			*Wind change forecast - potential conditions for 'dead man zone'*		*Wind change forecast - potential conditions for 'dead man zone'*	
Consequences	Community impact & loss:			High likelihood of pasture/crop/stock loss together with loss of rural assets such as fencing, machinery and buildings. Often producing large amounts of smoke and associated carbon emissions. Visability is likely to be limited due to smoke and dust, potentially impacting traffic management. Reduced biodiversity and habitat damage including loss of food supply for native fauna and traditional owners. Stem survival < 80%.		Extremely high likelihood of pasture/crop/stock loss together with loss of rural assets such as fencing, machinery and buildings. Often producing large amounts of smoke and associated carbon emissions. Visability is likely to be limited due to smoke and dust, potentially impacting traffic management. Reduced biodiversity and habitat damage including loss of food supply for native fauna and traditional owners. Stem survival < 20%.	
	Maximum potential fire area (without suppression):	Small fires that are typically <0.5 ha	Possible fires up to 1,000 ha	Large area fires up to 24,000 ha		Large area fires likely to exceed 5,000 ha and possibly exceeding 24,000 ha	
	Maximum potential fire perimeter (without suppression):	Small fire perimeters that are typically <0.5 km	Possible fire perimeters up to 13 km	Large fire perimeters up to 70 km		Large fire perimeters typically over 40 km and possibly exceeding 70 km	

Assumptions and methodology

Flame heights are based on Cheney & Sullivan figure for 'grazed' grassland

Rates of Spread are back-calculated based on Byram's fireline intensity and a range of fuel load varying from 5-8 t/ha (Based on fuel descriptions from 'Savanna Burning' p. 22, which states 'fuel loads generally range from 2-8 t/ha, together with a check of fuel loads from the Anderson etal 2011 grass curing datatset, where all fuels were <8 t/ha with one exception which was 10 t/ha of around 30 sample datapoints in Australian northern savanna)

Spotting distances are really general assumptions

Potential fire area and perimeter are based on a 4 hour fire run under max FDR (without suppression or containment) with a range of LB ratio (GRASS) as determined by wind speeds ranging from 10-40 km/hr (as per Cruz et al 2015 (on the back page)) and a fuel load varying from 7-14 t/ha

Table 2.36 NFDRS Research Prototype Fire Danger Rating Table for Mallee-heath fuels. Version 1_2018.

Mallee-heath

	Category	1	2	3	4	5	6
	Relevance:	**Mostly self-extinguishing fires**	**Typical prescribed burning conditions. Fires generally spread as surface fires and contained within road networks, fuel breaks (including scrub roll buffers) and recent fire scars.**	**Vigorous surface fires with intermittent crowning possible. Fires typically controlled within established road networks, wide fuel breaks (and scrub roll buffers) and recent fire scars.**	**Active crown fires that generally escalate very quickly and may require active suppression around assets with insufficient break widths.**	**Damaging crown fires with extremely rapid fire growth. Additional containment and active suppression may be required. High levels of threat to the environment and/or when in close proximity to people, assets and property. Safety of visitors and local communites top priority.**	
	Lower limit of fireline intensity (kW/m)	**0**	**150**	**7,000**	**10,000**	**20,000**	
	Upper limit of fireline intensity (kW/m)	**150**	**7,000**	**10,000**	**20,000**	**20,000+**	
	Primary threshold limits	**Probability of self-sustained surface fire lower than 50%.**	**Probability of self-sustained surface fire higher than 50%.**	**Probability of crown fire occurrence between 33 and 66%.**	**Probability of crown fire occurrence is between 66 and 100%**	**Probability of crown fire occurrence is 100%**	
	Other threshold limits		**Probability of crown fire occurrence is lower than 33%.**				
Indicative fire behaviour & fire weather	Description	Probability of self-sustained, surface fires is low.	Surface fires whereby the flame front is able overcome the fine scale fuel discontinuities. Isolated torching of overstorey fuels[1].	Intermittent crown fire. The passage of the flame front on surface fuels is followed by torching of overstorey fuels. Canopy fuel combustion occurs somewhat behind the leading edge of the flame front. Average flame front properties not affected by the level of torching and rate of fire spread largely determined by surface phase[1].	Active or dependent crown fire with crown phase determining the overall rate of spread. Fire propagates faster than observed for a surface or intermittent crown fire under same environmental conditions. A reduction of the surface phase heat output below a certain level will lead the fire to an intermittent crown fire regime[1].	Active or dependent crown fire.	
	ROS range:	<40 m/hr	<2 km/hr	1-3 km/hr	1.5-5.5 km/hr	Rates of spread in excess of 3 km/hr can be expected and possibly > 5.5 km/hr	
	Max flame length:	flame lengths <1 m	flame lengths up to 5 m	flame lengths up to 5.4 m	flame lengths up to 8 m	long flame lengths possibly over 8 m	
	Max flame height:	flame height <1 m	flame heights up to 5 m	flame heights up to 6 m	flame heights up to 8 m	flame heights possibly in excess of 8 m	
	Spotting potential:	Potential for any spotting is extremely limited.	Short range spotting possible up to 10 m.	Short range spotting up to 50 m likely, allowing fire to cross small areas of fuel discontinuity such as roads or small fuelbreaks.	Escalation in fire activity is typically accompanied by an increase in the number of firebrands generated and possible distances >50 m ahead of the flame front (Cruz et.al. 2010).	Escalation in fire activity is typically accompanied by an increase in the number of firebrands generated and possible distances >50 m ahead of the flame front[1].	
	Red flag warnings			*C-Haines >95th percentile (approx >10)* *Wind change forecast during the peak of the afternoon*	*C-Haines >95th percentile (approx >10)* *Wind change forecast during the peak of the afternoon*	*C-Haines >95th percentile (approx >10)* *Wind change forecast during the peak of the afternoon*	
Prescribed burn implications	NB. Descriptions here are offered as a general guide and appropriate fire behaviour models should be consulted to achieve burn prescription outcomes.	Marginal P/B conditions, even at peak of the day.	Typical prescribed burning conditions for hazard reduction. Simple burns with adequate fuel breaks, often going out overnight with higher humidity and fuel moisture.	P/B opportunities exist for complex burn plans with adequate resourcing and well established, wide boundaries/edges. Opportunities may exist away from the peak of the day when conditions are are suitable to achieve P/B objectives.	Conditions are likely to be unsuitable for P/B.	Forget it! Conditions not suitable for prescribed burning.	
	Red flag warnings				*wind change forecast*	*wind change forecast*	
Fire containment		Fire containment relatively simple and typically contained within simple road networks, fuel breaks and buffers without the need for active fire suppression.	Fires typically contained within road networks, fuel breaks (including recent fire scars) and buffers >3-4 m wide with active fire suppression.	Fire containment generally requiring wider roads, fuel breaks (including recent fire scars) or buffers (>10 m) together with active suppression. Active suppression around assets generally not necessary with adequate fuel breaks. Onset of crown fire activity can lead to rapid increase in rate of spread and intensity (2-3 x the surface fire spread rate).	Fires quickly becoming large and difficult to contain within existing road networks, fuel breaks (including scrub roll buffers) and fire scars. Fuel breaks (or buffers) >100 m are likely to be effective. Conditions on the fireground are likely to be extremely windy. Active suppression including indirect attack or machines may be required to protect areas of population, high conservation value and on high value built and cultural assets.	Fires quickly becoming large, complex and difficult to contain within existing road networks, fuel breaks (including scrub roll buffers) and fire scars. Fuel breaks (or buffers) >500 m are likely to be effective. Conditions on the fireground are likely to be extremely windy. Active suppression including indirect attack, scrub rolling or machines may be required to protect areas of population, high conservation value and on high value built and cultural assets.	
	Red flag warnings				*Wind change forecast - potential conditions for 'dead man zone'*	*Wind change forecast - potential conditions for 'dead man zone'*	
Consequences	Community impact & loss:				High likelihood of pasture/crop/stock loss together with loss of rural assets such as fencing, machinery and buildings. Increasing risk of damaging impacts on the environment. Fires often producing large amounts of smoke. Visability is likely to be limited due to smoke and dust, potentially impacting traffic management.	Extremely high likelihood of pasture/crop/stock loss together with loss of rural assets such as fencing, machinery and buildings. Very high risk of damaging impacts on the environment. Fires often producing large amounts of smoke and associated carbon emissions. Visability is likely to be limited due to smoke and dust, potentially impacting traffic management.	
	Maximum potential fire area (without suppression):	Small fires that are likely <1 ha	Possible fires up to 1500 ha	Possible fires up to 3,000 ha	Possible fires up to 12,000 ha	Large area fireslikely to exceed 1,500 ha and possibly exceeding 12,000 ha	
	Maximum potential fire perimeter (without suppression):	<0.5 km	Possible fire perimeter up to 17 km	Possible fire perimeter up to 25 km	Possible fire perimeter up to 50 km	Large fire perimeters likely to exceed 22 km and possibly exceeding 50 km	

Assumptions and methodology:

Flame lengths are based on Byrams (1959) flame length evaluated by Cruz et.al. 2010
Rates of Spread are back-calculated based on Byram's fireline intensity and a range of fuel load varying from 7-14 t/ha
Descriptions of spotting potential are based on Cruz et.al 2010
Potential fire area and perimeter are based on a 4 hour fire run under max FDR (without suppression or containment) with a range of LB ratio as determined by (GRASS) wind speeds ranging from 10-40 km/hr for forests (as per Cruz et al 2015 (on the back page)) and a fuel load varying from 7-14 t/ha
Developed for semi-arid mallee heath (Cruz et.al. 2013)
Flame heights are based on a re-analysis of Cruz etal, (2013) data whereby flame height is a function of rate of spread
Probability of self-sustained surface fire is calculated using 10 m open wind speed, moisture content of dead litter (determined by Temp & RH) and overstorey mallee cover.
Probability of crown fire occurrence is calculated based on 10 m open wind speed and moisture content of dead litter (determined by Temp & RH))
[1] Cruz etal 2010

Table 2.37 NFDRS Research Prototype Fire Danger Rating Table for Shrubland fuels. Version 1_2018.

Shrubland

		1	2	3	4	5	6
	Category	1	2	3	4	5	6
	Relevance:	**Fire is unlikely to spread.**	**Typical prescribed burning conditions including scrub rolled firebreaks. Spreading surface fires, generally easily contained within simple road networks, fuel breaks and buffers.**	**Fast moving, wind driven fires mostly crowning. Typically contained within established road networks, fuel breaks and buffers. Active suppression may be required where fuel breaks are insufficient around assets.**	**Rapidly growing crown fires that are difficult to contain and quickly become large. Mostly contained within established road networks, fuel breaks and buffers but may require active suppression where fuel breaks are insufficient around assets.**	**Damaging wildfires with extremely rapid fire growth. Active suppression may be required. High levels of threat to the environment and/or when in close proximity to people, assets and property. Safety of visitors and local communites top priority.**	
	Lower limit of fireline intensity (kW/m)	0	50	500	4,000	20,000	
	Upper limit of fireline intensity (kW/m)	50	500	4,000	20,000	20,000+	
Indicative fire behaviour & fire weather	Description	Flame dimensions are generally insufficient to breach sparse and discontinuous fuels or inter-hummock gaps.	Sustained spread of fire.	Fast moving, wind-driven fires that are mostly actively crowning.	Fast moving, wind-driven, crown fires with high potential for large fire areas. Mostly complete combustion of fuels and few unburnt patches.	Rapid fire growth, extremely fast moving, wind-driven fires. High potential for large fire areas with complete combustion of fuels and few unburnt patches.	
	ROS range:	<20 m/hr	<150 m/hr	<1.3 km/hr	0.3-6.5 km/hr	Rates of spread in excess of 1.5 km/hr and possibly >6.5 km/hr	
	Max flame height range:	<0.5 m	0.5-1.5 m	1-4 m	2-8 m	flame heights >4 m and likely >8 m	
	Spotting potential:	Potential for any spotting is extremely limited.	Potential for spotting is limited.	Potential for spotting is limited except where eucalypt/mallee trees are present where spotting is likely to be minimal and limited to short distances (<50 m). Any spot fires are typically overrun by the main headfire.	Possible short distance spotting mostly <20 m or where eucalypt/mallee trees are present where spotting is likely to be minimal and limited to short distances (<100 m). Any spot fires are typically overrun by the main headfire.	Possible short distance spotting mostly <40 m except where eucalypt/mallee trees are present where spotting may be up to 200 m with spot fires typically quickly overrun by the main headfire.	
	Red flag warnings			*C-Haines >95th percentile (approx >10)* *Wind change forecast during the peak of the afternoon*	*C-Haines >95th percentile (approx >10)* *Wind change forecast during the peak of the afternoon*	*C-Haines >95th percentile (approx >10)* *Wind change forecast during the peak of the afternoon*	
Prescribed burn implications	NB. Descriptions here are offered as a general guide and appropriate fire behaviour models should be consulted to achieve burn prescription outcomes.	Marginal conditions even at the peak of the day. The probability of sustained spread is minimal.	Typical prescribed burning conditions (including within scrubrolled firebreaks) where the fire will sustain spread.	P/B opportunities may exist away from assets and with well established, wide (>10 m) boundaries/edges. P/B opportunities may exist away from the peak of the day when conditions are optimal and lighting techniques are suitable to achieve P/B objectives.	Conditions are likely to be unsuitable for P/B however opportunities may exist away from assets and with well established, wide (>100 m) boundaries/edges or away from the peak of the day when conditions are optimal and lighting techniques are suitable to achieve P/B objectives.	Conditions are likely to be unsuitable for P/B.	
	Red flag warnings		*Wind change forecast*	*Wind change forecast*	*Wind change forecast*	*Wind change forecast*	
Fire suppression and containment		Fire containment relatively simple. Mostly contained within simple road networks, fuel breaks and buffers. Supression generally not neccesary.	Fire containment mostly simple. Fires typically contained within simple road networks, fuel breaks or buffers >3-4 m wide. Offensive, direct attack techniques on head-fire or flanks largely successful if fire control is neccessary.	Fires generally becoming more complex and requiring wider roads, larger fuel breaks or buffers >10 m for containment. Active suppression around assets generally not necessary unless fuel breaks around assets are inadequate. Combinations of direct, indirect or parrallel attack may be neccesary where fuel breaks are inadequate.	Fires quickly becoming large and difficult to contain with fuel breaks (or buffers) >100 m likely to be effective. Conditions on the fireground are likely to be extremely windy. Active suppression including indirect attack or machines may be required to protect areas of population, high conservation value and on high value built, agricultural and cultural assets.	Fires quickly becoming large, complex and difficult to contain within existing road networks, fuel breaks and buffers. Fuel breaks typically need to be >200 m to be effective. Conditions are likely to be extremely windy. Active suppression including indirect attack or machines may be required to protect areas of population, high conservation value and on high value built, agricultural and cultural assets.	
	Red flag warnings			*Wind change forecast*	*Wind change forecast*	*Wind change forecast*	
Consequences	Community Impact and loss:				High likelihood of pasture/crop/stock loss together with loss of rural assets such as fencing, machinery and buildings. Increasing risk of damaging impacts on the environment. Fires often producing large amounts of smoke. Visability is likely to be limited due to smoke and dust, potentially impacting traffic management.	Extremely high likelihood of pasture/crop/stock loss together with loss of rural assets such as fencing, machinery and buildings. Very high risk of damaging impacts on the environment. Fires often producing large amounts of smoke and associated carbon emissions. Visability is likely to be limited due to smoke and dust, potentially impacting traffic management.	
	Firefighter safety:				Increased risk to firefighter safety	Increased risk to firefighter safety	
	Potential fire area:	Small fires that are typically <0.5 ha	Possible fires up to 22 ha	Possible fires up to 1500 ha	Large area fires that potentially burn up to 35,000 ha	Large area fires that burn over 420 ha and possibly over 35,000 ha	
	Potential fire perimeter:	Small fire perimeters that are typically <0.5 km	Possible fire perimeters up to 2 km	Large fire perimeters up to 15 km	Large fire perimeters that can extend up to 68 km	Large fire perimeters that extend over 11 km and possibly over 68 km	

Assumptions and methodology

Flame heights are based on Miguels flame height equation for mallee-heath (Pers. Comm. Cruz 2017)
Rates of Spread are back-calculated based on Byram's fireline intensity and a range of fuel load varying from 6-30 t/ha (Based on steady state of shrublands (Bel K), McCaw etal 1989 wildfire in Fitzgerald River NP range of fuel loads together with Anderson etal 2015 in both the evaluation and modelling datasets (assuming that 6 t/ha is on the heavy end of a light fuel load)
Spotting distances are based on pers. Comm. with Ryan Butler 2017
Potential fire area and perimeter are based on a 4 hour fire run under max FDR (without suppression or containment) with a range of LB ratio (forest) as determined by wind speeds ranging from 10-40 km/hr (as per Cruz et al 2015 (on the back page)) and a fuel load varying from 6-30 t/ha

Table 2.38 NFDRS Research Prototype Fire Danger Rating Table for Buttongrass fuels. Version 1_2018.

Buttongrass

	Category	1	2	3	4	5	6
	Relevance:	Mostly self-extinguishing, trouble-free fires. Moorland FDR[1]: 0	Typical prescribed burning conditions, fires generally easy to suppress. Moorland FDR[1]: LOW (1-5)	Fires difficult to control. Moorland FDR[1]: MOD (6-12)	Initial attack success critical to prevent large fire development. Defensive suppression strategies. Moorland FDR[1]: HIGH (13-24)	Defensive suppression strategies. High levels of threat to life/property. Safety of firefigters & community paramount. Moorland FDR[1]: VERY HIGH (25-50)	Safety of firefighters and community most important. Without initial attack success, likelihood of very large fire development is very high. High probability of loss of life and property. Moorland FDR[1]: EXTREME (51-100)
	Lower ROS limit (m/hr):	0	30	450	1,020	2,040	4,200
	Upper ROS limit (m/hr):	30	450	1,020	2,040	4,200	4,200+
Indicative fire behaviour & fire weather	Description	Fires unlikely to be sustained and may be difficult to ignite.	Mostly slow spreading fires.	Typically wind driven and quicly spreading fires.	Wind driven, rapidly spreading fires with potential for development into large fire area/size and with the potential for short distance spotting and long flame lengths.	Extremely rapid fire growth and increasing likelihood of large final fire area/size. Possibility for fire behaviour to become erratic and plume driven. Strong convective column formation. Wind speed and direction likely to be erratic at times.	Extremely rapid fire growth and high likelihood of large final fire area/size. Possibility for fire behaviour to become erratic and plume driven. Strong convective column formation. Wind speed and direction likely to be erratic at times.
	Fireline intensity (kW/m):	<300	150-5,000	2,500-10,500	5,500-21,000	10,500-43,500	>21,500
	Max flame height range:	Small flame heights typically <1 m	<6 m	2-9 m	3-12 m	4-16 m	>8 m
	Spotting potential:	Potential for any spotting is minimal.	Possible short distance spotting up to 5 m can be expected	Possible short distance spotting up to 30 m can be expected	High risk of spotting across fire breaks. Spotting up to 500 m is common.	High risk of spotting across fire breaks. Spotting up to 2 km is common.	High risk of spotting across fire breaks. Spotting over 2 km is common.
	Red flag warnings			*C-Haines >95th Percentile (approx 5-7)* *wind change forecast during the peak of the afternoon*	*C-Haines >95th Percentile (approx 5-7)* *wind change forecast during the peak of the afternoon*	*C-Haines >95th Percentile (approx 5-7)* *wind change forecast during the peak of the afternoon*	*C-Haines >95th Percentile (approx 5-7)* *wind change forecast during the peak of the afternoon*
Prescribed burn implications	*NB. Descriptions here are offered as a general guide and appropriate fire behaviour models should be consulted to achieve burn prescription outcomes.*	Marginal P/B conditions, even at peak of the day. Fire may fail to sustain over fuel discontinuities.	Suitable fire behaviour for hazard reductions and ecosystem management burns.	Conditions suitable for prescribed burning provided sufficient, secure, non-flammable boundaries are present. Fire behaviour too intense to suppress fire without relying on non-flammable boundaries.	Conditions will be unsuitable for P/B. Potential rates of spread, long flame lengths and short distance spotting pose a serious risk of burn escapes and fire intensity may be inconsistent with land management objectives.	Conditions will be unsuitable for P/B. Potential fireline intensity and rates of spread pose a serious risk to firefighter safety and the community.	Forget it! Conditions will be unsuitable for P/B.
Fire suppression & containment		Fire control relatively simple. Mostly contained within simple, natural boundaries, road networks and fuel breaks >2 m. Delayed containment possible with suitable conditions. Head-fire readily suppressed with offensive, direct attack techniques. Initial attack success is typically very high.	Fire control mostly simple with sufficent resources and becoming more complex at higher intensities. Fires typically contained within natural boundaries, road networks and fuel breaks >5 m. Offensive, direct attack techniques on head-fire or flanks largely successful in fire control. Delayed containment sometimes possible with suitable conditions.	Fires generally becoming more complex and require more resources to control. Combinations of direct, indirect or parrallel attack may be neccesary for fire control. Requires increased effort and resources to contain fire within existing road networks and fuel break boundaries. Fires typically requiring fuel breaks 10-25 m wide and supported by pumps to acieve containment (control lines >5 m for flanks and back-fires).	Head-fire control very difficult with fuel breaks 25-50 m wide supported by tankers required for containment (control lines >10 m for flanks and back-fires). Personnel positioned down-wind and to the flanks of the fire should be made aware of the high risk of the fire jumping fire-breaks. Offensive strategies likely to be unsuccessful during the peak of the day, with focus largely centered on defensive strategies. Fire control is likely to be difficult and require increased resourcing.	Direct attack on fire not possible with fire control unlikely until conditions ease. Fuel breaks >100 m wide and supported by tankers are required for containment (control lines >10 m and supported by pumps for flanks and back-fires). Offensive strategies could position crews in danger. Essential no personnel be positioned down-wind or to the flank of the fire unless they have safe fuel-free zones to retreat into. Focus will be largely based on defensive strategies, ensuring firefighter and community preparedness and safety. Conditions on the fireground are likely to be extremely windy.	Fire control not possible until conditions ease and the level of fire behaviour is reduced. Focus will be largely based on defensive strategies, ensuring firefighter and community preparedness and safety. Offensive strategies could position crews in danger. Essential no personnel be positioned down-wind or to the flank of the fire unless they have safe fuel-free zones to retreat into. Conditions on the fireground are likely to be extremely windy.
	Red flag warnings			*Wind change forecast - potential conditions for 'dead man zone'*	*Wind change forecast - potential conditions for 'dead man zone'*	*Wind change forecast - potential conditions for 'dead man zone'*	*Wind change forecast - potential conditions for 'dead man zone'*
Consequences	Community loss (life & house):				High likelihood of pasture/crop/stock loss together with loss of rural assets such as fencing, machinery and buildings.	Increasingly high likelihood of pasture/crop/stock loss together with loss of rural assets such as fencing, machinery and buildings. Limited visibility due to smoke and dust.	Extremely high likelihood of pasture/crop/stock loss together with loss of rural assets such as fencing, machinery and buildings. Very limited visibility due to smoke and dust. Very high risk to the community related to inappropriate pre-considered plans, inadequate sheltering.
	Impact on infrastructure:					Strong winds are likely to impact infrastructure (e.g. power lines) and fall trees increasing the likelihood of obstructed roads and power outages.	Strong winds are very likely to impact infrastructure (e.g. power lines) and fall trees resulting in a high likelihood of obstructed roads and power outages.
	Firefighter safety:				Increased risk to firefighter safety	Increased risk to firefighter safety	Increased risk to firefighter safety
	Maximum potential fire area (without suppression):	Fires that are likely <1 ha	Possible fires up to 150 ha	Possible fires up to 850 ha	Possible fires up to 3,500 ha	Possible fires up to 15,000 ha	Large area fires exceeding 4,500 ha and potentially exceeding 15,500 ha
	Maximum potential fire perimeter (without suppression):	Fire perimeters that are likely <0.5 km	Possible fire perimeters up to 5 km	Possible fire perimeters up to 10 km	Possible fire perimeters up to 20 km	Possible fire perimeters up to 45 km	Large fire periemeters exceeding 35 km and potentially exceeding 45 km

Assumptions and methodology

Flame heights are determined using Marsden-Smedley etal 1999 equation for flame height (based on head-fire ROS, site productivity and site age)

Rates of Spread are based on those categorised in Table 9 of Marsden-Smedley etal 1999

Spotting distances are based on descriptions within Table 9 of Marsden-Smedley etal 1999

Potential fire area and perimeter are based on a 4 hour fire run under max FDR with a range of LB ratio (FOREST) as determined by wind speeds ranging from 10-40 km/hr (as per Cruz et al 2015 (on the back page)) and a fuel load varying from 10-20 t/ha

[1] Marsden-Smedley etal. 1999

2.8 Expectations, capacity and continuous improvement

Given the complexity of fire danger rating together with necessary evaluation and improvements that can only come with time, it would be unrealistic to have expectations a new fire danger rating system would be complete and performing consistently well in the relatively short development and evaluation period given to the NFDRS project (Jolly, 2009). In the absence of other agreed components of the NFDRS (i.e. ignition likelihood, suppression, fire impact), the Research Prototype is a 'fire behaviour index' based on the best science available.

Developing a fire danger rating system with improved practical fire management applications is driven by a combination of scientific knowledge and operational experience (Taylor and Alexander, 2006). So it is essential that managers of the system commit to continuous improvement as new information from fire experiments and bushfires becomes available (Luke and McArthur, 1977) with a team of skilled individuals that provide oversight and calibration of the system (Jolly, 2009). Analysis of fire events through case studies becomes particularly important to inform and use an evolving system.

Cheney and Gould (1995) noted that any changes over time to the fire danger rating by incorporating new fire spread equations have subsequent impacts on the thresholds set between categories and the number of fires that fall into each category. In a system, whereby continuous improvement is encouraged, this must always be a consideration and as such, any consequences of implementation of new fire behaviour and spread models would need to be investigated prior to going live.

2.9 Recommendations

The live trial evaluation of the Research Prototype provided an excellent opportunity for operational fire managers to test-drive the FDR Tables for their ease of use, appropriateness of thresholds and potential to aid fire management decision making in terms of fire behaviour, prescribed burning, suppression difficulty and potential impacts. While some issues and areas of improvement were identified during the live trial evaluation (outlined below), we also recognise the importance of following up participants to collect feedback that could be used to guide improvements and revisions to the Research Prototype and specifically the appropriateness of thresholds and descriptors we've used to define it.

A list of recommendations are provided here to guide improvements to the Research Prototype FDR tables:

- Survey of live trial participants. Conduct a survey of live trial participants to gather feedback and determine areas where the FDR Tables can be improved, specifically the appropriateness of thresholds and descriptors we've used to define fire danger.

- Revise descriptions of potential fire area and perimeter. Some confusion was observed throughout the live trial relating to descriptions of potential fire area and perimeter, what the values were indicative of and how they were calculated. It would also be worth considering alternative and/or additional measures of fire impact such as maximum or average burnt area, forward spread distance and perimeter at various elapsed times as well as minimum firebreak required to stop a head fire such as those described by McArthur (1966) and Fogarty and Alexander (1999). One way this may be achieved is by utilising mapped, past fires that have burnt after 2010 so that these can be linked with the NFDRS forecast of fire danger.

- Revise descriptions for use of initial attack and offensive strategies. Particular attention needs to be directed to improve descriptions of suppression strategies as they related to opportunities for initial attack and offensive strategies in the upper, most impacting categories. For example, during the Kilmore East and Taliesen fires (Chapter 9), despite the Category 6 and 5 ratings respectively, there were many instances of successful offensive strategies including initial attack on new fires and spot fires using direct attack techniques, so assuming all firefighting efforts would be focused on defensive strategies in these types of fires would be incorrect.

3 Fire behaviour models

In Australia, over 60 years of scientific research has produced numerous fire behaviour models. As fires spread and behave differently in different fuels, specific models have been built for major fuel types; e.g. grasslands, forests and shrublands (Cruz et al. 2015a). Over time, fire behaviour models for certain fuel types have been revised or adjusted, and new models have been developed for specific conditions or fuel types that were not explicitly described before (e.g. pine plantations). For some fuel types, multiple models have been developed (e.g. dry eucalypt forest – McArthur 1967, 1973a; Cheney et al. 2012).

In general, all fire behaviour models use some kind of weather input (e.g. wind speed), fuel moisture content (as a function of relative humidity and air temperature), and fuel information. Some models require more specific input such as grassland curing (Cheney et al. 1998; Cruz et al. 2015b), or fuel strata characteristics such as Fuel Hazard Scores or Fuel Hazard Ratings (Cheney et al. 2012). As outputs, all fire behaviour models provide a measure of rate of spread (m hr^{-1}), and some provide a measure of spotting (m) or flame height/length (m). Another measure we are taking into account as part of the Research Prototype is fireline intensity (kW m^{-1}), as described and discussed by Byram (1959).

Table 3.1 gives an overview of the fire behaviour models that we have selected for the Research Prototype, after consultation with well-established fire researchers at the science workshop at NSW RFS headquarters on 07/06/2017. The selected models and their characteristics are further discussed in the subchapters below.

Table 3.1 Fire behaviour model used for the Research Prototype project

Fire behaviour model	Short name	Reference	Fuel type
(1) CSIRO Grassland fire spread meter	Grassland	Cheney et al. (1998) and Cruz et al. (2015b)	Continuous grasslands
(2) CSIRO Grassland for northern Australia	Savanna	Cheney et al. (1998) and Cruz et al. (2015b)	Grassy woodlands and open forests
(3) Desert spinifex model	Spinifex	Burrows et al. (2017)	Hummock grasslands
(4) Buttongrass moorlands model	Buttongrass	Marsden-Smedley and Catchpole (1995b)	Buttongrass moorlands
(5) Dry Eucalypt Forest Fire Model (DEFFM or “Vesta”)	Forest	Cheney et al. (2012)	Shrubby dry eucalypt forests
(6) Mallee heath model	Mallee heath	Cruz et al. (2013)	Semi-arid mallee heath
(7) Heathland model	Shrubland	Anderson et al. (2015)	Temperate shrublands
(8) Adjusted Pine model	Pine	Cruz (pers. comm.)	Pine plantations

All models have their own limitations and assumptions. These are more extensively described in the original papers, and summarised in “A guide to rate of Fire Spread Models for Australian vegetation” (Cruz et al. 2015a). Some decisions had to be made before we could use the fire behaviour models for the Research Prototype. These decisions and considerations are described in more detail in the relevant subchapters below.

However, there remain fuel types for which fire behaviour models have not (yet) been developed (e.g. rainforests, arid shrublands, wetlands), as they are generally less flammable than the fuel types mentioned in Table 3.1. Also, human influenced fuel types such as crops and horticultural fields, or rural and (semi-)urban areas lack specific fire behaviour models. The classification of these fuel types is described in chapter 4.

3.1 Measures of fire behaviour

All fire behaviour models available for use in the Research Prototype produce rate of spread[1] as their primary output. In all cases rate of spread is a function of:

- Wind speed;
- Fuel moisture, either as an explicit variable calculated using a sub-model, or implicitly through the inclusion of air temperature and humidity in the model; and
- Fuel parameter(s).

Other derived variables, which were used in the Research Prototype, are:

Flame height, most commonly modelled as a function of rate of spread and a fuel parameter (e.g. fuel load, or fuel height), or back calculated from fire line intensity. For grass and shrub fires, or surface fires burning through the understory, flame length could be a more informative variable than flame height. But, because of the lack of published flame length equations (apart from Alexander 1982, M. Cruz. pers. comm.), and because of the limited time to develop the Research Prototype, it was decided to calculate flame height only. We do acknowledge that flame length calculations for certain fuel types deserve more attention.

- Fireline intensity, calculated from rate of spread and fuel load (Byram 1959).
- Spotting distance, for forest fuel types only, spotting distance was calculated using an equation fit to the Vesta/DEFFM spotting model (Gould et al. 2007a, K. Tolhurst pers. comm.[2]). This takes wind speed, estimated rate of spread and surface fuel hazard scores into account

Given these relationships, it is expected that all four output variables, i.e. rate of spread, flame height, fireline intensity and spotting distance, will be correlated. However, because flame dimensions and intensity include fuel 'twice' in their calculation, they are more sensitive to fuel parameters. This may be undesirable given that there is usually considerable uncertainty about fuel amounts. On the other hand, it may be desirable where rate of spread is only weakly correlated with fuel amount but it has a direct effect on suppression difficulty. Because it is relatively simple to calculate these four variables (spotting for forests only), we explored the use of all of them to examine which is most useful.

How these fire behaviour measures affect fire danger rating, or better said, how the fire danger rating thresholds were defined based on the above mentioned fire behaviour variables, is described in the previous chapter (chapter 2 – rating definitions).

3.1.1 Integral measures of fire danger

'Power of fire' is a measure of the rate of energy release from a fire, calculated as the integral of intensity around the perimeter of a fire, or as the rate of area growth x fuel load (Harris et al. 2012). Empirical studies (Harris et al. 2012) have shown power of fire for historical events to be well correlated with the *magnitude* of house loss, much better than FFDI or similar measures. While power of fire is a useful measure of the magnitude of a given fire (similar to cyclone categories) it is likely unsuited for use in the Research Prototype because power of fire combines the size and intensity of a fire. For a fire danger rating system, there is no information on the size of potential fires. During the 2015-16 NSW FDR trial, we attempted to estimate power of fire by simulating the ignition of fires at hourly intervals and allowing them to grow for a prescribed, arbitrary amount of time. These calculations were dominated by grass fires which had high rates of spread, outweighing their low fuel load relative to forests. This result runs counter to the observation that most house loss in Australia has been due to forest fires. If power is normalised to remove size then it reverts to intensity. We note as a further research question the relative merits of intensity and power as predictors of the *rate* of house loss.

[1] In m s^{-1}. The units we used for the Research Prototype are given in Table 3.3.

[2] As in the Advanced Fire Behaviour Prediction Standard Workbook, revised version 18 March 2015

It has been anecdotally observed that days with longer periods of elevated FDR are more dangerous than those with short peaks. This could be encapsulated in a fire danger rating that combines both the peak FDR and time above some threshold as an integral measure, ‘fat FDR’ (M. Plucinski pers. comm.), similar to the ‘hours above X’ product currently produced. While this approach has some merit it must be used with care as it has the potential to introduce degeneracy into the rating system, e.g. same rating for short Severe peak and long Very High peak, further compounding the issue of days with high wind speed and low temperature vs low wind speed and high temperatures. For the Research Prototype we did not use this measure and recommend retaining the current practice of using ‘time above X’ maps to assist with interpretation of FDR forecasts.

3.1.2 Other measures of fire behaviour and potential

The behaviour of the head fire is the core of the fire behaviour index and rating. However this is not the whole story. Other things which could be considered are:

- Atmospheric stability. If the atmosphere is unstable, or could be with the addition of heat, then fires which become large enough to interact with the upper atmosphere are potential more dangerous because they may draw down dry-windy air from aloft, form pyrocumulus clouds, etc. The most readily available measure of instability is the CHaines index (Mills and McCaw 2010). While CHaines has some limitations (e.g. where the mixed layer is very deep both levels used in calculation of CHaines may be in the mixed layer) it has proved to be useful. It is to be expected that CHaines would affect fire danger rating only at the upper range of the driving fire behaviour metric (e.g. intensity, flame height), since it is only under these conditions that fires are able to grow large enough and output sufficient heat to become coupled with the upper atmosphere. For the Research Prototype, CHaines was included in the calculations as a ‘red flag’ warning only. A flag was forecast at a point if the daily maximum CHaines exceeded the climatological 95th percentile value (See Chapter 12). A flag was forecast for a fire weather area if at least 10% of its areas exceeded the 95% percentile values. Towards the end of the live trial, a forecaster created pyro-convection outlook product became available, produced by the BoM’s Extreme Weather Desk. The Pyro-Cb outlook was displayed on the live trial static ratings page as a map. There were no Pyro-Cb observations recorded during the time the outlook was available so it was not formally evaluated.
- Spotting. Short and long distance spotting contributes to both the difficulty of suppression and potential to damage assets of fires burning in forests. Bark characteristics derived from fuel type maps, and spotting models will be used where there is significant spotting potential. Spotting is a local phenomenon linked to areas of forest with both bark fuels and sufficiently high fire behaviour conditions. As such, spotting was not incorporated directly into the FDR but was included in the outputs by displaying the 90th percentile value on the static daily ratings web page for fire weather areas that included forest.
- Wind change. Wind changes can be associated with increased fire danger through two mechanisms: instability in the vicinity of the change, and dramatic increases in fire size where the flank of an existing fire becomes the head fire. This behaviour has been associated with some of the most significant fire events in Australia (Cruz et al. 2012). While wind changes may have complex and varied structure, Huang and Mills (2006) have developed a wind change danger index which summarises various characteristics of changes into a single index. This index was included in the Research Prototype as a ‘red flag’ warning both for individual grid cells where the index exceeded 40, and for fire weather areas where at least 10% of the area exceeded 40.

3.2 Modifiers of fire behaviour

3.2.1 Drought and fuel availability

Dead fuel moisture is an important determinant of the potential for fires to start and spread (Matthews 2014). Two main approaches have been used including the effect of rainfall on operational fire spread models: increasing moisture content above the fibre saturation point, e.g. Marsden-Smedley and Catchpole (1995a), or reducing the amount of fuel available to burn e.g. the McArthur drought factor (Noble et al. 1980).

Live fuel fraction is also important for some fuel types, notably grasslands (Cruz et al. 2015c) and spinifex fuels (Burrows 2018). This effect may be included either using a curing function (e.g. Cheney and Sullivan 2008) or by including the live component in a bulk moisture content estimate (Burrows 2018).

Unfortunately, a complete set of drought or fuel availability models has not yet been developed for the eight major fuel types used in the Research Prototype (Table 3.2). For the grassland, savanna, spinifex and buttongrass models we used the recommended fuel availability model with observed and forecast inputs as required.

For the remaining four fuel types we adapted existing models. Some of the modifications have been made without a proper scientific foundation and we recommend that development of fuel availability models is a high research priority.

Table 3.2 Fuel availability models

Fuel type	Recommended fuel availability model	Adapted fuel availability model
Grassland	Cruz et al. (2015c) curing function	Recommended, using observed curing.
Savanna	Cruz et al. (2015c) curing function	Recommended, using observed curing.
Spinifex	Burrows (2017)	Recommended, using modelled soil moisture and observed time since fire.
Buttongrass	Marsden-Smedley and Catchpole (1999)	Recommended, using observed and forecast median rainfall.
Forest	None	Drought factor used to modify fuel amount
Mallee heath	None	Marsden-Smedley and Catchpole (1999)
Shrubland	None	Marsden-Smedley and Catchpole (1999)
Pine	Fine Fuel Moisture Code based models (van Wagner and Forest 1987)	Drought factor used to modify fuel amount

3.2.1.1 Forests

The DEFFM/Vesta model (Cheney et al. 2012) does not include fuel availability or rainfall effects in its fuel moisture models and no recommendations are made for treatment of these effects on either fuel moisture or fuel hazard scores. While a model exists which can be used for forest fuel moisture (e.g. Matthews 2006) implementation of a system of this complexity was not feasible for the Research Prototype. Instead, we developed simple fuel availability curves as functions of drought factor loosely based on fire occurrence observations presented by Cawson et al. (2017).

The <u>fuel availability modifier for dry forests</u> is (Fig. 3.1a):

$$Fuel\_availability = (DF \ * 0.1) \tag{3.1}$$

Where:
Fuel_availability = fraction of fuel available for combustion (value between 0 and 1)
DF = drought factor as calculated by the bureau of meteorology

The fuel availability modifier used for wet forests, is a logistic function (Fig. 3.1b):

$$Fuel\_availability\_WF = \left(\frac{1.135}{1 + e^{2*(9-DF)}}\right) \quad (3.2)$$

For all DEFFM/Vesta fire behaviour calculations both fuel hazard scores and fuel loads were multiplied by the fuel availability factor. Fuel heights were not modified. Development of more suitable methods of including fuel availability effects on the DEFFM/Vesta model is a high priority for future research and development.

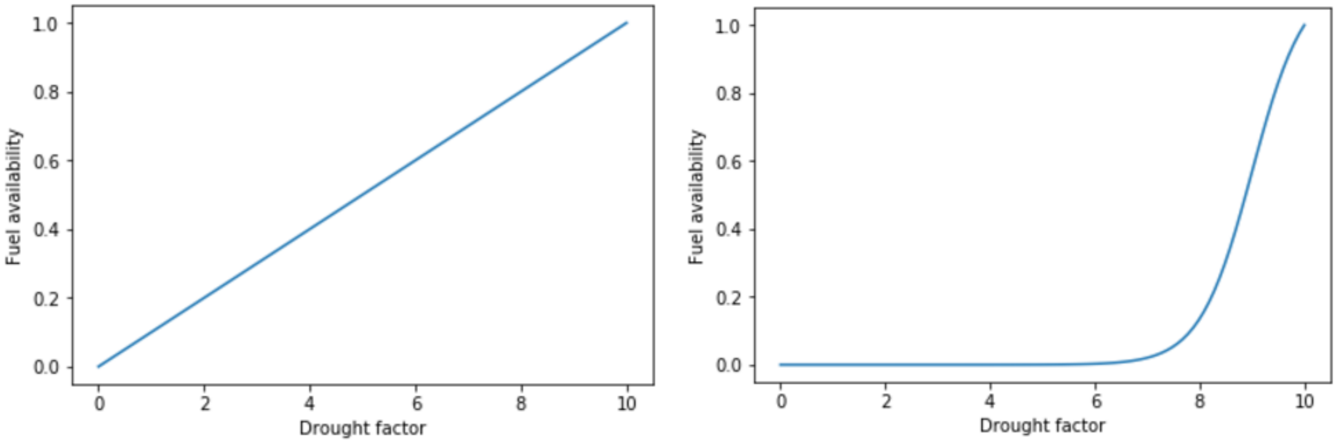

Fig. 3.1 (Left) Fuel availability models for dry forest, and (Right) wet forests.

3.2.1.2 Mallee heath and shrubland

The Cruz et al. (2013) mallee heath and Anderson et al. (2015) shrubland models do not include fuel availability or rainfall effects in their fuel moisture models and no recommendations are made for treatment of these effects on either fuel moisture or fuel cover/height. Because these fuel types are expected to become flammable more rapidly than a forest fuel type, we used the Marsden-Smedley and Catchpole (1999) fuel moisture modifier function originally developed for buttongrass. While these fuel types are structurally dissimilar, the buttongrass fuel moisture modification function has a response time of 1-2 days, making it suitable for fuel types with a large near-surface and elevated fuel component.

3.2.1.3 Pine

While a well-tested fuel moisture model is part of the Canadian Fire Weather Index (FWI) system (van Wagner and Forest 1987) it was not possible to implement this within the constraints of the Research Prototype. Instead we used a simple function to modify dead fuel amount (M. Cruz pers. comm.):

$$Fuel\ load = 0.3 + 0.075 * DF \quad (3.3)$$

Foliar moisture content was also modified:

$$Fuel\ moisture\ content = 150 - 5 * DF \quad (3.4)$$

Implementation of the Canadian FWI moisture models would be an obvious improvement for future work.

3.2.2 Build-up phase

Most available fire behaviour models assume fully dry conditions and a fully developed head fire e.g. CSIRO grassland (after allowing for curing factor), Vesta/DEFFM, and the heathland model. Since no satisfactory model exists for the build-up phase of a fire except in very mild conditions (Sullivan et al. 2013), and since we are interested in the maximum potential of fire spread, we calculated the maximum potential rate of spread, assuming that the fire has reached its quasi-steady state. Consequently, we might be over-predicting in cases where the fire is still in an initial state, or when we are dealing with damp fuels. This was investigated in the live trial by flagging fires that appeared to have been suppressed during the initial attack phase for separate analysis. However, defining initial attack is a challenging task Plucinski (2013); see further discussion in the results chapters of this report.

3.2.3 Topographic effects

Fires burning in hilly country are affected by topography at different scales. At a local scale, fires burn uphill faster and downhill slower than on flat ground. The accepted models for this are:

- For **uphill slopes** (Noble et al. 1980):

$$ROSpos.slope = ROS * e^{(0.0687\theta)} \quad (3.5)$$

- For **downhill slopes** (Sullivan et al. 2014):

$$ROSneg.slope = ROS * \frac{2^{(-\frac{\theta}{10})}}{2(2^{(-\frac{\theta}{10})}) - 1} \quad (3.6)$$

Where θ is slope in degrees.

Topography can also generate more complex fire behaviours such as lateral spread on lee slopes (Simpson et al. 2014; Simpson et al. 2016), or generation of mass spotting both of which can contribute to fire spread and place fire fighters at risk (Lahaye et al. 2018) Fire-fighting in mountainous terrain may be more challenging than on flat ground due to the difficulty of moving ground resources and lower density of track networks. On the other hand, topography may also offer opportunities for suppression by allowing use of up- or downslopes to facilitate back-burning or providing natural moisture boundaries.

On balance, it seems likely that steep topography should increase fire danger. However, there are no accepted models for estimating how much higher it should be, nor is it sensible to simply increase fire danger following equation 3.5. For the Research Prototype we did not include topographic effects. The system was built to allow inclusion of slope as a variable in future if required.

3.3 Detailed model descriptions

In the sections below, the eight selected fire behaviour models are discussed in detail. We tried to be as consistent as possible with the use of units. The units for input and output values are given for each variable in the specific section, and summarised here in Table 3.3. However, because of the different sources for the models and equations, sometimes it is/was needed to make conversions. For example, for the calculation of fireline intensity, conversions had to be made for fuel load from tonnes per hectare (tonne h^{-1}) to kilograms per square meter (kg m^{-2}), and for rate of spread from meter per hour (m h^{-1}) to meter per second (m s^{-1}). We encourage the reader of this chapter to be vigilant of these conversions.

Table 3.3 Input and output variables and their units, as used in the NFDRS Research Prototype project

Input/output variable	Unit
Wind speed	km h^{-1}
Temperature	°C
Relative humidity	%
Fuel load	tonnes ha^{-1}
Fuel moisture content	%
Curing	%
Heat yield	kJ kg^{-1}
Fuel cover (e.g. spinifex) or overstorey cover (e.g. mallee heath)	%
Near surface fuel height	cm
Elevated fuel height	m
Overstorey height	m
Rate of spread	m h^{-1}
Fireline intensity	kW m^{-1}
Flame height	m

3.3.1 CSIRO grassland fire spread model (Cheney et al. 1998)

This model predicts fire spread in continuous grasslands based on 10 m wind speed, dead fuel moisture content and degree of curing.

To describe the relationship between rate of spread and wind speed, a linear function is used for 10 m wind speeds below 5 km h^{-1} and a power function is used at 10 m wind speeds above 5 km h^{-1}.

Models for three types of grasslands are presented in the original paper (Cheney et al. 1998), i.e. (i) natural (undisturbed/ungrazed) grasslands, (ii) cut or grazed grasslands and (iii) eaten-out grasslands. Although the effect of fuel load on rate of spread in grasslands is still a topic of active research (Cruz et al. 2017b), we used the following thresholds in the Research Prototype:

(i) Grass fuel load ≥ 6 t ha^{-1} = natural grasslands
(ii) Grass fuel load between 3 and 6 tha^{-1} = grazed grasslands
(iii) Grass fuel load ≤ 3 t ha^{-1} = eaten out grasslands

This classification was designed to make use of current fuel reporting protocols for grass which report load and curing only. A future protocol which collects height and cover separately may be more suitable. Reported fuel load was used to select grass condition for some grassland types, while the grazed or eaten out condition was automatically selected for less flammable fuel types (see Table 4.1 and fuel type descriptions in Chapter 4).

- For natural grasslands (class (i)):
  - If 10 m wind speed < 5 km h^{-1}, the rate of spread is calculated as:

$$ROS_{natural} = (0.054 + 0.269 * U_{10}) * \Phi_{MC} * \Phi_{curing} * 1000 \tag{3.7}$$

  - If 10 m wind speed ≥ 5 km h^{-1}, the rate of spread is calculated as:

$$ROS_{natural} = (1.4 + 0.838 * (U_{10} - 5)^{0.844}) * \Phi_{MC} * \Phi_{curing} * 1000 \tag{3.8}$$

Where:
ROS = rate of spread in m h^{-1} [note: for consistency, the number was multiplied by a 1000 to convert from km h^{-1} to m h^{-1}]
U_{10} = 10 m wind speed (km h^{-1})
Φ_{MC} = fuel moisture coefficient
Φ_{curing}= curing coefficient

- For grazed grasslands (class (ii)
  - If 10 m wind speed < 5 km h^{-1}, the rate of spread is calculated as:

$$ROS_{grazed} = (0.054 + 0.209 * U_{10}) * \Phi_{MC} * \Phi_{curing} * 1000 \tag{3.9}$$

  - If 10 m wind speed ≥ 5 km h^{-1}, the rate of spread is calculated as:

$$ROS_{grazed} = (1.1 + 0.715 * (U_{10} - 5)^{0.844}) * \Phi_{MC} * \Phi_{curing} * 1000 \tag{3.10}$$

(Parameters as described above)

- For eaten out grasslands (class (iii)
  - If 10 m wind speed < 5 km h^{-1}, the rate of spread is calculated as:

$$ROS_{eaten\ out} = (0.054 + 0.209 * U_{10}) * \Phi_{MC} * \Phi_{curing} * 1000 \tag{3.11}$$

  - If 10 m wind speed ≥ 5 km h^{-1}, the rate of spread is calculated as:

$$ROS_{eaten\ out} = (0.55 + 0.357 * (U_{10} - 5)^{0.844}) * \Phi_{MC} * \Phi_{curing} * 1000 \tag{3.12}$$

(Parameters as described above)

Fuel Moisture Coefficient (Φ_{MC}), with application bounds of 2-24% is given below:

Moisture content (MC in %) is calculated based on McArthur (1966):

$$MC = 9.58 - 0.205 * T + 0.138 * RH \tag{3.13}$$

Where:
T = temperature (°C)
RH = relative humidity (%)

- If MC < 12%,

$$\Phi_{MC} = e^{(-0.108*MC)} \tag{3.14}$$

- If MC > 12% and U_{10} < 10 km h^{-1},

$$\Phi_{MC} = 0.684 - 0.0342 * MC \tag{3.15}$$

- If MC > 12% and U_{10} > 10 km h^{-1},

$$\Phi_{MC} = 0.547 - 0.228 * MC \tag{3.16}$$

The curing coefficient (Φ_{curing}) of Cheney et al. 1998 has been superseded by a new function (Cruz et al. 2015c). The previous function assumed that (i) fire spread would normally not occur at grass curing values less than 50%, and (ii) the major influence of grass curing on fire spread occurs when grass curing is between 70 and 90%. However, Cruz et al. (2015c) found that experimental fires did spread at curing values as low as 21%. The new curing equation is:

$$\Phi_{curing} = \frac{1.036}{1 + 103.989 * e^{(-0.0996*(curing-20))}} \tag{3.17}$$

Where:
curing = degree of grass curing in %.

For estimating fireline intensity, we use Byram's (1959) equation:

$$I_B = h * w * ROS \tag{3.18}$$

Where:
I_B = fireline intensity (kW m^{-1})
h = heat yield[3], assumed 18,600 kJ kg^{-1}
w = fuel load, as reported or estimated from the best data available, in kg m^{-2}. [note: fuel loads need to be converted from tonne ha^{-1} to kg m^{-2} – divide tonne ha^{-1} by 10].
ROS = rate of spread (m s^{-1}) [note: we will have to convert from m h^{-1} to m s^{-1} - simply divide ROS by 3600]

For flame height (in m) the following equations were used (M. Plucinski, pers. comm.):

[3] Please note, based on Table 3.1 in Cheney and Sullivan (2008), this value for heat yield in grass species could be lower than the commonly accepted 18,600 kJ kg^{-1}. This needs further investigation.

- For natural grasslands (class (i)):

$$F\_height\_natural = 2.66 * \left(\frac{ROS/1000}{3.6}\right)^{0.295} \quad (3.19)$$

- For grazed and eaten out grasslands (class (ii and iii):

$$F\_height = 1.12 * \left(\frac{ROS/1000}{3.6}\right)^{0.295} \quad (3.20)$$

3.3.2 CSIRO for northern Australia (Cheney et al. 1998 - adjusted)

In woodland-like vegetation types, i.e. grass with a (sparse) overstorey of trees (such as savannas), the presence of trees will reduce the wind speed near the ground and therefore the rate of spread through the surface and near-surface fuels. For these fuel types we still used the grassland model as presented above, but, a wind speed reduction factor and consequently a rate of spread reduction factor (WRF) were used following the suggestions in Cheney and Sullivan (2008), see Table 3.4 below.

Table 3.4 i) ratio between wind speed at 10 m and 2 m above the ground, and (ii) relative rate of spread in different vegetation types.

Type of vegetation	(i) Ratio 10- and 2- m wind speed	(ii) Rate of spread relative to spread in the open
Open grasslands	10:8	1.0
Woodlands (5-7 m tall)	10:6	0.5
Open forests (10-15 m tall)	10:4.2	0.3

3.3.3 Desert spinifex model (Burrows et al. 2017)[4]

Estimating fire behaviour in spinifex vegetation follows a two-step process: (i) determining the probability that a fire will spread ("go/no-go"); (ii) predicting the rate of spread, flame height and intensity.

To determine if a fire will spread, a spread index (SI) is calculated as follows:

$$SI = 0.336 * U_e + 0.308 * Cov_{ns} - 0.451 * MC - 7.213 \quad (3.21)$$

Where:
U_e = wind speed at 1.7 m (eye-level) (km h^{-1}) – this was achieved by dividing the 10 m wind speed by a factor 1.35
Cov_{ns} = live and dead spinifex fuel cover (and other vegetation < 2 m high) (%)
MC = clump profile moisture content (%)

If SI < 0 it is very unlikely that the fire will spread. If SI > 0, the fire is likely to spread. The more positive the SI-value, the more likely it is for a fire to spread and higher rates of spread can be expected. The probability of fires spreading is then determined by the following function:

[4] In April 2018, a newer version of the spinifex model was published. This should be incorporated in a newer version of the NFDRS.

$$P = \frac{1}{1 + e^{(-SI)}} \quad (3.22)$$

Where:
SI = spread index, as determined in equation 3.21
P = probability of spread; spread likely when P > 0.5

Table 3.5 Spread Index, probability of spread and potential rate of spread

Spread index (SI)	Probability of fire spread	Potential ROS (m/h)
SI ≤ 0	P ≤ 0.5 (unlikely to spread)	0 – 350
0 < SI ≤ 2	0.5 < P ≤ 0.9 (will spread)	351 – 1000
2 < SI ≤ 6	P > 0.9 (will spread)	1001 – 3000
6 < SI ≤ 10	P > 0.9 (will spread)	3001 – 5000
10 < SI ≤ 15	P > 0.9 (will spread)	5001 – 7000
15 < SI ≤ 20	P > 0.9 (will spread)	7001 – 9000
20+	P > 0.09 (will spread)	9001+

The next step is to calculate the likely rate of spread:

$$ROS = 143.4 * U_e + 28.7 * Cov_{ns} - 161.7 * MC + 708 \quad (3.23)$$

Where:
ROS = head fire rate of spread (m h^{-1})
U_e = wind speed at 1m70 (eye-level) (km h^{-1}) this is achieved by dividing the 10 m wind speed by a factor 1.35
FL_{ns} = (near surface) fuel load (tonne ha^{-1}, oven dry)
Cov_{ns} = live and dead spinifex fuel cover (%)
MC = clump profile moisture content (%)

For estimating fuel load we used:

$$FL_{ns} = 2.046 * TSF^{0.42} \quad (3.24)$$

With fuel load in tonne ha^{-1} and time since fire (TSF) in years.
(After N. Burrows pers. comm. 16/10/2017)

For estimating fuel cover we use:

$$COV_{ns} = 26.20 * TSF^{0.227} \quad (3.25)$$

With fuel cover in (%) and time since fire (TSF) in years.
(After N. Burrows pers. comm. 16/10/2017)

For estimating the moisture content of spinifex clumps we use relative soil moisture from the Australian Water Resources Assessment Landscape model (AWRA-L, Viney et al. 2015). Since older fuels have a higher proportion of dead material, corrections for the moisture content are applied.

The following fuel classes are defined based on time since fire (Table. 3.6; Burrows et al. 2015):

Table 3.6 Fuel class, time since fire and estimated cover as reported in Burrows et al. 2015

Fuel class	TSF (years)	Cover spinifex live (%)	Cover spinifex dead (%)
1	< 6	15 – 20	0
2	6 - 10	30 – 40	< 5
3	11 - 15	35 – 45	5 - 10
4	16 - 20	40 – 50	10 - 15
5	20 - 25	30 – 40	30 - 40

- For class 1 (0-5 years after fire) it is assumed that there is no dead spinifex cover, and live spinifex is too sparse to carry a fire. In case there is a continuous (>70%) cover of cured soft grass and/or herbs (e.g. after exceptional rainfall), the grassland model (Cheney et al. 1998) should be used. As we did not have access to a method for predicting or observing ephemeral grass growth this modification was not applied.
- For class 2 the following equation is used to calculate clump moisture content:

$$Class\ 2\ MC = 40(AWAP_{uf}) + 13 \qquad (3.26)$$

Where:
MC = class 2 clump moisture content (%)
$AWAP_{uf}$ = relevant “monthly relative soil moisture (upper layer) fraction” from AWRA-L (Viney et al. 2015).

Corrections for older fuels, with a higher proportion of dead fuel:

- $$Class\ 3\ MC = Class\ 2\ MC - \left(\left(\frac{1}{0.03*RH}\right)\right)*1.5 \qquad (3.27)$$

- $$Class\ 4\ MC = Class\ 2\ MC - \left(\left(\frac{1}{0.03*RH}\right)\right)*2.5 \qquad (3.28)$$

- $$Class\ 5\ MC = Class\ 2\ MC - \left(\left(\frac{1}{0.03*RH}\right)\right)*3.5 \qquad (3.29)$$

With the following thresholds:
If Class 3 MC ≤ 14%, then set Class 3 MC to 14%.
If Class 4 MC ≤ 13%, then set Class 4 MC to 13%.
If Class 5 MC ≤ 12%, then set Class 5 MC to 12%.
RH = relative humidity (%)
(Pers. comm. N. Burrows 16/10/2017)

If trees are present in the overstorey, we used a wind reduction factor (WRF) to the rate of spread as suggested in Table 3.6.

For estimating <u>fireline intensity</u>, we use Byram's (1959) equation:

$$I_B = h * w * ROS \tag{3.30}$$

Where:
I_B = fireline intensity (kW m^{-1})
h = heat yield[5], assumed 18,600 kJ kg^{-1}
w = FL_{ns} (from equation 3.24) [converted to kg m^{-2}]
ROS = rate of spread (m s^{-1})

<u>Flame height</u>

$$F\_height = 0.097 * ROS^{0.424} + 0.102 * FL_{ns} \tag{3.31}$$

Where:
ROS = head fire rate of spread (m h^{-1})
FL_{ns} = fuel load (tonne ha^{-1}, oven dry)

3.3.4 Buttongrass moorlands model (Marsden-Smedley & Catchpole 1995b)

Typical Tasmanian buttongrass moorlands burn very differently compared to other grasslands, heathlands or forests. As long as the fuel moisture content is below 70% and the age of the buttongrass moorlands is over 3 years, fires have been reported to spread - even over standing water. The threshold of dead fuel moisture content at which fires can be sustained in these moorlands is much higher (70%) compared to Eucalyptus litter (16-20%) or pine needles (30%) because moisture content is measured as a bulk value mixing live and dead fuels in contrast to other fuel types which consider dead fuel moisture only.

The key components of fire spread in buttongrass moorlands are (i) the openness of the moorlands (i.e. non-forested nature) and therefore the exposure to wind. And (ii) the substantial quantity of suspended dead fuels.

In addition to the fire behaviour model as presented in Marsden-Smedley and Catchpole (1995b), which basically describes the estimation of rate of spread, an overall report on buttongrass fire was released in 1999 (Marsden-Smedley et al. 1999[6]), where probability of sustained buttongrass moorland fires was added (see also Marsden-Smedley et al. 2001 IV). This probability of sustained fire spread ("go/no-go") is a value between 0 and 1 and is calculated as follows:

$$Probability = \frac{1}{(1 + e^{(-\left(-1+0.68*\frac{U_{10}}{1.2} - 0.07*MC - 0.0037*\frac{U_{10}}{1.2}*MC + 2.1*productivity\right))})} \tag{3.32}$$

Where:
U_{10} = wind speed at 10 m above the ground surface in km h^{-1}. To convert from 10 m to 1.7 m wind speeds 10 m winds speeds were divided by 1.2 (K. Tolhurst pers. comm.)
MC = dead fuel moisture content (%)
productivity = site productivity, low productivity sites = 1, medium productivity = 2

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[5] This value needs further investigation.
[6] Please note that in the 1999 report the equation has a typo (minus at the start of the denominator). In Marsden-Smedley et al. 2001, de correct equation was given.

In case sustained fire spread is likely, i.e. for the Research Prototype we decided to use probability > 0.5, the rate of spread can be estimated with a function that includes 1.7m wind speed, dead fuel moisture content and time since last fire (in years):

$$ROS = 0.678 * (U_{10}/1.2)^{1.312} * e^{(-0.0243*MC)} * \left(1 - e^{(-0.116*TSF)}\right) * 60 \quad (3.33)$$

Where:
ROS = rate of spread (m h^{-1}). [In the original equation (Marsden-Smedley & Catchpole 1995b) ROS was expressed in m min^{-1}. For consistency we multiplied it by 60 so ROS is expressed in m h^{-1}.]
U_{10} = wind speed at 10 m above the ground surface (km h^{-1}). To convert from 10 m to 1.7 m wind speeds, 10 m winds speeds were divided by 1.2 (K. Tolhurst pers comm.)
MC = dead fuel moisture content (%)
TSF = time since fire (yr)

For moisture content we used the equations presented in Marsden-Smedley et al. (1999):

$$MC = Rf + Hf \quad (3.34)$$

$$Rf = 67.128 * \left(1 - e^{(-3.132*rain)}\right) * e^{(-0.0858*t)} \quad (3.35)$$

$$Hf = e^{(1.660+0.0214*RH-0.0292*Tdew)} \quad (3.36)$$

Where:
MC = dead fuel moisture (%)
Rf = rainfall factor
Hf = humidity factor
rain = the amount of rain and/or dewfall in the last 48 hours (mm)
t = time since rainfall ceased (hours)
RH = relative humidity (%)
Tdew = dew-point temperature (°C)

Predicted fuel load (which is an input for fireline intensity calculations) was based on time since fire. It is unclear from the papers if total fuel will burn, or just a fraction of it (e.g. dead fuel load) and this is most likely related to the current fire weather, rate of spread and fire intensity. For the Research Prototype, we used total fuel load. This may lead to overestimation of intensity, because it is unlikely that all of this fuel will burn with a moving fire front (but there might be prolonged smouldering, Cheney 1990). The fuel load equations come from Marsden-Smedley et al. (1999):

$$Fuel_{low} = 11.73 * (1 - e^{(-0.106*TSF)}) \quad (3.37)$$

$$Fuel_{med} = 44.61 * (1 - e^{(-0.041*TSF)}) \quad (3.38)$$

$$Dead_{low} = \left(0.873 * \left(1 - e^{(-0.036*TSF)}\right)\right) * Fuel_{low} \quad (3.39)$$

$$Dead_{med} = \left(0.950 * \left(1 - e^{(-0.054*TSF)}\right)\right) * Fuel_{med} \quad (3.40)$$

Where:
$Fuel_{low}$ = total fuel load in low productivity sites (t ha^{-1})
$Fuel_{med}$ = total fuel load in medium productivity sites (t ha^{-1})

$Dead_{low}$ = dead-fuel load in low productivity sites (t ha^{-1})
$Dead_{med}$ = dead-fuel load in medium productivity sites (t ha^{-1})
TSF = time since fire (yr)

For estimating fireline intensity, we used Byram's (1959) equation:

$$I_B = h * w * ROS \tag{3.41}$$

Where:
I_B = fireline intensity (kW m^{-1})
h = heat yield, 19,900 kJ kg^{-1} for buttongrass moorlands (Marsden-Smedley and Catchpole 1995a, b)
w = total fuel load $Fuel_{low}$ or $Fuel_{med}$, as described above, but converted to kg m^{-2}
ROS = rate of spread (m s^{-1})

For flame height the following equation was suggested (Marsden-Smedley and Catchpole 1995b):

$$F\_height = 0.148 * I_B^{0.403} \tag{3.42}$$

Where:
F_height = flame height (m)
I_B = fireline intensity (kW m^{-1})

In the first few weeks of the live trial, we used the buttongrass model for low wetlands on mainland Australia (based on input from the science workshop, 07/06/2017). Since this led to clear overestimations of rate of spread and fire danger, we altered the system to model these low wetlands as chenopod shrublands instead, using the eaten-out grassland model (see chapter 4).

3.3.5 Dry Eucalypt Forest Fire Model "Vesta" (Cheney et al. 2012)

The DEFFM/Vesta was developed to predict the potential fire spread of a going fire in dry eucalypt forest with a shrubby understorey, under dry summer conditions. It assumes that the fire has reached its quasi-steady state. Even if this is not the case, for the Research Prototype Project we were interested in the maximum potential ROS, so using this model was valid.

DEFFM/Vesta incorporates the fuel structure of a forests, namely litter fuels, near-surface fuels, elevated fuels and bark. Following the paper (Cheney et al. 2012) there are two options to represent the fuel strata, i.e. by using Fuel Hazards Scores (FHS, a number ranging from 0 to 4), and Fuel Hazard Ratings (FHR, categories ranging from low to extreme). If available, using the scores (FHS) is the preferred option. If none of this information is available, default values as presented by Gould et al. (2011), CSIRO Pyropage (2015) and Plucinski et al. (2017) can be used.

After reviewing these options, we discovered that there are some inconsistencies with using the FHR option, as discussed in box 3.1. Hence for the Research Prototype we used the FHS option. In cases where we did not have information on the near surface fuel height - which is an important input for using the FHS – a default value was used. Where data was available as ratings rather than scores, these were converted as described in Chapter 4 (4.4.2).

In its general form, potential rate of spread (steady state) can be written as:

$$ROS = \Phi1(\text{wind}) * \Phi2(\text{fuel attributes}) * \Phi3(\text{moisture content}) * \Phi4(\text{slope}) \tag{3.43}$$

The functions for each of these equation components are further described below.

Wind:

When 10 m wind speed is ≤ 5 km h^{-1}, conditions are light and fire spread will be erratically in speed and direction. Therefore, the authors defined a threshold wind speed of 5 km h^{-1}.

- If U_{10} ≤ 5 km h^{-1} (and at a moisture content of 7%), ROS is predicted to be 30 m h^{-1}
- If U_{10} > 5 km h^{-1} the wind factor is represented by [1.5308 $(U_{10} – 5)^{0.8576}$] in Eq. 42 and 43.

Fuel attributes:

- Based on Fuel Hazard Scores (option 1):

$$ROS = 30 + 1.5308(U_{10} - 5)^{0.8576} * FHS_s^{0.9301} * (FHS_{ns} * H_{ns})^{0.6366} * 1.03 \tag{3.44}$$

Where:
ROS = rate of spread (m h^{-1})
U_{10} = 10 m open wind speed (km h^{-1})
FHS_s = Surface fuel hazard score (number between 0 and 4)
FHS_{ns} = Near-surface fuel hazard score (number between 0 and 4)
H_{ns} = Near-surface fuel height (cm)

However, instead of using wind speed at 10 m (U_{10}), we applied a wind reduction factor first (since the presence of trees will reduce the wind speed near the ground and therefore the rate of spread through the surface and near-surface fuels). This wind reduction factor is fuel type specific, and has been specified in our fuel look up tables (Chapter 4). The equation then becomes:

$$ROS = 30 + 1.5308(U_{mod} - 5)^{0.8576} * FHS_s^{0.9301} * (FHS_{ns} * H_{ns})^{0.6366} * 1.03 \tag{3.45}$$

Where:
U_{mod} = U_{10} * 3.0/wind reduction factor (K. Tolhurst pers. comm.)

It is important to note that for the fuel availability, we applied a drought factor modifier. This is described in paragraph 3.2.1.1 (equations 3.1 and 3.2).

Box. 3.1. When no fuel Hazard Scores are available, Fuel Hazard Ratings can be used with the following equation (option 2):

$$ROS = 30 + 2.3117 * (U_{10} - 5)^{0.8364} * e^{(\sum_{i=2}^{5} b2,i(Is)_i + \sum_{i=1}^{5} b3,i(Ins)_i)} * 1.02 \qquad (3.46)$$

which can be simplified to

$$ROS = 30 + 2.3117 * (U_{10} - 5)^{0.8364} * e^{(\beta si + \beta nsi)} * 1.02 \qquad (3.47)$$

Where:
βsi = the surface fuel coefficient for FHR_s
βnsi = the near surface fuel coefficient for FHR_{ns}

Table 3.7. Surface and near-surface regression coefficients for the FHR version of Vesta

FHR	βsi	Bnsi
Low (1)	0	0.4694
Moderate (2)	1.5608	0.7070
High (3)	2.1412	1.2772
Very high (4)	2.0548	1.7492
Extreme (5)	2.3251	1.2446

As you can see in Table 4.6, the beta values (coefficients) βsi and βnsi go down when the hazard rating goes up from high to very high (βsi) and from very high to extreme (βnsi) – highlighted in lilac. This is not only counterintuitive, but also a flaw in the model design (M. Plucinski, pers. comm.). Therefore, we avoided using this equation and stuck to option 1 (Eq. 3.43) for use in the Research Prototype after converting FHR to FHS.

For moisture content in dry eucalypt forests we used (Cheney et al. 2012):

$$\Phi 3(\text{moisture content}) = 18.35 * MC^{-1.495} \qquad (3.48)$$

Where MC is determined, depending on the time of day, as follows (Matthews et al. 2010):

- Period 1: sunny afternoon (clear skies), 12:00 – 17:00, October to March

$$MC = 2.76 + 0.124 * RH - 0.0187 * T \qquad (3.49)$$

- Period 2: overcast, day light hours

$$MC = 3.60 + 0.169 * RH - 0.0450 * T \qquad (3.50)$$

- Period 3: night time hours

$$MC = 3.08 + 0.198 * RH - 0.0483 * T \tag{3.51}$$

Where:
MC = moisture content (%)
RH = relative humidity (%)
T = temperature (°C)

For spotting we used an equation as currently used by Fire Behaviour Analysts in Australia (K. Tolhurst pers. comm.).

- If rate of spread < 150 m h^{-1}, spotting is estimated to be 50 m.
- If rate of spread ≥ 150 m h^{-1}:

$$Spotting\ distance = |176.969 * \arctan(FHS_s) * \left(\frac{ROS}{U_{10}{}^{0.25}}\right)^{0.5} + 1568800 * FHS_s{}^{-1} * \left(\frac{ROS}{U_{10}{}^{0.25}}\right)^{-1.5} - 3015.09| \tag{3.52}$$

With:
Spotting distance in m
FHS_s = Surface fuel hazard score
ROS = rate of spread (m h^{-1})
U_{10} = 10 m open wind speed (km h^{-1})

Predicted fuel load (which is an input for fireline intensity calculations) is based on the layers of fuel that are involved in the fire, and this again is based on flame height. For a general surface fire, the surface and near surface layer are included. Once the flame height is larger than 1 m, the elevated layer and bark layer are included. Once the flames are higher than 66% of the overstorey height, the canopy fuels are included as well.

The fuel loads are calculated based on Olson (1963) curves:

$$Fuel\_load_{surface} = FL_s * (1 - e^{-k_s * t}) \tag{3.53}$$

$$Fuel\_load_{near\ surface} = FL_{ns} * (1 - e^{-k_{ns} * t}) \tag{3.54}$$

$$Fuel\_load_{elevated} = FL_{el} * (1 - e^{-k_{el} * t}) \tag{3.55}$$

$$Fuel\_load_{bark} = FL_b * (1 - e^{-k_b * t}) \tag{3.56}$$

$$Fuel\_load_{canopy} = FL_o * (1 - e^{-k_o * t}) \tag{3.57}$$

Where:
All fuel loads are in tonne ha^{-1}
s= surface; ns= near surface, el=elevated, b= bark, o = overstorey
FL_x = steady state fuel load of specific fuel layer (tonne ha^{-1}, from fuel table, chapter 4)
k_x = fuel accumulation rate of specific fuel layer (k-value from fuel table, chapter 4)
t = time since fire (yr)

Also, it is important to note that for the fuel availability, we applied a drought factor modifier. This is described in paragraph 3.2.1.1 (equation 3.1 and 3.2).

Fuel load available for combustion, and therefore intensity calculations, then becomes:

$$Fuel\_load_{combustion} = Fuel_{availability} * Fuel\_load_x \qquad (3.58)$$

For estimating fireline intensity, we use Byram's (1959) equation:

$$I_B = h * w * ROS \qquad (3.59)$$

Where:
I_B = fireline intensity (kW m^{-1})
h = heat yield[7], assumed 18,600 kJ kg^{-1}
w = $Fuel\_load_{combustion}$, converted to kg m^{-2}
ROS = rate of spread (m s^{-1})

Flame height was calculated using surface ROS and elevated fuel height:

$$F\_height = 0.0193 * ROS^{0.723} * e^{(0.64*H_{el})} * 1.07 \qquad (3.60)$$

Where:
F_height = flame height (m)
H_{el} = elevated fuel height (m)

3.3.5.1 Adjustments for wet forests

Different forest types will display different fire behaviour. The composition, structure and moisture content of the forest, as well as the exposure to the elements, play a role in this. "Wet forests", such as rain forests, wet sclerophyll forests and swamp forests have a limited fuel availability for fires, because of the high moisture content in these fuels. Since fire behaviour models have not been developed for these specific fuel types (apart from the Red book, for Karri forests, Sneeuwjagt and Peet 1998) we decided to use Vesta with a drought factor modifier (as discussed in paragraph 3.2.1.1, equation 3.2).

3.3.6 Mallee heath model (Cruz et al. 2013)

The mallee heath model was designed for mallee fuel types with a shrubby understory. It goes through different steps:

- The likelihood of fire propagation is determined ("go/no-go").
- The type of fire is predicted, i.e. surface or crown fire.

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[7] This value needs further investigation.

- Rate of spread is determined for either a surface or a crown fire (or a weighted average of the two).

In Cruz et al. (2013) models for both wind speed at 2 m and 10 m were presented. We used the equations for wind speed at 10 m.

Moisture content is important both for predicting if fire propagation is likely and for estimating rate of spread in case of a self-sustaining fire.

We use the following equation:

$$MC = MC_1 + MC_2 \quad (3.61)$$

With MC_1 (after Cruz et al. 2015a):

$$MC_1 = 4.79 + 0.173 * RH - 0.1\ (T - 25) - \Delta 0.027 * RH \quad (3.62)$$

Where:
MC_1 = moisture content (%)
RH = relative humidity (%)
T = temperature (°C)
Δ = “1” for sunny days from 12:00 – 17:00 October to March; otherwise “0”

In addition, a fuel moisture modifier based on recent rainfall was used (MC_2, Marsden-Smedley et al. 1999):

$$MC_2 = 67.128 * (1 - e^{(-3.132*rain)}) * e^{(-0.0858*t)} \quad (3.64)$$

Where:
MC_2 = moisture content (%)
rain = precipitation in the last 48 hours (mm)
t = time since rain or dewfall stopped (h)

The likelihood of fire spread sustainability (“go/no-go”) is defined by:

$$ProbSpread = \frac{1}{(1 + e^{[-(14.624\ +\ 0.2066\ *\ U_{10} - 1.8719\ MC - 0.30442 * Cov_o)]})} \quad (3.64)$$

Where:
ProbSpread = Probability of spread (value between 0 and 1)
U_{10} = 10 m winds speed (km h^{-1})
MC = moisture content as described above (%)
Cov_o = overstorey cover (%)

If ProbSpread < 0.5, no significant fire spread is expected and the fire may self-extinguish; if ProbSpread ≥ 0.5 fire spread is likely and we will continue with the next step (determining the type of fire).

The type of fire (surface or crown) is then estimated by:

$$ProbCrown = \frac{1}{(1 + e^{[-(-11.138\ +\ 1.4054\ *\ U_{10} - 3.4217 * MC)]}\ )} \quad (3.65)$$

Where:
ProbCrown = probability of crowning (value between 0 and 1)
U_{10} = 10 m winds speed (km h^{-1})

MC = moisture content as described above (%)

If ProbCrown ≤ 0.01, no crowning is expected and we will use the surface fire spread model.

$$ROSs = \left(3.337 * U_{10} * \ e^{(-0.1284*MC)} * H_o^{-0.7073}\right) * 60 \tag{3.66}$$

Where:
ROSs = Rate of surface fire spread (m h^{-1})
U_{10} = 10 m wind speed (km h)
MC = moisture content as described above (%)
H_o = overstorey height (m)

[In the original equation (Cruz et al. 2013), ROSs was expressed in m min^{-1}. For consistency we multiplied it by 60 so ROSs is expressed in m h^{-1}]

If ProbCrown > 0.99, crowning is likely and we use the crown fire spread model.

$$ROSc = \left(9.5751 * \ U_{10} * e^{(-0.1795*MC)} * \left(\frac{Cov_o}{100}\right)^{0.3589}\right) * 60 \tag{3.67}$$

Where:
ROSc = Rate of crown fire spread (m h^{-1})
U_{10} = 10 m wind speed (km h^{-1})
MC = moisture content as described above (%)
Cov_o = overstorey cover (%)

[In the original equation (Cruz et al. 2013), ROSc was expressed in m min^{-1}. For consistency we multiplied it by 60 so ROSc is expressed in m h^{-1}]

- If ProbCrown is in between 0.01 and 0.99, a weighted average of surface and crown fire spread models is used.

$$ROSe = (1 - ProbCrown) * ROSs + ProbCrown * ROSc \tag{3.68}$$

Where:
ROSe = ensemble rate of spread (m h^{-1})
ProbCrown = probability of crowning (value between 0 and 1)
ROSs = Rate of surface fire spread (m h^{-1})
ROSc = Rate of crown fire spread (m h^{-1})

Predicted fuel load (which is an input for fireline intensity calculations) was based on Olson (1963) curves. This is further described in chapter 5.

For surface fires, the fuel load is then:

$$Fuel\_load_{surface} = FL_s * (1 - \ e^{-k_s*t}) \tag{3.69}$$

For crown fires, the fuel load is calculated as:

$$Fue\_load_{crown} = Fuel\_load_{surface} + FL_o * (1 - \ e^{-k_o*t}) \tag{3.70}$$

And when ProbCrown is between 0.01 and 0.99, an ensemble is used:

$$Fuel\_load_{ensemble} = Fuel\_load_{surface} + ProbCrown * Fuel\_load_{crown} \tag{3.71}$$

Where:
$Fuel\_load_{surface}$, $Fuel\_load_{crown}$ and $Fuel\_load_{ensemble}$ are all in tonne ha^{-1}
FL_s = steady state surface fuel load (tonne ha^{-1})
FL_o = steady state overstorey fuel load (tonne ha^{-1})
k_s = surface fuel accumulation rate (k-value from fuel table, chapter 4)
k_o = overstorey fuel accumulation rate (k-value from fuel table, chapter 4)
t = time since fire (yr)

For estimating fireline intensity, we use Byram's (1959) equation:

$$I_B = h * w * ROS \tag{3.72}$$

Where:
I_B = fireline intensity (kW m^{-1})
h = heat yield[8], assumed 18,600 (kJ kg^{-1})
w = consumed fuel in kg m^{-2}. Depending on the type of fire, this can be $FuelLoad_{surface}$, $FuelLoad_{crown}$ or $FuelLoad_{ensemble}$ as described above (eq. 59, 60, 61)
ROS = rate of spread (m s^{-1})

For flame height we use (Cruz et al. 2013):

$$F\_height = e^{-4.142} * I_B^{0.633} \tag{3.73}$$

Where:
F_height = flame height (m)
I_B = fireline intensity in Kw m^{-1} following Byram (as above)

3.3.7 Heathland model (Anderson et al. 2015)

In Anderson et al. (2015) a generic fire spread model was developed for shrublands, based on fires from Australia, New Zealand, Spain, Portugal and South Africa.

Two models were developed: in addition to wind speed, a wind reduction factor and elevated dead fuel moisture content, (i) one model included vegetation height, and (ii) the other bulk density. Since we do not have values (or estimates) for bulk density in the field, we will use (i) the height-model for the Research Prototype.

To convert from 10 m wind speed to 2 m wind speed the following wind reduction factors (WRF) were used:

- For shrublands without a canopy: WRF = 0.667
- For shrublands below a woodland: WRF = 0.35

To estimate rate of spread, the following equation is used (if $U_{10} \geq 5$ km h^{-1})[9]:

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[8] This value needs further investigation.

[9] An equation for wind speeds < 5 km h^{-1} was overlooked by developing the Research Prototype. This should be included in a next version of NFDRS.

$$ROS = 5.6715 * (WRF * U_{10})^{0.9102} * {H_{el}}^{0.227} * e^{(-0.0762*MC)} * 60 \quad (3.74)$$

Where:
ROS = Rate of spread (m h^{-1})
WRF = the wind reduction factor as explained above (0.667 or 0.35, depending on canopy)
U_{10} = 10 m wind speed (km h^{-1})
H_{el} = elevated height (m)
MC = moisture content (%)

In the original equation (Anderson et al. 2015), ROS was expressed in m min^{-1}. For consistency we multiplied it by 60 so ROS is expressed in m h^{-1}.

Dead fuel moisture content was described as

$$MC = MC_1 + Mc_2 \quad (3.75)$$

with the following equations (Cruz et al. 2015a, Marsden_Smedley et al. 1999):

$$MC_1 = 4.37 + 0.161 * RH - 0.1\ (T - 25) - 0.027 * RH * \Delta \quad (3.76)$$

$$MC_2 = 67.128 * (1 - e^{(-3.132*rain)}) * e^{(-0.0858*hours)} \quad (3.77)$$

Where:
MC = dead fuel moisture content (%)
RH = relative humidity (%)
T = temperature (°C)
Δ = the radiation factor, with “1.0” for a solar radiation intensity greater than 500 W m^{-2} (sunny days from 12:00 – 17:00 October to March); otherwise “0”. As the cloud cover is not always known, δ was set to be 1.0 if RH ≤ 60 %
rain = precipitation in the last 48 hours (mm)
hours = time since rain or dewfall stopped (h)

Predicted fuel load (which is an input for fireline intensity calculations) was based on Olson (1963) curves (in tonne ha^{-1}):

$$Fuel\_load_{heath} = FL_{total} * (1 - e^{-k_{total}*t}) \quad (3.78)$$

Where:
FL_total = steady state fuel load (tonne ha^{-1})
k_{total} = total fuel accumulation rate (k-value from fuel table, chapter 4)
t = time since fire (yr)

For estimating fireline intensity, we use Byram’s (1959) equation:

$$I_B = h * w * ROS \quad (3.79)$$

Where:
I_B = fireline intensity (kW m^{-1})

h = heat yield[10], assumed 18,600 (kJ kg^{-1})
w = FuelLoad_heath as described above, converted to kg m^{-2}
ROS = rate of spread (m s^{-1})

No equation for flame height was given in Anderson et al. (2015). Here we are using the flame height calculation for mallee heath shrublands (equation 3.73) as per (Cruz et al. 2013):

$$F\_height = e^{-4.142} * I_B^{0.633} \quad (3.80)$$

Where:
F_height = flame height (m)
I_B = fireline intensity in Kw m^{-1} following Byram (as above)

3.3.8 Adjusted pine model (M. Cruz pers. comm.)

Cruz et al. (2015a) recommend using the Cruz et al. (2008) for plantation fires. Due to the complexity of the model, it was not possible to implement it for the Research Prototype. Instead, we used a simplified version originally developed for use with the Spark modelling framework (Miller et al. 2015).

Fuel moisture is calculated using Equation 3.50.

Wind speed at flame height is calculated in two steps. First wind speed at stand height (km h^{-1}):

$$W_{stand\_height} = W_{10m} \frac{\ln\frac{0.36h}{0.13h}}{\ln\frac{10+0.36h}{0.13h}} \quad (3.81)$$

Where *h* is stand height (m). Wind at flame height is:

$$W_{mid\_flame} = W_{stand\_height} e^{-0.48} \quad (3.82)$$

A wind coefficient is then calculated:

$$C_{wind} = C\left(54.68 W_{mid\_flame}\right)^B \left(\frac{P}{P_o}\right)^{-E} \quad (3.83)$$

Where:

$$B = 0.02562\sigma^{0.54}$$

$$C = 7.47e^{-0.133\sigma^{0.55}}$$

$$E = 0.715e^{-0.000359\sigma}$$

P is the fuel packing ratio

P_o is the optimal fuel packing ratio

σ is the fuel surface area to volume ratio (m^{-1})

Surface rate of spread (m h^{-1}) is then calculated as:

$$ROS_{surface} = 18.288 \frac{R\chi(1+C_{wind})}{\rho N_h h_p} \quad (3.84)$$

Where

ρ is the litter bulk density

N_h is the effective heating number

---

[10] This value needs further investigation.

h_p is the heat of pre-ignition

R is the reaction intensity

X is the propagating flux ratio

See Cruz et al. (2008) for further details. To determine whether a crown fire can develop, the intensity of the surface fire required to ignite the crown, $I_{critical}$ is calculated:

$$I_{critcal} = \left(0.01 H_{canopy\_base} h_i\right)^{1.5} \quad (3.85)$$

Where H_{canopy_base} is the height of the canopy base above ground (m) and the heat of ignition, h_i is:

$$h_i = 460 + 25 m_{foliar} \quad (3.86)$$

and m_{foliar} is the foliar moisture content (%). To determine the whether a crown fire will be active or passive the criteria for active crowning (*CAC*) is used:

$$CAC = \frac{ROS_{active}}{60f/\rho_{canopy}} \quad (3.87)$$

Where

ROS_{active} is the rate of spread for an active crown fire (m h^{-1})

f is the critical mass flow rate

ρ_{bulk} is the canopy bulk density

And

$$ROS_{active} = 661.26 W_{stand\_height}^{0.8966} \rho_{canopy}^{0.1901} e^{-0.1714 m_{litter}} \quad (3.88)$$

Where m_{litter} (%) is the litter moisture content. The rate of spread of a passive crown fire is:

$$ROS_{passive} = ROS_{passive} e^{-CAC} \quad (3.89)$$

Finally, rate of spread (m h^{-1}) is calculated from the surface, passive, and active rates of spread:

$$ROS = \begin{matrix} ROS_{surface} & r_c \leq 1 \; or \; r_c > 1, CAC < 1, ROS_{passive} \leq ROS_{surface} \\ ROS_{active} & r_c > 1, CAC \geq 1 \\ ROS_{passive} & r_c > 1, CAC < 1, ROS_{passive} > ROS_{surface} \end{matrix} \quad (3.90)$$

Where the crowning ratio, r_c is:

$$r_c = \frac{I}{I_{critical}} \quad (3.91)$$

Where I is the intensity of the surface fire. Flame height (m) is estimated from intensity:

$$F_{height} = 0.07755 I^{0.46} + \Delta h \quad (3.92)$$

Where:

I = fireline intensity (kW m^{-1})

h is stand height (m)

and Δ is 1 if the fire is an active crown fire, 0 otherwise

4 Fuel type classification and data

4.1 System inputs

The NFDRS Research Prototype is a spatially explicit system, which uses a range of data inputs to calculate fire behaviour and fire danger outputs within a forecast grid system. The spatial inputs required for the system (Figure 4.1) are:

- Standard and additional Bureau of Meteorology (BoM) weather forecast grids (Chapter 5)
- Fuel type grid with a nationally consistent classification and format, linked to fuel parameter data. Fuel type is used to select the appropriate fire behaviour model; fuel parameters provide the input variables to the models
- Time since last fire grid to estimate the current fuel state for some fuel parameters
- Grass fuel state grids representing curing and fuel load, as supplied regularly by each jurisdiction to the BoM

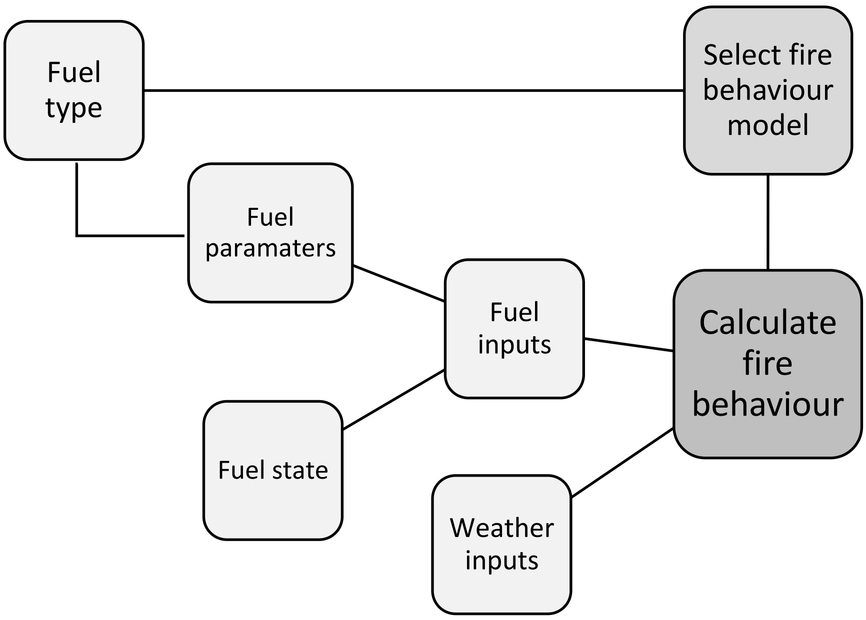

Figure 4.1 Research Prototype system inputs

Construction of the Research Prototype required an appropriate fuel type classification, construction of a fuel type grid, collation of fuel parameter data, and processing of fire history data to construct a time since fire grid. Existing operational grids were used for grass fuel state for the live trial period, while a default grass fuel load grid was created for the weather reanalysis period.

4.2 Fuel type classification

4.2.1 Australian fuel classification

Fuel classification and mapping in Australia is generally based around vegetation classification and mapping. This has developed for two main reasons:

- Fire behaviour models used operationally in Australia are empirical models developed through observation of fire in particular vegetation types (Cruz *et al.* 2015a, Hollis *et al.* 2015)
- Vegetation mapping exists as a convenient base layer from which to develop fuel type mapping

The focus of different vegetation maps may vary e.g. structure, floristics, climatic zone, bioregion, conservation status (Groves 1981, Specht & Specht 1999). From a fire behaviour perspective the vegetation stratum that will carry the fire is the most important (Sullivan *et al.* 2012), and hence structural vegetation classification is the most useful for fuel type classification. Climatic and bioregional variation influence ecosystem productivity, and hence fuel condition and dynamics (Watson 2009). Floristic information can provide information on some specific fuel attributes, e.g. bark type (Horsey & Watson 2012).

Work has been conducted through AFAC to develop a national Bushfire Fuel Classification (BFC) system (Hollis *et al.* 2015, Gould & Cruz 2015, AFAC 2017, Cruz *et al.* 2018). This system has been based primarily on Specht structural vegetation classification, which groups vegetation strata by life form, height and cover.

Principles from this system were used to inform fuel classification for the Research Prototype. However, implementation of the BFC was only in initial stages when developing the Research Prototype fuel classification. Hence, fuel classification was based on the needs of the Research Prototype, and mapping was developed from existing base state fuel type maps classified directly to the NFDRS fuel types.

Future work within each jurisdiction to implement the BFC system is being overseen by AFAC Predictive Service Group, with involvement of the NFDRS project team. There is potential in the future to integrate the fuel classification used in the NFDRS with the BFC. A high level comparison between the classifications is presented in Supplementary Table 4.7.1. While some fuel types are directly equivalent, others require a more nuanced comparison.

4.2.2 NFDRS fuel types

For the purpose of the Research Prototype, fuel type classification has been driven by the need to select an appropriate fire behaviour model, and to capture the range of variation in the fuel parameters that feed the inputs to the models. A hierarchy of classification describes the use of increasingly detailed fuel information within the Research Prototype (Figure 4.2).

Broad fuel types (Table 4.1; Figure 4.3) are defined by the available fire behaviour models developed for particular vegetation types (Cruz *et al.* 2015a). At this level, the fuel types reflect only vegetation structure. See Chapter 3 for specific details of the models and their application, and Chapter 2 for how the Research Prototype ratings have been defined and the Fire Danger Tables developed.

Vegetation types that don't have a specific fire behaviour model (e.g. rainforests, arid shrublands, wetlands, rural and urban areas) have been allocated to the model with the most similar fuel structure (as per Gould & Cruz 2015). However, there are often factors (broadly represented by climatic variation or human management) limiting the flammability, fuel availability or fuel connectivity in these vegetation types. These vegetation types have been classified as additional fuel types that identify which fire behaviour model is to be applied and what modifications are required to the fire behaviour calculations (as per Plucinski *et al.* 2017). The broad fuel types divided into these additional fuel types make up the full list of NFDRS fuel types (Table 4.1; Figure 4.4). A comparison between the NFDRS fuel types and other fuel and vegetation classifications is provided in Supplementary Table 4.7.1.

At the most detailed level, definition of state fuel types accounts for spatial variation in fuel parameters (e.g. bioregional and floristic influences) and allows for the use/adaptation of existing jurisdictional fuel type classification and fuel parameter data sets.

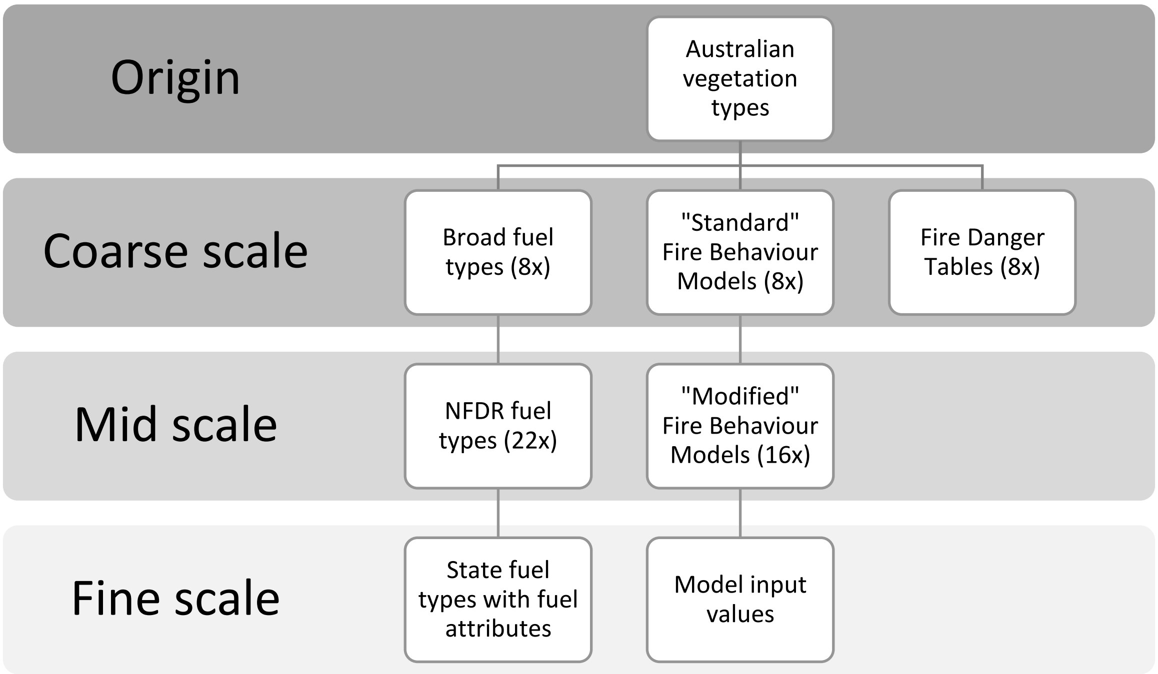

Figure 4.2 Fuel classification hierarchy

4.2.2.1 Grassland

The grassland broad fuel type includes all vegetation types where the fuel structure is predominately grass without a canopy cover. The CSIRO grassland model (Cheney *et al.* 1998) was developed for continuous and tussock grasslands, with variation based on fuel condition (natural, grazed, eaten out). The grass NFDRS fuel type applies to continuous and tussock grasslands, and uses the standard application of the CSIRO grassland model with reported grass fuel state as fuel inputs. The pasture and crop NFDRS fuel types have been treated the same way in the live trial of the Research Prototype, though segregating them in the classification allows for different treatment in future applications.

Low flammability shrublands such as chenopod and samphire (chenopod shrubland NFDRS fuel type) do not have a suitable fire behaviour model. The shrub layers are generally low (<1.5 m), discontinuous (cover <30%) and of low flammability (high salt and moisture content). Grasses and forbs of variable cover occur between the shrubs, while ephemeral grasses provide more continuous cover only after significant rainfall events. Fires are rare and most likely to occur when ephemeral grasses are present (Cruz *et al.* 2018). Cruz *et al.* 2018 suggest using the mallee-heath model in combination with the grassland model but do not describe how this combination should be implemented. For the Research Prototype the grassland model was selected as fire is most likely to run in the grass fuels, but fire behaviour reduced by selecting eaten out grass condition. More consideration of the most suitable model is required for this vegetation type. An option for future application would be to develop a threshold system based on grass growth (e.g. grass condition reporting, remote sensing, rainfall data, ephemeral grass growth modelling) to switch between models or grass condition.

Grassy wetlands (e.g. sedgelands, rushlands, herbfields) have variable combustibility depending on inundation levels. These were classified to the low wetland NFDRS fuel type, for which both the grassland and buttongrass models were considered. The buttongrass model may be more suitable for coastal swamp wetlands with flammable material above inundated ground, but was considered inappropriate for less flammable inland floodplain wetlands. Here, as in the chenopod shrublands, fire is most likely to be associated with ephemeral grass growth, and so the eaten out grass model was considered more appropriate. As the spatial majority of the low wetland fuel type is inland floodplain wetlands, this model was used during the live trial. It may be more appropriate to segregate this fuel type in to inland, coastal and alpine subtypes.

The NFDRS fuel types grass and pasture are covered by BFC (Cruz *et al.* 2018) grasslands (G#); Crop is included in BFC grassland (G#) and horticulture (HOR); Low wetland is included in BFC wetlands; Chenopod shrublands align with various BFC sparse and open shrublands (SL1, SL2, SM2).

4.2.2.2 Savanna

The savanna broad fuel type includes all vegetation types where the fuel structure is predominately grass understorey with a canopy cover. The CSIRO grassland model for northern Australia (Cheney *et al.* 1998) was developed for the tropical savanna woodlands of northern Australia, but can also be applied to structurally similar vegetation throughout Australia (Cruz *et al.* 2015a). The model uses the CSIRO grassland model with a ROS reduction factor based on canopy cover.

The NFDRS woodland fuel type includes all woodland and open forest vegetation with a grassy understorey, including tropical savanna, temperate grassy woodlands and semi-arid grassy woodlands. Reported grass fuel load is being used to select the grass condition.

Arid acacia shrublands do not have a suitable fire spread model (Cruz *et al.* 2015a). The NFDRS acacia woodland fuel type includes arid acacia shrublands and woodlands (i.e. mulga) and similar vegetation where there is little ground fuel except for chenopod shrubs and forbs, with ephemeral grass growth following rare large rain events. Fire is infrequent in these fuel types, coinciding with rain driven grass growth (Nano *et al.* 2012). The mallee-heath and savanna models were both considered, and both assumed likely to over-predict fire behaviour. The savanna model has been applied in eaten out grass condition to minimise over-predicting. As per chenopod shrublands, further consideration of a more appropriate model or threshold based on ephemeral grass growth would be helpful.

In managed landscapes the savanna model is being used with reduced grass condition. For general rural areas (e.g. rural residential, hobby farms) the grass condition is being treated as grazed. For urban areas with park or garden fuels (e.g. suburbs with gardens and tree cover, recreation areas, golf courses, cemeteries, etc.) and areas of perennial woody horticulture (e.g. orchards and vineyards) some fire propagation is possible, but the condition of potential fuel will be highly variable. The savanna model has been applied in eaten out condition. Cruz *et al.* 2018 do not make any fire behaviour model suggestions for any of these managed fuel types.

The NFDRS fuel type woodland occurs in various BFC woodland and forest fuel types with a grass mid-tier (e.g. W#_g#); Acacia woodland occurs in various BFC woodland (W#) and open shrubland (S#2) fuel types; Rural and urban are covered by BFC wildland-urban interface (WUI); Woody horticulture is within BFC horticulture (HOR).

4.2.2.3 Spinifex

All vegetation communities with a spinifex hummock grass understorey have been classified to the spinifex broad fuel type, and the desert spinifex model applied (Burrows *et al.* 2018). This includes NFDRS fuel types spinifex (<5% tree/shrub cover) and spinifex woodlands (woodlands and shrublands with a spinifex understorey). For spinifex woodlands the savanna model principle of a ROS reduction factor based on canopy cover has been applied.

The NFDRS fuel type spinifex is equivalent to BFC Hummock grasslands (HG#); spinifex woodland is equivalent to BFC fuel types with a hummock grass mid-tier (e.g. S#_hg# and W#_hg#).

4.2.2.4 Mallee heath

The mallee heath model (Cruz *et al.* 2013) model applies to semi-arid shrublands with a mallee form eucalypt canopy and shrubby understorey. Other semi-arid woodlands / shrublands of similar structure have been grouped into this fuel type. Note that vegetation described as mallee that has a spinifex understorey has been classified to spinifex woodland not mallee-heath as the spinifex is the dominant influence on the fire spread.

The NFDRS fuel type mallee heath occurs in various BFC shrublands (S#).

4.2.2.5 Shrubland

Originally developed for temperate heathlands, the shrubland model (Anderson *et al.* 2015) was extended to include a wide range of heathland and shrubland structures. The NFDRS heath fuel type is predominantly temperate heathlands, but also includes other shrublands that are not within other more specific fuel types (mallee heath, acacia woodland, spinifex woodland, buttongrass). Open woodlands with a dominant heath understorey are included in heath not forest, as are some low closed forests.

While a wet heath fuel type was included in the classification, no variation to the model was applied in the Research Prototype. However segregating them in the classification allows for different treatment in future applications.

The NFDRS fuel type heath occurs in various BFC shrublands (S#).

4.2.2.6 Buttongrass

The buttongrass moorlands model (Marsden-Smedley and Catchpole 1995a) has only been applied to Tasmanian buttongrass vegetation communities. The NFDRS fuel type buttongrass occurs in BFC low and low closed shrublands (SL3, SL4).

4.2.2.7 Forest

The Dry Eucalypt Forest Fire Model (DEFFM or “Vesta”, Cheney *et al.* 2012) was developed for dry sclerophyll forest with a litter and shrub dominated understorey, which provide vertical fuel continuity. The NFDRS forest fuel type is being applied to all dry sclerophyll forests and to temperate woodlands where litter and/or shrubs dominate the understorey. Note that forests and woodlands with a continuous grassy understorey have been classified to savanna, while open woodlands (<10% canopy cover) with a heath understorey have been classified to shrubland.

Wet sclerophyll forest, rainforest, and forested wetlands have been grouped in the NFDRS wet forest fuel type as the fuel structure is most similar to a litter and shrub dominated forest. However fuel availability is limited by fuel moisture due to forest structure (tall and or closed canopy), topography (gullies and southerly aspects), or inundation. Cruz *et al.* 2018 suggest the DEFFM forest model with a wind reduction factor for wet sclerophyll forest, but have no suggestion for rainforest or swamp forest.

Hardwood plantations have also been classified to the wet forest fuel type as the canopy species are most commonly tall eucalypt species typical of wet sclerophyll forests. However, the understorey fuel structure is highly modified and variable with management. For native plantations of shorter species the forest model without the adjusted moisture threshold may be more suitable. Cruz *et al.* 2018 have no suggested fire behaviour model for broadleaf plantations. Plucinski *et al.* 2017 apply either the DEFFM forest or northern grassland model depending on the understorey type.

For the Research Prototype, the forest model has been applied to wet forests with a wind reduction factor and a drought factor modification (Chapter 3). The same drought factor modification has been applied to all forests classified to wet forest, however there is likely to be significant differences in the actual threshold of fuel availability between rainforest, wet sclerophyll forest, and forested wetlands. This is an area requiring further research (Duff *et al.* 2018).

The NFDRS fuel type forest occurs in various BFC woodlands and open forests with a shrub mid-tier (e.g. W#_s# and FM3_s#); wet forest occurs in BFC tall open forest (FT3), closed forest (FM4, FT4) and wetlands (#Wet).

4.2.2.8 Pine Plantations

All softwood plantations (predominately *Pinus radiata*) have been classified to the NFDRS pine fuel type, and a simplified version of the pine model was applied. No attempt has been made in the Research Prototype to segregate softwood plantations by species type or management stage. While this has a significant effect on local fire behaviour, use of the worst case scenario was the most pragmatic decision for the scale considered for fire danger. Note that the pine fuel type only covers 0.2% of the nation, while the effort to acquire and regularly update management details from multiple agencies and private companies is significant. The NFDRS fuel type pine corresponds with BFC conifer plantations (PC).

Table 4.1 NFDRS Fuel Types

Broad Fuel Type / Fire Behaviour Model	NFDRS Fuel Type	Description	Limitations to Fire Behaviour Model Use	Modifications to Fire Behaviour Model Application
Grassland	Grass	Continuous and tussock grasslands	n/a	Standard; variation by reported grass fuel load
Grassland	Pasture	Modified or native pasture where primary land use is grazing	Fuel availability variable with management	Standard; variation by reported grass fuel load
Grassland	Crop	Non-irrigated cropping land (cereals, hay, sugar, etc.)	Fuel availability variable with management	Standard; variation by reported grass fuel load
Grassland	Low wetland	Wetland with low or no overstorey. E.g. low swamp heath, sedgeland, rushland	Fuel availability limited by moisture content	Eaten out grass condition
Grassland	Chenopod shrubland	Low arid shrublands dominated by chenopod (saltbush) species, or similar non-arid vegetation with samphire species. Limited flammability except when high cover of ephemeral grasses	Fuel connectivity limited and variable with ephemeral grass growth	Eaten out grass condition
Savanna	Woodland	Woodland and shrubland with a continuous grass understorey (minimal shrub or litter component). E.g. tropical savanna woodland, temperate grassy woodlands, semi-arid woodlands or shrublands with a perennial continuous grass understorey	n/a	Standard; variation by reported grass fuel load
Savanna	Acacia woodland	Arid woodland or shrubland (may be acacia, casuarina or eucalypt canopy) with an ephemeral grass understorey; fuel connectivity only when grass cover occurs after sufficient rain. E.g. Mulga	Fuel connectivity limited and variable with ephemeral grass growth	Eaten out grass condition
Savanna	Woody horticulture	Perennial woody horticulture, likely managed (mown, irrigated) grass understorey. E.g. orchards, vineyards	Fuel availability variable with management	Eaten out grass condition
Savanna	Rural	Rural residential areas. Typically continuous grass with variable tree cover. Note fuel management may be highly variable	Fuel availability variable with management	Grazed grass condition
Savanna	Urban	Urban residential areas with grass or garden and variable tree cover. Includes suburbs with tree cover, recreation areas within urban areas (e.g. parks, golf courses). Note fuel management may be highly variable	Fuel availability variable with management	Eaten out grass condition
Spinifex	Spinifex	Spinifex hummock grassland	n/a	Standard

Broad Fuel Type / Fire Behaviour Model	NFDRS Fuel Type	Description	Limitations to Fire Behaviour Model Use	Modifications to Fire Behaviour Model Application
Spinifex	Spinifex woodland	Woodland and shrubland with a hummock grass (spinifex) understorey. Note includes vegetation described as mallee if the understorey is spinifex	Overstorey presence reduces wind penetration	Wind reduction factor applied
Mallee heath	Mallee	Semi-arid woodland and shrubland with a shrub understorey. Includes mallee eucalypt, acacia and casuarina woodlands or shrublands	n/a	Standard
Shrubland	Heath	Shrublands. Includes heathland, tall closed shrubland, low closed forest, open woodland with heath understorey	n/a	Standard
Shrubland	Wet heath	Wetlands with a medium to tall shrubland structure. E.g. swamp heath, melaleuca shrubland	Fuel availability limited by moisture content	Standard
Buttongrass	Buttongrass	Buttongrass moorland	n/a	Standard
Forest	Forest	Dry eucalypt forest and temperate woodland with a shrubby understorey and litter surface fuel	n/a	Standard
Forest	Wet forest	Forests with high moisture content due to structure (closed forest cover >70%, tall forest >30m), topography, or inundation. E.g. rainforest, wet sclerophyll forest, swamp forest	Fuel availability limited by moisture content	Drought factor modifier applied
Pine	Pine	Pine plantation	n/a	Standard
Non-combustible	Horticulture	Seasonal horticulture, very low flammability. E.g. vegetables, herbs and irrigated crops		Nil calculations made
Non-combustible	Built up	Non-combustible urban areas and intensive land use. E.g. business districts, industrial areas, infrastructure, mining		Nil calculations made
Non-combustible	Non-combustible	Non-combustible areas of water, sand, rock, etc. Includes saline wetlands		Nil calculations made

Notes:

1. Broad fuel type = Fire behaviour model as per Table 3.1; Standard model application is described in Chapter 3

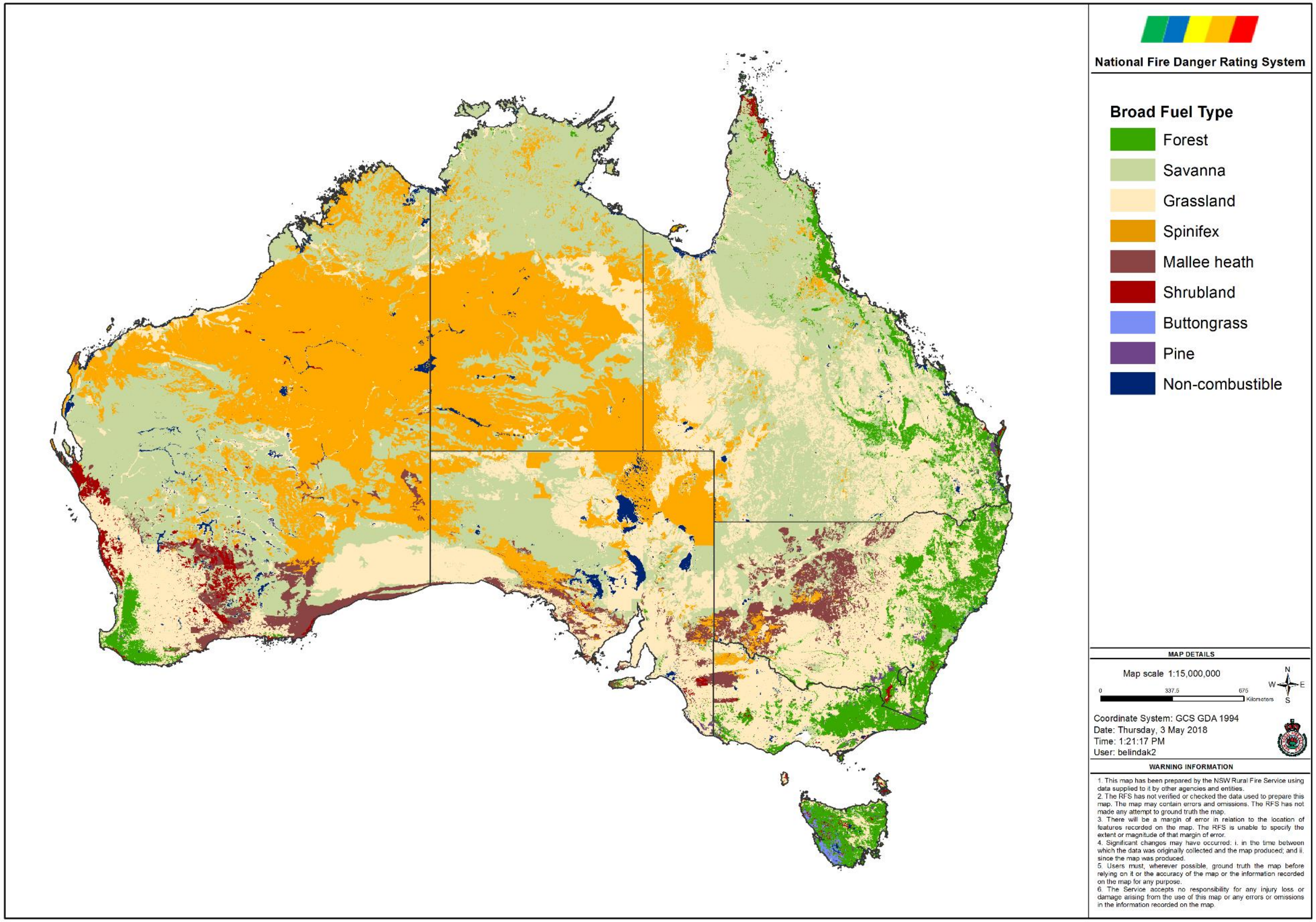

Figure 4.3 National broad fuel type map, at fire behaviour model level

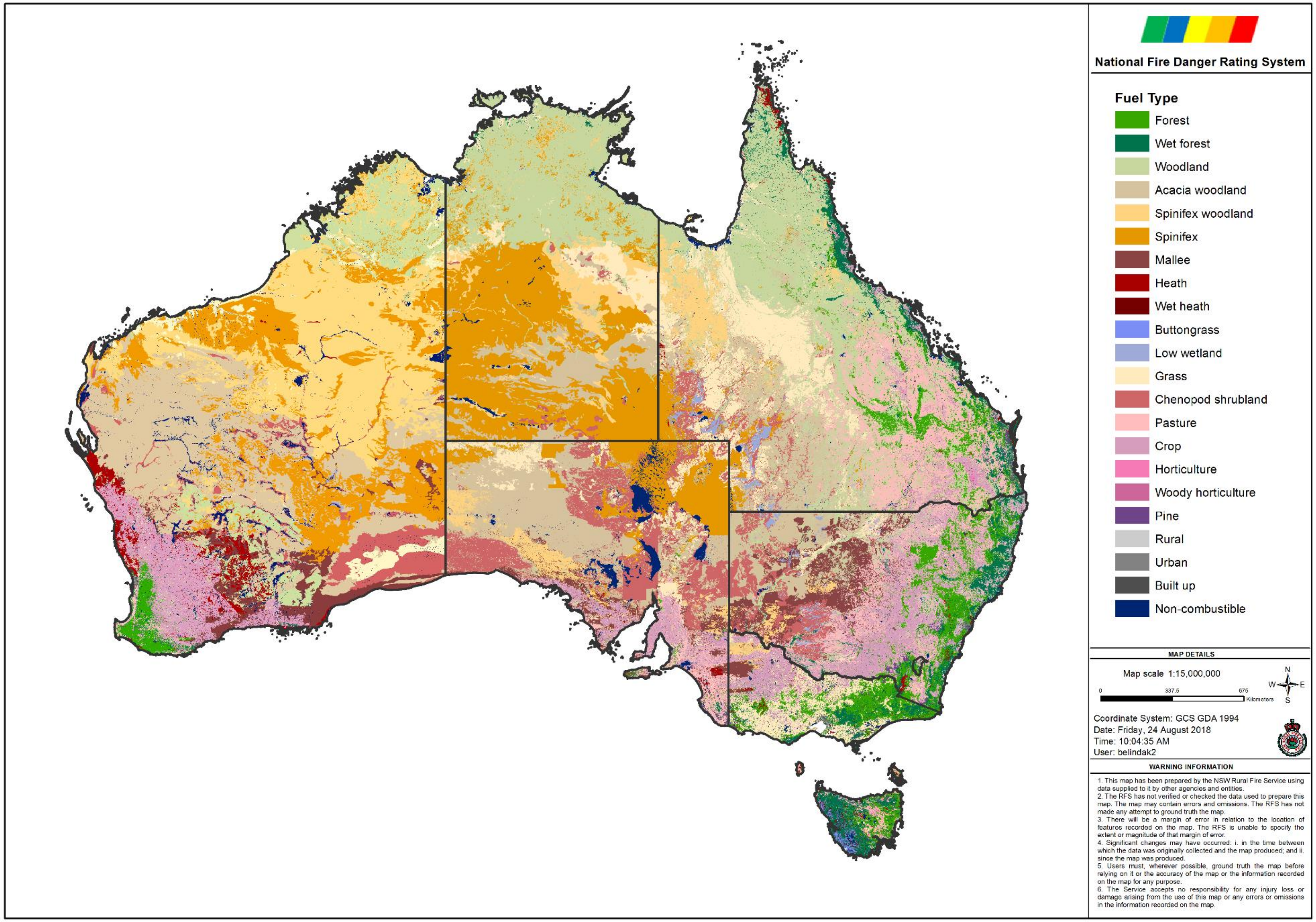

Figure 4.4 NFDRS fuel type map

4.3 Fuel type mapping

Developing the spatial fuel type layer required a consistent national approach, which involved:

- Translation of existing spatial data (existing fuel type, vegetation, land use, etc.) into the NFDRS fuel classification
- Processing spatial data into the required forecast grid scale and format

The output maps are displayed by NFDRS broad fuel type (Figure 4.3) and NFDRS fuel type (Figure 4.4).

4.3.1 National map

A preliminary fuel classification and map was produced based on the National Vegetation Information System (NVIS) and Australian Land Use Management Classification (ALUM). This was used during the development phase of the Research Prototype only, to provide full coverage spatial layers while more detailed State level data was still being developed.

NVIS was treated at a broad level (Major Vegetation Subgroup) that leaves some vegetation types lumped too broadly to segregate all fuel types accurately (e.g. forest and woodland lumped together, understorey not specified to a level to determine appropriate fire behaviour, etc.).

ALUM provides a way to divide non-native vegetation and cleared areas into fuel types based on primary land use. For example agricultural lands split into crop, pasture, horticulture; cleared areas split into rural, urban, built up. This provides a landscape level indication of land use, but may not be accurate at a fine spatial or temporal scale.

4.3.2 State maps

State level fuel maps were developed in consultation with representatives from each jurisdiction. Given the timeframe limits for development of the Research Prototype, the best currently available spatial and classification data (generally currently used operational fuel type data, e.g. Phoenix fuel raster) was sourced for each State and the fuel classification was based primarily on this.

Some additional processing was done as required to define source fuel types within the NFDRS classification. For many states this involved an overlay of land use data onto particular source fuel types as per the national map. For some states original vegetation map data was used to add or clarify details.

Details of the source data and processing steps are given in section 4.6. While all effort was made to be as consistent as possible, starting with different base classification and variable levels of detail led to some inconsistencies between states. Further investigation of alternate data sources was beyond the scope of the Research Prototype.

4.4 Fuel parameters

While fuel type gives us an understanding of the broad fuel structure, it is the finer detail within the fuel complex that influences fire behaviour. Characteristics such as fuel arrangement, quantity, and composition are important, and are measured by attributes such as height, dry weight, particle size, and mineral content, or described by surrogates such as fuel hazard scores (FHS). See Watson 2009 for a thorough review of fuel characteristics; Hollis *et al.* 2015 for an overview of fuel attributes; and the fire behaviour model references (Table 3.1) for the parameters assessed and used in the various models.

4.4.1 Required fuel parameters

The fuel parameters collated for the Research Prototype were those necessary to run the selected fire behaviour models. They were collated at the finest fuel classification level (State fuel type) to capture the spatial variation inherent in fuel structure across bioregions.

Collation of the necessary fuel parameter data was conducted by consultation with representatives from each jurisdiction. The primary input was existing fuel spreadsheets (e.g. Phoenix fuel type tables) with some supplementary information from other sources (section 4.6). Where no values were available for a particular parameter, generic values have been used (section 4.4.3).

Work has been conducted through AFAC to develop a standard format "fuel catalogue" to accompany the Bushfire Fuel Classification system (AFAC 2017), however this was in development at the same time as the Research Prototype and has not yet been implemented. Fuel parameter tables were collated based on the needs of the Research Prototype, however consultation has been conducted to align the two systems as closely as possible.

For each fuel type rate of spread, flame height and intensity are calculated (see Chapter 3 for details) The equations and hence required input fuel parameters vary between fuel types (Table 4.2).

Table 4.2 Required fuel parameters

Broad fuel type	Fuel load	Fuel hazard score	Height	Cover	Wind factor	Spotting
Grassland	Grass fuel state					
Savanna	Grass fuel state				Wind adjustment factor	
Spinifex	Time since fire			Time since fire	Wind adjustment factor	
Mallee-heath	Per strata		Overstorey	Overstorey		
Shrubland	Total		Elevated		Wind adjustment factor	
Buttongrass	Time since fire & productivity					
Forest	Per strata	Surface, near surface, elevated, bark	Near surface & elevated		Wind reduction factor	Spotting potential

Grass condition (natural, grazed, eaten out) and fuel load is set as a standard by fuel type and/or taken from the reported grass fuel load grid (as detailed in Table 4.1). Grass curing and fuel load grids are existing products supplied regularly by each jurisdiction to the BoM for GFDI calculation. No values are required in the fuel parameter table for grassland.

Time since fire is a surrogate for fuel values in the spinifex and buttongrass models. This is applied via the time since fire grid (section 4.5.1), not the fuel parameter table.

Fuel load is recorded as fine fuel (<6 mm diameter) in tha^{-1} per fuel strata (surface, near surface, elevated, bark, overstorey) for forest and mallee heath, and as a total value for shrubland.

Fuel hazard scores are recorded as per the project Vesta fuel assessment guide (Gould *et al.* 2007b) per fuel strata (surface, near surface, elevated, bark) for forest.

Fuel types with an overstorey have a form of wind adjustment factor. The mallee heath model uses overstorey cover for this purpose. The wind adjustments factors are used for shrubland and savanna as described in the models. Values are a decimal value between 0 and 1, where a value of 1 would apply to no overstorey cover. The savanna wind reduction factor has also been applied to the spinifex model for spinifex woodland. For forest a wind reduction factor has been applied as per the Wind Reduction Factor Guide in the Advanced Fire Behaviour Prediction Standard Workbook (Tolhurst pers. comm.), where values range between 1.5 and 6 based on tree height and canopy cover.

Potential for long range spotting has been recorded in the fuel parameter tables (estimated from bark hazard values), but is not currently being applied within the Research Prototype. Potential for long range spotting was recorded as a yes/no value base on bark FHS, where FHS => 3 = 1 (yes) and FHS < 3 = 0 (no).

All pine calculations were performed with set model values assuming maximum fuel state. This was done in the code, no values were recorded in the fuel parameter table. Fuel parameters would be required if the full version of the pine model was applied in future applications.

Fuel parameter values in the look up tables represent the steady state (i.e. fuel levels at maximum time since fire). Current fuel level was estimated by the use of Olson fuel accumulation curves (Equation 4.1; Olson 1963) for some fuel parameters (fuel load, hazard score, near surface height). Time since fire is taken from the time since fire grid (section 4.5.1), while k values were required in the fuel parameter table.

$$Fuel = Limit \times (1 - e^{-kt}) \tag{4.1}$$

Where: $\text{Fuel} = \text{current fuel value}$

$\text{Limit} = \text{steady state fuel value (from fuel parameter table)}$

$\text{k} = \text{fuel accumulation rate (from fuel parameter table)}$

$\text{t} = \text{time since fire (from time since fire grid)}$

Note that the original version of the Olson curve (Equation 4.1) has been implemented in the Research Prototype, not the version that adjusts for initial (immediate post-fire) fuel levels (Morrison *et al.* 1996). Initial fuel values have been included in the fuel parameter tables, so this version could be implemented in future versions. Also note that the Olson curve was developed to describe accumulation of litter fuel load, and has commonly been more widely applied to all fuel strata (i.e. surface, near surface, elevated and bark fuels). The use of the same fuel curve to estimate change of other fuel parameters (fuel hazard score and near surface height) is potentially beyond its scope, but has been implemented here as per project Vesta (Gould *et al.* 2007a), Spark (Hilton *et al.* 2016) and Phoenix (Tolhurst 2005).

4.4.2 Fuel parameter data conversion

There is variation between and within jurisdictions as to which fuel parameters are collated (e.g. fuel load vs overall fuel hazard ratings vs Vesta hazard scores). Conversion was often required to create the fuel parameter tables in a standard format.

The most common issue was data acquired as Phoenix fuel type tables, where the data are presented as fuel hazard ratings (as per the overall fuel hazard (OFH) assessment guide, Hines *et al.* 2010) for surface, elevated and bark fuel only. This requires conversion to both Vesta fuel hazard scores and fuel load, and gap filling of the absent near surface values.

Data was converted from OFH fuel hazard ratings (FHR) to Vesta fuel hazard scores (FHS) (Table 4.3) as per the standard conversion used by both systems (Hines *et al.* 2010, Cheney *et al.* 2012).

Table 4.3 Conversion from FHR to Vesta FHS

FHR Category	FHR Rating	FHS Score (surface, near-surface, elevated)	FHS Score (bark)
Low	1	1	0
Moderate	2	2	1
High	3	3	2
Very high	4	3.5	3
Extreme	5	4	4

Data was converted from OFH fuel hazard ratings to fine fuel load using the equations implemented in Phoenix (Tolhurst 2005) which are based on the conversion tables in the third edition OFH guide (McCarthy *et al.* 2009).

Most jurisdictional data sets did not have values for near-surface fuel. This is a major impediment to implementing the DEFFM forest model due to its dependence on near-surface fuel hazard scores and near-surface height. The approach taken to fill this gap in the Research Prototype (as described below) could lead to an over estimation of rate of spread.

Where no near-surface fuel hazard value was given, a proxy value was calculated as a proportion of the surface FHS. The calculation (FHSns = FHSs * 0.857) was based on the proportion of near-surface to surface fuels in the default FHS values at maximum time since fire (Cheney *et al.* 2012).

Where no near-surface fuel load value was given this was left as zero assuming that it had been included in values given for surface fuels. Where no near-surface height value was given a generic value was used.

4.4.3 Generic fuel parameter data

Where local fuel parameter data was not available data gaps were filled with generic values or values from equivalent fuel types in adjacent states. For non-standard fuel types requiring modification of the fire behaviour models, generic values have been chosen as appropriate to make the modifications (e.g. grass condition for managed fuel types such as rural).

Where possible, the generic values have been sourced from the published papers describing the fire behaviour models used. Other published fuel studies have been used where further data was required, however a comprehensive literature search was outside the scope of the Research Prototype build due to the limited timeframe. See Supplementary Table 4.7.2 for the generic values used in the Research Prototype and the source of these values.

4.5 Fuel state

4.5.1 Fire history

Fire history was used as a direct input for some fuel types (spinifex and buttongrass) or as a modifier to adjust other fuel parameters from their peak state. Fire history was processed into a time since fire grid for each jurisdiction.

State agencies are responsible for their own fire history data, and the format of data varies between states. Most agencies provided the data as a shape file with date of or time since last fire only (i.e. only the most recent fire in an area) as well as a separate shape file of entire fire history (i.e. all overlapping fires); while the Northern Territory provided separate annual raster files of monthly fire scars.

The date (recorded as date or month) of the fire was the only attribute required from the fire history file. Time since fire was calculated on an annual basis only (i.e. as integer not decimal data) such that:

$$\textit{time since fire} = 2017 - \textit{year of last fire} \tag{4.2}$$

For use in the live trial, only the most recent fire was required to calculate time since fire at the start of the trial (October 2017) or the date of the fire history file provided (data current at 1st June 2017 or as provided in September 2017). The time since fire grid was updated during the trial period for Northern Territory and Western Australia where fires are more frequent. For the other States the same grid was used throughout the trial period.

For use in the historical reanalysis, complete fire history was required so that more recent fires could be removed incrementally to create time since fire at 3 month time steps throughout the reanalysis period (2010 – 2015).

Time since fire was calculated at the native resolution of the provided input data before being scaled up to the required grid format (section 4.6.1). Where there was no fire history data (e.g. no recorded or no actual fire history) a generic value of 25 years was applied as most vegetation types reach steady state fuel limits by 25 years (e.g. Watson 2012).

4.5.2 Grassland curing and fuel load

Grassland curing and fuel load are currently provided by each state to the BoM as inputs to the GFDI calculation. There are some differences in the way the data is currently produced between states as well as the frequency of reporting. Standardisation of grassland data collection is currently being determined through the AFAC Predictive Services Group.

For the Research Prototype live trial these data sets were treated as BoM forecast inputs dealt with directly within the calculation system. Fuel load values were assigned to fuel condition categories for ROS calculation (Chapter 3) with the following values:

- Grass fuel load ≥ 6 tha^{-1} = natural grasslands
- Grass fuel load between 3 and 6 tha^{-1} = grazed grasslands
- Grass fuel load ≤ 3 tha^{-1} = eaten out grasslands

For the historical reanalysis period the availability of archived grass fuel load grids is patchy. This is due to different start dates for jurisdictions reporting grass fuel load as well as gaps in reporting (e.g. during non- fire danger period). Various options were explored to fill these gaps with other potential data sources (e.g. remote sensing data and pasture growth models). The options explored have been documented separately. There was not sufficient time to perform a detailed review of the various data sources and models to assess their applicability across different grassland types and at a national scale, so generic values were used (as described below).

Some jurisdictions already use a default value of 4.5 tha^{-1} for grass fuel load, either all the time (Victoria, Tasmania, Western Australia) or during gaps in reporting (e.g. NSW used to default to 4.5 tha^{-1} during non-fire danger period). This effectively takes the Purton variation out of the GFDI calculation. It was felt that this would potentially over or under estimate fuel load in many areas.

A variable generic fuel load map was created to account for variation in regional productivity. The primary drivers for growth in both native grass and pasture are climate, soil, and species type. To produce a basic grass fuel gradient, climate was considered the most important factor. Several BoM climate classifications were examined as potential proxies for grass productivity. The modified Köppen classes (Stern *et al.* 2000) were considered the most suitable, as they already combine rainfall and temperature. The Köppen classification maps show six major climate zones across Australia, which are defined with the climatic limits of vegetation in mind.

The range of operational grass fuel load values (1.5 to 6 tha^{-1}) was assigned across the Köppen major groups assuming lowest grass loads in the arid zone and highest in the tropics (Figure 4.5). Values were assigned to best match the operational application of the jurisdictions:

- Examination of the NSW reported grass fuel load data from 2011-2017 showed a pattern of decreasing fuel load from east to west, with eastern averages around 4.5 and western averages around 2 tha^{-1}
- Reported values at the time of assessment for Queensland, Northern Territory and South Australia show broadly similar patterns to the assigned values
- Victoria, Tasmania and Western Australia reported a standard 4.5 tha^{-1}

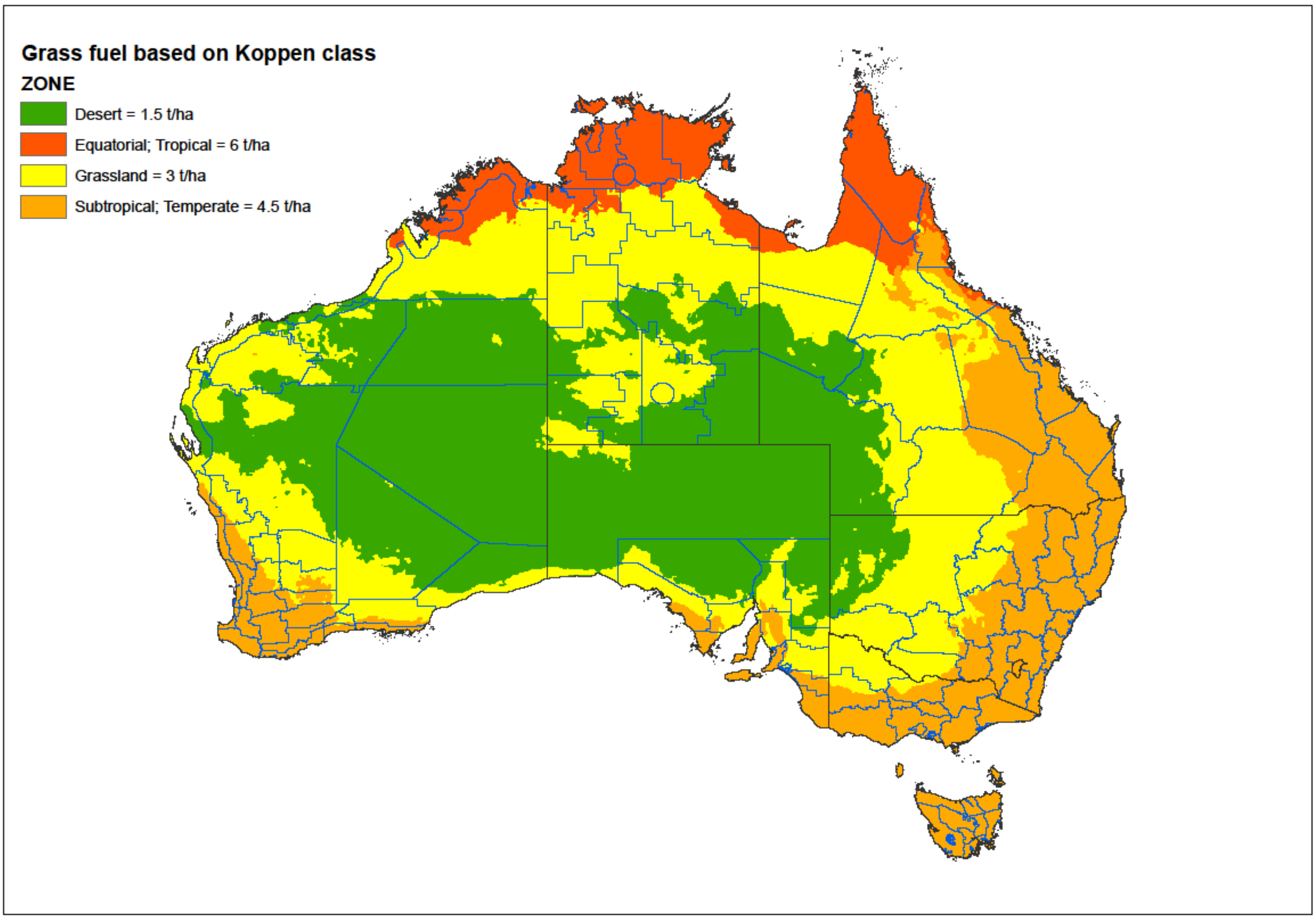

Figure 4.5 Generic grass fuel load based on Köppen climate zone

A further attempt was made to vary this base grass fuel load by seasonal rainfall to account for seasonal and annual fluctuations within the reanalysis period based on seasonal rainfall decile grids. Comparison of the output with reported fuel loads in NSW showed poor correlation, and a likely over estimation of the effect of the rainfall. Without adequate time to refine this approach it was decided to use the generic values (as per Figure 4.5) for the entire historical reanalysis period.

4.6 Data Sources and Processing

Full details on the data processing has been documented separately in “NFDRS Base Data Technical Specification”.

4.6.1 Spatial data format

The format, scale and projection of spatial data needs to be compatible with the BoM forecast grid. Current forecast grids are either at approximately 3 km (Victoria and Tasmania) or 6 km scale, though intentions are to move to a 1.5 km in the future. The forecast grids are produced independently for each State, and are not seamless across State boundaries.

The most compatible option between existing forecast grids, pre-processing requirements for the fuel input data, and systems architecture of the Research Prototype is to produce the fuel input data and perform calculations at a 1.5 km resolution.

Base grids were created per state using the ADFD grids for each state as a template. All grids were scaled to approximately 1.5 km (longitude spacing of 0.015 degrees) to nest within the ADFD grids. The input spatial data (fuel type and time since fire) were then processed to provide grids of dominant fuel type and average time since fire.

The fuel type grid represents the fuel type with the maximum area coverage within each grid cell. The underlying fuel type data was analysed to provide the area covered by each fuel type within each grid cell. The output *StateName*_Fuel_*version* shapefile contains the fuel type code (State specific) and percent area of the 3 fuel types with the greatest percent area coverage per grid cell. The netCDF grid used in the system calculations contains just the fuel type code of the dominant fuel type.

In cases where the maximum area coverage was a non-combustible fuel type with <70% coverage, the fuel type with the second greatest coverage area was used as the dominant fuel type (unless this was also a non-combustible fuel type).

The time since fire grid represents the average time since fire within each grid cell. The underlying fire history data was analysed to provide statistics per grid cell (average, median, minimum, maximum) on the time since the most recent fire. The output *StateName*_TSF_*date* shapefile contains all the statistics per grid cell. The netCDF grid used in the system calculations contains just the average time since fire. Before calculating statistics, all base data with no value (e.g. no recorded fire history) was given a value of 25 years since fire.

4.6.2 Fuel parameter data format

A schema was produced for the fuel parameter input data containing: the template for the look up tables; indication of the required values for each fuel type; descriptions, format and range for each field.

For each state a spreadsheet was collated containing: source fuel parameter data, references for the source data, conversions of source data into the required fields and formats, and version control of the output look up table.

The output look up tables (*StateName*_Fuel_LUT, csv format) provide the link to the spatial fuel type data (via unique fuel type code) to select the fire behaviour model (via NFDRS fuel type) and to perform the fire behaviour calculations (via the required fuel parameter fields).

4.6.3 Jurisdictional data sources

Source data and variations made are described below for fuel type maps and fuel parameters. See also Appendix 4.7.3 for a list of all data sources used, including fire history data. Full details on fuel type classification and fuel parameter data can be found in the fuel parameter spreadsheets for each jurisdiction.

4.6.3.1 New South Wales

The New South Wales fuel map used was the RFS Phoenix fuel type raster. Individual forest fuel types (based on Keith vegetation classes) were grouped back to the level at which the fuel curves are described in Watson (2012). Classification to NFDRS fuel type was based on descriptions of vegetation and fuel structure (Keith 2004, Keith & Simpson 2010, Watson *et al.* 2012).

Fuel parameter data was taken from the RFS fuel parameter spreadsheet which is a collation of published data (Gordon & Price 2015, Horsey & Watson 2012, Keith 2004, Keith & Simpson 2010, PlantNET, Tolhurst 2005, University of Wollongong 2013, Watson 2012, Watson *et al.* 2012). Generic values were used for near-surface height for some fuel types, and for wind adjustment factors for savanna and shrubland.

4.6.3.2 Northern Territory

The Northern Territory fuel type map was built by combining the Carbon Farming Initiative (CFI) fuel type map (supplied by Charles Darwin University) with NVIS mapping. The CFI map only covers CFI eligible vegetation types of the northern savanna high and low rainfall areas. For areas not covered by the CFI map, the NT NVIS map was used at sub-formation level (Level 4), which describes the dominant upper, mid and ground strata. NVIS sub-formations were grouped by structure and dominant species and then classified into NFDRS fuel types.

Fuel parameter data was collated from various sources. Fuel load data was from the CFI Methodology (2013) and Yates (2015). FHS and WRF values for wet forests were sourced from similar vegetation types in Queensland's fuel parameter table. Generic values were used for near-surface height, elevated height, and savanna wind adjustment factor.

4.6.3.3 Queensland

Queensland fuel data was provided by Queensland Fire and Emergency Services (QFES) as a raster and look up table in Phoenix format. The Phoenix fuel types were largely left as is and classified to NFDRS fuel type via the descriptions provided in the Phoenix parameter table, with clarification from additional descriptions of base vegetation types (Regional Ecosystem Broad Vegetation Groups; Queensland Herbarium 2016) and consultation with QFES staff.

Source fuel types requiring further data to classify to NFDRS fuel type were overlayed with Broad Vegetation Group vegetation data and ALUM land use data:

- Sparsely vegetated areas (14)
- Woodlands / Shrubland associated with coastal tussock grasslands (51)
- Woodland / Shrubland / Grass dominated by wetlands (54)
- Woodland / Shrubland / Grass dominated by wetlands (55)
- Exotic & hardwood plantation (56)
- Low grass or tree cover in rural areas (60)
- Nil to very low vegetation cover (62)

Fuel parameter data was primarily from the Phoenix parameter table. Fuel load data was taken from Leonard & Opie (2017). Generic values were used for near-surface height, elevated height, and wind adjustment factors for savanna and shrubland.

4.6.3.4 South Australia

South Australian fuel data was provided by Department of Environment, Water and Natural Resources (DEWNR) as a raster and look up table in Phoenix format. The Phoenix fuel types were largely left as is and classified to NFDRS fuel type via the descriptions provided in the Phoenix parameter table, with clarification by consultation with DEWNR staff.

Source fuel types requiring further data to classify to NFDRS fuel type:

- Natural grass (37) was split into grassland (pasture, crop) fuel types by overlaying ALUM land use data

Fuel parameter data was primarily from the Phoenix parameter table. Generic values were used for height (near-surface, elevated, overstorey), overstorey cover, and wind adjustment factors for savanna and shrubland.

4.6.3.5 Tasmania

Tasmanian fuel data was provided by Tasmania Fire Service (TFS) as a raster and look up table in Phoenix format, and by Tasmania Parks & Wildlife Service as a raster of BRAM fuel group and a draft version of the BFC Fuel Catalogue. The fuel type map was built using the TASVEG vegetation map as the spatial base layer, with fuel type classification based on information in the Phoenix fuel types, BRAM fuel groups, fire attribute categories (Pyrke & Marsden-Smedley 2005), and the TASVEG descriptions (Kitchener & Harris 2013).

Source vegetation types requiring further data to classify to NFDRS fuel type:

- Agricultural land (FAG) was split into grassland (pasture, crop), savanna (rural, urban, woody horticulture) and non-combustible (horticulture) fuel types by overlaying ALUM land use data
- Plantations (FPL, FPU) was split into plantation types (softwood = pine, hardwood = wet forest) by overlaying BRAM fuel group

Fuel parameter data was collated from various sources. FHS and forest WRF were taken from the Phoenix paramater table; fuel load was taken from the BRAM group (Wallace 2014); near-surface and elevated height were taken from TASVEG descriptions (Kitchener & Harris 2013) or generic values; wind adjustment factors for savanna and shrubland use generic values.

4.6.3.6 Victoria

Victorian fuel data was provided by Department of Environment, Land, Water and Planning (DELWP) as a raster and look up table in Phoenix format. The Phoenix fuel types were largely left as is and classified to NFDRS fuel type via the descriptions provided in the Phoenix parameter table, with clarification from additional descriptions of base vegetation types (Ecological Vegetation Class) and consultation with DELWP staff.

Source fuel types requiring further data to classify to NFDRS fuel type:

- Eaten-out grass (3046) was split into grassland (pasture, crop) and savanna (rural, urban) fuel types by overlaying ALUM land use data
- Non-combustible (3047) was split between non-combustible (built-up, horticulture, non-combustible) and savanna (urban, rural, woody horticulture) fuel types by overlaying ALUM land use data

Fuel parameter data was primarily from the Phoenix parameter table (based on Tolhurst 2005), with some additional information (overstorey height and cover) from descriptions of base vegetation types (Ecological Vegetation Classes). Generic values were used for overstorey fuel load, near-surface height, elevated height, and wind adjustment factors for savanna and shrubland.

4.6.3.7 Western Australia

Western Australian fuel data was provided by Department of Fire and Emergency Services (DFES) as a shape file of NVIS vegetation classified to fuel models used in DFES Bushfire Risk Analysis (BRAN) project and an accompanying fuel accumulation table. The BRAN fuel models were classified to NFDRS fuel type via the descriptions provided with clarification from vegetation descriptions (Beard *et al.* 2013, DEWR 2007) and consultation with DFES and Department of Biodiversity Conservation and Attractions staff.

Source fuel types requiring further data to classify to NFDRS fuel type:

- Open grassland was split into grassland (pasture, crop), savanna (rural, urban, woody horticulture) and non-combustible (horticulture, built up, non-combustible) fuel types by overlaying ALUM land use data

Fuel parameter data was primarily from the BRAN fuel accumulation table which is a collation of published data (Carpenter *et al.* 2013, CFI Methodology 2013, McCaw 1997, Sneeuwjagt & Peet 2011, Westacott 2014) with additional information sourced from the same and additional (Gosper 2014) sources. Generic values were used for height (near-surface and elevated) for some fuel types, and for wind adjustment factors for savanna and shrubland.

4.6.4 Acknowledgements

Many thanks to those who provided data and feedback on the fuel classification.

Jurisdiction	Agency	Staff member
Northern Territory	Bushfire NT	Mark Gardener Jing Sun
	Charles Darwin University	Dominique Lynch
Queensland	Queensland Fire and Emergency Services	Russell Stephens-Peacock Andrew Sturgess
South Australia	Department of Environment, Water and Natural Resources	Simeon Telfer Mike Wouters
Tasmania	Tasmania Fire Service	Rochelle Richards Samuel Ferguson
	Tasmania Parks & Wildlife Service	David Taylor
Victoria	Department of Environment, Land, Water and Planning	Andy Ackland
Western Australia	Department of Fire and Emergency Services	Sophie Edgar Agnes Kristina Jackson Parker
	Department of Biodiversity Conservation and Attractions	Glen Daniel Lachie McCaw
National	Australasian Fire and Emergency Service Authorities Council	Chris Morton

4.7 Supplementary tables

4.7.1 Comparison of NFDRS fuel types to other Australian fuel / vegetation classification systems

Broad Fuel Type	NFDRS Fuel Type	Bushfire Fuel Classification (Cruz *et al.* 2018)	Bushfire Fuel Classification (AFAC 2017)	Amicus (Plucinski *et al.* 2017)	Specht & Specht 1999	Keith & Tozer 2017	NVIS (DEWR 2007)
Grassland	Grass	G	G	Continuous open grasslands	Grassland	Tussock grasslands	MVG 19 Tussock Grassland
Grassland	Pasture	G	G_gra	n/a	n/a	n/a	n/a
Grassland	Crop	G; HOR	G_cro	n/a	n/a	n/a	n/a
Grassland	Low wetland	Wet	R; H	n/a	Grassland; Herbfield	Freshwater wetlands; Alpine herbfield	MVG21 Other Grasslands, Herblands, Sedgelands and Rushlands; MVG24 Inland aquatic – freshwater, salt lakes, lagoons
Grassland	Chenopod shrubland	SL1; SL2; SM2	SL2; SM2	n/a	Low shrubland	Arid subsucculent chenopod shrublands	MVG22 Chenopod Shrublands, Samphire Shrublands and Forblands
Savanna	Woodland	W_g	W_g	Woodlands; Open grassy forest (Northern Australia)	Open forest + savanna; Woodland + savanna	Savanna; Temperate woodlands (grassy)	MVG5 Eucalypt Woodlands
Savanna	Acacia woodland	S*2; W	S*2; W	n/a	Tall shrubland	Semi-arid acacia/casuarina woodlands; Arid sclerophyll shrublands	MVG6 Acacia Forest and Woodlands; MVG8 Casuarina Forests and Woodlands; MVG13 Acacia Open Woodlands; MVG16 Acacia Shrublands
Savanna	Woody horticulture	HOR	HOR	n/a	n/a	n/a	MVG10 Other Forests and Woodlands;MVG11 Eucalypt Open Woodlands; MVG12 Tropical Eucalypt Woodlands/Grasslands; MVG31 Other Open Woodlands
Savanna	Rural	WUI	D	n/a	n/a	n/a	n/a
Savanna	Urban	WUI	D	n/a	n/a	n/a	n/a
Spinifex	Spinifex	HG	HG	Spinifex	Hummock grassland	Hummock grasslands	MVG20 Hummock Grasslands
Spinifex	Spinifex woodland	W_hg; S_hg	W_hg; S_hg	n/a	Open scrub + hummock grass; Tall	Semi-arid eucalypt woodlands (hummock grass)	Various MVS with hummock grass understorey (10, 18, 23, 27, 51, 52, 66, 72)

Broad Fuel Type	NFDRS Fuel Type	Bushfire Fuel Classification (Cruz *et al.* 2018)	Bushfire Fuel Classification (AFAC 2017)	Amicus (Plucinski *et al.* 2017)	Specht & Specht 1999	Keith & Tozer 2017	NVIS (DEWR 2007)
					shrubland + hummock grass		
Mallee-heath	Mallee	W_s; S_s	W_s; S_s	Semi-arid mallee-heath	Open scrub	Semi-arid eucalypt woodlands (shrubby and heathy)	MVG14 Mallee Woodlands and Shrublands; MVG32 Mallee Open Woodlands and Sparse Mallee Shrublands
Shrubland	Heath	S; W_s	S; W_s	Temperate shrubland	Heathland	Heathlands	MVG18 Heathlands; MVG17 Other Shrublands; Various MVS with shrubland structure (28, 50, 53, 62)
Shrubland	Wet heath	S	S_W	n/a	Heathland; Freshwater swamp	Heathlands	MVG18 Heathlands
Buttongrass	Buttongrass	SL3; SL4	BG	Buttongrass	Heathland?	?	MVG21 Other Grasslands, Herblands, Sedgelands and Rushlands
Forest	Forest	F_s; F_lit; W_s	F_s; W_s	Dry eucalypt forest	Open forest + sclerophyll; Woodland + sclerophyll	Dry sclerophyll forests and woodlands; Temperate woodlands (shrubby)	Various open forest and woodland MVS with shrubby understorey (4, 5, 8, 16, 47, 70)
Forest	Wet forest	FT3; F*4; Wet	FT*; F*4; F_R; F_W	Wet eucalypt forest; Short rotation eucalypt plantation	Closed forest; Tall open forest; Forested wetland	Rainforests; Wet sclerophyll forests; Floodplain forests, woodlands and shrublands	MVG1 Rainforests and Vine Thickets; MVG2 Eucalypt Tall Open Forests; MVG9 Melaleuca Forests and Woodlands
Pine	Pine	PC	PC	Radiata pine; Maritime pine	n/a	n/a	n/a
Non-combustible	Horticulture	HOR	HOR	n/a	n/a	n/a	n/a
Non-combustible	Built up	NB	NB	n/a	n/a	n/a	n/a
Non-combustible	Non-combustible	NB	NB	n/a	Mangrove; Salt-marsh	Saline wetlands	MVG23 Mangroves; MVG27 Naturally bare, sand, rock, claypan, mudflat

4.7.2 Generic fuel parameters

NFDRS Fuel Type	FHS_s	FHS_ns	FL_s	FL_ns	FL_el	FL_b	FL_o	FL_total	Fk_s	Fk_ns	Fk_el	Fk_b	Fk_o	Fk_total	H_ns	H_el	H_o	Hk_ns	Cov_o	WF_Sav	WF_Heath	WRF_For	Productivity	References
Woodland (<30% overstorey)																				0.5				1
Woodland (>30% overstorey)																				0.3				1
Acacia woodland																				0.5				1*
Woody horticulture																				0.5				1*
Rural																				0.5				1*
Urban																				0.3				1*
Spinifex																				1				1*
Spinifex woodland																				0.5				1*
Mallee			3	1.5	2.3		1		0.2	0.2	0.2		0.2				4.5		18					2
Heath (<10% overstorey)								20						0.2		1.3					0.67			3
Heath (10-30% overstorey)								20						0.2		1.3					0.35			3
Buttongrass																							1	4
Forest	3.5	3	14	3.5	4	5	6		0.3	0.2	0.2	0.1	0.30		25	1.5		0.3				3		5-9
Wet forest	3.5	3	14	3.5	4	5	8		0.35	0.2	0.15	0.1	0.35		25	1.5		0.3				5		5-9

Notes:

- Fuel types that do not require inputs from the fuel parameter table (grasslands, pine, non-combustible) have not been included
- Non-required values per fuel type are shaded out

References:

1. Cheney & Sullivan 2008 (1* Based on Cheney & Sullivan 2008)
2. Cruz *et al.* 2010 (no k values provided)
3. Anderson *et al.* 2015
4. Marsden-Smedley & Catchpole 1995a
5. Cheney *et al.* 2012 (FHS, H_ns)
6. Gould *et al.* 2007b (FL)
7. Gould *et al.* 2007a (Fk_s, Fk_ns, H_el, Hk_ns)
8. Watson *et al.* 2012 (Fk_b, Fk_o)
9. Tolhurst (pers. com.) Wind Reduction Factor Guide; Advanced Fire Behaviour Prediction Standard Workbook (WRF)

4.7.3 Jurisdictional data sources

Jurisdiction	Input Data	Input Data Details	NFDRS Usage Notes
ACT	Full fire history	Fire history for period 1920 – 1/8/2017	Incorporated into NSW data collation process
National	NVIS vegetation	National Vegetation Information System Major Vegetation Subgroups Version 4.2	Base map for first draft national coverage fuel map (NFDRS v102)
National	ALUM land use	Catchment Scale Land Use of Australia; May 2016 (ABARES)	Overlayed on base map for non-native vegetation (NFDRS v102) and as required for NT, QLD, SA, VIC, Tas
National	ALUM land use	Catchment Scale Land Use of Australia; September 2017 (ABARES)	Overlayed on base map as required for WA
NSW	Phoenix fuel type	Fuel type map compiled by RFS from OEH & LPI source vegetation and land use data	Base map; classified to FDR State fuel types
NSW	RFS fuel parameter spreadsheet	Fuel data compiled by RFS from various source data	Formatted to NFDRS fuel parameter look up table
NSW	Full fire history	Fire history for period 1938 – 1/9/2017. Collated from multiple RFS source files (WF History, Incident, HR, NDMP) and ACT	Used for live trial and historical reanalysis
NT	CFI fuel type	Map of CFI eligible fuel types	Base map for area of coverage (CFI eligible fuel types)
NT	NVIS vegetation	NVIS Detailed Level 1-6 Version 4.2 (NT)	Base map for non-CFI areas; ALUM overlay for non-native vegetation
NT	CFI fuel load data	Documents: CFI Methodology (2013); Yates (2015)	Input for NFDRS fuel parameter look up table (CFI fuel types)
NT	Annual fire scar	NAFI Fire scar data processed by CDU. Monthly fire scars per year for period 2000 – 21/10/2017	Used for live trial and historical reanalysis
QLD	Phoenix fuel type	Fuel type map compiled by QFES from various source data	Base map; RE vegetation & ALUM overlay for some fuel types
QLD	Regional Ecosystem vegetation	Remnant 2015 Broad Vegetation Groups of Queensland (Version 3.0) derived from the regional ecosystem mapping	Overlayed on base map where required
QLD	Phoenix fuel parameters	Fuel data compiled by QFES	Formatted to NFDRS fuel parameter look up table
QLD	Full fire history	Fire history for period to 2000 - 1/7/2017	Used for live trial and historical reanalysis
SA	Phoenix fuel type	Fuel type map compiled by DEWNR from various source data	Base map; ALUM overlay for some fuel types
SA	Phoenix fuel parameters	Fuel data compiled by DEWNR from various source data	Formatted to NFDRS fuel parameter look up table
SA	Most recent fire	Fire history for period 1931 – 30/6/2017	Used for live trial

Jurisdiction	Input Data	Input Data Details	NFDRS Usage Notes
SA	Full fire history	Fire history for period 1931 – 30/6/2017	Used for historical reanalysis
TAS	TASVEG vegetation	TASVEG version 3.0 (2013)	Base map; BRAM & ALUM overlay for some fuel types
TAS	Phoenix fuel type	Fuel type map compiled by TFS from various source data	Primary classification of TASVEG data
TAS	BRAM fuel model	Fuel type map compiled by TPWS from various source data	Secondary classification of TASVEG data and overlay for plantation areas
TAS	Phoenix fuel parameters	Fuel data compiled by TFS	Formatted to NFDRS fuel parameter look up table
TAS	BOHM fuel accumulation data	BOHM documentation (Wallace 2014)	Input for NFDRS fuel parameter look up table
TAS	Most recent fire	Fire history for period 1970 – 1/7/2017 collated by TFS from multiple agency data	Used for live trial
TAS	Full fire history	Fire history for period 1970 – 1/7/2017 collated by TFS from multiple agency data	Used for historical reanalysis
VIC	Phoenix fuel type	Fuel type map compiled by DELWP from various source data	Base map; ALUM overlay for some fuel types
VIC	EVC vegetation map	Victorian Ecological Vegetation Communities 2005 (with Bioregional Conservation Status)	Only used for further information to clarify fuel types
VIC	Phoenix fuel parameters	Fuel data compiled by DELWP (based on Tolhurst 2005)	Formatted to NFDRS fuel parameter look up table
VIC	Most recent fire	Fire history for period 1903 – 30/6/2017	Used for live trial
VIC	Full fire history	Fire history for period 1903 – 30/6/2017	Used for historical reanalysis
WA	BRAN fuel type	Fuel type map compiled by DFES for Bushfire Risk Analysis project	Base map; NVIS & ALUM overlay for some fuel types
WA	NVIS Vegetation	NVIS Detailed Level 1-6 Version 4.2 (WA)	Used for verification and additional information
WA	BRAN fuel accumulation table	Fuel data compiled by DFES	Formatted to NFDRS fuel parameter look up table
WA	Time since last fire	Time since fire for period 1992 –1/7/2017 collated by DFES from multiple agency data	Used for live trial
WA	NAFI fire scar	NAFI Fire scar data for period 1/1/2017 – 1/10/2017	Used to update WA fire history for live trial
WA	Full fire history	Fire history for period 1926 – 31/10/2017 collated by DFES from multiple agency data	Used for historical reanalysis

5 Weather data

5.1 Introduction

Weather is a key input to a fire danger rating system. Different weather elements may have differing relative importance, depending on the properties of the fuels being modelled. For example, the buttongrass moorland fire behaviour model is sensitively dependent on small amounts of recent rainfall, and on wind, but much less sensitive to changes in temperature and relative humidity. This is a consequence of the relatively uniform, flat, fuel structure, exposed to rainfall and to wind. On the other hand, forest fuels, while still very responsive to wind, are not at all sensitive to amounts of rain less than 2mm, on account of canopy interception.

The Research Prototype employed Australian Digital Forecast Database (ADFD) grids of forecast weather, generated by forecasters at the Bureau of Meteorology’s seven State and Territory forecast centres. These grids are available across the whole of Australia and are routinely updated twice daily, with forecasts of a number of weather parameters extending to seven days.

The Research Prototype employed only the daytime issue, released routinely by 5:00 pm Local Time (for each State and Territory Bureau office), valid for the following day. The forecast grids were collected at 2:00 am AEDT and made available for evaluation at 12:00 AEDT on the day of validity. This was to ensure that operational decisions would not be made on the basis of these experimental products.

5.2 ADFD weather grids

ADFD weather data is generated by the Bureau of Meteorology's Graphical Forecast Editor (GFE) system, used by forecasters to manipulate existing forecast grids and blend them with numerical weather prediction model output. GFE produces modified estimates of the state of the atmosphere at hourly, three-hourly and daily resolution, depending on the parameter. ADFD forecast grids are available over all states and territories of Australia, and are updated twice daily. ADFD grids provide forecasts of basic weather parameters out to seven days. The spatial resolution of ADFD grids is six km over much of Australia and three km over Victoria and Tasmania due to their smaller size and relatively greater topographic diversity compared to other regions. ADFD grids were rescaled to 1.5 km for calculation of Research Prototype variables.

ADFD parameters used in the NFDRS fire behaviour calculations are listed in Table 5.1 below, including frequency of availability:

Table 5.1 Forecast weather variables

Parameter	Frequency
Surface (10 m) wind	hourly
Surface temperature	hourly
Surface relative humidity	hourly
Drought factor	three hourly
Precipitation	three hourly
Curing	daily
Grass fuel load	daily

5.3 AWRA data

Spinifex fuel availability calculation requires 0-10 cm soil moisture information. This was obtained from the Australian Water Resources Assessment (AWRA) information (Frost et al. 2016), available on the Bureau of Meteorology THREDDS server at: http://test-awratds.bom.gov.au/thredds/catalog.html and updated daily. The AWRA 0-10 cm soil moisture represents the percentage of available water content in the top 10 cm of the soil profile. Figure 5.1 displays upper (0-10 cm) soil moisture, from the AWRA-L website.

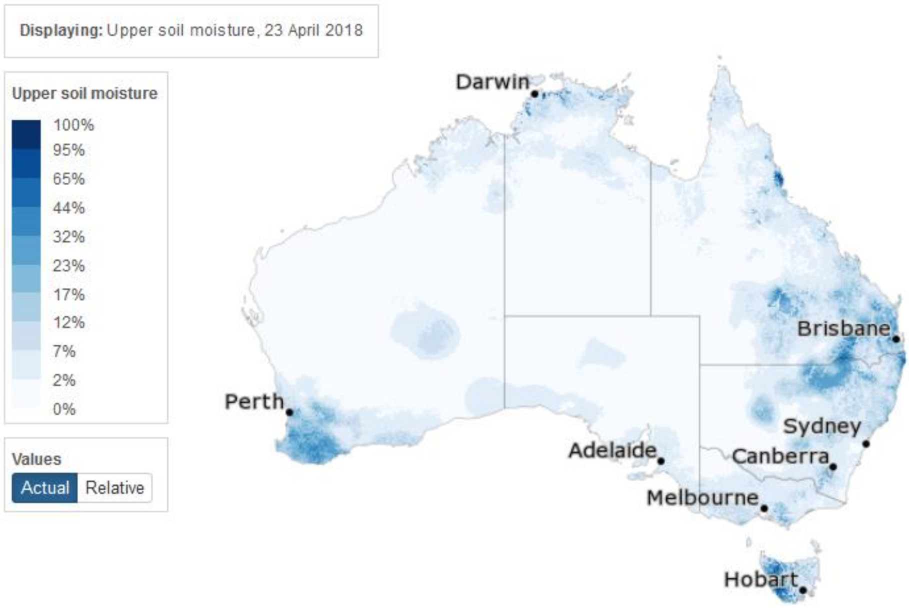

Figure 5.1 Sample of AWRA upper soil moisture field.

5.4 Red flag parameters

Three red flag quantities are tabulated in the Research Prototype: spotting distance, continuous Haines Index and Wind Change Danger Index (WCDI).

Spotting distance as described in Section 3.3.5, using (some of the) parameters listed above.

Continuous Haines Index (Mills and McCaw 2010) was obtained from ADFD grids (at three-hourly temporal resolution).

WCDI is derived from the algorithm outlined in Huang and Mills (2006), including the following ADFD parameters: Surface (10 m) wind gust strength (hourly), wind direction (hourly).

5.5 Demonstration products

Several research or experimental weather products were included as "demonstration" products for the Research Prototype. They were not ready to be incorporated into the system fully, but were included to demonstrate possibilities for its future development.

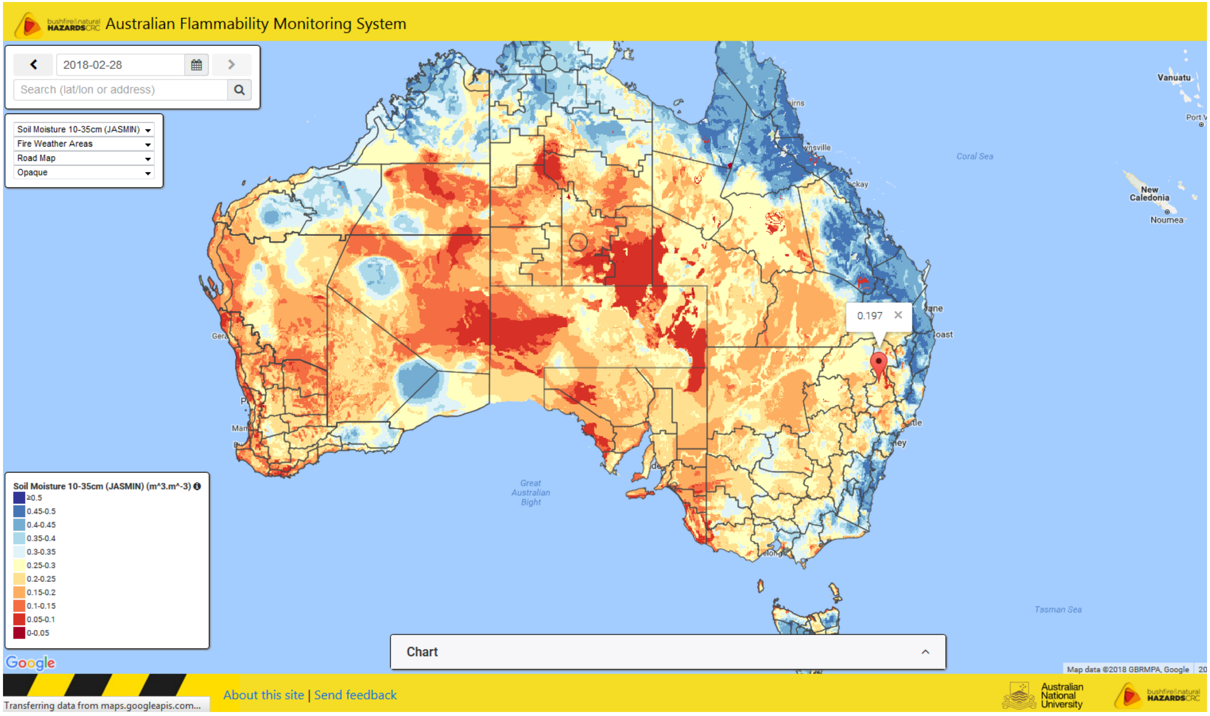

Figure 5.2: Sample of JASMIN data, for 28 February 2018, displayed on the ANU/Bushfire and Natural Hazards CRC Australian Flammability Monitoring System website .

JASMIN data became available for (non-realtime) review during the course of the trial. JASMIN is a four layer soil moisture system derived from the output of the Bureau of Meteorology's numerical weather prediction model, ACCESS (Dharssi and Vinodkumar, 2017). JASMIN output has been mapped to single layer products, resembling the Keetch-Byram Drought Index and Soil Dryness Index, to better enable integration into current fuel moisture systems. Grids of these quantities were presented during the course of the project on the Australian Flammability Monitoring System, established by the Australian National University as a Bushfire and Natural Hazards Co-operative Research Centre project (Figure 5.2).

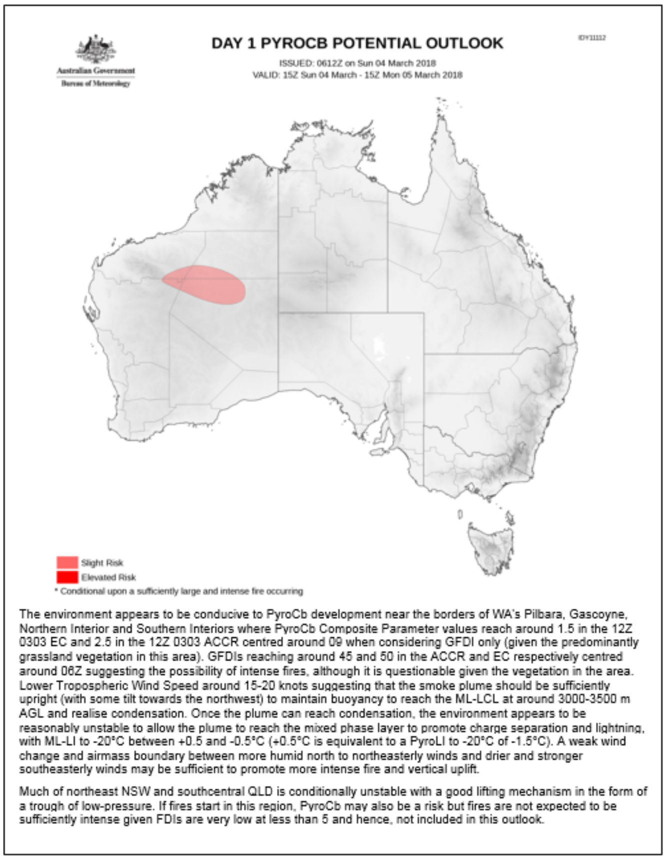

Figure 5.3: PyroCb Potential for 03 March 2018

Two demonstration products were trialled by the Extreme Weather Desk within the Bureau of Meteorology's National Operations Centre during the course of the Research Prototype project: maps detailing regions of potential pyrocumulonimbus development (Tory et al.2018, Figure 5.3) and dry lightning potential. An example of the latter is displayed in Figure 5.4.

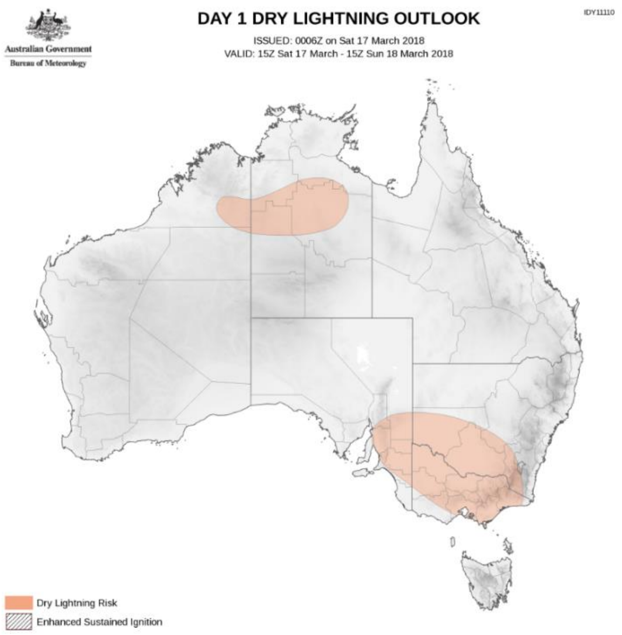

Figure 5.4: Dry Lightning Outlook issued by Extreme Weather Desk for 18 March 2018

6 Information Technology systems

The system that supported the NFDRS Research Prototype consisted of three components

- The calculation system built and run by the Bureau of Meteorology
- The daily ratings page hosted by the Bureau of Meteorology
- The interactive website hosted by the NSW Rural Fire Service

6.1 The calculation system

6.1.1 Calculation overview

The Bureau produced a daily 24hr run of the Research Prototype during the period of the trial.

To automate this a process was setup in collaboration with the NSW RFS. This system took various daily weather inputs from within the Bureau, combined them with static inputs provided by the NSW RFS and ran them through the Research Prototype calculation system (Figure 6.1).

The process produced gridded outputs in a NetCDF format and a static webpage summarising the daily results.

This system was setup on internal Bureau systems, automated using well known open source tools with the outputs delivered to the NSW RFS via standard bureau ftp and http portals.

Broadly, the system transformed all disparate inputs into a unified format, passed them through the various spread model calculations depending on relevant fuel type, and additionally produced threshold red flags based on several factors. These outputs were then processed to produce images and tables summarising the results that were bundled into the static webpage. Additionally, the RFS took the gridded outputs and fed them to their interactive web-based exploration tool.

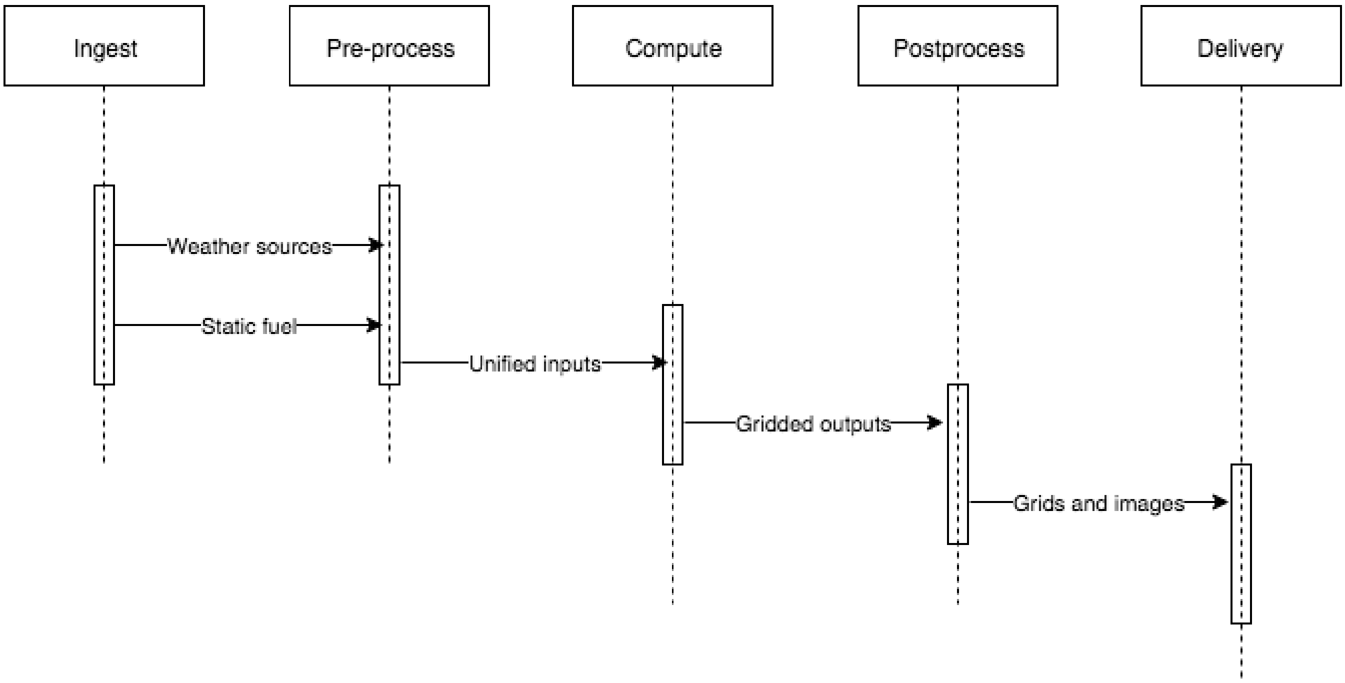

Figure 6.1 Overview of daily calculation flow

6.1.2 Inputs

To run the calculations the Research Prototype needed various sources of information describing the current and predicted state of the atmosphere in a gridded format. These were pulled from various places around the Bureau. One part of the system design was to collect a snapshot of these sources daily, unify them into the same projection and dimensions and fill in any blanks ready for calculation. For a more in-depth discussion of the weather inputs see Chapter 5.

This was automated using a Jenkins[11] job that would run various bash and python scripts to perform the ingestion, infill and unification of the data.

6.1.3 System overview

The calculation system was built in Python using Miniconda[12] which provided a consistent base. This allowed development to occur on both Windows and Linux with the final calculation system running on a Linux platform. Jenkins was used for the automation server and gitlab.com was used for source control and continuous integration.

Development was done using a combination of jupyter[13] notebooks and pure Python with some Bash and Jenkins scripts for automation. The Python side used a standard set of libraries (numpy, scipy, pandas, xarray etc.) and the code was shared with the RFS. The RFS was responsible for writing the spread models which the Bureau tested and integrated into the calculation system.

Code and data were shared using GitLab[14], automated tests were setup using py.test[15] for much of the system to ensure stable integration as changes were made. These were automated in GitLab through their continuous integration tools. All code that was submitted to merge into the central repository was automatically passed through the automated tests and a report was sent to the submitter if the code failed to pass. This made for a more robust system as it was being developed.

6.1.4 System execution

The automated Research Prototype was run on internal bureau systems using Jenkins as an automated server. The system would collect and ingest data at 02:00 AEDT daily and calculate the results per region in parallel at 05:00 AEDT. Calculation time was around 15 minutes for Queensland with the rest of the states taking less time. The bundled outputs were made available as soon as a successful run took place.

Figure 6.2 illustrates the process from ingestion to outputs.

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[11] https://jenkins.io/ Accessed 5 June 2018
[12] https://conda.io/miniconda.html Accessed 5 June 2018
[13] http://jupyter.org/ Accessed 5 June 2018
[14] https://about.gitlab.com/ Accessed 5 June 2018
[15] https://docs.pytest.org Accessed 5 June 2018

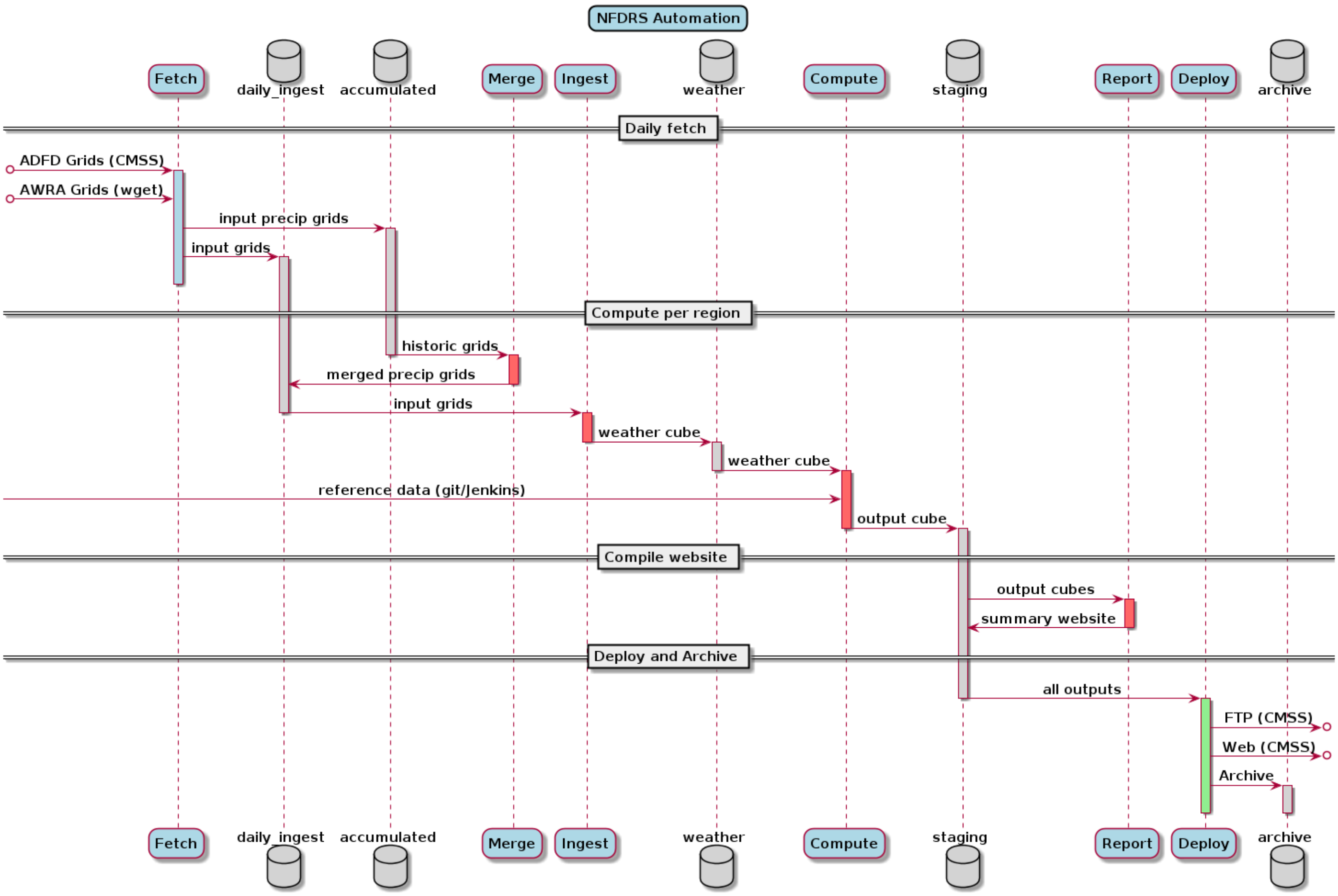

Figure 6.2 Research Prototype daily automation process

6.2 Static website

The bureau produced a static website summarising the daily run of the Research Prototype. This consisted of images summarising the FDR and FDI for the whole country and on a per state basis (Figure 6.3). Additional tables were generated summarising results for the fire areas using the same rules that summarise the current FDR (Figure 6.4). These tables included ‘red flags’ which were results for CHaines, spotting distance and the wind change danger metric coloured based on meeting certain thresholds. Images describing PyroCB and dry lightning were also included. This was delivered using the bureau’s registered-users websites. Example elements from the webpage can be seen below.

This website was built using Jinja2[16] as a templating engine. This meant that a standard form and layout was created, and the system simply built the images and tables and added them to the template to produce the final outputs.

[16] http://jinja.pocoo.org/ Accessed 5 June 2018

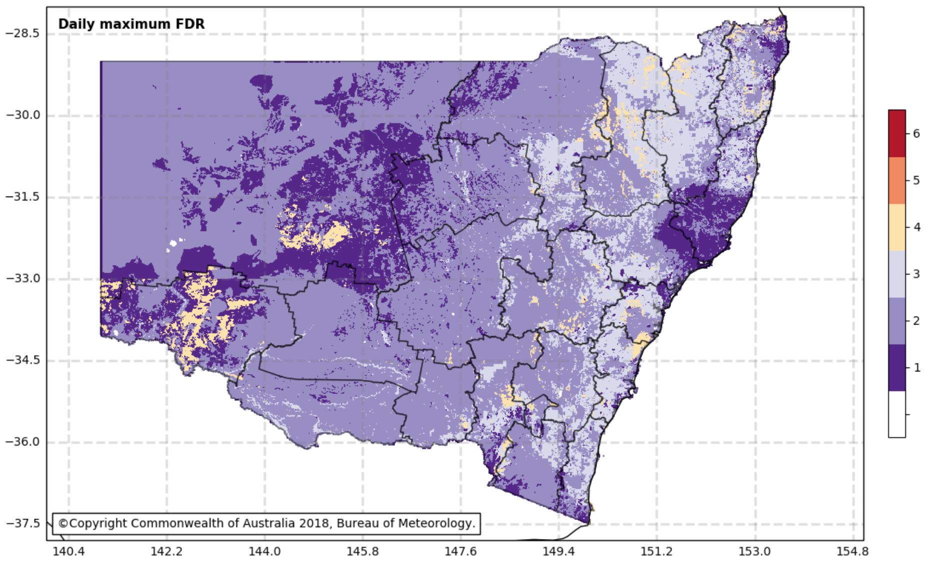

Figure 6.3 Example of static website NFDRS summary (NSW)

Region	AAC	Rating	CHaines	Spotting dist (m)	WCDI
Far North Coast	NSW_FW001	Category 3	No	362	No
New England	NSW_FW011	Category 3	No	359	No
North Western	NSW_FW013	Category 3	No	511	No
Northern Slopes	NSW_FW012	Category 3	No	533	No
Far Western	NSW_FW021	Category 2	No	308	No
North Coast	NSW_FW002	Category 3	No	355	No
Upper Central West Plains	NSW_FW014	Category 2	No	469	No
Greater Hunter	NSW_FW003	Category 3	No	344	No
Lower Central West Plains	NSW_FW015	Category 2	No	325	No

Figure 6.4 Example exert from static website fire region summary table (NSW)

6.3 The interactive website

Hourly forecasts of fire danger rating and other components were displayed on an interactive website to support evaluation of the system by the live trial participants. The main features of the website (Figure 6.5) were:

- Interactive (scrollable, zoomable) map display of ratings and other variables (Table 6.1) for the current and previous days at hourly intervals.
- Ability to view time series graphs for all variables at any selected location. This data could be downloaded as a spreadsheet for later analysis.
- Incident markers and information from agency feeds displayed
- Observed and forecast weather could be compared for Bureau automatic weather stations.

Table 6.1 Variables displayed in the interactive website. Unless noted, all were shown at hourly intervals.

Fire danger rating	Relative humidity (%)
Fuel type	Dew point (C)
Fire behaviour index	CHaines
Intensity (kW/m)	CHaines - daily red flag
Rate of spread (m/h)	CHaines - climate 95% threshold
Flame height (m)	Wind (kmh)
Spotting distance (m)	Wind gust (kmh)
Time since fire (y)	Wind change danger - daily index
FFDI	Wind change danger - daily red flag
GFDI	Drought factor
Temperature (C)	Soil moisture (0-1)
Grass curing (%)	Grass fuel load (t/ha)

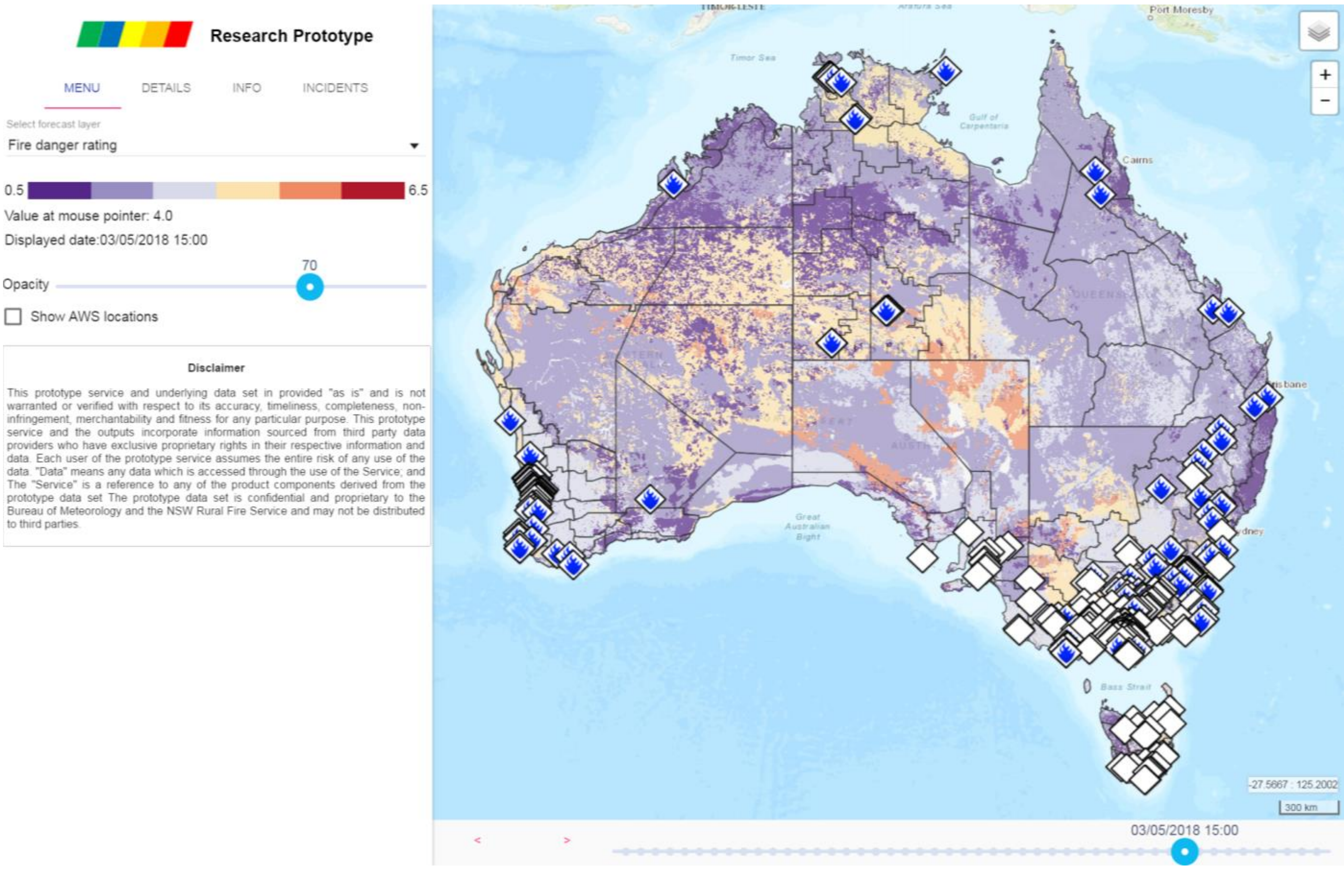

Figure 6.5 The interactive website showing fire danger ratings.

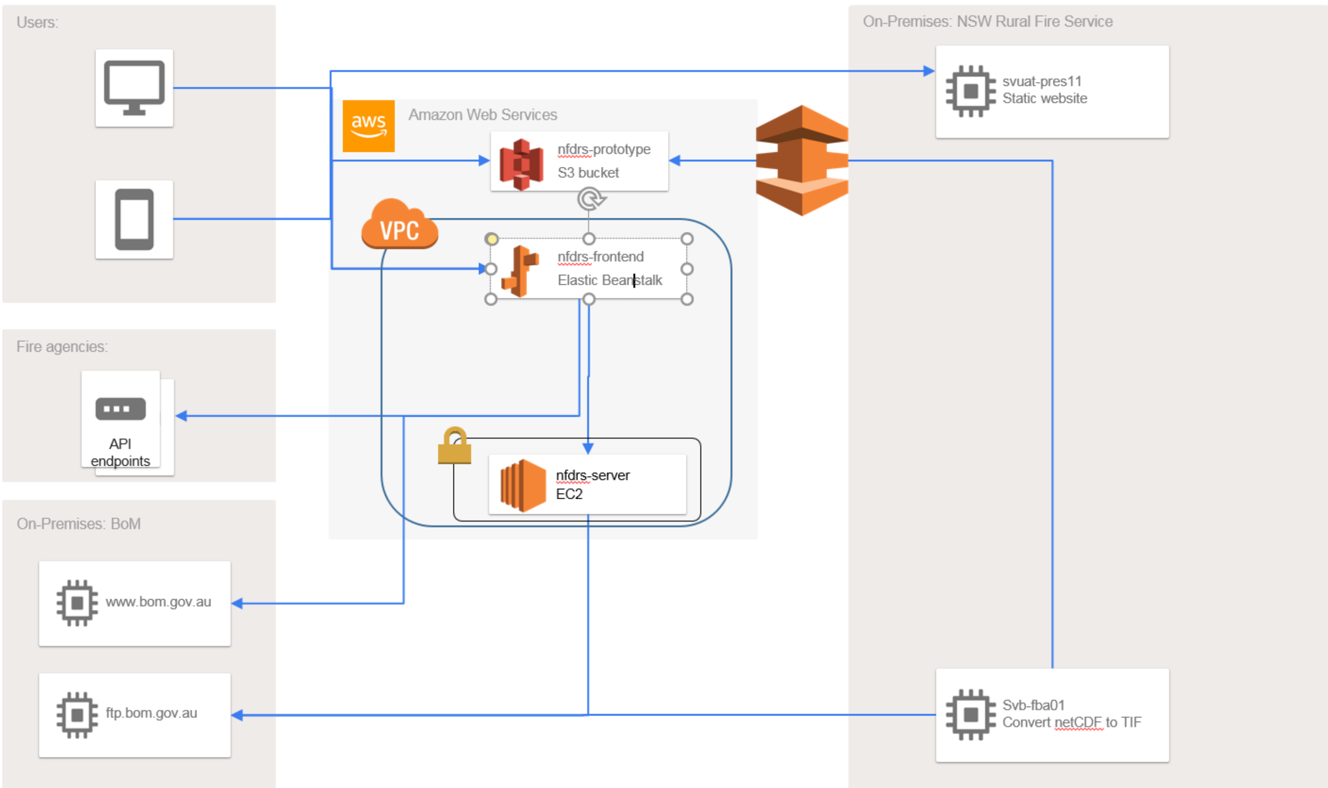

Figure 6.6 Data flows for the interactive website.

The interactive website was implemented as an AngularJS[17] single page application coded entirely as static files. These files were hosted on the RFS fire weather website (Figure 6.6), requiring users to log on with individual credentials.

The forecast maps and time series data shown on the interactive website were based on the netCDF grid files published by the Bureau on their FTP site.

To display the maps:

- A scheduled task ran on a server at the RFS which:
  - Downloaded the grid files, one file per jurisdiction
  - Converted each variable at each time step into a TIFF raster file
  - Compressed the rasters and uploaded them to n S3 storage bucket
  - Generated metadata files in JSON format describing the available time steps for each variable and jurisdiction, also uploaded to the S3 storage bucket
- The interactive webpage client running in the user's browser retrieved the TIFF files as required based on the variable and time step selected in the user interface and rendered the data using a custom LeafletJS[18] plugin

To display time series graphs:

- A scheduled task ran on an EC2 instance which downloaded a local copy of the netCDF grid files
- Requests from the interactive website specifying the required location were passed to the EC2 instance via an Elastic Beanstalk web app endpoint.
- A script running on the EC2 instance extracted the required time series and returned the data via the Elastic Beanstalk server as a JSON file
- The data were rendered as interactive time series graphs using an AngularJS charting module.

To compare forecast and observed weather conditions, an additional request was made to the Bureau's public website to retrieve recent weather station observations in JSON format, which were then rendered on the same graphs as the forecasts.

To display jurisdictional incident markers, requests to retrieve the feed data (Table 6.1) were proxied through the Elastic Beanstalk server and the resulting data was converted to properly formatted geoJSON in the client and displayed as a LeafletJS marker layer.

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[17] https://angularjs.org/ Accessed 4 May 2018.
[18] https://leafletjs.com/ Accessed 4 May 2018.

7 Live trial methods

7.1 Purpose and aims

The purpose of the NFDRS Research Prototype project was to demonstrate that it is feasible to develop a fire danger rating system based on fire behaviour models that is national, modular, and open to continuous improvement. The five critical success factors for the project were:

1. Define, and build a Research Prototype system
2. Operate the system and demonstrate that the ratings can be applied in a live trial
3. Build a system that is better than the current system
4. Identify knowledge gaps
5. Recommend a path forwards for future development

The live trial addressed factors 2 and 3 by:

- Operating the system from 5 October, 2017 to 31 March, 2018.
- Collecting observed ratings data from around the country based on application of rating definitions to incidents.
- Assessing the performance of the Research Prototype outputs against observed ratings.

The approach taken in the trial was to engage operational staff and volunteers to collect observations on real bush fire incident and prescribed burns. These observations were supplemented with data from case study fires (See Chapter 9 for more detail). As well as providing insight into the performance of the system for significant historical events the case studies also expanded the number of observations available for relatively rare Category 5 and 6 events.

7.2 Participants, training, and evaluation of sample incidents

Participants were drawn from fire and land management agencies around Australia. 71 participants were nominated through a process coordinated by the NFDRS National Board and the AFAC Predictive Services Group.

Prior to the commencement of the trial, participants were inducted into the project by participating in a webinar or face-to-face training session which:

- Explained the purpose of the project and the design of the Research Prototype system
- Demonstrated the use of the rating visualisation systems
- Walked participants through some demonstration exercises using sample incidents

Participants were also asked to complete two training observations using data provided by the project. These results were used to assess the variability in participant's assessment of a simple and a complex fire incident. The results of this assessment are presented in Chapter 8.

7.3 Operation of the live trial

During the live trial, Research Prototype products (See Chapter 6) were produced daily and published at midday (Eastern Time). Products were published at this time to prevent the use of the untested system for making operational planning decisions while still allowing live or near-live viewing by the trial participants during the afternoon when fires are most active.

Trial participants remained with their home agencies during the trial, rather than gathering at a central location. This allowed them full access to incident information and removed the risk of participants travelling to work with the project time at a time when there were few fires of interest.

The four RFS members of the project team operated a duty roster on weekdays with one member assigned to process incoming observations from other jurisdictions and complete assessments of fires in NSW. We were also granted access to incident management systems in Victoria, South Australia, and Western Australia to assist with data collection. Participants in other jurisdictions used a variety of approaches to collecting data.

7.3.1 Direction given to participants

Participants were asked to complete observations any prescribed burn, burn escape or wildfire and can represent any type of fire danger. The full spectrum of fire danger was required for evaluation, including those fires that typically fall into the lower ends of fire danger (e.g. Categories 1 and 2) however because of the limited numbers of fires likely to occur that represent the upper end of the fire danger, fires in categories 5 and 6 were prioritised.

We asked that observations be completed within 24 hours where possible. When this was not possible due to operational constraints, the project website allowed participants to download the forecast for the current and previous day, which allowed completion of observations at a later time. If more than 24 hours had passed and the forecast was no longer available on the interactive website, the NFDRS project team provided archived values using a tool built to extract forecasts based on the incident coordinates and a nominated time period.

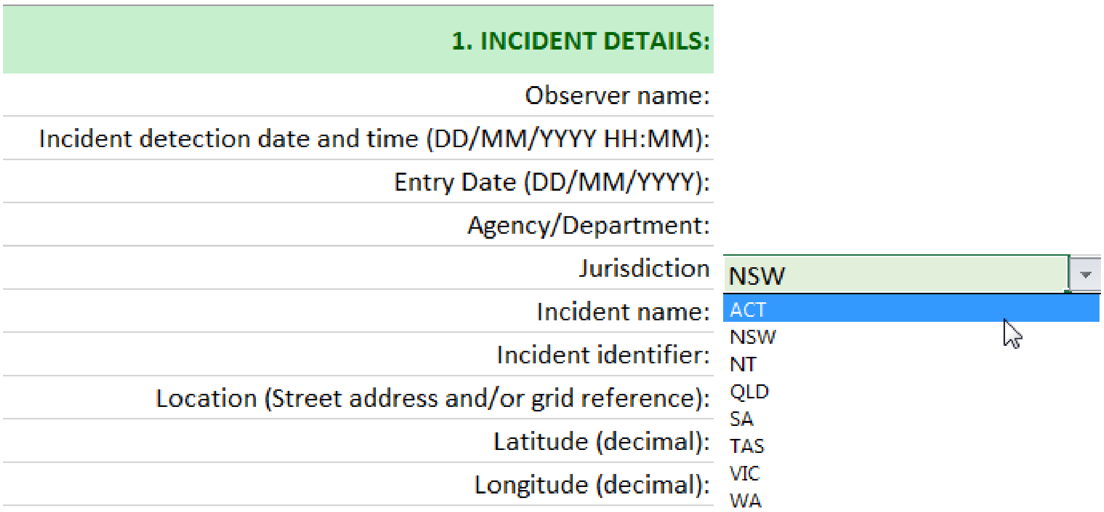
Selection of time periods within the life of an incident was a somewhat subjective process. We requested that participants select a time period to do an observation on a fire when it was likely that there was sufficient information to complete an observation. For example, when receiving observations on fire behaviour and fire area/perimeter from the field, or perhaps a linescan was performed, or after receiving photographs or information regarding suppression and resourcing. Alternatively, we suggested choosing a time period where there were significant consequences observed, for example property or house losses.

While the focus of data collection for participants using the incident appraisal form was characterising the incidents, participants were asked to estimate the performance of the rating(s) by comparing the forecasted FDR with what was actually observed. This was considered as expert opinion in our evaluation and highlighted the need for appropriately trained and practitioners to be selected for the evaluation process. Participants provided ratings assessments for both the Research Prototype ratings and the current system. Estimates of ratings for the current system were highly subjective because the rating categories of the current system have never been properly defined. However, this information allowed the predictive capacity of the current system to be evaluated on its own terms as it was not possible to directly align the current and Research Prototype rating categories.

In addition to ratings observations, the data form also allowed participants to record a range of other observations and evidence to support and explain the choice of rating for the incident. Participants were also encourage to submit additional evidence such as field reports, maps, and photographs as part of their reports.

7.3.2 Data collection process

A simple spreadsheet (Attached as Appendix D) was used to collect observations of the progress of fire incidents using the fire danger rating definitions. This section gives an outline of the data requested and some examples (indented samples in *italic* type).



1. INCIDENT DETAILS:

Observer name:

Incident detection date and time (DD/MM/YYYY HH:MM):

Entry Date (DD/MM/YYYY):

Agency/Department:

Jurisdiction NSW

Incident name:

Incident identifier:

Location (Street address and/or grid reference):

Latitude (decimal):

Longitude (decimal):

ACT
NSW
NT
QLD
SA
TAS
VIC
WA

Figure 7.1 Incident details section of the data collection form.

Jurisdiction was selected using a dropdown list (click the triangle on the right to open it). All other values can be typed.

For the incident identifier:

- ACT: incident number, e.g. 033058-14092017
- NSW: six-digit incident id, e.g. 274023
- NT: name and date notified, e.g. GREGORY PL, JABIRU 2017-09-14 20:11
- QLD: incident id, e.g. QF3-17-099469
- SA: incident number, e.g.1233569
- TAS: incident number, e.g. 254532
- VIC: incident id, e.g. 1646306
- WA: DFES unique identifier, e.g. 371297

Coordinates (Latitude/Longitude) were obtained on the interactive web page, using the mouse pointer coordinates that displayed at the bottom right corner of the map.

For short incidents a single entry was sufficient, for longer incidents participants used multiple columns or forms. There were no set time periods expected but as a guide it was expected that separate entries would be used for periods where the observed fire danger rating was different or significant escalation/de-escalation of the incident occurred.

2. INCIDENT OBSERVATIONS:	
Start of time period (DD/MM/YYYY HH:MM):	
End of time period (DD/MM/YYYY HH:MM):	
Status at the end of the time period (select):	
Status at the end of the time period (select):	
Fire type (select) i.e. P/B, wildfire or P/B escape:	
Fire size at the beginning of time period (ha):	
Fire size at the end time period (ha):	
Closest (or most representative) BoM AWS:	
Have you made an observation on this fire incident previously? (If yes, please provide date):	
Was the fire contained within 1 hr of suppression commencing? (i.e. initial attack success) (yes/no):	
Maximum Forecast FFDI during time period:	
Maximum Forecast NFDRS FIRE BEHAVIOUR INDEX for fuel type (number):	
Maximum Forecast NFDRS FIRE DANGER RATING for fuel type (number):	
Fuel type (i.e. FIRE DANGER RATING Table used) (select):	

Figure 7.2 Incident stats section of the data collection form.

A variety of terminology is used to describe the status of incidents. Some synonyms for the terms used here are:

- Out of control: Going, Responding, Not Yet Under Control
- Being controlled:
- Under control: Contained, Patrolled, Patrol, Controlled.
- Out: Closed, Complete, Safe.

Fire size was estimated if mapping was not available. Participants were asked to note when fire size was estimated (e.g. 10ha (estimated)).

FFDI, NFDRS rating and index, fuel type and the location of the closest BoM AWS were obtained from the Research Prototype website. Because fuel type mapping was presented at a course scale it was sometimes necessary to use a pixel near the fire that was most representative of the incident, e.g. for a heath fire mapped in an area with a mix of forest and heath participants choose one of the heath pixels even if the fire location was mapped as forest. For a fire that covered multiple fuel types participants chose the type that was most representative for the remainder of the form, e.g. the head fire. Both fire location and fuel type were audited by the project team at the end of the trial.

3 (a) FIRE DANGER OBSERVATIONS (for all fuel types):
Your observed NFDRS FIRE DANGER RATING (based on your own opinion/observations using the appropriate FDR TABLE) (number):
If the Forcasted NFDRS FIRE DANGER RATING does not match your Observed NFDRS FIRE DANGER RATING, what was the main reason in your opinion:
How confident are you in your observations? (Please rate):

Figure 7.3 The ratings section of the data collection form.

Participants used the fire danger rating definition tables to determine what the FDR rating should have been. This was based on the fire behaviour, prescribed burn implications, fire suppression and containment, and consequences descriptors.

If the forecasted NFDRS fire danger rating didn't match the observation, they were asked to specify what the main reason was.

Some examples of why the NFDRS fire danger rating might not match your observation are included below:

- *Fire behaviour, specifically rate of spread, was over- or under-estimated in the FDR table (and therefore in the NFDRS FDR rating).*
- *Grassland curing used in the NFDRS FDR was more (or less) than actual observations and has therefore had an impact on the rate of spread prediction (and FDR).*
- *The descriptions of prescribed burn implications were over- or underestimated.*
- *The descriptions of potential consequences hadn't sufficiently identified actual consequences that occurred.*

3 (b) GRASS FIRE DANGER OBSERVATIONS (only to be completed for grassfires):
Maximum Forecast GFDI during time period:
Predicted grassland curing (%):
Your observed grassland curing (%)

Figure 7.4 Additional grass fire danger section of the data collection form.

Forecast GFDI and Curing were obtained from the NFDRS interactive website. Visual estimates for observations of grassland curing were obtained from field guides, field personnel or photographs, and participants were asked to attach evidence to their report where possible.

4. FIRE BEHAVIOUR OBSERVATIONS:
Mean rate of spread during time period (m/hr):
Mean flame height during time period (m):
Spotting distance and frequency (describe):
Did the forecasted FIRE BEHAVIOUR DESCRIPTORS within the FDR Table broadly represent your observations of POTENTIAL fire behaviour (Yes, No-underestimated, No-overestimated):
How confident are you in your observations? (Please rate):

Figure 7.5 The fire behaviour section of the data collection form.

The Research Prototype used calculations based on modelled head fire behaviour to calculate fire danger rating. Observations of fire behaviour were requested for validating these calculations. Values were obtained from field personnel or estimated from maps, linescans, or photographs. If using maps or photographs, participants were asked to attach these.

EXAMPLE: In line number 45, please compare your observations of fire behaviour with the descriptions within the appropriate FDR table. For example, if you've observed rates of spread that are faster, and/or flame heights that are higher, and/or spotting distances are further than those described within the FDR table, you would record that the FDR table has 'underestimated' fire behaviour.

5. FUEL OBSERVATIONS:

Estimated fine fuel load (t/ha):
Please describe which fuel layers are represented in above figure (e.g. surface, elevated, bark, canopy):
Fuel age (years):
How confident are you in your observations? (Please rate):

Figure 7.6 The fuel observations section of the data collection form.

Any information on the fuels driving the fire derived from field intelligence or situation reports was reported here.

6. PRESCRIBED BURN IMPLICATIONS (only to be completed for prescribed burns):

Prescribed burn type (e.g. hazard reduction, pile burn, wind row, silvicultural, agriculatural etc):
Were there any burn escapes associated with prescribed burn (yes/no):
Did the PRESCRIBED BURN DESCRIPTORS within the FDR Table broadly represent your expectations and fire applications (Yes, No-underestimated, No-overestimated):

Figure 7.7 Prescribed burning section of the data collection form.

If the incident was a prescribed burn the type of burn and if there were any escapes related to the burn was described.

> *EXAMPLE: In line number 57, please compare your experience and knowledge of the prescribed burn with the descriptions of prescribed burn implications within the appropriate FDR table. For example, if there was difficulty getting the fire ignited and spreading while the FDR table had suggested that conditions were suitable, you would record that the FDR table has 'overestimated' prescribed burn conditions.*

7. RESOURCES, STRATEGIES and SUPPRESSION/CONTAINMENT DIFFICULTY:

Number of field personel operational during time period:
Number of tankers/trucks operational during time period:
Number of heavy plant operational during time period:
Number and type of aerial resources operating during time period:
What width fuel break (i.e. road networks, buffers etc) proved to be adequate in containing fire (m):
Was there any active fire suppression during time period:
If there was active fire suppression, describe any OFFENSIVE strategies used during the time period (e.g. direct, indirect, parallel attack):
If there was active fire suppression, describe any DEFENSIVE strategies used during the time period (e.g. property protection, evacuation, public notifications):
Did the SUPPRESSION/CONTAINMENT DESCRIPTORS within the FDR Table broadly represent the difficulty of containment and the strategies used (Yes, No-underestimated, No-overestimated):

Figure 7.8 The resources and suppression section of the data collection form.

In this section the observed described the resources working on the fire, and the strategies being applied. If this information was described in a situation report in more detail than the form allows, the situation report was attached to the observation.

> *EXAMPLE: In line number 68, please compare the suppression strategies that were used on the fire during the period of observation with the descriptions of fire suppression and containment within the FDR table. For example, if the strategies that were used on the fire were mostly 'defensive' strategies because*

'offensive strategies were not appropriate, however descriptions within the FDR table suggested that direct approaches would have been suitable and effective, you would record that that FDR table has 'underestimated' fire suppression and containment.

OFFENSIVE strategy: Offensive strategies are used when the fire can safely and effectively be attacked or extinguished, and include direct attack, parallel attack and indirect attack.

DEFENSIVE strategy: A firefighting strategy used where the protection of life and assets is a priority when a fire is: (i) located in inaccessible or remote location OR (ii) too intense to be safely or effectively attacked directly.

8. CONSEQUENCES:
Number of injuries during time period:
Number of deaths during time period:
Estimated houses threatened (number):
Houses lost (number):
Estimated other assests threatened e.g. mining infrastructure, electrical infrastructure, fence lines, machines, sheds, livestock) etc (describe):
Other sssests lost (describe):
Did the CONSEQUENCE DESCRIPTORS within the FDR Table broadly represent the POTENTIAL effects of the fire (Yes, No-underestimated, No-overestimated):

Figure 7.9 The consequences section of the data collection form.

In this section any losses (deaths, injuries, property) or threats to values that occurred were described. Estimates of losses were sometimes uncertain during an incident. As better information such as building impact analysis data was collected after the incident it was added retrospectively.

EXAMPLE: In line number 77, please compare your observations of POTENTIAL consequences with the decriptions of potential consequences within the FDR Table. This can be particularly tricky to do because we are specifically asking you to compare what has and may have actually happened with the descriptions of what may have happened in the FDR table. Please keep in mind that the descriptions of fire size in the FDR tables relate to the maximum potential spread of fire within a 4 hour period under the maximum forecasted FDR, so if the period you are observing is less than 4 hours, you'll need to take this into account. For example, if there were no known property losses and no known impacts on infrastructure and there was no comments relating to community or infrastructure loss within the FDR table, you could record 'Yes', that FDR table has broadly reflected potential consequences.

Once the observation spreadsheet was complete, it was emailed along with attachments to the NFDRS project email address.

The project team added each entry as a row in a consolidated spreadsheet, the 'evaluation database'. This was backed up each evening on a secure RFS network drive.

7.3.3 Data collection targets

To allow a reliable statistical analysis of the results were aimed for enough samples to cover at least:

- 30 observations in each of the 8 top level fuel types, and
- 30 observations in each of the 6 rating Categories.

7.3.4 Use of case studies

For some of the case study fires (See Chapter 9), sufficient information was available to complete observation spreadsheets and include these fires in the data analysis. For most of these fires, we produced several observations, each included as an entry in the evaluation database.

7.4 Data preparation

Prior to using the live trial and case study observations to evaluate the performance of the system, some preparatory work was done.

Database entries were audited to ensure that each incident was consistently reported and that the recorded locations and fuel types were accurate. Where errors were identified, the corrected values were entered into separate audit columns to allow recalculation of forecasts. The original entries were not modified or deleted. If an entry could not be corrected, it was marked for exclusion from the analysis but not deleted. In total 16 entries were excluded from the analysis.

If information in the report indicated that any of the fuel parameters were incorrect, then these were marked for recalculation using the value supplied in the observation. The number of changes made were:

- Grass fuel load, 7 times
- Grass curing, 17 times
- Time since fire, 12 times

If information in the report indicated that the weather forecast had been inaccurate, the nearest suitable weather station was identified and the entry was marked for recalculation. This was done for 21 entries.

For all fires that were marked for recalculation, NFDRS calculations will be done using the original grid data modified by the flagged values. The maximum rating category will be extracted automatically from the data and added to the evaluation database as an audited rating. The original values will not be overwritten. These recalculations are planned for the next revision of this report but are not included in the current version.

For fires where the report, fire size, or containment time indicated that the incident was affected by initial attack and did not reach its full potential, the row was marked to allow identification in the data analysis but not excluded. There is not a single accepted definition for initial attack (Plucinski, 2013) and some definitions allow fire sizes up to 100 ha and time to containment of up to 6 hours. On the basis of comments within the observations, and noting that fires require their head to be several 100m wide to reach steady state (Cheney *et al.*, 1998), we used a definition of 10 ha and time to containment of 90 minutes. 36 fires were identified as affected by initial attack.

7.5 Evaluation statistics

The primary evaluation tool was a multi-category contingency table analysis:

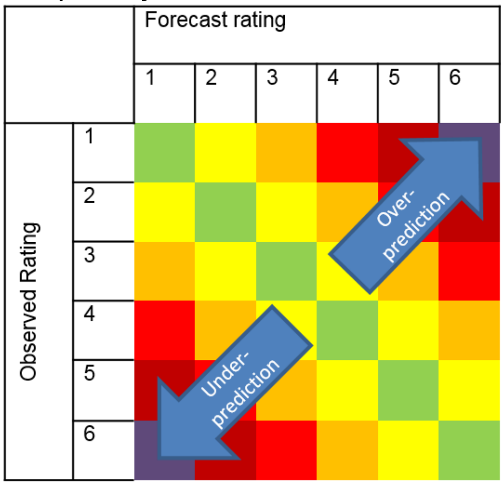


Figure 7.10 Multi-category contingency table. Green entries indicate correct forecasts. Yellow, orange, red, and purple correspond to increasingly severe under- and over- predictions.

These contingency tables, in combination with skill scores, give us information about the system performance. If the forecasted rating and observed rating match up, this means that the system performed well (green squares in Figure 7.10). If the forecasted rating was higher than the observed rating, this means that the system over-predicted the fire danger (top right corner, Figure 7.10). This is undesirable because of unnecessary Total Fire Ban declarations, or fire preparedness when not needed. If the forecasted rating was lower than the observed rating, this means that the system under-predicted the fire danger (bottom left corner, Figure 7.10). This can be dangerous because it might put firefighters and communities at risk (unexpected fire behaviour, unexpected suppression difficulties, unexpected consequences such as loss of assets or life).

There are several statistical measures that are suitable for the evaluation of multi-category forecasts. For the Research Prototype we selected the following:

- Fraction correct (a value between 0 and 1): fraction of the forecasts that match the observation (green cells in Figure 7.10).
- Fraction over-predicted (a value between 0 and 1): fraction of the forecasts that predicted higher ratings of fire danger than observed (all the entries above the diagonal green line in Figure 7.10).
- Fraction under-predicted a value between 0 and 1): fraction of the forecasts that predicted lower ratings of fire danger than observed (all the entries under the diagonal green line in Figure 7.10).
- Peirce skill score: fraction of correct forecasts after eliminating those that would be correct due to random chance (Peirce, 1884). The score ranges from -1 to +1. The higher the score the better the model performance. Zero indicates no skills, one (+1) is a perfect score.
- Gerrity skill score (a number between -1 and +1; the lower the score, the poorer the model performance (Gerrity Jr, 1992). Zero indicates no skill, one (+1) is a perfect score): This score rewards the ability of a model to correctly forecast rare events and is less affected by the most commonly occurring (low) rating categories than the Peirce score. With the Gerrity score, large forecast errors are penalised more than small forecast errors.

This analysis with contingency tables and skill scores can only consider the appropriateness of ratings to incidents (or periods within incidents) that actually occur. In other words, the absence of any fires in an area with an elevated rating counted as ‘no data’, not as an over prediction. There is a preliminary investigation of the use of fire danger rating to predict fire occurrence in Chapter 11.

The same analysis was also performed for the current system using forecast FFDI/GFDI and a participant assigned rating (Low-Moderate, High, etc.). There was considerable uncertainty with this approach because the rating categories in the current system are not objectively defined, nor are they applied consistently across the country (e.g. local variation in FFDI values used to declare total fire bans). But, we considered it the best possible approach.

The analysis as described above, was used to evaluate overall system performance on the raw and audited datasets. Also, we ran the analysis with and without the case studies. We evaluated the system performance per fuel type, and we also looked at the fires that we flagged as fires with initial attack success. The results of these evaluations are presented in Chapter 8.

7.6 Exploratory multivariate data analysis

As discussed before, there are many variables that were taken into account to define the fire danger rating. As input for the fire behaviour models there are the weather variables (wind speed, drought factor, relative humidity, air temperature) and fuel variables (fuel height, fuel load, fuel cover, curing, fuel moisture content). The outputs of the fire behaviour models are mostly fireline intensity, rate of spread, “go/no-go”, etc. Based on these fire behaviour outputs we calculated the fire danger rating (as discussed in chapter 4). In such a complex system with so many variables, is there a way to assess how it all fits together? Are we indeed looking at the right variables? What could be the best predictor/driver of fire danger rating? And are there fuel specific differences?

7.6.1 Principal components analysis

We attempted to use multivariate ordination techniques, namely, principal component analyses (PCA) to answer these questions. With ordination techniques, all measured variables of our “objects” (i.e. data entries; in this case the incident observations) can be simultaneously plotted in a multidimensional space. Similar “objects” are grouped/clustered near each other, while dissimilar “objects” are farther apart. Patterns in the dataset can be extricated and component axes are defined. These component axes identify the most important gradients of variation in the dataset.

We had the following aims:

- To evaluate (some of) the specific inputs of the fire behaviour models used, how they vary per fuel type and how they affect fire behaviour. This gives us information on what fire behaviour variable could/would be the best predictor for defining fire danger rating.
- To evaluate how the models compare to reality, i.e. comparing the results from the live trial with what we would expect based on our current knowledge of fire behaviour.

To do this, we used the “vegan” package in R version 3.4.3 (R Core team 2017). R is a software environment for statistical computing. With the right commands, R can make ordination diagrams and calculate ordination scores for each data entry (incident observation). Also, it gives us information on how much of the variance can be explained by the component axes. The first component axis is defined in such a way that it accounts for the largest possible variation in the dataset. The next component axis is than defined to capture the largest possible variation in the dataset, given the constraint that it is orthogonal to the previous component axis. The output from R also gives us the component loadings, which give us information on how much the variables (as measured or calculated for all data entries) correlate to the component axes.

First we cleaned the live trial dataset from empty or faulty values. Next, we selected the variables that we were interested in for the PCA analysis. We split the dataset in two parts, namely, the grasslands and savanna fuel types combined, and the “non-grassy” fuel types (i.e. buttongrass, forest, mallee heath, pine, shrubland and spinifex) grouped together. We decided to split the dataset like this, because curing is (assumed to be) a very important factor for fire behaviour in grass, but not for the “non-grassy” fuel types. Also, we had access to data on fuel load for grasslands and savanna, but not for the “non-grassy” fuel types.

7.6.2 Correlation matrices

Next to the PCA analyses, we also plotted correlation matrices for both data subsets (i.e. the grassland/savanna subset, and the “non-grassy” fuel types subset), and visually assessed the results. Correlation matrices show the relationships between sets of variables. The variables that we included were similar to the ones that we used for the PCA analysis, i.e. fire behaviour variables (rate of spread, fireline intensity and flame height) and environmental variables (weather and fuel inputs). On top of that we included the fire danger metrics GFDI/FFDI, forecasted fire danger rating as predicted by the Research Prototype (NFDR_for) and observed fire danger rating as observed by the live trial participants (NFDR_obs) (Table 7.2).

The correlation matrix was presented as a collation of scatterplots for each pairwise combination of variables. We visually assessed the patterns in these scatterplots. In some cases clear patterns could be seen, suggesting positive or negative relationships between the two variables. In other cases, the scatterplot looked like a cloud of datapoints without a strong direction or shape. In a follow-up analysis, the pairwise relationships could be investigated in more detail, but that was beyond the scope of the current Research Prototype project.

The results of these analyses are described in chapter 9.

Table 7.1 Variables as used for the PCA analysis and correlation matrix. The variables highlighted in yellow were included for the grassland/savanna subset only.

Environmental variables	Fire behaviour variables	Fire danger metrics
Relative humidity	Rate of spread	GFDI
Drought factor	Fireline intensity	FFDI
Wins speed	Flame height	Forecasted fire danger rating
Air temperature		Observed fire danger rating
Curing		
Grassland fuel load		

8 Live trial results

8.1 Estimating potential bias within observations

8.1.1 Background and methodology

In order to evaluate and determine applicability of the NFDRS Research Prototype, live trial participants were asked to provide their opinion of fire incident (or observation) of what they considered the correct NFDRS fire danger rating as well as the correct fire danger rating using the current system. Because participants were either part of the NFDRS team (NSW RFS, Fire Behaviour Analyst) or nominated by their agencies or departments and were considered to be in the best position to complete accurate and relevant assessments, we have considered their observations to be estimates based on expert judgement. However, there is potential for bias or variation in opinion that can be attributed to the participants role, their experience and training, the fire management agency they represent as well as the way the survey form was interpreted by the individual (Plucinski *et al.*, 2012). This variation underlies the dataset that was collected and how the results of our study should be considered.

In order to quantify how much variation is represented within the dataset, live trial participants were asked during the briefing and training process to complete an observation survey (the same used throughout the live trial evaluation period) for two ‘live’ scenarios from New South Wales. Participants were provided with maps, vegetation type, Situation Reports as well as the forecasts for the Research Prototype rating and the fire danger rating based on the current system. A summary of the conditions and characteristics of fires used for the scenarios is included below in Table 8.1. Scenario 1 was selected to represent a simple fire with adequate background information to support decision making, while Scenario 2 was selected to represent a more complex fire, with limited supporting information (which can often be the case for fires with increasing complexity).

Table 8.1 Conditions and characteristics of the fires used for the scenarios.

Characteristics and Conditions	Scenario 1	Scenario 2
Fire type	Wildfire	Wildfire
Forecast NFDRS Rating (*Index*)	2 (*2*)	4 (*89*)
Forecast FDR (*index*)	Low/Moderate (GFDI: *1*)	High (FFDI: *19*)
Final fire area	0.1 ha	123 ha
Vegetation type / FDR Table	Grass / Grassland	Forest / Forest
Strength of resourcing	4 Personnel (1 tanker)	44 Personnel (13 tankers, 1 aircraft, 1 dozer)
Suppression/Containment	Blacking out with direct attack	Direct and parallel attack, property protection
Consequences	NIL	Infrastructure and private assets threatened

8.1.2 Results

Of the 71 live trial registered participants, 28 completed observation surveys over the fire season between October 2017 and March 2018. 21 participants completed the Scenario 1 bias exercise and 22 completed Scenario 2. Six of these were from fire management personnel that didn't complete any observation surveys.

There was little variation (or bias) in responses within the Scenario 1 exercise (Figure 8.1). With the exception of 1 response, all participants rated the NFDRS as a Category 2, in agreement with the forecast. Similarly, participants consistently rated the fire as Low-Moderate fire danger using the current system.

In contrast, there was considerable variation in responses for the Scenario 2 exercise (Figure 8.1). While the median response for NFDRS category was 4, supporting the forecasted fire danger, responses ranged mostly between 2 and 4 (based on the range of values that fell within 1.5 times the interquartile range beyond the box in Figure 8.1). This suggests that participants felt the fire was best described as anything between 'typical prescribed burning conditions with fires generally easy to suppress' through to a fire where 'initial attack is critical to prevent large fire development and defensive strategies are used'. There was an even greater amount of variation in responses to the rating of fire danger using the current system for this scenario. The median response rated the fire as Very High, a category higher than forecast, with responses ranging mostly between Low/Moderate and Severe. While it is difficult to determine the meaning of this variation in the absence of clear and consistent definitions (between states and fire management agencies/departments), the AEMC - National Bushfire Warnings Taskforce (2009) descriptors and messages, suggest the fire could be described as anything between fires that 'can be easily controlled' through to 'fires that are difficult to control'.

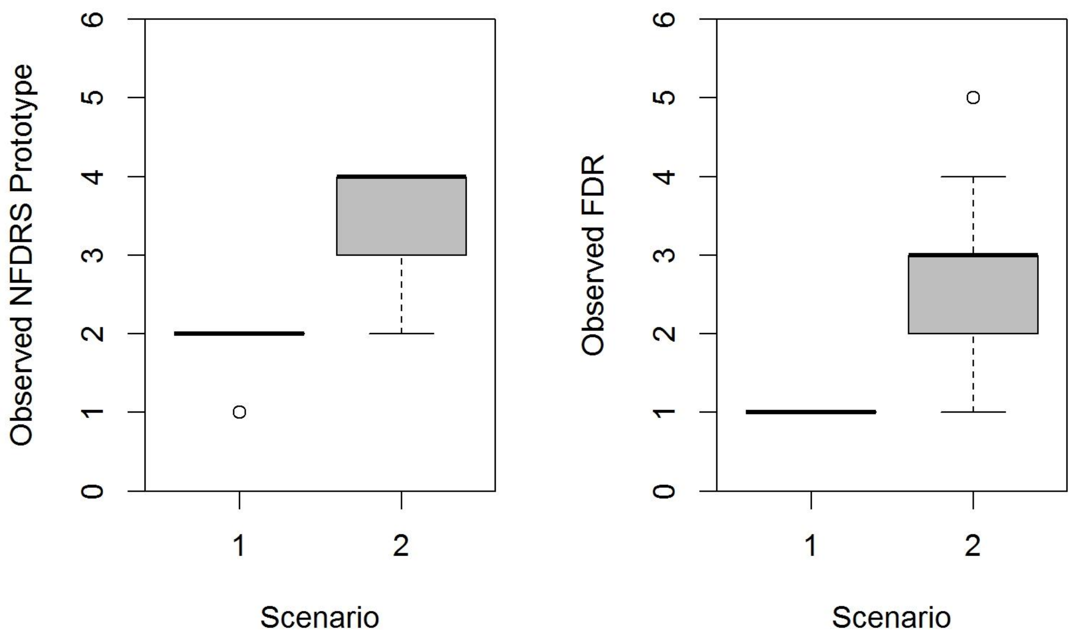


Figure 8.1 Boxplots showing the variation in participant responses for the two scenarios. The boxes represent the upper and lower quartile around the median (bar), the vertical lines (whiskers) indicate the ranges of values that fall within 1.5 times the interquartile range beyond the box. Points indicate outliers. For the Observed FDR (current system) 1=Low/Moderate, 2=High, 3=Very High, 4=Severe, 5=Extreme and 6=Catastrophic.

8.1.3 Implications for the dataset

The results of the bias analysis suggest that fairly simple fire incidents, supported with adequate background information are highly likely to have consistent observed ratings of the Research Prototype and FDR (current system) across the dataset. However, more complex fires and/or those that have minimal supporting information on fire behaviour, suppression/containment response and consequences are likely to have resulted in considerable variation in observed rating, particularly of the current FDR system. The clearly defined descriptors for the Research Prototype (i.e. relating to fire behaviour, suppression/containment and consequences) are likely to have reduced the amount of variation that can be attributed to subjective interpretation and therefore reduced some of the bias evident in the Scenario 2 exercise, but also for Research Prototype observed ratings within the dataset as a whole.

It is important to note that while participants selected the same time frame to evaluate for the Scenario 1 exercise, there were discrepancies in the Scenario 2 exercise where participants selected different time periods to evaluate. Mostly participants selected one of two distinct time periods, however the difference can potentially result in differences in observed ratings. Participants were provided with the same supporting information for Scenario 2, and some of the potential for differences between time periods, would have been limited by the basic, minimal information provided (Table 8.1). Because of this, and for the purposes of this report, each of the responses were treated as evaluating the same time period. Ideally, participants should have been directed to evaluate the same time period to ensure consistency across the bias analyses and this should be noted and considered if a more thorough or detailed determination of bias is required and additional bias exercises are to be completed beyond the scope of the current project.

8.2 Summary statistics

A total of 265 observations were used in the data analysis, supplemented by 72 case study observations (Figure 8.2). Observations were contributed by 28 different observers including the 4 NSW RFS members of the project team. The majority of observations (63%) were contributed by the project team with the remainder (37%) from other jurisdictions. Some contributors were very active, with two non-project team members recording 18 (Jonathon Palmer, WA DFES) and 21 (Musa Kilinc, Vic CFA) observations. Engagement was generally challenging however and 43 of the 71 nominated participants returned no observations.

Observations were collected covering all jurisdictions (Table 8.2), all major fuel types (Table 8.3) and all rating categories (Table 8.4). We set a target of 30 observations for each major fuel type and category. This target was met for forest and grass fuels and fires in categories 2 to 5 once case studies were included in the dataset. Insufficient data were collected for pine, spinifex and buttongrass fuels and the performance of the system for these fuel types is uncertain.

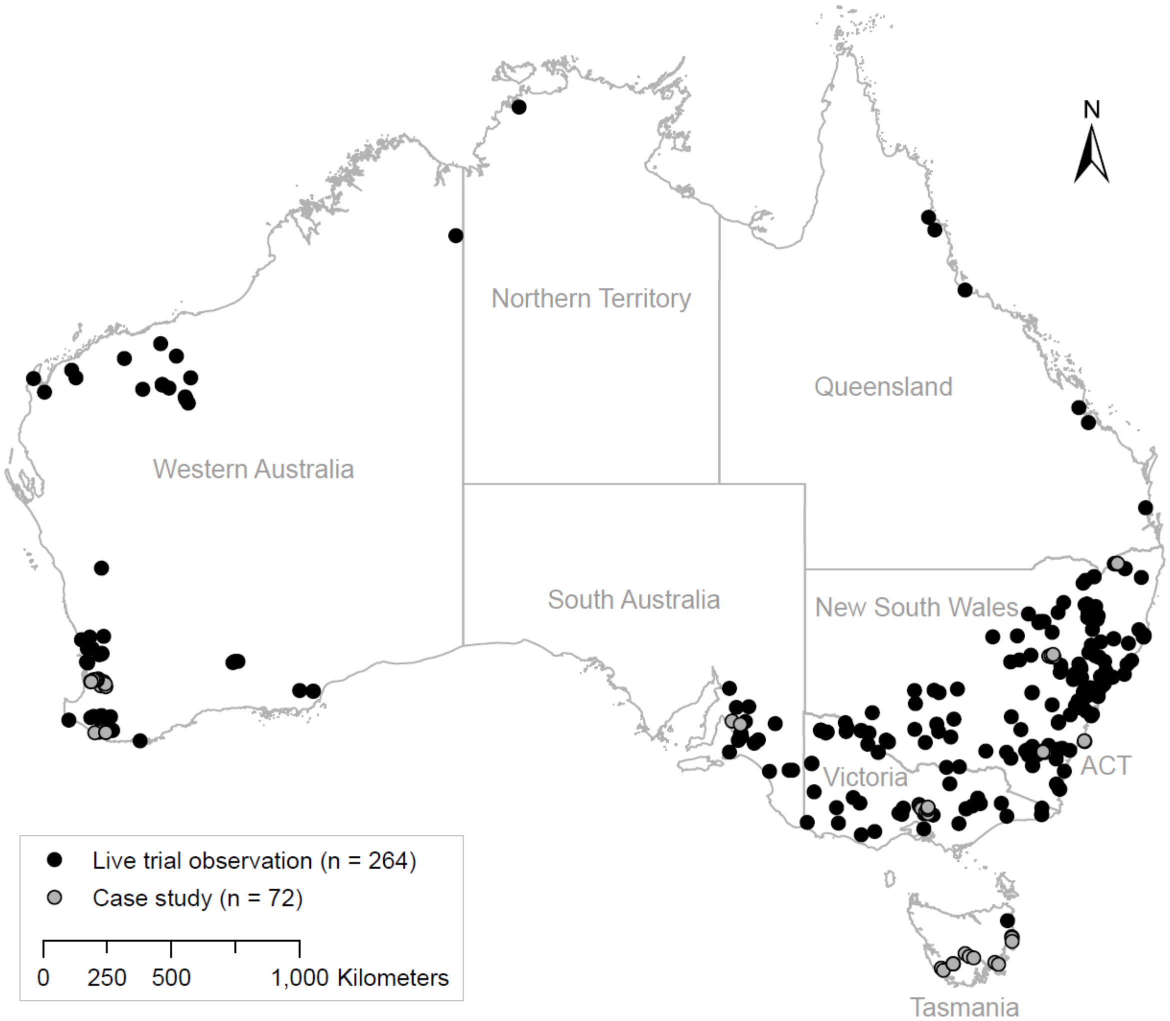


Figure 8.2 Observations used in the evaluation of the system. The dataset included 264 live trial observations (black) and 72 case study observations (grey).

Table 8.2 Number of fire danger rating observations by jurisdiction.

Jurisdiction	Live trial	Case studies	Total
Australian Capital Territory	6	0	6
New South Wales	142	14	156
Northern Territory	1	0	1
Queensland	6	9	15
South Australia	15	2	17
Tasmania	1	15	16
Victoria	42	10	52
Western Australia	51	22	73

Table 8.3 Number of fire danger rating observations by fuel type.

Fuel type	Live trial	Case studies	Total
Forest	139	48	187
Grassland	63	14	77
Spinifex	10	0	10
Pine	5	0	5
Savanna	18	0	18
Mallee-Heath	15	0	15
Shrubland	14	4	18
Buttongrass	0	6	6

Table 8.4 Number of fire danger rating observations by observed rating category.

Observed rating	Live trial	Case studies	Total
Category 1	21	0	22
Category 2	88	6	94
Category 3	75	17	92
Category 4	64	9	73
Category 5	15	26	41
Category 6	1	13	14

8.3 Seasonal conditions

The live trial was associated with neutral or weak La Nina conditions (Figure 8.3). This pattern is generally associated with increased rainfall in eastern, central, and northern Australia. While there were large areas of above average rainfall across the continent (Figure 8.4), rainfall was below average for many of the most fire prone parts of country, including areas near the coast in south-west Western Australia, eastern and south-east South Australia, most of Victoria, parts of Tasmania, coastal and northern New South Wales, central Queensland and the region between Mackay and Townsville. However, 6-month rainfall deficits were below drought values for almost all areas. Daytime air temperatures were above average for most of the country except the east of Western Australia, central parts of the Northern Territory, and much of eastern Queensland (Figure 8.5).

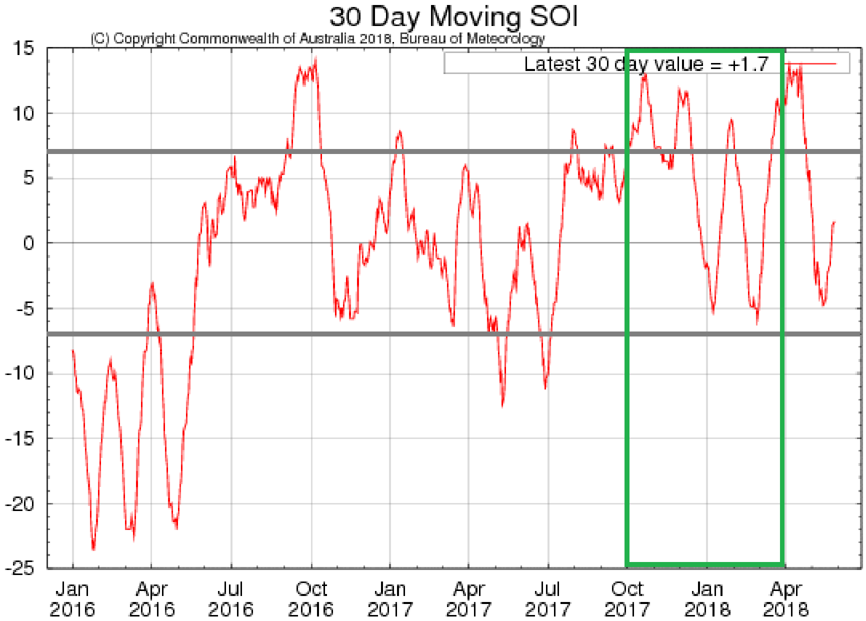


Figure 8.3 Southern Oscillation Index values (red). Values above 7 indicate La Nina conditions, below -7 indicate El Nino. The live trial period is outlined in green. Image courtesy Bureau of Meteorology.

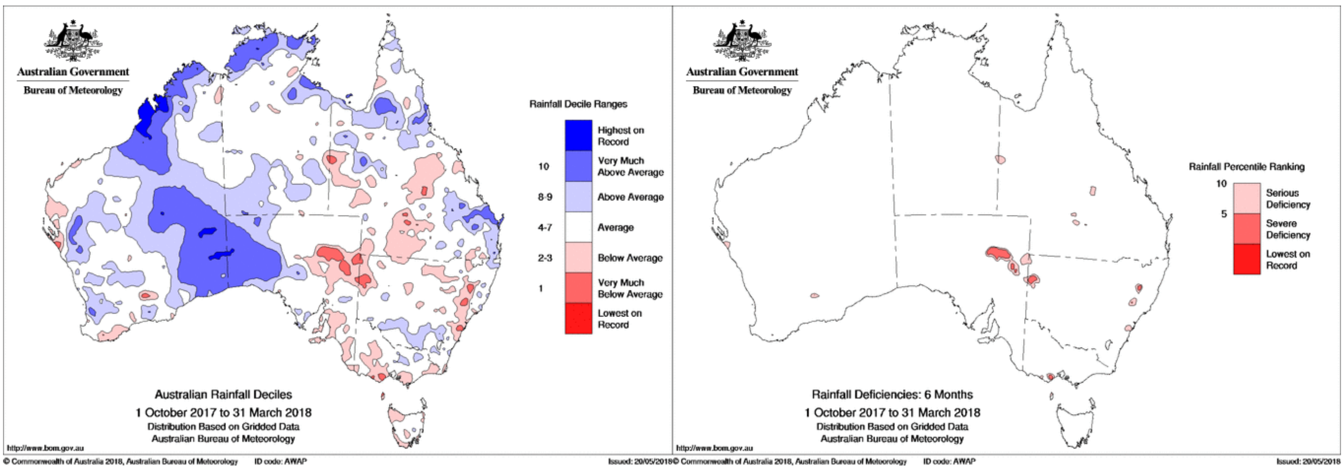


Figure 8.4 Rainfall deciles for the live trial period (Left); Drought severity during the live trial (Right). Images courtesy Bureau of Meteorology.

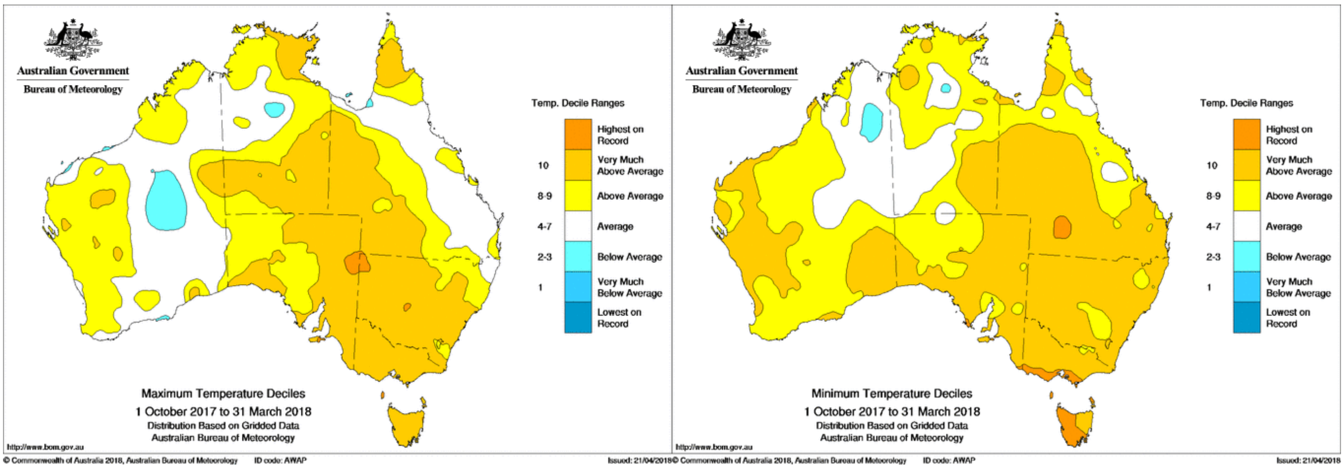


Figure 8.5 Maximum temperature deciles for the live trial period (Left); Minimum temperature deciles during the live trial (Right). Images courtesy Bureau of Meteorology.

8.4 Internal consistency of the rating tables

The Research Prototype rating tables included descriptions for each rating Category across four different areas: fire behaviour, prescribed burning, suppression, and consequences. During the trial, concerns were raised that there might be some inconsistency between areas (rows in the tables) when reading down the rating Categories (columns in Tables 2.31 to 2.35). For example, there might be cases where fire behaviour was correctly predicted but the suppression effort required is over-predicted. If there were inconsistencies then it would be necessary to revisit and possibly revise some of the table entries to ensure most incidents could be unambiguously assigned to a single rating Category.

To assess the consistency of NFDRS categories we examined participant responses to questions which asked them to rate system forecasts as correct, over-, or under-predicted for the fire behaviour, suppression, and consequences rows of the rating tables. The prescribed burning row was omitted as there were too few responses.

Figure 8.6 shows three Sankey diagrams (Schmidt, 2008) for the responses after first segregating them into three sets based on the responses to the fire behaviour question. For the majority of responses the fire behaviour descriptors were rated as correct and for these both suppression and consequences were also rated as correct.

For observations where fire behaviour was over-predicted, about two-thirds were also rated as over-predictions for suppression and consequences, with most of the remainder rated as correct for both categories. This suggests that for most over-predictions the rating tables were consistent. Where only fire behaviour was over-predicted, this suggests that there situations where due to other factors suppression or consequences drove the rating selection and the fire was challenging to manage given its level of intensity.

There were too few under-predictions of fire behaviour to draw meaningful conclusions.

Taken together, these results indicate that, on the basis of respondent opinions, the rating tables are internally consistent. Closer examination of the group of incidents with fire behaviour over-predicted but the other areas correctly described may yield further insights allowing further refinement of the tables.

These analyses may be limited by possible error in participant's observations. During the live trial evaluation, some participants have had different interpretations of methodology resulting in an inconsistent assessment of whether the descriptors were correct, over-predictions or under-prediction. This may have related to up to 80 points. Further investigation is required to identify these sources of error and amend the dataset to reflect internal consistency. This will improve the analyses and reduce the error that may exist.

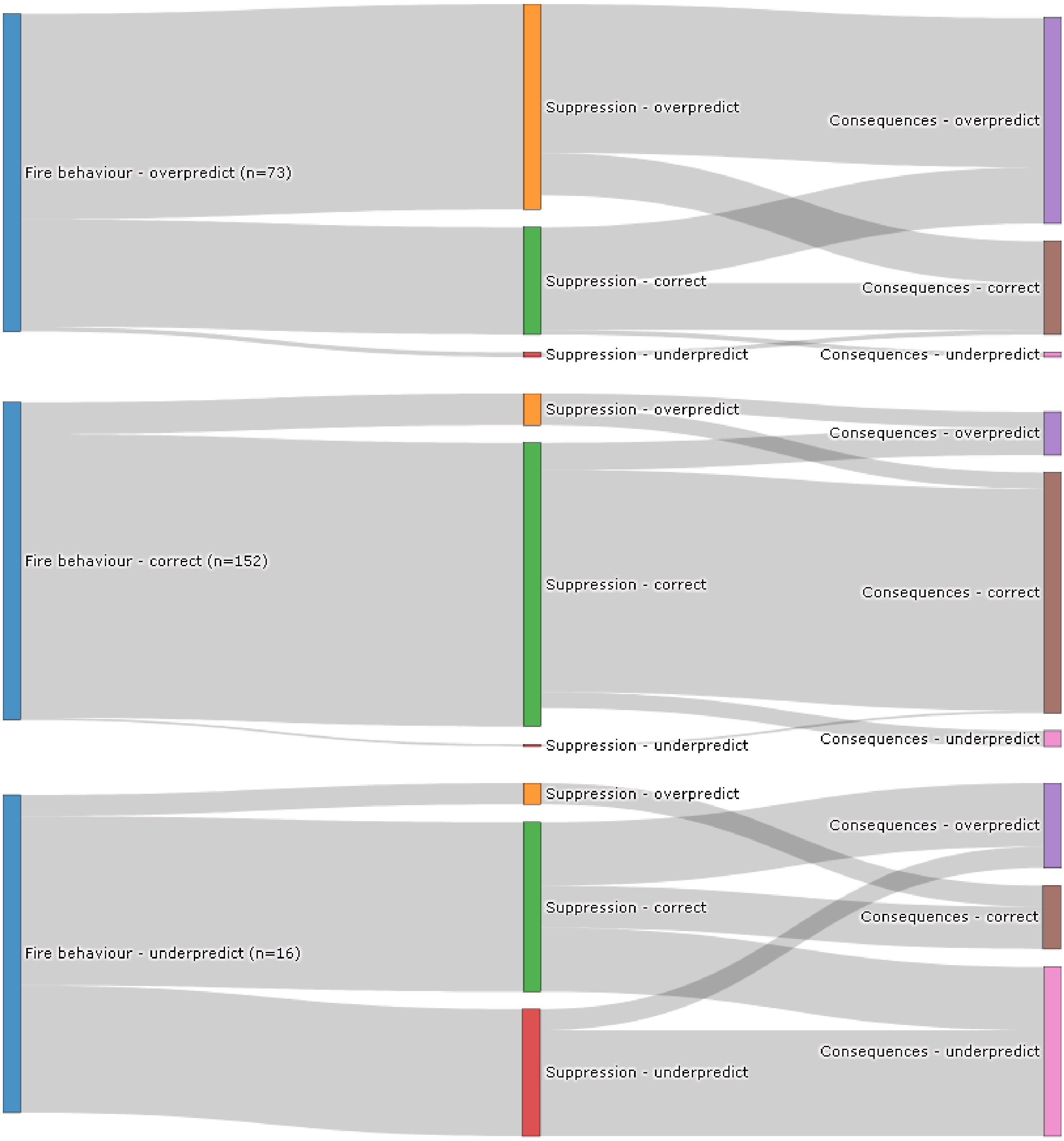


Figure 8.6 Sankey diagram for user evaluation of rating descriptions. The relative width of the grey bars indicates the fraction of observations common to the categories at each end.

8.5 Contingency tables and skill scores

8.5.1 Result interpretation

In this sub-chapter the results of the Research Prototype live trial are presented and discussed. As discussed in Chapter 7, a multi-category contingency table analysis was used as the evaluation tool, in combination with skill score statistics. For correct interpretation of the results, it is important to be aware of the following matters:

- The thresholds that set the fire danger categories do not take into account the uncertainty in model inputs or the observers' use of the rating tables. For example, when a Category 3 fire is forecasted, but at the lower end of 3, with some very minor changes in model input it could also have been a (high) Category 2 fire.
- When we classified the FFDI and GFDI into categories (low-moderate, high, very high etc.) for use in the contingency table, we realised that it has not been documented what should be done when the fire danger index is right on the limits of its category. For example, when the FFDI/GFDI is 12, should that be included as low moderate, or high? An index value of 24, should that be classified as high, or very high? And so on. This deserves some more attention and has been flagged as a follow up action. We experimented with both approaches and found that it does affect the outcome of the skills scores slightly. We decided to group the threshold index values (12, 24, 50, 75, 100 and 150), with their lower category.
- Also, observed fire danger was not always easy to define as there were several occasions where the observed rating would fall in between categories (pers. obs. from trial participants) but assignment of half-categories was not permitted.

Because of these three threshold-related topics discussed here, a discrepancy of one category is a possibility and not necessarily incorrect. However, when there is a discrepancy of two categories, we can say with confidence that the forecast was incorrect. A discrepancy of three categories means the forecast was extremely incorrect.

8.5.2 Result presentation

As described in Chapter 7, in an auditing process we double checked the incoming observations for location, fuel type, time since fire and curing. Columns were added to the database with the corrected (audited) values in case there were errors in the original entry. We also excluded some of the entries in case they were faulty, e.g. when there was not enough information to support the observation, or when an inconsistency in fuel type, fire behaviour model or location could not be resolved.

In the evaluation presented here, we used the original observations as reported by the trial observers (raw-dataset), minus the entries that had to be excluded (n = 15). The recalculation of outputs for the audited dataset could not be completed within the timeframe of the Research Prototype, but will be included in the next iteration of our evaluation.

Here we report on the performance of the Research Prototype system, compared to the current system in use. First we show the overall performance (for all observations), then the performance for the case studies in isolation, then for the final dataset which includes all observations plus case studies. Next, we present and compare the performance of the systems per fuel type. Also, some special cases such as fires in wet forests and 'initial attack' fires are described.

8.5.3 Raw dataset: unaudited observations, faulty entries excluded, without case studies (n = 264)

Prototype system

Forecast (columns) / Observed (rows)

Observed \ Forecast	1	2	3	4	5	6
1	12	6	3	0	0	0
2	7	43	28	9	1	0
3	1	2	40	25	7	0
4	1	4	5	40	13	1
5	0	1	1	4	7	2
6	0	0	0	0	0	1

Current system

Forecast (columns) / Observed (rows)

Observed \ Forecast	L-M	H	VH	S	E	C
L-M	67	19	7	1	0	0
H	34	19	13	3	0	0
VH	14	22	31	3	0	0
S	2	7	13	3	0	0
E	2	1	1	1	0	1
C	0	0	0	0	0	0

Legend
Correct
Under-predicted
Over-predicted

Figure 8.7 (Left) Contingency table for the raw dataset, NFDRS Research Prototype and (Right) current system.

Table 8.5 Skill scores for the two systems - raw dataset

	Research Prototype	Current system	Comment
Fraction over-predicted	0.36	0.18	0 to 1. Lower is better
Fraction correct	0.54	0.45	0 to 1. Higher is better
Fraction under-predicted	0.10	0.37	0 to 1. Lower is better
Peirce skill score	0.41	0.22	-1 to 1. Higher is better
Gerrity skill score	0.65	N/A	-1 to 1. Higher is better

- The Research Prototype correctly predicted the fire danger for 54% of observations, compared to 45% for the current system.
- The Research Prototype over-predicts more, but under-predicts less than the current system.
- The Peirce skill score is higher for the Research Prototype, this might be explained by the spread of the observations. While the entries are fairly well spread out on a diagonal axis in the Research Prototype (Figure 8.7 - left), in contrast, most of the entries were grouped in the top left corner in the current system (Figure 8.7 - right).
- The Gerrity skill score was not available for the current system because no observed fires were assigned a Catastrophic rating.

8.5.4 Case studies (n = 72)

Prototype system

Forecast (columns) / Observed (rows)

	1	2	3	4	5	6
1	0	0	0	0	1	0
2	0	2	4	0	0	0
3	0	0	8	7	2	0
4	0	0	1	4	4	0
5	0	0	2	0	19	5
6	0	0	0	1	1	11

Current system

Forecast (columns) / Observed (rows)

	L-M	H	VH	S	E	C
L-M	6	2	0	0	0	0
H	3	2	3	0	0	0
VH	3	7	4	0	0	0
S	2	3	5	2	0	0
E	1	5	6	1	1	1
C	0	1	2	2	1	9

Legend
Correct
Under-predicted
Over-predicted

Figure 8.8 (Left) Contingency table for the case studies only, NFDRS Research Prototype and (Right) current system.

Table 8.6 Skill scores for the two systems - case studies only

	Research Prototype	Current system	Comment
Fraction over-predicted	0.32	0.03	0 to 1. Lower is better
Fraction correct	0.61	0.33	0 to 1. Higher is better
Fraction under-predicted	0.07	0.58	0 to 1. Lower is better
Peirce skill score	0.48	0.22	-1 to 1. Higher is better
Gerrity skill score	0.46	0.48	-1 to 1. Higher is better

- The case studies were included in our system evaluation, next to the general observations by trial participants. This was done to include observations from large destructive fires, at the higher end of the rating system. 9 detailed and 11 other case study fires were assessed (Chapter 9), resulting in 72 observations.
- When we evaluated the case studies in isolation, it became apparent that the Research Prototype predicted most of the case study observations correctly, or one category higher (encircled in green, Figure 8.8). The current system under-predicted by two or more categories in several cases (red circles in Figure 8.8). Under-predicting the fire danger rating is dangerous, especially at the higher end of the scale, because it can put firefighters and communities at risk. This evaluation shows that the Research Prototype is better at predicting fire danger at the higher end of the scale.
- The Research Prototype predicted 61% of the case study observations correctly, compared to 33% by the current system (Table 8.6).The Peirce skill score also showed that the Research Prototype is performing better than the current system (0.47 versus 0.23). However, the Gerrity skill scores for both systems are very similar (0.45 versus 0.49). We tested if this had to do with the outlier, encircled in orange (Figure 8.8), and indeed, the Research Prototype was “punished” by the Gerrity skill score for the outlier. When we adjusted the forecasted rating from 5 to 1 (based on the knowledge that recent rain was not taken into account properly in the original calculations), the Gerrity score was 0.70 (results not shown). This confirms the adequacy of the skill scores.

8.5.5 Final dataset: unaudited observations, faulty entries excluded, case studies included (n = 336)

Prototype system

Forecast (columns) / Observed (rows)

Observed	1	2	3	4	5	6
1	12	6	3	0	1	0
2	7	45	32	9	1	0
3	1	2	48	32	9	0
4	1	4	6	44	17	1
5	0	1	3	4	26	7
6	0	0	0	1	1	12

Current system

Forecast (columns) / Observed (rows)

Observed	L-M	H	VH	S	E	C
L-M	73	21	7	1	0	0
H	37	21	16	3	0	0
VH	17	29	35	3	0	0
S	4	10	18	5	0	0
E	3	6	7	2	1	2
C	0	1	2	2	1	9

Legend
Correct
Under-predicted
Over-predicted

Figure 8.9 (Left) Contingency table for the combined dataset, NFDRS Research Prototype and (Right) current system.

Table 8.7 Skill scores for the two systems - final dataset

	Research Prototype	Current system	Comment
Fraction over-predicted	0.35	0.16	0 to 1. Lower is better
Fraction correct	0.56	0.43	0 to 1. Higher is better
Fraction under-predicted	0.09	0.41	0 to 1. Lower is better
Peirce skill score	0.45	0.23	-1 to 1. Higher is better
Gerrity skill score	0.66	0.42	-1 to 1. Higher is better

- For the final dataset we used the raw (unaudited) observations, excluded the entries that were faulty, and included the case studies. We ended up with a dataset of 336 entries.
- While the entries are fairly well spread out on a diagonal axis in the Research Prototype (Figure 8.9 - left), in contrast, most of the entries were grouped in the top left corner in the current system (Figure 8.9 - right).
- The Research Prototype correctly predicted the fire danger for 56% of the entries, compared to 43% for the current system. The Research Prototype over-predicted more than the current system (35% versus 16%), but under-predicted less (9% versus 41%).
- Both the Peirce and Gerrity skill score were higher for the Research Prototype (Table 8.7). This means that the Research Prototype performed better than the current system. There is still room for improvement though, since 45% of the entries were not predicted correctly. In the following sub-chapters we tried to disentangle the system performance per fuel type, and for certain conditions (e.g. initial attack).

8.6 Results per fuel type

8.6.1 Grasslands (n = 77)

Prototype system

Observed \ Forecast	1	2	3	4	5	6
1	0	2	1	0	0	0
2	1	16	9	1	0	0
3	0	1	13	6	3	0
4	0	0	2	5	4	0
5	0	0	0	2	5	4
6	0	0	0	0	0	2

Current system

Observed \ Forecast	L-M	H	VH	S	E	C
L-M	20	1	1	0	0	0
H	18	3	0	0	0	0
VH	5	4	6	1	0	0
S	0	1	7	1	0	0
E	2	1	1	1	1	2
C	0	0	0	0	1	0

Legend
Correct
Under-predicted
Over-predicted

Figure 8.10 (Left) Contingency table for grassland fires, NFDRS Research Prototype and (Right) current system.

Table 8.8 Skill scores for grassland fires

	Research Prototype	Current system	Comment
Fraction over-predicted	0.39	0.06	0 to 1. Lower is better
Fraction correct	0.53	0.40	0 to 1. Higher is better
Fraction under-predicted	0.08	0.53	0 to 1. Lower is better
Peirce skill score	0.40	0.20	-1 to 1. Higher is better
Gerrity skill score	0.60	0.36	-1 to 1. Higher is better

- For grassland fires, the Research Prototype over-predicted by one category in several occasions (Figure 8.10 - left). While over-predicting is undesirable because of the economic and political impacts of declaring total fire bans, under-predicting is actually more dangerous because it can put firefighters and the public at risk. The current system under-predicted in 53% of the cases, compared to 8% for the Research Prototype (Table 8.8).
- The Research Prototype predicted 53% of the fire danger rating for grassland entries correctly, compared to 40% with the current system. The Peirce and Gerrity skill score also showed a better performance of the Research Prototype compared to the current system, i.e. 0.40 versus 0.20 for the Peirce skill score, and 0.60 versus 0.36 for the Gerrity skill score (Table 8.8).
- Notable is the distribution of the entries in the two contingency tables. While the entries are fairly well spread out on a diagonal axis in the Research Prototype (Figure 8.10 - left), in contrast, most of the entries were grouped in the top left corner in the current system (Figure 8.10 - right).
- Given that only 53% of the fire danger was predicted correctly, there is still room for improvement. This is beyond the scope of this project, but we suggest improvements could be made in relation to the fuel input (e.g. inclusion of fuel cover and fuel height, rather than just grassland fuel load and curing). Also, at the moment we used the grassland fire behaviour model for crops and pasture, as well as chenopod shrublands with ephemeral grasses (see section 10.1.2.1). A research project has been proposed to examine fire behaviour specifically for crops (pers. comm. M. Kilinc).

8.6.2 Savanna (n = 18)

Prototype system

Forecast (columns) / Observed (rows)

	1	2		4	5	
1	1	2		0	0	
2	0	6		0	0	
4	0	1		7	0	
5	0	0		1	0	

Current system

Forecast (columns) / Observed (rows)

	L-M	H	VH	S	E	C
L-M	6	0	0	0	0	0
H	2	1	1	0	0	0
VH	1	3	2	1	0	0
S	0	0	1	0	0	0
E	0	0	0	0	0	0
C	0	0	0	0	0	0

Legend
Correct
Under-predicted
Over-predicted

Figure 8.11 (Left) Contingency table for savanna fires, NFDRS Research Prototype and (Right) current system.

Table 8.9 Skill scores for savanna fires

	Research Prototype	Current system	Comment
Fraction over-predicted	0.11	0.11	0 to 1. Lower is better
Fraction correct	0.78	0.50	0 to 1. Higher is better
Fraction under-predicted	0.11	0.39	0 to 1. Lower is better
Peirce skill score	0.61	0.28	-1 to 1. Higher is better
Gerrity skill score	N/A	0.22	-1 to 1. Higher is better

- For savanna fires, the Research Prototype predicted the fire danger rating correctly for 78% of the incidents. This is an improvement compared to the current system, which correctly predicted half of the savanna fires (50%, Table 8.9).
- Both systems over-predicted 11% of the entries, but, the current system under-predicted in 7 cases (39%), compared to 2 fires (11%) in the Research Prototype.
- The Peirce skill score showed an improvement in the prediction of the fire danger rating by the Research Prototype (Peirce skill score = 0.61), compared to the current system (Peirce skill score = 0.28).
- The sample size for savanna fires is fairly small (n = 18), and some of these entries were from acacia woodland, rural, and urban fuel types (therefore not representing true savanna fires). However, these first results are promising. If the trial period could be extended to the fire season in the northern part of the country (June – September), this would be a great learning opportunity.

8.6.3 Spinifex (n = 9)

Prototype system

Observed (rows) / Forecast (columns)

	1	2	3	4	5	6
1	5	0	0	0	0	0
2	0	0	0	1	0	0
3	0	0	0	0	0	0
4	0	0	0	3	1	0
5	0	0	0	0	0	0
6	0	0	0	0	0	0

Current system

Observed (rows) / Forecast (columns)

	L-M	H	VH	S	E	C
L-M	3	1	2	0	0	0
H	0	0	1	1	0	0
VH	0	0	2	0	0	0
S	0	0	0	0	0	0
E	0	0	0	0	0	0
C	0	0	0	0	0	0

Legend
Correct
Under-predicted
Over-predicted

Figure 8.12 (Left) Contingency table for spinifex fires, NFDRS Research Prototype and (Right) current system.

Table 8.10 Skill scores for spinifex fires

	Research Prototype	Current system	Comment
Fraction over-predicted	0.22	0.56	0 to 1. Lower is better
Fraction correct	0.78	0.44	0 to 1. Higher is better
Fraction under-predicted	0.00	0.00	0 to 1. Lower is better
Peirce skill score	0.67	0.36	-1 to 1. Higher is better
Gerrity skill score	N/A	N/A	-1 to 1. Higher is better

- Neither of the systems under-predicted the fire danger, so both systems were either right or over-predicting (Figure 8.12).
- For spinifex fires, the Research Prototype predicted the fire danger rating correctly 7 out of 9 times (78%). This is an improvement compared to the current system, which only correctly predicted 4 out of 9 times (44%) and tended to over-predict (Figure 8.12, Table 8.10).
- The sample size for spinifex fires was small (n = 9). If the trial period could be extended, this would be a great learning opportunity. Overall, the skill scores for the Research Prototype are very high, but more data is needed to be confident in these results. For example, 5 out of our 9 fires were in the lowest Category (predicted and observed rating of 1). Also, we did not have any fires at the higher end of the spectrum (i.e. no observed ratings of 5, Figure 8.12).

8.6.4 Buttongrass (n = 6)

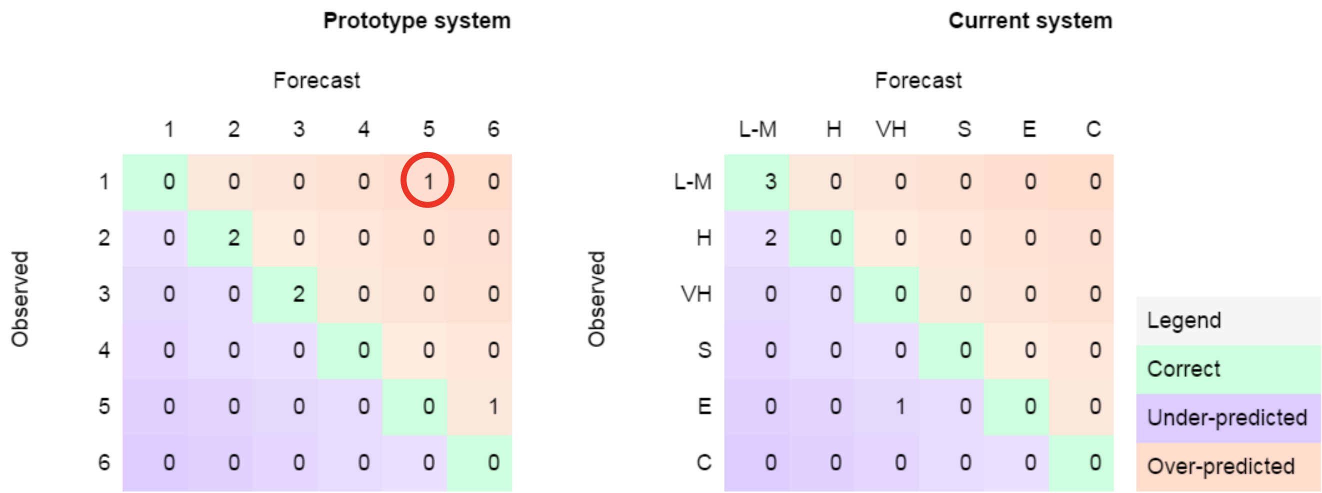


Figure 8.13 (Left) Contingency table for buttongrass fires, NFDRS Research Prototype and (Right) current system.

Table 8.11 Skill scores for buttongrass fires

	Research Prototype	Current system	Comment
Fraction over-predicted	0.33	0.00	0 to 1. Lower is better
Fraction correct	0.67	0.50	0 to 1. Higher is better
Fraction under-predicted	0.00	0.50	0 to 1. Lower is better
Peirce skill score	0.58	0.14	-1 to 1. Higher is better
Gerrity skill score	N/A	N/A	-1 to 1. Higher is better

- Four out of six (67%) buttongrass fires were correctly predicted by the Research Prototype, compared to three out of six (50%) for the current system. The Research Prototype over-predicted in two cases, while the current system under-predicted in three cases (Figure 8.13).
- It is noteworthy that the current system had 5 out of 6 entries grouped in the top left corner of the contingency table, forecasting low-moderate fire danger conditions, while the Research Prototype forecasted these as Category 2 or 3. Since the current system calculates the fire danger rating based on forest fuel types, it is not taking into account the special characteristics of buttongrass, and the fact that buttongrass can burn under relatively high moisture conditions (Chapter 3).
- A special case is the observation encircled in red (Figure 8.13), with the Research Prototype predicting a Category 5 fire danger rating, but the observed value was Category 1. The reason for this is most likely rainfall, which was not documented properly in this case (see below, section 8.8).
- The sample size for buttongrass is very small (n = 6). So even though the skill scores for the Research Prototype are fairly high, more data is needed to be confident in these results. For example, we did not have any entries with a forecasted rating of Category 1 or 4. Neither did we have any entries with an observed Category 4 or 6. Further research and data collection will give us a more robust understanding of the predictive power of the system we built.

8.6.5 Forest (n = 188)

Prototype system

Observed \ Forecast	1	2	3	4	5	6
1	6	1	2	0	0	0
2	6	18	22	5	1	0
3	1	1	32	18	4	0
4	1	0	4	16	12	1
5	0	1	2	1	19	1
6	0	0	0	1	1	10

Current system

Observed \ Forecast	L-M	H	VH	S	E	C
L-M	39	17	3	0	0	0
H	10	14	14	2	0	0
VH	8	15	21	0	0	0
S	1	7	9	3	0	0
E	1	4	4	1	0	0
C	0	1	2	2	0	9

Legend
Correct
Under-predicted
Over-predicted

Figure 8.14 (Left) Contingency table for forest fires, NFDRS Research Prototype and (Right) current system.

Table 8.12 Skill scores for forest fires

	Research Prototype	Current system	Comment
Fraction over-predicted	0.36	0.19	0 to 1. Lower is better
Fraction correct	0.54	0.46	0 to 1. Higher is better
Fraction under-predicted	0.10	0.35	0 to 1. Lower is better
Peirce skill score	0.43	0.28	-1 to 1. Higher is better
Gerrity skill score	0.66	0.45	-1 to 1. Higher is better

- For forest fires, the Research Prototype under-predicts less than the current system (10% versus 35%, Table 8.12). This is an important improvement, because under-predicting fire danger rating, especially at the higher end of the scale, can put firefighters and communities at risk.
- The percentage correct was better for the Research Prototype, i.e. 54% versus 46%. The current model was designed to predict forest fires, so it is not surprising that it is performing reasonably well for forests.
- Both the Peirce and Gerrity skill score, however, show better performance by the Research Prototype compared to the current system (Table 8.12). This might be because of the distribution of the fires across the categories (see next point).
- Notable is the distribution of the entries in the two contingency tables. While the entries are fairly well spread out along a diagonal band in the Research Prototype (top left to bottom right, Figure 8.14 - left), in contrast, most of the entries were grouped in the top left corner in the current system (Figure 8.14 - right).
- If not correctly predicting, the Research Prototype tends to over-predict the fire danger rating with one category or more, more so than the current system (36% versus 19%). And, as noted before, over-predicting is undesirable because of the economic and political impacts of declaring total fire bans. Improvements can be made in relation to model inputs, especially fuel inputs such as near-surface hazard scores and near surface height (Chapter 4). Also, the fire behaviour model that we used for forests (i.e. DEFFM/Vesta), was developed for "*going fires in dry eucalypt forest with a shrubby understorey, under dry summer conditions*". It assumes that the fire has reached its quasi-steady state, while this might not have been the case. This is further discussed below (section 8.7).

8.6.5.1 Wet forest (n = 26)

Prototype system

Forecast (columns) / Observed (rows)

	1	2	3	4	5	6
1	5	0	0	0	0	0
2	4	6	2	2	0	0
3	1	0	2	1	0	0
4	1	0	0	0	0	0
5	0	1	0	0	0	1
6	0	0	0	0	0	0

Current system

Forecast (columns) / Observed (rows)

	L-M	H	VH	S	E	C
L-M	9	4	1	0	0	0
H	1	0	4	1	0	0
VH	1	1	0	0	0	1
S	0	0	1	1	0	0
E	0	0	0	1	0	0
C	0	0	0	0	0	0

Legend: Correct; Under-predicted; Over-predicted

Figure 8.15 (Left) Contingency table for fires in wet forests, NFDRS Research Prototype and (Right) current system.

Table 8.13 Skill scores for wet forest fires

	Research Prototype	Current system	Comment
Fraction over-predicted	0.23	0.42	0 to 1. Lower is better
Fraction correct	0.50	0.38	0 to 1. Higher is better
Fraction under-predicted	0.27	0.19	0 to 1. Lower is better
Peirce skill score	0.38	0.12	-1 to 1. Higher is better
Gerrity skill score	N/A	N/A	-1 to 1. Higher is better

- Since no specific fire behaviour model is available for wet forests, we used a drought factor adjustment in an attempt to adjust for fuel availability (Chapter 3). The forecasted – observed ratings for wet forest differed by 2 or more categories in some occasions. The ones that were off by 3 categories are encircled in red in Figure 8.15.
- The Research Prototype performed slightly better than the current system. 50% of the entries for wet forests were predicted correctly by the Research Prototype, compared to 38% for the current system. The Peirce score was 0.38 for the Research Prototype, compared to 0.12 for the current system. Both systems over- and under-predicted (Table 8.13).
- The wet forest fuel type covers a wide range of vegetation types, and classification could be refined. The Research Prototype performed better in some wet forest types than others (Chapter 10)
- There is significant room for improvement in the model structure, in particular the drought factor adjustment that was used (Chapter 3) is well supported. The drought factor adjustment curves for wet forests are part of active research. A joint agency project between DELWP, CFA and the University of Melbourne will be focusing on the moisture effects in forests (pers. comm. M. Kilinc). The outcomes of this research would be a welcome add-on for the development of the National Fire Danger Rating System.

8.6.6 Mallee-heath (n = 15)

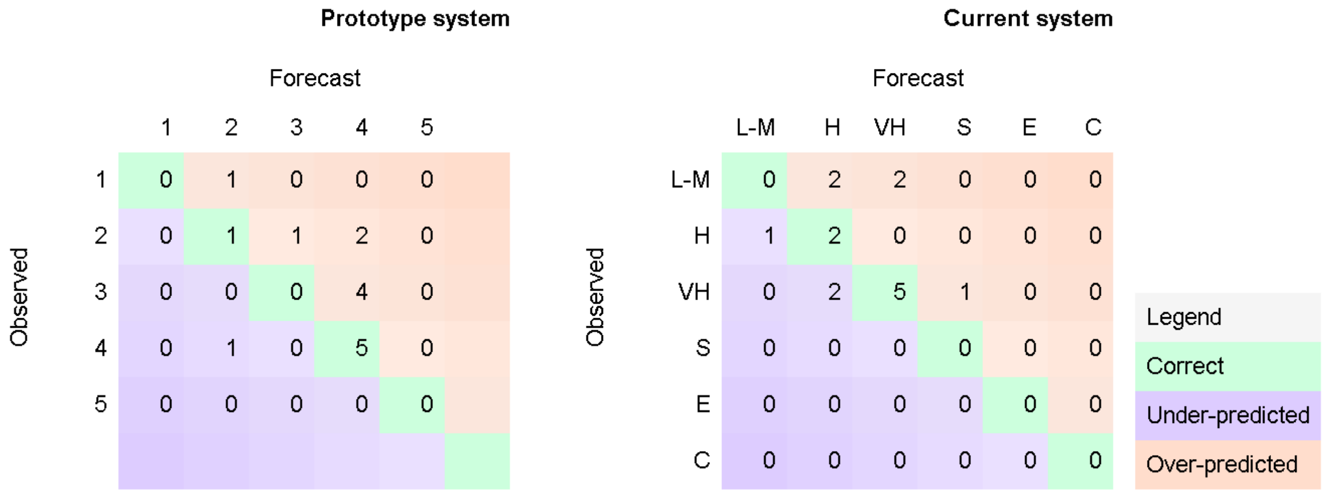


Figure 8.16 (Left) Contingency table for mallee-heath fires, NFDRS Research Prototype and (Right) current system.

Table 8.14 Skill scores for mallee heath fires

	Research Prototype	Current system	Comment
Fraction over-predicted	0.53	0.33	0 to 1. Lower is better
Fraction correct	0.40	0.47	0 to 1. Higher is better
Fraction under-predicted	0.07	0.20	0 to 1. Lower is better
Peirce skill score	0.05	0.20	-1 to 1. Higher is better
Gerrity skill score	N/A	N/A	-1 to 1. Higher is better

- Both systems over-predicted considerably, the Research Prototype more than the current system (53% versus 33%). The percentage of entries that were predicted correctly were similar for both systems (40% and 47%) (Table 8.14).
- The sample size for mallee heath fires is small (n = 15) and more observations are needed to evaluate the system performance properly.
- The Peirce skill score for the Research Prototype was very low (0.05).
- The complex vegetative structure of mallee heath, with horizontal and vertical gaps between the fuel layers, uses a go/no-go approach (Chapter 3). We agree with this reasoning, but given the specific local conditions of the fuel, several outcomes of fire behaviour are possible and maybe this is not well-captured by the model. The thresholds of the categories, and how they align with the observed fire behaviour, can still use more attention. Also, mallee can have different understories (e.g. spinifex). The model that we used here was designed for mallee heath fuel types, so we classified the mallee with spinifex understorey as a spinifex fuel type with a woody canopy. Future research could focus on mallee fuel types with different understory fuel conditions (species composition, surface fuel load, fuel connectivity, etc.).

8.6.7 Shrubland (n = 18)

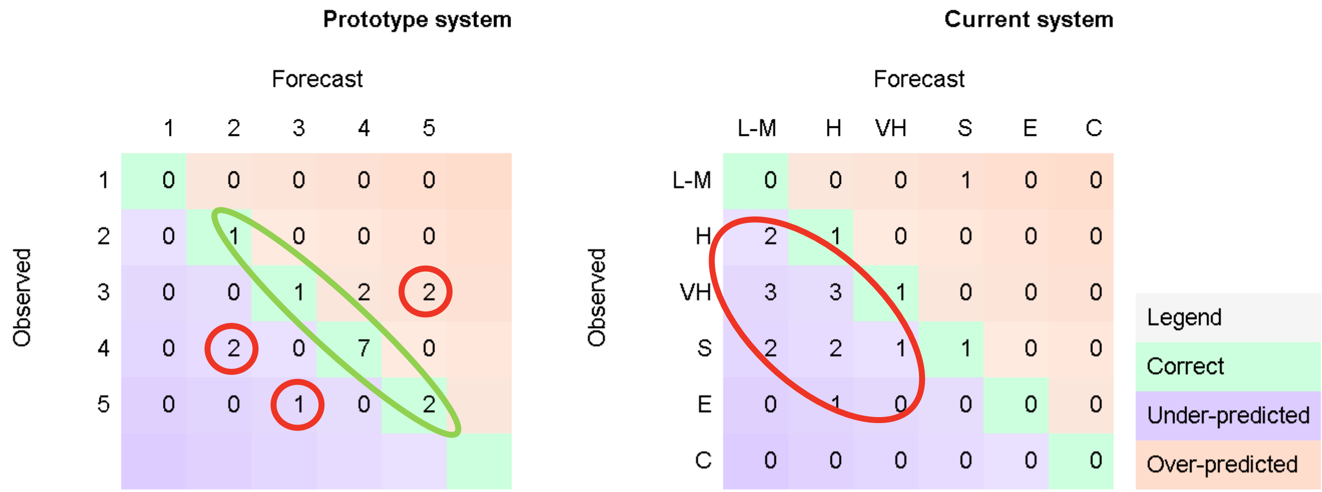


Figure 8.17 (Left) Contingency table for shrubland fires, NFDRS Research Prototype and (Right) current system.

Table 8.15 Skill scores for shrubland fires

	Research Prototype	Current system	Comment
Fraction over-predicted	0.22	0.06	0 to 1. Lower is better
Fraction correct	0.61	0.17	0 to 1. Higher is better
Fraction under-predicted	0.17	0.78	0 to 1. Lower is better
Peirce skill score	0.44	0.00	-1 to 1. Higher is better
Gerrity skill score	N/A	-0.08	-1 to 1. Higher is better

- For shrubland fires, the current system under-predicted 78% of the incidents (red ellipse Figure 8.17 - right, Table 8.15). The Research Prototype performed much better, only under-predicting 3 out of 18 fires (17%). Also, 61% of the fires were correctly predicted by the Research Prototype (green ellipse Figure 8.17), compared to 17% for the current system (Table 8.15).
- The skill scores also confirmed that the current system is not appropriate for predicting fires in shrublands. The Peirce and Gerrity score, 0.00 and -0.08 respectively (Table 8.15), are the lowest skill scores observed in this trial.
- The reason that the current system (i.e. FFDI) is mostly under-predicting can be ascribed to the fuel specific characteristics of shrublands, which are well aerated and exposed to the wind. Also, the small leaves of the shrubs and the open structure of the shrublands make this fuel type prone to faster moisture loss (drying out) in comparison to forest fuel types. This is a clear example of how the inclusion of fuel characteristics, as well as the use of fuel-specific fire behaviour models, can improve the calculation of fire danger ratings.
- Even though the Research Prototype performed much better than the current system, there is still room for improvement because five fires were off by two categories (encircled in red, Figure 8.17 - left). Weather forecast, model input, fire behaviour model specifications, slope, and initial suppression attack can all affect the calculation of fire danger, and these topics are all part of ongoing research and calibration. The modular format of the Research Prototype makes it possible to improve the way we include aforementioned features when new science becomes available.

8.6.8 Pine (n = 5)

Prototype system

Forecast

Observed	1	2	3	4	5	6
1	0	0	0	0	0	0
2	0	1	0	0	0	0
3	0	0	0	2	0	0
4	0	0	0	1	0	0
5	0	0	0	0	0	1
6	0	0	0	0	0	0

Current system

Forecast

Observed	L-M	H	VH	S	E	C
L-M	1	0	0	0	0	0
H	2	0	0	0	0	0
VH	0	0	0	0	0	0
S	0	1	0	0	0	0
E	0	0	1	0	0	0
C	0	0	0	0	0	0

Legend
Correct
Under-predicted
Over-predicted

Figure 8.18 (Left) Contingency table for pine forest fires, NFDRS Research Prototype and (Right) current system.

Table 8.16 Skill scores for pine fires

	Research Prototype	Current system	Comment
Fraction over-predicted	0.60	0.00	0 to 1. Lower is better
Fraction correct	0.40	0.20	0 to 1. Higher is better
Fraction under-predicted	0.00	0.80	0 to 1. Lower is better
Peirce skill score	0.33	-0.00	-1 to 1. Higher is better
Gerrity skill score	N/A	N/A	-1 to 1. Higher is better

- At a first glance, the Research Prototype seems to perform better than the current system (40% versus 20% correctly predicted). However, the sample size of 5 is too small to draw any conclusions.

8.6.9 Other fuel types (n = 53)

Prototype system

Forecast (columns) / Observed (rows)

Observed \ Forecast	1	2	3	4	5	6
1	5	1	0	0	1	0
2	0	5	1	3	0	0
3	0	0	3	8	2	0
4	0	3	0	15	1	0
5	0	0	1	0	2	2
6	0	0	0	0	0	0

Current system

Forecast (columns) / Observed (rows)

Observed \ Forecast	L-M	H	VH	S	E	C
L-M	7	3	4	1	0	0
H	7	3	1	1	0	0
VH	3	5	7	1	0	0
S	2	3	1	1	0	0
E	0	1	2	0	0	0
C	0	0	0	0	0	0

Legend: Correct; Under-predicted; Over-predicted

Figure 8.19 (Left) Contingency table for other fires, NFDRS Research Prototype and (Right) current system.

Table 8.17 Skill scores for fires in other fuel types

	Research Prototype	Current system	Comment
Fraction over-predicted	0.36	0.21	0 to 1. Lower is better
Fraction correct	0.57	0.34	0 to 1. Higher is better
Fraction under-predicted	0.08	0.45	0 to 1. Lower is better
Peirce skill score	0.42	0.10	-1 to 1. Higher is better
Gerrity skill score	N/A	N/A	-1 to 1. Higher is better

- The Research Prototype was designed to take fuel types and their characteristics into account. In this evaluation on other fuel types, we compared the performance of the Research Prototype and the current system when focusing on the fuel types not considered explicitly in the current system. That means, we looked at the system performance for spinifex, buttongrass, mallee heath, shrubland and pine combined.
- As expected, the Research Prototype performed better than the current system for the other fuel types; 57% of the entries were correctly evaluated by the Research Prototype, compared to 34% by the current system. Also, the Research Prototype tends to under-predict less (e.g. see evaluation for shrublands). The Peirce skill score for the Research Prototype is much higher (0.42) than the skill score for the current system (0.10).
- These results underline the importance of taking fuel types and their characteristics into account. More research is needed to fine-tune the input and fire behaviour models for these other fuel types, but here we clearly showed that a blanket model for forest or grassland is not appropriate.

8.7 Initial attack success (n = 34)

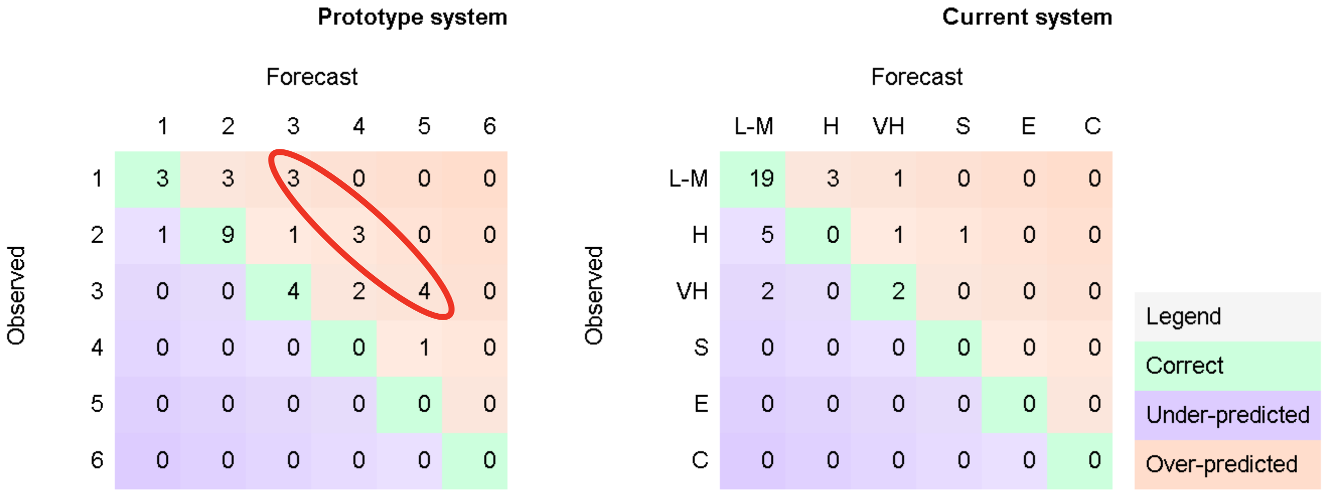


Figure 8.20 (Left) Contingency table for fires with initial attack success, NFDRS Research Prototype and (Right) current system.

Table 8.18 Skill scores for forest fires with initial attack success

	Research Prototype	Current system	Comment
Fraction over-predicted	0.50	0.18	0 to 1. Lower is better
Fraction correct	0.47	0.62	0 to 1. Higher is better
Fraction under-predicted	0.03	0.21	0 to 1. Lower is better
Peirce skill score	0.33	0.14	-1 to 1. Higher is better
Gerrity skill score	N/A	N/A	-1 to 1. Higher is better

- More research is needed into the build-up phase of fires. We tried to flag the fires that were still in the build-up phase (not fully developed) and when initial attack was successful (e.g. fires smaller than 10 ha, successful suppression within 90 min). For the fires with initial attack success, the fire danger rating was over-predicted in both systems, although much more in the Research Prototype (50%) than in the current system (18%) (red ellipse in Figure 8.20 - left, Table 8.18).
- It is interesting to see that the current system, which was built based on (mostly) small experimental fires (McArthur (1967), for forests at least), predicts the fires with initial attack fairly well (e.g. 19 of the 34 fires fell in the low-moderate category). In line with this, the percentage correctly predicted fires was higher for the current system (62%) than for the Research Prototype (47%). The Peirce score, however, showed that the Research Prototype performed better than the current system (0.33 versus 0.14, respectively). This might be explained by the distribution of the entries in the contingency table; while the entries are grouped in a diagonal cloud in the top-left of the left figure, the distribution is more scatter for the current system (Figure 8.20 - right).
- The Research Prototype only under-predicted in 1 occasion, compared to 7 occasions in the current system. At least two of these fires that were under-predicted by the current system were in shrublands. The tendency to under-predict fire danger in shrublands has been discussed before (section 8.6.7).

8.7.1 Examples of initial attack fires

92 One Tree Hill (SA) Grass fire 13 December 2017

NFDRS Forecast 5 Observed 3

The One Tree Hill fire started in grassland directly adjacent to 2 homes and a vineyard. It was contained to 1.5 ha within 38 minutes with substantial suppression resources (45 personnel, 9 tankers and 6 aircraft).

Figure 8.21 Extent of grass fire at One Tree Hill (SA) © SA CFS / DEWNR

75 Baerami Range (NSW) Forest fire 24 November 2017

NFDRS Forecast 4 Observed 2

The Baerami Range fire started from a lightning strike in steep terrain in Wollemi National Park. RAFT crew with aircraft bucketing support were successful in knocking the fire down and containing it to <1 ha.

Figure 8.22 Photo of Baerami Range fire (NSW) © NSW NPWS, Source RFS ICON

236 Mount Bass Fire Trail (NSW) Heath fire 5 February 2018

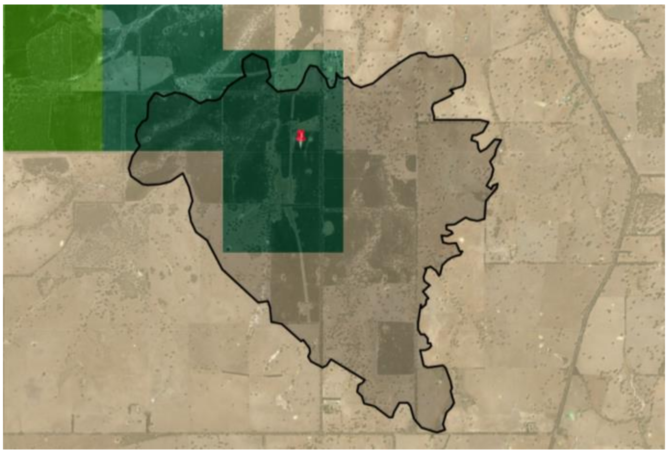
NFDRS Forecast 5 Observed 3

The Mount Bass Fire trail fire started in heath in Royal National Park. There were substantial suppression resources on scene within the first hour (35 personnel, 7 appliances, bulk water carrier, 4 aircraft), containing the fire to 3 ha.

Figure 8.23 Extent of heath fire in Royal National Park (NSW) © RFS ICON

8.8 Predictions with large errors (3 or more categories)

141 Mooralla - Carters Rd (VIC) Forest fire 13 December 2017

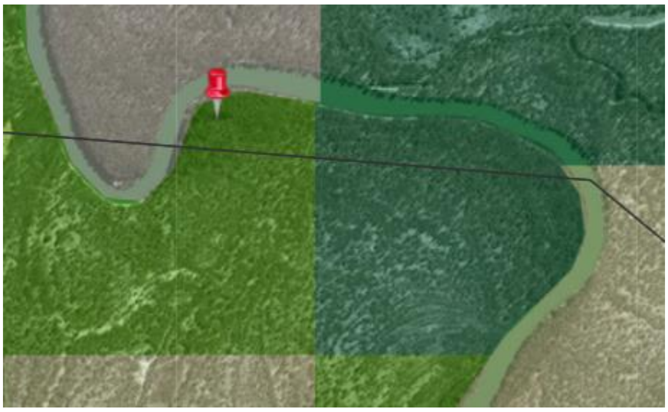


NFDRS Forecast 1 Observed 4

The fire was burning in a mix of native plantation and grass. NFDRS calculations were done using the wet forest model, which with a drought factor of 6 significantly under-predicted fire behaviour (Category 1). The forecast for adjacent areas of grass and dry forest were both Category 3. Possible remedies include treating native plantations as dry forest where appropriate, or improving fuel availability modelling.

Figure 8.24 Extent and fuel grid for Carters Road Mooralla fire (VIC) © NFDRS Research Prototype

158 Yungera Island-Gearbox Loop (VIC) Forest fire 9 January 2018



NFDRS Forecast 5 Observed 2

The fire was burning in forest in a meander of the Murray River and was suppressed while still small (0.4 ha). The suppression time (143 m) was outside the criterion used to define initial attack fires (90 m). In spite of initial attack effects fire behaviour was likely still over-predicted. This type of riverine forest has been seen to over predict in other observations (see 10.1.2.3). In this case the fuel type grid at the location was for dry forest (underlying fuel map of bracken/shrubby woodland), while an adjacent grid cell of wet forest (riparian shrubby forest) gave a forecast of Category 3.

Figure 8.25 Extent and fuel grid for Yungera Island fire (VIC) © NFDRS Research Prototype

289 Giblin River (TAS) Buttongrass fire (case study) 3 January 2013

NFDRS Forecast 5 Observed 1

Based on information in Marsden-Smedley (2014) it appears that the weather forecast did not reflect rain which fell on the fire ground around the time of ignition.

263 Reedy Swamp (NSW) Forest fire 18 March 2018 (Wet forest pixel)

NFDRS Forecast 2 Observed 5

This observation was for a wet forest pixel of the Reedy Swamp fire that destroyed dozens of houses in the coastal community of Tathra. The prediction for a nearby dry forest pixel was Category 5, which matched observations. It is possible the forecast drought factor of 8 did not completely reflect the dryness of the landscape but more likely that improvements in modelling fuel availability for wet forests are required.

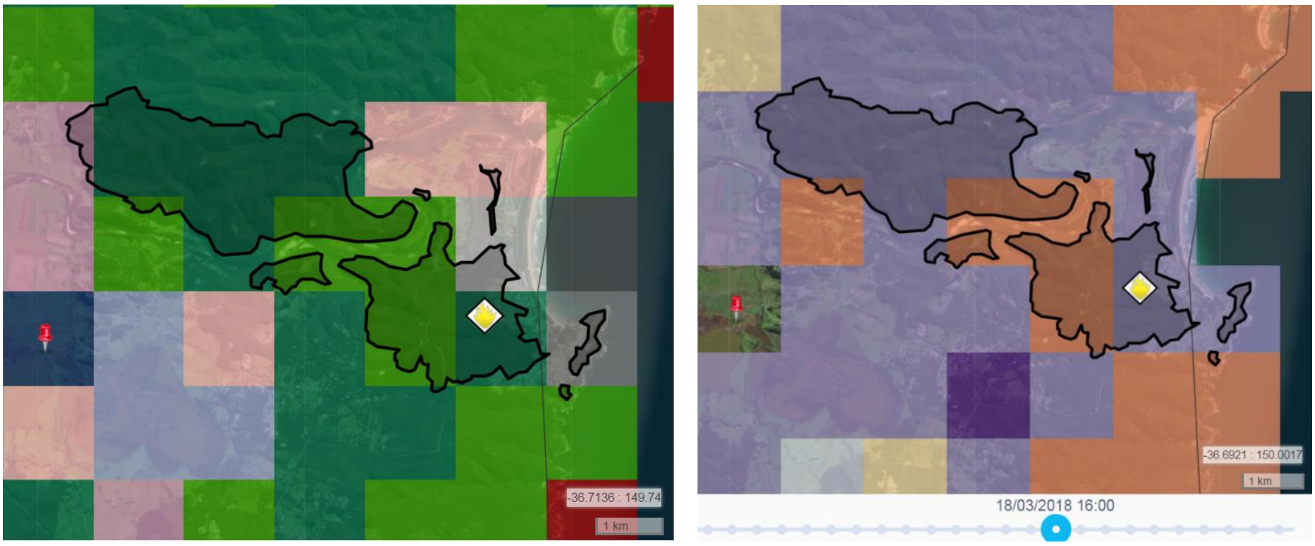


Figure 8.26 Extent and fuel grid (left) and NFDRS forecast (right) for Reedy Swamp fire (NSW) © NFDRS Research Prototype

8.9 Observed category 6 fire

144 Sherwood fire (SA) Grass fire 6 January 2018

NFDRS Forecast 6 Observed 6

This was a large fast moving grass fire, with ROS of 8,000-10,000 m/hr and flame height of 4 m during the first 2 hours. There was extensive suppression resources (136 personnel, 39 tankers, 8 aircraft) with a primary focus on asset protection, and emergency warnings issued. There were widespread rural asset impacts, including 2 houses, sheds, machinery, fences, powerlines, crops, orchards, and large livestock losses. There were no injuries or deaths. Note there is not much difference between Cat 5 and 6 in the grassland ratings table other than fire behaviour.

Figure 8.27 Post-fire image of Sherwood grass fire (SA) © DEWNR

8.10 Explorative multivariate analysis of potential drivers of fire danger rating

To evaluate what fire behaviour variable is the best descriptor of fire danger rating, we performed a Principal Component Analysis (PCA) to see how the environmental variables (weather input etc.) and fire behaviour variables (rate of spread, fireline intensity and flame height) fit together when using the data of the NFDRS Research Prototype live trial. This gives us the opportunity to see if there are any patterns per fuel type, and we can check if the observed patterns match up with our expectations based on our current understanding of fire behaviour and the models and equations in use.

With ordination techniques such as PCA, similar objects are clustered together, while dissimilar objects are further apart. Patterns in the dataset can then be unravelled by plotting the objects in multidimensional space. If the dataset can be considered as a cloud of data points, with ordination techniques component axes are defined that explain most of the variation in the dataset, and these component axes themselves are related to the variables measured on each data entry.

In the next sections the results of our PCA analyses are described. We split the dataset in two parts, namely, the grasslands and savanna fuel types combined ("grassy" subset), and the other, "non-grassy" fuel types (i.e. buttongrass, forest, mallee heath, pine, shrubland and spinifex) grouped together. We decided to split the dataset like this, because curing is (assumed to be) a very important factor for fire behaviour in grass, but not for the "non-grassy" fuel types. Also, fuel load is treated differently, with grass fuel load reported by agencies to the BoM for "grassy" fuel types, and estimated from fuel models and time since fire for "non-grassy" fuel types (see section 4.4.1).

Next to the PCA analyses, we also plotted correlation matrices for both data subsets and visually interpreted the results. Correlation matrices show the relationships between sets of variables. The variables that we included were:

- Fire behaviour variables (rate of spread, fireline intensity and flame height),
- Weather inputs (relative humidity, drought factor, wind speed, air temperature), and fuel inputs (curing and fuel load) - for the grassland/savanna subset.
- GFDI/FFDI, forecasted fire danger as predicted by the Research Prototype, and observed fire danger as observed by the live trial participants.

8.10.1 Principal component analysis for grassland and savanna

For the grassland and savanna fuel types combined, 46.5% of the variance in observations could be explained by the first PCA axis, 15.8% by the second PCA axis, and 12.0% by the third axis. Together, the first three axes explained 74.2% of the variance in our dataset for grasslands and savanna fires (Table 8.19).

Table 8.19 Importance of components for grasslands and savanna

Components	Cumulative variance explained	Cumulative percentage variance explained
PCA 1	46.5	46.5
PCA 2	15.8	62.3
PCA 3	12.0	74.2

No clear pattern can be seen in the data entries per fuel type (i.e. when we compare savanna entries with grassland entries; see coloured dots in Figure 8.28). For this evaluation, we only had 12 savanna fires, compared to 63 grassland fires, but even so, the savanna fires (green dots) were well spread out over the diagram.

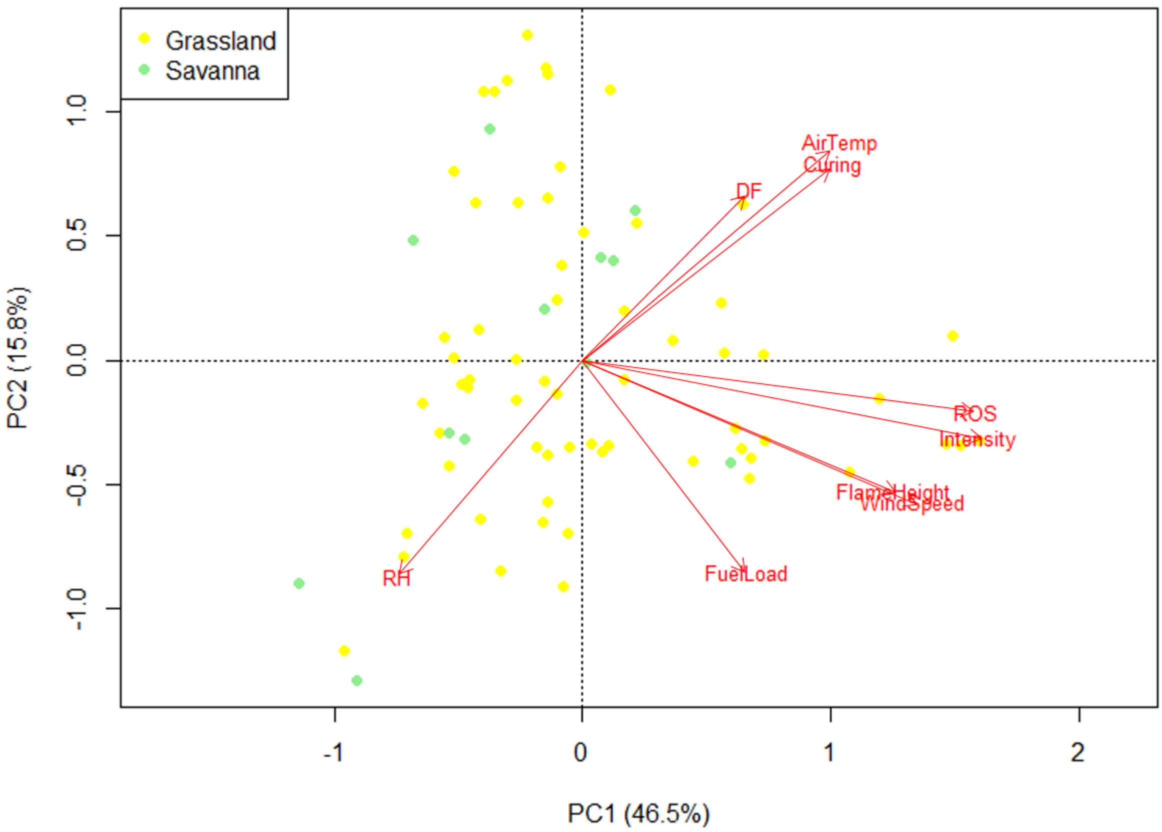


Figure 8.28 Ordination plot for observed fires in grassland and savanna fuel types. RH = relative humidity (%), DF = drought factor (a value between 0 and 10). Each coloured dot represents a data entry (yellow for grassland, light green for savanna).

Table 8.20 Component loadings, i.e. correlations of each variable with each of the three PCA axes in the grassland/savanna subset. Rate of spread, intensity and flame height are fire behaviour model outputs (top three rows), while relative humidity, drought factor, wind speed, air temperature, curing and fuel load are fire behaviour model inputs. Values are between 0 and 1; a higher value means a higher correlation of the variable with the component axis.

Variable	PCA1	PCA2	PCA3
Rate of spread	0.458	-0.101	-0.025
Intensity	0.462	-0.157	-0.042
Flame height	0.362	-0.261	-0.173
Relative humidity	-0.216	-0.431	0.623
Drought factor	0.196	0.341	0.645
Wind speed	0.385	-0.283	0.243
Air temperature	0.300	0.431	-0.172
Curing	0.292	0.388	0.261
Fuel load	0.192	-0.421	-0.085

- Mostly aligned with the first PCA axis, are rate of spread (ROS), fireline intensity, flame height and wind speed (Figure 8.28, Table 8.20). In Table 8.20, the higher values are highlighted in red. This is done by visual assessment since there are no hard rules for what is high or what is low when interpreting PCA results, and this is case specific. A higher value means a higher correlation of the variable with the component axis. Negative correlations are presented with a minus in front of the compound loading.
  - Wind speed can be seen as the main driver of the fire behaviour output variables (ROS, intensity and flame height).
  - Since the vectors for ROS, intensity and flame height all point in the same direction, this confirms our background understanding of how the environmental variables (wind speed, relative humidity, drought factor, air temperature, curing and fuel load) define the fire behaviour outputs.
  - The vectors of ROS and intensity are very close together and are similar in their length; based on the results here, they can be considered as interchangeable. This means that for the build of a fire danger rating for grasslands and savannas, both ROS and intensity could be used to set the thresholds and define the fire danger ratings. Compared to ROS and intensity, flame height was slightly less correlated to the first PCA axis, and slightly more with the second PCA axis (Table 8.20). Also, its vector length was shorter. Therefore, we believe that ROS or intensity is a better descriptor for fire behaviour.
  - Grassland fuel load is partly related to the first PCA axis, but more so to the second PCA axis. Actually, it is mostly related to a fourth PCA axis in a multi-dimensional framework (component loading = -0.796, results not shown here). Relative humidity and drought factor were also partly correlated with the first 2 PCA axes, but more so to the third PCA axis (Table 8.20).
- As can be expected, relative humidity (RH), was in the opposite direction to drought factor and air temperature (opposite position in the diagram, Figure 8.28). Also, relative humidity was on the other side of the spectrum compared to the fire behaviour outputs. This means that at higher relative humidity, there is a lower rate of spread, lower fireline intensity and lower flame height.
- Air temperature, drought factor and curing were all grouped in the top right corner of the diagram (Figure 8.28). And again, this is what we expect based on our understanding of environmental conditions. At higher temperatures, the fine fuels will be drier (higher drought factor). And the drier the conditions, more grassland curing can be expected.

All in all, this principal component confirmed our understanding of environmental (weather) conditions in the real world and how fire behaviour relates to them. This gives us confidence in the way we calculate the fire behaviour variables at this stage. At higher wind speeds, fire behaviour will be more extreme. At higher temperatures conditions will be drier and more grassland curing can occur. Higher relative humidity co-occurs with lower temperature, and fire behaviour will be more benign under these conditions.

8.10.2 Bivariate correlations for grasslands and savanna

In figure 8.29 each variable (as predicted, calculated and observed for grassland and savanna fires) was compared pairwise with the other variables. Here we briefly discuss the results, by visually interpreting the scatterplots.

- Rate of spread and intensity were positively correlated which means that at higher fireline intensities there were higher rate of spreads (or vice versa).
- Flame height was positively correlated to ROS and intensity, i.e. higher flame heights were associated with higher fireline intensities and higher rates of spread. The fact that we can see two (exponential) curves in the flame height quadrants, can be explained by the two different flame height equations, i.e. for natural grasslands (equation 3.19, Chapter 3) and for grazed and eaten out grasslands (equation 3.20, Chapter 3).

- Relative humidity does not seem to be strongly correlated to any of the fire behaviour variables, although there is an empty corner in the top left of the RH-quadrats. This means that there were no fires with high ROS, high intensity or high flame heights, at humid conditions (high RH).
- At low drought factors, ROS and fireline intensity were low. At higher drought factors, a range of rate of spread and fireline intensities was observed.
- Wind speed was positively correlated with ROS, fireline intensity and (to a slightly lesser extent) with flame height. At higher wind speeds, the fires had a higher rate of spread, higher fireline intensities and higher flame heights.
- At low air temperatures, ROS and fireline intensity were low. At higher air temperatures however, a range of ROS and intensity values were observed. Air temperature seemed to be unrelated to flame height.
- When curing values were low (i.e. grass is green), ROS, fireline intensity and flame height were low. At high curing values, a range of ROS, fireline intensities and flame heights were observed.
- For fuel loads no clear relationship could be seen in the quadrants, but one of the observations had a far higher fuel load (~ 10 tha^{-1}) then all the other observations. This can be seen as an outlier on the right hand side in the fuel load quadrants. This observation came out of the Northern Territory, where fuel loads can be very high. Since the Research Prototype live trial was run during the wet season in the northern territory, we do not have any other observations in such high fuel loads. We recommend to extend the live trial into the dry season for the northern part of Australia, to capture fires in those regions.
- GFDI was positively related to ROS, fireline intensity and flame height. At a higher fire danger index, higher rates of spread, higher fireline intensities and higher flame heights were observed. GFDI also seemed to be positively related to wind speed and air temperature.
- The forecasted fire danger rating (NFDR_for), as calculated by the Research Prototype, was positively correlated to ROS and intensity. The relationship with flame height also seemed to be positive, but was not as clearly defined as the latter two. Wind speed, air temperature and curing were also positively correlated with the forecasted fire danger rating (NFDR_for). There seemed to be a positive exponential relationship between GFDI and NFDR_for.
- The observed fire danger rating (NFDR_obs), as observed by the live trial participants, was positively correlated to ROS and intensity. The relationship with flame height also seemed to be positive, but was not as clearly defined as the latter two. Wind speed, air temperature and curing were also positively correlated with the observed fire danger rating (NFDR_obs). There seemed to be a positive exponential relationship between GFDI and NFDR_obs.
- The forecasted and observed fire danger rating as calculated and observed as part of the Research Prototype were positively related. There is some spread in the observations at the mid categories, but in general, at low forecasted fire danger ratings, low fire danger ratings were observed. And at high forecasted fire danger ratings, high fire danger ratings were observed.

Figure 8.29 Correlation matrix for grassland and savanna fires, including fire behaviour variables (ROS = rate of spread, intensity and flame height), weather inputs (RH = relative humidity, DF = drought factor, wind speed, air temperature) fuel inputs (curing and fuel load), and calculated GFDI (grass fire danger index), forecasted national fire danger (NFDR_for) and observed fire danger (NFDR_obs)

8.10.3 Principal component analysis for "non-grassy" fuel types i.e.

For the "non-grassy" fuel types combined (i.e. buttongrass, forest, mallee heath, pine, shrubland and spinifex), 50.9% of the variance in observations could be explained by the first PCA axis, 16.6% by the second PCA axis and 11.6% by the third axis. Together, the first three axis (components) explained 79.2% of the variance in our dataset for fires in these "non-grassy" fuel types (Table 8.21).

No clear pattern could be seen in the data entries per fuel type. Most of the entries came from forest fires (dark green dots in Figure 8.30). The mallee heath fires seemed to be grouped together just above the centre of the diagram (brown dots, Figure 8.30), the pine fires (purple, n = 2) are both on the left hand side of the data cloud, and the buttongrass (light blue, n = 2) are both at the bottom part of the data cloud. The shrubland fires (red) are spread out across the diagram. If we had more observations for the other (non-forest) fuel types, maybe some grouping could have been seen. But with the low sample size, no comments can be made about ordination per fuel type.

Table 8.21 Importance of components for "non-grassy" fuel types

Components	Cumulative variance explained	Cumulative percentage variance explained
PCA 1	50.9	50.9
PCA 2	16.6	67.5
PCA 3	11.6	79.2

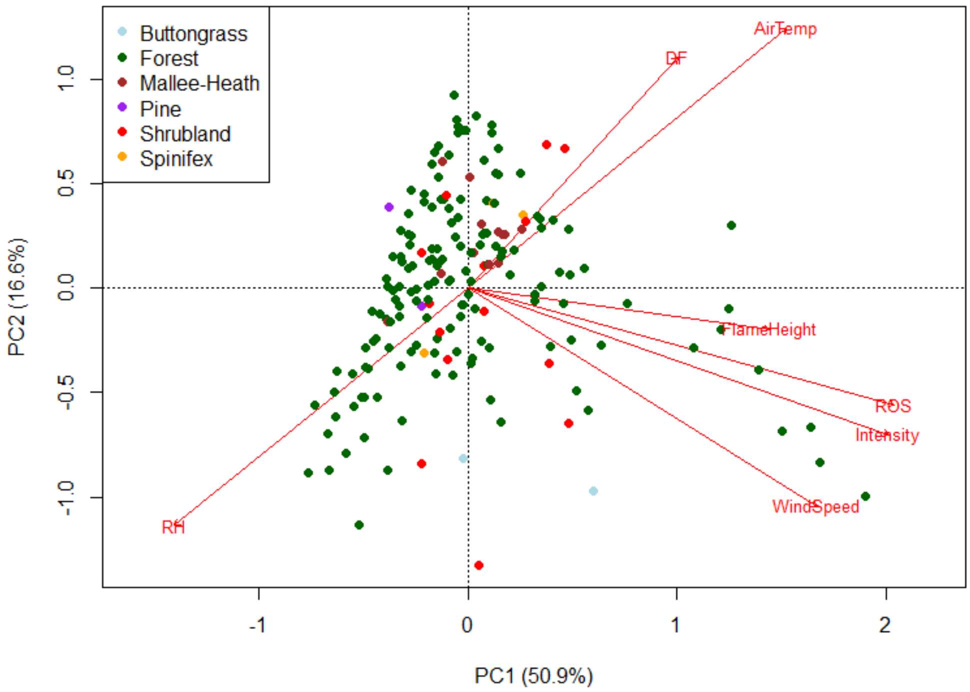


Figure 8.30 Ordination plot for observed fires in "non-grassy" fuel types. RH = relative humidity (%), DF = drought factor (a value between 0 and 10). Each coloured dot represents a data entry (colour code for fuel type as per legend).

Table 8.22 Component loadings, i.e. correlations of each variable with each of the three PCA axes, for "non-grassy" fuel types. Rate of spread, intensity and flame height are fire behaviour model outputs (top three rows), while relative humidity, drought factor, wind speed and air temperature are fire model behaviour inputs. Values are between 0 and 1; a higher value means a higher correlation of the variable with the component axis.

Variable	PCA1	PCA2	PCA3
Rate of spread	0.476	-0.229	0.036
Intensity	0.469	-0.288	0.123
Flame height	0.338	-0.080	0.152
Relative humidity	-0.327	-0.464	0.508
Drought factor	0.234	0.451	0.787
Wind speed	0.389	-0.428	-0.145
Air temperature	0.355	0.507	-0.247

- Mostly aligned with the first PCA axis, are rate of spread (ROS) and fireline intensity (Figure 8.30, Table 8.22). Flame height and wind speed were also related to the first PCA axis, but slightly less than ROS and intensity.
  - Since wind speed is in line with ROS, intensity and flame height, wind speed can be seen as the main driver of the fire behaviour output variables.
  - Since the vectors for ROS, intensity and flame height all point in the same direction, this confirms our background understanding of how the environmental variables (wind speed, relative humidity, drought factor and air temperature) define the fire behaviour outputs.
  - The vectors of ROS and intensity are very close together and are similar in their length. Based on the results here, they can be considered as interchangeable. This means that for the build of a fire danger rating for all "non-grassy" fuel types, just like for grasslands and savanna, both ROS and intensity could be used to set the thresholds and define the fire danger ratings. Flame height was slightly less correlated to the first PCA axis, and its vector length was shorter. Therefore, we believe that ROS or intensity is a better descriptor for fire behaviour.
  - Relative humidity and drought factor were related to the third PCA axis in a multidimensional framework (Table 8.22). Flame height was most strongly related to a fourth PCA axis (component loading = 0.885, results not shown here).
- Similar to what we found for grassland and savanna fires, relative humidity (RH) worked in the opposite direction to drought factor and air temperature (opposite position in the ordination plot, Figure 8.30). At higher air temperatures, the relative humidity is lower. Also, relative humidity was on the other side of the spectrum compared to the fire behaviour outputs. This means that at higher relative humidity, there is a lower rate of spread, lower fireline intensity and lower flame height.
- Air temperature and drought factor were grouped in the top right corner of the diagram (Figure 8.30). And this is what we expect based on our understanding of environmental conditions. At higher temperature (and lower relative humidity), fine fuels will be drier (higher drought factor).

Similar to what we found for grassland and savanna fires, this analysis on the "non-grassy" fuel types confirmed our understanding of environmental (weather) conditions in the real world, and how fire behaviour relates to them. This gives us confidence in the way we calculate the fire behaviour variables at this stage. At higher wind speeds, fire behaviour (such as rate of spread, intensity and flame heights) will be more extreme. At higher temperatures, fine fuel conditions will be drier. Higher relative humidity co-occurs with lower temperature, and fire behaviour will be more benign under these conditions.

8.10.4 Bivariate correlations for "non-grassy" fuel types i.e.

In figure 8.31 each variable (as predicted, calculated and observed for fuel types other than grassland and savanna) was compared pairwise with the other variables. Overall, the patterns were very similar to what we saw for grassland and savanna (section 8.10.2, Figure 8.29). Here we briefly discuss the results, by visually interpreting the scatterplots.

- Rate of spread and intensity were positively correlated which means that at higher fireline intensities there were higher rate of spreads (or vice versa).
- Flame height was positively correlated to ROS and intensity, i.e. higher flame heights were associated with higher fireline intensities and higher rates of spread.
    - One observation for flame height showed a much higher value than all the other observations. A flame height of 140 m was calculated for a fire in "western shrub grass dry sclerophyll forest" based on the weather and fuel inputs. It is true that the conditions for that specific fire were extreme, but flame heights of 140 m seem to be outside the bounds of what can be realistically expected. This fuel type has very high elevated fuel heights, and we think that this goes beyond the limits of application of the DEFFM/Vesta model. We recommend future research into fire behaviour in fuel types with very high elevated fuel heights, or fuel types with characteristics outside the bounds that the original model was designed for.
- Relative humidity does not seem to be strongly correlated to any of the fire behaviour variables, although there is an empty corner in the top left of the top two RH-quadrats. This means that there were no fires with high ROS or high intensity at humid conditions (high RH). Relative humidity does not seem to be strongly correlated to flame height. However, because the outlier (as discussed in previous point), set the limits for the y-axis, the other data points are compressed. Since this is only a visual interpretation of the results, we cannot show numbers here to prove if there is a relationship or not. Future research could look into the detailed relationships between flame height and other variables.
- At low drought factors, ROS and fireline intensity were low. At higher drought factors, a range of rate of spread and fireline intensities was observed. Drought factor does not seem to be strongly correlated to flame height. However, because the flame height outlier (as discussed before), set the limits for the y-axis, the other data points are compressed and we cannot visually evaluate if there was a relationship between the drought factor and flame height.
- Wind speed was positively correlated with ROS, fireline intensity and it also seemed to be positively correlated with flame height (but see previous points). At higher wind speeds, the fires had a higher rate of spread, higher fireline intensities and higher flame heights.
- At low air temperatures, ROS was low. At higher air temperatures however, a range of ROS was observed. The relationships between air temperature and intensity or flame height was not very clear.
- FFDI was positively related to ROS and fireline intensity and possibly also to flame height. At a higher FFDI, higher rates of spread, higher fireline intensities and higher flame heights were observed. FFDI showed an exponential decaying relationship with RH; i.e. at humid conditions FFDI was low, but at dry conditions FFDI was high. At low drought factors, FFDI was low. At high drought factors however, FFDI ranges from low to high. At higher air temperatures and higher wind speeds, FFDI was higher (as can be expected from the McArthur fire danger meter (McArthur, 1967)).
- The forecasted fire danger rating (NFDR_for), as calculated by the Research Prototype, was positively correlated to ROS and intensity, and from looking at the figures this might be an exponential relationship. The relationship with flame height also seemed to be positive, but was not as clearly defined as the latter two. Drought factor, wind speed, air temperature and curing were also positively correlated with the forecasted fire danger rating (NFDR_for), while RH seemed to be negatively related to NFDR_for (but the observations showed a lot of variation). There seemed to be a positive exponential relationship between FFDI and NFDR_for.

- The observed fire danger rating (NFDR_obs), as observed by the live trial participants, seems to be positively related to ROS and intensity. The relationship with flame height was not clear. Drought factor, wind speed and air temperature were positively correlated with the observed fire danger rating (NFDR_obs) while RH seemed to be negatively related to NFDR_for (but the observations showed a lot of variation). There seemed to be a positive trend between FFDI and NFDR_obs, but the relationship is not very clear.
- The forecasted and observed fire danger rating as calculated and observed as part of the Research Prototype were positively related, but there was a lot of spread in the observations, more so than in for grassland and savanna fires (section 8.10.2, Figure 8.29). In section 8.5 and 8.6 we discussed the relationship between the forecasted and observed NFDR values in detail, as part of our system performance evaluation.

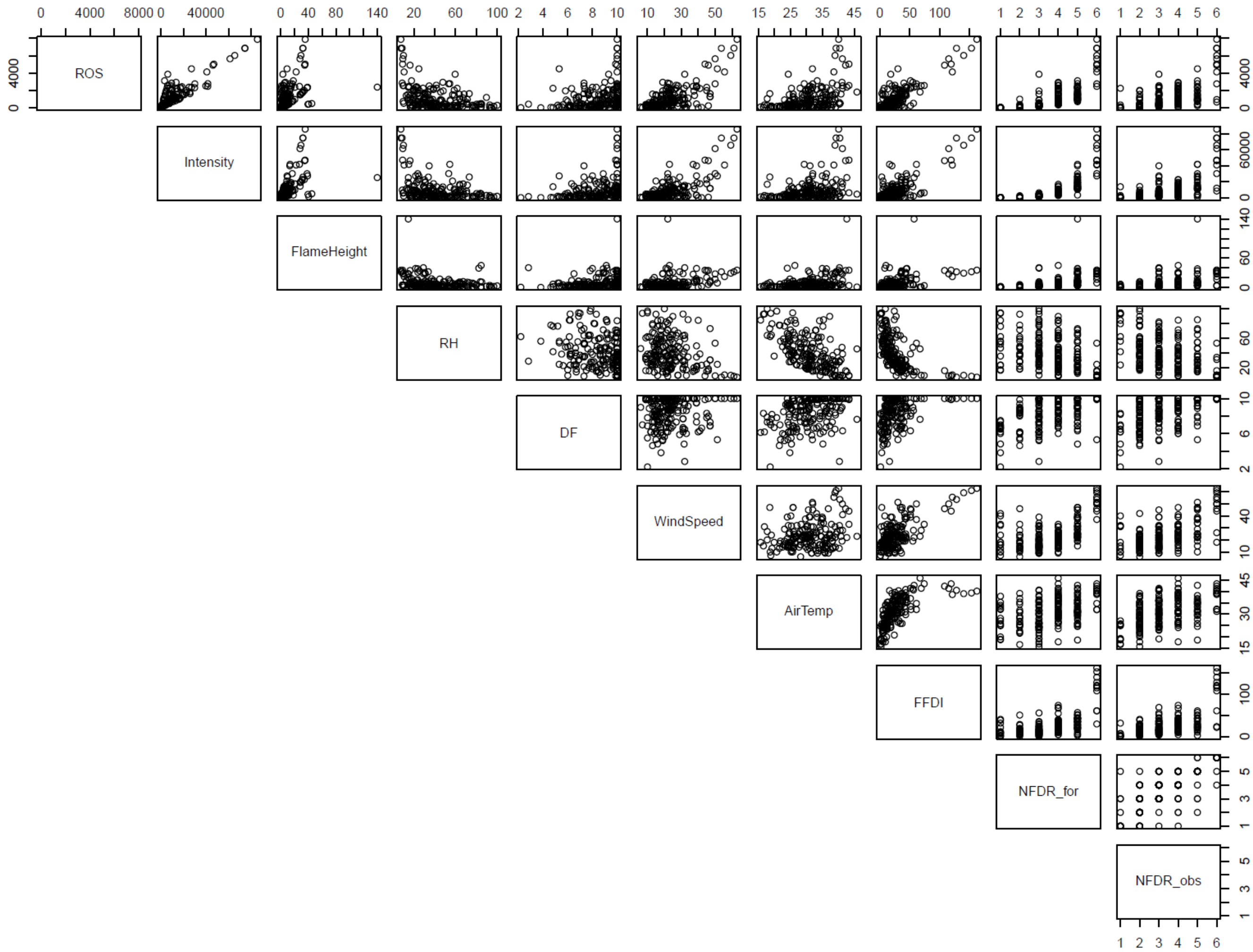


Figure 8.31 Correlation matrix for fires in buttongrass, forest, mallee heath, pine, shrubland and spinifex, including fire behaviour variables (ROS = rate of spread, intensity and flame height), weather inputs (RH = relative humidity, DF = drought factor, wind speed, air temperature) and calculated FFDI (forest fire danger index), forecasted national fire danger (NFDR_for) and observed fire danger (NFDR_obs)

9 Analysis of historical case studies

9.1 Introduction

Historical case studies provide an opportunity to evaluate the NFDRS Research Prototype against historically significant fires, where the accurate forecast of fire danger is particularly important. They also supplement the higher end of the fire danger scale within our evaluation dataset, which was characterised by a large proportion of points representing fire danger conditions under which most fires occur in the middle of the FDR scale. The Bureau of Meteorology high-resolution atmospheric reanalysis project (see Chapter 12) has provided an opportunity to re-run accurate historical forecasts of both the FFDI or GFDI as well as the Research Prototype, which we otherwise would be unable to do with such confidence.

We sought to identify case studies of historically significant fires from different fuel types around Australia and use them in two ways. Firstly, to take a close look at the performance of the Research Prototype against the fires and in particular, to identify how appropriate the forecast was and discuss where it has worked particularly well and where it didn't. Secondly, we aimed to use each of the case studies to supplement the overall evaluation dataset, increasing the number of points representing the top end of the FDR scale.

We were limited to fires where sufficient descriptions of fire behaviour, suppression and containment as well as the consequences of the fire had been well documented throughout the duration of the fire. Case studies were also limited to those occurring after 2010 in order to access Bureau of Meteorology high-resolution atmospheric reanalysis or forecast data (see Chapter 12). However, some case studies that had been particularly well documented prior to 2010 presented opportunities and for these fires, the FFDI (or GFDI) and NFDRS forecasts have been determined using historical data from the closest or most representative automatic weather station.

For each case study, we have provided a tabulated summary of forecasted conditions against observations of fire behaviour, suppression and containment as well as actual consequences. We identified where forecasts were correct and where there was an over- or under-prediction based on the alignment with descriptions within the NFDRS FDR Tables and expert judgement of how appropriate the actual forecasted FFDI or GFDI were. Where possible, we determined these in collaboration with the relevant state agencies familiar with the each fire case study. We also sought to explore and identify possible sources of error where there was an over- or under-prediction based on the alignment with descriptions. In some instances, this was particularly difficult. We have aimed to provide these in context to the fires and the conditions under which they burnt, highlighting some of the reasons why each fire was so significant.

The case studies are presented in chronological order:

- Billo Road fire, New South Wales, December 2006
- Kilmore East (Black Saturday) fire, Victoria, February 2009
- Ballandean (Hidden Creek) fire, Queensland, October-November 2014
- Lower Hotham fire, Western Australia, January-February 2015
- O'Sullivan fire, Western Australia, January-February 2015
- Cascade fire, Western Australia, November 2015
- Pinery fire, South Australia, November 2015
- Beecroft Peninsula fire, New South Wales, November 2015
- Waroona fire, Western Australia, December 2016
- Sir Ivan fire, New South Wales, February 2017
- Taliesin (Carwoola) fire, New South Wales, February 2017

9.2 Billo Road fire, New South Wales, December 2006

Overview

The Billo Road fire burned almost 10,000 ha of pine forest in December 2006. It was the largest pine plantation fire ever recorded in NSW.

Fire behaviour and containment

The Billo Road fire was started by the arson ignition of a car on the evening of 9th December 2006, and detected on the morning of 10th December. From 10 to 14 December the fire grew to almost 11,000 ha with most of the growth occurring in three major fire runs. During these runs, the fire spread at up to 2,400 mh^{-1} as a sustained crown fire with short distance spotting. Fire behaviour within the major runs varied with fuel structure and all ages of pine plantation were burned, ranging from logging slash and newly established plantation through to mature >20 year old forest.

Up to 240 fire fighters and 12 aircraft worked on the fire until it was contained on the morning of 14th December. Up to 320 fire fighters worked in subsequent days to maintain containment.

Impacts

The Billo Road fire burn over 9,500 ha of pine plantation.

Figure 9.1 Fire crowning in 15-year old radiata plantation on 10th December 2006. Stand height is approximately 18 m (LEFT); Post-fire view of surface fuel consumption in an unthinned 18-year old radiata pine stand (RIGHT). Source: Cruz and Plucinski (2007).

NFDRS point forecast

The Billo Road fire occurred before publication of forecast grids started in 2009. Two sources of weather observations were available both with significant issues: from the Wagga Wagga weather station, 90 km from the fire, and from a weather station mounted at the Forests NSW office at Bondo, near the fire but with significant siting and calibration issues, see Cruz and Plucinski (2007) for details. Without a definitive source of weather information we performed calculations using observations from both stations, e.g. FFDI for period 1 in Table 9.1 was 22 at Wagga Wagga and 7 using the data from Bondo. The two sets of calculations are shown in the table as Wagga Wagga/Bondo for FFDI, NFDRS index, and NFDRS rating.

Observed rating varied from Category 3 to 6 in line with diurnal variation in the weather. Neither set of forecasts was correct over the set of 9 observation periods. The Wagga Wagga AWS based calculations were correct or over-predicted during peak fire behaviour but consistently over-predicted when the observed rating was Category 3. Conversely, the Bondo AWS derived calculations tended to under-predict the most extreme fire behaviour and were correct for more moderate conditions.

Taken together, these results are inconclusive given the high uncertainty in the quality of the weather inputs used in the calculations. However once reanalysis data becomes available the excellent fire behaviour observations available mean this major pine fire should be revisited.

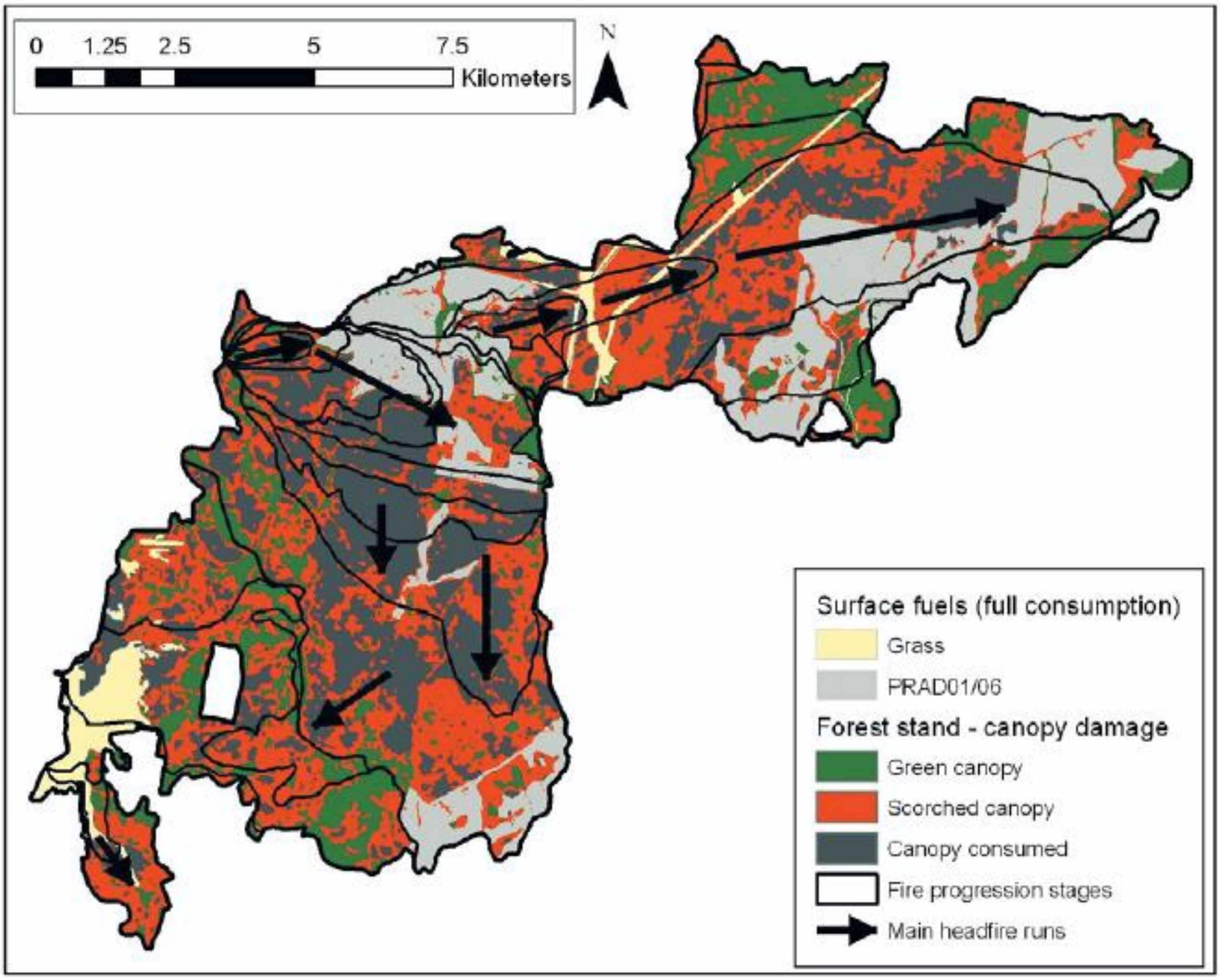


Figure 9.2 Spread map for the Billo Roajd fire showing the progression of the fire and fire severity. Source: Cruz and Plucinski (2007).

Related references

Cruz MG and Plucinski MP (2007) Billo Road Fire: Report on Fire Behaviour Phenomena and Suppression Activities, Bushfire CRC Technical Report A.07.02, Bushfire CRC, Melbourne, 102pp.

Table 9.1 Summary table of forecasted conditions against observations for the Billo Road fire (Wagga Wagga/Bondo AWSs)

Incident name:	Billo Road	Date:	10-13/12/2006
Daily regional FFDI forecast rating:	NA, no grids available in 2006	*C-Haines red flag warning:*	NA, no grids available in 2006
Daily regional NFDRS forecast rating:	NA, no grids available in 2006	*Wind change red flag warning:*	NA, no grids available in 2006

Incident details	Time period	1	2	3	4	5	6	7	8	9
	Date	10/12/2006	10/12/2006	10/12/2006	10/12/2006	11/12/2006	11/12/2006	11/12/2006	12/12/2006	13/12/2006
	Time period start	0:00:00	9:00:00	11:00:00	18:00:00	0:00:00	13:00:00	19:00:00	0:00:00	0:00:00
	Time period finish	9:00:00	11:00:00	18:00:00	23:59:00	13:00:00	19:00:00	23:59:00	23:59:00	23:59:00
	Latitude	AWS	AWS	AWS	AWS	AWS	AWS	AWS	AWS	AWS
	Longitude	AWS	AWS	AWS	AWS	AWS	AWS	AWS	AWS	AWS
Fuels	Fuel type/s	Pine	Pine	Pine	Pine	Pine	Pine	Pine	Pine	Pine
	FDR Table	Pine	Pine	Pine	Pine	Pine	Pine	Pine	Pine	Pine
Fire Danger Rating	FFDI (max)	22/7	39/12	67/23	36/16	53/12	37/15	25/3	23/7	28/13
	GDFI (max)									
	Observed McArthur fire danger rating	Low-Moderate	Very high	Extreme	Severe	High	Extreme	High	Very high	Very high
NFDRS forecast	Forecast NFDRS Fire Behaviour Index (max)	219/24	316/62	526/232	280/70	530/72	408/94	355/39	239/37	253/68
	Forecast NFDRS Fire Danger Rating (max)	5/3	6/4	6/5	5/4	6/4	6/5	6/3	5/4	5/4
	Observed NFDRS FIRE DANGER RATING	3	3	6	5	3	6	3	4	4
Fire behaviour & fire weather	Obs fireline intensity (kW/m)	Low		23,200	14,200	Quiet	61,500		Moderate	Moderate
	Obs mean ROS (m/hr)	Creeping		2,200	1,300		2,500			
	Obs mean flame height (m)		6	Crown	Crown	Surface fire	Intermittent crown	Surface fire	Intermittent crown	Intermittent crown
	Obs spotting distance (m)			Profuse			Short range			
	Wind change observed (Y/N)	N	N	N	Y	Y	N	N	N	N
	Forecast fire behaviour accurate?	No - over-predict	No - over-predict	Yes	Yes/No	No - over-predict	Yes	No/Yes	No/Yes	No/Yes
Fire suppression & containment	Fire suppression (Y/N)	N	Y	Y	Y	Y	Y	Y	Y	Y
	Operational strength in field personnel	0	20	90	90	120	130	130	130	240
	Operational strength in aerial resources	0	1	8	8	8	11	11	11	12
	OFFENSIVE strategies (Y/N)	N	Y	Y	Y	Y	Y	Y	Y	Y
	DEFENSIVE strategies (Y/N)						Y			Y
	Forecast suppression/containment accurate?	NA	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Consequences	Fire area at end of time period		6	1,001	2,447	4,476	7,110		10,935	11,232
	Fire perimeter at end of time period		0.9	15.2	21.8	34.3	56.7		87.9	97.4
	Houses lost during time period (Number/Y/N)									
	Other assets lost during time period (Y/N)	Y	Y	Y	Y	Y	Y	Y	Y	Y
	Lives lost during time period (Number/Y/N)	N	N	N	N	N	N	N	N	N
	Infrastructure impacted during time period (Y/N)									
	Forecast consequences accurate?	No - over-predict	No - over-predict	Yes	Yes	Yes	Yes	Yes	Yes	No - over-predict

9.3 Kilmore East (Black Saturday) fire, Victoria, February 2009

Overview

The Kilmore East fire, together with over 300 fires that occurred in south-eastern Australia on 7th February 2009 (now recognised as Black Saturday) are arguably the most significant and catastrophic fires to have occurred in Australian history. Together they burned over 450,000 ha and resulted in 173 fatalities, forever changing the lives of many Victorians, with countless examples of deeds of great courage and compassion. The Kilmore East fire was the most significant of these fires and ignited at approximately 11:45 as a result of arcing from a broken power line on private farmland. 119 people lost their lives due to the Kilmore East fire.

Conditions were driven by the development of a deep pool of very hot air over central Australia that brought hot air into Victoria, which combined with a strong cold front moving south of Australia, creating very strong hot north-westerly winds ahead of a frontal passage in western and central Victoria. The fire developed quickly, burning through many communities including the townships of Arthurs Creek, Wandong, Strathewen, Kinglake, Kinglake West, Steels Creek, Reedy Creek, Strath Creek, St Andrews, Yarra Glen, Humevale, Flowerdale and Hazeldene and over 100,000 of mostly dry sclerophyll eucalypt forest as well as grasslands/open woodland and mixed dry-wet sclerophyll eucalypt forest in less than 12 hours.

Figure 9.3 MODIS Aqua satellite image of smoke plumes and a pyrocumulus cloud northeast of Melbourne during the morning of 7th February 2009 (LEFT) and a gumleaf from the memorial tree erected in tribute to the many victims of Black Saturday in the fire-affected community of Strathewen (RIGHT, source: Amanda Gibson).

Fire behaviour and containment

The fire was characterised by a dynamic of profuse short range spotting, rates of fire spread up to 9.1 $kmhr^{-1}$ and average fireline intensities up to 88,000 kWm^{-1}. Strong winds aloft and the development of a strong convection plume led to the transport of firebrands over considerable distances causing the ignition of spotfires up to 33 km ahead of the main fire front. The passage of a wind change between 17:30 and 18:30 turned the approximately 55 km long eastern flank of the fire into a headfire. Spotting and fire behaviour associated with this wide front resulted in the greater development of a pyrocumulonimbus cloud that injected smoke and other combustion products into the lower stratosphere.

Throughout the day, fire fighting resources were stretched to the limits with 316 grass, forest or scrub ignitions throughout the state. Over the course of the day, fire fighting efforts focused on the western and eastern flanks using mostly defensive strategies, prioritising life and property. While any offensive strategies had little impact on the growth and size of the larger fires on the day, there were attempts of direct attack on flanks and spot fires as well as both parallel and indirect attack and there were many initial attack successes of suppression on new starts (from power lines) and spot fire ignitions. Some spot fires were later over-run by the preceding headfire. Aircraft played an important role, however their effectiveness was restricted by the size of the fire/s, extreme wind speeds and limited visibility, which in many cases made flying unsafe. At times, conditions on the fireground were chaotic, communications were difficult, and fire fighters were required to operate in life threatening and stressful conditions.

Figure 9.4 Spread map for the Kilmore East fire showing the progression of the fire through the ten (mostly hourly) time periods.

Impacts

The Kilmore East fire was responsible for the death of 119 people as well as extensive, wide reaching impacts on property (1,242 houses were lost) and the infrastructure that supports communities (such as loss of power and telecommunications). Burning through over 100,000 ha including Kinglake National Park, there was also substantial environmental impact, which will take years to fully reveal itself. The 2009 Royal Commission estimated that together, the Black Saturday fires cost over $4 billion and resulted in one of the largest relief and recovery efforts seen in Australia.

NFDRS point forecast

The NFDRS forecast for each of the time periods (as defined by Cruz et al. 2012) was for Category 6 (Table 1). During the first 1 ¼ hour, during which the fire was developing through grassland despite suppression efforts, observations of fire danger against descriptors were best described by Category 5 (using the Grassland FDR Table). This is likely to be related to the effect of suppression efforts as well as the effect of the fire still developing potential. Many of the observations within the Research Prototype evaluation dataset represent this initial time period when development is occurring and suppression efforts are likely to impact ratings resulting in a discrepancy between the forecast and observations (i.e. what may appear like and over-prediction, actually captures the effect of development and suppression).

From 13:00 through until midnight, the Research Prototype accurately described fire behaviour, suppression difficulty and the consequences that were observed (using the Forest FDR Table). It should also be noted that despite the Category 6 rating, there were many instances of successful initial attack on new fires and spot fires using direct attack techniques, so assuming all firefighting efforts would be focused on “defensive’ strategies in these types of fires would be incorrect. Adequately capturing this within the FDR tables would make an important improvement.

Under the current McArthur based Fire Danger Rating, the forecasted FFDI varied from 61 to 162 (ranging from Severe to Catastrophic), with a GFDI of 148 (Catastrophic) at the time of ignition. In the first 1 ¼ hours when the forecast was Catastrophic (GFDI >148), conditions observed were Extreme, with the discrepancy likely to be related to suppression and development as described above. Based on the definitions by AEMC (2009) the current FDR also over-predicted Catastrophic conditions throughout each of the time periods throughout the fires progression (defined by rate of spread as 10+ kmh^{-1}), however one could argue that the conditions observed were truly catastrophic. Actual observations of spotting distance were greater than those defined. The Catastrophic ‘impact assessment’ descriptions by AEMC (2009) appear to be suitable for the conditions observed.

Daily FWA and Red Flag warnings

The daily regional NFDRS forecast was for Category 6 which appears to have described well the fire danger observed for the Kilmore East fire. While C-Haines wasn’t measured or reported in 2009, the atmospheric instability evident on February 7th, would have also been identified via a ‘red flag warning’ using the Research Prototype. A NFDRS ‘red flag’ warning for wind change would have also been issued on the day and would have captured the potential for this to impact fire behaviour and potential conditions for the ‘dead man zone’ through the descriptions of suppression difficulty. The regional FFDI forecast for the day was for ‘Catastrophic’ conditions. Whittaker et al (2013) noted that the potential fire danger and conditions were accurately forecast, and Victorians had been warned to prepare for ‘the worst [fire danger] day in the history of the State’ (Premier of Victoria, John Brumby, cited in Moncrief (2009)).

Acknowledgements

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Whittaker, J, Haynes, K, Handmer, J, McLennan, J (2013) Community safety during the 2009 Australian ‘Black Saturday’ bushfires: an analysis of household preparedness and response. International Journal of Wildland Fire 22, 841-849.

Table 9.2 Summary table of forecasted conditions against observations for the Kilmore East fire

Incident name:	Kilmore East (Black Saturday)	Date:	7/02/2018
Daily regional FFDI forecast rating:	Catastrophic	*C-Haines red flag warning:*	Wasn't available in 2009
Daily regional NFDRS forecast rating:	6	*Wind change red flag warning:*	*Yes*

Incident details	Time period	1	2	3	4	5	6	7	8	9	10
	Date	7/02/2009	7/02/2009	7/02/2009	7/02/2009	7/02/2009	7/02/2009	7/02/2009	7/02/2009	7/02/2009	7/02/2009
	Time period start	11:45:00	12:00:00	13:00:00	14:00:00	15:00:00	16:00:00	17:00:00	18:00:00	19:00:00	20:00:00
	Time period finish	12:00:00	13:00:00	14:00:00	15:00:00	16:00:00	17:00:00	18:00:00	19:00:00	20:00:00	0:00:00
	Latitude	-37.2649	-37.2945	-37.3358	-37.374	-37.4135	-37.5144	-37.5832	-37.4353	-37.3773	-37.3587
	Longitude	145.0116	145.0132	145.0532	145.0721	145.0975	145.2485	145.3368	145.3241	145.3302	145.3271
Fuels	Fuel type/s	Grass	Grass	Grass/Forest	Forest	Forest	Forest/Wet Forest	Forest/Wet Forest	Forest	Forest/Wet Forest	Forest
	FDR Table	Grassland	Grassland	Forest	Forest	Forest	Forest	Forest	Forest	Forest	Forest
Fire Danger Rating	FFDI (max)	102	113	121	140	153	162	137	128	115	61
	GDFI (max)	148	163	173	224	255	276	206	177	151	89
	Observed (FFDI) FIRE DANGER RATING	Extreme	Extreme	Catastrophic	Catastrophic	Catastrophic	Catastrophic	Catastrophic	Catastrophic	Catastrophic	Catastrophic
NFDRS forecast	Forecast NFDRS Fire Behaviour Index (max)	211.75	224	633.9375	735	838	857	1444.875	1326.3125	1326.3125	300
	Forecast NFDRS Fire Danger Rating (max)	6	6	6	6	6	6	6	6	6	6
	Observed NFDRS FIRE DANGER RATING	5	5	6	6	6	6	6	6	6	6
Fire behaviour & fire weather	Obs fireline intensity (kW/m)		6603		39,209	88,220			73,228	82,677	limited fire propagation
	Obs mean ROS (m/hr)		4,260	4,380	4,080	9,180			7,620	5,400	
	Obs mean flame height (m)	<1		above the canopy							
	Obs spotting distance (m)		700			up to 41,000	up to 40,000	medium, long range			short range spotting
	Wind change observed (Y/N)								Y		
	Forecast fire behaviour accurate?	Over-predicted	Over-predicted	Y	Y	Y	Y	Y	Y	Y	Over-predicted
Fire suppression & containment	Fire suppression (Y/N)	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	Operational strength in field personnel	~>20		~>100			~>200			1,077 personnel & 117 fire agency appliances	
	Operational strength in aerial resources	0	~4	~4	~5	~5	~6	~4	~5	~7	~8
	OFFENSIVE strategies (Y/N)	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	DEFENSIVE strategies (Y/N)	?	?	?	Y	Y	Y	Y	Y	Y	Y
	Forecast suppression/containment accurate?	Over-predicted	Y	Y	Y	Y	Y	Y	Y	Y	Y
Consequences	Fire area at end of time period	5	250	1800	3100	7350	17,500	26,500	62,900	75,000	99,000
	Fire perimeter at end of time period	1.3	10	21	30	50	106	143	217	311	487
	Houses lost during time period (Number/Y/N)	N	N	N	Y	Y	Y	Y	Y	Y	Y
	Other assets lost during time period (Y/N)	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	Lives lost during time period (Number/Y/N)	N	N	N	N	Y	Y	Y	Y	Y	Y
	Infrastructure impacted during time period	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	Forecast consequences accurate?	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y

9.4 Ballandean (Hidden Creek) fire, Queensland, October-November 2014

Overview

The Ballandean (Hidden Creek) started on 27th October 2014 after sparks from the use of a tractor and slasher on a local vineyard ignited nearby grassland. Over the following six days the fire burnt through over 1,040 ha of mixed eucalypt woodland and open forest, including part of the Girraween National Park. The fire proved to be complex and expensive to contain with periods during the early stages of the fire when direct attack was deemed unsafe. Back-burning operations were possible throughout operations and proved to be an important tool for both property protection and containment.

Fire behaviour and containment

The fire grew quickly in the early stages of development through 12 year old forest fuels with an approximate fuel load of 15 tha^{-1}. Rates of spread of up to approximately 500 mh^{-1} were observed, sometimes accompanied by short distance spotting.

Impacts

The consequences of the fire included extensive environmental damage to the forest. Asset losses were limited to the loss of some chardonnay vines along with other rural assets such as farm fencing.


Figure 9.5 Damage to chardonnay vines at Twisted Gum Wines at Ballandean on 27/10/2014 (LEFT, source: T. Coelli) and firefighters back burn at a Eukey property on 29/10/2014 (RIGHT, source: H. Smith / Stanthorpe Border Post).

NFDRS point forecast

During the first 2 hours after ignition, on the morning of 27th October when the fire grew quickly, the Research Prototype appears to have captured the potential fire danger well with a forecasted Category 3 (Forest). Over the following two days (46 hours) the NFDRS forecast Category 4, however fire danger appears to be more accurately described by Category 3. Over the remaining four days till the fire was effectively contained, there is not sufficient information to confirm the accuracy of the NFDRS forecast, nor the FFDI based forecast however, the limited information available suggests that the forecasted conditions which were all Category 3, were mostly relevant, possible over-predicting fire danger.

Without clear definitions of the fire danger rating categories as they are applied throughout Queensland, it is difficult to ascertain the accuracy of the FFDI based forecast which ranged from 9 (Low) through to 37 (Very High) over the duration of the fire. During the first two hours, it appears that the FFDI forecast of “High’ has tended to under-predict observed fire danger which was better captured by ‘Very High’. Over the following two days when the FFDI forecast increased to ‘Very High’, observations were better described by ‘High’. The biggest discrepancy appears to have been on the third day, when forecast condition were ‘Low’, but observations were better described by ‘Very High’.

Daily FWA and Red Flag warnings

The daily regional NFDRS forecast was for Category 5 (forest) for the first two days which appears to have been an over-prediction based on attempts to work offensively on the fire during this time and because the consequences of the fire were relatively small despite several properties being within the fire perimeter. Comparably, the regional FFDI based forecast for the same time period was for 'Severe' on the 27th and 'Very High' on the 28th which similarly appears to have over-predicted observations on the first day which tended to be better described by 'Very High'. The regional FFDI forecast of 'Very High' was possibly a better alignment with observed fire danger on the second day, than the NFDRS forecast. Over the following days, the regional forecast reduced to Category 4 on the 29th and Category 3 on the 30th, still possible over-predicting fire danger slightly. Likewise the regional FFDI forecast also reduced to 'High' when conditions observed were better described by 'High' and 'Low-Moderate'.

Throughout the fire, there were no wind change red flags forecast, which mostly represents conditions with the exception of a wind change overnight from 28th – 29th October. The C-Haines red flag was forecast for the duration of the fire which may explain some of the difficulties observed with fire containment, however doesn't appear to have had an impact resulting in increased fire danger.

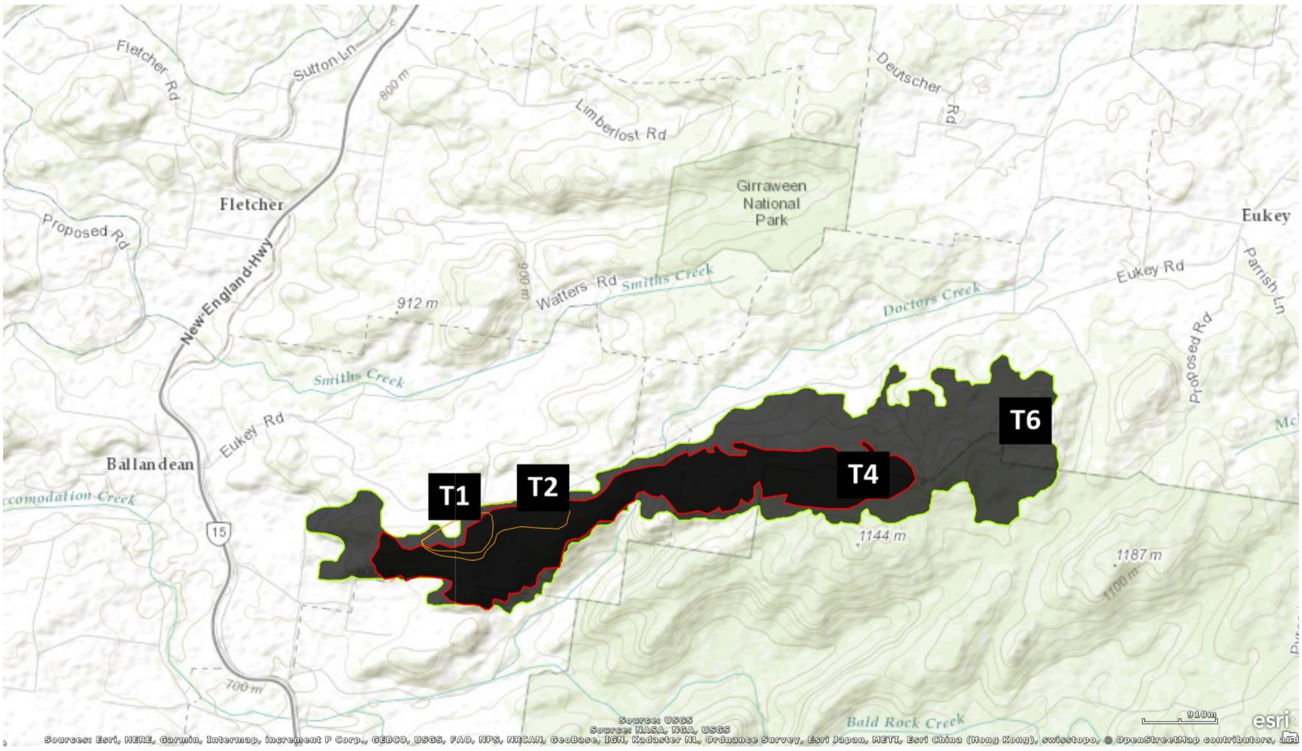

Figure 9.6 Development of the Ballandean fire with the time periods 1, 2 4 and 6 displayed.

Acknowledgements

Thanks to Andrew Sturgess and Kent Barron from Queensland Fire and Emergency Services for providing information.

Related references

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Table 9.3 Summary table of forecasted conditions against observations for the Ballandean fire

Incident name:	Ballandean (Hidden Creek)										
	Date:	27/10/2014			28/10/2014		29/10/2014			30/10/2014	
	Daily regional FFDI forecast rating:	Severe			Very high		Very high			High	
	Daily regional NFDRS forecast rating:	5			5		4			3	
	C-Haines red flag warning:	*Yes*			*Yes*		*Yes*			*Yes*	
	Wind change red flag warning:	*No*			*No*		*No*			*No*	
Incident details	Time period	1	2	3	4	5	6	7	8	9	10
	Date	27/10/2014	27/10/2014	27-28 (o/n)	28/10/2014	28-29 (o/n)	29/10/2014	29/10/2014	29-30 (o/n)	30/10/2014	30/10 - 02/11
	Time period start	9:00:00	11:00:00	16:00:00	9:00:00	16:40:00	9:00:00	11:40:00	18:30:00	9:00:00	18:30:00
	Time period finish	11:00:00	16:00:00	9:00:00	16:40:00	9:00:00	11:40:00	18:30:00	9:00:00	18:30:00	18:30:00
	Latitude	-28.8086	-28.8075	-28.8061	-28.8026	-28.8008	-28.7962	-28.7959	-28.7959	-28.8171	-28.7976
	Longitude	151.8762	151.8841	151.8937	151.9149	151.9359	151.9415	151.9455	151.9455	151.9783	151.9826
Fuels	Fuel type/s	Grass/Forest	Forest	Forest	Forest	Forest	Forest	Forest	Forest	Forest	Forest
	FDR Table	Forest	Forest	Forest	Forest	Forest	Forest	Forest	Forest	Forest	Forest
Fire Danger Rating	FFDI (max)	18	37	34	32	30	11	17	9	15	24
	Observed (FFDI) FIRE DANGER RATING	Very High	High	High	Very High	High	Very High		Low-Moderate	High	Low-Moderate
NFDRS forecast	Forecast NFDRS Fire Behaviour Index (max)	20.3	59.3	57.7	73.6	67.7	13.7	21.2	10.7	21	43
	Forecast NFDRS Fire Danger Rating (max)	3	4	4	4	4	3	3	3	3	3 (1 hour of 4)
	Observed NFDRS FIRE DANGER RATING	3	3	3	3	3	3		2	3	2
Fire behaviour & fire weather	Obs fireline intensity (kW/m)				6,000						
	Obs mean ROS (m/hr)	<500	190	62	391	approx 60	337				limited
	Obs mean flame height (m)										
	Obs spotting distance (m)									Spotting from back-burning	
	Wind change observed (Y/N)	N	N	N	N	N	N	N	Y	N	N
	Forecast fire behaviour accurate?	Y	Over-predicted	Over-predicted	Y	Over-predicted	Y		Over-predicted	Y	Over-predicted
Fire suppression & containment	Fire suppression (Y/N)			Y	Y	Y	Y	Y	Y	Y	Y
	Operational strength in field personnel										
	Operational strength in aerial resources						1	1		1	
	OFFENSIVE strategies (Y/N)			Y	Y	Y	Y	Y	Y	Y	Y
	DEFENSIVE strategies (Y/N)										
	Forecast suppression/containment accurate?			Over-predicted	Over-predicted	Over-predicted	Y	Y	Y	Y	Y
Consequences	Fire area at end of time period	29	69		423		1,040				
	Fire perimeter at end of time period										
	Houses lost during time period (Number/Y/N)					N	N	N	N	N	N
	Other assets lost during time period (Y/N)		Y	Y	Y	N	N	N	N	N	N
	Lives lost during time period (Number/Y/N)	N	N	N	N	N	N	N	N	N	N
	Infrastructure impacted during time period (Y/N)	N	N	N	N	N	N	N	N	N	N
	Forecast consequences accurate?	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y

9.5 Lower Hotham fire, Western Australia, January-February 2015

Overview

The Lower Hotham fire started on 31st January 2015 as a result of a re-ignition from a lightning strike to a marri tree in a grassy paddock on private property on 29th January 2015. Over the following seven days until the fire was largely contained on 6th February, the fire proved to be difficult, complex and expensive to contain and continued to burn around 52,000 ha of forest and farmland.

Fire behaviour and containment

Despite the 'Very High' Fire Danger Rating throughout the time until containment (<40 FFDI, McArthur), fire behaviour was extreme, with reported head fire rates of spread over 3.5 kmh^{-1} and violent pyro-convection and formation of pyro-cumulonimbus cloud. Fire-line intensity peaked at ~45,000 kWm^{-1} and there were frequent observations of mass short and medium distance spotting with some estimates up to 5 km. Flame heights in excess of 30 m resulted in extensive runs of high intensity crown fire with around 60% of the forest being defoliated. For many times throughout the fire, suppression and containment were hampered by steep and varying terrain as well as thick smoke that obstructed visibility.

Impacts

The consequences of the fire included extensive, long term physical and environmental damage to the forest and its wildlife. While asset losses were limited to 1 house, several sheds, farm fencing, some livestock, parts of plantations and the Long Gully Bridge, at various times the surrounding communities of Boddington, Collie, Williams and Quindanning were potentially at risk of suffering more severe impacts. Impacts on infrastructure included the Boddington town-site losing power, a communications tower being disabled as well as several road and track closures.

Figure 9.7 Pyro-cumulonimbus cloud, Lower Hotham fire 11:18hrs 04/02/2015 (LEFT, source: S. Carnaby, DPaW); Defoliation in mixed jarrah/wandoo forest on Match Brook Road (RIGHT, source: N. Burrows, DPaW).

NFDRS point forecast and Red Flag warnings

For the first four days following ignition on 31st January, the NFDRS forecast potential Category 5 conditions (Forest) which appears to have accurately described the fire behaviour and the difficulty experienced with suppression and containment accurately. From the evening on 3rd February until late morning on the 4th February, the NFDRS forecast Category 3 (with Red Flag warning for both wind change and C-Haines), however during this time the fire made a large southerly run with conditions observed more in line with the descriptors for Category 5. The discrepancy could be attributed to the fire becoming largely plume driven (Fig. 5.1a) which resulted when the south-eastern flank become the head-fire after the wind-change at the beginning of time period 4 (Fig. 5.2) together with mass spotting and subsequent fires ahead of the main fire front contributing significant energy to the convection column, increasing fire winds and fire behaviour. Potential for fire-atmospheric interactions during this time was flagged by the forecast of a C-Haines Red Flag warning, and appears to have accurately forecast the conditions observed.

The NFDRS forecast appears to have well defined the fire danger, suppression and consequences of the Lower Hotham fire from late morning on 4th February until the evening of the 5th February (Category 4), as well as afterwards when the forecast dropped to Category 3.

In comparison, the FFDI (McArthur) forecast High to Very High conditions throughout the fire's progression, peaking at 35 during time period 5 on 5th February, suggesting that mostly parallel attack would have been successful with crown fires occurring and direct attack too dangerous at the upper range (Department of Parks and Wildlife 2017). Operational staff have estimated that the fire danger was better described as Severe to Extreme. By AEMC - National Bushfire Warnings Taskforce (2009) standards, the 'Very High' fire danger rating falls well short of the fire behaviour observed.

Daily FWA

The daily regional NFDRS forecast for the first five days of the fire consistently sat on a Category 4, which is a category lower than issued for the particular point forecasts during the first four days. This is largely due to the fire district (Upper Great Southern) being predominantly made up of 'crop' fuel type (74%) rather than forest (23%) and so largely driven by the grassland fire danger rating.

On the 4th February, the daily regional NFDRS forecast increased to Category 5 at a time when observed fire danger was mostly decreasing, again due to the increases within the grassland predictions. By comparison, the FFDI regional forecasts for the area were in agreement with the point locations (High – Very High), which both under-predicted fire danger based on operational observations of Severe and Extreme.

Acknowledgements

Thanks to Neil Burrows, Drew Griffiths, Peter Gibson, Greg Mair, Michael Pasotti, Anthony Desmond and the team at DBCA for providing information and help assessing the NFDRS forecast.

Related references

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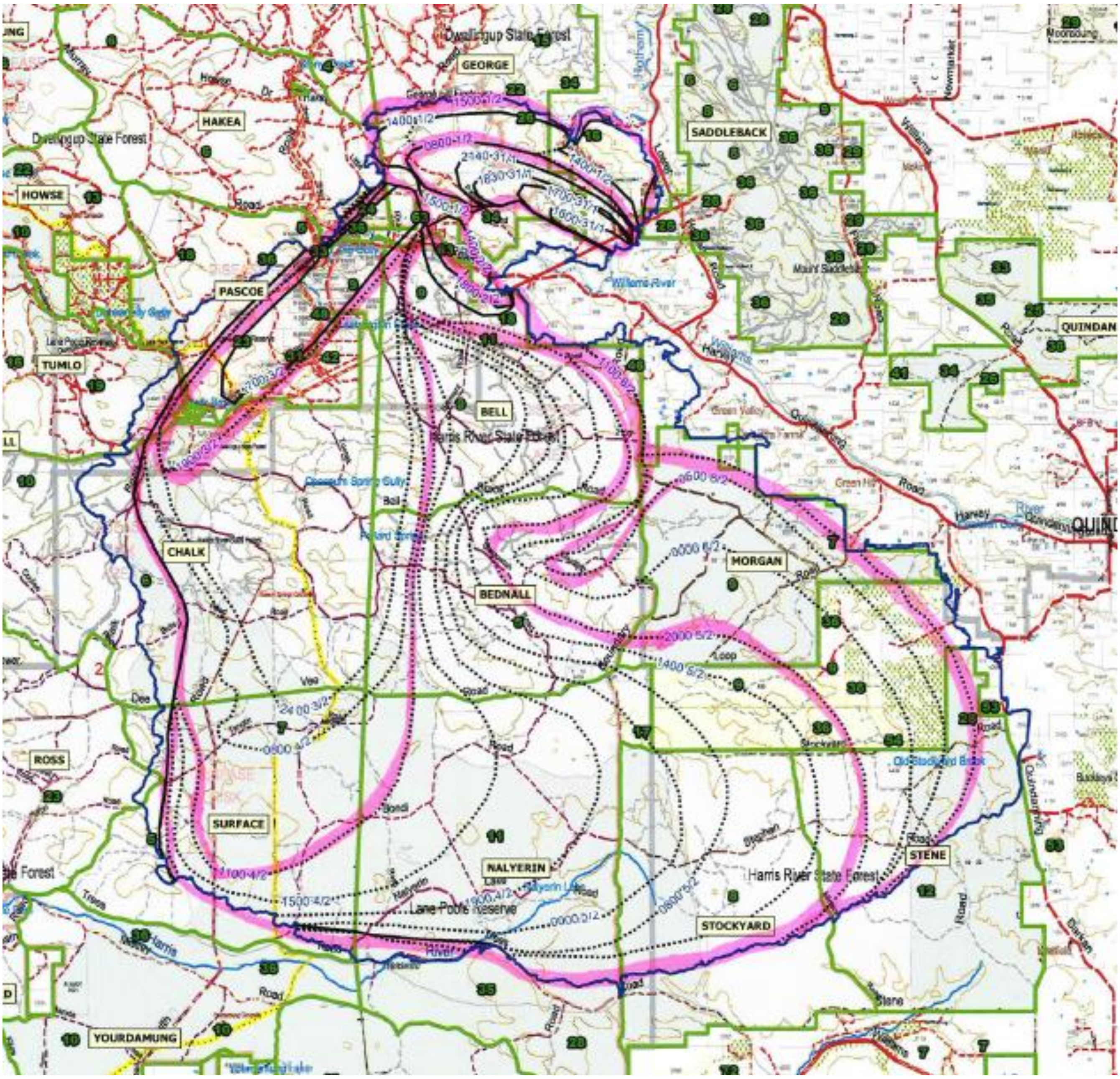

Figure 9.8 Spread map highlighting (in pink) the fire isochrones used to delineate the time periods represented in the case study.

Table 9.4 Summary table of forecasted conditions against observations for the Lower Hotham fire

Incident name: Lower Hotham Fire		Date:	31 January - 6 February, 2015				
		Daily regional FFDI forecast rating:	Very High	High -Very High	Very High	Very High	Very High	Very High - High
		Daily regional NFDRS forecast rating:	4	4	4	4	4-5	5
		C-Haines red flag warning:	*Yes*	*No*	*No*	*Yes*	*Yes*	*No*
		Wind change red flag warning:	*No*	*No*	*No*	*No*	*No*	*No*
Incident details	Time period		1	2	3	4	5	6
	Date		31/01 - 01/02/2015	01/02 - 02/02/2015	02/02 - 03/02/2015	03/02 - 04/02/2015	04/02 - 05/02/2015	05/02 - 06/02/2015
	Time period start		15:25:00	8:00:00	18:00:00	19:00:00	11:00:00	20:00:00
	Time period finish		8:00:00	18:00:00	19:00:00	11:00:00	20:00:00	11:00:00
	Latitude		-32.9479	-32.9631	-33.0167	-33.0945	-33.1268	-33.0364
	Longitude		116.3728	116.36	116.2591	116.2755	116.4485	116.4347
Fuels	Fuel type/s		Grass, Forest	Grass, Forest	Forest	Forest	Forest	Forest
	FDR Table		Forest	Forest	Forest	Forest	Forest	Forest
Fire Danger Rating	FFDI (max)		26	22	29	22	35	10
	GDFI (max)		20	15	16	11	20	6
	Observed (FFDI) FIRE DANGER RATING		Extreme	Extreme	Extreme	Extreme	Severe	Very High
NFDRS forecast	Forecast NFDRS Fire Behaviour Index (max)		133.1	105.5	226.4	38.1	92.4	20
	Forecast NFDRS Fire Danger Rating (max)		5	5	5	3	4	3
	Observed NFDRS FIRE DANGER RATING		5	5	5	5	4	3
Fire behaviour & fire weather	Obs fireline intensity (kW/m)		29,040	1,455	45,227	14,220	7,700	
	Obs mean ROS (m/hr)		145-2,640	900-4,000	1,550-3,692	80-1,580	170-1,285	200-700
	Obs mean flame height (m)		10-20m	10-20m	up to 30m	up to 30m	10-20m	
	Obs spotting distance (m)		spotting observed	4,000-5,000	up to 5,000	short distance		
	Wind change observed (Y/N)		N	N	Y	Y	Y	Y
	Forecast fire behaviour accurate?		Y	Y	Y	No - Under-predict	Y	Y
Fire suppression & containment	Fire suppression (Y/N)		Y	N	Y	Y	Y	Y
	Operational strength in field personnel		16	30	30	45	50	50
	Operational strength in aerial resources		1	1	1	1	1	1
	OFFENSIVE strategies (Y/N)		Y	N	Y		Y	Y
	DEFENSIVE strategies (Y/N)		Y	Y	Y	Y	Y	Y
	Forecast suppression/containment accurate?		Y	Y	Y	No - Under-predict	Y	Y
Consequences	Fire area at end of time period		2,000	4,000	10,000	20,000	41,000	50,000
	Fire perimeter at end of time period		20	28	60	88	125	140
	Houses lost during time period (Number/Y/N)		N	N	N	N	1	N
	Other assets lost during time period (Y/N)		N	Y	N	N	Y	N
	Lives lost during time period (Number/Y/N)		N	N	N	N	N	N
	Infrastructure impacted during time period			Y			Y	
	Forecast consequences accurate?		Y	Y	Y	Y	No - Under-predict	Y

9.6 O’Sullivan fire, Western Australia, January – February 2015

Overview

The O’Sullivan fire (Donnelly Fire 19) in south-west Western Australia, was one of 13 fires ignited by lightning following widespread thunderstorms in late January 2015. Detected in the Shannon National Park on the morning of 30th January 2015 at approximately 0.5 ha, the fire continued to burn over the following 10 days, burning more than 98,600 ha (including 4,506 ha of private land). It was the largest individual fire in the south-west forest region since the Dwellingup fire in January 1961. The fire was particularly complex due to its size and the scale and duration of suppression operations.

Fire behaviour and containment

The fire burnt during dry summer conditions with a Drought Factor of 10 and Mount Soil Dryness Index exceeding 160 mm using Pemberton and Shannon as representative weather observation sites. Throughout the fire, rates of spread up to 1,600 mh^{-1} were observed, accompanied by crowning and flames heights well above the canopy and spotting over 2.5 km ahead of the fire front. At several times, the fire became too intense and unsafe for direct attack and firefighting efforts focussed on the protection of life and property on freehold land. It took fire agencies 10 days to contain the perimeter on 8th February, 2015.

One of the important and interesting features of the O’Sullivan fire was that it was burning in a mixture of tall karri and jarrah/marri forest, much of which had been unburnt for >15 years and carried heavy fuel loads. Because the deep fuel beds in these forests were dry to mineral soil, and fully available to burn, at times there appeared to be an enormous release of heat and energy in the convective column and the fire continued to burn strongly even when the air temperature and relative humidity was quite mild.

Impacts

While no lives were lost, thousands of hectares of forest were burnt by high intensity fire with significant and long-lasting environmental implications on forest productivity and biodiversity (the south-west is recognised as a biodiversity hot spot, one of only 34 hot spots nominated around the world, and the only one in Australia). Four dwellings were lost along with farm fencing, pasture and livestock. The fire also resulted in significant social and economic impacts on the local Northcliffe community and more broadly across the lower south-west, including closure of the South West Highway between Middleton Road and Northcliffe for a period of three weeks.

Figure 9.9 Mature karri forest (LEFT, source: DBCA); 10.30 on 4th January 2015 (MIDDLE); northern flank of the fire burning in dense karri forest at Muirillup Rock in the Boorara-Gardner National Park, 15:16 hr on 1st February 2015 (RIGHT, source: Bob Hagan).

Figure 9.10 Perimeter of the O'Sullivan fire in the evening of 5th February 2015

NFDRS point forecast

Over the following seven days from 30th January, the NFDRS forecast varied from Category 3 to 5 with a peak of Category 5 continuing from Day 2 (31st January) through until 4 days later on 3rd February. In the first 24 hrs, when the fire did not grow appreciably in forest, the NFDRS forecasted maximum was Category 4, however observations were better described by Category 3. This may have been because the fire was burning in forest burnt by prescribed fire 5 years previously and so characterised by relatively moderate fuel loads. There also was some evidence that the fire did not escalate until it burnt into the Shannon River which is unlikely to have burnt during the prescribed fire (i.e. carried older and more flammable vegetation). Over the next 4 days, the forecast maximum was Category 5, which appears to have adequately described fire behaviour and the difficulty experienced containing the fire. This can be particularly seen with the increased usage of defensive property protection and times when ground crews were withdrawn due to safety concerns arising from poor visibility and the inability to work directly on the fire's edge. It's possible that fire behaviour and consequences may have been over-predicted during the day on 1st February (time period 4), however fire behaviour was still described as intense and a strong convection column developed by late afternoon. There was also some discrepancy between the NFDRS forecast and observations when the fire did a major run in heathland and coastal woodland overnight on 3rd February. During this time the forecast (Shrubland) was for Category 3, however the fire behaviour, suppression difficulty and consequences were better described by Category 4 (Shrubland FDR Table). Some of the difference may have been linked to a particularly high atmospheric instability, which was identified by the issue of a red flag warning (C-Haines) for this time period however, further work is required to confirm possible interactions.

The FFDI over the seven days varied from 5 through to 37 (mean = 19) representing fire danger of High to Very High on the post-2009, 6 Category FDR scale. Under these conditions on the pre-2009, 5 category FDR scale where "Very High' is the second highest category recognised by the Department of Parks and

Wildlife (2017), direct or parallel attack with machines is too dangerous except in areas of low fuel with good access and visibility. Indirect attack may be possible provided the back burn can be controlled and is sufficiently deep to capture spot fires. Crown fires are likely at the upper range particularly in heavy fuels. The forecast FFDI tended to underestimate the difficulty of suppression, particularly overnight when fire behaviour remained very intense in heavy, dry fuels despite cooler temperatures and higher relative humidity. Throughout time periods 2 to 8 observed fire behaviour was consistent with the description of Very High difficulty of suppression whereas the forecast FFDI was mostly in the High category.

Daily FWA and Red Flag warnings

Apart from the first and last time periods (i.e. Days 1 and 4), the regional forecast was for NFDRS Category 5 which generally seems to have captured potential fire danger in the region well. For the first and last time periods the regional forecasts were for Category 3, which has also described the fire danger conditions observed accurately during these times. The C-Haines red flag warning was issued over four time periods assessed. The first coincided with the first 24 hrs after detection when the NFDRS forecast was for Category 4. As mentioned above, observations were better captured by Category 3 and the effect of atmospheric instability may not have been evident, possibly due to lighter fuels and heavy forest canopy and didn't grow to a size where it became responsive to atmospheric instability.

The next C-Haines red flags were issued for time periods 3 and 4, which seems to have captured conditions well with the escalation to a Level 3 bushfire, the fire being too intense for direct attack, several spotfires and the development of a convection column mid-afternoon during time period 4. A red flag warning for C-Haines was also issued overnight on 3rd February when the fire did a major run in heathland and coastal woodland, and may explain the difference between the Forecast Category 3 (Shrubland) and an Observed Category 5 for the same time period. It's important to note that the regional forecast for the fire weather area was for a Category 5, which was largely influenced by the higher proportion of forest fuels within that fire weather area. This demonstrates how fire managers may choose to increase the fire danger category as a result of the red flag warning (for example in this case the fire manager could have issued a Category 4, rather than 3).

Throughout the seven days, there were no red flags issued for wind change, which appears to have been appropriate.

Acknowledgements

Thanks to Lachie McCaw and the team at DBCA for providing information and help assessing the NFDRS forecast.

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Table 9.5 Summary table of forecasted conditions against observations for the O'Sullivan fire

Incident name:	O'Sullivan Fire (Northcliffe) Date	30/01/2015	31/05/2015		01/02/2015		02/02/2015	03/02/2015	04/02/2015	05/02/2015
	Daily regional FFDI forecast rating:	High	Very high		High		Very high	Very high	Very high	Low-moderate
	Daily regional NFDRS forecast rating:	3	5		5		5	5	5	3
	C-Haines red flag warning:	*Yes*	*No*		*Yes*		*No*	*Yes*	*No*	*No*
	Wind change red flag warning:	*No*	*No*		*No*		*No*	*No*	*No*	*No*
Incident details	Time period	1	2	3	4	5	6	7	8	9
	Date	30/01 - 31/01/2015	31/01/2015	31/01 - 1/02/2015	1/02/2015	1 - 2/02/2015	2 - 3/02/2015	3 -4/02/2015	4/02/2018	4 - 5/02/2015
	Time period start	9:55:00	8:00:00	18:00:00	8:00:00	18:00:00	6:00:00	20:00:00	8:00:00	20:00:00
	Time period finish	8:00:00	18:00:00	5:00:00	18:00:00	6:00:00	20:00:00	8:00:00	20:00:00	20:00:00
	Latitude	-34.68	-34.67562	-34.68618	-34.65811	-34.71768		-34.74313	-34.73411	
	Longitude	116.38	116.34721	116.30764	116.26378	116.22327		116.06366	116.45394	
Fuels	Fuel type/s	Wet forest, forest	Wet forest, forest	Wet forest, forest	Wet forest, forest	Wet forest, forest and Heathland	Wet forest, forest and Heathland	Heathland, Woodland	Wet forest, forest and Heathland	
	FDR Table	Forest	Forest	Forest	Forest	Forest	Forest	Shrubland	Forest	Forest
Fire Danger Rating	FFDI (max)	14	21	11	19	20	28	15	37	5
	GDFI (max)	11	18	12	14	14	11	9	22	4
	Observed (FFDI) FIRE DANGER RATING	High	Very High	Very High	Very High	Very High	Very High	Very High	Very High	Moderate
NFDRS forecast	Forecast NFDRS Fire Behaviour Index (max)	64.5	171.6	105.2	154.7	155.1	156.6	16.3	288	36.9
	Forecast NFDRS Fire Danger Rating (max)	4	5	5	5	5	5	3	5	3
	Observed NFDRS FIRE DANGER RATING	3	5	5	4	5	5	5	5	3
Fire behaviour & fire weather	Obs fireline intensity (kW/m)									
	Obs mean ROS (m/hr)	<100	650	550	460	1,000	Rapid	1,600	1,000	
	Obs mean flame height (m)			15-20		>40	>40			
	Obs spotting distance (m)		Spotting observed	Up to 2,800						
	Wind change observed (Y/N)									
	Forecast fire behaviour accurate?	Over-predicted	Y	Y	Over-predicted	Y	Y	Under-predicted	Y	Y
Fire suppression & containment	Fire suppression (Y/N)	Y	Y	Y	Y	Y	Y	Y	Y	Y
	Operational strength in field personnel	Approx.. 12								
	Operational strength in aerial resources	Y. 2 water bombers	Y							
	OFFENSIVE strategies (Y/N)	Y	Y	Y	Y	Y	Y	Y	Y	Y
	DEFENSIVE strategies (Y/N)	N	N	Y	Y	Y	Y	Y	Y	
	Forecast suppression/containment accurate?	Y	Y	Y	Y	Y	Y	Under-predicted	Y	Y
Consequences	Fire area at end of time period	4	200	2,491			17,224		32,365	79,862
	Fire perimeter at end of time period						101		164	299
	Houses lost during time period (Number/Y/N)	N	N	N	N	Y	N	Y	N	N
	Other assets lost during time period (Y/N)	N					Y			
	Lives lost during time period (Number/Y/N)	N	N	N	N	N	N	N	N	N
	Infrastructure impacted during time period	N		Y			Y	Y	Y	Y
	Forecast consequences accurate?	Y	Over-predicted	Over-predicted	Over-predicted	Y	Y	Under-predicted	Y	Y

9.7 Cascade fire, Western Australia, November 2015

Overview

The Cascade fire started on the 15th of November 2015, after a trough system moved through the region accompanied with thunderstorms and lightning. Hot and dry conditions leading up to this weather event led to a high level of fire activity across the southern part of WA, of which 10 fires occurred in the Shire of Esperance area.

After two days of relatively slow and steady fire spread through mallee heath in Unallocated Crown Land, the Cascade fire escalated under catastrophic fire conditions on the 17th of November. The fire burned in a SE direction, through mostly unharvested and fully cured crops (grain). During its major run, the fire spread ~70 km within 5 hours, averaging 14 km h^{-1}. With estimated fireline intensities of up to 45,000 kW m^{-1}, the Cascade fire is thought to be the hottest grassland fire ever recorded in WA, and possibly Australia.

Next to the loss and damage of properties and infrastructure, as well as the economic impact on the agricultural community, most sadly 4 people lost their lives on November 17th. Three of them were trying to flee the fire, while one of them was trying to warn the neighbours.

Conditions leading up to the fire

In 2015, the winter rainfall was above average, which led to rapid growth of the crops. Followed by a very warm dry spring (Figure 9.11), the crops were fully cured (~5 tha^{-1}, 100% cured). On average, about 40-50% of the yield was harvested at the time of the fires.

Approximately 40 fires started by lightning strikes across the southern part of WA over the weekend of 14-15 November. On top of ~40 prescribed burns from the prior week, there was a high level of fire activity in the landscape (Figure 9.11). This meant that there was a real competition for resources, and fire crews were fatigued. With the upcoming predicted catastrophic conditions, resources were allocated to the more densely populated areas (Perth and SW of the state) and to fires which posed a high risk to life and property.

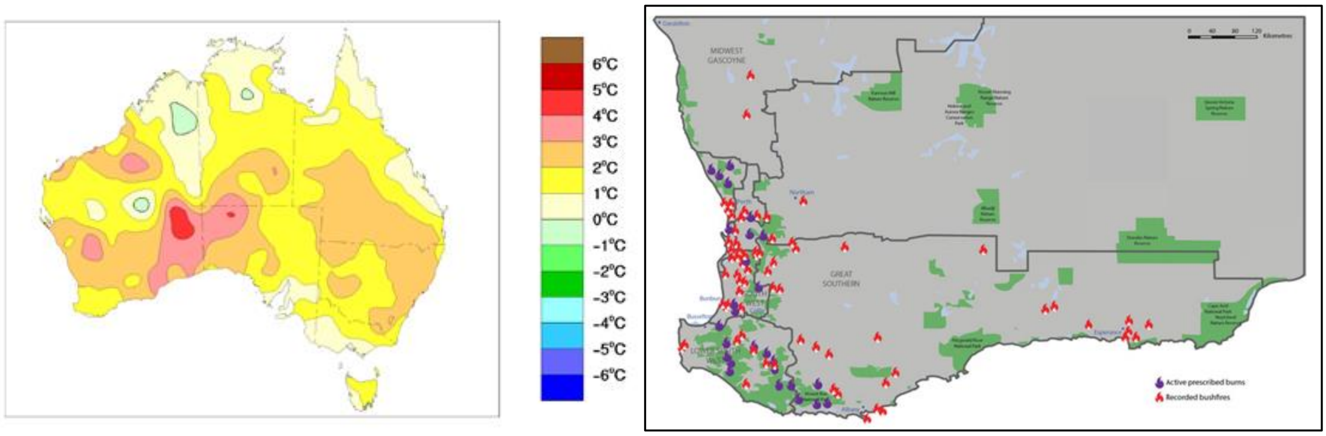

Figure 9.11 Anomalies of mean daily minimum temperature in November 2015 (LEFT, source: monthly weather review, Bureau of meteorology 2015); Active bushfires and prescribed burns across WA on 15 November 2015 (RIGHT), based on data from DFES and P&W records, Nous Group report 2016.

Fire behaviour and containment

While the fire was slowly growing under benign conditions on November 15th and 16th, crews and farmers used machines, scrub rolling and crop harvesting to contain the fire. It is unknown if there was any direct attack. The IMT set up in Esperance, was under-resourced with only 3 (later 4) people. In combination with subsequent power outages and lack of radio communication, there was no good information on fire behaviour (e.g. isochrones) available, and no good records on crew strength and suppression activities.

Figure 9.12 Fire scar through unharvested crops (LEFT) and the fire front approaching Scaddan, 17 November 2015 (RIGHT). Source: AAP www.perthnow.com.au

The remoteness of the area and the difficult terrain proved to be challenging for fire suppression, with one machine being bogged in the lake system. With the forecasted catastrophic fire conditions for the 17th of November, a bushfire advice alert was given and a Total Fire Ban declared from midnight onward. Additional external resources were requested but not allocated to the Esperance region, because of anticipated fire risks in other areas of the state.

On November 17th, fire behaviour in the mallee picked up in the morning (avg ROS 6000 m h^{-1}; reported spotting 200-400 m). Around 11:00, a 5 km fire front reached the farmlands. Under catastrophic fire conditions (42°C, 3.5% RH, wind speeds of 50-60 km h^{-1} (NW), gusting 70-80 km h^{-1}) the fire behaviour escalated quickly, and travelled ~70 km within 5 hours at the peak of the day (between 12:00 and 17:00). Direct fire suppression strategies under these conditions were not possible. Watch and Act and later Emergency warnings were given, and evacuations were undertaken from Salmon Gums and Grass Patch. Around 15:50, four people lost their lives when they were overrun by the fire on Griggs Road. After 17:00 there was a sudden SW wind change. This led to an abrupt increase in RH (up to 65% by 19:00) and drop in temperature (down to 20°C by 19:00). The winds eased to 20-30 km h^{-1}. The final size of the fire is 128,000 ha.

Due to the overwhelming nature of this fire, and under-resourcement of the IMT, no exact numbers of responding crews or suppression activities are available. No aerial resources were available for this fire, because they were deployed somewhere else. After the fire escalated badly, external resources were made available and containment effort continued 18 – 24 November.

Impacts

Four people lost their lives in this fire. The fire burned through farmland and destroyed approximately 30,000 ha of crops. An estimated 500,000 tonnes of grain were lost. 4,500 head of livestock died. The Scaddan town hall, 16 non-residential structures, 1 house and dozens of vehicles were destroyed. The Coolgardie-Esperance highway and powerlines were impacted, while the rail line, a gas pipeline and 3 public schools were at risk. The economic loss to the region is estimated to exceed 150 million dollars.

NFDRS point forecast

The NFDRS forecast for the specified timeframes (Table 9.6) did not always match up with observations from the fireground. For the first time step (15-17 November), the NFDRS predicted a Category 1 (mostly self-extinguishing) fire, while the observed fire behaviour and consequences match Category 2 instead. During the build-up phase, in the morning of the 17th, the NFDR forecast resembled the conditions as experienced on the fire ground. In the early afternoon, the NFDRS might have been over-predicting for that specific time period (11:40 – 13:20), with the ROS and consequences slightly lower than in the NFDR table, but this is open to interpretation. At the peak of the fire, the forecast and observed conditions were catastrophic, at the highest category of fire danger. Wind gusts exceeding 90 km h^{-1} combined with the hot dry wind led to catastrophic fire behaviour. This made fire suppression impossible and evacuating was the only option.

The forecasted GFDI's were well and truly into the extreme and catastrophic category, but the conditions that day (observed GFDI of 222) are possibly the worst possible fire weather conditions ever experienced in Australia.

After the abrupt wind change (~17:00), the NFDRS over-predicted. Winds eased, temperatures decreased and relative humidity increased. This sudden change was not forecasted until later in the evening.

Daily FWA and Red Flag warnings

The regional forecasted fire danger indices (FFDI/GFDI) on November 17th were for catastrophic conditions, and these certainly eventuated. A total fire ban and emergency warnings were in place. Even so, everyone was overwhelmed when the Cascade fire escalated. The *regional* forecasted NFDRS rating was 5, although the rating at the peak of the day for the Cascade fire was 6. This makes sense, given that the regional maximum forecast is calculated based on the 90th percentile of the grids, for a far larger area than the specific area where the fire occurred. A C-Haines red flag warning was in place for November 17th. This seems reasonable, although we do not have any reports of PyroCb events. There was a wind change red flag warning in place, and this wind change indeed occurred, although earlier than expected.

Related references

Burrows, N. (2015) Fuels, Weather and Behaviour of the Cascade Fire (Esperance Fire #6), 15-17 November 2015. Science and Conservation Division. Department of Parks and Wildlife.

Nous group (2016) Major Incident Review of the Esperance district fires. Department of Fire and emergency Services.

Cascade Scaddan Fire Review Ltd (2016), written report by Pacer Legal Pty Ltd.

Table 9.6 Summary table of forecasted conditions against observations for the Cascade fire

	Incident name:	Cascade Fire				
	Date:	15/11/2015	16/11/2015	17/11/2015		
	Daily regional FFDI forecast rating:	Very High	High	Catastrophic		
	Daily regional NFDRS forecast rating:	4	3	5		
	C-Haines red flag warning:			*Yes*		
	Wind change red flag warning:	*No*	*No*	*Yes*		
Incident details	Time period	1	2	3	4	5
	Date	15-17 November 2015	17/11/2015	17/11/2015	17/11/2015	17/11/2015
	Time period start	15/11/2015 9:30	17/11/2015 10:50	17/11/2015 11:40	17/11/2015 13:20	17/11/2015 17:50
	Time period finish	17/11/2015 10:50	17/11/2015 11:40	17/11/2015 13:20	17/11/2015 17:50	17/11/2015 19:00
	Latitude	-33.117	-33.13	-33.161	-33.23	-33.319
	Longitude	121.023	121.06	121.109	121.21	121.793
Fuels	Fuel type	Mallee heath	Mallee heath	Crop	Crop	Crop
	FDR Table	Mallee heath	Mallee heath	Grassland	Grassland	Grassland
Fire Danger Rating	FFDI (max)	34	33	81	97	45
	GDFI (max)	25	18	83	121	39
NFDRS forecast	Forecast NFDRS Fire Behaviour Index (max)	0	80	176	207	114
	Forecast NFDRS Fire Danger Rating (max)	1	4	6	6	5
	Observed NFDRS FIRE DANGER RATING	2	4	5	6	3
Fire behaviour & fire weather	Obs fireline intensity (kW/m)			36,000	40,000	
	Obs mean ROS (m/hr)	slow but steady, convoluted	6,000	7,700	14,000	
	Obs mean flame height (m)		1.5-2	1.5-2	1.5-2, flaring to 7	
	Obs spotting distance (m)		200-400	> 100	> 100	
	Wind change observed (Y/N)	N	Y	N	N	Y
	Forecast fire behaviour accurate?	No - Under-predicted	Y	No - Over-predicted	Y	No - Over-predicted
Fire suppression & containment	Fire suppression (Y/N)	Y	Y	Y?	N, not possible	Y
	Operational strength in field personnel	Local brigades, DFES and P&W (numbers unknown). 4 IMT personnel.				
	Operational strength in aerial resources	None	None available	None available	N, not possible	requested
	OFFENSIVE strategies (Y/N)	Y	Y	Y	Y	Y
	DEFENSIVE strategies (Y/N)	Y	Y	Y	Y	Y
	Forecast suppression/containment accurate?	No - Under-predicted	Y	Y	Y	No - Over-predicted
Consequences	Fire area at end of time period	1,100	3,850	11,800	128,000	128,000
	Fire perimeter at end of time period				315	315
	Houses lost during time period (Number/Y/N)	N	N	Y	Y	N
	Other assets lost during time period (Y/N)	N	N	Y	Y	Y
	Lives lost during time period (Number/Y/N)	N	N	N	4	N
	Infrastructure impacted during time period	N	N	Y	Y	Y
	Forecast consequences accurate?	No - Under-predicted	Y	No - Over-predicted	Y	No - Over-predicted

9.8 Pinery fire, South Australia, November 2015

Overview

Hot and very dry conditions with strong and gusty winds affected much of South Australia on November 25th 2015, leading to dangerous fire weather. Several fires occurred but the most serious was the Pinery fire in the Mid North district to the north of Adelaide. The fire danger rating was forecast as Extreme for the Mid North, but observed conditions reached a Catastrophic rating.

Figure 9.13 Pinery fire (LEFT, source: Zimmerman (2017)) and Pinery fire impact north of Mallala (RIGHT, source: Adelaide Now © Dylan Coker).

Fire behaviour and containment

The Pinery fire was reported at 12:05 on November 25th 2015 and was assessed on arrival as already beyond initial suppression capability, having rapidly covered 200 hectares with 10 m flame heights. The fire occurred in a grain growing area where harvesting had commenced, burning through a mix of standing crops and retained stubble.

The first run was nearly 50 km in a south easterly direction with spotting reported one to two kilometres ahead of the fire-front. The wind shifted around 3 pm turning the flank into a long fire front heading north east. By about 1800 hours winds had eased, at which time suppression became practical and the fire was largely contained. The total area burnt was about 82,500 hectares, nearly all of it within the first six hours.

During the peak of the fire at least 340 personnel, 73 tankers and 9 aircraft were involved in suppression. The Pinery fire was the first time that the VLAT was deployed in South Australia. The Pinery fire was declared contained on 27 November and controlled on 1 December. Over the course of the fire many SA Country Fire Services (CFS) resources were involved including more than 1,000 CFS volunteers, staff, farm fire units and hundreds of vehicles, supported by SA Metropolitan Fire Service, SA State Emergency Service and more than 300 fire fighters from Victoria plus aircraft from New South Wales.

Impacts

The first Emergency Warning was issued at 12:27 and the Mallala area was the first to be impacted from 12:45. Other areas with significant impact were Owen, Hamley Bridge, Wasleys, Kapunda, Freeling, Tarlee and Greenock. There were 2 fatalities during the peak of the fire. There were also 31 injuries, including 5 severe injuries, and 3 fire crew burn-overs reported.

Property damage and stock losses were extensive. 97 houses were destroyed and 49 damaged; 580 sheds / outbuildings were destroyed or damaged; 413 vehicles / machinery were destroyed or damaged. Confirmed agricultural losses included 18,000 sheep, 600 other stock, 54,000 poultry, $30 million in crops, hay and straw. Infrastructure impacts included power outages and multiple road closures (including 3 main highways). Schools were evacuated and remained closed for a few days. Multiple relief centres were established.

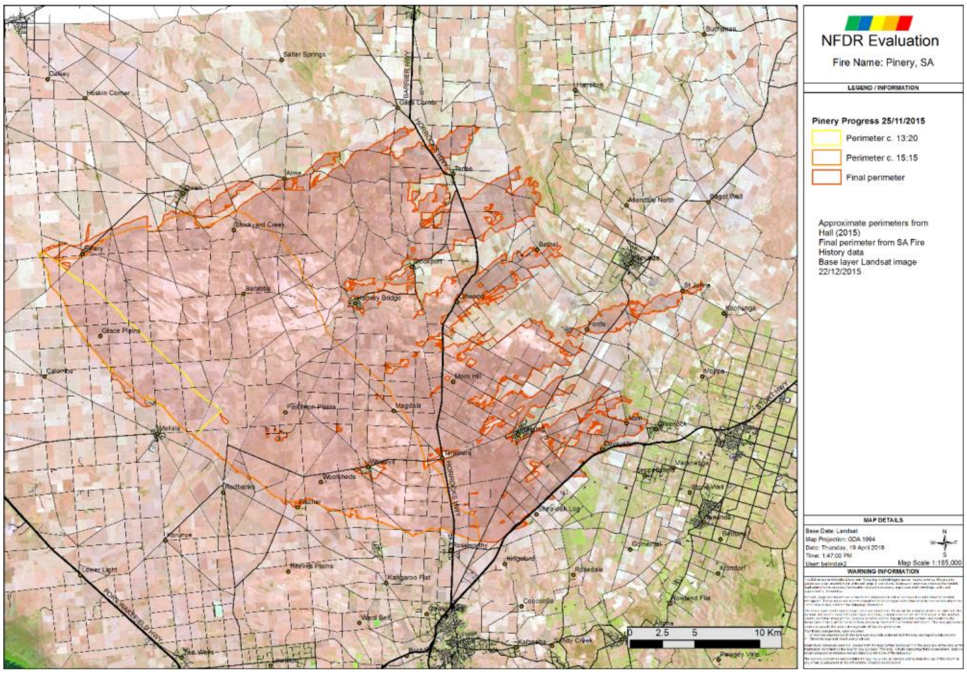

Figure 9.14 Fire spread map for Pinery. Data from Hall (2015), DEWNR fire history, Landsat.

NFDRS forecast

The daily regional forecast (based on GFDI) for the Mid North district was Extreme and a Total Fire Ban had been declared. The conditions reported on the fire-ground and the observations at Roseworthy AWS (on the southern edge of the main fire run) reached Catastrophic. The daily regional forecast calculated by the NFDRS was for Category 6.

The fire danger for the day peaked during the first 3 hour run of the fire. The forecast near the ignition location at Pinery gave a NFDRS Category 6, while the GFDI peaked at just over 100 (Extreme) before dropping back into Severe. The observed wind speed during this period (at Roseworthy AWS) was higher than forecast, leading to calculated GFDI values in Extreme and Catastrophic (and NFDRS Category 6). From the observed fire behaviour and consequences, the Category 6 rating was appropriate, as would have been a Catastrophic rating.

The second run of the fire was after the wind shift which saw a rapid rise in the relative humidity. The forecast near Templers was still in a NFDRS Category 6 for 1 hour before dropping to 5 then 4; GFDI for this time period dropped from Severe to Very High. From the observed fire behaviour the Category 6 was an over prediction, though the suppression effort and consequences were still significant during this period. The rating was down to a Category 4 by the time the suppression efforts managed to halt the forward progress of the fire.

The red flag warnings indicated instability and a wind change. The wind change experienced was from NNW to WSW, appearing in the AWS observations as a gradual shift between 13:00 and 15:00.

Acknowledgements

Thanks to Simeon Telfer (SA DEWNR) for provision of information and revision of this summary.

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Zimmermann, A (2017) Pinery fire recovery final report. Local Recovery Coordinator. Department for Communities and Social Inclusion

Table 9.7 Summary table of forecasted conditions against observations for the Pinery fire

Incident name:	Pinery
Date:	25/11/2015
Daily regional FFDI forecast rating:	Extreme
Daily regional NFDRS forecast rating:	6
C-Haines red flag warning:	*Yes*
Wind change red flag warning:	*Yes*

Incident details	Time period	1	2
	Date	25/11/2015	25/11/2015
	Time period start	12:05:00	15:15:00
	Time period finish	15:15:00	18:00:00
	Latitude	-34.33	-34.45
	Longitude	138.45	138.74
Fuels	Fuel type/s	Crop	Crop
	FDR Table	Grassland	Grassland
Fire Danger Rating	FFDI (max)	87	72
	GDFI (max)	106	88
NFDRS forecast	Forecast NFDRS Fire Behaviour Index (max)	184	167
	Forecast NFDRS Fire Danger Rating (max)	6	6
	Observed NFDRS FIRE DANGER RATING	6	5
Fire behaviour & fire weather	Obs fireline intensity (kW/m)		
	Obs mean ROS (m/hr)	13,000	5,000
	Obs mean flame height (m)	10	
	Obs spotting distance (m)	1000	Yes
	Wind change observed (Y/N)	Yes	No
	Forecast fire behaviour accurate?	Yes	No – Over-predicted
Fire suppression & containment	Fire suppression (Y/N)	Yes	Yes
	Operational strength in field personnel	340	340
	Operational strength in aerial resources	7	9
	OFFENSIVE strategies (Y/N)	Yes	Yes
	DEFENSIVE strategies (Y/N)	Yes	Yes
	Forecast suppression/containment accurate?	Yes	Yes
Consequences	Fire area at end of time period	39,700	78,260
	Fire perimeter at end of time period	97	850
	Houses lost during time period (Number/Y/N)	54	43
	Other assets lost during time period (Y/N)	Yes	Yes
	Lives lost during time period (Number/Y/N)	2	No
	Infrastructure impacted during time period (Y/N)	Yes	Yes
	Forecast consequences accurate?	Yes	Yes

9.9 Beecroft Peninsula fire, New South Wales, November 2015

Overview

The Shoalhaven region of NSW has current fire danger ratings set by FFDI. The region contains some large areas of heathland, particularly around Jervis Bay. The weather on the 26th of November 2015 was considered mostly benign, with a regional fire danger rating of Very High. Medium to strong north-westerly winds and a southerly change were forecast.

Fire behaviour and containment

The Beecroft Peninsula fire started in heathland on the Beecroft Peninsula at 11:42 on 26th November 2015. The fire burned eastward until a wind change at 14:55 pushed the fire northwards towards the township of Currarong. The fire behaved as a wind driven heath fire with relatively low sensitivity to the rise in humidity behind the change.

Because the fire was burning in an artillery range (Beecroft Weapons Range under the control of the Department of Defence) no suppression was attempted during the early stages of the fire. The LAT and VLAT made multiple drops to build a retardant line in an east-west direction along a fire trail (Track 8) to the south of Currarong. Ground crews only entered the fire-ground in the evening to commence back burning and mopping up along identified trails.

During the fire's main northerly run the average ROS was 1,750 mh^{-1} and it jumped three wide fire trails. The fire slowed after crossing Track 11 and entering an area burnt in 2010. The fire's forward progression was halted on Track 8, a fire trail with wide slashed verges, multiple retardant lines, and active water bombing. The area to the north of Track 8 had been burnt in 2014.

The fire was declared contained on 29th November and out on 2nd December. The total area burned was 801 hectares, 260 ha in the initial run on the 26th, with a significant area of back burning conducted on subsequent days.

Impacts

Strike teams were deployed to Curragong on standby for property protection, but were not required. There were no assets or infrastructure impacted by the fire, with only minor disruptions in Curragong.

Figure 9.15 Extent of the initial easterly run. Photo taken c. 13:30 (LEFT); Extent of the main fire run after the wind change; northern extent is retardant line at Track 8. Linesscan taken at 16:45 (RIGHT).

NFDRS forecast

The Beecroft Peninsula fire provides a good example of a forecast (moderate drought factor, high humidity, but high wind speed) that was mild by FFDI standards (maximum for the location was in High, dropping into Low-Moderate after the wind change) but had significant heath fire potential (NFDRS Shrubland Category 4-5).

The NFDRS forecast (Category 5) was an over prediction for the first time step while the fire was developing under the original westerly wind. The assumed ROS of 500 mh^{-1} puts the observation into a Category 3 or 4, though the actual ROS may have been higher. This was estimated from the extent shown on the linescan taken at 13:42, by which time the fire had already reached its maximum possible easterly extent.

The forecast and observed NFDRS ratings matched well after the wind change, peaking at a Category 5 when the fire was most intense. At this point the FFDI had dropped to 3 (Low-Moderate) due to the increased humidity. The NFDRS forecast drop to a Category 4 at 16:00 was based on the reduced time since fire beyond Track 11, and this was also seen in the reduced fire behaviour and ability to pull the fire up on Track 8 with suppression assistance.

The red flag warnings indicated both a wind change (which occurred and significantly increased the ROS and size of the fire) and instability.

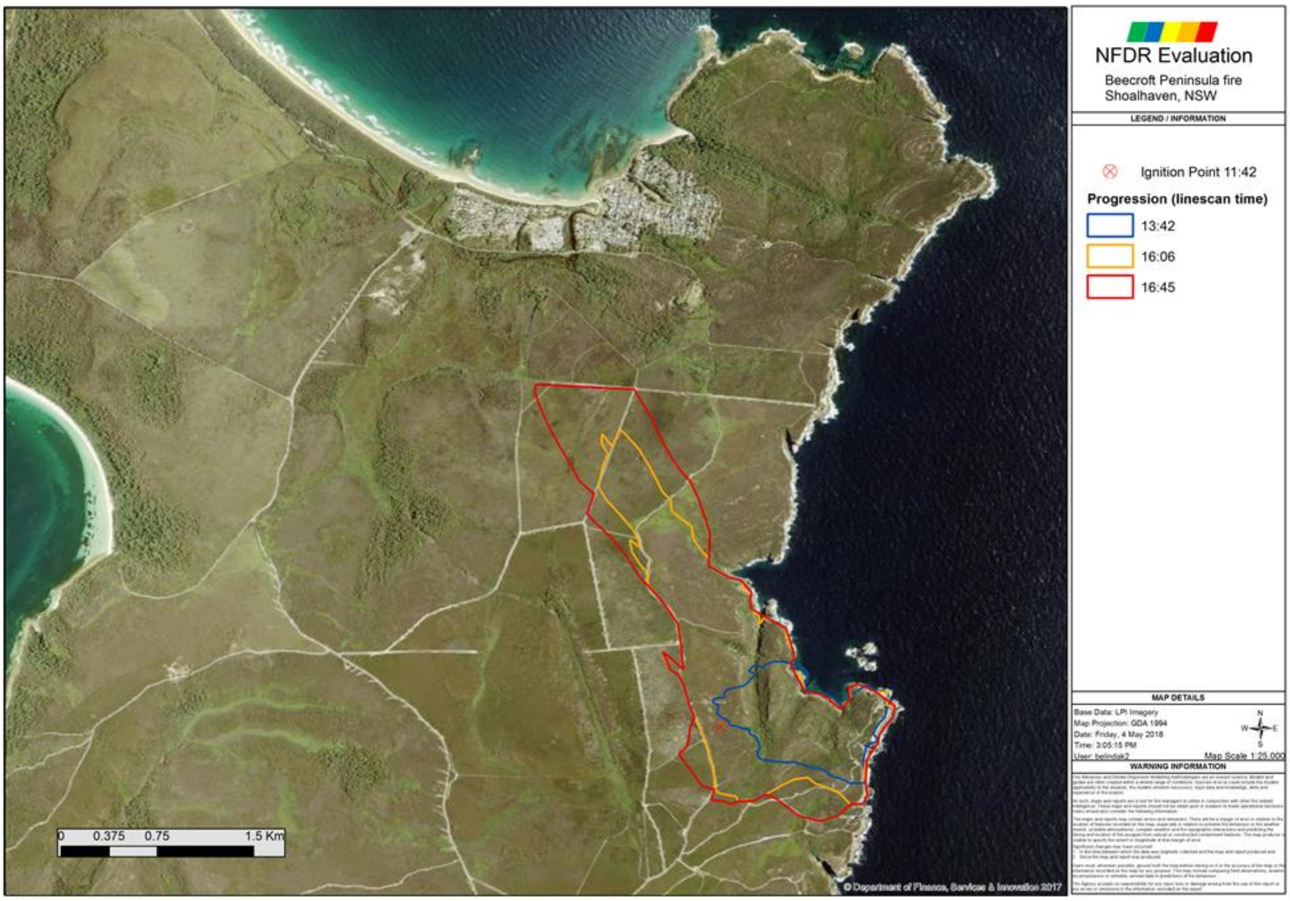

Figure 9.16 Spread map of the Beecroft Peninsula fire

References

Data, maps and images were acquired from NSW Rural Fire Service ICON system and internal reports.

Table 9.8 Summary table of forecasted conditions against observations for the Beecroft Peninsula fire

Incident name:	Beecroft Peninsula
Date:	26/11/2015
Daily regional FFDI forecast rating:	Very High
Daily regional NFDRS forecast rating:	5
C-Haines red flag warning:	*Y*
Wind change red flag warning:	*Y*

Incident details	Time period	1	2	3
	Date	26/11/2015	26/11/2015	26/11/2015
	Time period start	11:42:00	14:55:00	16:06:00
	Time period finish	13:42:00	16:06:00	16:45:00
	Latitude	-35.05	-35.045	-35.03
	Longitude	150.835	150.83	150.82
Fuels	Fuel type/s	Heath	Heath	Heath
	FDR Table	Shrubland	Shrubland	Shrubland
Fire Danger Rating	FFDI (max)	20	3	5
	GDFI (max)	0	0	0
	Observed	Very High	Severe	Very High
NFDRS forecast	Forecast NFDRS Fire Behaviour Index (max)	380	180	60
	Forecast NFDRS Fire Danger Rating (max)	5	5	4
	Observed NFDRS FIRE DANGER RATING	3	5	4
Fire behaviour & fire weather	Obs fireline intensity (kW/m)			
	Obs mean ROS (m/hr)	500	1,750	650
	Obs mean flame height (m)			
	Obs spotting distance (m)		>20?	
	Wind change observed (Y/N)	N	Y	N
	Forecast fire behaviour accurate?	No – Over-predicted	Y	Y
Fire suppression & containment	Fire suppression (Y/N)	Y	Y	Y
	Operational strength in field personnel	50	86	86
	Operational strength in aerial resources	0	4	6
	OFFENSIVE strategies (Y/N)	N	N	Y
	DEFENSIVE strategies (Y/N)	Y	Y	Y
	Forecast suppression/containment accurate?	No – Over-predicted	Y	Y
Consequences	Fire area at end of time period	60	185	260
	Fire perimeter at end of time period	3.9	9.2	10.2
	Houses lost during time period (Number/Y/N)	N	N	N
	Other assets lost during time period (Y/N)	N	N	N
	Lives lost during time period (Number/Y/N)	N	N	N
	Infrastructure impacted during time period (Y/N)	N	N	N
	Forecast consequences accurate?	No – Over-predicted	No – Over-predicted	No – Over-predicted

9.10 Waroona fire, Western Australia, December 2016

Overview

The Waroona fire was ignited by a lightning strike on the evening of 5th December 2016 in forest in south-west Western Australia. Over the next two days the fire burned to the coast through a mix of forested and agricultural land to reach a final size of almost 70,000 ha. Pyro-convective events on 6th and 7th December escalated fire behaviour well above what would be expected based on surface conditions alone, combined with extensive spotting.

On Thursday evening the fire impacted the town of Yarloop resulting in 2 deaths and the loss of 166 properties. The Waroona fire was the second largest fire in SW WA since the 1961 Dwellingup fire and one of the most destructive.

Fire behaviour and containment

The Waroona fire burned in a mix of fuels including forests, agricultural land and coast heath and forest vegetation. On both days the fire burned fiercely in forests with intensity up to 22,000 kWm^{-1} and rates of spread over 2,000 mh^{-1} accompanied by crowning and spotting. A notable feature of this fire was the development of pyro-convection on both days, which contributed to the extremity of the fire behaviour, well in excess of what would be predicted on the basis of forecast surface conditions. Meteorological aspects of the fire have been the subject of much research, see e.g. Peace et al. (2017).

Figure 9.17 Pyro-cumulonimbus cloud visible at 19:34 hr on 6th January from Dwellingup, about 19 km north of the headfire position at that time (LEFT, Photo: Allan Clarke, Parks & Wildlife Dwellingup) and jarrah forest defoliated by crown fire north of Driver Rd at Willowdale during later morning on 7 February (RIGHT) both photos sourced from McCaw et al. (2016).

Impacts

The Waroona fire was one of the most destructive in recent history. The fire destroyed 181 properties, 166 in Yarloop, and resulted in the loss of two lives. It also destroyed many thousands of hectares of farmland and commercial forestry as well as causing significant damage to the electricity and road networks. Total cost including the suppression response and damage caused by the fire was estimated to be $155M.

NFDRS point forecast

The NFDRS rating peaked at Category 5 on the afternoon of the 6th and remained at Category 5 throughout the night and the day of the 7th, dropping to Category 4 in the evening of the 7th. For the majority of both days the Category 5 rating was appropriate except for the times of the pyro-convective events. These events are important misses for the NFDRS system as it forecast only Category 4 at the time the fire impacted Yarloop with devastating consequences.

FFDI was in the High or low end of the Very High range throughout the 6th and 7th, peaking at 30 on both days. This was a significant underestimate of fire danger at all times except in the very early stages of the development of the fire.

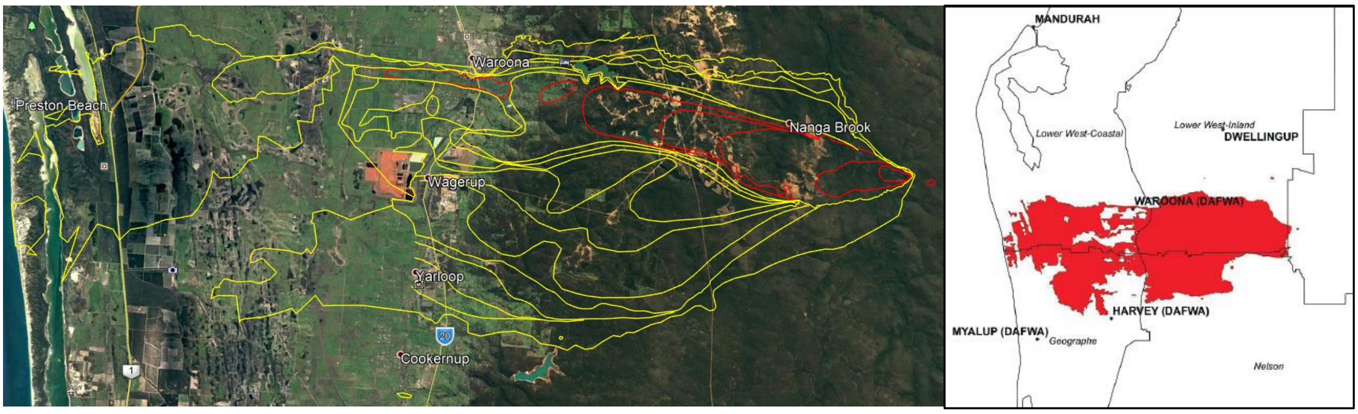

Figure 9.18 Spread map for the Waroona fire on 6th (red) and 7th (yellow) January 2016. Data supplied by Department of Biodiversity, Conservation and Attractions, WA (LEFT). Final burned area (red) and Bureau of Meteorology fire weather areas (*italic* text) (source: Bureau of Meteorology (2016)) (RIGHT)

Daily FWA and Red Flag warnings

The Waroona fire spanned four fire weather areas. For both 6th and 7th December the area ratings for the current system was High or Very high, greatly underestimating the behaviour and consequences of the fire. NFDRS area ratings were Category 5 on both days for the Geographe, Nelson, and Lower West-Inland areas; Category 4 for the Lower West-Coastal area. This was also an under-forecast, likely due to the Research Prototype not including the effects of instability and pyro-convective potential in the rating calculation.

Acknowledgements

Thanks to Lachie McCaw, Neil Burrows, and Mika Peace for making investigations into the Waroona fire available to us.

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Table 9.9 Summary table of forecasted conditions against observations for the Waroona fire

		1	2	3	4	5	6	7	8	9a	9b
	Incident name:	Waroona									
	Date:	6/01/2016					7/01/2016				
	Daily regional FFDI forecast rating:	High					Very high				
	Daily regional NFDRS forecast rating:	Category 5					Category 5				
	C-Haines red flag warning:	Yes					Yes				
	Wind change red flag warning:	No					Yes				
	Time period	1	2	3	4	5	6	7	8	9a	9b
Incident details	Date	6/01/2016	6/01/2016	6/01/2016	6/01/2016	6/01/2016	6/01/2016	7/01/2016	7/01/2016	7/01/2016	7/01/2016
	Time period start	6:30:00	13:30:00	14:50:00	18:00:00	19:00:00	23:00:00	9:30:00	13:30:00	18:30:00	18:30:00
	Time period finish	13:30:00	14:50:00	18:00:00	19:00:00	23:00:00	9:30:00	13:30:00	18:30:00	23:59:00	23:59:00
	Latitude	-32.888	-32.895	-32.899	-32.881	-32.886	-32.899	-32.928	-32.939	-32.9498	-32.9498
	Longitude	116.147	116.141	116.128	116.084	116.02	115.988	115.935	115.925	115.927	115.9421
Fuels	Fuel type/s	Forest	Forest	Forest	Forest	Forest	Forest	Forest	Forest	Grass	Forest
	FDR Table	Forest	Forest	Forest	Forest	Forest	Forest	Forest	Forest	Grass	Forest
Fire Danger Rating	FFDI (max)	22	28	30	24	20	23	21	30	20	22
	GDFI (max)	13	15	18	21	18	27	26	17	8	9
	Observed McArthur fire danger rating	Very high	Severe	Severe	Extreme	Severe		Severe	Very high	Severe	Catastrophic
NFDRS forecast	Forecast NFDRS Fire Behaviour Index (max)	79	110	130	118	108	142	136	138	40	60
	Forecast NFDRS Fire Danger Rating (max)	4	5	5	5	5	5	5	5	3	4
	Observed NFDRS FIRE DANGER RATING	3	5	5	6	5		5	4	4	6
Fire behaviour & fire weather	Obs fireline intensity (kW/m)		12,155	14,530		22,000		16,500		2,764	22,000
	Obs mean ROS (m/hr)		1,105	1,320	3,272	2,000		1,500	reduced	3,566	2,000
	Obs mean flame height (m)				Crown	Some crowning		Crown	Scorch		Crown
	Obs spotting distance (m)					Long					Mass
	Wind change observed (Y/N)										
	Forecast fire behaviour accurate?	Over-predicted	Under-predicted	Yes	Under-predicted	Yes		Yes	Yes	Under-predicted	Under-predicted
Fire suppression & containment	Fire suppression (Y/N)	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	Operational strength in field personnel	27		60			175	391	391		
	Operational strength in aerial resources	9	9	9	9	9	11	11	11	11	11
	OFFENSIVE strategies (Y/N)										
	DEFENSIVE strategies (Y/N)			Y	Y	Y				Y	Y
	Forecast suppression/containment accurate?										
Consequences	Fire area at end of time period	160		800	2,800		12,000			69,165	69,165
	Fire perimeter at end of time period										
	Houses lost during time period (Number/Y/N)	N	N							Y	Y
	Other assets lost during time period (Y/N)	N	Y	Y	Y	Y	Y	Y	Y	Y	Y
	Lives lost during time period (Number/Y/N)	N	N	N	N	N	N	N	N	Y	Y
	Infrastructure impacted during time period (Y/N)	Power, telecommunication, mine, and road infrastructure, times not clear									
	Forecast consequences accurate?									Under-predicted	Under-predicted

9.11 Sir Ivan fire, New South Wales, February 2017

Overview

January and February 2017 saw 3 distinct heatwaves in southeast Australia, the worst over 9-12th February. A state-wide Total Fire Ban was declared for the weekend of 11-12th February, with Catastrophic fire danger forecast for 3 fire weather areas on Sunday 12th (North Western, Central Ranges, Greater Hunter).

Fire behaviour and containment

At 12:20 on Saturday 12th February a grass fire was reported near Sir Ivan Dougherty Drive at Leadville. Spreading rapidly to the east, the fire was soon in forest and had grown to 780 ha by 15:30. With multiple crews and heavy plant the focus was on parallel attack and property protection with support from aircraft (including the LAT and VLAT arriving later in the afternoon). There were multiple reports of the fire breaching containment lines and retardant drops before the main forward spread was slowed around 17:30.

With winds strengthening mid-morning on Sunday, multiple spot fires were occurring and the fire broke containment around 11:00 taking a fast (c. 6 kmh^{-1}) easterly run initially through grass then into forest. An Emergency Warning was issued at 11:40 and crews were advised to fall back to safe locations and only conduct property protection. With the south westerly wind change around 16:00, the northern flank started burning through forest to the north-east, crowning and spotting as the change triggered the development of a pyrocumulonimbus cloud.

The Sir Ivan fire was declared contained on the 16th February and out on the 6th March. The final fire size was 55,000 hectares, the majority of which burnt on Sunday 12th.

Figure 9.19 Images during and after Sir Ivan fire © RFS ICON.

Impacts

Eight emergency alert messages were sent on Sunday afternoon. 35 homes, 131 outbuildings, a community hall and church were destroyed, and a further 11 homes and 42 outbuildings damaged. There were significant agricultural losses including 3000 livestock and extensive fencing. Infrastructure impacts included damage to power lines, telecommunications equipment (Telstra, GRN, NBN), and water mains. Infrastructure disruptions included power and communications outages, closed roads (including the highway), and critically low water supply in Cassilis.

NFDRS forecast

The daily regional forecast for North Western fire weather area was for Very High fire danger on Saturday and Catastrophic on Sunday. NFDRS regional forecast was category 4 on Saturday and Category 6 on Sunday.

The NFDRS forecast for Saturday was at Category 5 from 10:00 to 19:00, which was appropriate for the fire behaviour observed. The fire suppression and consequences align more with a Category 4. This may reflect the high level of suppression resources available due to anticipation of the weekend's conditions.

For the first time period assessed on Sunday when the fire first broke containment and was spreading through grass, the NFDRS forecast Category 6 was an over prediction of the observed fire behaviour, though the suppression and consequences could fit in either category 5 or 6. Again this may reflect the level of high level of suppression resources on the scene.

For Sunday afternoon, the NFDRS forecast (Category 6, dropping to Category 5 at 17:00 in grass and at 18:00 in forest) was an accurate reflection of the observed fire behaviour, suppression, and consequences.

The red flag warnings indicated a wind change and instability, both of which were observed and had a significant influence on the fire behaviour and size.

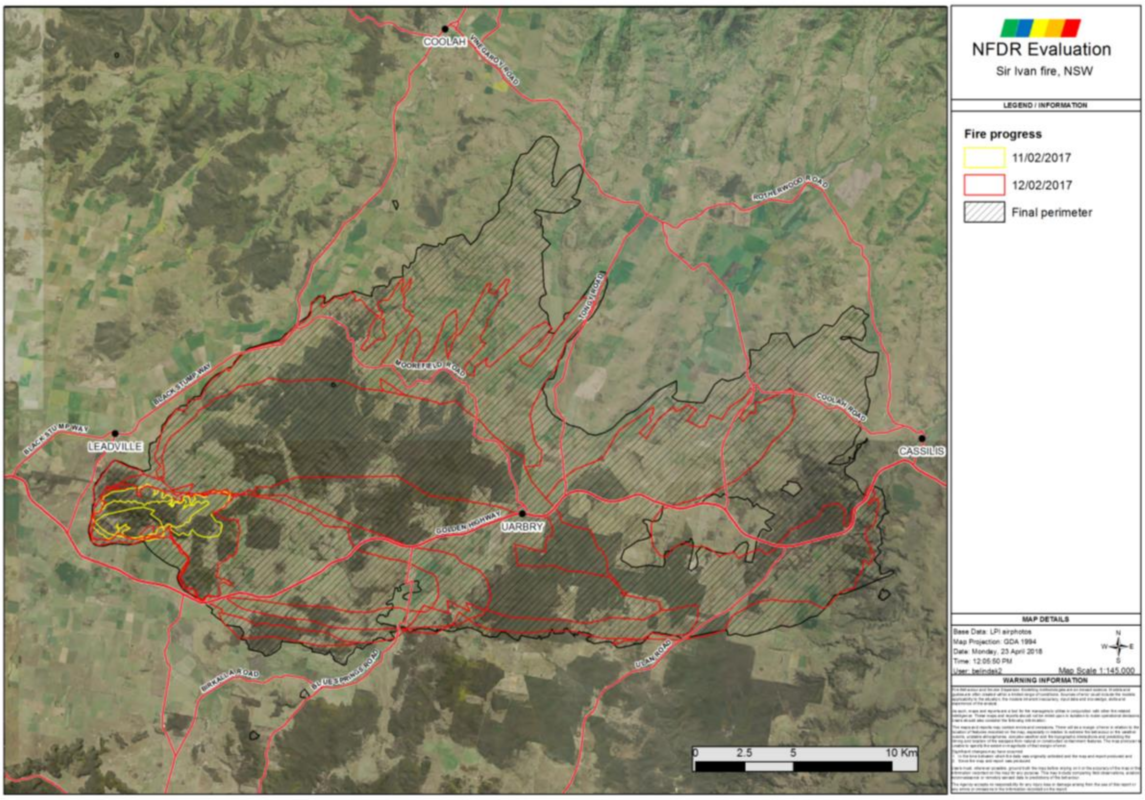

Figure 9.20 Spread map for Sir Ivan fire. Data sourced from RFS ICON.

References

Bureau of Meteorology (2015) Monthly weather review, Australia February 2017

NSW Rural Fire Service ICON system

NSW Rural Fire Service (2017) Catastrophic fire conditions. Bush Fire Bulletin 39(1):5-7

NSW Rural Fire Service (2017) Volunteer stories from the Sire Ivan fire. NSW RFS website news

Whittaker, J. & Taylor, M. (2018) Community preparedness and responses to the 2017 New South Wales bushfires. Bushfire Natural Hazards CRC

Table 9.10 Summary table of forecasted conditions against observations for the Sir Ivan fire

Incident name:	Sir Ivan	
Date:	11/02/2017	12/02/2017
Daily regional FFDI forecast rating:	Very high	Catastrophic
Daily regional NFDRS forecast rating:	4	6
C-Haines red flag warning:	*Yes*	*Yes*
Wind change red flag warning:	*No*	*Yes*

Incident details	Time period	1	2	3	4
	Date	11/02/2017	12/02/2017	12/02/2017	12/02/2017
	Time period start	12:20:00	11:21:00	13:19:00	17:17:00
	Time period finish	15:33:00	13:19	17:17:00	19:30:00
	Latitude	-32.05	-32.08	-32.08	-31.99
	Longitude	149.57	149.68	149.76	149.72
Fuels	Fuel type/s	Forest	Pasture	Forest	Pasture
	FDR Table	Forest	Grassland	Forest	Grassland
Fire Danger Rating	FFDI (max)	57	118	119	74
	GDFI (max)	24	94	57	48
	Observed current FDR	Severe	Severe	Catastrophic	Extreme
NFDRS forecast	Forecast NFDRS Fire Behaviour Index (max)	250	208	470	137
	Forecast NFDRS Fire Danger Rating (max)	5	6	6	5
	Observed NFDRS FIRE DANGER RATING	5	5	6	5
Fire behaviour & fire weather	Obs fireline intensity (kW/m)				
	Obs mean ROS (m/hr)	1900	6500	3500	5000
	Obs mean flame height (m)				Crowning, Pyroconvective
	Obs spotting distance (m)	100		>100	500
	Wind change observed (Y/N)			Y	
	Forecast fire behaviour accurate?	Yes	Over-predicted	Yes	Yes
Fire suppression & containment	Fire suppression (Y/N)	Y	Y	Y	Y
	Operational strength in field personnel	22	55	98	98
	Operational strength in aerial resources	6	4	13	13
	OFFENSIVE strategies (Y/N)	Y	Y	Y	Y
	DEFENSIVE strategies (Y/N)		Y	Y	Y
	Forecast suppression/containment accurate?	Over-predicted	Yes	Yes	Yes
Consequences	Fire area at end of time period	780	8,580	25,700	41,650
	Fire perimeter at end of time period	9	53	83	203
	Houses lost during time period (Number/Y/N)	N	2	12	16
	Other assets lost during time period (Y/N)		Y	Y	Y
	Lives lost during time period (Number/Y/N)	N	N	N	N
	Infrastructure impacted during time period (Y/N)		Y	Y	Y
	Forecast consequences accurate?	Over-predicted	Yes	Yes	Yes

9.12 Taliesin (Carwoola) fire, New South Wales, February 2017

Overview

The Taliesin (Carwoola) fire started on 17th February, 2017 at 11:56 am after sparks from a grinder ignited nearby grassland on a semi-rural property on a day of Total Fire Ban.

Fire behaviour and containment

The fire quickly burnt through over 3,000 ha of rural pasture and horticulture, often characterised by patchy areas of low to medium density trees. Rates of spread in excess of 7.5 kmh^{-1} were observed with spotting reported up to 2km ahead of the fire front. In forested areas, the fire often transitioned to crowning. Conditions were extremely windy, often with poor visibility. Suppression and containment were difficult and at times, fire crews were unable to use offensive strategies (time periods 2 and 3) until conditions eased.

Impacts

The consequences of the fire were extensive and included the loss of 11 houses (plus another 12 damaged), 55 Outbuildings (plus another 24 damaged), 25 vehicles, 34 livestock (dog, alpacas, cattle, sheep, chickens, horse and donkey) and 182 km of fencing.

During the peak of the fire, two firefighting trucks were severely damaged, two firefighters were injured requiring hospitalisation and three members of the public were injured.

Figure 9.21 Fire impacting the communities of Carwoola and Widgiewa Road 14:15 on 17th February (LEFT, source: NSW RFS, RIGHT, source: ABCNews).

NFDRS point forecast

During the first 40 minutes after ignition at approximately 11:54 when the fire spread through grassland, the NFDRS forecast was for Category 5 (Grassland), however descriptions of fire behaviour, fire suppression and consequence were observed at Category 3. This discrepancy is likely to be largely due to the initial attack response having some impact on fire behaviour, together with the fire still being in early stages of development. Over the course of the following hour until 13:41 the NFDRS forecast remained at Category 5, which appears to have captured the difficulty firefighters has suppressing and containing the fire, but overestimated fire behaviour and the consequences that were observed during this time (more appropriately aligned to Category 4). During this time, strategies moved from offensive to defensive, so would have had minimal impact on limiting fire behaviour.

From 13:41, the NFDRS forecast described well the difficulty firefighters had suppressing the fire and the potential consequences however, it generally over-predicted fire behaviour, with the exception of the main run during time period 4 (14:20-14:57) when firefighters observed the fire crowning through forested areas, spotting short to medium distances and rates of spread around 7.6 kmh^{-1}. During this time, the

NFDRS forecast Category 5 and the descriptors for fire behaviour, suppression difficulty and possible consequences were accurate.

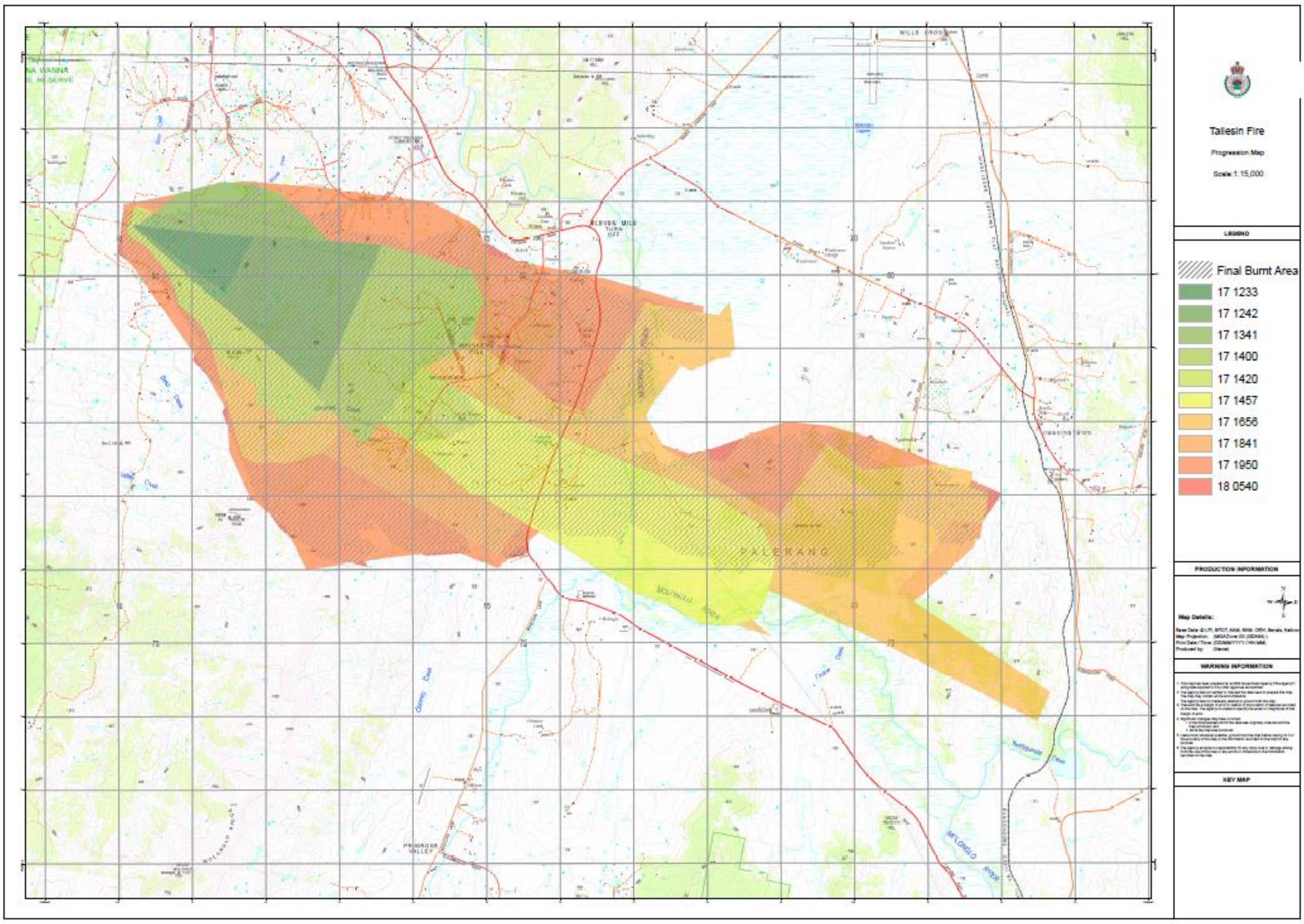

Figure 9.22 Spread isochrones at containment of the Taliesin fire (source: NSW RFS).

The discrepancies observed relating to fire behaviour are possibly due to the effect of patches of forests and paddocks with light to medium density trees. The fire burnt through typical rural pasture and horticulture and was characterised by areas that were fairly densely forested with locals describing the fuels as ‘scrubby’, ‘forested patches’ or ‘grassy woodland’ in between grassy paddocks with low to medium density trees.

The NFDRS fuel layer defines the fuels for this fire as ‘pasture’ or ‘crop’ (Figure 9.23, therefore using the grass model to predict rate of spread and intensity), so would assume there are no trees to slow rates of spread and no wind reduction factor is applied. By considering the fuel type as forest alone, resulted in NFDRS forecasts that generally under-predicted fire behaviour throughout the fires spread. By applying the savanna spread model (therefore incorporating a wind reduction factor into the grassland model, as per ‘rural’ fuel types) would have resulted in a consistent NFDRS forecast of Category 4 throughout the fires spread. This may have better described potential rates of spread, where the range is quite broad (1-8 kmh^{-1}) but generally loses some meaning because descriptors within the FDR Table for savanna are not targeted to rural landscapes such as this one. This highlights the potential differences in forecasts and descriptors for different fuel types and some of the difficulties in defining the most appropriate fuel type for an area.

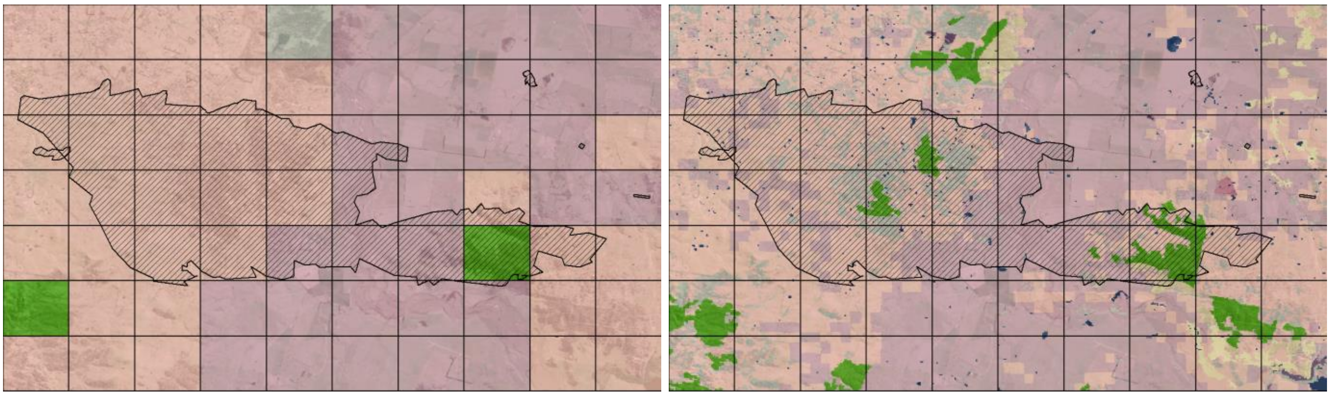

Figure 9.23 Fuel layers within the Taliesin fire perimeter as defined by the NFDRS Research Prototype, characterised by 'pasture' in light pink and ''crop' in dark pink. Fuel grid (LEFT); Fuel map at native resolution (RIGHT)

Daily FWA and Red Flag warnings

The daily regional NFDRS forecast of Category 5 appears to have appropriately predicted fire danger conditions. In comparison, the maximum FFDI forecast for the day within the fire area was 48 and maximum GFDI of 45 (both being 'Very High'). Operational staff have described that Severe under the current fire danger rating system best described the fire danger observed on the day (NSW Rural Fire Service, 2014).

The NFDRS forecast a red flag warning for C-Haines on the day of the fire which appears to have appropriately captured some of the difficulties experienced containing the fire but doesn't appear to have influenced fire danger rating by way of increased fire behaviour.

Acknowledgements

Thanks to Tim Carroll, Darren Marks and Jason McWhirter from the NSW Rural Fire Service for providing background information relating to the fires behaviour, suppression and consequences.

Related references

AEMC - National Bushfire Warnings Taskforce (2009). Australia's revised arrangements for bushfire advice and alerts. Version 1.1.

NSW Rural Fire Service (2014) WFB Wildfire behaviour (2014) manual. NSW Rural Fire Service, Granville, NSW.

Table 9.11 Summary table of forecasted conditions against observations for the Taliesin Road fire

Incident name:	Taliesin Rd, Carwoola, Queanbeyan-Palerang
Date:	17/02/2017
Daily regional FFDI forecast rating:	Very High
Daily regional NFDRS forecast rating:	5
C-Haines red flag warning:	*Yes*
Wind change red flag warning:	*No*

Incident details	Time period	1	2	3	4	5	6
	Date	17/02/2017	17/02/2017	17/02/2017	17/02/2017	17/02/2017	17/02/2017
	Time period start	11:54:00	12:33:00	13:41:00	14:20:00	14:57:00	16:56:00
	Time period finish	12:33:00	13:41:00	14:20:00	14:57:00	16:56:00	19:50:00
	Latitude	-35.3967	-35.4032	-35.4149	-35.4279	-35.4381	-35.4088
	Longitude	149.3232	149.338	149.3581	149.3845	149.429	149.3747
Fuels	Fuel type/s	Pasture	Pasture	Pasture	Crop	Crop	Pasture
	FDR Table	Grass	Grass	Grass	Grass	Grass	Grass
Fire Danger Rating	FFDI (max)	43	44	48	48	41	35
	GDFI (max)	21	45	39	39	39	24
	Observed (GFDI) FIRE DANGER RATING	Very High	Very High	Severe	Severe	Severe	Very High
NFDRS forecast	Forecast NFDRS Fire Behaviour Index (max)	103.5	122.1	124.4	124.4	118.4	96.7
	Forecast NFDRS Fire Danger Rating (max)	5	5	5	5	5	4
	Observed NFDRS FIRE DANGER RATING	3	4	5	5	5	3
Fire behaviour & fire weather	Obs fireline intensity (kW/m)						
	Obs mean ROS (m/hr)	990	1,460	3,340	7,620	1,940	976
	Obs mean flame height (m)	2-5m	2-5m	5-10m	5-10m	5-10m	2-5m
	Obs spotting distance (m)			2,000	spotting observed	spotting observed	
	Wind change observed (Y/N)	N	N	N	N	N	N
	Forecast fire behaviour accurate?	Over-predicted	Over-predicted	Y	Y	Over-predicted	Over-predicted
Fire suppression & containment	Fire suppression (Y/N)	Y	Y	Y	Y	Y	Y
	Operational strength in field personnel	20			86	120	222
	Operational strength in aerial resources	0	0	0	0	10	10
	OFFENSIVE strategies (Y/N)	Y	N	N	Y	Y	Y
	DEFENSIVE strategies (Y/N)	Y	Y	Y	Y	Y	Y
	Forecast suppression/containment accurate?	Over-predicted	Y	Y	Y	Y	Y
Consequences	Fire area at end of time period	20		794		1,400	2,531
	Fire perimeter at end of time period						
	Houses lost during time period (Number/Y/N)	N	N	Y	Y	Y	N
	Other assets lost during time period (Y/N)	N	N	Y	Y	Y	N
	Lives lost during time period (Number/Y/N)	N	N	N	N	N	N
	Infrastructure impacted during time period (Y/N)	N	N	Y	Y	Y	N
	Forecast consequences accurate?	Over-predicted	Over-predicted	Y	Y	Y	Y

9.13 Key findings

Some of the key findings identified through analysis of NFDRS forecasts for significant fires in case studies include:

- Combined, the case studies have demonstrated instances where the Research Prototype has mostly either appropriately forecast fire danger or provided a forecast that is typically out by one category throughout the course of a fire event. The biggest discrepancies were observed:
  - Early on in the development of some fires, and
  - During the most impacting time of the Waroona fire when both the NFDRS forecast (Categories 3-4) and FFDI forecast (High) significantly underestimated the fire behaviour and consequences observed including the loss of two lives and 181 properties destroyed.

  Instances where the Research Prototype has over- and under-predicted fire danger were observed.
- The Research Prototype does not reflect fire development and the effect of suppression. The Research Prototype represents the maximum steady state irrespective of any initial attack, suppression or the time it takes for a fire to develop and reach a steady state. Because of this, the Research Prototype may appear to over-predict fire danger, however more realistically represents a broader fire danger within that period of time. This was observed within some case studies (e.g. Kilmore East, Taliesen) but will also be a characteristic within the live trial dataset and the statistics produced, particularly for forest fuel types and fires where initial attack is largely effective.
- Improvements can be made by incorporating initial attack and offensive strategies in Categories 5 and 6. For the most impacting FDR Categories (i.e. Categories 5 and 6), the FDR Tables currently assume that nearly all firefighting efforts will be focused on defensive strategies however important improvements can be made by incorporating the importance of successful initial attack on new fires and spot fires and opportunities for using direct attack techniques at these levels of fire danger.
- There is a need to prioritise the collection and documentation of case studies. Investigating the accuracy of the Research Prototype through case studies has been an important component of the evaluation process. Despite this, our use of case studies from around Australia has been limited by the number of well-documented case studies with adequate descriptions of fire behaviour, suppression and impact. Access to well-documented case studies for future important fire events would benefit the NFDRS project but also provide useful information for other studies such as those relating to the development of the ignition likelihood, fire suppression and fire impact indices as part of this work.
- Observations of FFDI and GFDI performance are subjective. Without clear, consistent and objective definitions of the current FFDI or GFDI based fire danger rating system, it was difficult to determine how relevant and appropriate forecasts were for each fire case study. While observations have been largely based on current practice within the relevant state and agency, ultimately, many of the observations are subjective. This will also be a characteristic of live trial dataset and the statistics produced.
- Atmospheric instability, plume driven fire behaviour and coupled fire-atmosphere interactions are important. Atmospheric instability is currently identified as a red flag warning in the Research Prototype with no impact on the overall rating of potential fire danger. This allows practitioners to estimate the impact of the red flag on conditions based on local conditions and their own experience however makes it difficult to quantify the impact of atmospheric instability and potential fire-atmosphere interactions on fire danger. Further work is required in this area to quantify possible interactions and review how atmospheric instability is recognised in the NFDRS.
- The Research Prototype is dependent on accurate mapping of fuel types. The NFDRS fuel layer defines fuels on a 1.5 km grid spatial scale and because it is driven by the prediction of fire spread within recognised fuel types, it is very dependent on the accuracy of fuel mapping. Inconsistencies,

errors, as well as applying inappropriate fire behaviour models to some poorly-understood fuel types can result in significant errors.

10 Fuel data analysis

10.1 Fuel type distribution

10.1.1 Methods

Summaries of fuel type distribution are presented below, with coverage calculated by overall area and within fire weather areas. Within fire weather areas (FWA), fuel types were considered from the perspective of dominant (fuel category with the greatest area coverage within a FWA) and significant to setting the fire danger ratings (at least 10% area coverage within a FWA). Note that fire weather areas are variable in size, generally reflecting population density.

Fuel types are presented in both the NFDRS broad fuel types (i.e. by fire behaviour model; Figures 4.3, 10.5 & 10.6) and the more detailed NFDRS fuel types (includes modifications to fire behaviour models; Figures 4.4, 10.5 & 10.7).

Comparisons were made to the fuel types used to set the FFDI and GFDI in the current FDR system (grass, forest, combined; Figures 10.1 & 10.3). For this comparison, NFDRS fuel types were grouped into categories that show where the usage is equivalent (grass or forest), modified (modified grass or forest) or completely different (the other fire behaviour models) to the current FDR fuel type (Table 10.1; Figures 10.2 & 10.4).

Table 10.1 NFDRS fuel types in current FDR equivalent categories

Category	Description	NFDRS fuel types
Grassland	Grass fuel types using reported fuel load input	Grass, Pasture, Crop
Grassland modified	Grass fuel types with some modification (wind adjustment or forced fuel state)	All Savanna fuel types, Low wetland, Chenopod shrubland
Forest	Forest fuel type	Forest
Forest modified	Wet forest type (forest model with drought factor modification)	Wet forest
Other	Fuel types using fire behaviour models other than grass or forest	All fuel types in: Spinifex, Mallee heath, Shrubland, Buttongrass, Pine, Non-combustible

10.1.2 Overview

Grass-like fuels cover the largest area of Australia. Descriptions of 75% of Australia being grass fuel (Cheney & Sullivan 2008; Sullivan *et al.* 2012) include a variety of fuel types: tussock grassland, pasture and crop land (i.e. grassland); tropical grasslands (i.e. savanna) and hummock grass (i.e. spinifex).

Current fire danger ratings are primarily set by GFDI (89% of area, dominates 77% of fire weather areas). FFDI (7% of area, dominates 20% of fire weather areas) is only significant in south-east and south-west coastal areas.

Under the NFDRS fuel classification grass fuels cover the greatest area nationally (61% of area, dominates 66% of FWAs), however much of this is in a modified version of the grass fire behaviour model which includes the savanna broad fuel type. Forest covers only 6% of the nation, though dominates 18% of FWAs.

The other fire behaviour models, which are not currently considered when calculating fire danger ratings, collectively cover a significant portion (32% of area, dominate 16% of FWAs) of Australia. Of these, spinifex is the most prevalent, followed by mallee heath and shrubland. No fire weather areas are dominated by buttongrass, pine, or non-combustible fuel types.

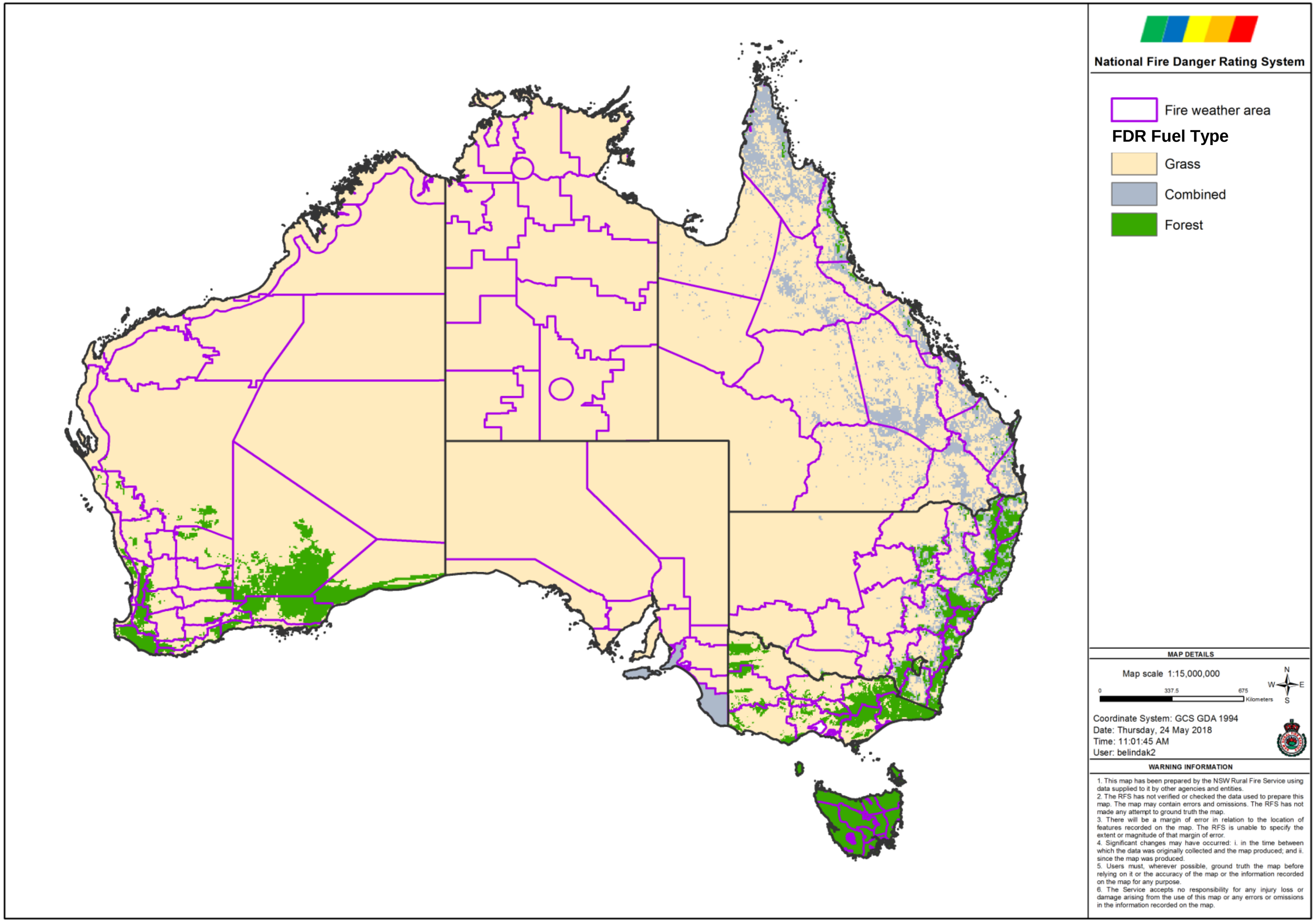

Figure 10.1 Current FDR fuel type used to determine GFDI and FFDI calculation

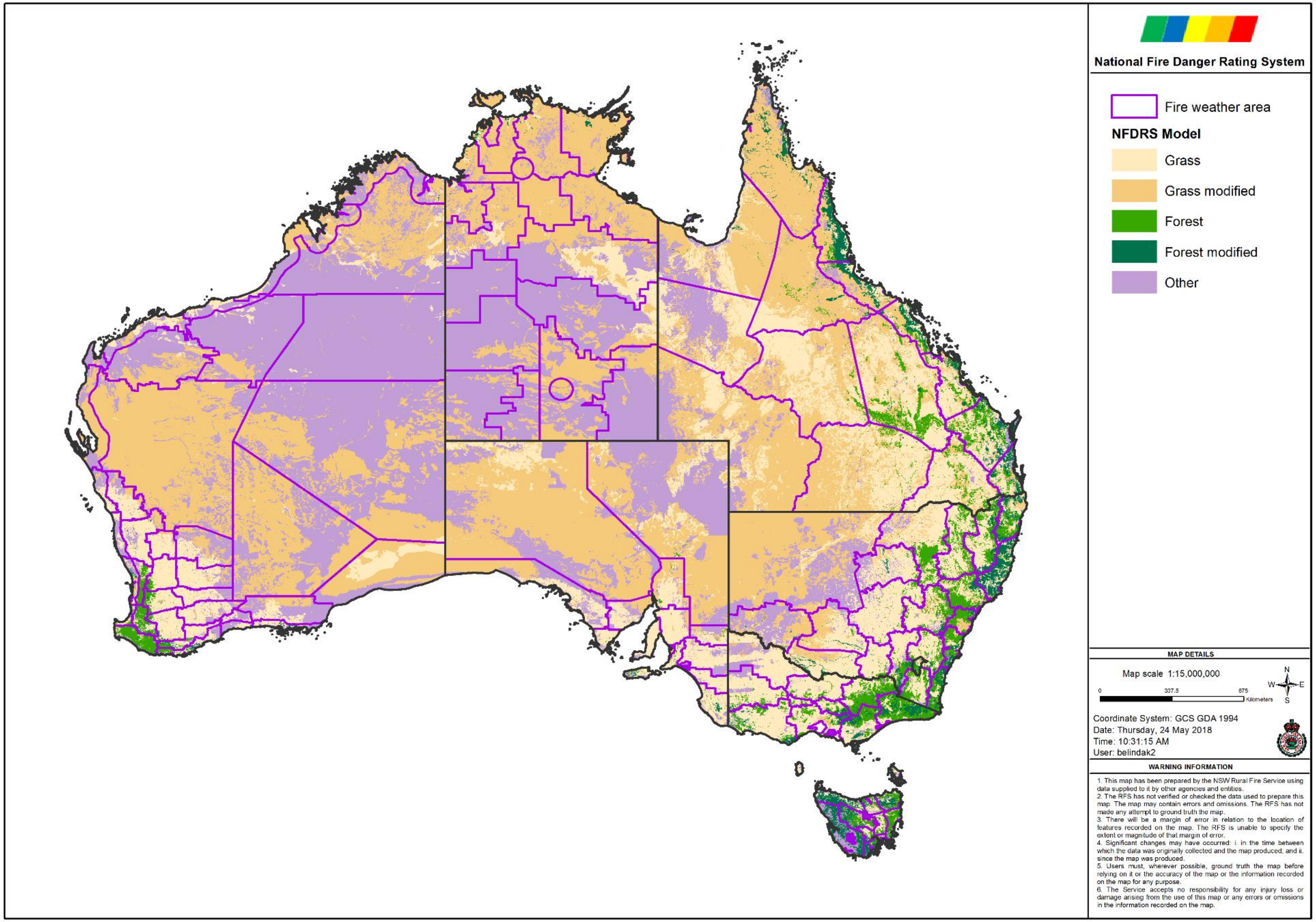

Figure 10.2 NFDRS fuel type displayed as current FDR equivalent fuel category

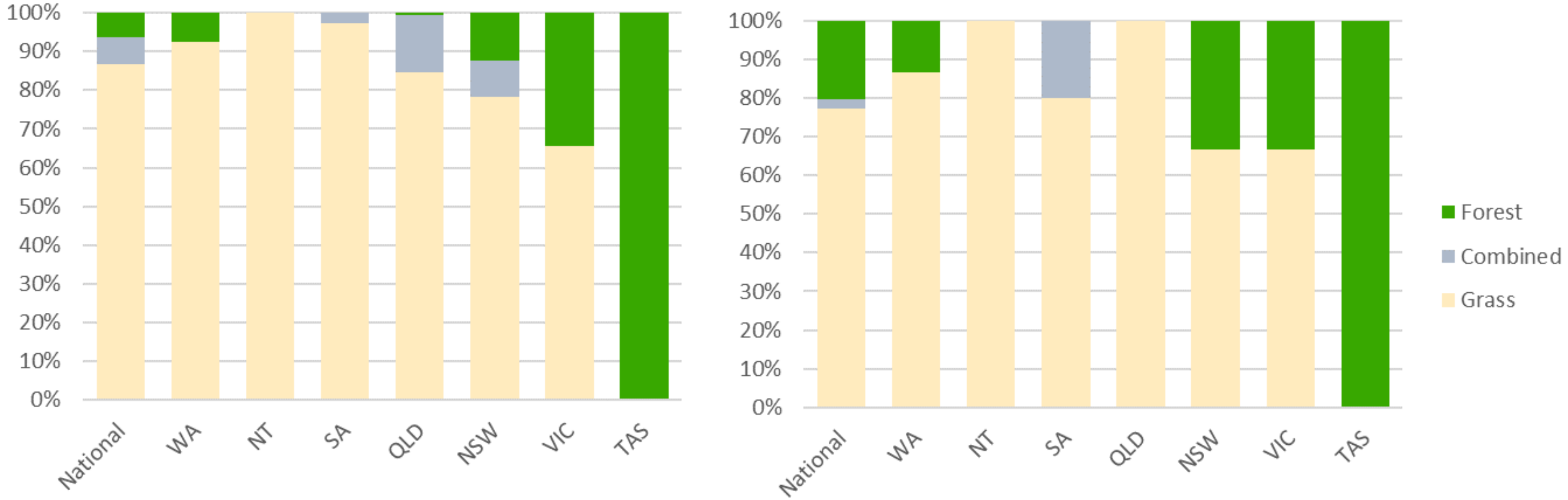

Figure 10.3 Current FDR fuel type coverage by area (left) and by number of fire weather areas (right)

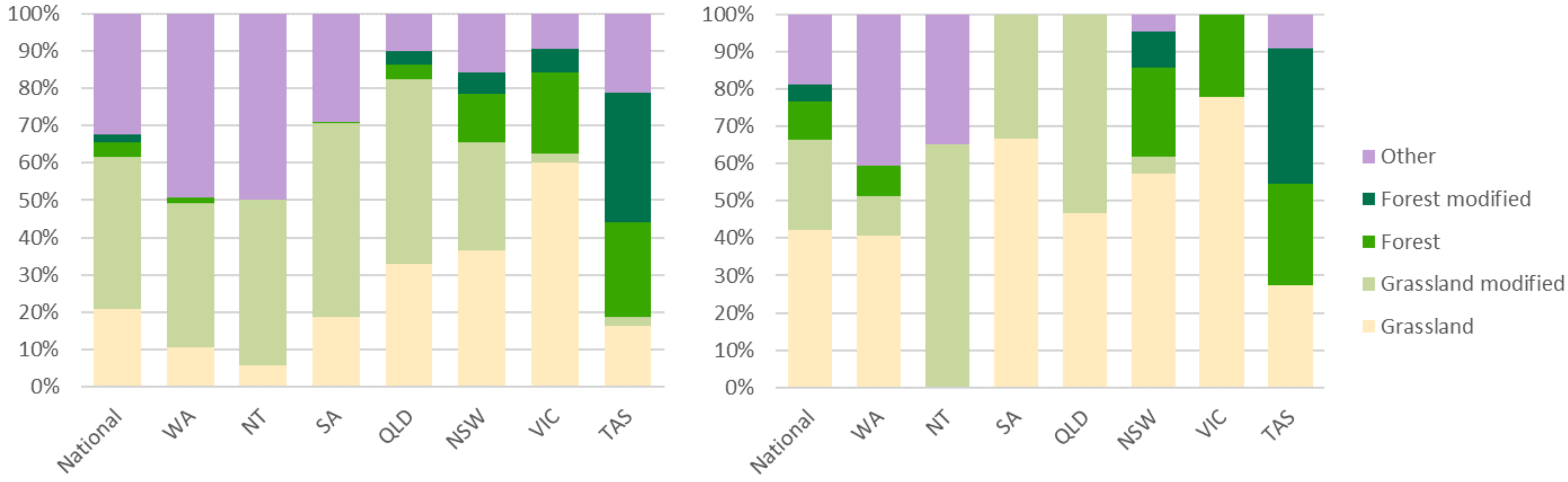

Figure 10.4 NFDRS fuel type coverage (as FDR equivalent categories) by area (left) and by number of fire weather areas (right)

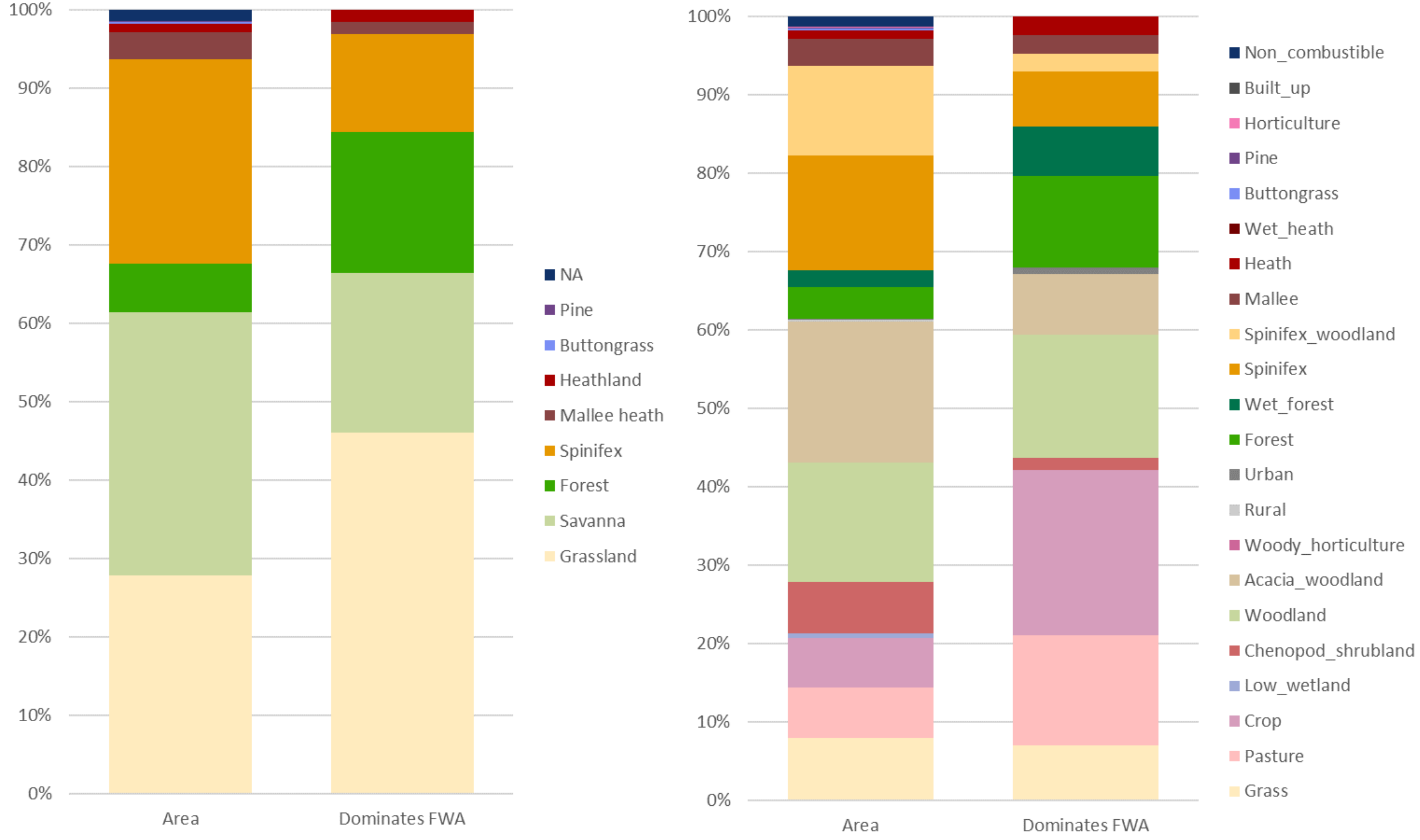

Figure 10.5 National coverage of NFDRS Fuel types by area and FWA dominant fuel type. Broad fuel type (left), Fuel type (right)

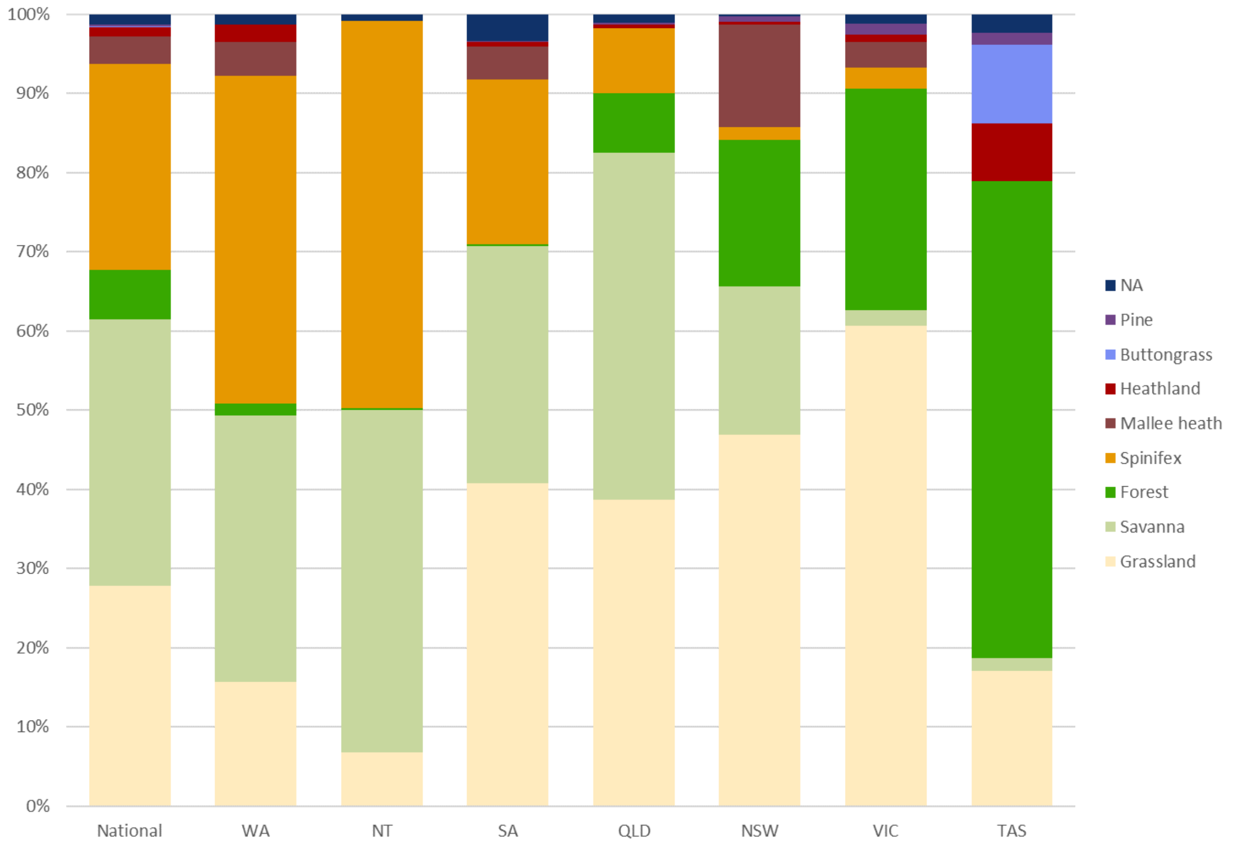

Figure 10.6 Area coverage of NFDRS Broad Fuel Types by State

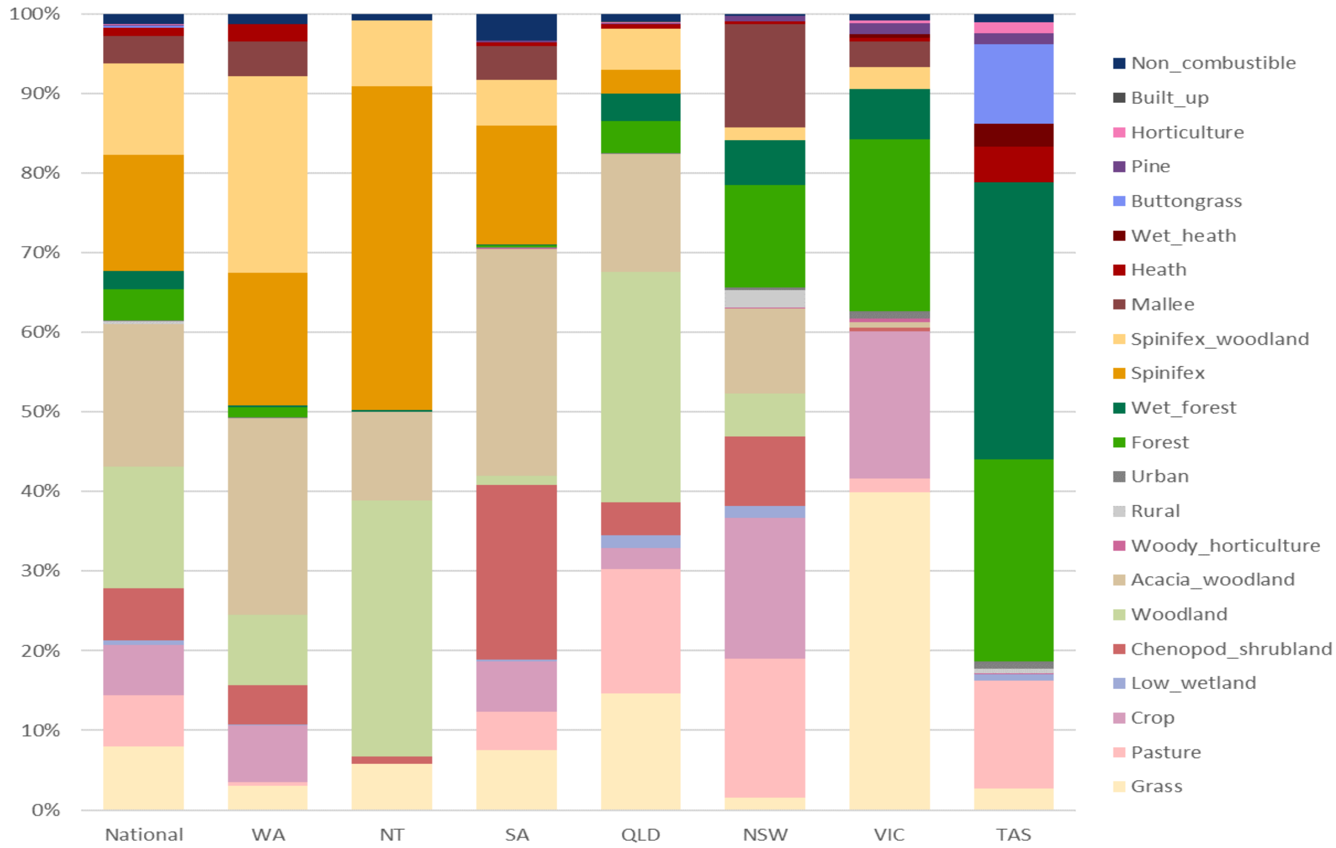

Figure 10.7 Area coverage of NFDRS Fuel Types by State

10.1.3 NFDRS fuel types

10.1.3.1 Grassland

The grassland and savanna broad fuel types dominate the Australian landscape. Savanna covers a greater area, but grassland has a greater influence at a fire weather area scale (Figure 10.5). Grassland is a very significant factor in setting fire danger ratings, dominating 46% of FWAs (primarily in agricultural regions), and with a significant influence on 76% of FWAs (Figure 10.8). However, the current FDR still over-represents the amount of grass by using GFDI for most non-forest vegetation. Northern Australia in particular could benefit from using the savanna and spinifex models instead of grassland (Figures 10.3, 10.4 & 10.6).

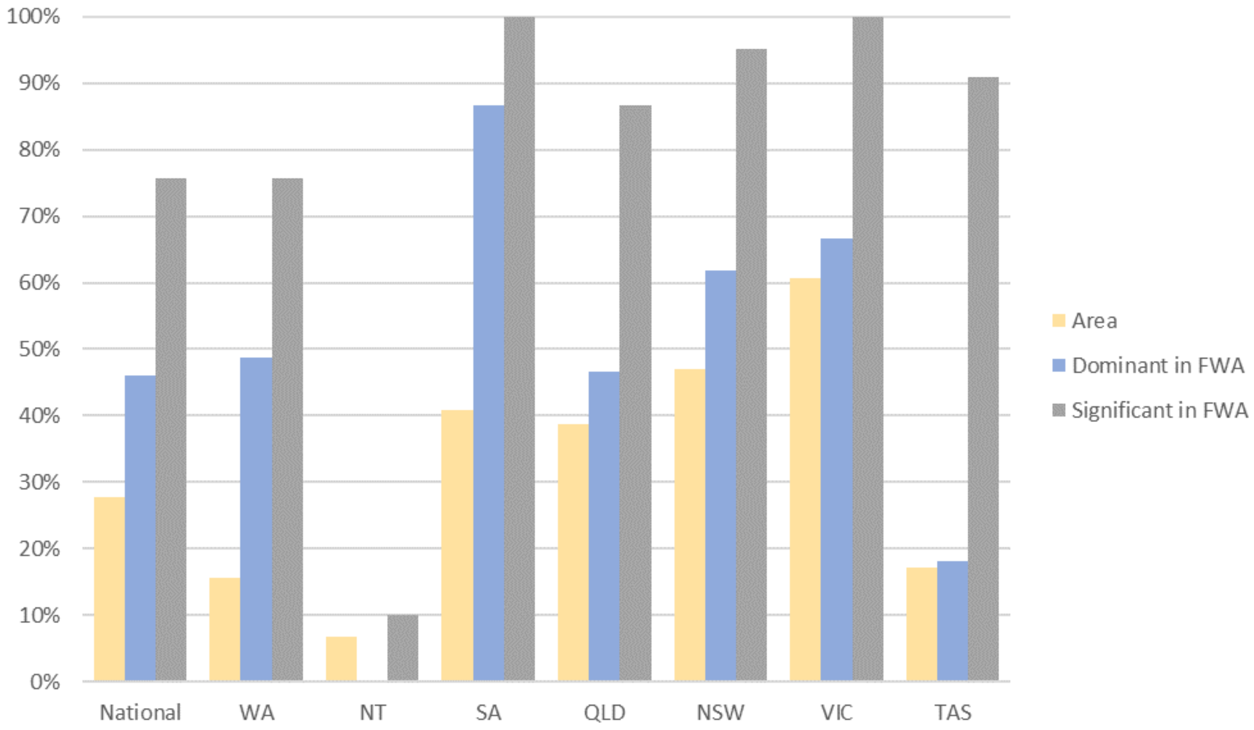

Figure 10.8 Coverage of Grassland broad fuel type by area, percent of FWAs dominated, percent of FWAs with significant (at least 10%) coverage

During the Research Prototype the grass, pasture and crop fuel types were all treated the same (with reported grass fuel load) and occur in fairly equal proportions, though this varies by jurisdiction (Figure 10.7). Grass performed the best of the three, with pasture and crop having a higher proportion of over-predictions. There is scope to vary the model application between these fuel types in future systems with improvements in grass fuel state reporting or further research. The delineation of these could also be improved with better mapping inputs (currently based primarily on land use mapping).

Chenopod shrublands were included in the grassland broad fuel type as the most flammable component of the vegetation is ephemeral grasses. This fuel type covers a substantial area of South Australia (22%; Figure 10.7) and dominates 1 FWA each in SA and WA, as well as being significant in neighbouring FWAs of NSW and Queensland. As discussed in Chapter 4, further consideration of the most suitable treatment of this fuel type is required. While the application of an eaten-out grass model appeared to work adequately during the live trial, not enough observations were received to make a robust assessment of its performance (4 out of 5 observations correct, 1 over-prediction).

The low wetland fuel type was also included within grassland with some uncertainty around the best application of fire behaviour model, and whether to further segregate this fuel type in to inland, coastal and alpine subtypes. Low wetlands are not spatially significant (only 0.6% area nationally), have no influence on setting fire danger ratings, and only one (correct) observation was received during the live trial.

10.1.3.2 Savanna

Savanna covers the greatest physical area, though in less populated areas than grassland, and thus affects less fire weather areas (dominates 20% of FWAs, significant in 51% of FWAs; Figure 10.9). While the number of reported incidents in savanna (37% of total reported incidents; Chapter 11) roughly reflects the area coverage (34%), savanna was under-represented in observations received during the live trial of the Research Prototype (5% of observations; Chapter 8)

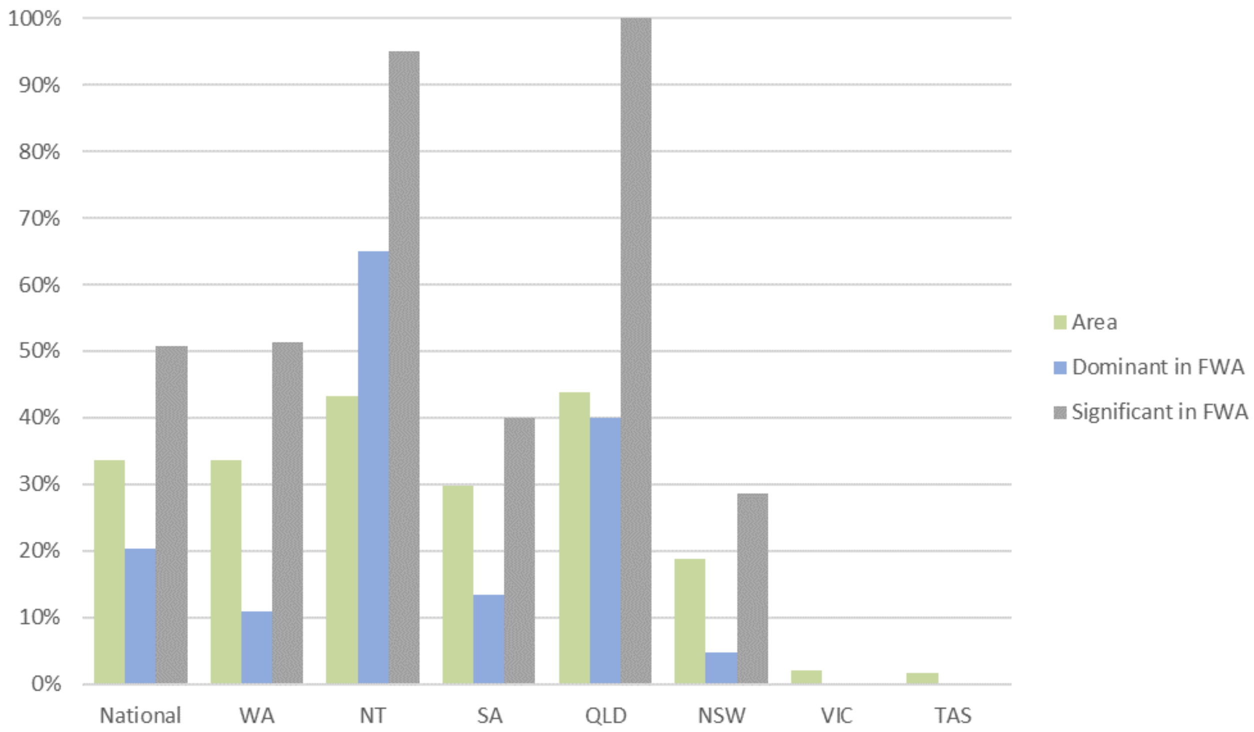

Figure 10.9 Coverage of Savanna broad fuel type by area, percent of FWAs dominated, percent of FWAs with significant (at least 10%) coverage

The savanna broad fuel type is split primarily between the woodland (tropical savanna and other grassy woodlands) and acacia woodland (mulga and other semi-arid and arid shrublands and woodlands) fuel types (Figure 10.7).

Woodland dominates 20 FWAs and is significant in 32 FWAs across northern Australia. Relatively few observations were received for woodland during the live trial, and most of these for grassy woodlands in the southern states, as the live trial occurred during the northern wet season.

Acacia woodland dominates 10 FWAs and is significant in 27 FWAs throughout inland Australia. The best application of a fire behaviour model for the acacia woodland fuel type was unclear (Chapter 4). Like chenopod shrublands, it was considered that ephemeral grasses were the most likely fuel strata to carry a fire. While the application of eaten-out grass appears to have performed well, this is an area requiring further investigation.

The other modified versions of the savanna fuel type (rural, urban and woody horticulture) are not spatially significant for setting fire danger ratings, but they are important from the perspective of potential impact on agricultural and residential assets.

Overall, the savanna model performed well during the live trial (Chapter 8). When examined by individual fuel types within savanna, the proportion of correct to over- and under-predicted remained equivalent, thus the variations appear to have been reasonably applied.

10.1.3.3 Forest

While forest only covers 6% of the area of Australia, it coincides with the areas of greatest population, and is the fuel type most likely to impact on residential areas. Nationally forest dominates 18% of FWAs and is significant in 38% of FWAs, though these proportions are far higher within the south-eastern states (Figure 10.10).

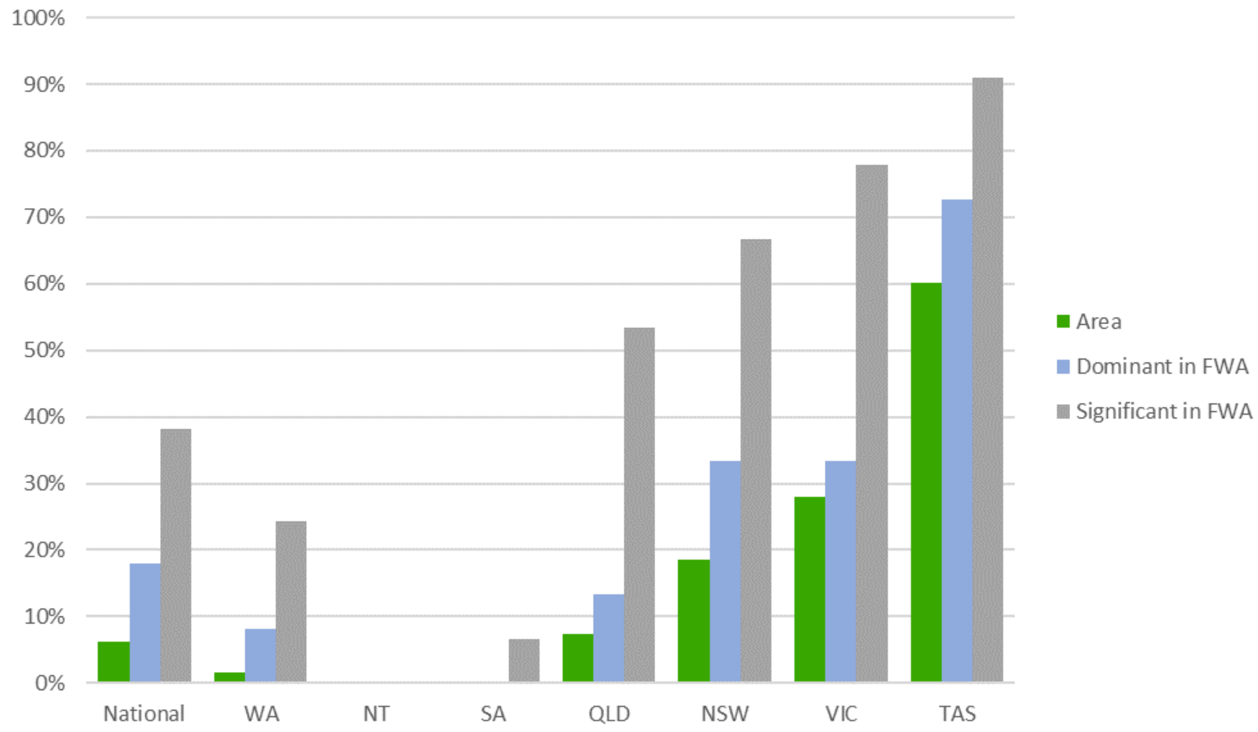

Figure 10.10 Coverage of Forest broad fuel type by area, percent of FWAs dominated, percent of FWAs with significant (at least 10%) coverage

Forest fires represented the greatest number of observations (57%) received during the live trial (Chapter 8), and a significant proportion (20%) of all reported incidents (Chapter 11). The prevalence of forest fire incidents compared to the area coverage reflects the proximity to population.

The forest fuel type was split into dry and wet forest, with a drought factor modification applied to wet forest (Chapter 3). The forest model in general performed well, with the majority of observations (77%) for dry forest. When incorrect, dry forest was more likely to over- than under-predict, while wet forest was more likely to under-predict (Chapter 8).

The wet forest fuel type covers a wide range of vegetation types, including rainforest, wet sclerophyll forest, swamp forest and native plantations. Of these, riverine forests performed the worst, with 1 correct observation, 3 over-predictions, and further fires observed but not evaluated (due to insufficient information) also indicating over-prediction. The classification of swamp forest (particularly riverine forests) and native plantation requires further consideration (see observation examples 199 & 261 in this chapter, and 141 & 158 in Chapter 8).

From general observation during the live trial and comments made in several observations (see observation example 40 in this chapter, and 263 in Chapter 8), the drought factor modification appeared to work best for rainforest and wet sclerophyll forest within gullies, while leading to under prediction for wet sclerophyll forest on ridges and upper slopes. The need to get the fuel availability threshold correct for wet sclerophyll forests is important as these forests have high fuel loads and can carry significant and devastating fires when the fuel is dry enough (e.g. Black Saturday fires). This is an area requiring further research (Duff *et al.* 2018, M. Klinic pers. comm.).

10.1.3.4 Spinifex

Spinifex covers 26% of the nation, but coincides with the most arid, remote and sparsely populated areas. Spinifex is most relevant to fire danger ratings in the Northern Territory and Western Australia, dominating 16 FWAs, and having a significant influence on all but the most northern FWAs of the NT. Spinifex also has an influence on FWAs in the arid regions of all the mainland states (Figures 4.3 & 10.11).

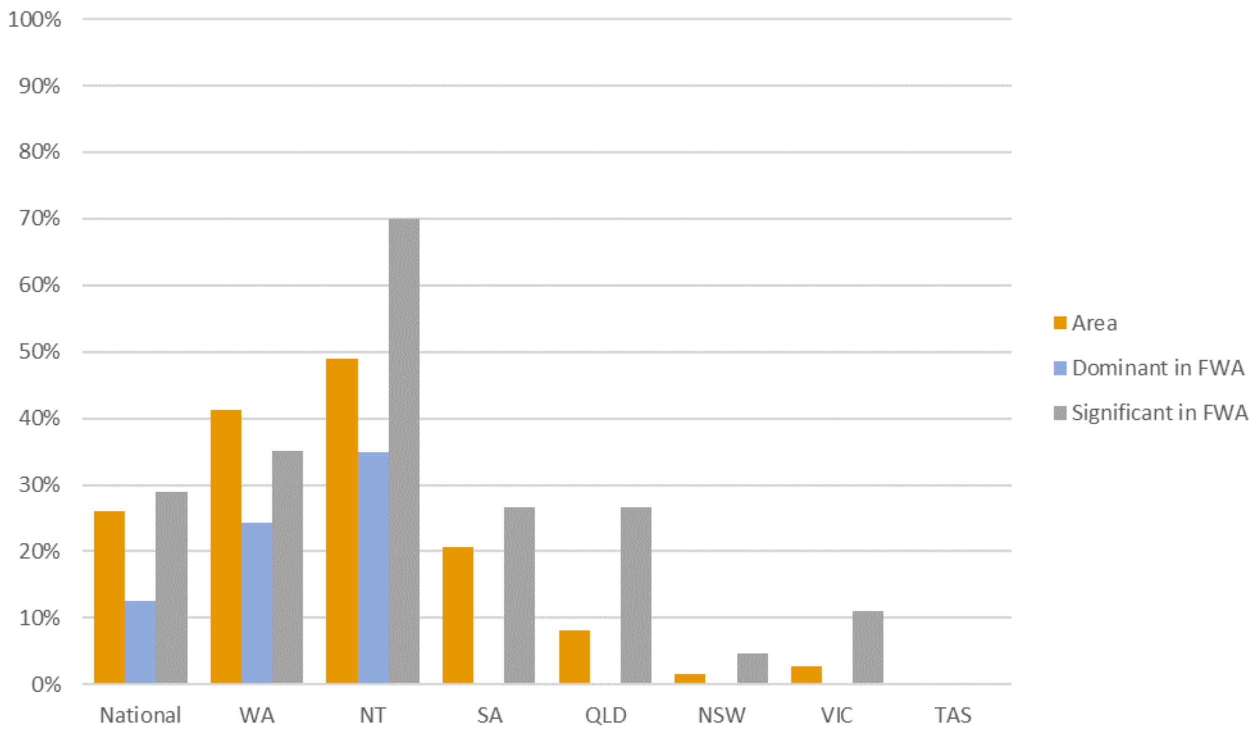

Figure 10.11 Coverage of Spinifex broad fuel type by area, percent of FWAs dominated, percent of FWAs with significant (at least 10%) coverage.

Spinifex incidents are under-represented in the Research Prototype dataset, with only 2% of reported incidents (Chapter 11), and 3% of observations received (Chapter 8). This is a combination of the under reporting of fires in remote areas as well as the timing of the live trial likely missing the peak of spinifex fire activity (September to October; Nano *et al.* 2012).

While the observations received indicated a very good performance, this is based on a very small dataset with poor coverage of the NFDRS ratings categories. Where observations were incorrect they were over-predicted (Chapter 8).

General observation of the system during the live trial indicated significant over-prediction within spinifex. The FWAs identified as producing a very high number of category 5 ratings during the live trial (Chapter 11) correlate with the FWAs that have a significant proportion of spinifex.

The interaction with time since fire has a significant influence on the fire behaviour calculations and hence fire danger rating in spinifex, so it is important to have accurate and regularly updated fire history data for spinifex areas.

10.1.3.5 Mallee heath

Mallee heath covers 3.5% of the nation, occurring in all the southern mainland states (as 3-13% area within states; Figure 10.12). Mallee heath only dominates 2 FWAs in southern Western Australia, but is significant in 21 FWAs across 4 states.

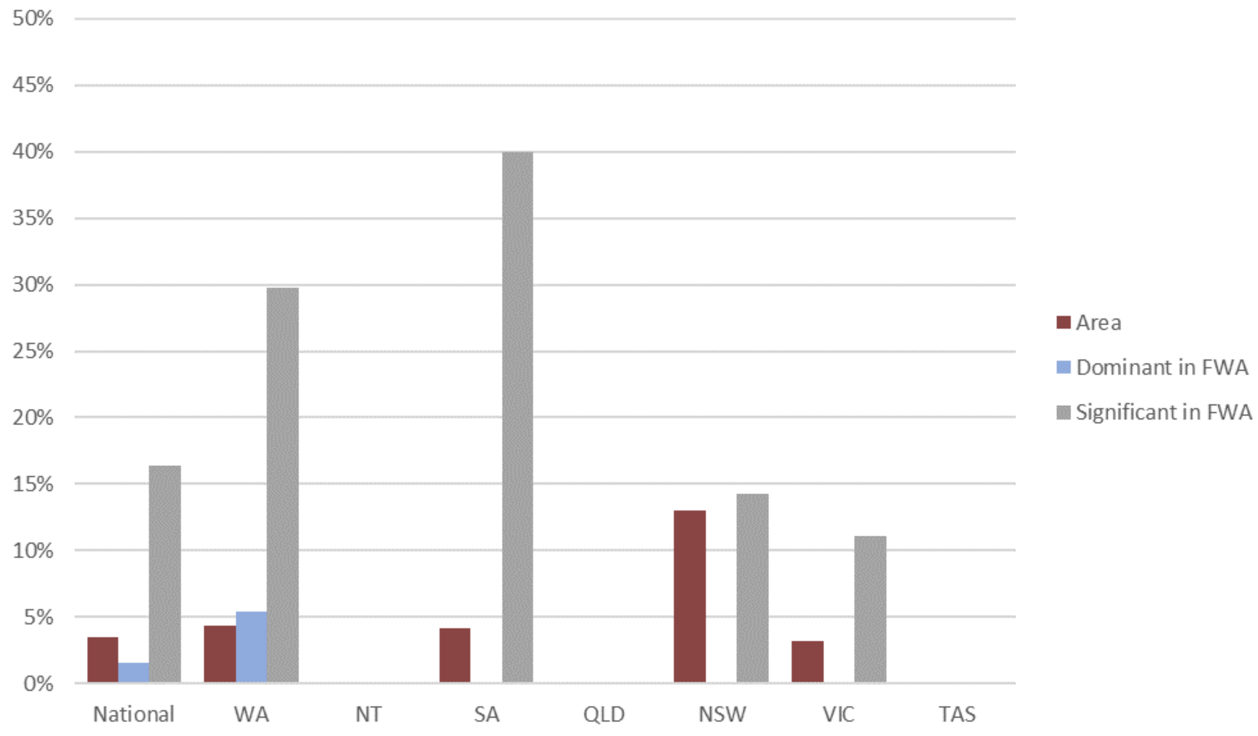

Figure 10.12 Coverage of Mallee heath broad fuel type by area, percent of FWAs dominated, percent of FWAs with significant (at least 10%) coverage

While not a lot of data was collected on mallee heath during the live trial, the number of observations received (4.5%; Chapter 8) was reasonable given the spatial coverage and number of reported incidents (1%; Chapter 11).

The classification between mallee heath, spinifex woodland and acacia woodland could use more careful review for future application of the NFDRS fuel classification, as there is a lot of overlap in descriptions of semi-arid vegetation types.

10.1.3.6 Shrubland

Shrublands occur in small quantities (0.5 - 7% of area) in all states except the Northern Territory, being most prevalent in Tasmania (Figure 10.6). Shrublands only influence fire weather areas in Tasmania and Western Australia (dominate 2 FWAs, significant in 10).

The number of observations collected for shrubland was good (4%; Chapter 8) given the spatial coverage (1%) and number of reported incident (1%; Chapter 11).

While spatially restricted, heathlands are highly flammable and remain so throughout much more of the year than forests (Keith *et al.* 2002). With the potential for very rapid fire growth and high fire intensity, heath fires near populated areas can be particularly dangerous on windy days when the FFDI has not indicated elevated fire danger. This makes it important to calculate and observe fire danger ratings at a gridded forecast scale rather than just FWA reporting so that potential heath fire days are not ignored.

This was seen during the live trial (Chapter 8), with most shrubland observations occurring under a maximum FFDI in the low-moderate or high category. See observation example 204 and the Beecroft Peninsula case study (Chapter 9).

10.1.3.7 Buttongrass

The buttongrass model was only used for the buttongrass moorlands of Tasmania. Buttongrass covers 10% of Tasmania, primarily in the south-west which is covered by the large Western FWA. This is the only FWA that buttongrass is significant in, and it contains a higher proportion of forest (55%) than buttongrass (35%). Five other FWAs contain small amounts of buttongrass.

The only data acquired on buttongrass for the Research Prototype was from case studies.

The potential use of the buttongrass model for other low swamp heath vegetation types was discussed during the Science Workshop but was not implemented, partly due to the non-standard weather inputs required, and that it has not been validated in any other vegetation types. Such vegetation types were classified either to low wetland or wet heath, and are not spatially significant.

10.1.3.8 Pine plantation

Pine plantations cover a very small area (0.2%) of the nation, with a maximum of 1.5% of any state (Tasmania and Victoria) (Figure 10.6). No FWAs are dominated or significantly influenced by pine. The highest proportion of pine within in any FWA is 6-8% in 2 NSW, 2 Tasmanian, and 1 South Australian FWA.

However, where pine plantations do occur they tend to be concentrated in a location and can cover large areas (up to 50,000 hectares). Pine is both highly flammable and hence a risk to surrounding assets, as well as a significant economic asset of its own that can be impacted by fires starting in adjacent forest or grassland.

The application of the pine model in the Research Prototype assumed maximum fuel inputs. From the few observations received as well as scrutiny of pine areas during the live trial, this is leading to over-prediction of fire danger.

Acquiring and continually maintaining the inputs (management regime, rotation, and age) to run the full pine plantation model would be a significant impost as data would need to be acquired regularly from multiple government agencies, private companies, and individuals. Such information would be very valuable at a local scale for operational fire behaviour analysis and risk management planning, but is less significant at the scale of fire danger ratings.

For future application it is worth considering if other options provide a better balance between prediction accuracy and implementation effort, keeping in mind the minor spatial coverage.

10.1.4 Observation examples

40 Little Losy (NSW) Wet forest (Wet sclerophyll forest) 29 November 2017
NFDRS Forecast 1 Observed 2
Issue: Application of fuel availability modifier between different wet forest types (DF value 6.8)

The Little Losy fire in the NSW Upper Hunter occurred in an area with a mix of wet sclerophyll forest and rainforest. The fire only burnt along the ridges and downslope on north-west aspects within the wet sclerophyll forest, while self-extinguishing along the rainforest boundary (Figure 10.13). The NFDRS forecast was a category 1 which was accurate for the rainforest, but not for the wet sclerophyll forest.

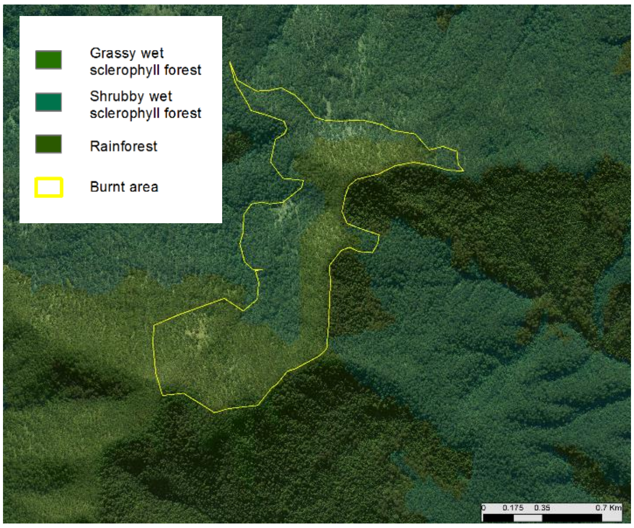

Figure 10.13 Fire extent and fuel type map (left) and photo (right) of wet sclerophyll forest fire. Stewarts Brook, NSW © RFS ICON

261 Riverside Drive (NSW) Wet forest (Riverine forest) 27 February 2018
NFDRS Forecast 3 Observed 2
Issue: Classification of inland riverine forest to wet forest

Several incidents were observed in narrow strips of river red gum along inland rivers (Figure 10.14). In NSW this vegetation type had been classified to wet forest, which is probably not appropriate. The observations and additional incidents should be examined further to find the best fuel classification (possibly woodland) for these communities.

Figure 10.14 Location map (left) and post-fire image (right) of riverine forest fire. Murrin Bridge, NSW © RFS ICON

199 Dartmoor Palpara Settlement Road (VIC) Wet forest (hardwood plantation) 18 January 2018

NFDRS Forecast 3 Observed 3
Issue: Classification of native plantation to wet forest

Only a couple of observations were received in hardwood plantations. In plantations with tall trees and a dense canopy (Figure 10.15), the wet forest fuel type is probably the best option. For future operational NFDRS application, individual native plantation types might need more detailed examination prior to classification.

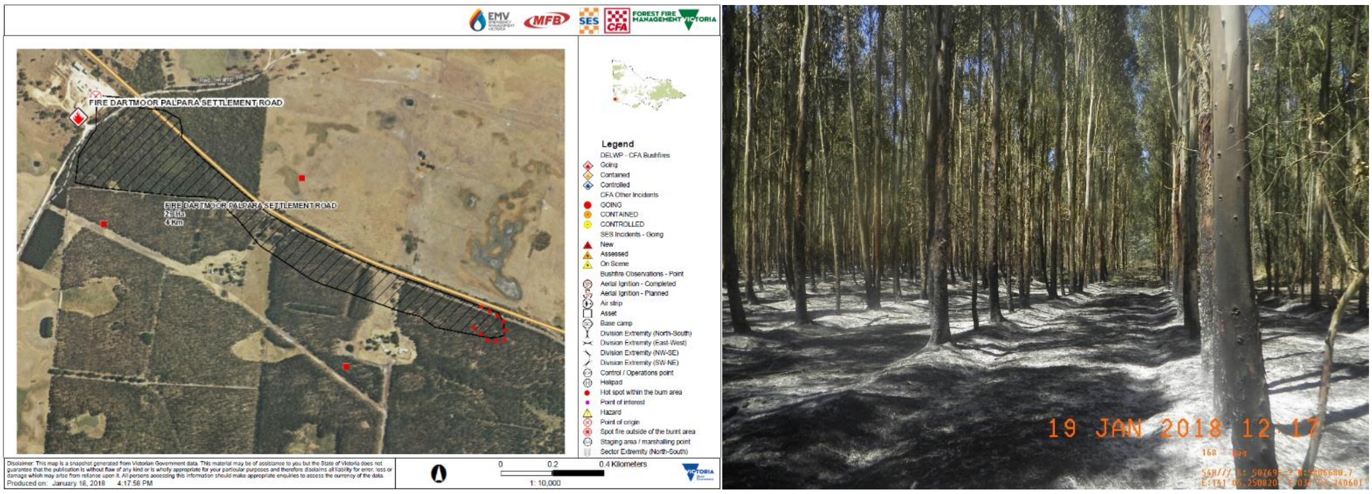

Figure 10.15 Operational map and post-fire photo of native plantation fire. Dartmoor, Victoria © DELWP FireWeb

204 Sir Betram Stevens Drive, Royal National Park (NSW) Shrubland (Heath) 22 January 2018
NFDRS Forecast 5 Observed 5
Issue: FFDI under prediction for heath fire

The Sir Betram Stevens Drive fire started around midday on a busy Saturday in the Royal National Park. The fire escalated rapidly, doubling the rate of spread when it moved from forest into heath. The fire triggered emergency warnings and the evacuation or relocation of local residents and a large number of park visitors (Figure 10.16). The FFDI forecast for the location was 17 (High).

Sydney's Royal National Park bushfire downgraded after burning 600 hectares

ABC NEWS

By Paige Cockburn and Philippa McDonald
Updated 21 Jan 2018, 9:38am

'It shouldn't be this bad'

RFS senior deputy captain John Oakley said the fire took off very quickly despite manageable conditions.

"It shouldn't be this bad yet this has really taken off," he said.

"Sydney and Illawarra are both on very high fire danger, but not on severe.

"There are no total fire bans.

"And there is a north-easterly breeze, so reasonably high humidity and not too strong a wind."

He said firefighting efforts will continue over the next few days.

Currently there are 25 tankers on scene and heavy aerial attacks taking place.

Figure 10.16 News story about heath fire. Sydney, NSW © ABC News; Photo @dinos22

10.2 Fuel parameter data

10.2.1 Fuel hazard scores

Most State data sets did not have values for near-surface fuel. This is a major impediment to implementing the Vesta forest model due to its dependence on near-surface fuel hazard scores and height. There was concern that the approach taken to fill this gap in the Research Prototype could lead to an over estimation of rate of spread.

Where no near-surface fuel hazard value was given, a proxy value was calculated as a proportion of the surface FHS based on the proportion of near-surface to surface in the default FHS values at maximum time since fire (FHSs = 3.5 FHS ns = 3.0) (Cheney *et al.* 2012).

The proportional calculation (FHSns = FHSs * 0.857) was conservative compared to calculations based on the NSW Vesta FHS data set (from Watson *et al.* 2012), which gave a higher proportion (0.9 – 1.1).

It is unclear whether any of the original data (FHRs) included an increase in the surface FHR to account for high near surface fuel (as per McCarthy *et al.* 1999 and DEH 2006), and hence whether the FHSs should have been reduced before making the conversions to FHS.

The alternate options for all affected forest fuel types would have been:

- Reduce surface FHR before converting to FHS and calculating proportional near surface FHS
- Use converted surface FHS but generic near surface FHS
- Use generic values for both surface and near-surface FHS

A comparison was made between the generic values for surface and near-surface FHS and the values in each State fuel parameter table for all forest fuel types. Table 10.2 shows the average hazard score values per State as well as the number of fuel types where the actual value was less than versus greater than or equal to the generic value. This analysis showed that the majority (72%) of forest fuel types had surface and near surface FHS values less than the generic values (Table 10.2). This implies that using the generic values (either for both or just for near surface fuel) would have in general led to greater calculated ROS.

Table 10.2 Analysis of surface and near-surface FHS values

State	Data type	Average value		Number of fuel types with FHSs & FHSns values	
		FHSs	FHSns	Greater than or equal to generic values	Less than generic values
NSW	Vesta data	3.32	3.30	2	4
NSW	Phoenix conversion	3.08	2.64	2	8
NT	Phoenix conversion	2.51	2.15	1	3
QLD	Phoenix conversion	2.96	2.54	11	20
SA	Phoenix conversion	3.10	2.66	4	5
TAS	Phoenix conversion	2.97	2.56	4	14
VIC	Phoenix conversion	3.19	2.73	3	17
WA	Vesta data	3.14	2.78	3	2
WA	Vesta conversion	2.33	2.27	0	3
All	Combined	3.02	2.63	30	76
	Generic values	3.5	3.0		

10.3 Data processing

10.3.1 Scaling process

The scaling process to convert input data sets to the NFDRS 1.5 km forecast grid results in the loss of some fine scale spatial detail. The resolution of input data (fuel and fire history) varied between jurisdictions, with some input in polygon format, and most in raster format ranging from 30 to 250 m resolution.

Basic analysis shows the change is not significant, though this should be assessed in more detail for future data builds.

10.3.1.1 Fuel type

The fuel type grid represents the fuel type (at the most detailed State fuel type level) with the maximum area coverage within each 1.5 km grid cell. The average area covered by the dominant fuel type within a grid cell was 84%, with only 8% of grid cells containing less than 50% of a single fuel type. At a State scale the average ranges from 61% to 92% with a gradient from the smaller south-eastern states (with generally more detailed underlying vegetation mapping) to the north and west (Table 10.3).

Table 10.3 Details of the maximum fuel type calculated per grid cell

Maximum fuel type statistics	National	WA	NT	SA	QLD	NSW	VIC	TAS
Mean percent area of grid cell	84.3	92.1	91.0	86.7	74.9	75.2	71.0	61.3
Minimum percent area of grid cell	15.8	15.5	17.1	16.1	14.9	16.9	14.9	15.2
Maximum percent area of grid cell	100	100	100	100	100	100	100	100
Percent of grid cells with maximum fuel type <50% area of grid cell	7.8	1.9	2.7	4.7	14.4	15.9	17.8	34.0

The descriptive statistics presented earlier in this chapter were calculated at the grid scale. To assess the potential loss of detail in the scaling process, the fuel type coverage was also calculated at the resolution of the input fuel raster (Table 10.4). In most cases the changes are small, the largest changes being a gain in grassland coverage.

Table 10.4 Change in percent fuel type coverage from raster resolution to grid format

Broad Fuel Type	National	WA	NT	SA	QLD	NSW	VIC	TAS
Grassland	2.0	1.7	0.0	1.9	2.8	2.9	6.0	0.8
Savanna	-0.9	0.2	0.2	-1.3	-2.0	-3.4	-0.1	-0.2
Spinifex	-0.2	-1.0	0.0	0.2	0.2	0.0	0.0	0.0
Mallee heath	0.1	0.3	0.0	0.0	0.0	0.1	-0.4	0.0
Heathland	0.0	0.0	0.0	0.1	-0.1	0.0	-0.4	-1.5
Buttongrass	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.4
Forest	0.0	0.1	0.0	0.0	-0.5	0.9	-1.2	1.1
Pine	0.0	0.0	0.0	0.0	0.0	0.1	-0.1	-0.3
Non-combustible	-0.9	-1.2	-0.2	-1.0	-0.4	-0.6	-3.8	-1.2
Maximum change	**2.0**	**1.7**	**0.2**	**1.9**	**2.8**	**3.4**	**6.0**	**1.5**

The decrease in coverage of non-combustible fuels is an effect of the processing method. For grid cells where the maximum area coverage was a non-combustible fuel type with <70% coverage, the fuel type with the second greatest coverage area was used as the dominant fuel type (unless this was also a non-combustible fuel type).

Scale was flagged as an issue in selecting the correct fuel type for 10 observations received during the live trial, all for small fires (0.5 – 60 ha) well below the size of a single grid cell (c. 200 ha). See observation examples 50 and 69 below.

For larger fires in heterogeneous fuels, the evaluator generally had the option of selecting the forecast from a grid cell with the appropriate fuel type, though see the Carwoola case study (Chapter 9).

10.3.1.2 Fire history

The time since fire (TSF) grid represents the mean time since fire within each grid cell. The mean time since fire shows a clear pattern of more recent fires in the northern parts of the country.

To assess the potential loss of detail in the scaling process the statistics calculated during creation of the grid were summarised (Table 10.5). Overall 60% of grid cells had a uniform time since fire (i.e. no impact of the scaling process), though this was very variable between states, with Queensland having very variable data and South Australia having the most uniform data.

Table 10.5 Summary statistics of time since fire grid

Statistic	National	WA	NT	SA	QLD	NSW	VIC	TAS
Mean TSF value		15.9	8.7	24.2	11.9	23.8	25.9	23.4
Mean range within grid cells		3.9	4.7	2.0	12.0	2.6	9.0	6.1
Percent grid cells with uniform TSF (Range = 0)	59.4	66.5	50.2	88.6	22.6	86.6	71.7	68.2

The variance in time since fire is most pronounced where fire history is heterogeneous on a small scale (i.e. less than the 200 ha grid cell size) and in the grid cells around the boundaries of large fires.

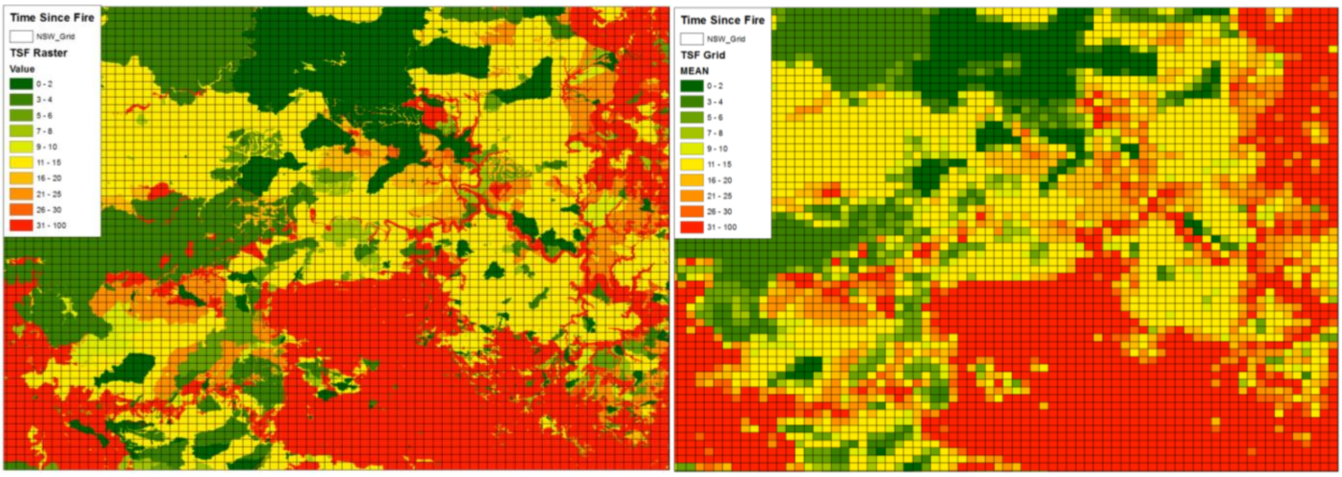

Figure 10.17 Example from NSW time since fire raster (left) and grid (right)

Before calculating the mean time since fire within each grid cell, all base data with no value (e.g. no recorded fire history) was given a value of 25 years since fire. This step could be refined by masking out non-combustible fuel types first so they do not influence the calculations.

Few observations received during the live trial flagged time since fire as an issue in selecting an accurate forecast (see observation example 50 below), however the evaluator is probably less likely to notice the fire history than the fuel type.

10.3.2 Observation examples

50 Woy Woy Bay Fire Trail (NSW) Forest (Wet forest) 13 November 2017

NFDRS Forecast 3 Observed 2

Issue: Scale of fuel heterogeneity; Source map accuracy; Time since fire averaging

The Woy Woy Bay fire was a small (8 ha) fire that occurred in an area of high spatial variability. The fire location was in the corner of a grid cell that was half water, part bushland, and part residential.

The fuel type grid had adjacent cells of wet forest, heath, and dry forest. The vegetation map used as input indicated that the fire area was wet forest (Figure 10.8). The fuel type on the ground was assessed as dry forest by the evaluator who was present on the fireground as RAFT crew. This is an additional issue of accuracy of the underlying mapping.

The time since fire grid has adjacent cells of 14 and 20 years, compared to the value of 30 years in the underlying input data (Figure 10.19).

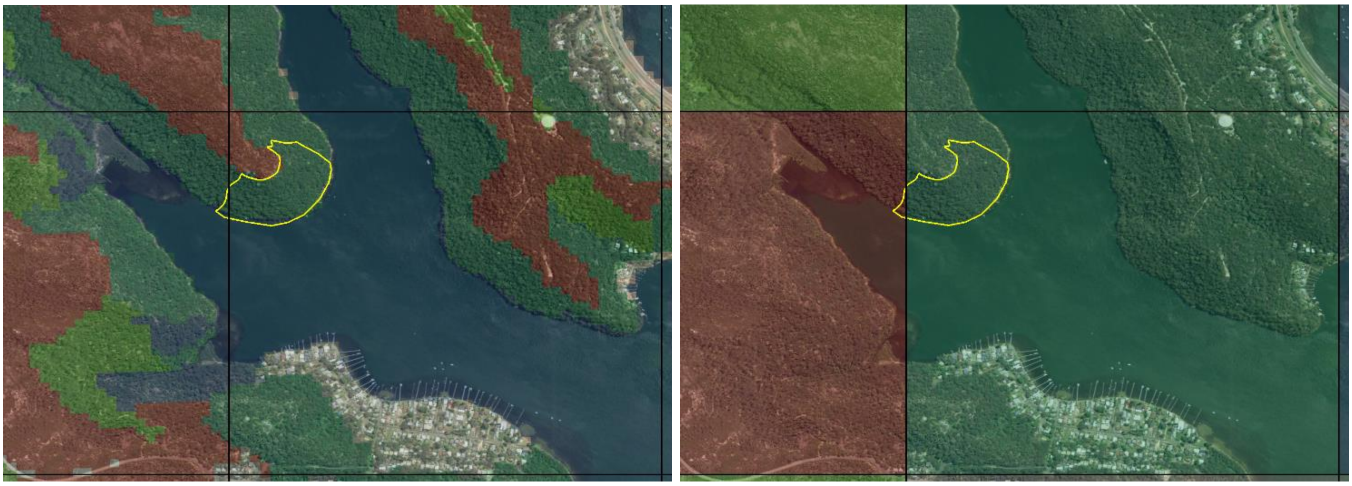

Figure 10.18 Scaling of heterogeneous fuel: Input fuel type (left); Grid scale fuel type (right). Dark green = wet forest; light green = dry forest; dark red = heath; grey = urban; blue = non-combustible. Woy Woy, NSW © RFS ICON & NFDRS data

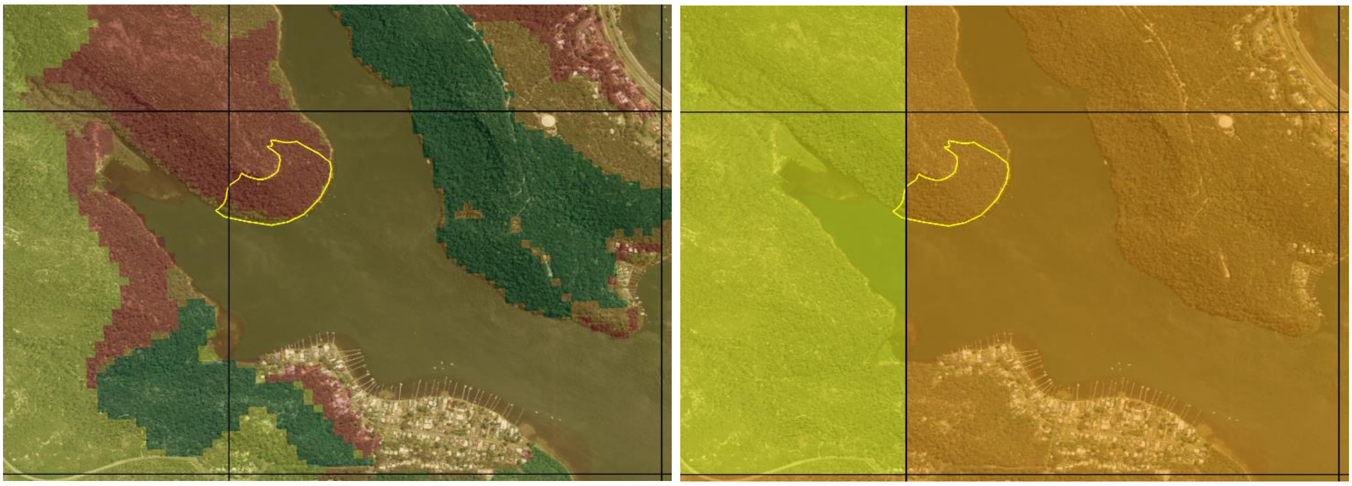

Figure 10.19 Averaging of heterogeneous fire history: Input TSF (left); Grid scale TSF (right). Colour scale: dark green (low TSF), light green, yellow, orange, red (high TSF). Woy Woy, NSW © RFS ICON & NFDRS data

69 Duffy Terrace (WA) Woodland (Urban) 24 November 2017

NFDRS Forecast 2 Observed 3

Issue: Scale of fuel heterogeneity

The Duffy Terrace fire in Woodvale WA was in a small pocket of Banksia woodland and swamp within an urban and industrial area (Figure 10.20). The underlying mapping has some forest and heath but the dominant fuel type within the grid was urban.

Figure 10.20 Fire area (left) and Google Street View (right) of fire in isolated urban bushland. Woodvale, WA © DFES

10.4 Data improvements and application

The Research Prototype was built in a very limited time frame as a proof of concept system. As such the fuel data inputs were based on the most readily available data and were not extensively validated. Significant improvements could be made to the inputs by further consultation with each jurisdiction about the classification applied, additional data sources, and expert validation. Sensitivity analysis of the upscaling process for both fuel type and time since fire could also be of benefit.

Implementation of a NFDRS operational system would require regular updates of the fuel data inputs to ensure the most accurate output. Fire history is a constantly changing input and would require updates at agreed timeframes throughout the fire season. Fuel type and fuel parameters are updated less frequently on an as needs basis, or as new information is collated.

The data sets that the NFDRS was built from are all the responsibility of the individual jurisdictions. Significant work was done to align them with a consistent classification and format. An operational NFDRS system would require a system for data updating, sharing, and formatting that allowed each jurisdiction to maintain custodianship of their data while applying the necessary consistency.

The data sets (fuel type, fuel parameter, and fire history) developed for the Research Prototype represent an important step in the development of nationally consistent data with a direct operational application. There is a wide range of applications for this data beyond the NFDRS including operational agency use, inter-operability between jurisdictions, input to fire spread models, and input to research projects.

11 Daily ratings and fire occurrence data

The live trial evaluation and case studies aimed to understand when and why the NFDRS Research Prototype performed well or poorly by carefully evaluating the behaviour and response to individual fires. In this chapter we take a different approach, looking at broad patterns of fire danger ratings and fire occurrence in Australia to identify trends that may not be apparent when looking at individual incidents.

This chapter uses two data sets:

- Daily fire weather area ratings for each day of the trial and each fire weather area in Australia (Figure 11.1)
- Incident reporting information collected from publicly available information on fire agency websites in each jurisdiction.

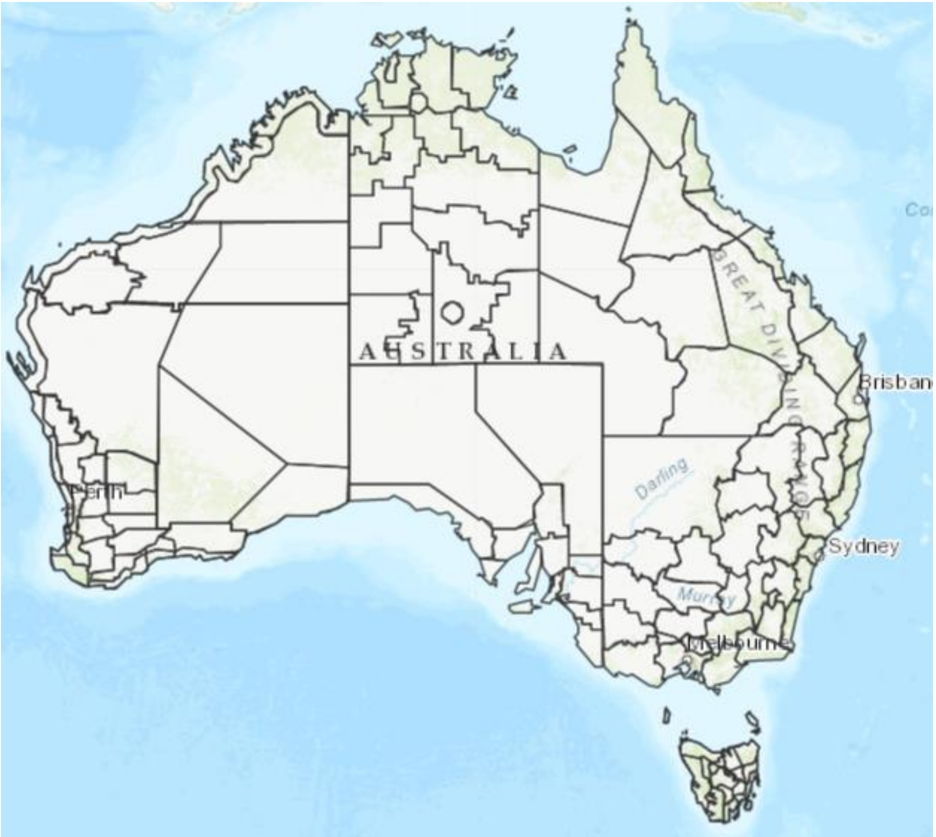

Figure 11.1 Fire Weather Areas of Australia. The size of each area is correlated with population, with smaller areas tending to be associated with heavily populated parts of the country.

11.1 Data collection and processing

All jurisdictions in Australia publish a live feed of going incidents. These are provided in a variety of text formats and also shown on public websites using a map or table based interface to inform the general public about fire and other emergency incidents. A list of these sources is given in Table 11.1 and reported variables in Table 11.2.

The feed from each jurisdiction at any point in time contains a list of incidents with a range of information about each incident. The information for an individual incident is regularly updated, usually at intervals ranging from a few minutes to a few hours. These updates are commonly called situation reports or ‘SitReps’.

To create a record of SitReps for all jurisdictions a simple piece of software was created to:

- Poll each incident feed every 5 minutes;
- Convert to geoJSON feeds that were not in geoJSON format;
- Extract the incident identifier and SitRep publication time of each incident in the feed; and
- Insert SitReps into a database if the combination of state, incident number, and SitRep publication time had not previously been seen (Table 11.3).

To ensure the recording process was as simple and reliable as possible, no post-processing of the SitReps was done. This allowed maximum flexibility in extracting information from SitReps at the end of trial.

Each jurisdiction reported a different collection of information in SitReps (Table 11.2) with incident location and status the only field common to all feeds. The first post-processing step was conversion of all SitReps to a standard set of fields stored in a database table (Table 11.4). Fields that were not available in a jurisdiction's feed were left blank.

From the parsed SitReps a table of fire incidents (Table 11.5) was constructed by:

- Selecting distinct incident identifiers from SitReps that were described as bush fires in the fire type field (Prescribed burns were excluded);
- Extracting basic incident information from the SitReps (Table 11.4) as well as the date-time of the first and last SitReps for each incident; and
- Assigning each incident to the fire weather area in which its location was first reported based on its latitude and longitude.

This process represents minimal handling of the available data. A richer analysis would be possible in the future, particularly if the approach can be tailored to the information provided by each jurisdiction.

Table 11.1 Source of public incident feeds.

Jurisdiction	Feed location
ACT	esa.act.gov.au/feeds/allincidents.json
NSW	feeds.rfs.nsw.gov.au/majorincidents.json
NT	www.pfes.nt.gov.au/incidentmap/json/ntfrsincidents.json
QLD	www.qfes.qld.gov.au/data/alerts/bushfireAlert.xml
SA	data.eso.sa.gov.au/prod/cfs/criimson/cfs_current_incidents.json
TAS	www.fire.tas.gov.au/Show?pageId=bfKml
VIC	emergency.vic.gov.au/public/osom-geojson.json
WA	www.emergency.wa.gov.au/data/incident_FCAD.json

Table 11.2 Fields reported in jurisdictional incident feeds

Field	NSW	ACT	NT	QLD	SA	TAS	VIC	WA
Feed format	GeoJSON	JSON	JSON	XML	JSON	KML	GeoJSON	GeoJSON
Incident id	✓	✓		✓	✓	✓	✓	✓
Update date	✓	✓		✓	✓	✓	✓	✓
Notified or created date		✓	✓	✓		✓	✓	✓
Closed date			✓					
Title	✓	✓		✓		✓	✓	
Warning category	✓	✓		✓		✓		✓
Descriptive location	✓	✓	✓		✓		✓	✓
Region					✓			✓
District					✓			
Local government area	✓							✓
Suburb		✓						✓
Status e.g. going, under control	✓	✓	✓	✓	✓	✓	✓	✓
Incident type e.g. fire, MVA	✓		✓	✓	✓	✓	✓	✓
Fire type e.g. HR, scrub	✓	✓	✓	✓	✓	✓	✓	✓
Is a fire	✓							
Is an incident or warning							✓	
Size – hectares	Sometimes					Sometimes	Sometimes	Sometimes
Size – description e.g small, medium							Sometimes	
Incident level					✓			
Resources					✓	✓	✓	✓
Aircraft					✓			
Agency	✓	✓				✓	✓	
Geometry	Point or polygon	Point	Point	Point	Point	Point	Point or polygon	Point

Table 11.3 Schema for recording raw SitReps

ID	Name	Type	Comment
0	timestamp	INTEGER	UTC timestamp when processed
1	state	TEXT	2/3 letter jurisdiction code
2	id	TEXT	Incident identifier
3	sitrep_id	TEXT	Sitrep identifier (publication time for most jurisdictions)
4	sitrep_geojson	TEXT	Sitrep content converted to geoJSON but not parsed
5	parsed	BOOLEAN	Flag indicating whether row has been parsed

Table 11.4 Schema for processed SitReps

ID	Name	Type	Comment
0	timestamp	INTEGER	UTC timestamp when processed
1	state	TEXT	2/3 letter jurisdiction code
2	incident_id	TEXT	Incident identifier
3	sitrep_id	TEXT	Sitrep identifier (publication time for most jurisdictions)
4	title	TEXT	
5	notified_date	DATETIME	UTC date time: YYYY-MM-DD HH:MM:SS
6	update_date	DATETIME	UTC date time: YYYY-MM-DD HH:MM:SS
7	closed_date	DATETIME	UTC date time: YYYY-MM-DD HH:MM:SS
8	status	TEXT	
9	warning_category	TEXT	
10	incident_level	INTEGER	
11	fire_type	TEXT	
12	descriptive_location	TEXT	
13	lat	FLOAT	
14	lon	FLOAT	
15	size_description	TEXT	
16	size_ha	FLOAT	
17	resources	INTEGER	
18	aircraft	INTEGER	
19	agency	TEXT	

Table 11.5 Schema for fire incidents

ID	Name	Type	Comment
0	timestamp	INTEGER	UTC timestamp when processed
1	state	TEXT	2/3 letter jurisdiction code
2	incident_id	TEXT	Incident identifier
3	title	TEXT	
4	first_seen_date	DATETIME	UTC date time: YYYY-MM-DD HH:MM:SS Derived from the first time the incident appears in the SitRep table
5	under_control_date	DATETIME	UTC date time: YYYY-MM-DD HH:MM:SS Derived from SitRep content
6	last_seen_date	DATETIME	UTC date time: YYYY-MM-DD HH:MM:SS Derived from the last time the incident appears in the SitRep table
7	max_warning_category	TEXT	Highest of ['Advice','Watch and Act','Emergency Warning'] where reported
8	lat	FLOAT	
9	lon	FLOAT	
10	max_size_ha	FLOAT	Maximum of all fire sizes where reported
11	agency	TEXT	
12	fire_weather_area_code	TEXT	Determined using incident lat-lon
13	fire_weather_area_name	TEXT	Determined using incident lat-lon
14	first_seen_local	DATETIME	Local date when incident was first seen: YYYYMMDD Used to align incidents with ratings

11.2 Descriptive statistics

During the six months of the live trial 322, 675 unique SitReps were recorded. After processing to remove non-fire related incidents, this corresponded to 31,945 fire incidents. For remote parts of Australia, fire reporting was not a good proxy for actual fire occurrence. Figure 11.2 shows reported incidents (left) and burnt area mapped by the MODIS satellite for the tropics (right). These maps show large burned areas without corresponding incident markers, indicating that for remote fuel types incident reporting is most likely to occur if the fire occurs near human activity. This is particularly noticeable in the Northern Territory map (Figure 11.2 - left) where most incidents were reported near Darwin, Katherine, and Alice Springs. This difference between reporting and occurrence means that use of the database to understand or model fire ignition should be limited to areas with sufficient population density to ensure most or all fires are reported and recorded as incidents. For the present, limited study, we discuss general trends in the data and leave more detailed analyses to future studies.

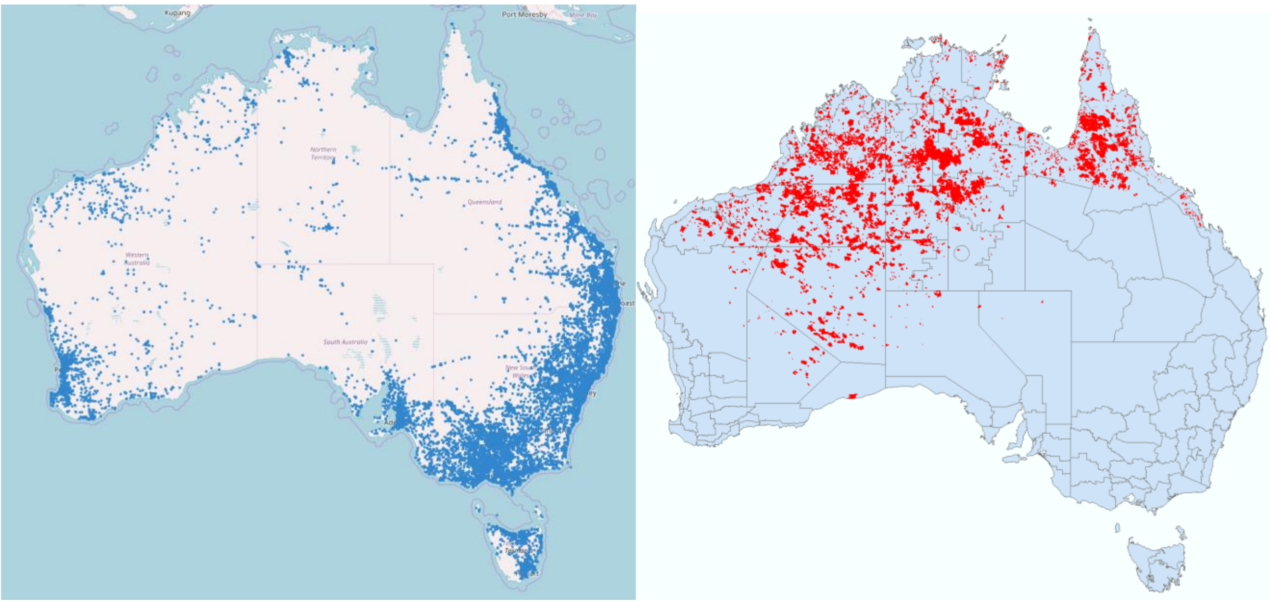

Figure 11.2 (Left) Fire incidents from public information data feeds. Fires are represented as points regardless of final area. (Right) Burned area derived from 250m resolution MODIS images for the live trial period. Data courtesy of the Northern Australia and Rangelands Fire Information site[19] (right).

Table 11.6 Number of fire incidents by NFDRS fuel type within each state.

Model used	ACT	NSW	NT	QLD	SA	TAS	VIC	WA	Total
Buttongrass	-	-	-	-	-	4	-	-	4
Forest	11	2,379	1	1,921	40	366	1,311	436	6,465
Grass	76	3,086	4	1,912	970	334	3,492	745	10,619
Shrubland	-	79	-	41	7	20	23	110	280
Mallee heath	-	40	-	-	23	-	11	122	196
Pine	1	51	-	60	12	17	53	10	204
Savanna	67	4,224	1,298	2,375	608	725	986	1,547	11,830
Spinifex	-	3	158	59	10	-	7	293	530
Non-combustible	-	161	-	1,491	32	46	61	26	1,817
Total	155	10,023	1,461	7,859	1,702	1,512	5,944	3,289	31,945

[19] http://www.firenorth.org.au/nafi3/. Accessed 1 May 2018.

To estimate the frequency of opportunities to observe fires in each of the eight NFDRS major fuel types, the frequencies of incidents in each fuel type was calculated. For each fire incident in the database, fuel type was assigned by determining the fuel type code each of the incident's coordinates. The fuel type code for each incident was then used to select the fire behaviour model in the NFDRS calculations. There are important caveats on the accuracy of this data including:

- The fuel type at the incident location may not be representative of all fuels burned by a fire, in addition to which the mapped location may not be accurate;
- This data can only represent fires captured in agency reporting systems; and
- Inspection of fires mapped as being in non-combustible fuels showed them to be mainly fires in small pockets of vegetation in urban and suburban areas. The relatively high number of these fires in QLD may be due to limitations in the information that is included in the dataset about fire type.

Bearing these limitations in mind there are still some interesting features of this dataset, particularly:

- Almost 96% of fires were recorded in forest, grass, or savanna fuel types (excluding fires in non-combustible pixels). This means that the current grass-forest fuel division could be made to cover the vast majority of fires if grassy fuels were remapped to distinguish grassland from savanna.
- There were relatively few opportunities to observe fires in other fuel types. This may partially explain why most observations in the evaluation database were for grass or forest fires.
- The relative rarity of fires in other fuel types does not mean they can be safely ignored as these fuel types may occur near populated areas (e.g. coastal heath around Sydney),have high economic value (e.g. pine plantations) or make up large proportions of Australia's land mass (e.g. spinifex).
- The fires included in the live trial data set represent about 1% of recorded incidents.

11.3 Analysis of ratings

Histograms of daily NFDRS ratings are shown for each jurisdiction in in Figure 11.3, with counts tabulated in Table 11.7. For this analysis, the ACT fire weather area was captured within NSW. Several interesting patterns are evident in these figures, including:

- There were very few Category 1 ratings. This partly reflects that the live trial was run over the southern summer. It is also partly a function of the use of the 90th percentile pixel rating to set the area rating, so that it required only a small area of dry fuel or of one of the rapidly drying fuel types such as shrubland or spinifex to set the rating at one of the higher categories;
- For all jurisdictions the most common rating was either Category 3 (NSW, VIC, QLD, TAS) or Category 4 (SA, WA, NT). It is likely that the higher ratings for those jurisdictions with more Category 4 forecasts was due to the prevalence of savanna fuels (which do not have Category 3) in many fire weather areas. Combined analysis of observations from fuel types with differing numbers of categories needs to be carefully considered.
- A very large number of Category 5 ratings were recorded, far more than is reasonable if this category is assumed to correspond with the issuing of total fire bans. For example, in NSW the NFDRS produced 175 area ratings of Category 5 or 6 compared to the 69 Total Fire Bans that were actually issued using the current system. A definitive assessment of over- or under-forecasting is not currently possible as there is no agreed standard for validating the correctness of fire weather area ratings. A similar tendency to over-predict ratings was also evident in the live trial analysis. While some of the ratings were due to issues with application of the spinifex model (See below), adjustment of the calculation system to give sensible distributions of ratings is a high priority for future work on the NFDRS system.
- Category 6 ratings were recorded in NSW (n = 5), VIC (n = 5), SA (n = 27) and WA (n = 1).

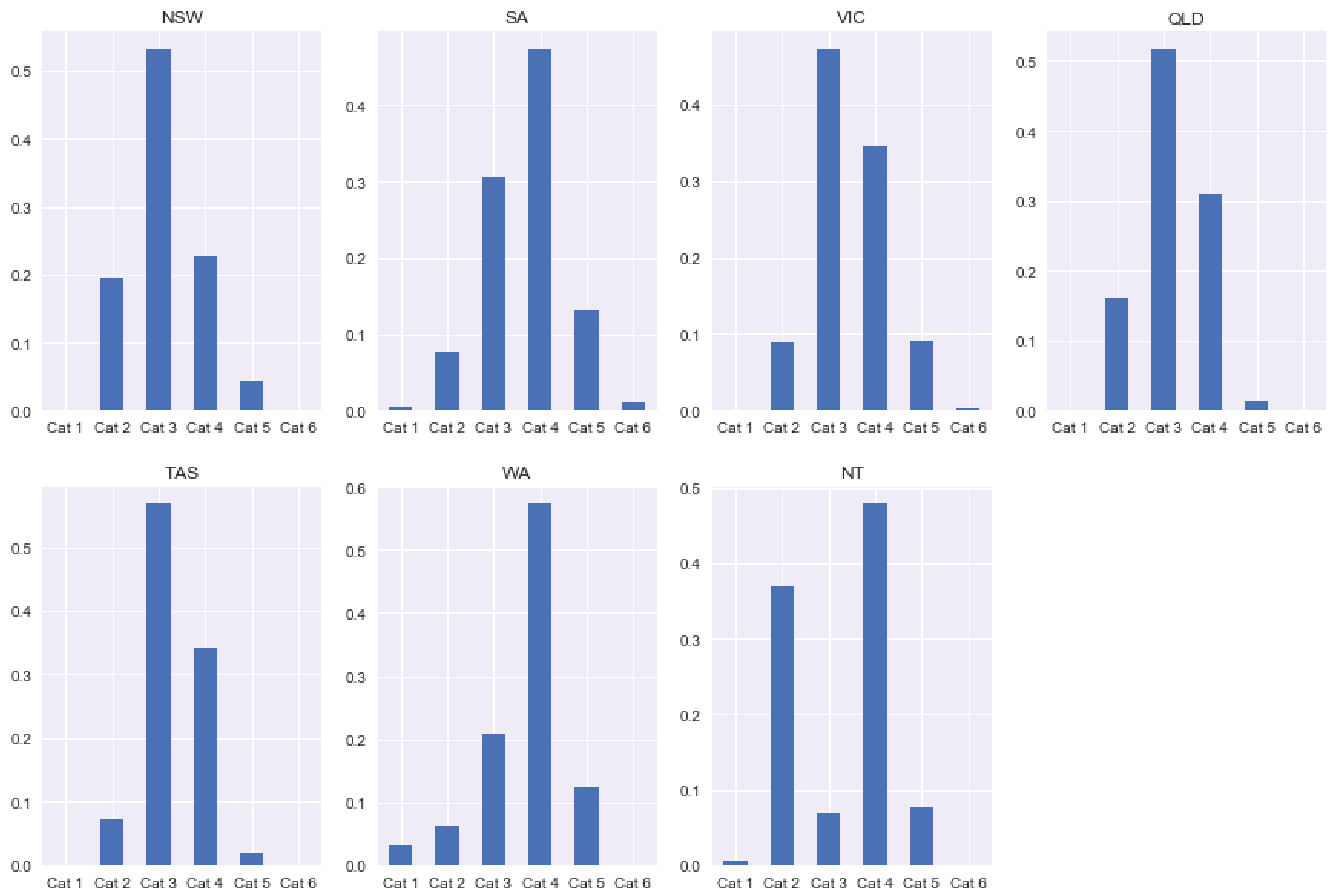

Figure 11.3 Relative frequencies of NFDRS rating categories calculated from daily fire weather area ratings in each state.

Table 11.7 Counts of NFDRS daily fire weather area ratings for each jurisdiction and category.

Rating	ACT/NSW	SA	VIC	QLD	TAS	WA	NT
Category 1	1	11	0	0	0	235	22
Category 2	746	211	145	435	141	433	1311
Category 3	2032	838	777	1402	1167	1533	242
Category 4	868	1296	570	839	705	4130	1693
Category 5	170	353	150	39	37	909	272
Category 6	5	20	5	0	0	1	0

Table 11.8 Dates with Category 6 fire weather area ratings

Date	Fire weather area	
13/12/2017	SA_FW002	Yorke Peninsula
	SA_FW004	Upper South East
	SA_FW005	Lower South East
	SA_FW007	Murraylands
	SA_FW008	Mid North
	SA_FW015	Mount Lofty Ranges
27/12/2017	SA_FW002	Yorke Peninsula
	SA_FW008	Mid North
	SA_FW011	Eastern Eyre Peninsula
	SA_FW015	Mount Lofty Ranges
6/1/2018	SA_FW001	Adelaide Metropolitan
	SA_FW002	Yorke Peninsula
	SA_FW004	Upper South East
	SA_FW005	Lower South East
	SA_FW006	Riverland
	SA_FW007	Murraylands
	SA_FW008	Mid North
	SA_FW012	Lower Eyre Peninsula
	SA_FW015	Mount Lofty Ranges
	VIC_FW001	Mallee
	VIC_FW002	Wimmera
	VIC_FW007	Central
	VIC_FW008	North Central
	VIC_FW009	South West
7/1/2018	NSW_FW004	Greater Sydney Region
12/1/2018	WA_FW004	East Pilbara Coast
18/1/2018	SA_FW005	Lower South East
19/1/2018	SA_FW002	Yorke Peninsula
	SA_FW008	Mid North
	SA_FW015	Mount Lofty Ranges
14/2/2018	NSW_FW004	Greater Sydney Region
	NSW_FW005	Illawarra/Shoalhaven
18/3/2018	NSW_FW004	Greater Sydney Region
	NSW_FW005	Illawarra/Shoalhaven

11.4 Distribution of Category 5 and 6 ratings

While methods for mapping Research Prototype rating categories to the issuing of Total Fire Bans (TFB) have not been developed, it is likely that Categories 5 and 6 align with TFB conditions on the basis of the suppression and impact components of the rating definitions. This means that the relatively large number of the ratings in Table 11.7 suggests that the system would over-warn if it was used to issue TFBs as it is currently configured. Figures 11.4 to 11.10 show the days on which Category 5 and 6 ratings were assigned to each fire weather area (FWA) in each state. The NSW, SA, NT and Victoria plots (Figure 11.4) also shows days and fire weather areas for which TFBs were actually issued using the current system. TFBs in other states are issued for areas that do not align with fire weather areas.

For some FWAs Category 5 ratings were assigned for a high proportion of days. Examples include the South Western area in NSW and the Mallee area in Victoria. Analysis of fuel type distributions (See Chapters 4 and 10) showed that FWAs with consistent Category 5 ratings were mainly those with at least 10% coverage of spinifex fuels, allowing spinifex fuels to drive the ratings. Closer examination of data during the live trial also showed a tendency for spinifex fuels to drive a forecast of Category 4 or 5 ratings, unless they were recently burned or were wet. This suggests that a closer examination of spread modelling and the thresholds used to define NFDRS categories within spinifex fuels is required to eliminate any tendancy to over predict that may exisit.

For NSW, of the 170 Category 5 ratings, 74 were calculated for the South Western area, meaning that improving handling of spinifex fuels is likely to significantly reduce over-warning. Across the other FWAs, the tendency for Category 5 and 6 to be issued appears to be more in line, but still more than current practice of TFB issued. There were 14 extra days with TFBs and more areas affected on some days with 27 more TFBs implied than were actually issued. A more thorough examination of fuel and fire models and rating definitions is required to ensure appropriate thresholds are used to trigger the issue of TFBs. It would be a valuable future exercise to relate issued TFBs with significant fires.

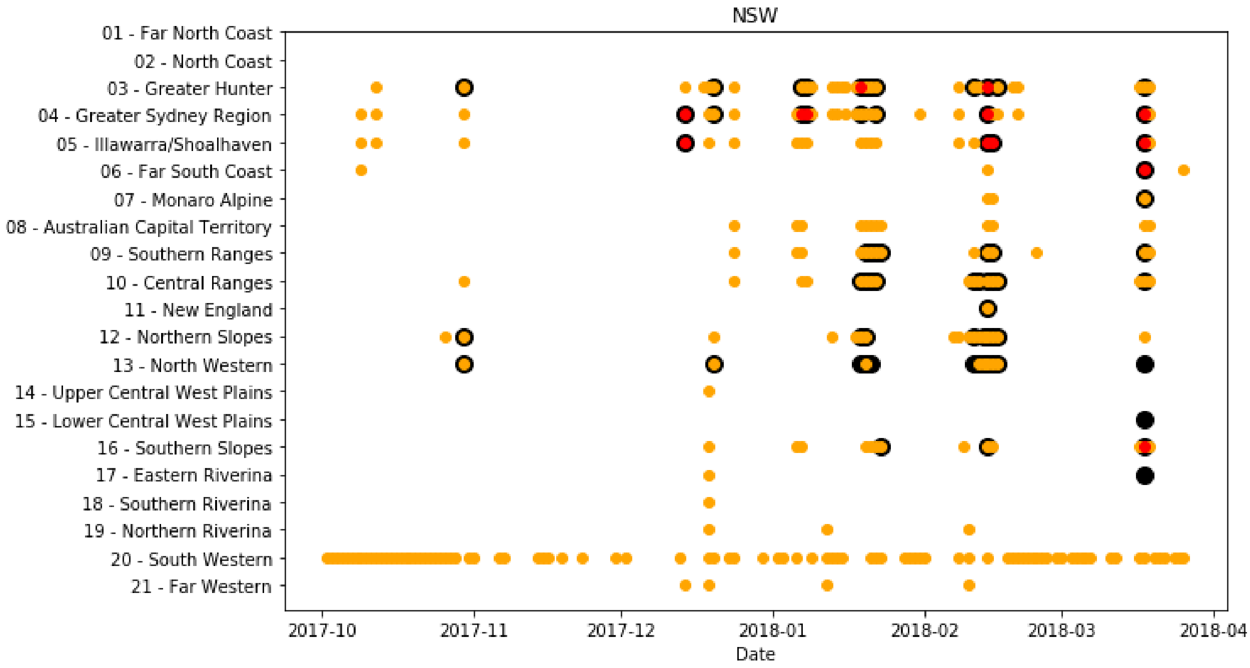

Figure 11.4 Dates and fire weather areas with Research Prototype Category 5 (orange dots) and 6 (red dots) ratings in NSW. Black dots indicate Total Fire Bans issued using the current system.

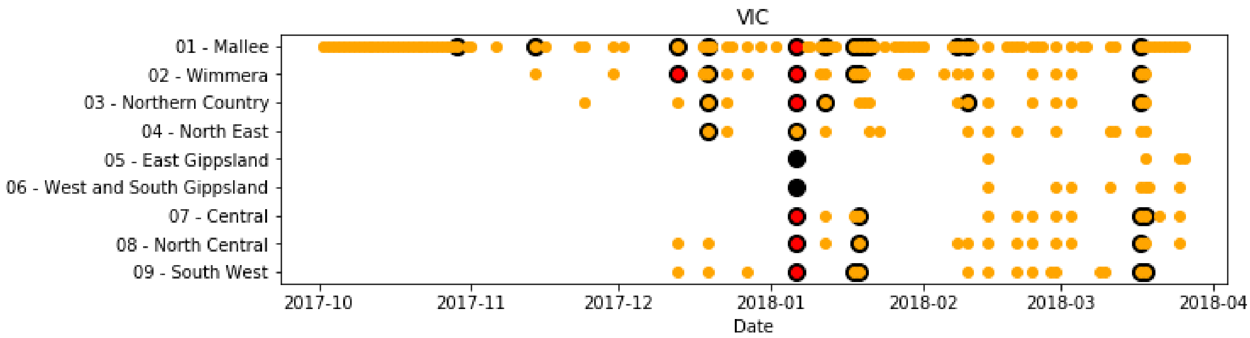

Figure 11.5 Dates and fire weather areas with Research Prototype Category 5 (orange dots) and 6 (red dots) ratings in Victoria. Black dots indicate Total Fire Bans issued using the current system.

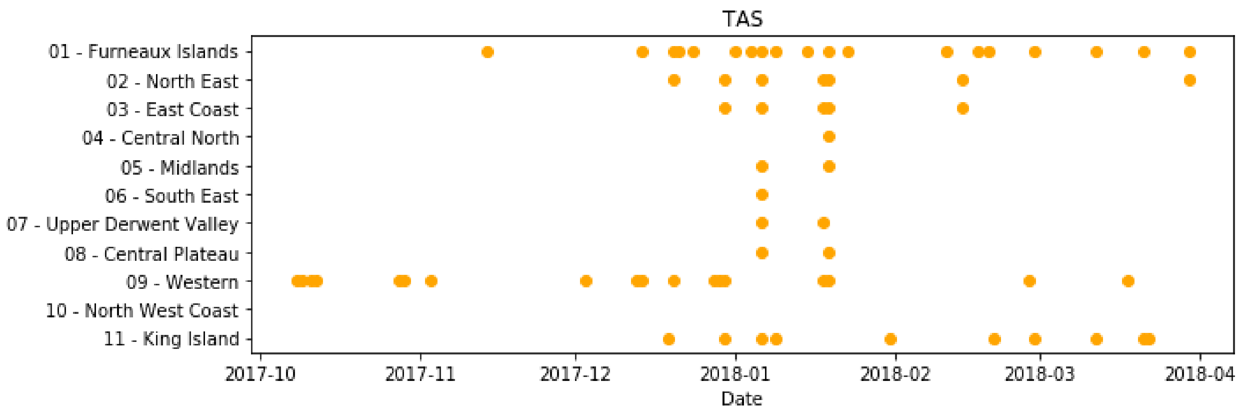

Figure 11.6 Dates and fire weather areas with Research Prototype Category 5 (orange dots) and 6 (red dots) ratings in Tasmania.

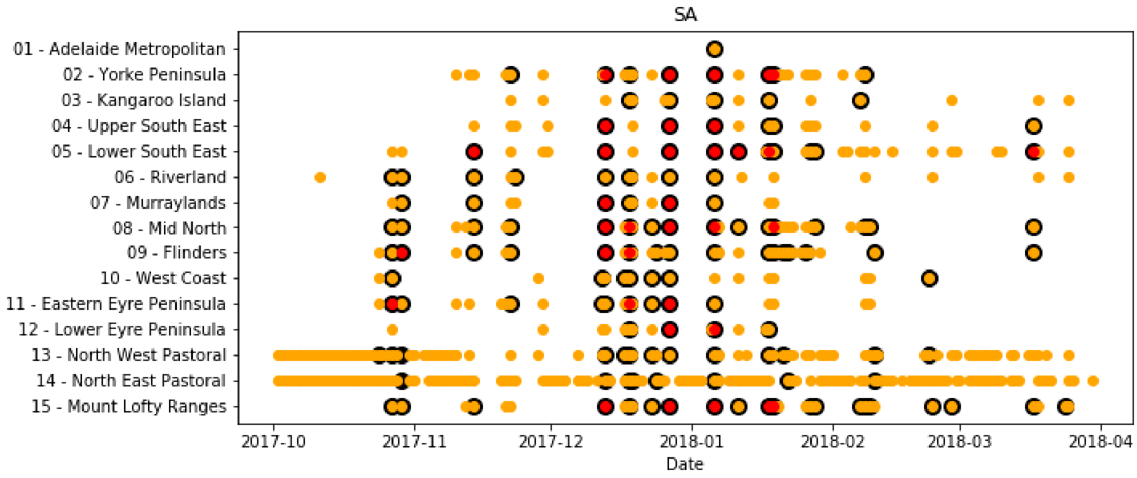

Figure 11.7 Dates and fire weather areas with Research Prototype Category 5 (orange dots) and 6 (red dots) ratings in South Australia. Black dots indicate Total Fire Bans issued using the current system.

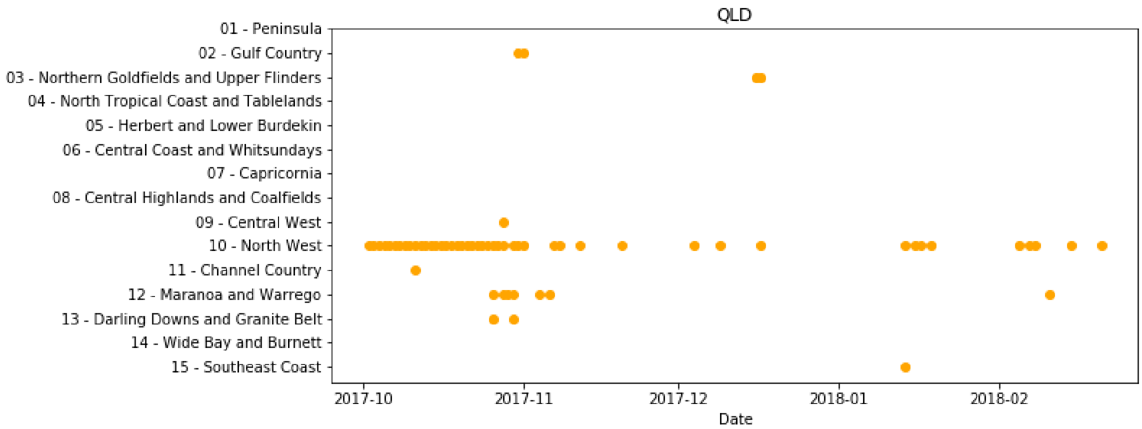

Figure 11.8 Dates and fire weather areas with Research Prototype Category 5 (orange dots) and 6 (red dots) ratings in Queensland.

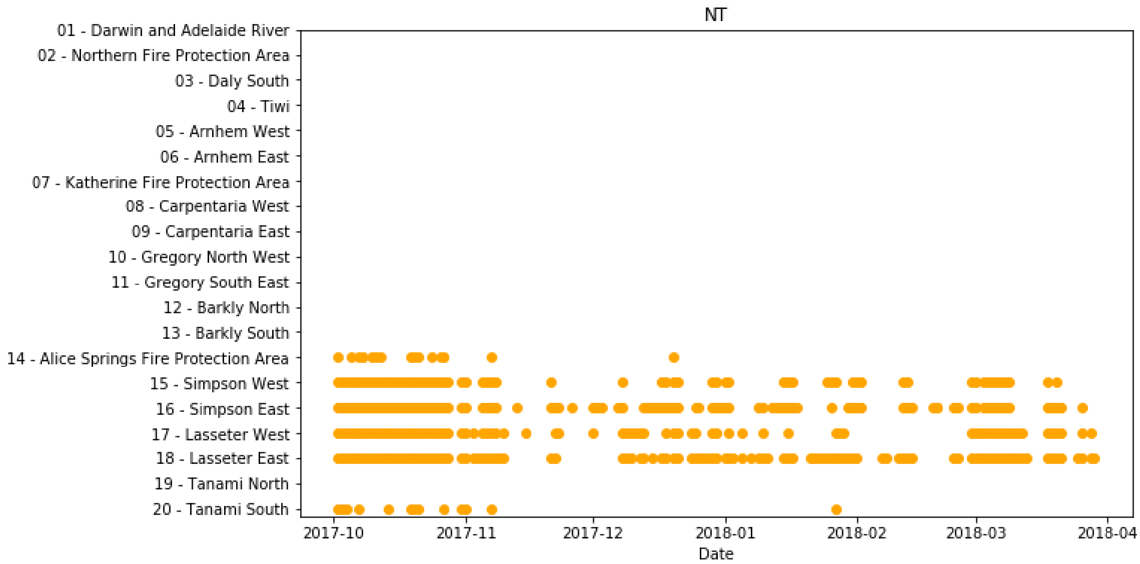

Figure 11.9 Dates and fire weather areas with Research Prototype Category 5 (orange dots) and 6 (red dots) ratings in the Northern Territory. No Total Fire Bans were issued during the trial period.

Figure 11.10 Dates and fire weather areas with Research Prototype Category 5 (orange dots) and 6 (red dots) ratings in Western Australia.

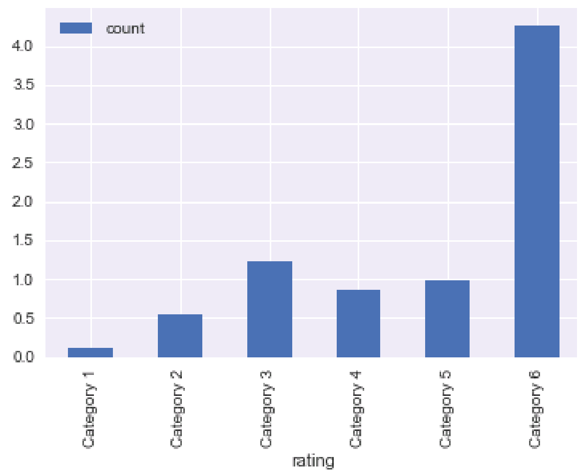

Figure 11.11 Average number of reported new fires per rating category averaged over the live trial period for Australia.

11.5 Analysis of fire starts

The number of new fires was related to fire weather area ratings by associating each fire incident with the local date on which it was first recorded in the database as well as the fire weather area in which its reported location occurred. The number of new fires was then counted for each day and fire weather area. The average number of ignitions for each NFDRS category are presented in Figure 11.11. Histograms of number of ignitions for each category (Figure 11.12) for the whole country and for each jurisdiction (again merging ACT into NSW for this analysis). Days with 10 or more ignitions in a single fire weather area are combined into a single 10+ bin to better represent days with a high number of new fires.

As well as the issues with under-reporting of remote fires already discussed, this analysis is also likely to be impacted by the varying number and size of fire weather areas in each jurisdiction (Figure 11.1). No attempt has been made to scale number of fires to the areas of the fire weather areas because it is not clear how this should be done. Although some FWAs are very much larger than others, the larger areas are generally also more remote and likely to suffer under-reporting.

Across the country, the number of new fires tended to increase with rating category (Figure 11.11), although there was a small drop from Category 3 to 5. This may be explained by some mix of over-forecasting or ratings, lack of Category 3 in some fuel types, and under-reporting of fires in remote FWAs dominated by savanna and spinifex fuel types.

For all rating categories, the most common number of daily new fires in each FWA was zero (Figure 11.12). This result highlights the importance of ignition sources in addition to fuel and fire weather. There was a slight trend to increasing number of 10+ ignition days with rating class and a large drop in the chance of no fires at Category 6.

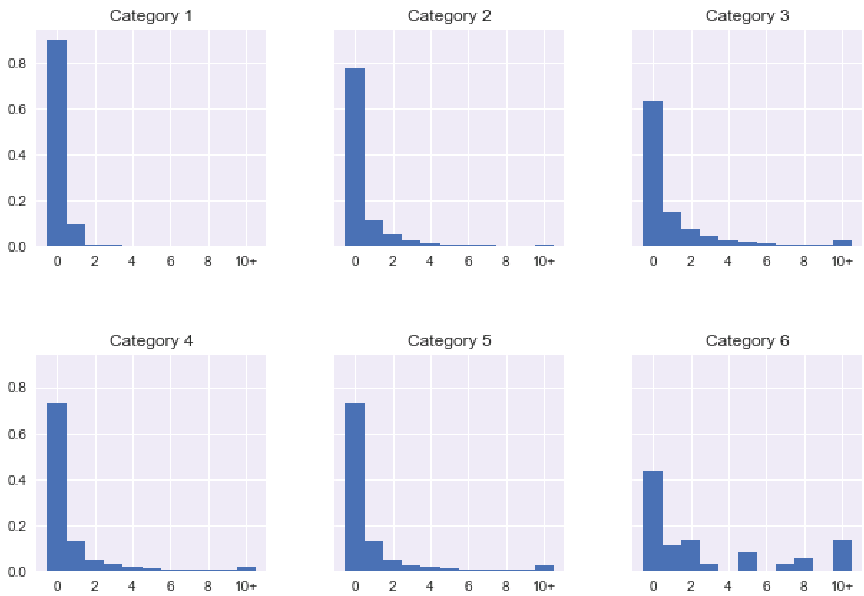

Figure 11.12 Relative frequency of the number of reported new fires per rating category averaged over the live trial period for Australia. Entries with 10 or more new fires are combined into a 10+ bin.

11.5.1 New South Wales and Australian Capital Territory

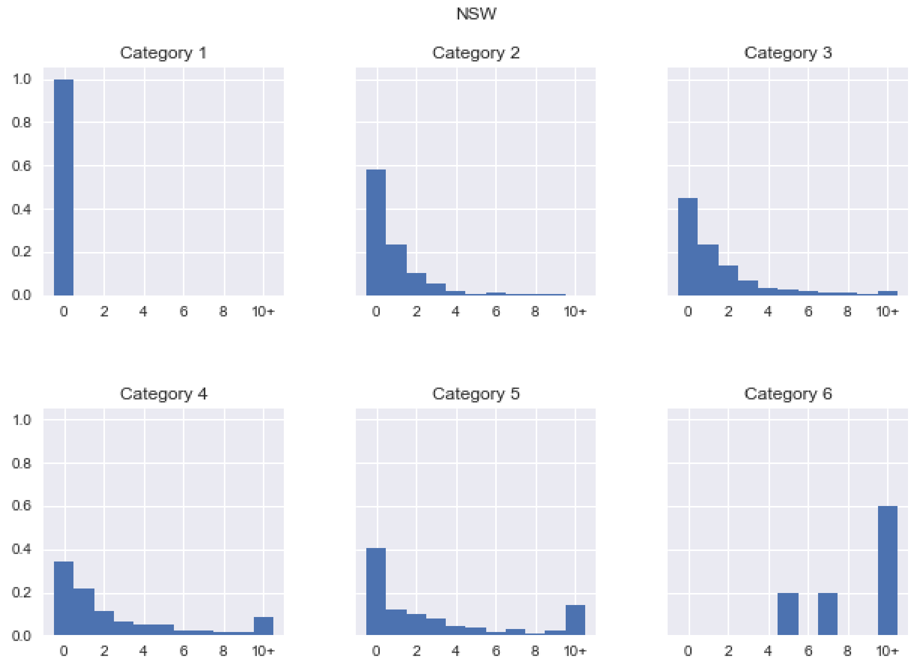

Figure 11.13 Relative frequency of the number of reported new fires per rating category averaged over the live trial period for NSW and ACT.

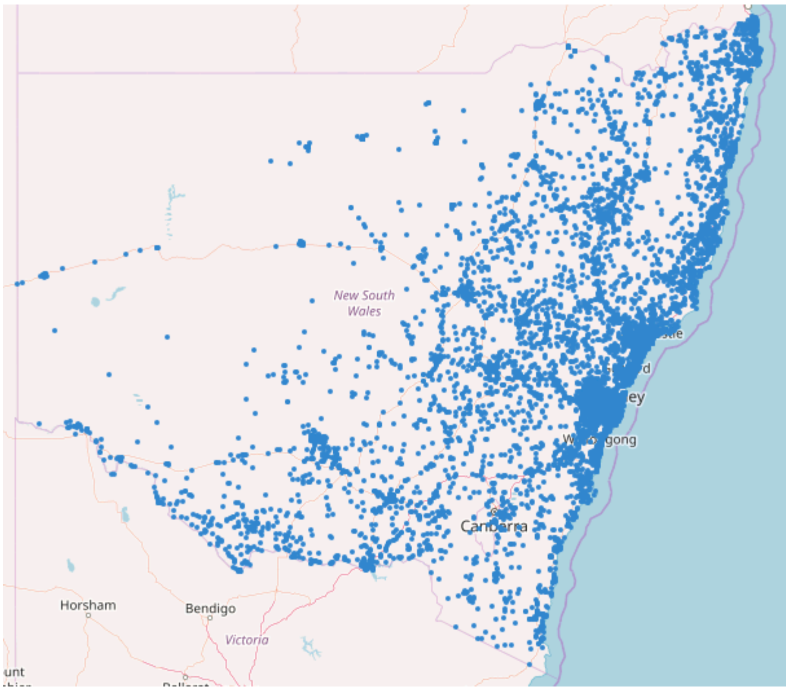

Figure 11.14 Locations of reported fires during the live trial period in NSW and ACT.

The chance of having 10 or more new fires increased consistently with rating category in NSW. While there was a general decrease in the chance of no fires, there was a slight increase between Categories 4 and 5. All five Category 6 days resulted in at least five new fires.

11.5.2 Victoria

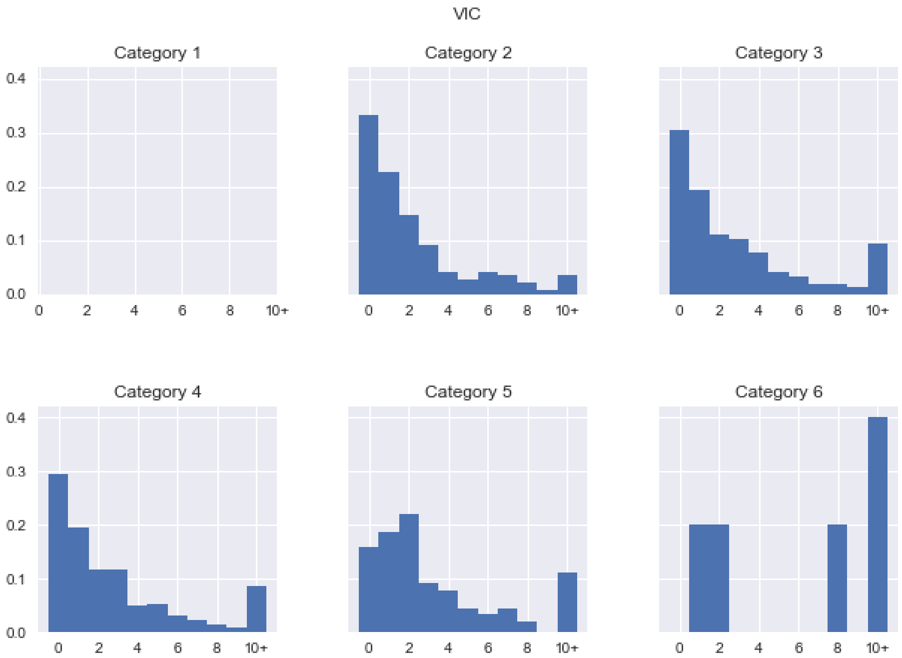

Figure 11.15 Relative frequency of the number of reported new fires per rating category averaged over the live trial period for Victoria

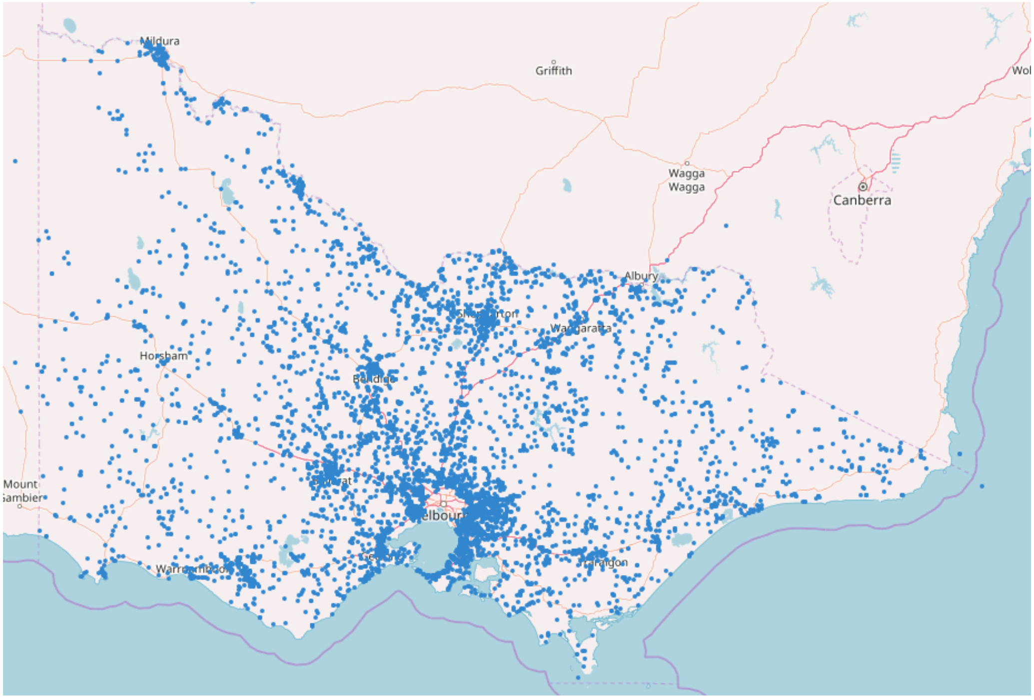

Figure 11.16 Locations of reported fires during the live trial period in Victoria.

The probability of no fires was much lower than the national average for all rating categories in Victoria, probably reflecting the fact that most fires would have been reported due to the relative small proportion of the state being remote from populated areas. The frequency of 10+ fire days was lowest for Category 2 days and highest for Category 6 with Categories 3 to 5 intermediate however trends are not apparent. At Category 5 the chance of zero fires was less than 1 or 2 fires. These results suggest that in areas where most fires are reported the fire danger rating has potential to forecast the chance of having at least one, or more than 10 fires.

11.5.3 Tasmania

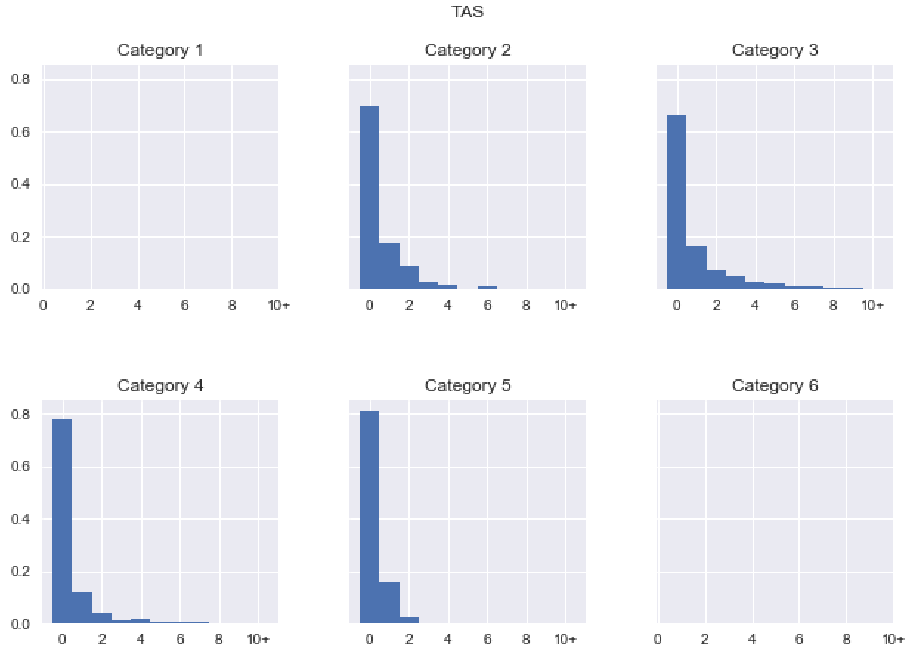

Figure 11.17 Relative frequency of the number of reported new fires per rating category averaged over the live trial period for Tasmania.

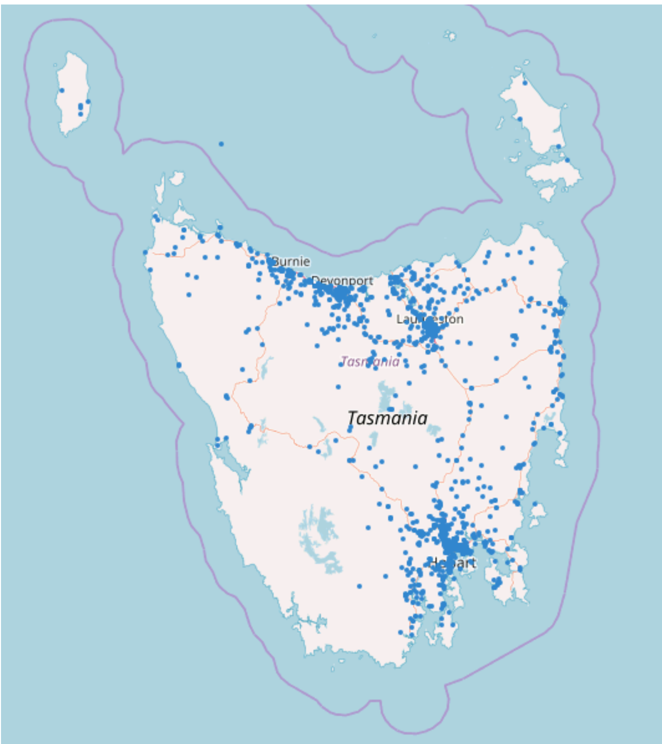

Figure 11.18 Locations of reported fires during the live trial period in Tasmania.

No Category 1 or 6 ratings were recorded for Tasmania. The frequency of larger numbers of new fires was higher in the tails of the distributions for Categories 3 and 4 with two or fewer new fires for Category 5 ratings. This suggests an over-representation of Category 5 ratings likely due to relatively large areas of heath vegetation, which is sensitive to wind but less sensitive moisture during the damp windy conditions common in parts of Tasmania.

11.5.4 South Australia

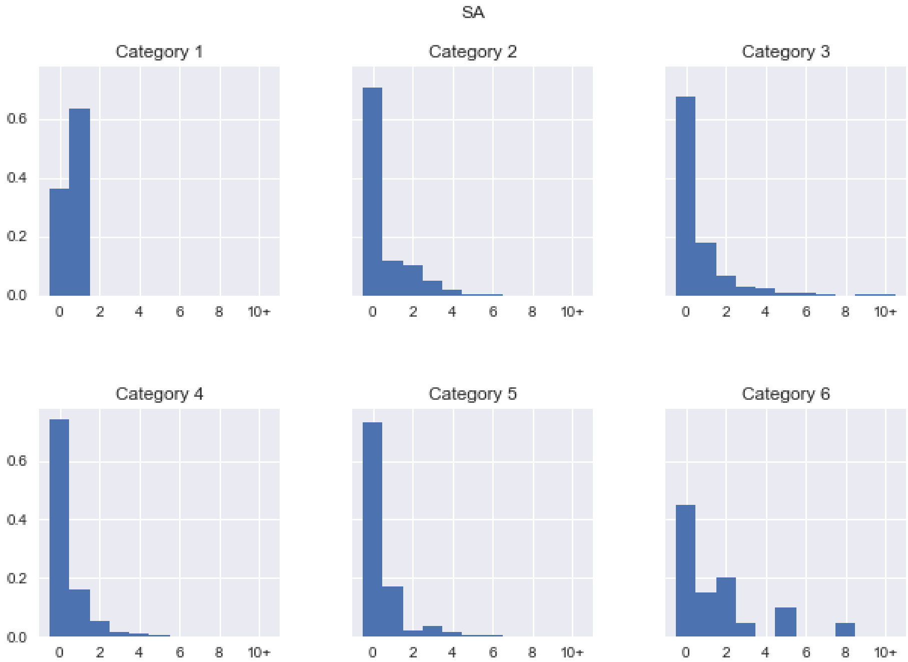

Figure 11.19 Relative frequency of the number of reported new fires per rating category averaged over the live trial period for South Australia.

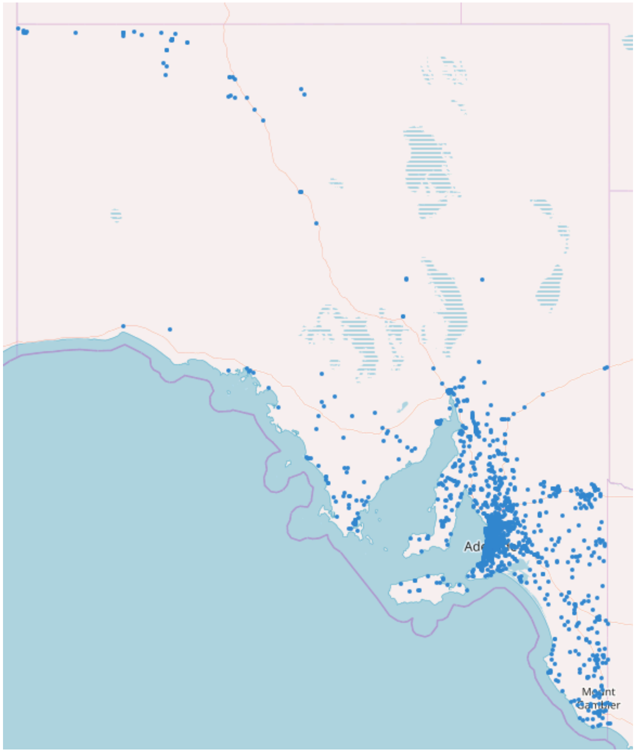

Figure 11.20 Locations of reported fires during the live trial period in South Australia.

Although relatively few fires were reported in remote parts of South Australia, the northern and western parts of the state are covered by three very large fire weather areas (Figure 11.1). Despite this, a clear trend in new ignitions was not evident for Categories 2 to 5. For the Category 6 forecasts, which were concentrated in the south east of the state, larger numbers of ignitions were more frequent than at lower ratings.

11.5.5 Queensland

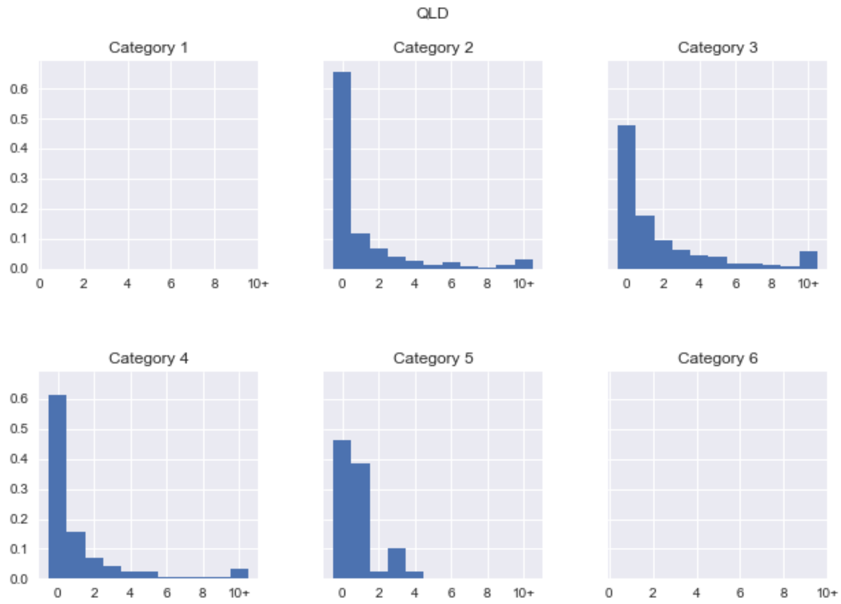

Figure 11.21 Relative frequency of the number of reported new fires per rating category averaged over the live trial period for Queensland.

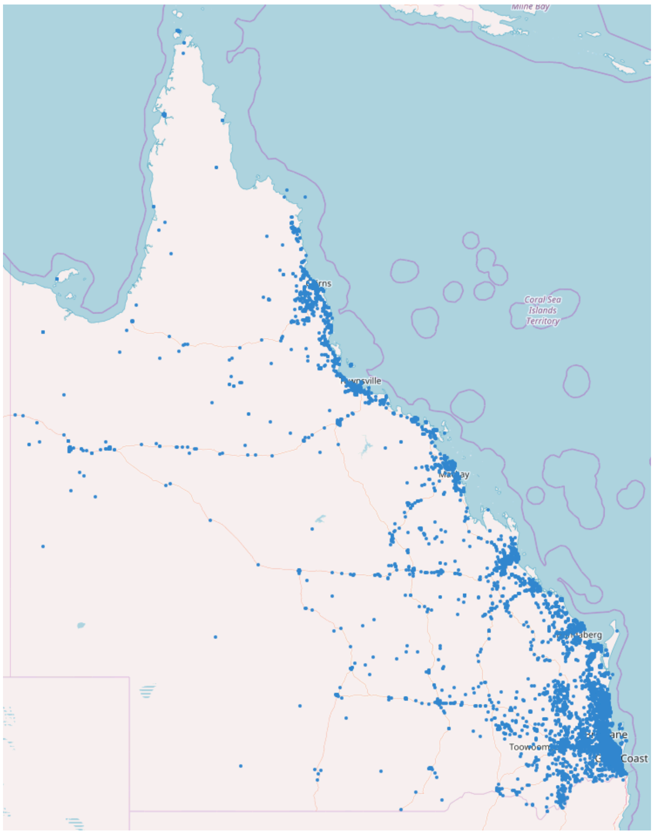

Figure 11.22 Locations of reported fires during the live trial period in Queensland.

As with the other large jurisdictions covering remote areas around Australia, it is likely that incidents were not published for fires away from the coast and major inland roads. In spite of this, there were some trends in the data, with decreasing chance of no new fires from Categories 2 to 5 and an increase in 10+ new fires from Categories 2 to 4.

11.5.6 Northern Territory

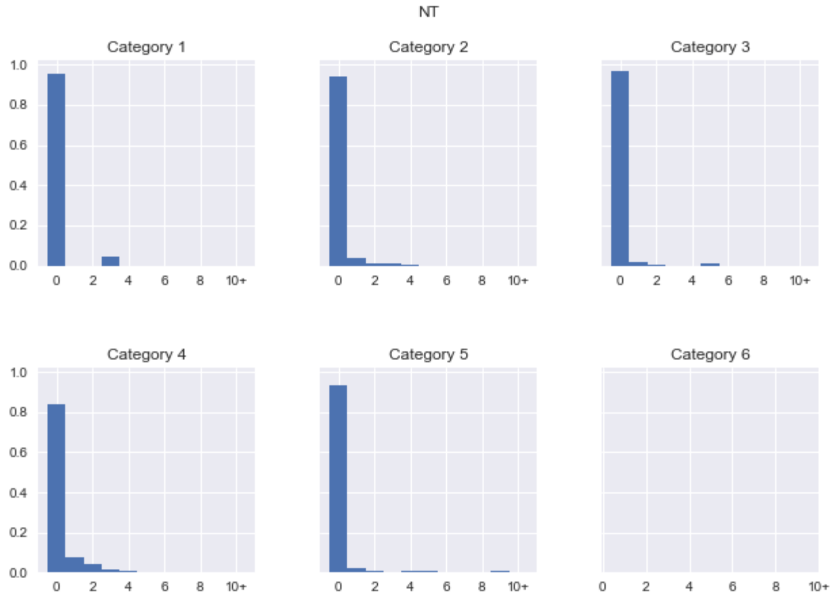

Figure 11.23 Relative frequency of the number of reported new fires per rating category averaged over the live trial period for the Northern Territory.

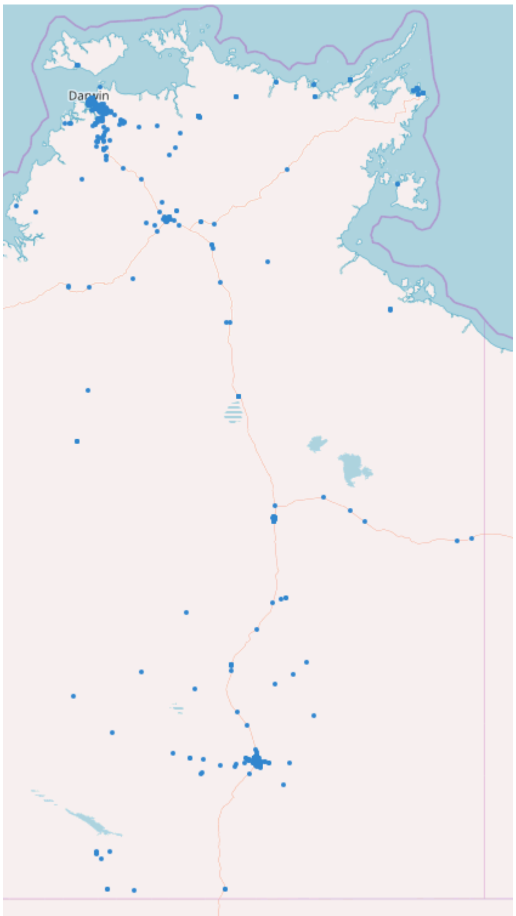

Figure 11.24 Locations of reported fires during the live trial period in the Northern Territory.

Because such a small proportion of fires in the Northern Territory are reported, occurrence statistics are not meaningful, nor were there any apparent patterns in the data.

11.5.7 Western Australia

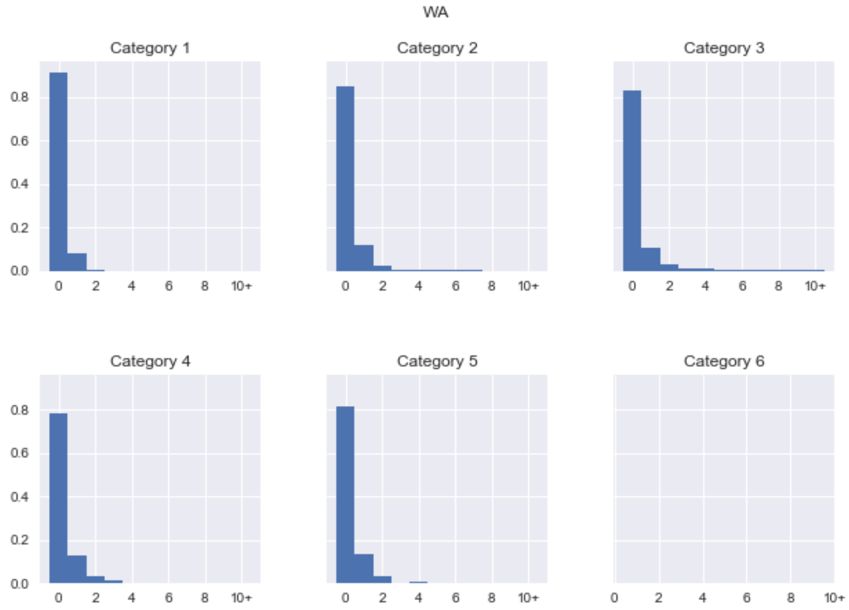

Figure 11.25 Relative frequency of the number of reported new fires per rating category averaged over the live trial period for Western Australia.

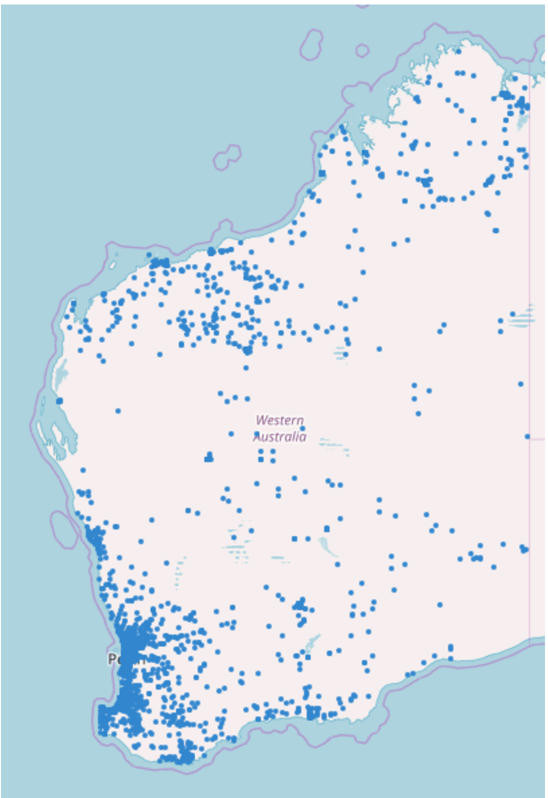

Figure 11.26 Locations of reported fires during the live trial period in Western Australia.

The majority of fires reported in Western Australia were in the more densely populated southwest of the state. There were no clear trends in the data, most likely due to the statistics being dominated by the large areas of the state with few reported fires.

12 Reanalysis climatology of the Research Prototype

12.1 Reanalysis background

The Bureau of Meteorology is currently generating a weather reanalysis of the Australian region from 1990 to at least 2017. A reanalysis uses all available weather observations, including satellite data, to generate the best possible estimate of the state of the atmosphere over time using advanced numerical weather prediction techniques applied by the current (or even near-future) generation of operational weather models. This process ensures a consistent treatment of the observational data over the timespan of the reanalysis, and removes from the time series of reanalysis weather data the effect of the truly remarkable increase in capacity and accuracy in numerical weather prediction that has occurred over the last several decades.

The reanalysis, known as BARRA, for Bureau of Meteorology Atmospheric high-resolution Regional Reanalysis for Australia, details nearly 100 atmospheric parameters at 12 km horizontal resolution over Australia and the surrounding region (Figure 12.1), through 70 vertical levels in the atmosphere (with four soil layers), every hour from 1990 (Jakob *et al*. 2017). When complete, in mid- to late-2019, the data volume is expected to be in excess of 2 petabytes. In addition, several higher resolution subdomains have been defined, corresponding closely to operational ACCESS-C domains. Within the subdomains, over Tasmania, southwest Western Australia, eastern NSW and southeast South Australia, the horizontal resolution is 1.5 km, allowing for more detailed analysis of the weather than is possible over the whole BARRA domain.

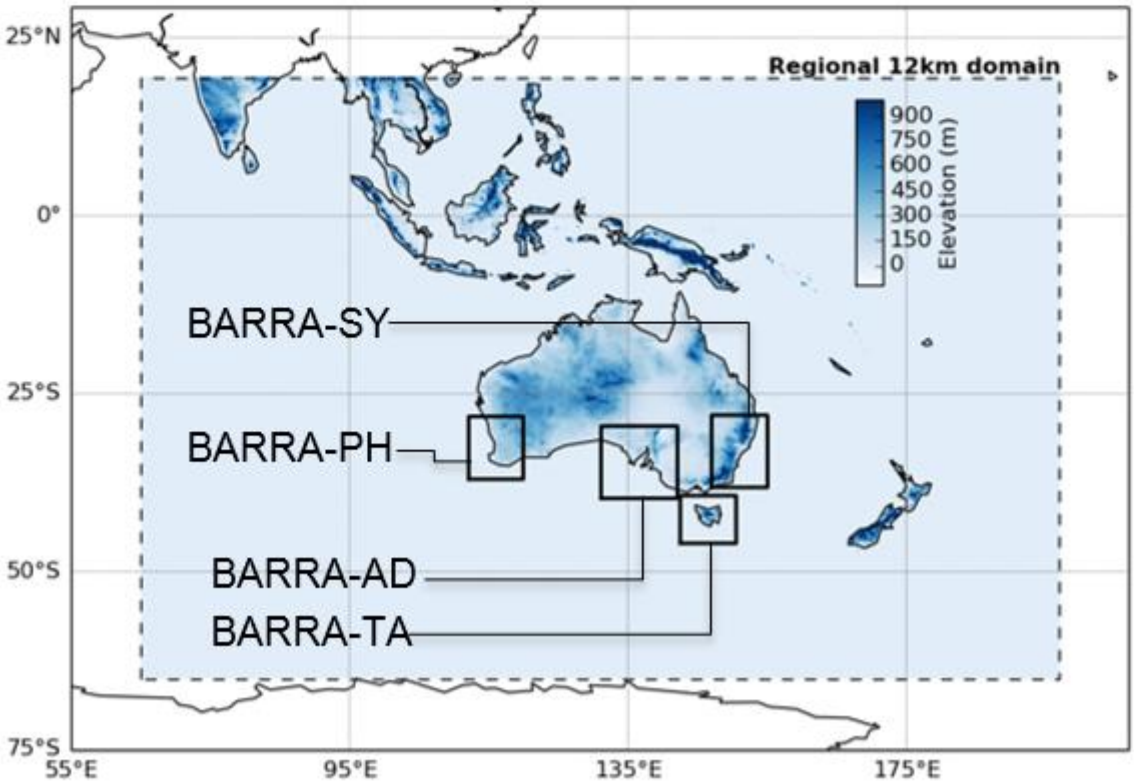

Figure 12.1 BARRA domain and subdomains

During the course of the NFDRS Research Prototype project, the BARRA project team released the first tranche of six years of Australian regional reanalysis data from 2010 through 2015. This data was used to derive a preliminary climatology of the Research Prototype over Australia. A full climatology would require a longer period of data in order for users to be confident in its findings, however the preliminary climatology will still provide useful indicative data.

12.2 Value of a climatology of the Research Prototype

The Research Prototype produced daily output between October 2017 and March 2018 inclusive. Analysis of its output is valuable, particularly when evaluated against observations of fire activity. It is however limited. It extended over only one southern fire season, and there are often substantial variations between successive seasons. The availability of the reanalysis climatology over six full southern and northern fire seasons addresses, to some extent at least, both of the above considerations. Importantly, it permits an assessment of the appropriateness of the currently defined rating category thresholds – are they too high or too low? This is especially important for the higher thresholds, which will likely be tied to public warnings, should the NFDRS be implemented operationally. The climatology also permits an understanding of the characteristics of the Research Prototype. These will change, of course, if the NFDRS is implemented operationally, but with successive implementations new climatologies can be derived and there will be considerable value in comparing the old and new climatologies.

12.3 Climatology of continuous Haines Index

The continuous Haines Index (cHI) is a "red flag" quantity in the Research Prototype, with forecast values in excess of the 95th percentile cHI flagged for each forecast fire weather district. Being a purely atmospheric variable, it is readily calculated from the reanalysis, requiring no fuel or fire history information. A climatology of the cHI is of interest apart from the current project as, until very recently a gridded climatology has not been available. Dowdy and Pepler (2018) have published a map of 95th percentile cHI based on the ERA-I global reanalysis dataset for the 0600 UTC timestep, as the most representative time across Australia for peak fire activity. Prior to this, only a relatively small sample of values were available, from the original publication introducing the cHI (Mills and McCaw 2010).

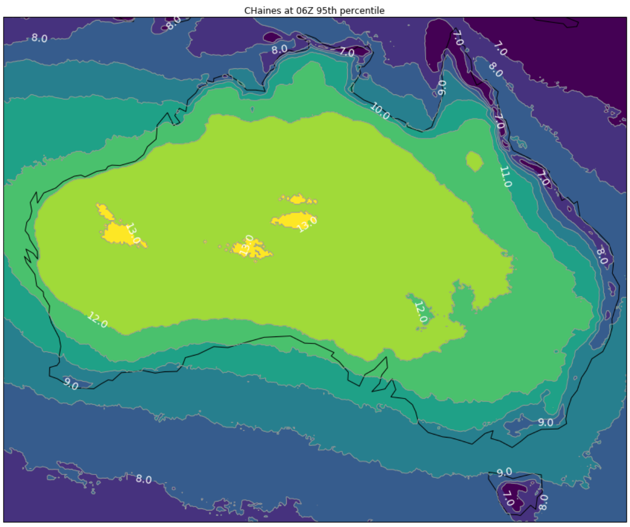

Figure 12.2: 95th cHI at 0600 UTC

A plot of 95th percentile cHI at 0600 UTC (Figure 12.2) was produced for comparison against that of Dowdy and Pepler (2018). The two plots are very similar, confirming the derivation of cHI within the Research Prototype project. The two plots are not, however, identical, as ERA-I extends over a different, longer, period than BARRA, but BARRA's horizontal resolution is approximately six times greater than that of ERA-I.

Because BARRA has hourly temporal resolution (as opposed to six-hourly, in the case of ERA-I), it is useful to calculate 95th percentile daily maximum cHI, rather that that at a single time. This plot is displayed in Figure 12.3. While the general structure of the two plots are similar, with a peak over central and western Australia, values in Figure 12.3 are generally 1 to 2 higher than in Figure 12.2, particularly over Tasmania and about the Queensland and Top End coastal strips.

This raises the question of when the peak daily cHI actually occurs. BARRA can answer that question, to within hourly resolution. Figure 12.4 shows mean time of maximum daily cHI across Australia.

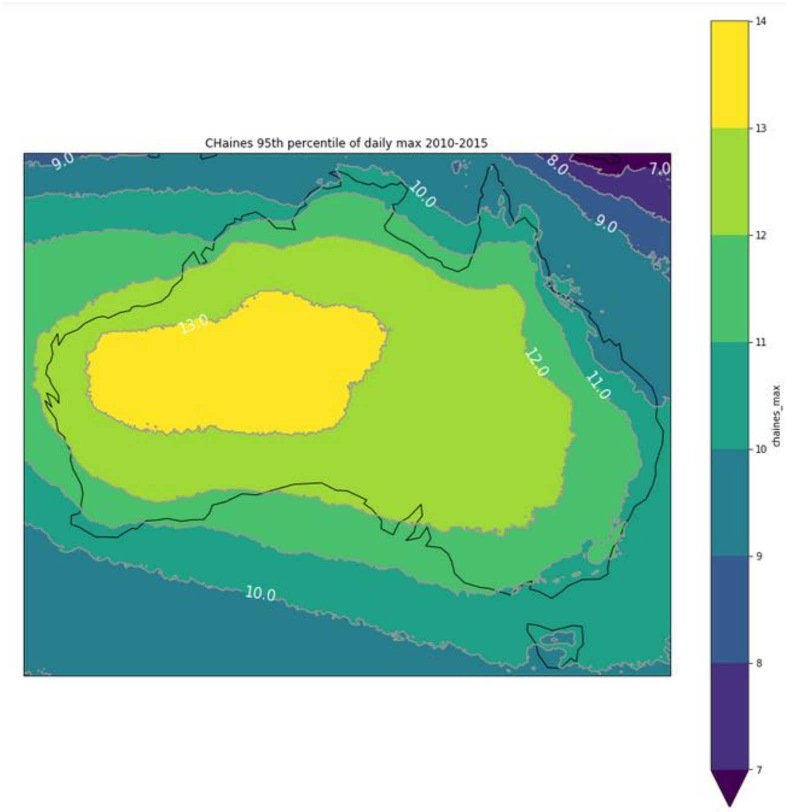

Figure 12.3:95th percentile daily maximum cHI

The mean peak of cHI occurs in early to mid-afternoon over much of the Australian continent, but over much of the continental margin (including most of Victoria and all of Tasmania), the peak is in the late morning.

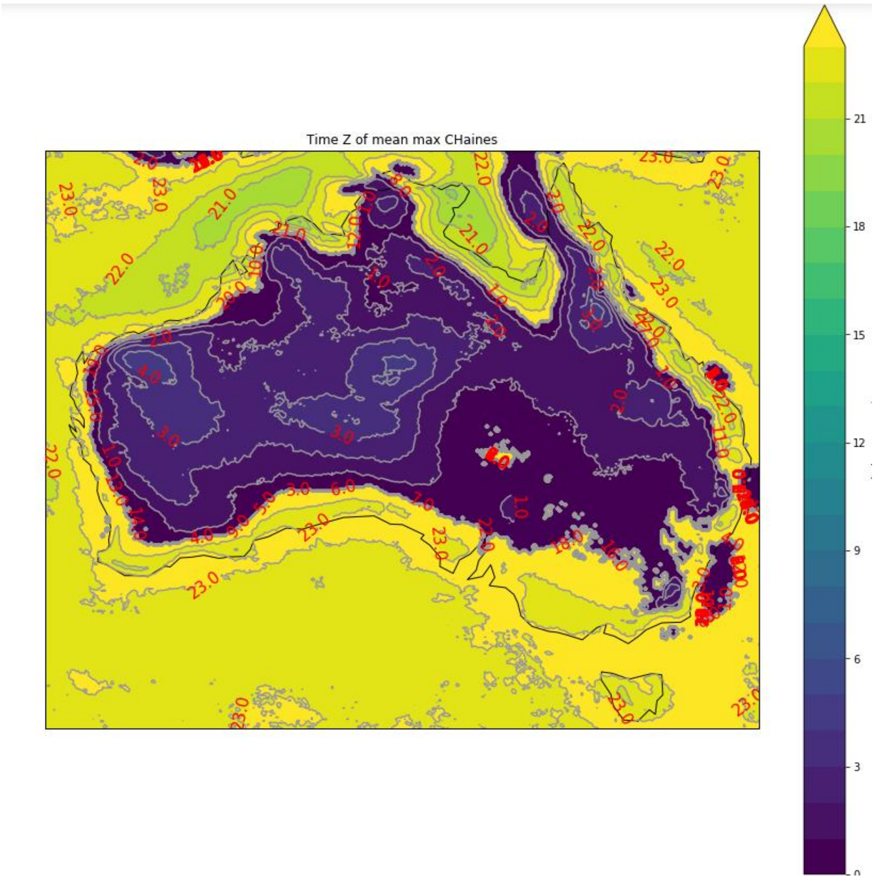

Figure 12.4: Mean time of maximum cHI

These plots enable an appropriate trigger for the Research Prototype forecast red flags. However, they also offer insight into the diurnal behaviour of an index associated with heightened fire activity and are therefore potentially important for operational fire management.

12.4 Broad characteristics of the Research Prototype

A number of percentile maps of daily maximum values of the Research Prototype, over the Australian domain, are presented in this section to provide an overview of typically occurring values, and how these compare across regions (Figure 12.5). Thus, for example, the 90th percentile map of the Research Prototype displays values at each grid point which the daily maximum value of the Research Prototype will not exceed on 90% of days – if the 90th percentile value of the Research Prototype is Category 5 at a grid location, the rating should be no higher than 5 on nine days out of ten. The plots displayed are of the 50th, 90th and 95th percentile values of FDR, for the southern fire season, nominally October – March, as this is the period for which the initial evaluation of the Research Prototype system occurred. The mean is taken over the period of the currently available regional reanalysis, 2010-2015. Of course, a separate analysis will be required to understand the characteristics of the Research Prototype over the northern Australian fire season.

Each plot contains a large amount of information on the distribution of fire danger rating values across Australia, which will require careful analysis as the Research Prototype is developed. Initial observation suggests that, for example, some (largely spinifex) regions have a category 5 threshold set too low. This can be seen in Figure 12.5(a), where the 50th percentile FDR value is 5 over some parts of South Australia and Western Australia.

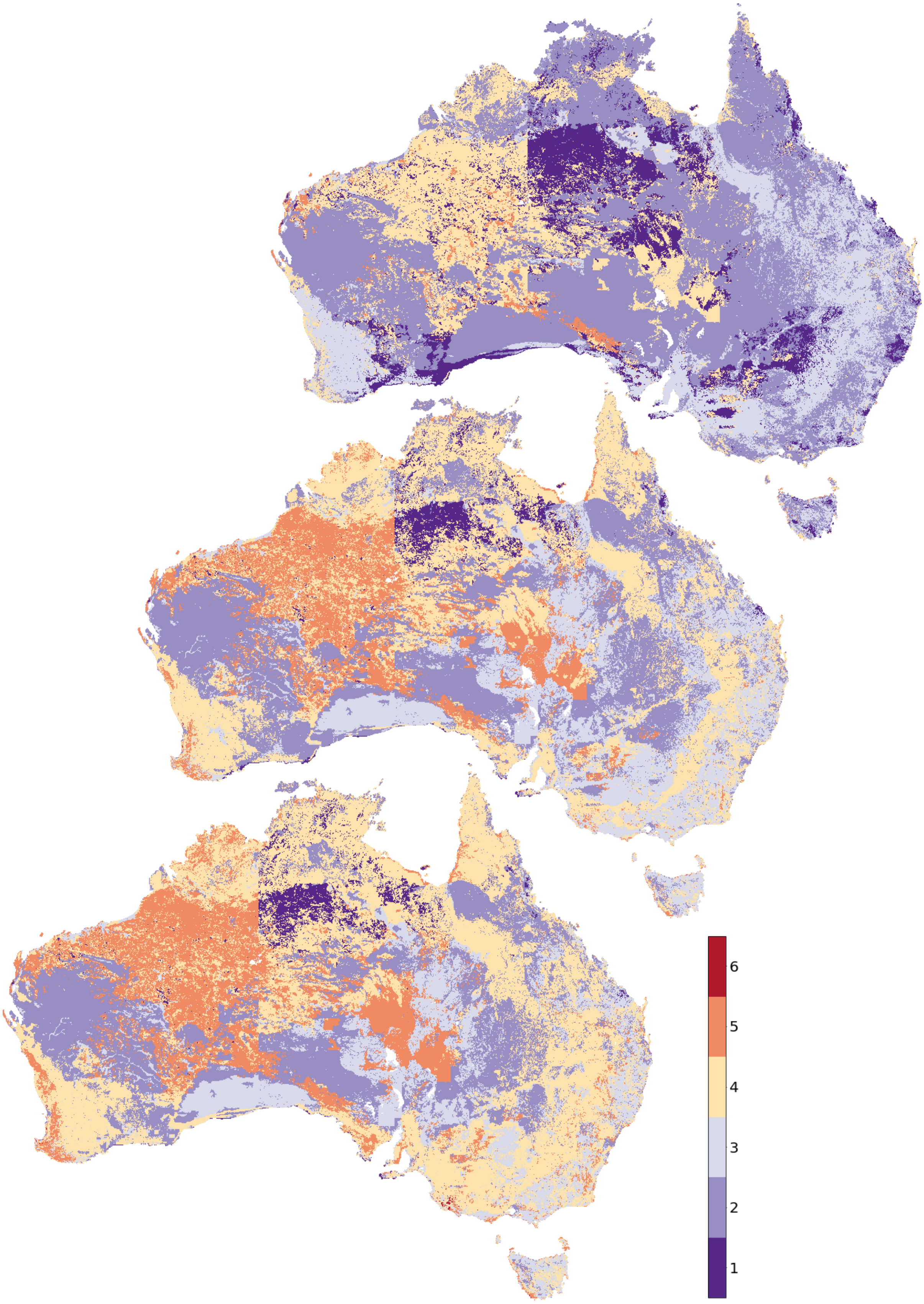

Figure 12.5: Percentile values of daily maximum FDR: (top) 50th (middle) 90th and (bottom) 95th percentile, for October - March. Colours indicate NFDRS rating category.

12.5 Climatology of fire danger rating categories

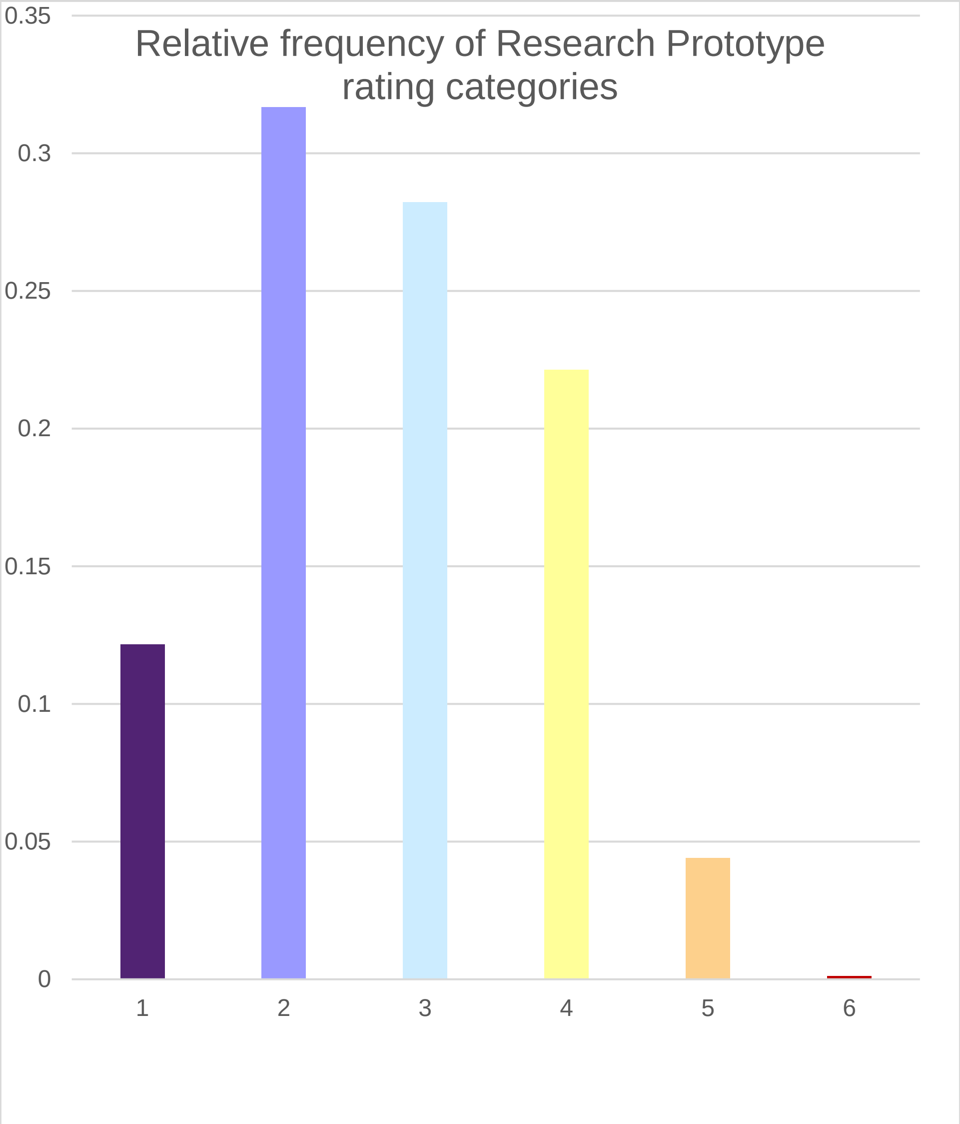

Figure 12.6 Relative frequency of Research Prototype categories

The reanalysis climatology of the Research Prototype permits an assessment of the appropriateness of the threshold values used to delineate rating categories. The current operational fire danger system and the Research Prototype both aggregate fire danger ratings on a district basis. For this reason, district-based tables of frequency of each FDR category over the six-year period of the reanalysis are presented in Table 12.1. Figure 12.6 presents an overall summary of the relative frequency of the six categories, aggregated across all districts and fuel types. The data represent the relative frequency of each category across Australia over the October – March southern Australian fire season, during the years for which BARRA is currently available, 2010-2015. Figure 12.6 shows that, for the reanalysis period, the distribution of FDR across the categories is broadly similar to that observed during the live trial October 2017 – March 2018. That is, the most commonly observed category is 2, followed by 3, 4, 1 and then 5, with a very small proportion of observations in category 6 (0.11% over the reanalysis period). Table 2 summarises the relative frequency of each rating category by state. The southeast of the continent can be seen to experience the highest proportion of category 6, consistent with current understanding of the distribution of extreme fire weather events.

12.6 Seasonality of the Research Prototype

Seasonality of fire weather is largely assumed to be in accord with the map originally published in Luke and McArthur (1978), reproduced in Figure 12.7. It is useful to know whether the Research Prototype FDR seasonality conforms to this model.

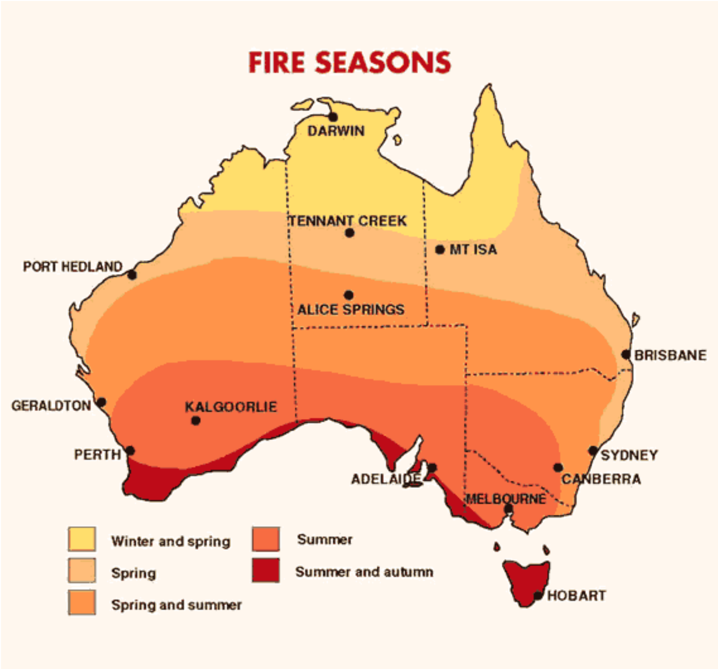

Figure 12.7: Australian fire weather seasonality, from Luke and McArthur 1978.

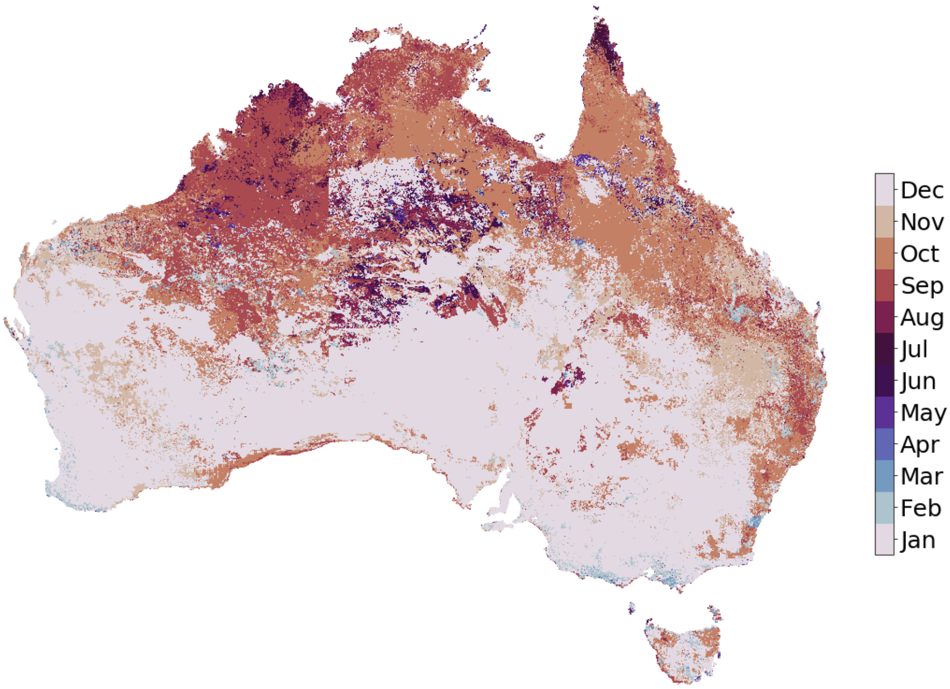

Figure 12.8: Seasonality of Research Prototype. Colours indicate the season of peak fire danger.

Figure 12.8 presents a plot of the month in which the monthly average of daily maximum FDR is highest, during the initial BARRA period of 2010-2015. There are regions of similarity between the two images: much of southern Australia experiences a mid to late summer fire danger peak, and parts of northern Australia see a late winter-spring peak, for example. There are differences as well: the resolution, both spatially and temporally, of the Research Prototype is considerably higher. In addition, there are regions in both southern and northern Australia where the peak fire season is substantially different to that indicated in Figure 12.7. Parts of Tasmania experience a springtime fire danger peak, and the highest monthly values of the FDR occur during summer over areas of northern Australia. The two diagrams do not show exactly the same thing: Figure 12.7 presents a seasonal aggregation of fire danger, while Figure 12.8 permits a higher, monthly resolution. Nonetheless, further investigation is warranted into the differences that the two figures suggest.

12.7 Diurnal peaks of the Research Prototype

It is usually assumed that the diurnal peak of fire danger occurs in mid-afternoon, although there is evidence that this is far from always the case (Fox-Hughes 2011, Kepert *et al*. 2012), and additional evidence that fire danger at high elevations has an earlier peak than at sea level (Fox-Hughes 2008, Sharples *et al*. 2012). The hourly temporal resolution of BARRA permits an investigation of the diurnality of the Research Prototype, which will be important, should it progress to operational implementation.

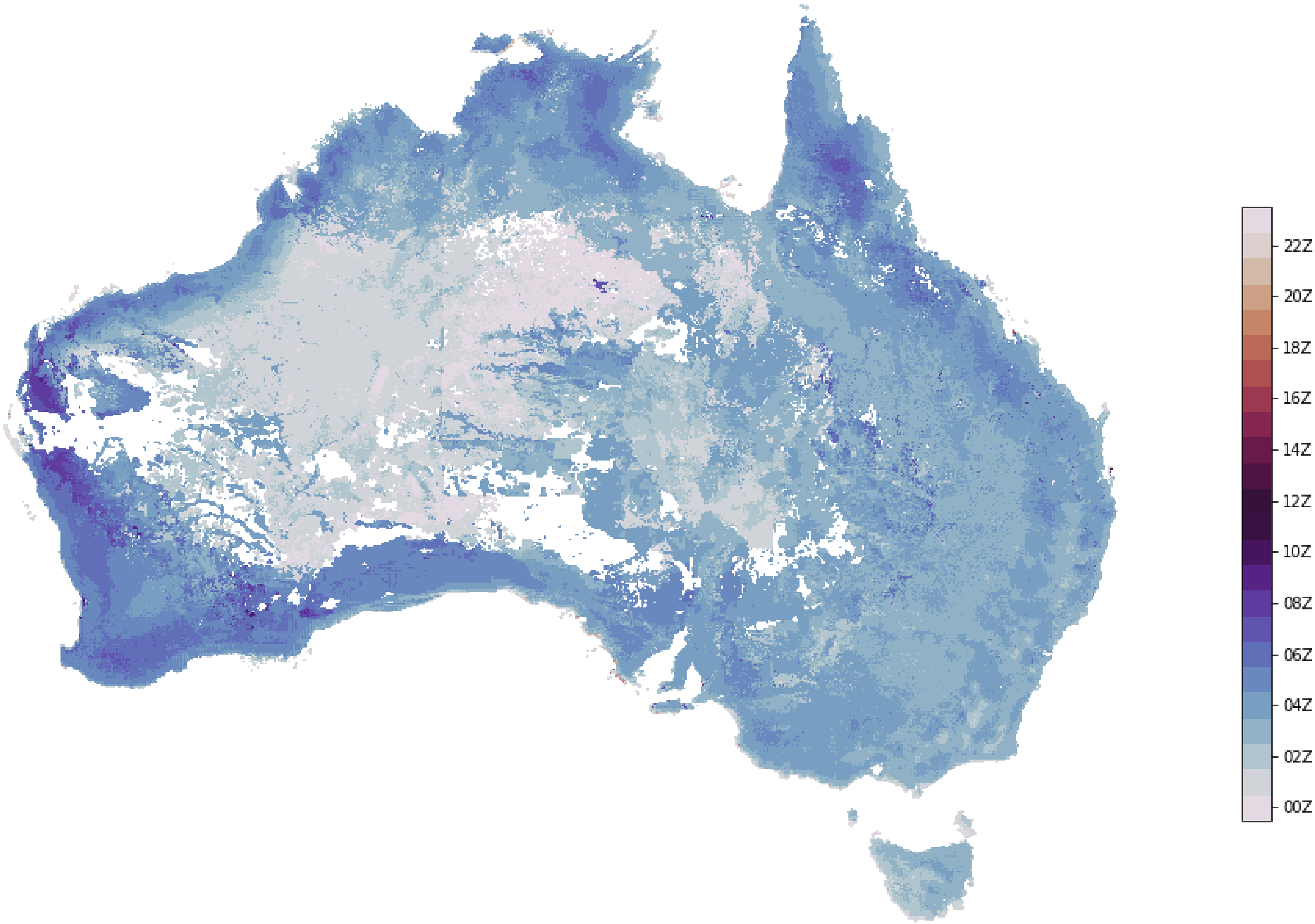

Figure 12.9: Diurnality of the Research Prototype

Figure 12.9 displays the mean time during the day when the fire behaviour index on which the Research Prototype is based achieves its maximum value. As previously, the mean is taken over days in the southern Australian fire season between October – March, the period during which the Research Prototype evaluation occurred. The time in the figure is in UTC, to avoid complications associated with the numerous time zones employed across Australia. Artefacts of the calculation have resulted in some stippling in some coastal regions which have no significance.

While it is clear that much of the country experiences a peak during the early- to mid- afternoon, this is not universally the case, with many areas typically seeing a peak during the mid-late morning.

12.8 Summary

A great deal of information is available from this initial climatology, and this document has touched only briefly on some aspects that are likely to be of strategic and operational use. Further detail will be investigated over the next twelve months. Neither the NFDRS nor the reanalysis are complete, however, and some refinements of the climatology are to be expected. Successive iterations of both the NFDRS and climatology will permit additional useful analyses and greater refinement of the information currently available.

Table 12.1 Fire weather district rating summary. Values are the fraction (0-1) of daily rating values in each category for the reanalysis.

District name	District code	Cat 1	Cat 2	Cat 3	Cat 4	Cat 5	Cat 6
Western	TAS_FW009	0.1007	0.3203	0.3308	0.1582	0.0802	0.0006
Upper Derwent Valley	TAS_FW007	0.1782	0.3156	0.4088	0.0813	0.0057	0.0005
East Coast	TAS_FW003	0.13	0.2501	0.4739	0.1217	0.016	0.0001
South East	TAS_FW006	0.2062	0.2787	0.4049	0.0729	0.0228	0.0001
North East	TAS_FW002	0.2701	0.2732	0.3464	0.0816	0.0194	0.0002
Central North	TAS_FW004	0.1153	0.2873	0.428	0.0958	0.009	0.0001
Central Plateau	TAS_FW008	0.1068	0.2507	0.5073	0.1014	0.0135	0
Midlands	TAS_FW005	0.0549	0.2849	0.4996	0.113	0.0101	0.0001
King Island	TAS_FW011	0.1095	0.2794	0.306	0.2427	0.0611	0
North West Coast	TAS_FW010	0.1736	0.2937	0.4034	0.0694	0.0218	0
Furneaux Islands	TAS_FW001	0.0264	0.1374	0.3098	0.4102	0.1028	0
Mallee	VIC_FW001	0.0455	0.1515	0.5289	0.1976	0.0576	0.0004
Wimmera	VIC_FW002	0.1017	0.1525	0.4973	0.2045	0.0333	0.0027
Northern Country	VIC_FW003	0.0296	0.2075	0.5653	0.161	0.0178	0.0008
North East	VIC_FW004	0.1016	0.3315	0.4609	0.0867	0.0117	0.0007
North Central	VIC_FW008	0.0915	0.2706	0.4746	0.1387	0.0212	0.0014
South West	VIC_FW009	0.0962	0.2373	0.4299	0.1866	0.0327	0.0045
Central	VIC_FW007	0.0699	0.3362	0.3976	0.1501	0.031	0.0028
East Gippsland	VIC_FW005	0.2125	0.2566	0.3969	0.1137	0.0176	0.0007
West and South Gippsland	VIC_FW006	0.152	0.3482	0.3408	0.1298	0.0175	0.0014

Far North Coast	NSW_FW001	0.1128	0.3695	0.438	0.0721	0.0049	0.0002
New England	NSW_FW011	0.125	0.3574	0.4402	0.0683	0.0086	0.0002
North Western	NSW_FW013	0.073	0.2739	0.4513	0.1799	0.0206	0.0008
Northern Slopes	NSW_FW012	0.0716	0.2543	0.4834	0.1569	0.0298	0.0011
Far Western	NSW_FW021	0.0923	0.679	0.1513	0.0703	0.0049	0
North Coast	NSW_FW002	0.358	0.2889	0.2866	0.0504	0.0067	0.0002
Upper Central West Plains	NSW_FW014	0.1218	0.2699	0.4684	0.1296	0.0098	0.0004
Greater Hunter	NSW_FW003	0.1318	0.3344	0.394	0.1093	0.0224	0.0018
Lower Central West Plains	NSW_FW015	0.0418	0.1569	0.5617	0.2128	0.0244	0.0009
Central Ranges	NSW_FW010	0.0529	0.3523	0.4195	0.1457	0.0268	0.0023
Northern Riverina	NSW_FW019	0.0512	0.2508	0.5832	0.1038	0.0081	0.0005
South Western	NSW_FW020	0.1325	0.3105	0.3066	0.187	0.0607	0
Greater Sydney Region	NSW_FW004	0.1303	0.3611	0.3323	0.1272	0.0296	0.0037
Illawarra/Shoalhaven	NSW_FW005	0.1595	0.248	0.4078	0.1381	0.034	0.0033
Southern Ranges	NSW_FW009	0.0348	0.3219	0.4789	0.1282	0.0266	0.0019
Southern Slopes	NSW_FW016	0.0537	0.2754	0.4827	0.1629	0.0207	0.0025
Eastern Riverina	NSW_FW017	0.0484	0.2058	0.4909	0.2187	0.0298	0.0037
Southern Riverina	NSW_FW018	0.025	0.2493	0.5828	0.1296	0.0108	0.0005
Australian Capital Territory	NSW_FW008	0.0214	0.2832	0.5042	0.1556	0.0317	0.003
Far South Coast	NSW_FW006	0.0882	0.1672	0.4932	0.2114	0.0347	0.0024
Monaro Alpine	NSW_FW007	0.019	0.2771	0.4882	0.1725	0.0346	0.0017
Gulf Country	QLD_FW002	0.1379	0.5467	0.1351	0.1499	0.0065	0.0003
North Tropical Coast and Tablelands	QLD_FW004	0.2876	0.4731	0.1214	0.1026	0.005	0
Northern Goldfields and Upper Flinders	QLD_FW003	0.0245	0.6912	0.1657	0.1158	0.0018	0
Herbert and Lower Burdekin	QLD_FW005	0.1373	0.5342	0.1452	0.154	0.0062	0
North West	QLD_FW010	0.1484	0.4308	0.2118	0.1901	0.0187	0
Central Coast and Whitsundays	QLD_FW006	0.1372	0.4669	0.267	0.1053	0.0042	0
Central Highlands and Coalfields	QLD_FW008	0.0328	0.4211	0.4208	0.1163	0.0032	0
Central West	QLD_FW009	0.0054	0.4789	0.3587	0.1472	0.0086	0
Channel Country	QLD_FW011	0.0629	0.6079	0.2159	0.0818	0.0257	0
Capricornia	QLD_FW007	0.0867	0.3767	0.4012	0.0951	0.001	0
Wide Bay and Burnett	QLD_FW014	0.0836	0.3176	0.4443	0.1396	0.0066	0.0002

Maranoa and Warrego	QLD_FW012	0.0046	0.5333	0.3449	0.1091	0.005	0.0001
Darling Downs and Granite Belt	QLD_FW013	0.0144	0.3015	0.4783	0.1767	0.0153	0.0002
Southeast Coast	QLD_FW015	0.071	0.285	0.3717	0.1944	0.0159	0.0006
Peninsula	QLD_FW001	0.0711	0.5796	0.0365	0.2979	0.004	0.0001
Central and Eastern	WA_FW039	0.078	0.5567	0.0527	0.1939	0.1054	0
Northern	WA_FW038	0.17	0.219	0.0302	0.4381	0.1289	0
North Kimberley Coast	WA_FW001	0.2168	0.3276	0.0231	0.3726	0.0155	0.0001
West Kimberley Coast	WA_FW002	0.1652	0.3581	0.0635	0.3288	0.0495	0.0001
Kimberley Inland	WA_FW003	0.1421	0.3514	0.0392	0.4128	0.0514	0
East Pilbara Coast	WA_FW004	0.188	0.1551	0.1842	0.269	0.1614	0
West Pilbara Coast	WA_FW005	0.1027	0.1421	0.165	0.325	0.1973	0
Ashburton Inland	WA_FW007	0.1168	0.4229	0.0197	0.3009	0.1391	0
East Pilbara Inland	WA_FW006	0.2025	0.1625	0.0162	0.4442	0.1731	0
Exmouth Gulf Coast	WA_FW008	0.1434	0.1588	0.029	0.2648	0.3525	0
North Interior	WA_FW013	0.1966	0.0198	0.0061	0.5602	0.1995	0
Gascoyne Coast	WA_FW009	0.0162	0.5734	0.0951	0.1716	0.0852	0
Gascoyne Inland	WA_FW010	0.0094	0.8043	0.0297	0.0955	0.043	0
Goldfields	WA_FW011	0.0645	0.6324	0.0448	0.1702	0.0677	0
South Interior	WA_FW014	0.1239	0.3343	0.0342	0.3106	0.1911	0
Eucla	WA_FW012	0.1423	0.5996	0.233	0.024	0.0003	0
South West Land Division	WA_FW040	0.0903	0.168	0.3377	0.3471	0.0461	0.0015
Jilbadgie	WA_FW037	0.0461	0.1427	0.499	0.295	0.0148	0.0003
Avon	WA_FW036	0.0036	0.042	0.5329	0.3756	0.0447	0.0005
Coastal Central West - North	WA_FW015	0.0084	0.1068	0.1843	0.6114	0.0801	0.0015
Inland Central West - North	WA_FW016	0.0121	0.1998	0.2803	0.4798	0.0276	0.0001
Coastal Central West - South	WA_FW017	0.0091	0.0184	0.2019	0.7039	0.056	0.0004
Inland Central West - South	WA_FW018	0.0087	0.1601	0.2928	0.4801	0.0474	0.0002
Lower West Coast	WA_FW019	0.0067	0.2472	0.2419	0.4349	0.0506	0.0082
Lower West Inland	WA_FW020	0.0073	0.0728	0.2242	0.4959	0.1941	0.0049
Geographe	WA_FW021	0.0263	0.183	0.2924	0.3238	0.1515	0.0105
Leeuwin	WA_FW022	0.0303	0.0899	0.205	0.4063	0.2426	0.0135
Nelson	WA_FW023	0.0233	0.102	0.3348	0.3852	0.1463	0.0049
Stirling Coast	WA_FW024	0.2124	0.1532	0.3508	0.2205	0.0526	0.004

Stirling Inland	WA_FW025	0.0754	0.1312	0.4385	0.3035	0.0496	0.0015
Ravensthorpe Shire Coast	WA_FW026	0.5079	0.1122	0.2147	0.1399	0.0163	0.0011
Ravensthorpe Shire Inland	WA_FW027	0.2854	0.1188	0.3431	0.2339	0.0179	0.0009
Esperance Shire Coast	WA_FW028	0.2625	0.1041	0.3779	0.2151	0.0167	0.001
Esperance Shire Inland	WA_FW029	0.3444	0.324	0.1897	0.1229	0.0053	0.0003
Upper Great Southern	WA_FW030	0.0129	0.0856	0.4268	0.4153	0.0571	0.0007
Roe	WA_FW031	0.0983	0.1124	0.388	0.362	0.0325	0.0007
Beaufort	WA_FW032	0.014	0.1268	0.4634	0.3537	0.0393	0.0005
Lakes	WA_FW033	0.083	0.0847	0.3814	0.4032	0.0342	0.0008
Mortlock	WA_FW034	0.003	0.0907	0.5863	0.2708	0.0067	0
Ninghan	WA_FW035	0.0557	0.3492	0.2582	0.3054	0.0138	0
Flinders	SA_FW009	0.0174	0.3985	0.432	0.1299	0.019	0.0008
Yorke Peninsula	SA_FW002	0.066	0.0931	0.4531	0.3077	0.0574	0.0026
Mid North	SA_FW008	0.0419	0.1576	0.4598	0.2802	0.0415	0.0021
Riverland	SA_FW006	0.107	0.2797	0.403	0.1721	0.03	0.0007
Adelaide Metropolitan	SA_FW001	0.0017	0.8396	0.1468	0.0118	0.0001	0
Eastern Eyre Peninsula	SA_FW011	0.0939	0.292	0.3549	0.2082	0.0433	0.0009
Lower Eyre Peninsula	SA_FW012	0.1184	0.1192	0.3802	0.2907	0.0666	0.0046
Kangaroo Island	SA_FW003	0.3242	0.1613	0.3157	0.1598	0.0305	0.0034
Lower South East	SA_FW005	0.0467	0.2139	0.3954	0.2569	0.0455	0.0131
Upper South East	SA_FW004	0.0337	0.1114	0.4652	0.3272	0.049	0.0035
Murraylands	SA_FW007	0.0856	0.1362	0.5659	0.1937	0.0103	0.0002
Mount Lofty Ranges	SA_FW015	0.0331	0.3038	0.4528	0.1597	0.0375	0.0064
West Coast	SA_PW010	0.1276	0.2524	0.3571	0.1956	0.061	0.0003
North East Pastoral	SA_PW014	0.0357	0.3778	0.1843	0.2122	0.1355	0
North West Pastoral	SA_PW013	0.0152	0.6617	0.1264	0.0841	0.0828	0
Darwin and Adelaide River	NT_FW001	0.1094	0.6571	0.0226	0.1861	0.0044	0.0001
Carpentaria East	NT_FW009	0.0987	0.5744	0.0034	0.3075	0.0008	0
Carpentaria West	NT_FW008	0.0279	0.8395	0.0099	0.1225	0.0001	0
Alice Springs Fire Protection Area	NT_FW014	0.1681	0.6224	0	0.1769	0.0327	0
Simpson East	NT_FW016	0.3809	0.2033	0.005	0.3106	0.0979	0
Tanami North	NT_FW019	0.8495	0.0438	0	0.0935	0.0035	0

Barkly South	NT_FW013	0.5343	0.2415	0.0449	0.1653	0.0117	0
Gregory South East	NT_FW011	0.2629	0.487	0.0903	0.1589	0.0009	0
Gregory North West	NT_FW010	0.1981	0.4974	0.0198	0.2644	0.0024	0.0001
Tiwi	NT_FW004	0.1008	0.7939	0.0017	0.0502	0	0
Daly South	NT_FW003	0.174	0.5566	0.0234	0.2184	0.0021	0.0002
Northern Fire Protection Area	NT_FW002	0.0869	0.6442	0.0376	0.222	0.0046	0.0003
Arnhem West	NT_FW005	0.1504	0.5596	0.0123	0.2689	0.0032	0.0002
Arnhem East	NT_FW006	0.0675	0.6062	0.0059	0.3065	0.001	0
Tanami South	NT_FW020	0.5065	0.1702	0	0.2679	0.0371	0
Barkly North	NT_FW012	0.3716	0.323	0.1821	0.1196	0.0018	0
Simpson West	NT_FW015	0.2003	0.5024	0.0254	0.2107	0.0605	0
Lasseter West	NT_FW017	0.2599	0.1953	0.0005	0.4449	0.079	0
Lasseter East	NT_FW018	0.2187	0.222	0.014	0.4199	0.1103	0
Katherine Fire Protection Area	NT_FW007	0.085	0.612	0.0046	0.2958	0.0009	0

Table 12.2 Fraction (0-1) of daily rating values falling in each category for each state

State	Category 1	Category 2	Category 3	Category 4	Category 5	Category 6
Tasmania	0.1366	0.2831	0.4039	0.1199	0.0358	0.0002
Victoria	0.0937	0.2389	0.4631	0.1607	0.0303	0.0018
ACT/NSW	0.0899	0.4007	0.3651	0.1234	0.0175	0.0008
Queensland	0.0658	0.5113	0.2626	0.1412	0.0103	0.0001
Western Australia	0.1123	0.3824	0.085	0.3018	0.1053	0.0002
South Australia	0.038	0.471	0.2113	0.1552	0.0908	0.0005
Northern Territory	0.3167	0.3749	0.0403	0.2321	0.028	0

13 Sensitivity analysis of fire behaviour models

The models use to calculate fire behaviour in the NFDRS Research Prototype use a wide variety of models forms and combinations of fuel and weather inputs. Where the system has not performed well (See Chapters 8 to 11) it was not always immediately clear the origin of the error due to the complexity of the system. As a first step to guiding investigation and investment in improvements to the models a sensitivity study was conducted. This study examined the relative importance of the model inputs in determining predicted rate of spread. When effort needs to be put into improving inputs, particularly fuel parameters which may require expensive field surveys, this analysis will help to identify which parameters should be the highest priority.

13.1 The relative sensitivity score

To examine the sensitivity of a model to changes in input conditions we used the relative sensitivity (RS) index. This index quantifies the proportional response of the model to changes in a perturbed input parameter. Due to the non-linear nature of the fire behaviour models tested, we apply a sensitivity analysis method over the range of the input variable and with other inputs being perturbed through a Monte-Carlo simulation method. The index is defined as (Bartelink, 1998):

$$RS = \frac{\partial y / \partial x \cdot \Delta x}{y_{def} \cdot \Delta_{IV}} \qquad (13.1)$$

where y *is* the resulting value of the output parameter when the value of the input parameter, x, is changed by ±5% (Δ_x); y_{def} is the output parameter under default conditions and Δ_{IV} is the range of the perturbation (fixed at 0.1). A simple interpretation of the RS is given in Table 13.1. The sensitivity tests were based on 1000 runs with randomly selected input conditions within the range specified in Table 13.2.

Table 13.1 Interpretation of Relative Sensitivity (RS) scores.

RS value	Interpretation
0.5	Change in the output is half the change in the perturbation; e.g. a change of 10 % in the input causes a change of 5% in the output.
1	Change in the output is proportional to change in the input. E.g., a change of 10% in the input causes a change of 10% in the output.
2	Change in the output is double that of the input; e.g., a 10% perturbation in the input causes a 20% change in the output.
4	Change in the output is 4 x that of the perturbation.

Table 13.2 Variables and range used in the Monte Carlo simulations.

Variable	Min	Max	Fuel type model
10-m open wind speed (km/h)	5	50	Dry eucalypt forest Grassland Shrubland Pine plantation
2-m wind speed (km/h)	5	30	Spinifex Buttongrass moorland Semi-arid heath
Dead fuel moisture content (MC)	2	20	Dry eucalypt forest Grassland Shrubland Buttongrass moorland Semi-arid shrubland Pine plantation
Compound dead and live fuel moisture content (CMC)	5	30	Spinifex
Surface fuel Fuel Hazard Score (FHS)	1	4	Dry eucalypt forest
Near-surface fuel FHS	1	4	Dry eucalypt forest
Near-surface fuel height (cm)	5	20	Dry eucalypt forest
Near-surface percent cover score (PCS)	1	4	Mallee-heath
Elevated Fuel Hazard Score (FHS)	1	4	Mallee-heath
Curing level (%)	20	100	Grassland
Fuel bed height (m)	0.25	4	Shrubland
Fuel age (years)	2	80	Buttongrass moorland
Fuel cover (%)	20	80	Spinifex

13.2 Buttongrass moorlands model, Marsden-Smedley and Catchpole (1995b).

Marsden-Smedley and Catchpole (1995b) used data from experimental fires (n = 44), operational prescribed fires (n = 11) and wildfires (n = 5) to develop a model of fire spread in buttongrass moorlands. Non-linear regression analysis was used to model the head-fire rate of spread (R, m min^{-1}):

$$R = 0.678\, U_2{}^{1.312}\, exp(-0.0243\, MC)\, \big(1 - exp(-0.116\, AGE)\big) \qquad (13.2)$$

where U_2 is the wind speed (km h^{-1}) measured at a 2-m height, MC is the dead fuel moisture content (%) and AGE is time since the last fire in years, a surrogate of other fuel characteristics such as fuel load and fraction of dead fuel. Fuel age in the experimental fires varied between 4 and 25 years.

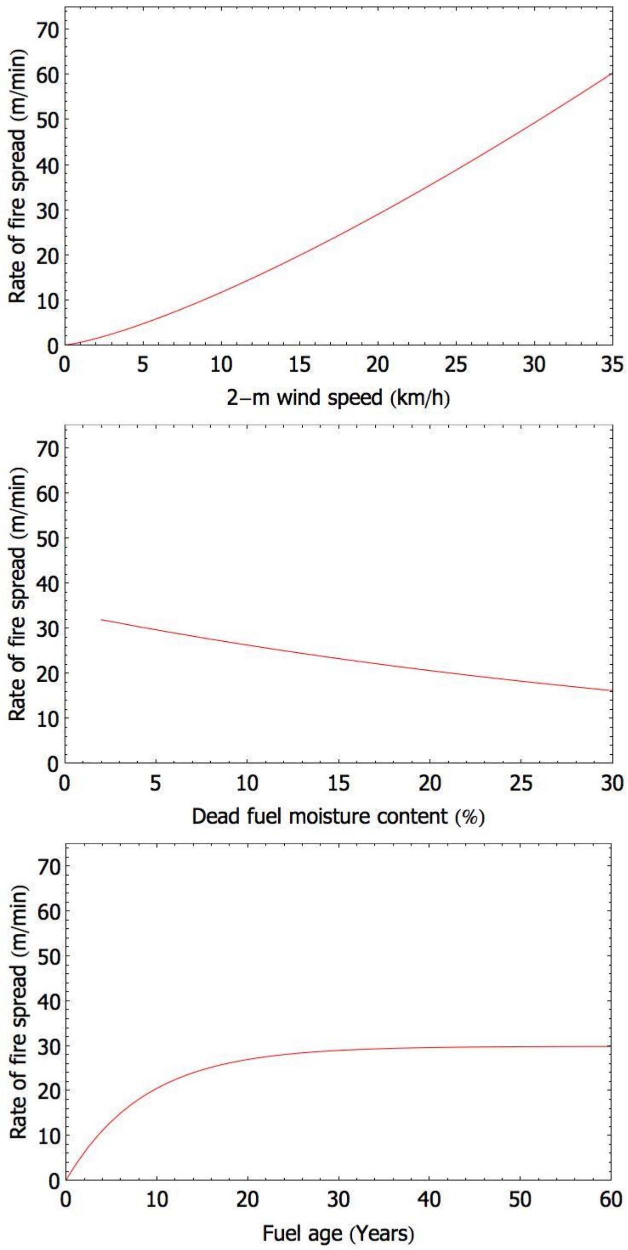

Figure 13.1 Effect of wind speed (top), dead fuel moisture (middle) and fuel age (bottom) on rate of fire spread predicted in buttongrass moorlands by Marsden-Smedley and Catchpole (1995b) model. Variables held fixed while an input varied were: 2-m wind speed: 20 km

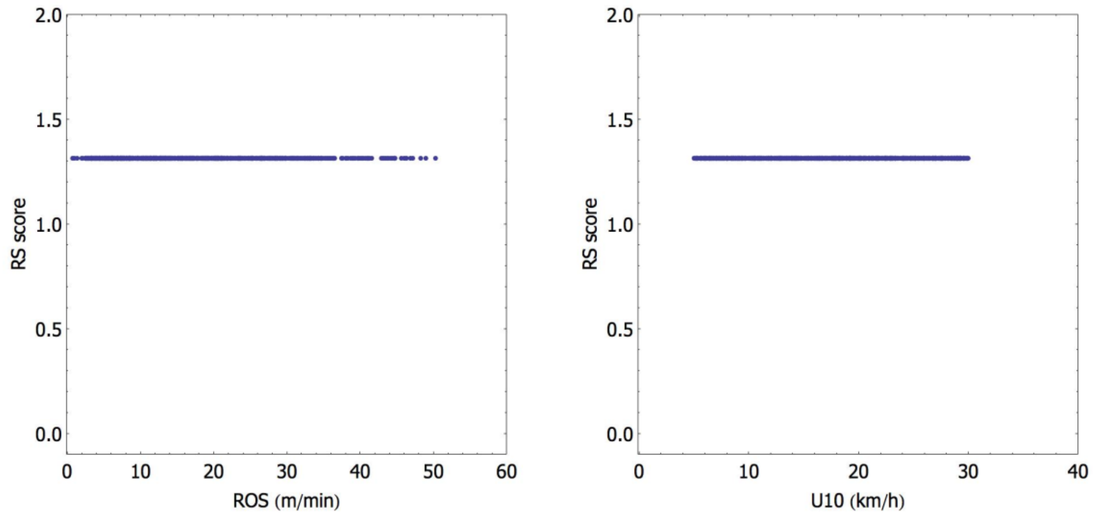

Figure 13.2 Relative sensitivity (RS) score as a function of 10-m open wind speed (U10) perturbation. Left: RS score as a function of modelled rate of fire spread. Right: RS score as a function of open wind speed.

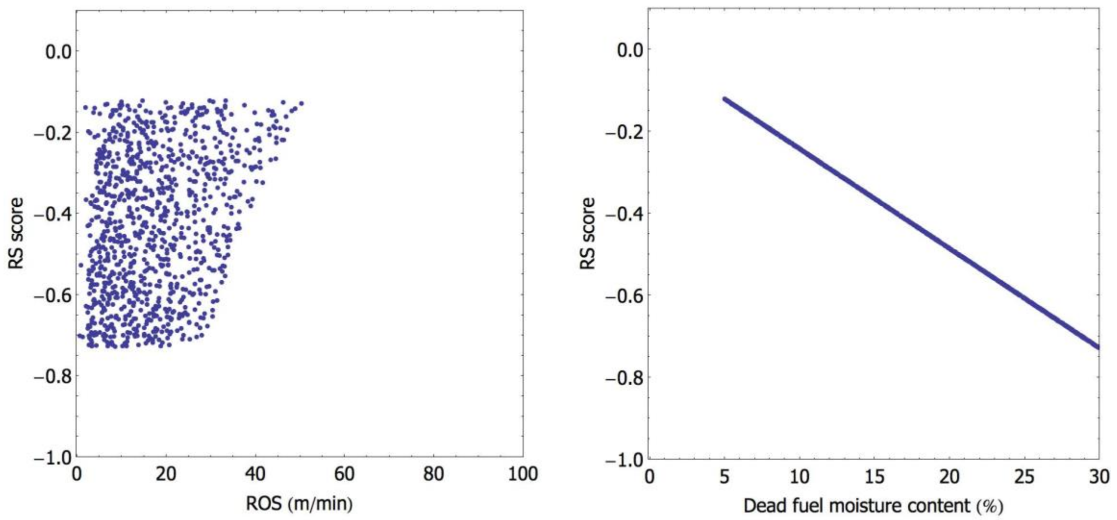

Figure 13.3 Relative sensitivity (RS) score as a function of dead fuel moisture content perturbation. Left: RS score as a function of modelled rate of fire spread. Right: RS score as a function of dead fuel moisture content.

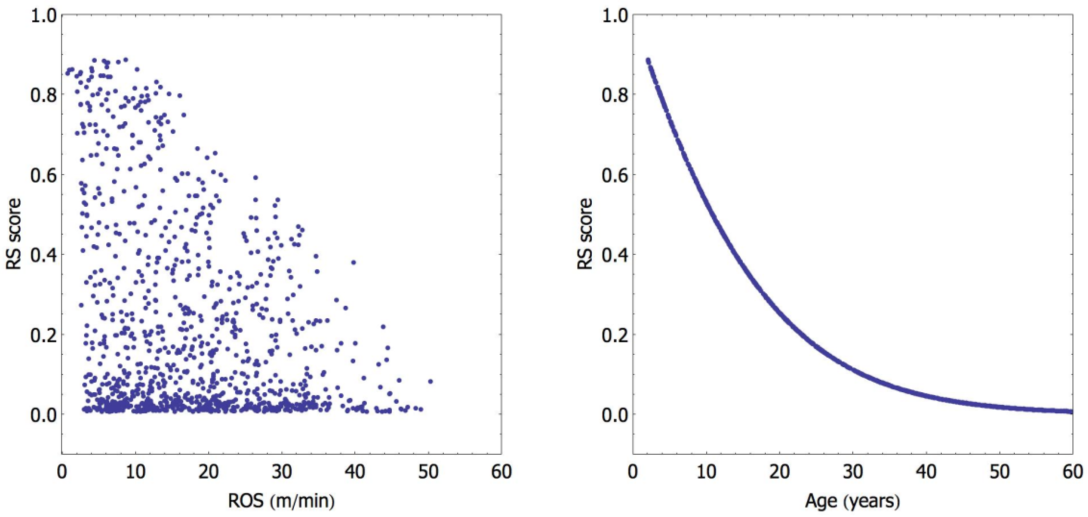

Figure 13.4 Relative sensitivity (RS) score as a function of surface fuel FHS perturbation. Left: RS score as a function of modelled rate of fire spread. Right: RS score as a function of surface fuel FHS.

Table 13.3 Mean relative sensitivity score per 2-m wind speed class.

	2-m open wind speed (km/h)				
	5 – 10	10 - 15	15 - 20	20 - 25	25 - 30
Mean RS (St. dev.)	1.3 (<0.01)	1.3 (<0.01)	1.3 (<0.01)	1.3 (<0.01)	1.3 (<0.01)

Table 13.4 Mean relative sensitivity score per dead fuel moisture content class.

	Dead fuel moisture content (%)			
	5 - 10	10 - 15	15 - 20	20 - 30
Mean RS (St. dev.)	-0.2 (0.03)	-0.3 (0.03)	-0.4 (0.03)	-0.6 (0.07)

Table 13.5 Mean relative sensitivity score per fuel age.

	Fuel age (Years)			
	5 – 20	20 – 40	40 – 60	60 – 80
Mean RS (St. dev.)	0.46 (0.14)	0.12 (0.1)	0.02 (0.01)	0.002 (<0.01)

13.3 Grassland fire spread model Cheney *et al*. (1998).

Combining data from experimental fires conducted in the Northern Territory and wildfires case studies Cheney *et al*. (1998) developed a model for predicting the rate of spread of grassland fires in undisturbed (R_n, km h^{-1}) and cut/grazed (R_{cu}, km h^{-1}) pastures:

$$R_n = \begin{cases} (0.054 + 0.269\, U_{10})\, \phi M\, \phi C & U_{10} < 5 \text{ km h}^{-1} \\ (1.4 + 0.838(U_{10} - 5)^{0.844})\, \phi M\, \phi C & U_{10} \geq 5 \text{ km h}^{-1} \end{cases} \tag{13.3}$$

$$R_{cu} = \begin{cases} (0.054 + 0.209\, U_{10})\, \phi M\, \phi C & U_{10} < 5 \text{ km h}^{-1} \\ (1.1 + 0.705(U_{10} - 5)^{0.844})\, \phi M\, \phi C & U_{10} \geq 5 \text{ km h}^{-1} \end{cases} \tag{13.4}$$

where U_{10} is the 10-m open wind speed (km h^{-1}), ϕM is the fuel moisture coefficient and ϕC is the curing coefficient.

A model was also developed for rate of spread for eaten out grasslands (R_e, km/h) based on the evidence from a few grassfires spreading in this fuel condition that fires would spread at about half the rate of spread of those observed in grazed pastures (Equation 13.4):

$$R_e = (0.55 + 0.357\, (U_{10} - 5)^{0.844})\, \phi M\, \phi C \qquad U_{10} \geq 5 \text{ km h}^{-1} \tag{13.5}$$

In turn, ϕM is given by:

$$\phi M = \begin{cases} exp(-0.108\, MC) & MC < 12\,\% \\ 0.684 - 0.0342\, MC & MC \geq 12\,\%, \mathrm{U}_{10} < 10\, km\, \mathrm{h}^{-1} \\ 0.547 - 0.0228\, MC & MC \geq 12\,\%, \mathrm{U}_{10} \geq 10\, km\, \mathrm{h}^{-1} \end{cases} \tag{13.6}$$

where *MC* is the dead fuel moisture content (% oven-dry weight basis) with application bounds of 2 to 24%. For further details on the model development see Cheney *et al*. (1998) and the revision by Cruz *et al*. (2015c).

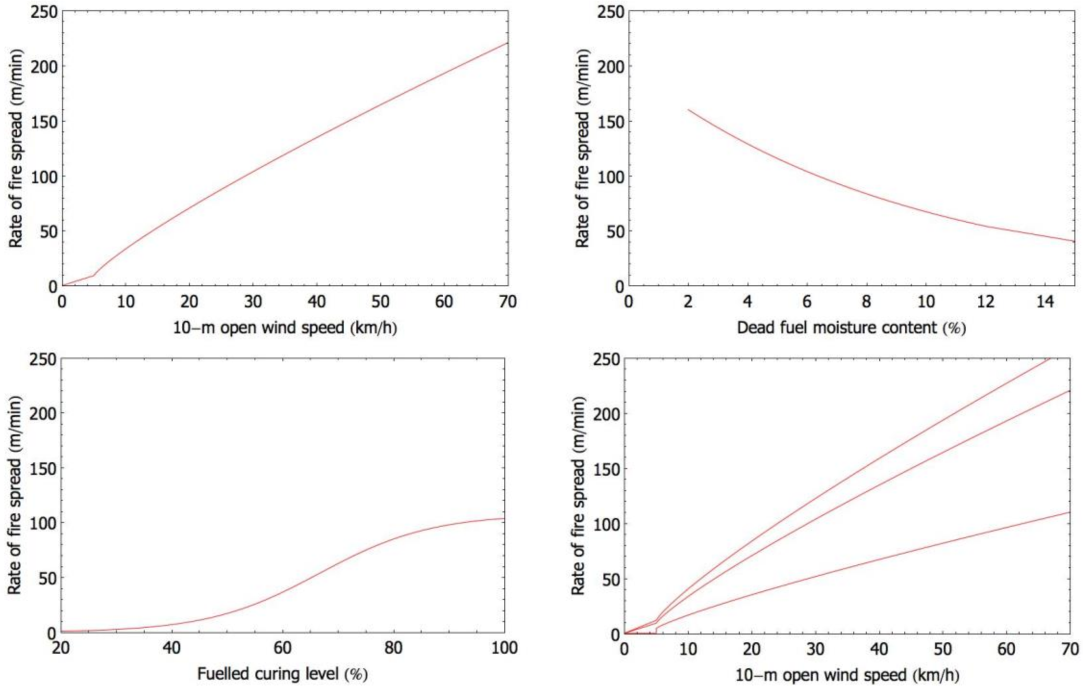

Figure 13.5 Effect of wind speed (top left), dead fuel moisture (top right), curing level (bottom left) and fuel type (e.g. undisturbed, cut/grazed and eaten-out; bottom right) on rate of fire spread

predicted in grasslands by Cheney *et al*. (1998) model. Variables held fixed while an input varied were: 10-m open wind speed: 30 km/h; dead fuel moisture content: 6%; Curing level: 100%.

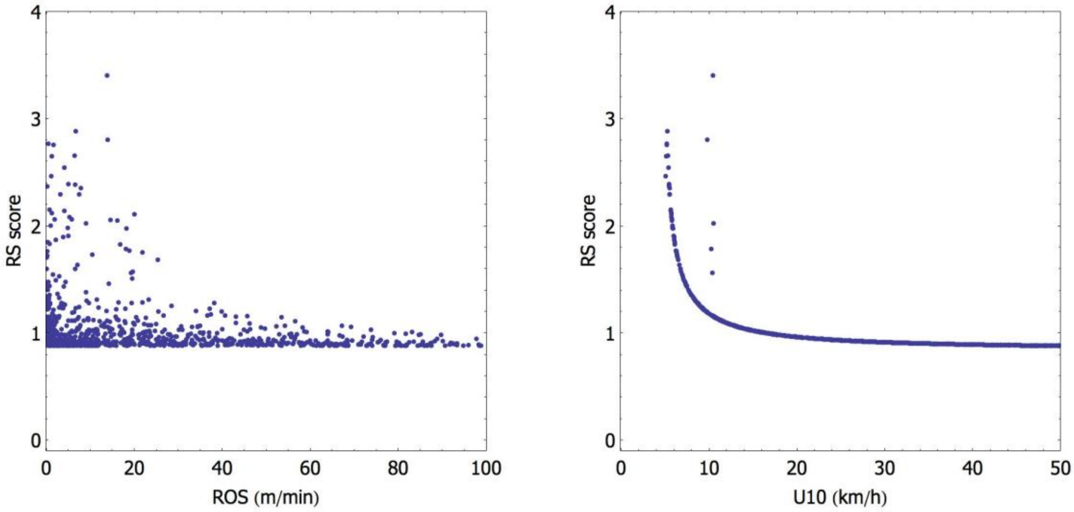

Figure 13.6 Relative sensitivity (RS) score as a function of 10-m open wind speed (U10) perturbation. Left: RS score as a function of modelled rate of fire spread. Right: RS score as a function of open wind speed.

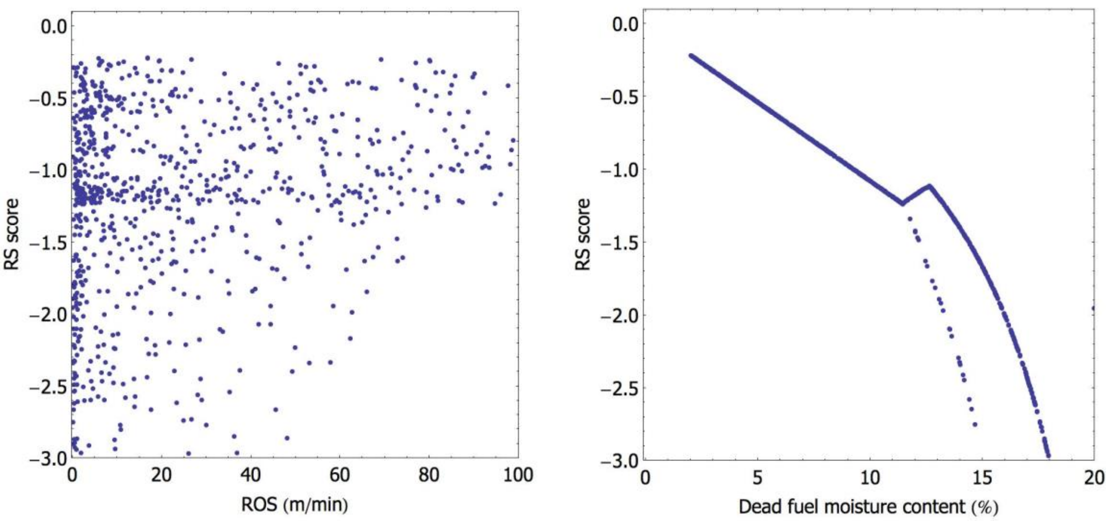

Figure 13.7 Relative sensitivity (RS) score as a function of dead fuel moisture content perturbation. Left: RS score as a function of modelled rate of fire spread. Right: RS score as a function of dead fuel moisture content.

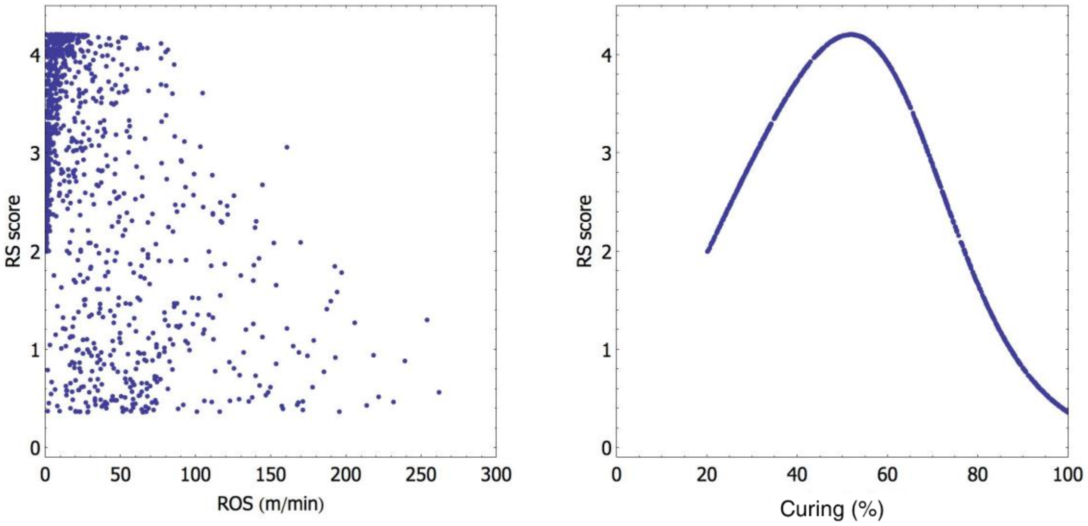

Figure 13.8 Relative sensitivity (RS) score as a function of curing level perturbation. Left: RS score as a function of modelled rate of fire spread. Right: RS score as a function of curing level.

Table 13.6 Mean relative sensitivity score per 10-m open wind speed class.

	10-m open wind speed (km/h)				
	5 – 10	10 - 20	20 - 30	30 - 40	40 - 50
Mean RS (St. dev.)	1.9 (2.7)	1.1 (0.4)	0.93 (0.01)	0.90 (0.01)	0.88 (0.1)

Table 13.7 Mean relative sensitivity score per dead fuel moisture content class

	Dead fuel moisture content (%)			
	2 – 5	5 - 10	10 - 15	15 - 20
Mean RS (St. dev.)	-0.4 (0.09)	-0.8 (0.16)	-1.4 (0.28)	-3.8 (4.8)

Table 13.8 Mean relative sensitivity score per curing level class

	Curing level (%)			
	20 – 40	40 - 60	60 - 80	80 - 100
Mean RS (St. dev.)	2.9 (0.5)	4.1 (0.12)	2.9 (0.66)	0.85 (0.37)

13.4 Pine plantation model, Cruz *et al*. (2008)

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 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. 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 as they total more than 100. They can be reviewed in the publications cited above and are available in C++ code in Cruz (2004).

The primary inputs into the PPPY model system are: wind speed (either the 10-m open standard or within stand measure), weather variables determining dead fuel moisture content (i.e. air temperature, relative humidity, cloud cover), 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 (Cruz *et al.*, 2004), 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).

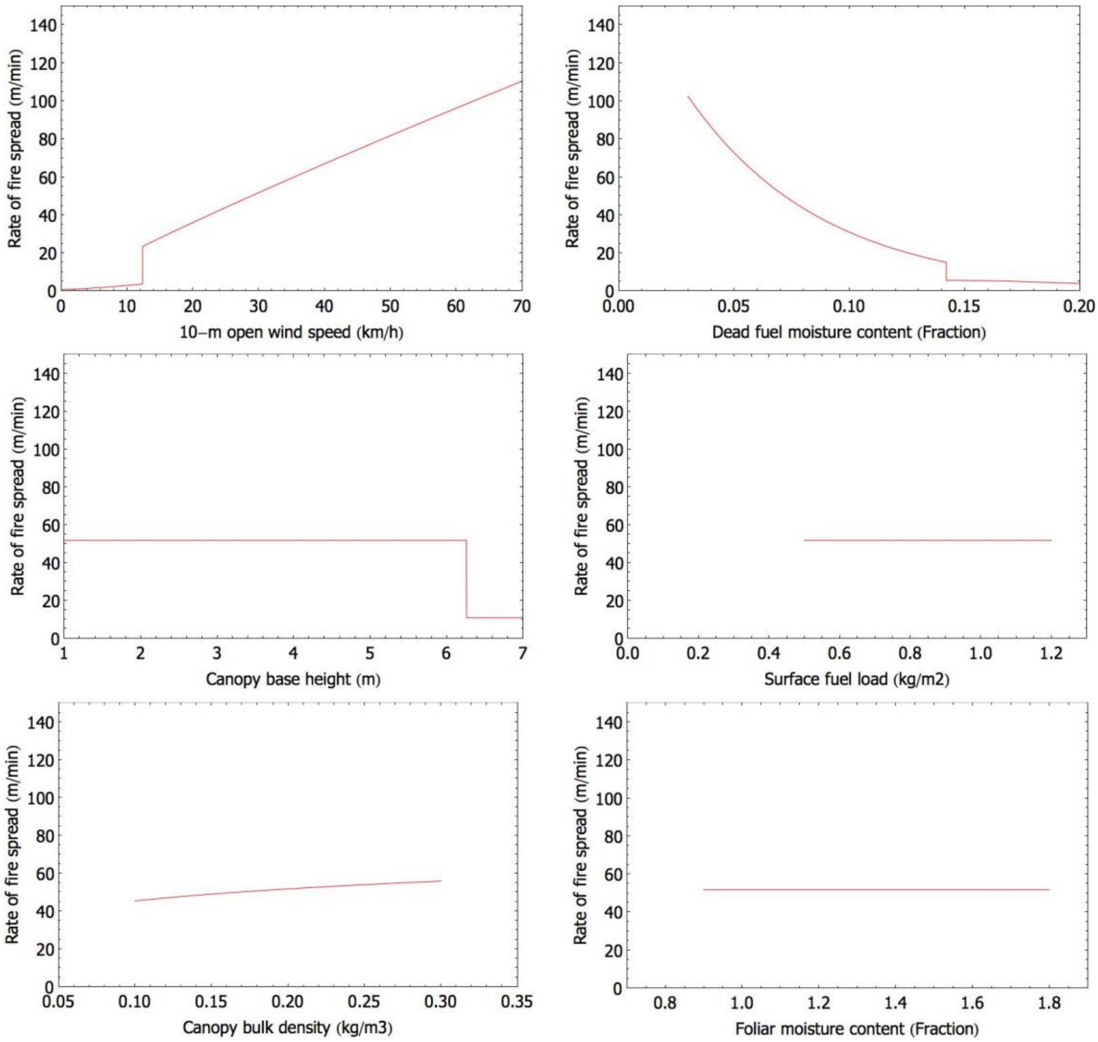

Figure 13.9 Effect of wind speed (top left), dead fuel moisture (top right), canopy base height (middle left), surface fuel load (middle right), canopy bulk density (bottom left) and foliar moisture content (bottom right) on rate of fire spread predicted in pine plantations by Cruz *et al*. (2008) model. Variables held fixed while an input varied were: 10-m open wind speed: 30 km/h; dead fuel moisture content: 7%; canopy base height: 3 m; available surface fuel load: 0.8 kg/m2; canopy bulk density: 0.2 kg/m3; foliar moisture content: 100%.

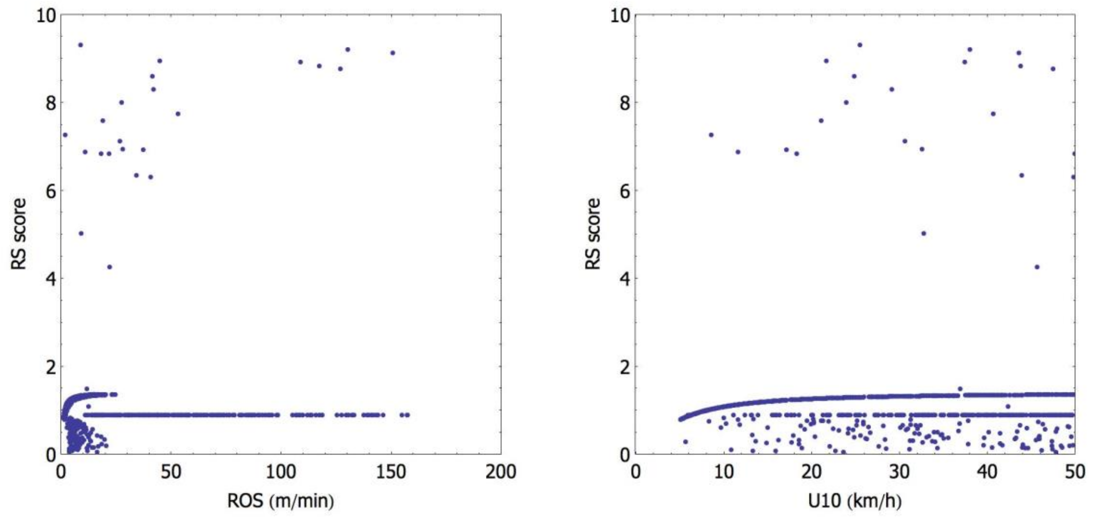

Figure 13.10 Relative sensitivity (RS) score as a function of 10-m open wind speed (U10) perturbation. Left: RS score as a function of modelled rate of fire spread. Right: RS score as a function of open wind speed.

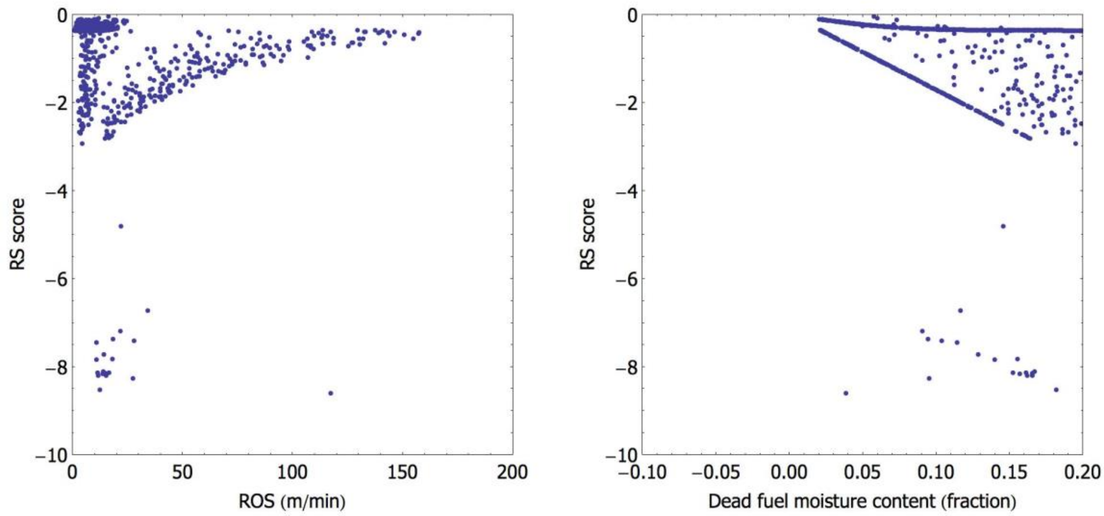

Figure 13.11 Relative sensitivity (RS) score as a function of dead fuel moisture content perturbation. Left: RS score as a function of modelled rate of fire spread. Right: RS score as a function of dead fuel moisture content.

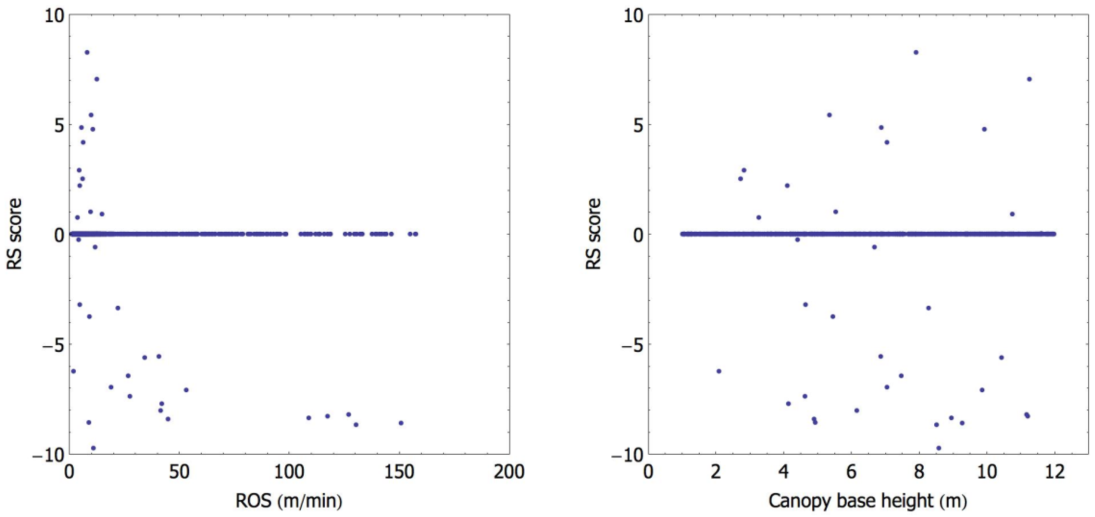

Figure 13.12 Relative sensitivity (RS) score as a function of canopy base height perturbation. Left: RS score as a function of modelled rate of fire spread. Right: RS score as a function of canopy base height.

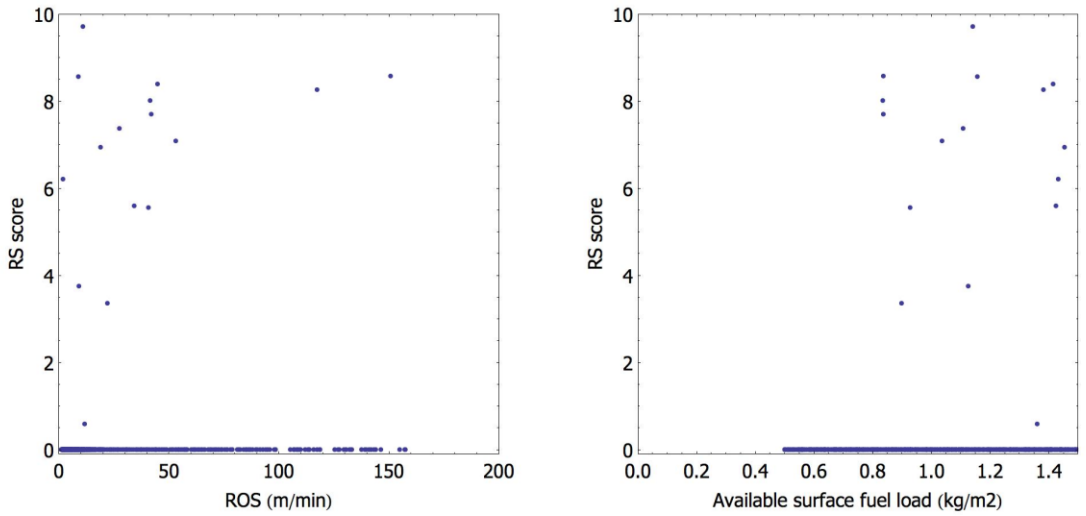

Figure 13.13 Relative sensitivity (RS) score as a function of surface fuel load perturbation. Left: RS score as a function of modelled rate of fire spread. Right: RS score as a function of surface fuel load.

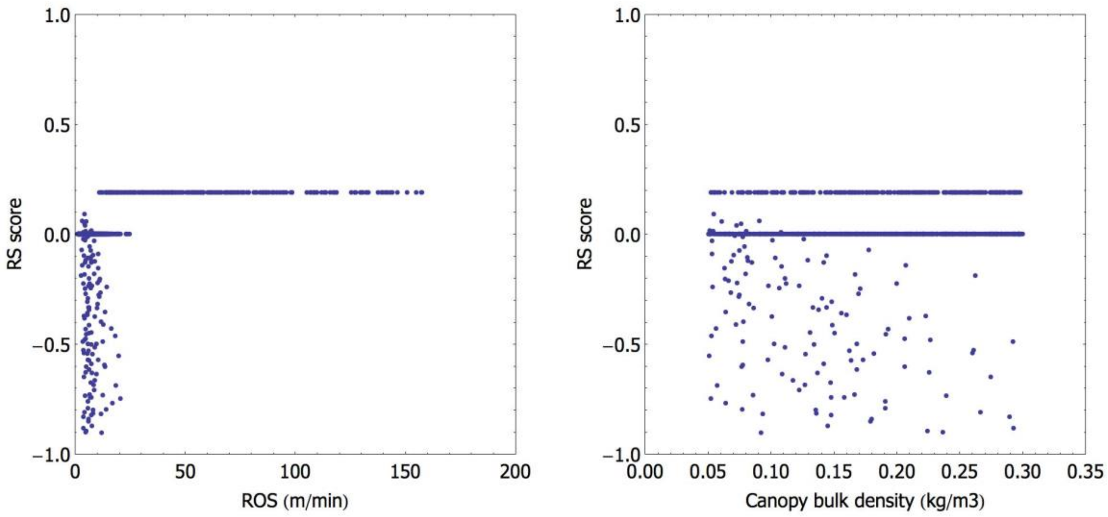

Figure 13.14 Relative sensitivity (RS) score as a function of canopy bulk density perturbation. Left: RS score as a function of modelled rate of fire spread. Right: RS score as a function of canopy bulk density.

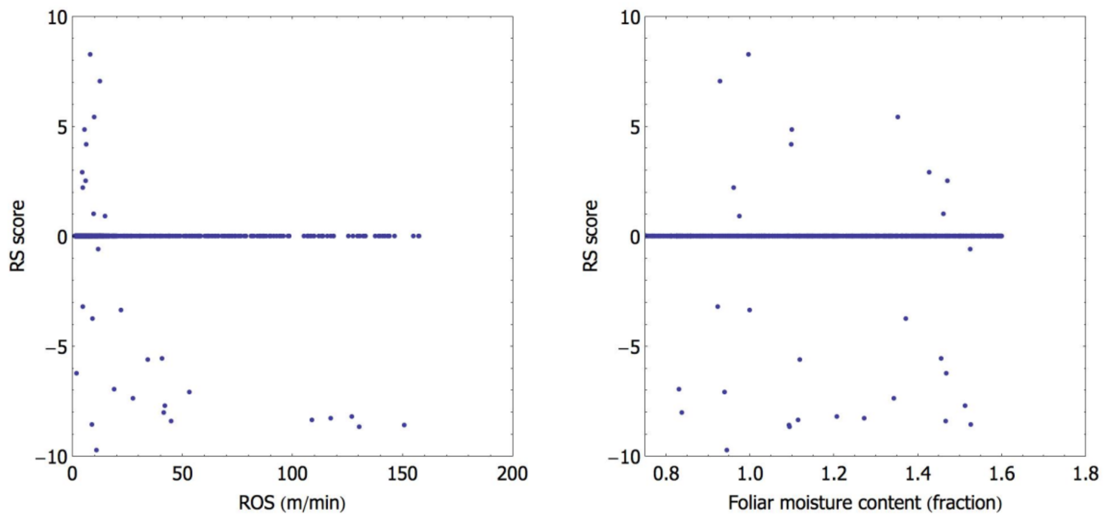

Figure 13.15 Relative sensitivity (RS) score as a function of foliar moisture content perturbation. Left: RS score as a function of modelled rate of fire spread. Right: RS score as a function of foliar moisture content.

Table 13.9 Mean relative sensitivity score per 10-m open wind speed class

	10-m open wind speed (km/h)				
	5 – 10	10 - 20	20 - 30	30 - 40	40 - 50
Mean RS (St. dev.)	1.07 (0.79)	1.30 (2.41)	1.21 (1.39)	1.31 (2.21)	1.27 (2.92)

Table 13.10 Mean relative sensitivity score per dead fuel moisture content class

	Dead fuel moisture content (%)			
	2 – 5	5 - 10	10 - 15	15 – 20
Mean RS (St. dev.)	-0.36 (0.23)	-0.91 (2.03)	-1.20 (2.07)	-1.25 (2.95)

Table 13.11 Mean relative sensitivity score per canopy base height class

	Canopy base height (m)		
	1 - 3	3 - 6	6 - 10
Mean RS (St. dev.)	-0.11 (0.91)	-0.82 (5.79)	-0.76 (5.68)

Table 13.12 Mean relative sensitivity score per available surface fuel load class

	Surface fuel load (kg/m2)		
	0.5 – 0.8	0.8 – 1.2	1.2 – 1.5
Mean RS (St. dev.)	0.52 (4.38)	0.47 (5.33)	0.64 (5.40)

Table 13.13 Mean relative sensitivity score per canopy bulk density class

	Canopy bulk density (kg/m3)		
	0.05 – 0.1	0.1 – 0.2	0.2 – 0.3
Mean RS (St. dev.)	0.11 (0.69)	0.13 (1.46)	0.19 (1.36)

Table 13.14 Mean relative sensitivity score per foliar moisture content class

	Foliar moisture content (%)		
	80 – 120	120 – 150	150 – 180
Mean RS (St. dev.)	-0.78 (6.15)	-0.88 (5.86)	-0.02 (0.64)

13.5 Semi-arid heath fire spread model Cruz *et al*. (2010).

The semi-arid heath fire spread model system integrates a series of models aimed at predicting the likelihood of fire propagation and the associated rate of spread. The probability of successful fire spread was modelled using logistic regression analysis:

$$P_S(y=1)=\frac{1}{1+\exp(2.926+2.132\ U_2+2.32\ MC+5.31\ PCS_{el})} \tag{13.7}$$

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^{-1}), *MC* is the moisture content (%) of dead suspended fuels, and PCS_{el} is the elevated 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%).

Fuel moisture contents (*MC*, %) are calculated from calendar date, cloud cover, air temperature (T, °C) and relative humidity (RH, %) as:

$$MC = 4.37 + 0.161\ RH - 0.1\ (T - 25) - \Delta\, 0.027\ RH \tag{13.8}$$

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

The surface fire rate of spread model for heath fuels (R_{Heath}, m min^{-1}) is as follows:

$$R_{Heath} = 2.455\ U_2^{\ 1.2}\ exp(-0.11\ MC)\ FHS_{el}^{\ 0.90} \tag{13.9}$$

where FHS_{el} is the elevated fuel layer Fuel Hazard Score.

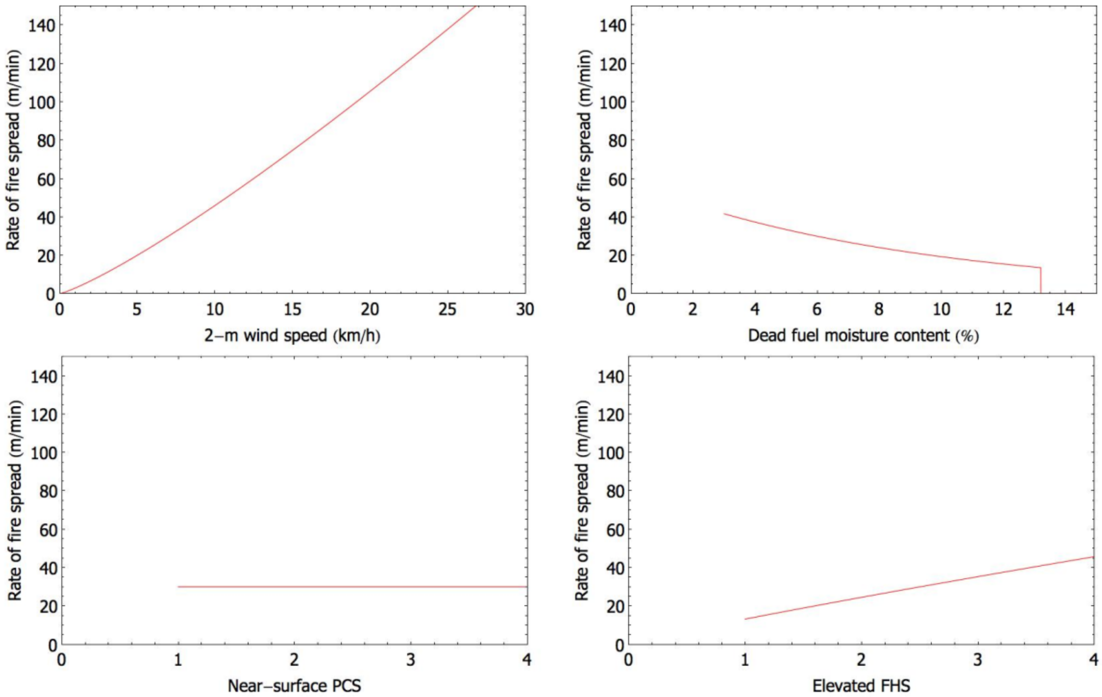

Figure 13.16 Effect of wind speed (top left), dead fuel moisture (top right), near-surface fuel PCS (bottom left) and elevated fuel FHS (bottom right) on rate of fire spread predicted in semi arid heathlands by Cruz *et al* (2010) model. Variables held fixed while an input varied were: 2-m wind speed: 7 km/h; dead fuel moisture content: 6%; near surface PCS: 2.5; Elevated fuel FHS: 2.5.

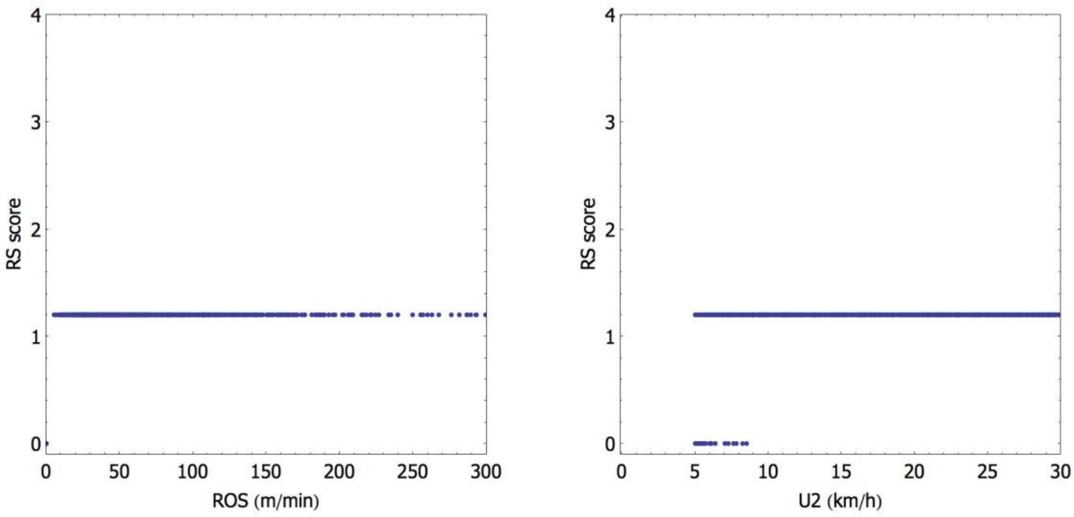

Figure 13.17 Relative sensitivity (RS) score as a function of 2-m wind speed (U2) perturbation. Left: RS score as a function of modelled rate of fire spread. Right: RS score as a function of open wind speed.

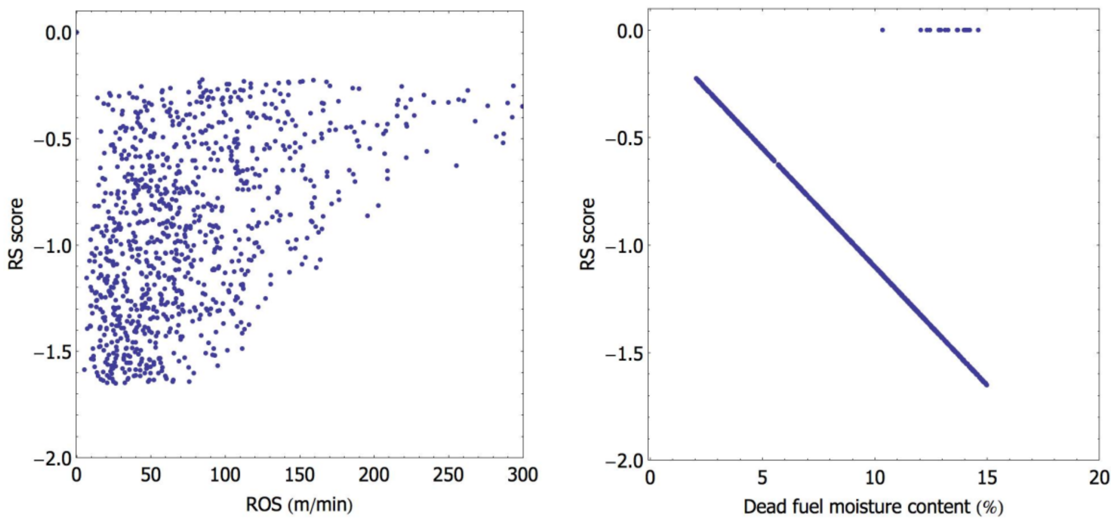

Figure 13.18 Relative sensitivity (RS) score as a function of dead fuel moisture content perturbation. Left: RS score as a function of modelled rate of fire spread. Right: RS score as a function of dead fuel moisture content.

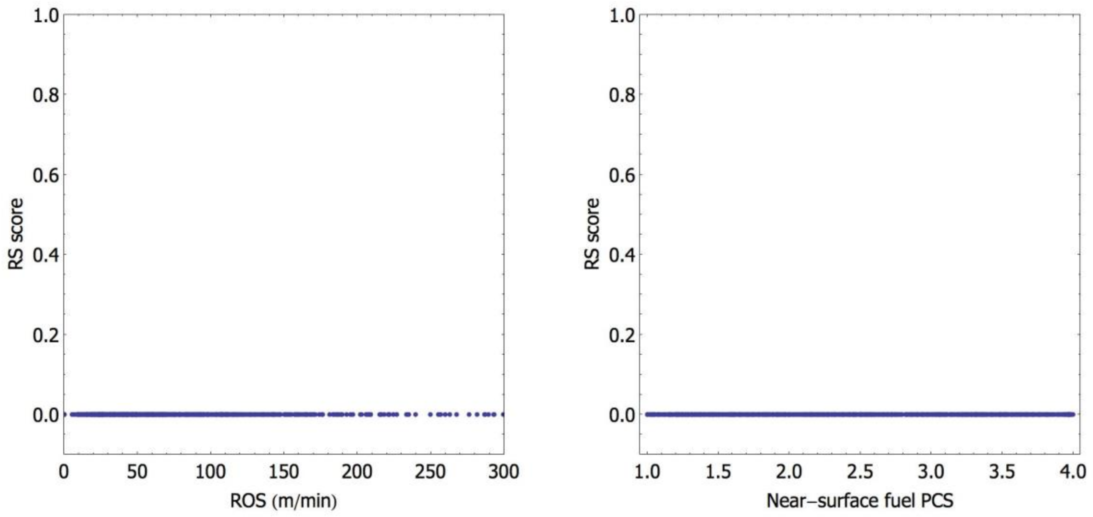

Figure 13.19 Relative sensitivity (RS) score as a function of near-surface fuel PCS perturbation. Left: RS score as a function of modelled rate of fire spread. Right: RS score as a function of fuel cover. Near-surface fuel PCS is used in the go/no-go calculation.

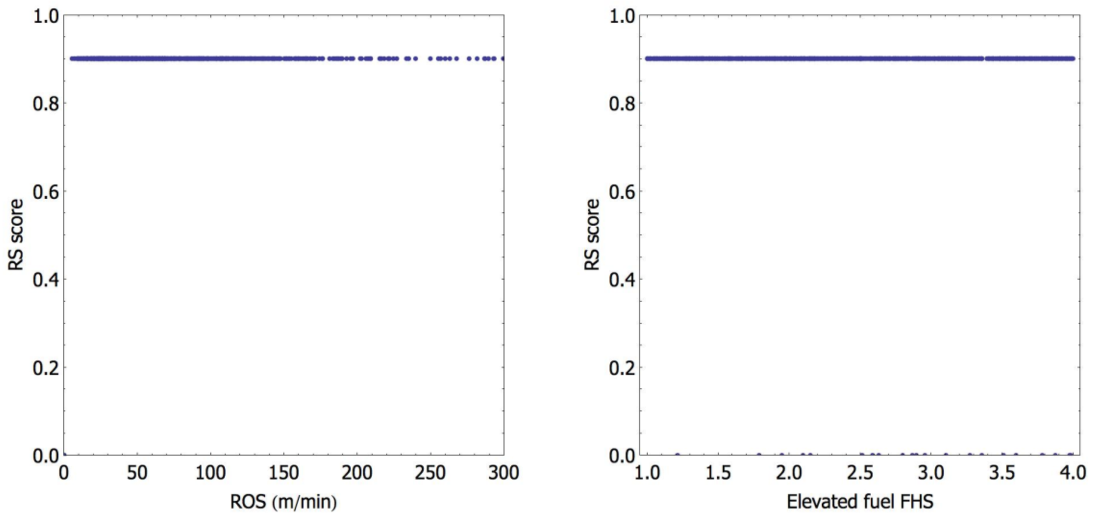

Figure 13.20 Relative sensitivity (RS) score as a function of elevated fuel FHS perturbation. Left: RS score as a function of modelled rate of fire spread. Right: RS score as a function of fuel cover.

Table 13.15 Mean relative sensitivity score per 2-m wind speed class

	2-m wind speed (km/h)				
	5 – 10	10 - 15	15 - 20	20 - 25	25 - 30
Mean RS (St. dev.)	-1.08 (0.35)	1.19 (0.00)	1.19 (0.00)	1.19 (0.00)	1.19 (0.00)

Table 13.16 Mean relative sensitivity score per dead fuel moisture content class

	Dead fuel moisture content (%)	
	5 - 10	10 - 15
Mean RS (St. dev.)	-0.88 (0.71)	-1.29 (0.33)

Table 13.17 Mean relative sensitivity score per near-surface Percent Cover Score (PCS)

	Near surface PCS		
	1 - 2	2 – 3	3 – 4
Mean RS (St. dev.)	0.11 (1.07)	0.0 (0.0)	0.0 (0.0)

Table 13.18 Mean relative sensitivity score per elevated Fuel Hazard Score (FHS)

	Elevated FHS (%)		
	1 - 2	2 – 3	3 – 4
Mean RS (St. dev.)	0.89 (0.09)	0.87 (0.14)	0.87 (0.16)

13.6 Dry eucalypt forest fire model (Vesta), Cheney *et al*. (2012).

The DEFFM or Vesta model is a model suited to predict fire spread rates in eucalypt forests under dry summer conditions (i.e. does not incorporate the effect of recent rainfall in decreasing fuel availability). The model is based on the analysis of experimental fire data and incorporates the effect of open wind speed, fine dead fuel moisture and three different understorey fuel descriptors: the surface fuel Fuel Hazard Score (FHS), and the near surface fuel FHS and height. The model form is (Cheney *et al*. 2012):

$$R = \begin{cases} 30 + \Phi M_f & , U_{10} \leq 5\text{km/h} \\ [30 + 1.531\,(U_{10} - 5)^{0.858}\; FHS_s^{0.93}\; (FHS_{ns}\, H_{ns})^{0.637}\, B_1]\, \Phi M_f & , U_{10} > 5\text{km/h} \end{cases} \quad (13.10)$$

where R is the rate of fire spread (km/h), 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 is (after Burrows (1999)):

$$\Phi M_f = 18.35\, MC^{-1.495} \quad (13.11)$$

With MC being the moisture content of fine dead fuels. For further details on the model development see Cheney *et al*. (2012) and Cruz *et al*. (2015a).

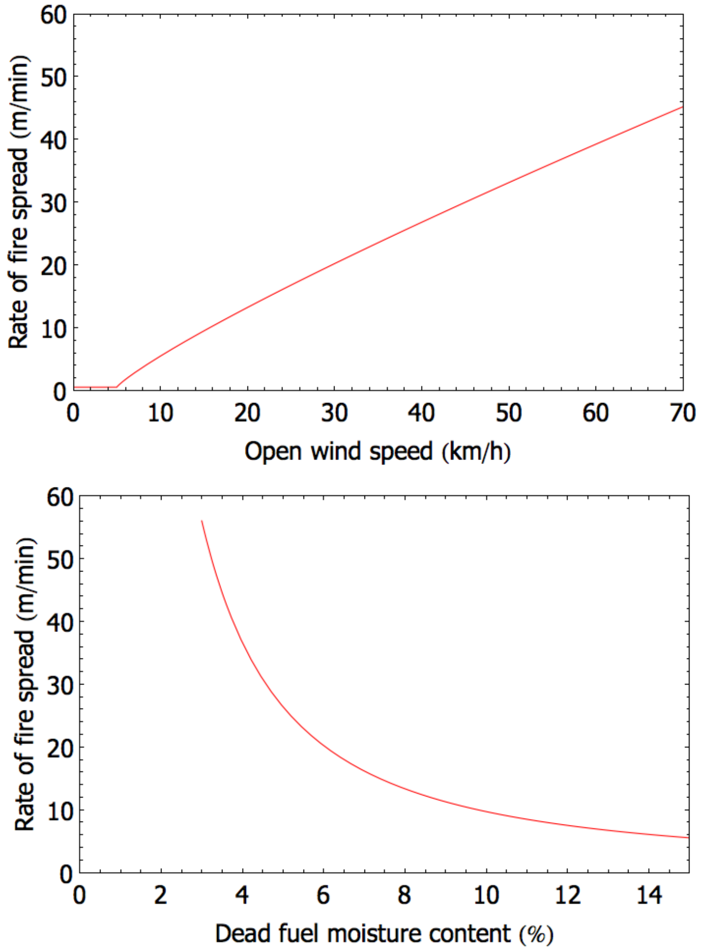

Figure 13.21 Effect of wind speed (top) and dead fuel moisture (bottom) on rate of fire spread predicted in dry eucalypt forests by Cheney *et al*. (2012) model. Variables held fixed while an input varied were: 10-m open wind speed: 30 km/h; dead fuel moisture content: 6%; surface fuel FHS: 3; near surface fuel FHS: 3; near-surface fuel height: 20 cm.

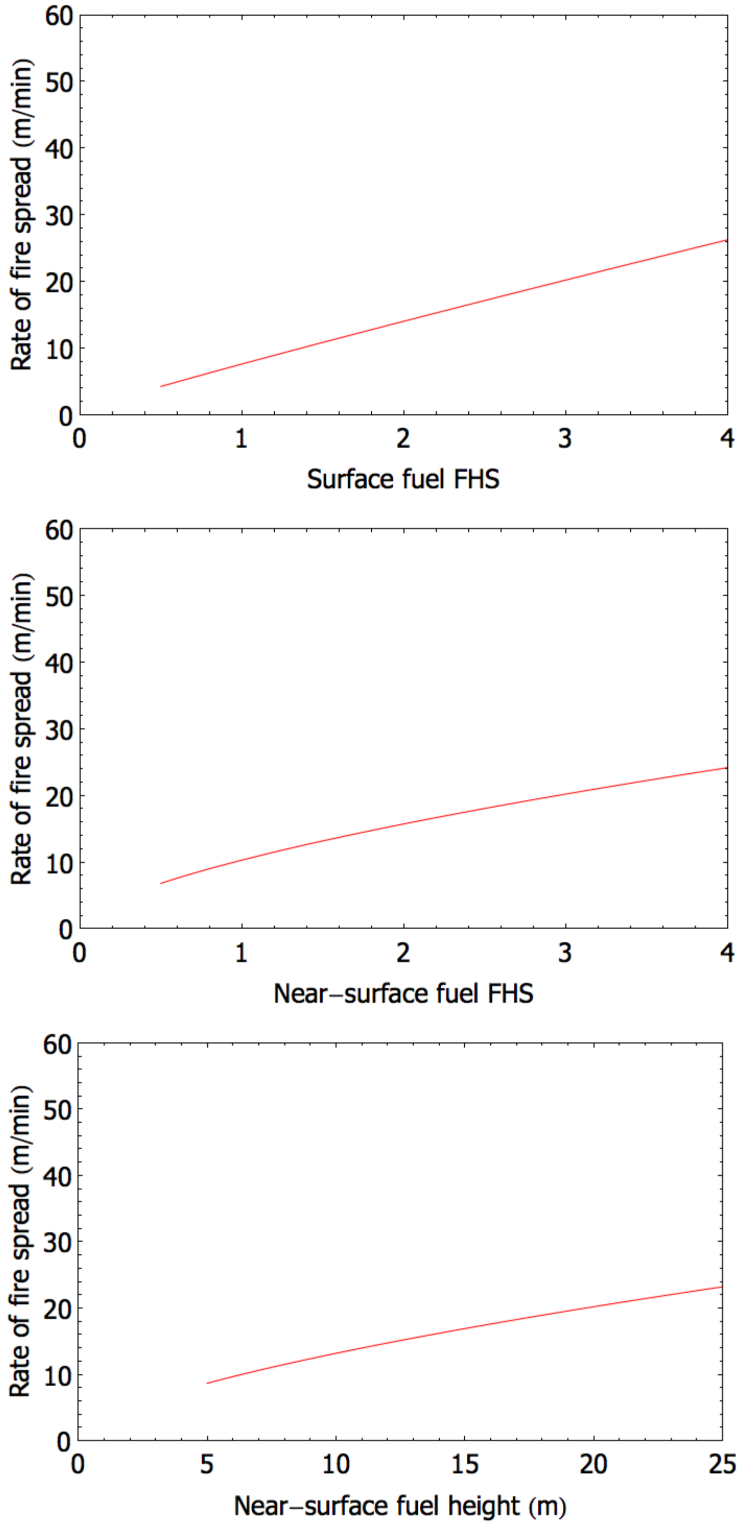

Figure 13.22 Effect of surface fuel FHS (top), and near surface fuel FHS (middle) and near surface fuel height (bottom) on rate of fire spread predicted in dry eucalypt forests by Cheney *et al*. (2012) model. Variables held fixed while an input varied were: 10-m open wind speed: 30 km/h; dead fuel moisture content: 6%; surface fuel FHS: 3; near surface fuel FHS: 3; near-surface fuel height: 20 cm.

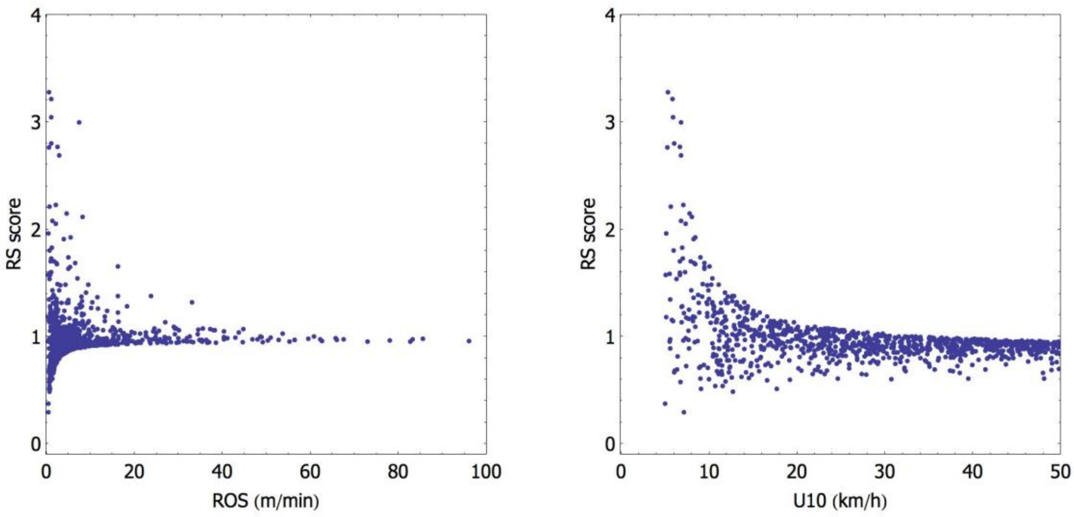

Figure 13.23 Relative sensitivity (RS) score as a function of 10-m open wind speed (U10) perturbation. Left: RS score as a function of modelled rate of fire spread. Right: RS score as a function of open wind speed.

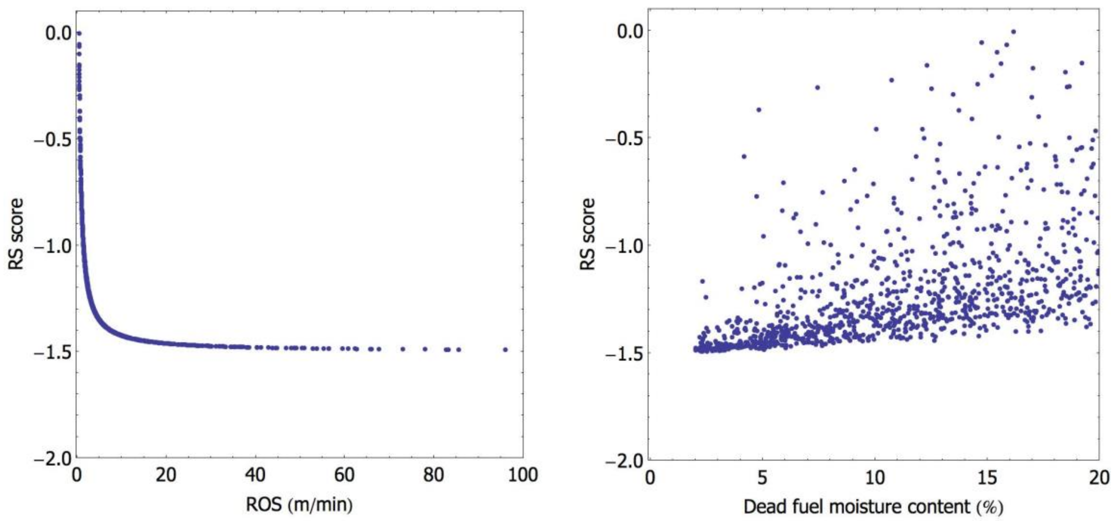

Figure 13.24 Relative sensitivity (RS) score as a function of dead fuel moisture content perturbation. Left: RS score as a function of modelled rate of fire spread. Right: RS score as a function of dead fuel moisture content.

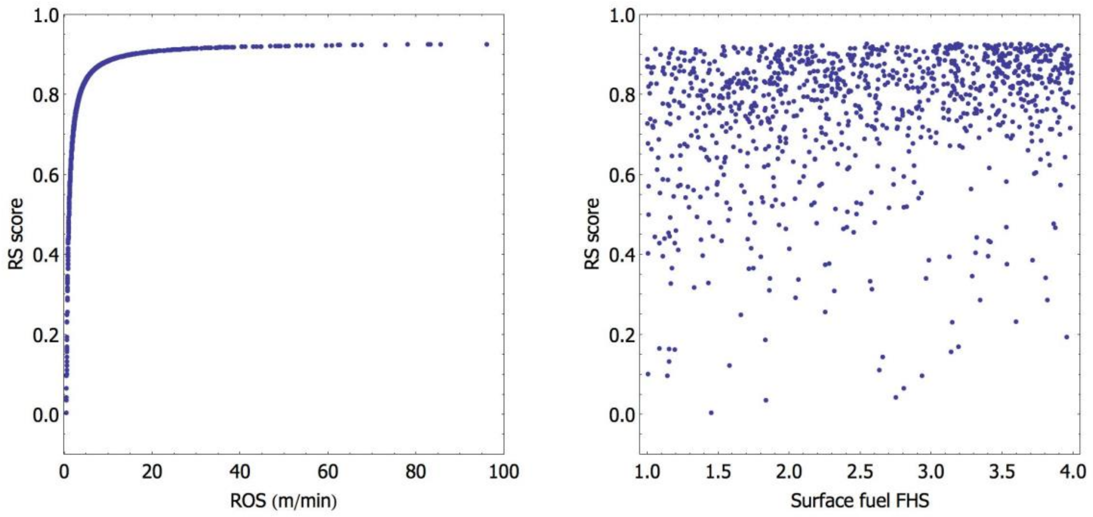

Figure 13.25 Relative sensitivity (RS) score as a function of surface fuel FHS perturbation. Left: RS score as a function of modelled rate of fire spread. Right: RS score as a function of surface fuel FHS.

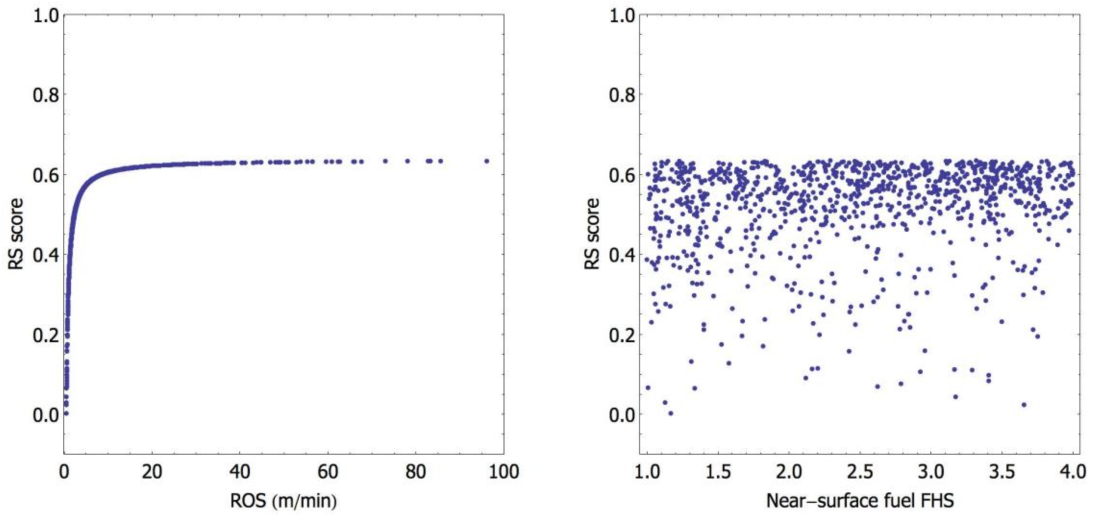

Figure 13.26 Relative sensitivity (RS) score as a function of near-surface fuel FHS perturbation. Left: RS score as a function of modelled rate of fire spread. Right: RS score as a function of near-surface fuel FHS.

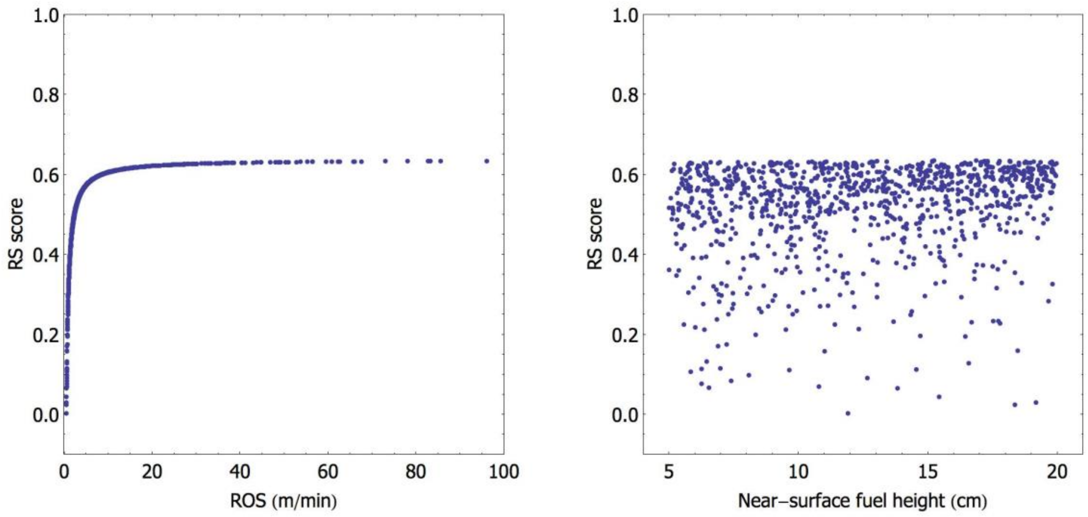

Figure 13.27 Relative sensitivity (RS) score as a function of near-surface fuel height perturbation. Left: RS score as a function of modelled rate of fire spread. Right: RS score as a function of near-surface fuel height.

Table 13.19 Mean relative sensitivity score per 10-m open wind speed class

	10-m open wind speed (km/h)				
	5 – 10	10 - 20	20 - 30	30 - 40	40 - 50
Mean RS (St. dev.)	1.7 (1.1)	1.0 (0.2)	0.9 (0.1)	0.9 (0.1)	0.9 (0.1)

Table 13.20 Mean relative sensitivity score per dead fuel moisture content class

	Dead fuel moisture content (%)			
	2 – 5	5 - 10	10 - 15	15 - 20
Mean RS (St. dev.)	-1.4 (0.1)	-1.3 (0.2)	-1.2 (0.3)	-1.05 (0.3)

Table 13.21 Mean relative sensitivity score per surface fuel FHS class

	Surface fuel FHS (%)			
	<1.5	1.5 - 2.5	2.5 – 3.5	>3.5
Mean RS (St. dev.)	0.7 (0.2)	0.75 (0.16)	0.78 (0.16)	0.81 (0.13)

Table 13.22 Mean relative sensitivity score per near-surface fuel FHS class

	Near-surface fuel FHS (%)			
	<1.5	1.5 - 2.5	2.5 – 3.5	>3.5
Mean RS (St. dev.)	0.49 (0.12)	0.52 (0.11)	0.53 (0.11)	0.54 (0.11)

Table 13.23 Mean relative sensitivity score per near-surface fuel height class

	Near-surface fuel height (cm)		
	<10	10 - 15	15 - 20
Mean RS (St. dev.)	0.49 (0.12)	0.52 (0.11)	0.54 (0.1)

13.7 Mallee-heath model, Cruz *et al*. (2013)

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^{-1}; air temperature varied between 16 and 39°C; and relative humidity ranged from 7 to 80%. The total fuel load, comprised of 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^{-1} in a 7-year old stand and 14.8 t ha^{-1} 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^{-1} and 735 and 17,200 kW m^{-1}, respectively. Flame height varied between 1 and 8 m, with an average of 3.8 m.

The model system to predict the full range of fire behaviour in mallee-heath shrubland comprises linkages between four models. This includes: a model for fire spread sustainability (Equation33) and if the environmental conditions suggest that a fire will propagate then a model is used to determine the type of fire -- i.e. surface fire or crown fire. Based on this result, the rate of fire spread is determined for either a surface fire or a crown fire.

As in Cruz *et al*. (2010), two groups of models 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:

$$P_S(y = 1) = \frac{1}{1+exp[-(14.62+0.207\ U_{10}-1.872\ MC-0.304\ Cov_O)]} \tag{13.12}$$

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^{-1}), *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 probability of crown fire occurrence was modelled through logistic regression analysis:

$$P_C(y=1) = \frac{1}{1+exp[-(-11.138+1.4054\,U_{10}-3.4217\,MC)]} \tag{13.13}$$

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.

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^{-1}) model was:

$$R_S = 3.337\,{U_{10}}^{1.0}\,exp(-0.1284\,MC)\,{H_O}^{-0.7073} \tag{13.14}$$

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^{-1}) was:

$$R_C = 9.5751\,{U_{10}}^{1.0}\,exp(-0.1795\,MC)\,(Cov_O/100)^{0.3589} \tag{13.15}$$

The use of the model system first requires an estimation of the likelihood of sustained fire spread, P_S. If $P_S < 0.5$, then it is assumed that a line ignition will be self-extinguishing. If $P_S > 0.5$, 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. If $P_C < 0.01$, the fire is assumed to be spreading but largely controlled by the surface phase and surface fire behaviour characteristics are in turn estimated (e.g. Equation 36). If $P_C > 0.99$, fire propagation by crowning is assumed and the crown fire rate of spread model is applied. 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 $0.01 < P_C < 0.99$. 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:

$$R = \begin{cases} R_S, & P_C \le 0.01 \\ (1-P_C)\cdot R_S + P_C \cdot R_C, & 0.01 < P_C \le 0.99 \\ R_C, & P_C > 0.99 \end{cases} \tag{13.16}$$

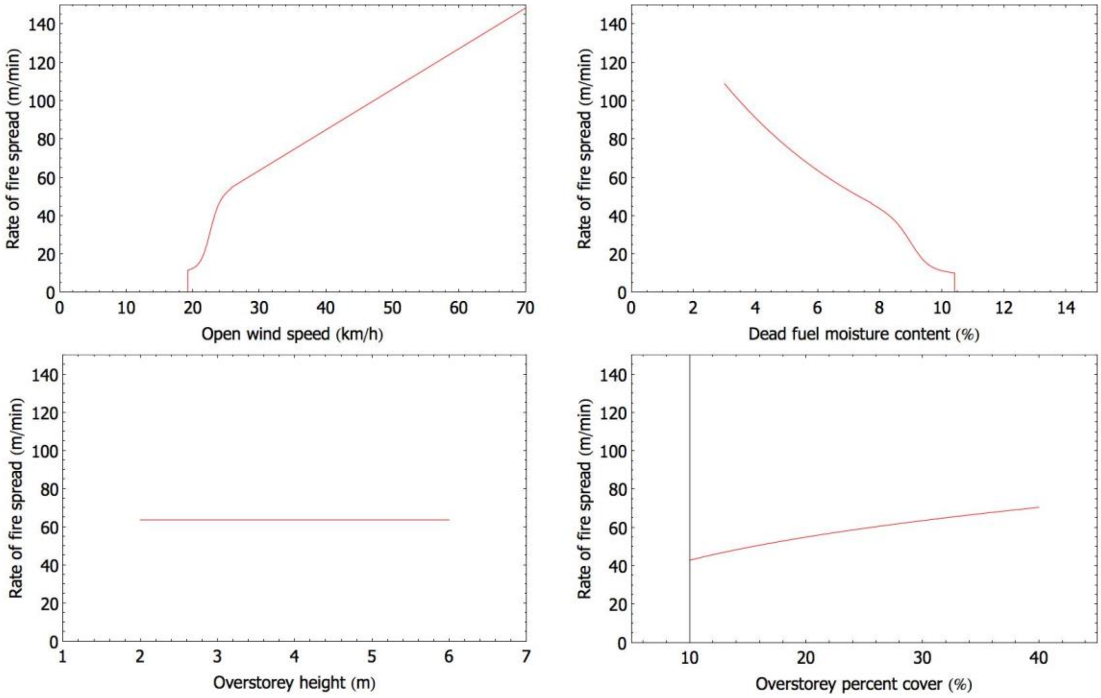

Figure 13.28 Effect of wind speed (top left), dead fuel moisture (top right), Overstorey height (bottom left) and Overstorey cover (bottom right) on rate of fire spread predicted in semi-arid mallee-heath fuels by Cruz *et al* (2013) model. Variables held fixed while an input varied were: 10-m wind speed: 30 km/h; dead fuel moisture content: 6%; Overstorey height: 4 m; Overstorey cover: 30%.

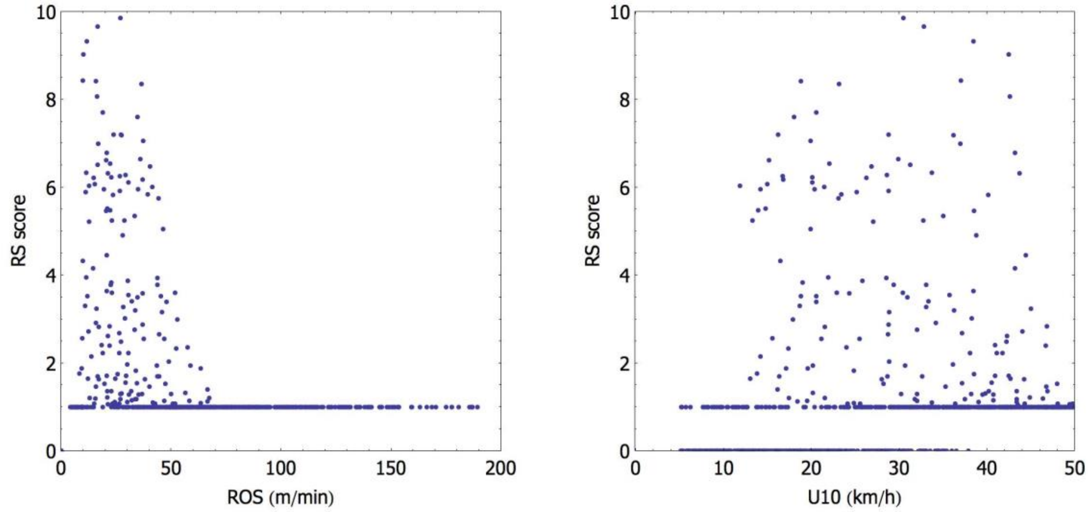

Figure 13.29 Relative sensitivity (RS) score as a function of 2-m wind speed (U2) perturbation. Left: RS score as a function of modelled rate of fire spread. Right: RS score as a function of open wind speed.

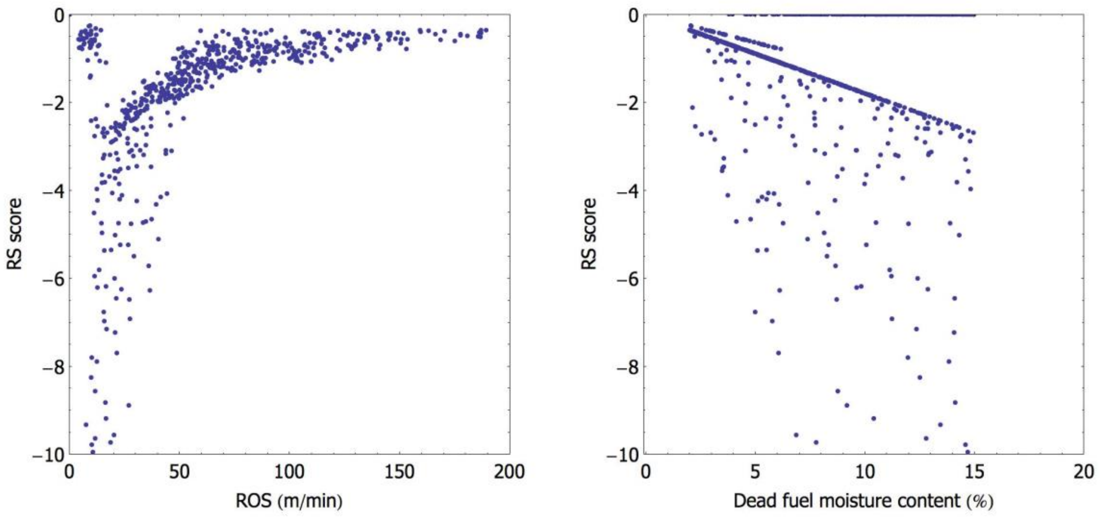

Figure 13.30 Relative sensitivity (RS) score as a function of dead fuel moisture content perturbation. Left: RS score as a function of modelled rate of fire spread. Right: RS score as a function of dead fuel moisture content.

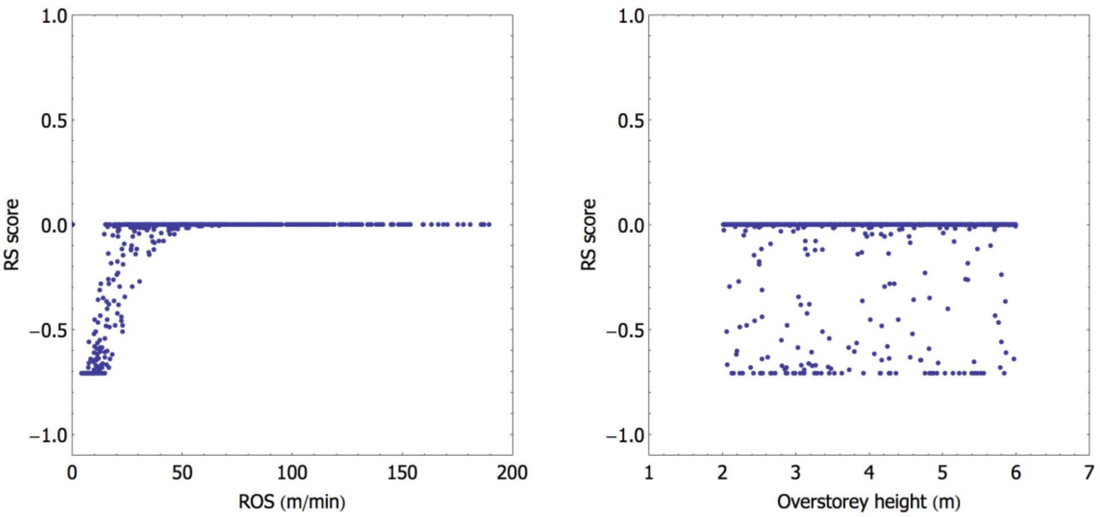

Figure 13.31 Relative sensitivity (RS) score as a function of Overstorey height perturbation. Left: RS score as a function of modelled rate of fire spread. Right: RS score as a function of overstorey height. Overstorey height is used in the go/no-go calculation.

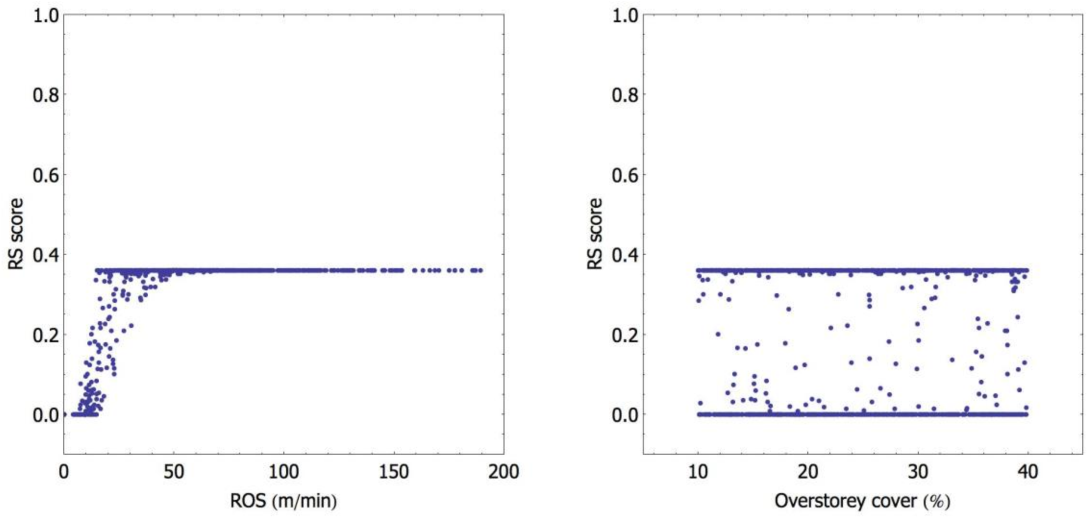

Figure 13.32 Relative sensitivity (RS) score as a function of overstorey cover perturbation. Left: RS score as a function of modelled rate of fire spread. Right: RS score as a function of overstorey cover.

Table 13.24 Mean relative sensitivity score per 10-m open wind speed class

	10-m open wind speed (km/h)				
	5 – 10	10 - 20	20 - 30	30 - 40	40 - 50
Mean RS (St. dev.)	0.18 (0.39)	0.70 (1.65)	1.12 (1.85)	1.36 (1.66)	1.26 (1.01)

Table 13.25 Mean relative sensitivity score per dead fuel moisture content class

	Dead fuel moisture content (%)	
	5 - 10	10 - 15
Mean RS (St. dev.)	-1.29 (1.57)	-1.02 (1.93)

Table 13.26 Mean relative sensitivity score per overstorey height class

	Overstorey height (m)	
	2 - 4	4 – 6
Mean RS (St. dev.)	-0.08 (0.21)	0.6 (0.18)

Table 13.27 Mean relative sensitivity score per overstorey cover class

	Overstorey cover (%)		
	10 – 20	20 – 30	30 – 40
Mean RS (St. dev.)	0.11 (0.79)	0.14 (0.59)	0.19 (0.17)

13.8 Temperate shrubland model, Anderson *et al*. (2015).

Anderson *et al.* (2015) used a dataset from experimental fire data (n = 79) from Australia, Europe and South Africa to develop a model the spread rates in temperate shrublands, or heath, fires.. The rate of fire spread model (R, m min^{-1}) with vegetation height (H, m) as an input variable was:

$$R = \begin{cases} [R_0 + 0.2(5.67\,(5\,WF)^{0.91} - R_0)U_{10}]H^{0.22}\exp(-0.076\,MC) & ,U_{10} < 5\ \mathrm{km\,h^{-1}} \\ 5.67\,(WF\,U_{10})^{0.91}H^{0.22}\exp(-0.076\,MC) & ,U_{10} \geq 5\ \mathrm{km\,h^{-1}} \end{cases} \quad (13.17)$$

where U_{10} is the 10-m open wind speed (km h^{-1}), H is the average vegetation height (m) and MC is the moisture content of dead suspended fuels (%). WF is a wind reduction factor, which for the current parameterization 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^{-1}

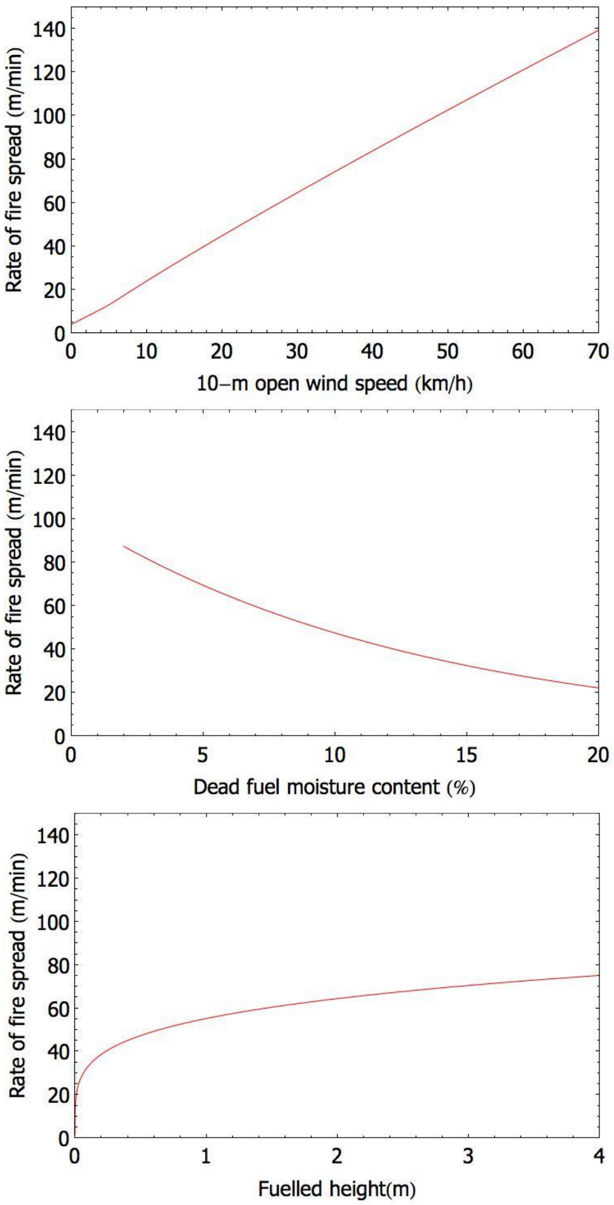

Figure 13.33 Effect of wind speed (top), dead fuel moisture (middle) and fuel bed height (bottom) on rate of fire spread predicted in temperate shrublands by Anderson *et al*. (2015) model. Variables held fixed while an input varied were: 10-m open wind speed: 30 km/h; dead fuel moisture content: 6%; fuel bed height: 2 m.

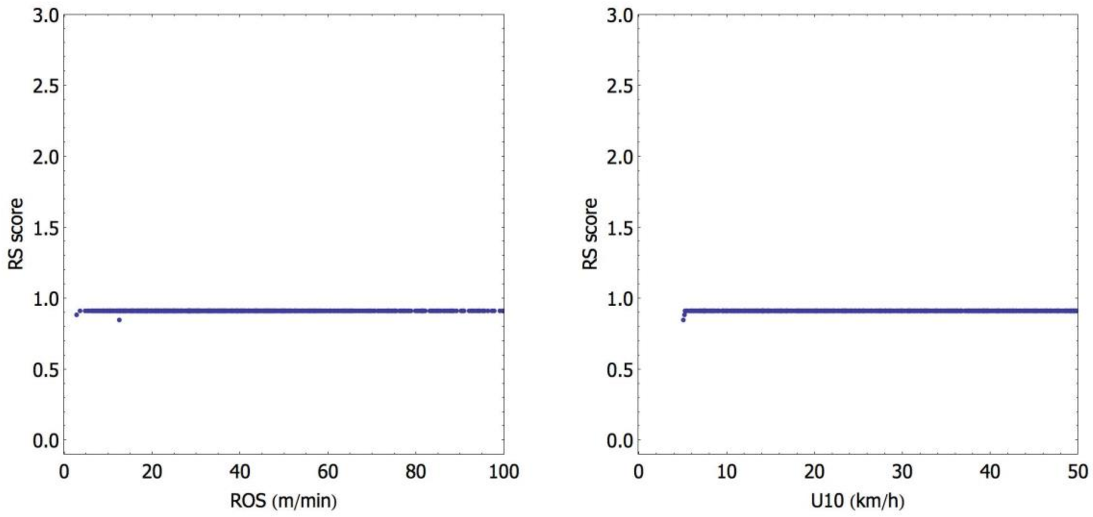

Figure 13.34 Relative sensitivity (RS) score as a function of 10-m open wind speed (U10) perturbation. Left: RS score as a function of modelled rate of fire spread. Right: RS score as a function of open wind speed.

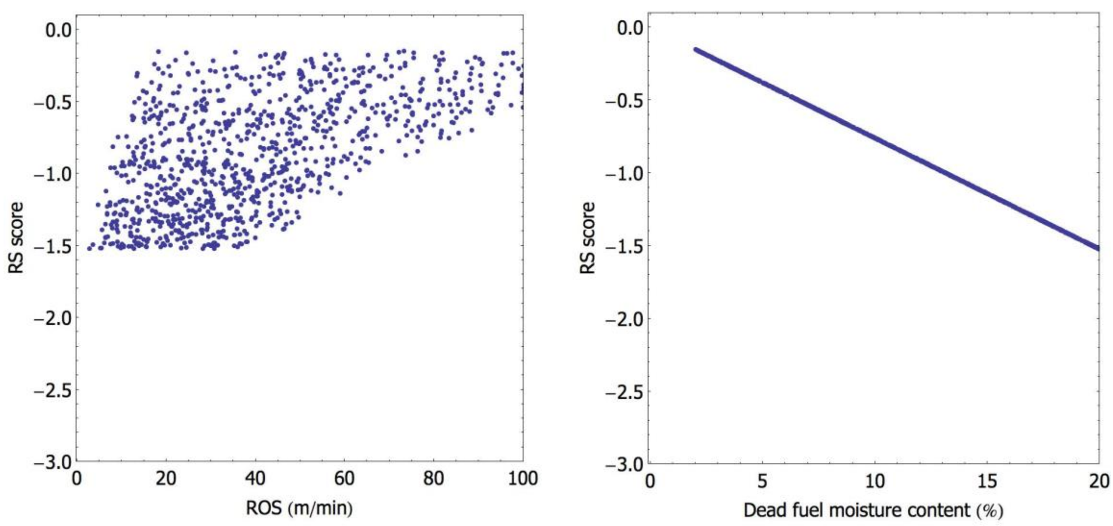

Figure 13.35 Relative sensitivity (RS) score as a function of dead fuel moisture content perturbation. Left: RS score as a function of modelled rate of fire spread. Right: RS score as a function of dead fuel moisture content.

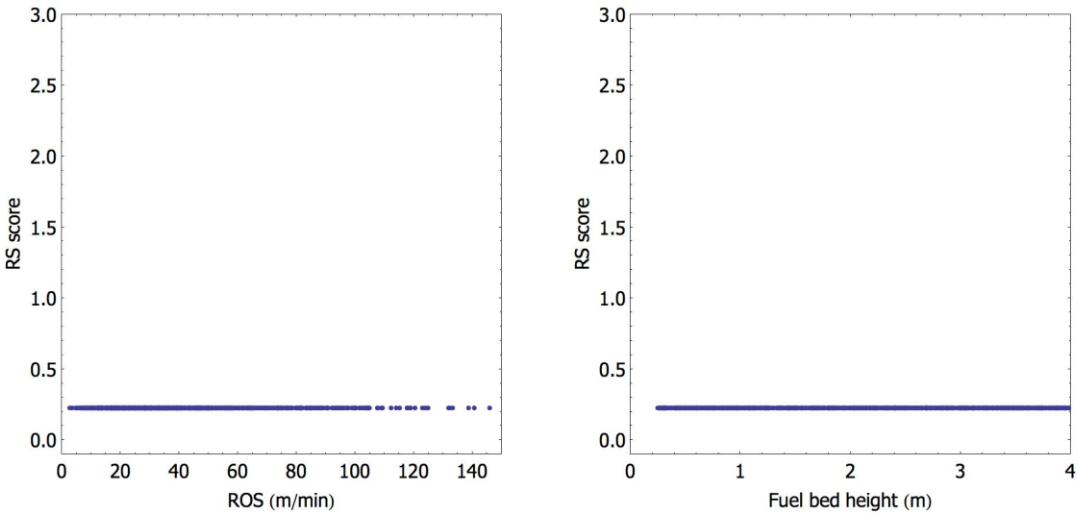

Figure 13.36 Relative sensitivity (RS) score as a function of surface fuel FHS perturbation. Left: RS score as a function of modelled rate of fire spread. Right: RS score as a function of surface fuel FHS.

Table 13.28 Mean relative sensitivity score per 10-m open wind speed class

	10-m open wind speed (km/h)				
	5 – 10	10 - 20	20 - 30	30 - 40	40 - 50
Mean RS (St. dev.)	0.91 (0.01)	0.91 (<0.01)	0.91 (<0.01)	0.91 (<0.01)	0.91 (<0.01)

Table 13.29 Mean relative sensitivity score per dead fuel moisture content class

	Dead fuel moisture content (%)			
	2 – 5	5 - 10	10 - 15	15 - 20
Mean RS (St. dev.)	-0.26 (0.06)	-0.57 (0.1)	-0.96 (0.1)	-1.34 (0.1)

Table 13.30 Mean relative sensitivity score per fuel bed height

	Fuel bed height (m)			
	<1	1 - 2	2 – 3	3 – 4
Mean RS (St. dev.)	0.22 (0.01)	0.22 (0.01)	0.22 (0.01)	0.22 (0.01)

13.9 Spinifex model, Burrows *et al*. (2015) – calculations based on code in NFDRS on Jan-2018

Due to the discontinuous nature of spinifex fuels the calculation of the rate of fire spread requires a prior assessment of the likelihood of sustained fire spread (Gill *et al.*, 1995). A first calculation determines if conditions for sustained fire spread ('go'/'no-go') exist, in the forst of a the Fire Spread Index (SI_{FL}):

$$SI_{FL} = 0.332(U_2) + 0.308(FuelCover) - 0.451(MC) - 7.213 \quad (13.18)$$

where U_2 is the average wind speed (km h^{-1}) at a height of 2-m, *FuelCover* is the cover of spinifex and other fine fuel load (%) and *MC* is the compound fuel moisture content (%) incorporating both dead and live fuel components. The SI_{FL} describes the likelihood of a fire to spread. If $SI_{FL} < 0$, then it is unlikely that sustained fire spread will occur. For $SI_{FL} > 0$, higher SI_{FL} values correspond to a higher likelihood that a free-spreading fire will occur.

If the SI_{FL} value indicates that a fire is likely to spread, the forward rate of fire spread (R_{FL}, m h^{-1}) is calculated as:

$$R_{FL} = 708 + 143.4(U_2) + 28.7(FuelCover) - 161.7(MC) \quad (13.19)$$

Note that this is the model provided in the NFDRS code not the recently published version (Burrows *et al*. 2018). See further discussion in Chapter 3

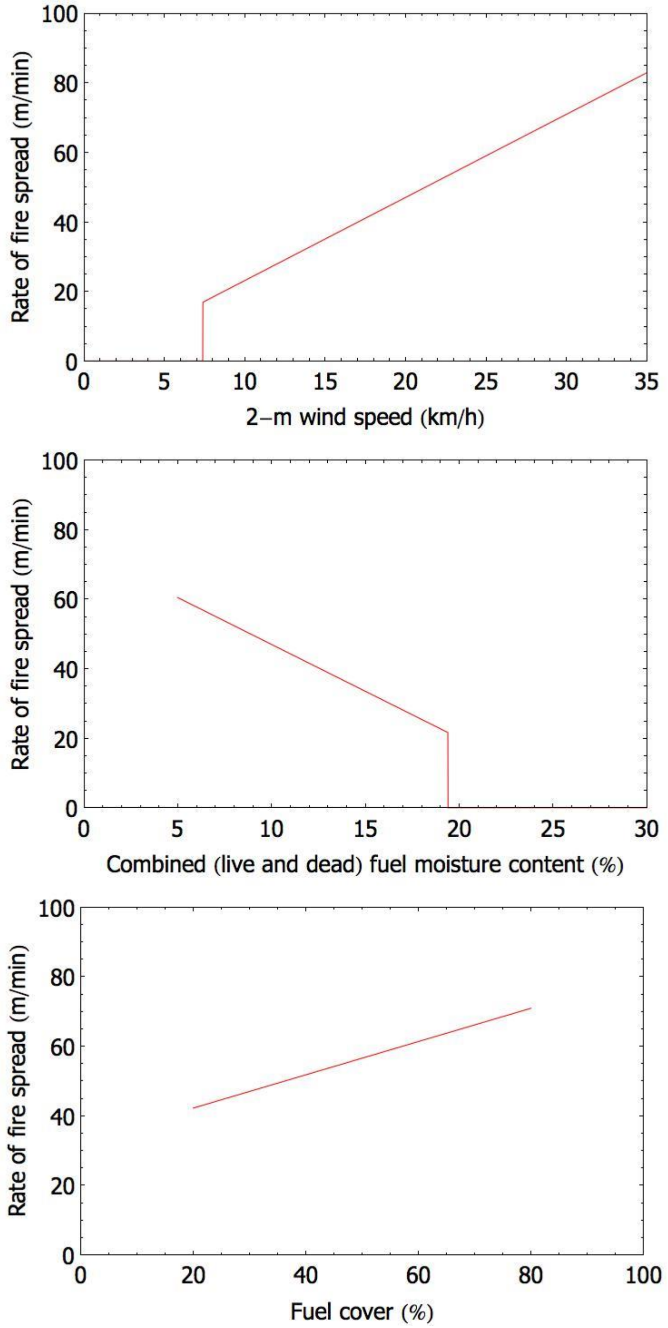

Figure 13.37 Effect of wind speed (top), dead fuel moisture (middle) and fuel cover (bottom) on rate of fire spread predicted in spinifex grasslands by Burrows *et al.* (2015) model. Variables held fixed while an input varied were: 2-m wind speed: 20 km/h; dead fuel moisture content: 10%; fuel cover: 30%.

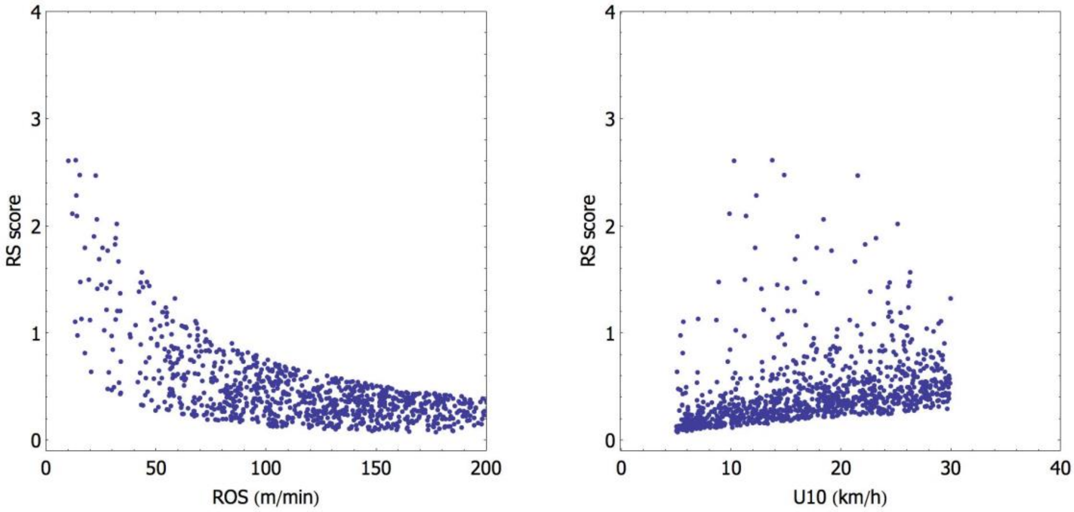

Figure 13.38 Relative sensitivity (RS) score as a function of 10-m open wind speed (U10) perturbation. Left: RS score as a function of modelled rate of fire spread. Right: RS score as a function of open wind speed.

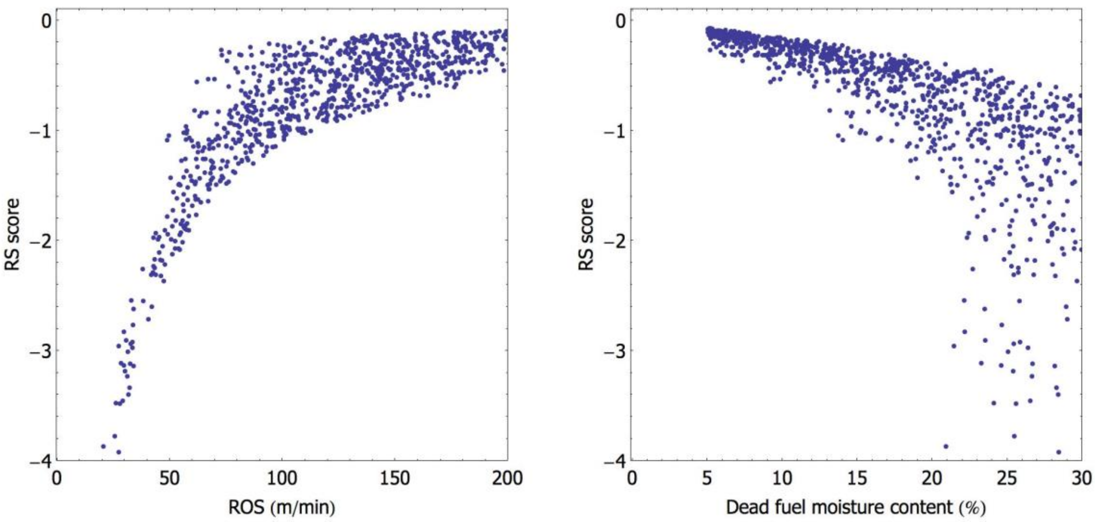

Figure 13.39 Relative sensitivity (RS) score as a function of dead fuel moisture content perturbation. Left: RS score as a function of modelled rate of fire spread. Right: RS score as a function of dead fuel moisture content.

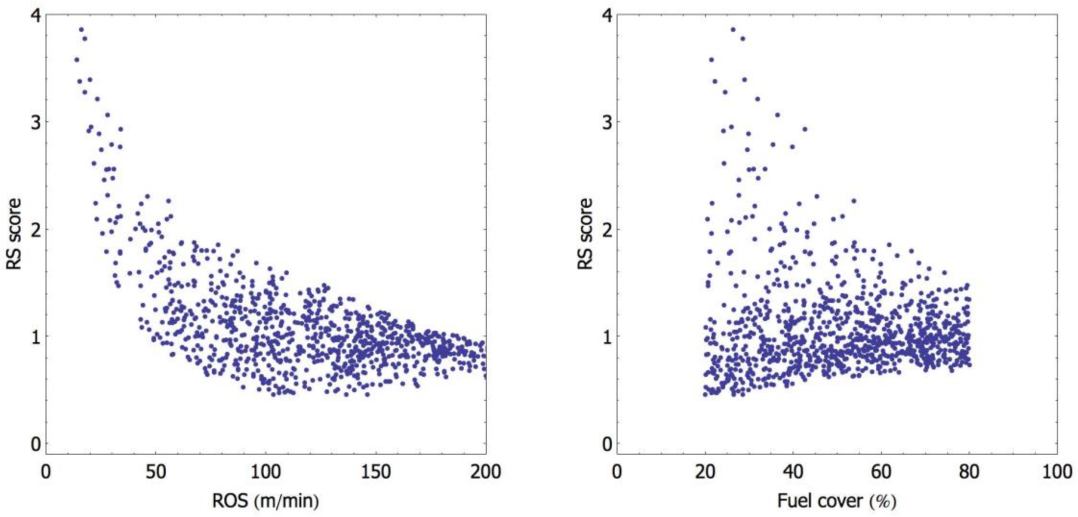

Figure 13.40 Relative sensitivity (RS) score as a function of fuel cover perturbation. Left: RS score as a function of modelled rate of fire spread. Right: RS score as a function of fuel cover.

Table 13.31 Mean relative sensitivity score per 2-m wind speed class

	2-m open wind speed (km/h)				
	5 – 10	10 - 15	15 - 20	20 - 25	25 - 30
Mean RS (St. dev.)	-0.27 (4.6)	0.43 (1.29)	0.48 (0.31)	0.52 (0.33)	0.57 (0.26)

Table 13.32 Mean relative sensitivity score per dead fuel moisture content class

	Dead fuel moisture content (%)			
	5 - 10	10 - 15	15 - 20	20 - 30
Mean RS (St. dev.)	-0.19 (0.1)	-0.36 (0.16)	-0.59 (0.23)	-0.3 (15)

Table 13.33 Mean relative sensitivity score per fuel cover

	Fuel cover (%)		
	20-40	40 – 60	60 – 80
Mean RS (St. dev.)	0.39 (9.2)	1.1 (0.3)	1.1 (0.2)

14 Discussion and recommendations

The NFDRS Research Prototype has met and exceeded its aim of demonstrating that it is feasible to develop a fire danger rating system based on fire behaviour models that is national, modular, and open to continuous improvement. As described in the preceding chapters, the system we built met these design requirements and well as out-performing the existing system on several performance measures. In this section we reflect on lessons drawn from reflecting on the results across the individual results chapters, identify knowledge gaps and limitations, and make recommendations for future work.

The use of rating definitions based on observable features of fire incidents proved fruitful both for developing understanding of how fire managers use ratings and also for testing the Research Prototype system. Unlike other natural hazards, bush fires cannot be quantified by a single physical quantity such as wind speed for cyclones or height for floods. This is partly due to the complexity of bush fires as physical phenomena but also because the scale and consequences of bush fires depend in most cases on how fire fighters and the community respond to the fire. Nevertheless, we were able to use a range of simple physical parameters such as fire intensity to predict ratings that were defined in terms of fire behaviour, prescribed burning opportunities, suppression response and consequences.

Previous studies have evaluated the predictive ability of fire danger rating systems. These have used fire occurrence (Vasilakos *et al.* (2007); Sebastián-López *et al.* (2008); Padilla and Vega-García (2011); Eastaugh *et al.* (2012); Plucinski (2014)), and in some cases also fire area (Viegas *et al.* (2000); Andrews *et al.* (2003); Walding *et al.* (2018)) to evaluate the systems. As far as we can tell, the Research Prototype is the first attempt to evaluate other characteristics of fires such as fire behaviour, suppression difficulty, and consequences. While the manual data collection required for this approach requires considerable effort, we believe this is worthwhile. Partly because it allows detailed insight into the performance of the system but also because our analysis of summary statistics showed that for most conditions the expected number of fires is zero.

The results of the live trial showed that it was possible to build a system that performed well across a wide variety of fuel types and fire danger using fire behaviour models appropriate to each fuel type. We identified several important gaps in scientific knowledge, so it is heartening that the Research Prototype performed well in spite of these weaknesses. Specifically, the Research Prototype out-performed the current system even for forest fuels, for which the FFDI was designed, and where the lack of suitable fuel availability models was most clearly a problem. The Research Prototype also demonstrated its value in fuel types that do not conform to the current grass-forest split.

As expected during a short trial during a single fire season, large or highly destructive events were under-represented in the live trial dataset. The use of case studies to expand the number of Category 5 and 6 observations was valuable and we are grateful for the work done in reporting on these fires that enabled us to extract useful information years after the fires. It would be useful to continue to assemble assessments of fire behaviour and suppression response for future events.

The reanalysis study further highlighted the need to construct a climatology of NFDRS ratings prior to implementation. In particular, it identified areas requiring improvement that might have been obvious from the live trial alone. The reanalysis data set will also be useful for characterising the timing and intensity of future fire seasons once the final design of the NFDRS has been determined.

Current fire danger ratings are primarily set by GFDI, which is being used for most fuel types except forest. Under the NFDRS fuel classification grass-like fuels are divided between grassland and savanna, as well as modified versions of these. These distinctions have seen an improvement in performance, and allow for easy adoption of improved knowledge (e.g. research on variations of fire behaviour by fuel type) and inputs (e.g. methods and scale of grass fuel state reporting).

While forest only covers a small area of Australia, it coincides with the areas of greatest population, predominately within the south-eastern states. Hence, forest represents a greater influence on setting fire danger ratings and a greater proportion of reported incidents than simple area covered would imply. The coverage of forest is equivalent between the current FDR system and the Research Prototype, but the segregation into dry and wet forest and the inclusion of local fuel parameter inputs allows for distinction between different forest types that is not currently accounted for.

The other fire behaviour models, which are not currently considered when calculating fire danger ratings, cover a significant portion of Australia. Collectively these fuel types considerably out-performed the current FDR system.

The data sets (fuel type, fuel parameters, and fire history) developed for the Research Prototype represent an important step in the development of nationally consistent data with a direct operational application. There is a wide range of applications for this data beyond the NFDRS including operational agency use, inter-operability between jurisdictions, input to fire spread models, and input to research projects.

Analysis of area ratings of the duration of the live trial was useful for identifying features of the Research Prototype that were not visible in the detailed analysis of the incident data observations. In particular the area ratings showed that the system has a tendency to over warn. This was in large part driven by spinifex fuels but also indicated the need to improve understanding of the interactions of fuel, fire behaviour, and fire danger in other areas such as the forest areas around Sydney.

It is also worth noting that the Research Prototype did not examine the validity of using the 90th percentile rule to set area ratings. This would be a valuable topic of future study, particularly with some effort to understand the importance of spatial patterns in determining ratings. For example, should the rule be modified to require ratings to be set by contiguous areas of grid cells with a given rating, rather than allowing small, scattered pockets of value to determine ratings?

The sensitivity analysis performed on the fire behaviour models will assist efforts to improve the accuracy if the system. For all models this analysis demonstrated the strong sensitivity to wind speed and fuel moisture, highlighting the importance of accurate weather forecasts and fuel dryness models. Sensitivity to fuel parameters varied widely amongst fuel types and at different times since fire. These results will help to target efforts to collect data or generate improved fuel models. Continuing improvements in the skill of weather forecast models will also improve the accuracy of predictions.

14.1 Knowledge gaps and limitations

In order to build the Research Prototype in the time available to the project team it was necessary to use existing data and models. Consequently the system uncovered gaps in existing knowledge and required some compromises and decisions to use the 'least worst' available information. It was also necessary to use or apply models that we knew to be poor, for example application of the drought factor to the DEFFM/Vesta forest fire spread model. Table 14.1 lists in detail the gaps and compromises identified during the build of the Research Prototype. Key knowledge gaps and opportunities were:

- There are significant gaps in our understanding of application of fire behaviour models to fire danger ratings including: how to best use models designed to predict the spread of fully developed head fires, how to incorporate slope and other terrain effects, how to include fuel availability models into calculations, how to apply existing models to fuel types which do not have a specific fire behaviour model
- How to best incorporate red flag warnings into the system, including use of new products such as pyroconvection and dry lightning forecasts.
- How to include uncertainty and ensemble modelling approaches into the calculation and communication of fire danger rating
- How to best calculate fire weather area ratings from detailed gridded calculations. We used the existing 90th percentile rule, alternative approaches are possible but were not investigated.

- Climatology calculations were completed for only 6 years of historical weather. This analysis would need to be extended to use the full 25 year dataset when it becomes available to provide reliable statistics.
- Topography was not included in the Research Prototype, either in the fire behaviour models or through its influence on suppression difficulty.
- The data set developed by Plucinski (2013) that included information on suppression for initial attack fires was identified as a potential data source for testing the Research Prototype but was not used.
- Several of the major fuel types did not use all six rating Categories. This causes some issues for statistical analysis because predicted ratings were either correct or out by at least two classes. It also meant that rating maps frequently showed Category 4 ratings in all but the mildest conditions, potentially affecting the credibility of the system. For fuel types that did not have Category 3 in the Research Prototype, this could be added if the boundaries introduced are consistent with operational practice and fire metrics, not merely artificial boundaries introduced for statistical convenience. Lack of Category 6 was less of a problem and those fuel types for which it is not considered necessary to have Category 6 could remain without it although there may be a need to include it to ensure consistency.

At the conclusion of the Research Prototype project a survey of participants who returned observations was conducted. Although there was not time to include the results of the survey in this report, an initial reading of the comments indicated that several ideas for improvements were identified. These will be considered in the next phase of the project. The results of the survey and participant feedback will be published in a future report.

14.2 Recommendations

- Continue the phased implementation of the NFDRS building on the Research Prototype. The next phase should be an 'Operational calibration' of the system which will:
  - Address the observed over-prediction bias of the Research Prototype, particularly identified problems with application of some fire behaviour models causing over-prediction
  - Address some identified issues with fuel type classification and fuel parameter inputs, and allow for continual improvement of base data
  - Revise the rating tables to improve their consistency and clarity
  - Include a live trial period that covers the dry season in northern Australia
  - Evaluate the implications of adopting the NFDRS for prescribed burn planning
  - Engage operational decision makers in evaluation of the system
- Commence a research program to address knowledge gaps identified in this report. The research will be part of a continuous improvement program to support the NFDRS into the future. Key topics for the initial research are
  - Develop adequate fuel availability models and their application to fire behaviour models
  - Develop a better understanding of application of fire spread models to fire danger, including: the build-up phase, topographic effects, the role of spotting, estimation of heat yield, and application to less common fuel types,
  - Develop an understanding of representation of uncertainty in fire danger forecasting including inclusion of uncertainty in weather forecasts, treatment of effectively unknowable quantities (e.g. some fuel parameters), and sensitivity to spatial scale and rating thresholds.

- Consider using the same number of rating categories for all fuel types where this does not introduce artificial boundaries, with broadly similar meanings for each category across all fuel types to assists with consistent messaging. The number of categories will be informed by the social research project and may differ for internal and public facing presentation of the NFDRS.
- Extend the calculation of the NFDRS climatology to use the full weather reanalysis dataset when it is available. If it is feasible, also consider the effects of climate change on fire danger rating.
- Pursue the development of the remaining components of the full NFDRS: ignition, suppression, and impact indices.

Table 14.1 Detailed list of recommended changes and improvements.

Topic (Report section)	Comment/description	Recommendation (Priority)
Rating definitions (2)	Extension of Australian and International literature review	An extension of the literature cited here and more comprehensive review of both Australian and international literature is necessary to better document and inform the work defining fire danger rating. (medium)
System name (2)	"NFDRS" is well recognised as the name of the system currently in place in the United States and has been since 1972	To avoid confusion in reporting and in usage throughout the world, we recommend changing the name. (high)
Predicting consequences (2)	Previous research (e.g. such as Blanchi *et al.* (2010) and Blanchi *et al.* (2012)) has identified measures of impact or consequence related to fire danger rating. However, without direct links to fire behaviour variables (such as rate of spread, fireline intensity or flame height) it was difficult to apply these values or represent them numerically within the Research Prototype or use them to forecast potential consequences.	Revisit these studies and explore the data to identify areas where the NFDRS could be aligned with and more accurately estimate potential consequences such as fatalities and house loss. (medium)
Consequences for natural assets (2)	While many of studies described in this report have important links to fire danger in terms of potential community impacts such as life and house loss, they fail to recognise the consequences of fire on natural assets such as biodiversity or threatened and vulnerable species.	Further investigation is needed to identify ways to incorporate the spatial and/or categorical valuation of assets at risk such into the fire danger rating that result in improved usefulness of the NFDRS. (medium)

Topic (Report section)	Comment/description	Recommendation (Priority)
Rating definitions (2)	During the live trial evaluation, some participants have had different interpretations of methodology resulting in an inconsistent observation of whether the descriptors were correct, over-predictions or under-prediction. This may have related to up to 80 points.	To improve the analysis and our understanding of how each of the descriptive categories aligned with the fire danger rating, each observation should be re-visited to check alignment is against forecast rather than observation. (medium)
Flame length (3.1)	Only flame *height* was taken into account, while flame *length* could be a more informative variable for fire behaviour and fire suppression - for grass and shrub fires, and surface fires spreading through the understory.	Investigate relative importance for flame length vs. flame height for specified fuel types. (medium)
Spotting (3.1.2)	Spotting equations are missing for all fuel types except forests.	More research into spotting behaviour is needed. For forests, but also for other fuel types (e.g. mallee, heath and pine). (medium)
Drought and fuel availability (3.2.1)	There have been recent advances in estimation of drought and seasonal moisture changes and opportunities may exist utilising the DPI Combined Drought Index to estimate fuel availability on a spatial scale	Explore the use of the DPI Combined Drought Index as a proxy for fuel availability (low)
Drought factor adjustments for wet forests (3.2.1.1, 10.1.2.3)	No well-documented information exists for when fuel becomes available in wet forests. The equation used is a rough estimation without solid scientific backup. Observations indicated it work well for the wettest forest types (rainforest, WSF in gullies) but not for drier variations (WSF on ridges, drier aspects)	Further validation of performance of model application used. More research into fuel availability of wet forests is needed. (high)
Fuel moisture model for pine (3.2.1.4)	Simple functions to modify dead fuel amount and fuel moisture content were used. Uncertain how accurate these are.	Implementing the Canadian FWI moisture models for the next NFDRS version.(medium)
Build up phase (3.2.2)	No satisfactory model exists to estimate the build-up phase of a model.	More research into the build-up phase of fires is needed. (high)
Slope (3.2.3)	Slope-effects were not included.	More research into topography and slope effects is needed. Slope effects could (should) be incorporated in a next version of the NFDRS. (high)

Topic (Report section)	Comment/description	Recommendation (Priority)
Grass condition (3.3.1, 4.5.2)	At the moment only curing and fuel load is used. No information on height or cover. Current grass fuel load reporting practices may not adequately represent variation between native and managed grasslands or other sources of variation. Inconsistency in methods of determining and reporting grass fuel load between jurisdictions	Future grass load reporting could be more detailed. PSG is working to develop standard methods and reporting (high)
Heat yield (caloric content) (3.3)	Unless a peer reviewed value was readily available, we used 18,600 kJ/kg. This value can vary widely with species/ecosystem composition.	Literature review for published data on heat of combustion values. Re-analyse data with most appropriate values per fuel type. (medium)
Spinifex model update (3.3.3)	In April 2018, a newer version of the spinifex model was published (Burrows et al. 2018).	The newer model should be used in the next version of the NFDRS. (medium)
Heathland model for wind speed <5 km/h (3.3.7)	We overlooked the equation for wind speed <5 km/h	The equation for winds < 5 km/h should be included in a next version of the NFDRS. (high)
Pine model (3.3.8, 10.1.2.8)	A simplified version of the pine model was applied for ease of model application and removing the need for complicated fuel inputs. Pine has limited spatial coverage and won't influence FWA level ratings	Consider if other options provide a better balance between prediction accuracy and implementation effort (low)
Pine model for flame height (3.3.8)	Flame height for crown fires was not correctly handled	Fix the coding error. (high)
Fuel types without fire behaviour models (4.2.2)	For some fuel types, relevant fire behaviour models have not been developed. E.g. acacia woodlands, chenopod shrublands, low wetlands, rural, urban, horticulture	Further validation of performance of model application used. More fire behaviour research needed in these fuel types. (medium)
Fuel types with ephemeral grass (4.2.2)	Some arid fuel types (chenopod shrubland, acacia woodland) are only flammable when ephemeral grass growth is high	Develop a threshold system based on grass growth (e.g. grass condition reporting, remote sensing, rainfall data, ephemeral grass growth modelling) to switch between models or grass condition (medium)

Topic (Report section)	Comment/description	Recommendation (Priority)
Fuel parameter data quality (4.4)	Fuel parameter tables were collated from existing jurisdiction fuel data. Values were converted from supplied to required formats Gaps were filled with generic values. Comprehensive search for additional values was out of scope.	Validation of values and conversions used; additional source data suggestions from jurisdictions Long term: Incorporate fuel parameter data into BFC Fuel Catalogue; Jurisdictions to have custodianship of data and updates (high)
Spotting (4.4.1)	Potential for long range spotting has been recorded in the fuel parameter tables (estimated from bark hazard values or other information), but has not been applied within the Research Prototype	Determine if this data is useful for adjusting spotting calculations in future NFDRS versions (medium)
Fuel load (4.4.2)	The original version of the Olson curve (assumes fuel returns to 0 t/ha after fire) has been implemented in the Research Prototype, not the version that adjusts for initial (immediate post-fire) fuel levels	Initial fuel values have been included in the fuel parameter tables, so this could be implemented in future NFDRS versions (medium)
Near surface fuel (4.4.2)	Most State data sets did not have values for near-surface fuel. This is a major impediment to implementing the Vesta forest model due to its dependence on near-surface fuel hazard scores and height. The approach taken to fill this gap in the Research Prototype could lead to an over estimation of rate of spread.	Short-term: Determine most appropriate way to fill gaps in near-surface fuel data. Long-term: Research to collect better data on near-surface fuel or develop a version of the Vesta model that is less reliant on near-surface fuel. (high)
Fire history data currency (4.5.1, 10.4)	Fire history data would require regular updates in an ongoing NFDRS system. Each jurisdiction are responsible for their own data	PSG are working to develop protocols around data sharing and storage. A data portal would be a good way of getting updated fire history input data into the NFDRS system in future (high)
Fuel type map revision (4.6)	Classification of State fuel types to NFDRS fuel types and map processing was done rapidly	Greater verification of fuel classification and spatial data by each jurisdiction is required for future application (high)

Topic (Report section)	Comment/description	Recommendation (Priority)
Fuel data improvements (4.6, 10.4)	Each jurisdiction have their own priorities for updating of fuel data with new research or improved base mapping	PSG are working to develop protocols around data sharing and storage. A data portal would be a good way of getting updated fuel input data into the NFDRS system in future (high)
Data scaling (4.6.1, 10.3)	The scaling process to convert input data sets to the NFDRS 1.5 km forecast grid results in the loss of some fine scale spatial detail. Only basic analysis of the effect was done	Further sensitivity analysis of scaling process (medium)
Thresholds for categories (8)	Threshold definitions for FFDI/GDI should clarified. If the index is 12, should that be included in low moderate or high? 24, should that be included in high, or very high? Etc.	Double check with the BoM how it is done at the moment. Otherwise, come up with some sensible rules. (low)
Northern Australia observations (8, 10.1.2, 11)	Spinifex and tropical savanna observations are under-represented in the NFDRS dataset due to timing of the live trial	Include a live trial period that covers the dry season in northern Australia (high)
Use of case study data (8.5.4, 9)	To improve the range of conditions represented within the live trial dataset, various time periods for each of the case studies have been included in analyses. In some cases, up to 10 time periods were included from the same fire event.	Consider how many points from each fire event should be used before they may bias results. (low)
Application bounds of Vesta model (8.10.4)	For one observation flame heights of 140 m were predicted in western shrub grass dry sclerophyll forest. This fuel type has very high elevated fuel heights, this seems to be beyond the limits of application of the Vesta flame height calculations.	Future research into fire behaviour in fuel types with high elevated fuel heights. (medium)
Case studies (9)	Investigating the accuracy of the Research Prototype through case studies has been an important component of the evaluation process. Despite this, our use of case studies from around Australia has been limited by the number of well-documented case studies with adequate descriptions of fire behaviour, suppression and impact.	Support development of well-documented case studies from future important fire events. (high)

Topic (Report section)	Comment/description	Recommendation (Priority)
Grass fuel types (10.1.2.1)	Potential for different fire behaviour between grass, pasture and crop	Further validation of performance of model application used. More fire behaviour research; CFA have a proposal to study crop/stubble fire behaviour (medium)
Classification of some wet forest fuel types (10.1.2.3)	The classification of swamp forest (particularly riverine forests), karri forest and native plantation requires further consideration	Further validation of performance of model application used and further consideration of classification (medium)
Spinifex model (10.1.2.4, 11)	General observation of the system during the live trial indicated over-prediction within spinifex. The FWAs identified as producing a very high number of category 5 ratings during the live trial correlate with the FWAs that have a significant proportion of spinifex	Further consideration of spinifex model application / thresholds for ratings categories (high)
Fire weather areas (11)	It has been noted in feedback that some existing fire weather areas are not well matched to climate zones or fuels	Support existing efforts to revise fire weather areas. (low)

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Appendix A. Workshop 1 - For operational staff - Summary of outcomes and feedback

Date:	**Tuesday 6th June 2017**
Time:	10.00am – 3.00pm (optional session from 3.15pm-5.00pm)
Location:	NSW RURAL FIRE SERVICE Headquarters 15 Carter Street Lidcombe NSW
Chair:	Simon Heemstra, Manager Community Planning, NSW RFS
Meeting contact:	Jen Hollis, 02 6128 0653, jennifer.hollis@rfs.nsw.gov.au

At this workshop the RFS project team worked together with participants to develop defined categories and thresholds for the National Fire Danger Rating System Research Prototype that would be useful for operational response to fires. The aim of the day was to develop draft fire danger rating (FDR) categories for each of the major fuel types in terms of;

- suppression difficulty and strategy,
- fire behaviour and fire weather,
- prescribed burning opportunities and
- consequences - rate of fire growth, potential house losses, time to containment, final fire size.

Before attending the workshop, participants were asked to complete a Questionnaire and related Exercises in preparation and to bring along for consideration and to assist in practical exercises. This document records the broad outcomes for the workshop as well as a summary of Questionnaire responses. Pre-workshop exercises and the feedback provided during workshop practical sessions have also been summarised below. These outcomes and feedback will be used to inform the development of FDR categories for the Research Prototype and will also contribute to the project's recommendations for future research required to implement the full system.

Key messages and feedback from Workshop 1

1. Participants agreed that our current approach to Fire Danger Rating (FDR) in Australia can be improved, largely through better consideration of fuels, fire behaviour and suppression difficulty.
2. Most participants considered the most important limitation of the current FFDI/GFDI based FDR was that it was limited to two fuel types and that it does not account for fuel variability (e.g. availability, load, type and structure).
3. Most participants felt that improvements will directly benefit fire management mostly through improved preparedness, accuracy and more timely and targeted community notifications. It will provide a better quantification of risk and support for decision making as well as improving the alignment with fire behaviour, suppression difficulty and impact.
4. Participants agreed that including a category targeting prescribed burning conditions within the FDR would be helpful for fire practitioners to identify typical, indicative burning conditions, provided the FDR does not replace the need for practitioners to consult burn prescriptions and the appropriate fire spread model.
5. The pre-workshop Questionnaire and Exercises, together with the workshop practical sessions encouraged diverse discussion, constructive debate and broad ranging feedback regarding the setting of thresholds to be used for FDR categories.
6. Participants generally found it possible to agree on general FDR categories, however more specific numerical thresholds that define the difference between FDR categories were largely provided via participant feedback in the pre-workshop Questionnaire and Exercise.

Questionnaire and Exercise feedback from participants – PART A

Table 1. Q1. How does your agency/department use the current FFDI or GFDI based Fire Danger Rating and how important do you consider this application? (on a scale of 1 (not important) – 10 (very important))		
	Importance	Sample no.
Public notifications	9	10
Declaration of fire bans	9	9
Readiness determination	8	12
Resource allocation	8	12
Identifying suitable prescribed burn conditions	7	12
Identifying possible fire behaviour	7	12
Assessment of suppression difficulty and selection of suppression strategy	6	12
Participants added the following uses;		
Identification of state-wide risk	8	1
Consideration between forecast versus actual	10	1
Bushfire construction standards/ development assessment	10	2
Pine plantation operations and closure of prescriptions	9	1
Fire load and firefighter/community safety	9	1
Potential fire growth and occurrence	9	1

Table 2. Q2. What models do you, and your colleagues from your agency/department, currently consider for predicting fire behaviour in your state?	
	Number of users
McArthur Mk5 Forest Fire Behaviour Meter (McArthur, 1967)	11
Forest Fire Behaviour Guide – Vesta (Cheney *et al.*, 2012b)	6
Forest Fire Behaviour Tables for WA - Red Book (Sneeuwjagt and Peet, 1998a)	3
McArthur control burning guide (Leaflet 80) (McArthur, 1962b)	10
CSIRO Grassland Fire Spread (Cheney *et al.*, 1998)	11
CSIRO Fire Spread for Northern Australia (Cheney and Sullivan, 2008)	6
Quick Guide for fire behaviour prediction in semi-arid mallee-heath (Cruz *et al.*, 2010; Cruz *et al.*, 2013)	6
Shrubland Model (Anderson *et al.*, 2015b)	7
Buttongrass Fire Behaviour Model (Marsden-Smedley and Catchpole, 1995)	2
Radiata Pine Fire Behaviour Model (Cruz *et al.*, 2008)	5
WA mallee heath shrubland (McCaw, 1997)	2
Spinifex grasslands (Burrows *et al.*, 2009b)	4
Participants also use these tools/models;	
Canadian Fire Behaviour Prediction System NZ SCION FB Toolkit (Podocarpus fuel type)	1 1

Pheonix Rapidfire	1
Sharples/McRae Simple Index	1
Cheney *et al.* 1992 – Prescribed burning guide for SE regrowth forest NSW	1

Q3. What do you consider to be the most important limitation/s (or failing/s) of the current FFDI/GFDI based FDR in Australia?

Most participants (n = 9) felt that the most important limitation of the current FFDI/GFDI based FDR was that it was limited to two fuel types and that it does not account for fuel variability (e.g. availability, load, type and structure). Participants (n = 5) also pointed to the large degree of error of current FDR with over and under predictions occurring for specific fuel types and weather conditions. Other important limitations that were raised included how the current FDR can represent very different fire behaviour in different climatic areas which is not aligned with fire management consideration (n = 2), is sometimes poorly understood (by both practitioners and the public) and without context (n = 3), does not take account of atmospheric stability and potential coupling between fire and the atmosphere (n = 1) and is not suitably targeted toward different audiences with the same FDR use for a broad range of applications (development assessment, suppression difficulty, impact/consequence determination) and audiences (scientists, practitioners, burn planners, general public (n = 1). While many limitations were identified, one participant felt that the current FDR is both valuable and effective for fire management agencies.

Q4. In your agency/department, what things are done differently between an FFDI of 60, and an FFDI of above 100?

Most participant responses regarding operational differences between an FFDI of 60, compared to > 100 relate to the level of readiness (or preparedness, with consideration given to pre-deployment of resources to strategic locations to enable rapid response, n = 7) as well as an escalation in notifications including public warnings, fire bans and restrictions to industry (e.g. harvest bans) and public places (e.g. park closures) (n = 8). Participants also noted a decrease in confidence in fire behaviour models but an increase in liaison and integration between state and local governments and industry. No differences in fire behaviour or suppression strategy were noted.

EXERCISE 1: Participants were asked whether current established categories of SUPPRESSION DIFFICULTY in forest reflected current practice in their agency/department?

Most participants broadly agreed that the categories describing suppression difficulty reflected current practice in their agency/department with minor, technical suggestions for each category to better reflect current suppression strategies or more appropriately describe local practices. Several participants recommended incorporating aircraft support within operational strategy descriptions as well as reference to initial (or 'first') attack strategies. One participant commented that the suppression component of the FDR should aim to provide a 'suppressability' measure, by taking into account likelihood of ignition, likelihood of initial attack success, extent and duration of campaign fires, likely resource requirements and implications of likely spotting. Another participant noted that consideration is generally given to a number of factors (not just FDR) when developing operational/suppression strategies including weather outlook, terrain, resource availability, particularly aviation support, accessibility, fire size, cost-effectiveness and on-ground decisions on strength and feasibility of success.

EXERCISES 2 & 3: Participants were asked whether current established categories of FIRE BEHAVIOUR aligned with suppression difficulty in forest reflected their experience in fire operations? Participants were then asked to describe possible fire weather together with fire behaviour categories.

Like the suppression difficulty exercise, most participants broadly agreed with the break-up of fire behaviour categories and there were many technical suggestions relating to descriptors or fire behaviour to improve each category (e.g. descriptions of spotting distance, fuel moisture content, crowning behaviour, rate of spread, flame height and fire propagation). Participants generally found it more difficult (some hesitant) to align fire weather descriptors with the fire behaviour and suppression difficulty descriptors stating difficulties associated with such large variation in fire weather leading to variations in fire behaviour and being dependent on fuel type, arrangement and terrain. Those that attempted the exercise, aligned weather descriptors such as wind speed, C-Haines and descriptions of convective column formation and atmospheric stability, relative humidity, temperature, forecasted wind changes and overnight conditions.

Setting Fire Danger Rating categories and thresholds:

Feedback from <u>Exercise 4</u> and the workshop <u>Practical sessions</u>

Participants were broken into four groups to establish FDR categories for eucalypt forest (Practical session 1) while in Practical session 2, each group worked on a different fuel type, namely; grassland, savanna, heathland and pine plantations. Together, Exercise 4 and the workshop Practical sessions encouraged diverse discussion and broad ranging feedback regarding the setting of thresholds to be used for FDR categories. Several participants completed Exercise 4 prior to attending the workshop which was particularly helpful feedback (THANK YOU to those people!) and aided group discussion during the workshop practical sessions. Generally, groups of participants were able to identify broad categories of FDR for some of the main vegetation types however found it difficult (or didn't attempt) to set thresholds based on agreed values. The outcomes for Exercise 4 and the workshop practical sessions in establishing thresholds are summarised below.

Eucalypt forest

Participants mostly agreed that including prescribed burning within FDR categories would be useful at a strategic level however the FDR should not replace the need for practitioners to consult burn prescriptions and the appropriate fire spread model. A prescribed burning category within the FDR should be indicative only and fire practitioners shouldn't rely on it in isolation without a complete assessment of conditions.

In terms of incorporating atmospheric stability, spotting potential and forecasted wind changes into the FDR, participants generally agreed that a 'red flag warning' would be most suitable, rather than bumping up an FDR category as the 'red flag warning' allows fire practitioners the ability to determine the relative effect of these conditions on FDR in their own local environment and conditions.

Participants noted a difference exists between low FDR and high FDR where low FDR's are about suppression strategies while high FDR's are more about consequences. For example, the fire behaviour isn't very different in terms of defensive strategies at the top end of the FDR scale, but other issues become a problem including extensive wind damage, trees down, lack of visibility with dust and smoke, damage to key infrastructure (e.g. power lines), and possibly being unable to operate aircraft.

There was a spilt in opinion relating to the appropriateness of using fireline intensity for FDR. While some thought it was the best variable for both agencies and for public warning, other participants expressed concern that fireline intensity may not be the best variable to use for FDR largely because it isn't transferable between vegetation types and because fire practitioners and the public would have difficulty 'measuring' or visualising it. These participants suggested that the variable needs to be measurable and have a meaning that is consistent such as flame height, rate of spread, flame depth, residence time and spotting. The participants also commented on the possibility that FDR thresholds could be established based on threshold of change in fire behaviour and the transitions between states of fire propagation (i.e. surface, elevated, crown).

The FDR categories and thresholds that were recommended for eucalypt forest as part of Exercise 4 or during the workshop Practical sessions are summarised in Table 3 below, together with a comparison with existing categories referred to in agency/departmental training resources.

Table 3 - FDR categories and thresholds that were recommended for eucalypt forest

Fuel type	FDR Category alignment against (lower limit) fireline intensity							Thresholds set by:
	1	2	3	4	5	6	7	
Forest	0	?	?	1000	3000	4000	16,000	Group 1
	0	1000	2000	4000				Participant 1
	100	200	500	1000	4000			Participant 2
	0	500	1,000	2,500	4000	10,000	25,000	Participant 3
	0	500	2,000	4,000	10,000	30,000		Participant 4
	0	500	1,000	3,000	10,000	25,000		Participant 5
	0	100	750	2,000	8,000	36,000		Participant 6
	0	1,000	3,000	4,000	16,000			Participant 7
	0	*50*	*800*	*2,000*	*3,000*			*Department of Parks and Wildlife (2016)*
	0	*800*	*2,000*	*4,000*				*Smith (2009) citing Muller, 2008*
	0	*50*	*500*	*2,000*	*4,000*			*NSW Rural Fire Service (2005)*
	0	*50*	*500*	*2,000*	*12,000*			*NSW Rural Fire Service (2014)*
	0	50	500	2,000	4,000			*Country Fire Authority (2005)*

Grassland

The group working to set thresholds for grassland fuels recommended that FDR categories be established more on flame characteristics (e.g. flame height), than on fireline intensity for the reasons described above and as such, specific numerical thresholds were not set. The group agreed that recent advances in an improved curing function (Cruz *et al.*, 2015c) should be incorporated into the FDR. Several participants did establish FDR categories as part of Exercise 4, and these are presented below in Table 4.

Table 4 - FDR categories and thresholds that were recommended for grassland

Fuel type	FDR Category alignment against (lower limit) fireline intensity							Thresholds set by:
	1	2	3	4	5	6	7	
Grassland	0	1,000	2,000	4,000				Participant 1

	50	2,000	8,000					Participant 2
	0	600	2,000	5,000	12,000	25,000		Participant 3
	0	200	4,000	8,000	15,000			Participant 4
	0	1,000	3,000	4,000	16,000			Participant 7
	0	*800*	*5000*	*8000*				*Smith (2009) citing Muller, 2008*

Shrubland and Heathland

The group working to establish FDR categories for shrubland and/or heathland identified that this fuel type could be comparable to buttongrass, scrub and mallee because of the go/no-go behaviour that typifies the fuel type (however tended to focus primarily on heath fuels) whereby fires tend to be either:

1) self-extinguishing;
2) within the narrow window for prescribed burning;
3) difficult to control.

Because of this, the group agreed that the above three categories of FDR would be suitable for FDR.

Numerical thresholds between categories were not established by the group however several participants did establish FDR categories for shrubland as part of Exercise 4, and these are presented below in Table 5.

Table 5 - FDR categories and thresholds that were recommended for shrubland

Fuel type	FDR Category alignment against (lower limit) fireline intensity							Thresholds set by:
	1	2	3	4	5	6	7	
Shrubland	0	1,000	2,000	4,000				Participant 1
	0	500	2,000					Participant 2
	0	100	1,250	5,000	10,000	36,000		Participant 6
	0	1,000	3,000	4,000	16,000			Participant 7
	0	*800*	*2,000*	*8,000*				*Smith 2009 (citing Muller, 2008)*

Savanna

The group working to set thresholds for savanna fuels recommended four FDR categories be established based on fireline intensity as follows;

1) 0-500kW/m: fires will generally self-extinguish. Too wet, too green;

2) 500-1500kW/m: 50-70% cured, ideal prescribed burning conditions. Rates of spread typically 200-600m/hr;

3) 1500-2000kW/m: mild wildfire potential. Suspend prescribed burning. Rates of spread >600m/hr, dewpoint <13% overnight, >70% cured;

4) >2000kW/m: Long flame length and depth. Typically associated with stock and wildlife loss. Kills woody vegetation.

The participants in this group noted how higher intensities can typically be suppressed with offensive suppression strategies compared to eucalypt forests and that perhaps rate of spread or flame length may provide a more useful measure of fire danger instead. The group agreed that using the CSIRO northern grasslands spread model would be best suited for this fuel type, and to consider using the spinifex model in central Australia.

Pine plantation

The group working on establishing categories for pine plantations identified that four FDR categories would suit this fuel type best and aligned these categories with the Forest Fire Danger Index (FFDI: McArthur, 1967);

1) Low: FFDI 0-10: older, established fuels won't burn, new weedy fuel may burn. Fires easily controlled with early detection. Low consequences.
2) Mod: FFDI 11-15: fire development depends on level of ladder fuels, weeds, thinning and pruning. Normal detection and response arrangements.
3) High: FFDI 16-24: Resources stand up. Reliant on successful initial attack.
4) Very High: FFDI >25: Potential for crown fire. Potential loss and recovery rate dependant on age class. Difficult or impossible to suppress. Fall back to major roads. Use heavy plant. Restricted harvest/forest closures

Because prescribed burning is mostly done in tropical pine, not for southern *pinus radiata*, the group agreed that including prescribed burning as an FDR category wasn't beneficial. It was also noted that at the upper end of the FDR scale, pine plantation fuels would be comparable to eucalypt forest where consequences and safety are of utmost importance.

Spinifex

Numerical thresholds between categories were not directly discussed during the workshop for spinifex fuels however one participant did recommend the following FDR categories as part of Exercise 4:

1) 0-1000kW/m: Prescribed burning may be difficult if insufficient wind, fires easily suppressed with direct attack;

2) 1000-2000kW/m: Prescribed burning with experienced crew (complex burns). Fires suppressed with effort. Direct attack;

3) 2000-4000kW/m: Prescribed burning difficult (high intensity burns). Fires suppressed with difficulty. Direct or parallel attack,;

4) >4000kW/m: Prescribed burning not recommended. Fires quickly become unsuppressable. Parallel or indirect attack. Asset protection.

Case studies, fuels and fire danger rating

There are some knowledge gaps relating to particularly tricky fuel types (e.g. wet sclerophyll, rainforest, coastal swamps) concerning when fuel types become available and in the absence of having a targeted fire spread model in these vegetation types, some assumptions need to be made that recognise their availability and the most appropriate spread model.

Participants agreed to assist to identify and provide suitable case studies that may help to identify some go/no-go thresholds and the variables that pinpoint availability in these difficult fuels. Some suggested variables that could be used included;

- SDI/KBDI (e.g. SDI of between 60-80 is currently applied in karri forest in WA as general a threshold for availability) and

- Time since rain (e.g. used as a general rule of thumb in Tasmanian buttongrass).

End of Workshop Questionnaire feedback from participants – PART B

Participants (*n* = 11) agreed that Fire Danger Rating (FDR) in Australia can be improved and that including prescribed burning conditions within the FDR would be helpful (*n* = 11). Participants identified a range of tools that would meet the needs of their agency/department including a range of electronic gridded maps with either the FDR or the fire danger indicator (with or without monte-carlo likelihood) as well as broad regional forecasts of the FDR or fire behaviour indicator. Several participants also commented that a phone application of FDR categories (including either regional or spot forecasts) would be beneficial.

The majority of participants felt that improved consideration of fuels (type, arrangement, availability etc., *n* = 6), fire behaviour (usage of appropriate fire behaviour models, *n* = 6) and/or suppression difficulty (effectiveness, resource availability, *n* = 4) were paramount to facilitating improved FDR. The difficulty of course is in the detail and participants recognised that improved FDR needs to seek to meet the different needs of each agency and jurisdiction (*n* = 4). Other considerations that participants thought would facilitate improved FDR included: meeting the changing needs of users (*n* = 1), capability to adapt with better information and technology (*n* = 2), better consideration of ignition likelihood (*n* = 2), fire load (*n* = 2), being based on quality, verified data (*n* = 1) and being capable of taking impact/consequence into account (*n* = 1).

Participants commented that improved FDR, that takes into account the above described considerations, would directly benefit fire management mostly through improved preparedness (and resourcing, *n* = 7), accuracy (*n* = 5) and more timely and targeted community notifications (*n* = 5). It would provide a better quantification of risk (*n* = 4) and support for decision making (*n* = 2) as well as improving the alignment with fire behaviour, suppression difficulty and impact (*n* = 2). Improved FDR would create an environment suitable for better agency and departmental liaison (*n* = 2) with a greater awareness and improved knowledge of fire practitioners (*n* = 1). It would also enable better planning for determination of suppression tactics (*n* = 1).

Workshop participants

Name	State	Agency
Jason Heffernan	NSW	NSW Rural Fire Service
Dave Kelly	NSW	NSW National Parks and Wildlife Service
Sandra Whight	TAS	Tasmanian Fire Service
Jeremy Smith	TAS	Tasmanian Fire Service
Alen Slijepcevic	VIC	Country Fire Authority (VIC)
Tim Wells	VIC	Country Fire Authority (VIC)
Rob Sandford	SA	Country Fire Service (SA)
Mike Wouters	SA	Department of Environment, Water and Natural Resources (SA)
Lachie McCaw	WA	Department of Parks and Wildlife (WA)
Jackson Parker	WA	Department of Fire and Emergency Services (WA)
Peter Leeson	QLD	Qld Parks and Wildlife Service
James Haigh	QLD	Queensland Fire and Emergency Services
Neil Cooper	ACT	ACT Parks and Conservation Service
Rohan Scott	ACT	ACT Rural Fire Service
Charlie Taylor	NSW	Forestry Corp NSW

Tim McGuffog	NSW	Forestry Corp NSW
Jim Gould	ACT	CSIRO Land & Water Honorary Fellow
Simon Heemstra	NSW	NSW Rural Fire Service (NFDRS project team)
Stuart Matthews	NSW	NSW Rural Fire Service (NFDRS project team)
Saskia Grootemaat	NSW	NSW Rural Fire Service (NFDRS project team)
Belinda Kenny	NSW	NSW Rural Fire Service (NFDRS project team)
Jennifer Hollis	NSW	NSW Rural Fire Service (NFDRS project team)

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Appendix B. Workshop 2 - For researchers - Summary of outcomes

Date:	**Wednesday 7th June 2017**
Time:	10.00am – 3.00pm
Location:	NSW RURAL FIRE SERVICE Headquarters 15 Carter Street Lidcombe NSW
Chair:	Simon Heemstra, Manager Community Planning, NSW RFS
Meeting contact:	Stuart Matthews, 02 8741 5422, stuart.matthews@rfs.nsw.gov.au

At this workshop the RFS project team presented their plans for the structure and implementation of the NFDRS rating system, sought feedback on these plans, and examined issues where there is uncertainty or controversy about application of fire behaviour models and supporting data. The day included four sessions covering:

- Defining and measuring ratings
- Fire behaviour models
- Auxiliary models for spotting, instability, and wind changes
- Fuels, including: determination of fuel parameters, application of models to fuels that do not have dedicated fire behaviour models, and use of fire history in fire danger.

All sessions generated robust and constructive debate. This document records outcomes for each session, particularly noting areas where consensus was reached, where significant disagreements remained, or where follow up discussion is required. It is not a transcript of all conversations on the day. The presenter's slides for each session are attached. These outcomes will be used to inform the development of the Research Prototype and will also contribute to the project's recommendations for future research required to implement the full system.

Session 1 – Defining and measuring ratings

- Spatial and temporal scales were identified as important issues. There was discussion of the need to keep rating as a broad area measure in contrast to fire behaviour which applies to specific fires. It was noted that this presents a particular challenge when using fire incidents – which happen at a particular time and place – to validate/falsify predicted danger ratings. It was agreed that ratings need to be calculated on a sub-daily (e.g. hourly) time step to account for diurnal changes in fire behaviour and danger, a single daily maximum is not adequate in this context even though a single maximum rating is issued to the public. It was noted that fire agencies are currently given access to hourly ratings by the Bureau of Meteorology but it is not clear how widely these are used by fire managers.
- The use of different fire behaviour metrics such as rate of spread, intensity, and flame dimensions was considered. There was no clear favourite. As all metrics are simple to calculate it was generally agreed that the project should examine some or all of them to test their performance.
- It was noted that some of the issues for evaluation of fire danger also apply to meteorological forecasts that have a stochastic element such as thunderstorms. It was recommended that the project make use of the Bureau's expertise in forecast evaluation.
- It was noted that attempting to develop a Fire Behaviour Index was an ambitious aim and that expectations about how much will be achieved in a few months need to be managed given that there is not an index already developed to be applied to the Research Prototype.
- It was noted that there are opportunities to use remote sensing data as part of the characterisation of fires as part of the evaluation component of the project.

- There was some discussion of how to interpret initial attack success when evaluating predicted ratings in the absence of a fire acceleration point. No clear conclusions were arrived at.

Session 2 - Fire behaviour models

- Where possible the best available models supported by published science should be used, noting there may be practical limitations on application of some models.
- The CSIRO/AFAC guide to fire spread models (Cruz *et al.*, 2015a) should be used as the model reference for the project.
- The CSIRO grassland model (Cheney *et al.*, 1998) should be used for native grasslands. Fuel load does not affect rate of spread, regardless of fuel load, so the Natural version of the model should be used unless fuels have been modified. It was noted that existing fuel state reporting methods do not resolve this level of detail. The updated Cruz *et al.* (2015c) curing function should be used.
- There is no model for use in crops or pastures yet, so the CSIRO grassland model will be used.
- The CSIRO grassland model for 'Northern Australia' should be used for fuel types where the fire is carried by grass but there is a sparse tree canopy. There was no consensus on what fraction of tree cover requires use of the Northern Australia model, with figures from 5 to 20% suggested. There was consensus that a forest model should be used here canopy cover is >30%.
- The Burrows *et al.* (2009a) model should be used for Spinifex. This model requires bulk fuel moisture as an input for which there are no models. The project team will liaise with experts to develop a suitable method to apply the model based on operational practice.
- The existing Marsden-Smedley *et al.* (1999b) fire danger rating system for buttongrass moorlands has been working well and will be included in the Research Prototype in the form currently implemented by the Bureau of Meteorology.
- When applying the Anderson *et al.* (2015a) heath model, the Research Prototype will use fuel height as an input, since data on fuel height are more readily available than data on bulk density. It was noted that slope has a weak effect on heath fires relative to forests.
- The Cruz *et al.* (2013) mallee-heath model will be used.
- The Vesta/Dry Eucalypt Forest Fire Model (Cheney *et al.*, 2012a) will be used for forests. The forest fire danger meter (McArthur, 1967) and forest fire behaviour tables (Sneeuwjagt and Peet, 1985) will not be used as these are suitable for prescribed burning or small fires burning under mild conditions only.
- The difficulty of specifying fuel hazard parameters for the DEFFM, or estimating them from existing fuel load models was discussed, as was the difficulty of estimating hazard scores consistently in the field (Volkova *et al.*, 2016). Options for working with the DEFFM included: use sensitivity approach or use default values. A default value FHS worked quite well in the Spark evaluation. It was noted that DEFFM may not be appropriate where there is a grassy understorey.
- Adjustments of the DEFFM may be needed for fuel types other than dry sclerophyll forests. For example, wind reduction factor has been used with the DEFFM for wet forests but further validation is required.
- The difficulty of identifying a direct effect of drought on fire behaviour was considered. It was noted that there was good empirical evidence that drought affects landscape connectivity and the potential for large fires.
- It was noted that fuel availability models will be needed for all fuel types. Presently these are available only for buttongrass (based on rainfall and time since rain) and grassland (curing, no short term rainfall response). It was noted that the drought factor (McArthur, 1967) responds only to rainfall amount and time since rain, it does not adequately represent the effect of differences in fuels or post-rain weather on fuel availability. There was some discussion of whether heath needed a drought factor, given it will burn even when quite wet - provided enough effort is put into igniting it. No clear agreement on this point. It was noted that studies by the University of Melbourne on fuel availability in wet mist forests in Victoria may be of assistance.

Session 3 - Auxiliary models for spotting, instability, and wind changes

- Stability is only important at the higher end of fire behaviour in most cases. A noteable exception is high intensity prescribed burning which has been observed to causes problems even at moderate levels of fire danger.
- CHaines (Mills and McCaw, 2010) is the only available operational measure of instability but is has some limitations particularly when applied on days with a deep mixing layer. The project team will investigate how new experimental products being produced for 2017-18 by the Bureau's Extreme Weather Desk can be included in the Research Prototype.
- There was general agreement that stability should be included in the system as a 'red flag' warning rather than being used to modify the rating.
- It was noted that spotting is a local phenomenon and is important only in some fuel types, so is only suitable for use as a 'red flag'. It was suggested that this may not add much useful information as the distribution of fuel types that spot is static and so the same fire weather areas would always be flagged. An alternative viewpoint offered was that spotting distance and likelihood of embers igniting fires does vary with weather.
- There was consensus that wind changes should be treated as a 'red flag'. The wind change danger index (Huang and Mills, 2006) is the mode readily available measure which can represent this complex phenomenon as a single index. The project team will investigate how new experimental products being produced for 2017-18 by the Bureau's Extreme Weather Desk can be included in the Research Prototype. It was noted that some wind changes lower fire danger by pushing fires back into themselves but that many large historical losses have been associated with wind changes.

Session 4 - Fuels and fire history

- There was discussion of the most suitable way to apply existing fire behaviour models to fuel types which do not have a dedicated fire behaviour model. Suggestions included: assessment of the fuel layer which drives the fire (e.g. litte, grass, elevated); examination of fuel structure as defined in the fuel classification system; modification of the models by e.g. introducing wind modification factors, go-nogo thresholds, etc
- The issue of differences in scale between vegetation data (10s of m) and weather grids (kms) was considered. It was suggested that the system should perform calculations at the finest scale that is feasible and then agreggate to larger scales. It was suggested that a multi-scale approach could be used due to differences in the scale of relevant features across the landscape, e.g. central Australia vs the urban interface. It was agreed this was largely a technical issue to be resolved by the project team.
- The issue to arid areas where fuels change from widely separated shrubs to ephermal grasslands after rainfall was considered. It was suggested that remote sensing may be useful for detecting these events and that fuel type could be altered for areas where the fuel type that carries the fire changes from shrubs to grass. Process based modelling of grass growth was also put forward as an alternative approach for both arid and temperate grasslands.
- It was suggested that the buttongrass model be used for wet heath/swamp/sedge as the heath model is likely to overpredict.
- There was general agreement that the simplified approach to representing fire history was appropriate given the scale and application of fire danger ratings. It was noted that in the future fire severity measures could be used to model the magnitude of fuel modifiction by fire. It was agreed that inclusion of fire history is mainly important after very large fires where ratings would otherwise be high even though there is very little fuel left, this was an issue post Black Saturday in Victoria.
- It was noted that small parcels of vegetation may be locally significant but not be large enough to set the rating for an entire fire weather area (e.g. heath in an area that is mainly forest). Maps of danger rating will be important for identifying these cases.

Other comments

- There was agreement that the NFDRS sytem should be modular to allow future improvements.
- The project must document and be transparent about modelling and data decisions that are made.

- It was generally recognised that some degree of compromise on data and science quality will be needed to produce a Research Prototype that has complete spatial coverage of the country.
- The project team needs to bo cognisant of the differences in the scales at which fire danger and fire behaviour concepts apply.

Workshop participants

Name	Agency
Lew Short	AFAC
Deb Sparkes	AFAC
Marta Yebra	ANU
Michael Rumsewicz	BNHCRC
Mika Peace	BoM
Nathan Faggian	BoM
Simon Louis	BoM
Musa Kilinc	CFA
Tim Wells	CFA
Andrew Sullivan	CSIRO
Matt Plucinski	CSIRO
Miguel Cruz	CSIRO
Mike Wouters	DEWNR
Lachie McCaw	DPAW
Belinda Kenny	NSW RFS
Brad Davies	NSW RFS
Jen Hollis	NSW RFS
Saskia Grootemaat	NSW RFS
Simon Heemstra	NSW RFS
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Bryan Hally	RMIT
Karin Reinke	RMIT
Luke Wallace	RMIT
Simon Jones	RMIT
Mark Chladil	TFS
Jason Sharples	UNSW
Meaghan Jenkins	UoW
Ross Bradstock	UoW
Jim Gould	
Wendy Anderson	

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Appendix C. Post-implementation review comments from researchers

On 30 January, 2018 a 'peer review' webinar was held to present the NFDRS Research Prototype to participants from the workshops held earlier in the project for operational staff and researchers. Below are a summary of comments from participants and responses from the project team.

Analysis of results

> It would be nice to have a few fires where the NFDRS or the FFDI did provide good results and bad results. For each fire you could then discuss why, as an example, the NFDRS worked fine and the FFDI did not for fire A. And vice versa for fire B. This would allow people to understand why the system is superior in some case and maybe not in others and what needs to be done to improve it.
>
> Also, where and in what fuel type was that fire that was forecasted with a FDR or low/moderate but classified as an Extreme?

This is a good idea, and something we will aim to do for some fires where either or both systems were out by several categories (including the data pointed noted above).

> I liked the tables you presented, but maybe as a follow up to provide a separate analysis for fires with FDR >=3. This might give more insight into how things are working when decisions matter the most.

Also a good idea.

> There was some talk of reverting to McArthur forest model instead of Vesta/DEFFM. I believe this change would be a step back. We know that Vesta provides more accurate fire spread predictions than the FFDM from Musa work.

The planned calculations with the McArthur spread model will be used to investigate the sensitivity of the results to the fire spread model but is of particular interest because both models are used operationally for fire spread prediction. As well as using the best model, understanding how to use the outputs of head fire spread models for fire danger estimation will be a focus of future work.

> I've recently been look at some of the suppression intensity threshold literature and realised how few observations that they are based on (see Hirsch & Martell's 1996 review in IJWF for a good summary). You are potentially going to end up with a better dataset on this than currently exists for this in the literature, certainly for Australian fuel types (considering the observations that you have confidence in). If so, I think that you should consider taking this further! This is probably also true for some of the other consequence categories.

Yes, we hope the data we have collected will be a rich source for a lot more analysis than we expect to do in the next couple of months.

Fuel data

> One of the issues that might exist is that the fireline intensity calculation for forest is based on a fuel load calculation that may have been built to make the FFDM work better. I suspect that some of those fuel load numbers were inflated to make FFDM output give more sensible results.

The fuel models used in the system were built with the best data that was available from each jurisdiction within the constraints of data availability and time. We are not aware of anyone modifying fuels to compensate for model deficiencies.

Re pine age, I saw a fire in young pine behaving very similar to open grassland, with high ROS but also with high intensity due to significant fuel loads. Clear felled and young pine up to canopy closure, eg to age 4 or there abouts, if age is available, could adopt either the grassland model, or assume no forest canopy reduction factor. If age not available, due to rapid annual harvest and establishment changes, then maybe a qualifier on the model reliability in early establishment stages?

Representing managed vegetation where the structure varies greatly with time such as plantation rotations or crop harvesting is a challenge. Within the constraints of the project we had to treat plantations as the worst case: unthinned, unpruned mature trees. Either including silvicultural information or using local knowledge to interpret ratings would be an improvement.

Spatial aspects

Reviewing the demo program, I think the results are more a point source (1.5 km grid?) information on the potential fire behaviour of the day, which will have the potential to be developed into an excellent operational planning tool. I disagree the fire danger rating should not be presented at this scale, but within a fire danger class or rating of a region, you could use the 1.5 grid to should the potential fire behaviour based on fuel type, topography, weather, etc. Example, when we were doing the Tumbarumba experiments there was a total fire ban for the region. The ban was based on the hot, dry, windy weather forecast with fully cured grassland region, but the high country the weather forecast was milder conditions. Thus regional rating was warrant, but the potential fire behaviour varied depending on the fuel type, topography, fuel condition, etc. Here I see the potential in the application of your proposed fire behaviour rating within a fire danger class.

Yes, and this reflects current operational practice in some jurisdictions where both the broad Fire Weather Area ratings and more detailed grids are used for planning and decision making.

Also, has there been any consideration for looking at other boundaries other than Bureau weather districts? For example Municipal/LGA boundaries? There are only 9 weather districts in Victoria and they cover very broad landscapes – the best example is 'central' which covers metropolitan Melbourne, the western grasslands and the eastern ranges.

There was some discussion a while back about changing the district boundaries to more accurately capture coherent conditions across a district (ie districts more closely aligned with fuel type/topography/population and infrastructure). Has there been any further progress on this?

Fire weather area boundaries is not something this project has looked at. We are aware of efforts to better align boundaries with climate and/or vegetation zones in some jurisdictions.

Slope and topography

The US NFDRS has slope, but no user uses slope in their calculations - they always assume flat terrain, even if they are in the Rocky Mountains.

The omission of topographic slope will also have implications for field validation – a fire observed burning on a 10 degree slope may be perceived as belonging to a higher category than the same fire burning on flat ground.

The omission of slope will also have more serious consequences for fire danger categorisation over rugged terrain. I know you mentioned that terrain ruggedness might be something you'll need to revisit, but surely there is enough literature already to support inclusion of such terrain measures in a fire danger rating system? Terrain-based interactions are what often drives a fire to its most dangerous states!

> Also topographic interactions are important for fire danger/risk. I think some of this will be able to be "added on" in future when we have more rigorous science, but I still think the trial over-emphasises fuel types and surface winds.

We agree that there is a role for including topography in the system for a variety of reasons including: local effects on fire behaviour, influence on blow-up fire behaviours, and the increased challenges for conducting suppression operations in steep topography. The, as far as we can tell, unanswered question is how to sensibly include these effects in the system.

Fire behaviour models

> Is it possible to get documentation on all of the models being used? I know some of them are in the "Guide to rate of fire spread models…" book, but it would also be good to know exactly (i.e. mathematically) what the 'customised' pine model and the 'northern grass/savanna' model are. Also, it would be good to know exactly how drought factor is blended with DEFFM, and to better understand the rationale for doing so.

We are busy documenting the system and all these details will be in the project report, planned for completion at the end of June.

> I was wondering what fire spread model is used in the Mallee-spinifex communities in SA, VIC, and NSW. From the map you presented it seemed a lot of that area was characterised as grassland (or crops).

Mallee-over-spinifex is treated using the spinifex model with a wind reduction factor to allow for the presence of the tree canopy.

> For the chenopod shrublands I wonder if you should use the heath model from the CSIRO Ngarkat experiments (published only in the technical report). The younger heath was probably structurally similar to the chenopod shrublands. It might have some advantages over the eaten out grass fuel type as there will be a go no go process.

We will consider this in any future work.

> Is fire behaviour in crops a worthy research topic that would justify some dollars for some research burns. It seems that CFA is devoting some resources to better understand it, and economically it sure is an important issue. I suspect that the wildfires used by Cheney et al 1998 to develop the grassland models were very likely burning over a myriad of fuel types including crops. So, the model may already be describing fire in those fuels.

Yes, there is broad agency interest in and support for a crop fire model, including a project being coordinated by the CFA to collect case study data. If this does get built, then the modular approach of the NFDRS will allow it to be incorporated.

> The models that underpin the NFDRS all (still!) assume that fires will be spreading at a quasi-steady state. In my opinion this will be a huge issue for the field validation part of the project, particularly for the Cat 5 and 6 ratings, for which there is now substantial literature that suggests that fires will likely behave in a distinctly non-steady state manner.

Good points. The fire behaviour descriptions for the top categories could be expanded to include the potential for non-steady behaviour (mass spotting, VLS, etc), either linked with predictive models for those behaviours or a recognition that any of these things occurring makes the fire a top category event.

The atmosphere above the surface

> What is the basis for listing 95th percentile c-Haines as a red flag for fuels like buttongrass? For example, is there any literature to support the notion that high c-Haines will trigger dangerous fire development in Cat 3 fires (or even Cat 6)?

There is no evidence we are aware of either way for this, in addition to which there are well known limitation to CHaines as an indicator of potential fire induced convection. However, until better products become available, CHaines is generally regarded as useful. While other thresholds could be used, expert guidance from the BoM recommended use of the 95th percentile.

> I'd still like to see greater emphasis on the above-surface meteorological ingredients and temporal and spatial changes.

So would we! We look forward to some of the products such as the lightning and PyroCb outlooks that are being tested within the BoM becoming more widely available. There is also a research question around how to include this type of information in fire danger ratings.

Design of ratings

> The top end of the scale (ie 5-6, especially 6) has less sensitivity than the "current" system, it seems to condense that separation between Severe, Extreme and Catastrophic back to a single level. Obviously there are ways to subjectively communicate the risks, but is it sufficient to discriminate between a bad day (eg current rating FDI 55) and a day like BS? (and how do we communicate the message from 6 to" really bad 6 " to the general public?)

Categories 5 and 6 were designed to broadly cover the same ground as S, Ex, Cat, i.e. 2 categories instead of 3. This was done to reflect agency issues with inability to distinguish 3 categories and lack of distinctive changes in fire behaviour. This could be adjusted in future and will depend on the outcomes of the planned social science research in 2018-19.

> I have a question relating to the performance categories (indicative fire behaviour and weather, prescribed burn implications, fire suppression & containment, and other consequences) and how they line up with the index categories. I think that it is a big ask to come up with an index that can line up with all of these, and think that there is a good chance that there will be a variety of outcomes with the performance categories. If the trial results are like that, is there still potential to go down the path of having different indices for these – i.e specific indices for fire behaviour, community impact, suppression etc.?

During the trial we have sometimes found it challenging to come up with a consistent rating across the four performance categories, probably reflecting these issues. It is part of the design to the NFDRS program to allow for a (more detailed) agency view of the outputs and separate a (less detailed) community view. The separation of fire weather, fuel, fire behaviour, ignition, suppression, and impact components in the full design will support this.

> My overarching concern is that the NFDRS will still assess 'fire danger', across the entire spectrum of fire environment conditions, using models that were developed over quite a restricted set of fire environment conditions. This immediately casts doubt upon the validity of the Cat 5 and 6 ratings and perhaps even Cat 4. The extrapolatory nature of the FFDI-based rating system has been cited as one of the weaknesses of the current system, but the Research Prototype has the same inherent design flaw. The current system at least acknowledges the lack of certainty about how the fire might be expected to behave at categories beyond 'Extreme' – shouldn't the NFDRS have similar caveats?

Yes, there is increased uncertainty at the higher end of the spectrum and that was part of the motivation for having 2 categories at the upper end vs 3 in the current system. We do note that the fire behaviour models have incorporated wildfire data where possible (see e.g. Cruz MG, Alexander ME, Sullivan AL (2017) Mantras of wildland fire behaviour modelling: facts or fallacies? International Journal of Wildland Fire 26, 973-981.) but when better models become available they can be incorporated.

Drought and fuel moisture

> I'm concerned that we are using DF in the new system, similar reasons to above, because of the lack of sensitivity at the high end of the scale (10 to 10 + to 10++). There are new soil moisture measures coming in and it would be good to see an assessment of soil moisture/drought factor as part of the trial. I appreciate that isn't straightforward due to the limited information and resources available. But, I'd like to see it highlighted as part of the evaluation and future plans if possible.

Lack of suitable fuel availability models for most fuel types other than grass and buttongrass is a significant weakness of the system. This is likely to be highlighted as a significant knowledge gap in our recommendations for future research. There is lots of promising work being done in this area with modelling and remote sensing but it is not yet clear how it can be applied to fire behaviour or fire danger modelling, e.g. neither soil moisture nor live fuel moisture appear in fire spread models. Neither of the promising BNHCRC products (JASMIN from BoM and live moisture from ANU) were operational for the start of the live trial so we haven't been able to include them, this could be done retrospectively in future work.

> Re forest type categories, Queensland rainforest types in my opinion can be regarded for all intents as non-flammable. This may differ from Vic or Tas rainforest which might carry active fire during dryer periods. Discussion mentioned fuel becoming available at DF8. My experience is that in severe fire weather or drought conditions (eg. KBDI 160+, FFDI VH or 35+, DF 10, no recent effective rain), fire can carry in rainforest as a mild surface fire, suggesting to me that DF 8 still over-predicts available fuel, and that the intensity of fire in severe conditions is low and easily treatable or no threat to life and property. Hence for simplicity regard as non-flammable. Qualifiers though, this does not account for weed infestation which alters the fuel and availability, lantana infestation for example creates more interesting fire intensity. Also this is genuine rainforest as mapped. If you separate "moist forest" from rainforest (no sclerophyll component), these moist tall open forest, or eucalypt forest with mesic understorey can dry out in drought and late fire season, under KBDI levels exceeding say 160, and these do burn with high intensity, and might align with the availability assumptions adopted.

We struggled with fuel availability for rainforest and wet forest types, see the previous comment as well. The approach adopted was loosely based on the little bit of literature we could find. As you note, it probably over does things for a lot of rainforest conditions. Similarly, it seems to under do things for some moisture types which are flammable at lower KBDI and DF.

Potential implementation

> If the trial is considered successful, how long before you envisage national implementation? Is it still 4-5 years away as initially indicated?

The program office is currently reviewing the original 5-year plan in light of lessons learned from the Research Prototype. The pace of any change will depend on lots of factors, including the complexity of the technical build, the extent of changes in the public facing part of the system (e.g. rating signs), and linkages with policy and legislation that are linked to FDR. All of this is also subject to a decision by governments to proceed with a change.

Appendix D. Sample incident data collection form

1. INCIDENT DETAILS:	Evaluation #1
Observer name:	
Incident detection date and time (DD/MM/YYYY HH:MM):	
Entry Date (DD/MM/YYYY):	
Agency/Department:	
Jurisdiction	
Incident name:	
Incident identifier:	
Location (Street address and/or grid reference):	
Latitude (decimal):	
Longitude (decimal):	
2. INCIDENT OBSERVATIONS:	
Start of time period (DD/MM/YYYY HH:MM):	
End of time period (DD/MM/YYYY HH:MM):	
Status at the beginning of the time period (select):	
Status at the end of the time period (select):	
Fire type (select) i.e. P/B, wildfire or P/B escape:	
Fire size at the beginning of time period (ha):	
Fire size at the end time period (ha):	
Closest (or most representative) BoM AWS (available on NFDRS interactive website):	
Have you made an observation on this fire incident previously? (If yes, please provide date):	
If the fire was contained during your observations, what was the containment time since detection (mins):	
Maximum Forecast FFDI during time period:	
Maximum Forecast NFDRS FIRE BEHAVIOUR INDEX for fuel type (number):	
Maximum Forecast NFDRS FIRE DANGER RATING for fuel type (number):	
FIRE DANGER RATING Table used (select):	
Fuel type (select):	
3 (a) FIRE DANGER OBSERVATIONS (for all fuel types):	
Your observed NFDRS FIRE DANGER RATING (based on your own opinion/observations using the appropriate FDR TABLE) (number):	
If the Forecasted NFDRS FIRE DANGER RATING does not match your Observed NFDRS FIRE DANGER RATING, what was the main reason in your opinion:	
How confident are you in your observations? (Please rate):	
Based on your experience, what rating in the current system best describes this fire?	
3 (b) GRASS FIRE DANGER OBSERVATIONS (only to be completed for grassfires):	
Maximum Forecast GFDI during time period:	
Predicted grassland curing (%):	
Your observed grassland curing (%)	
4. FIRE BEHAVIOUR OBSERVATIONS:	
Mean rate of spread during time period (m/hr):	
Mean flame height during time period (m):	
Spotting distance and frequency (describe):	
Did the forecasted FIRE BEHAVIOUR DESCRIPTORS and Red Flag warnings within the FDR Table broadly represent your observations of POTENTIAL fire behaviour (Yes, No-underestimated, No-	
How confident are you in your observations? (Please rate using the drop down options):	

5. FUEL OBSERVATIONS:	
Estimated fine fuel load (t/ha):	
Please describe which fuel layers are represented in above figure (e.g. surface, elevated, bark, canopy):	
Fuel age (years):	
How confident are you in your observations? (Please rate):	
6. PRESCRIBED BURN IMPLICATIONS (only to be completed for prescribed burns):	
Prescribed burn type (e.g. hazard reduction, pile burn, wind row, silvicultural, agricultural etc):	
Were there any burn escapes associated with prescribed burn (yes/no):	
Did the PRESCRIBED BURN DESCRIPTORS and Red Flag warnings within the FDR Table broadly represent your expectations and fire applications (Yes, No-underestimated, No-overestimated):	
7. RESOURCES, STRATEGIES and SUPPRESSION/CONTAINMENT DIFFICULTY:	
Number of field personnel operational during time period:	
Number of tankers/trucks operational during time period:	
Number of heavy plant operational during time period:	
Number and type of aerial resources operating during time period:	
What width fuel break (i.e. road networks, buffers etc) proved to be adequate in containing fire (m):	
Was there any active fire suppression during time period:	
If there was active fire suppression, describe any OFFENSIVE strategies used during the time period (e.g. direct, indirect, parallel attack):	
If there was active fire suppression, describe any DEFENSIVE strategies used during the time period (e.g. property protection, evacuation, public notifications):	
Did the SUPPRESSION/CONTAINMENT DESCRIPTORS and Red Flag warnings within the FDR Table broadly represent the difficulty of containment and the strategies used (Yes, No-underestimated, No-overestimated):	
8. CONSEQUENCES:	
Number of injuries during time period:	
Number of deaths during time period:	
Estimated houses threatened (number):	
Houses lost (number):	
Estimated other assets threatened e.g. mining infrastructure, electrical infrastructure, fence lines, machines, sheds, livestock) etc (describe):	
Other assets lost (describe):	
Did the CONSEQUENCE DESCRIPTORS within the FDR Table broadly represent the POTENTIAL effects of the fire (Yes, No-underestimated, No-overestimated):	
9. OTHER:	
Other comments (e.g. sources of information, background information):	
Attachments (eg. Spread maps, photos, incident reports):	

Appendix E. Incident data collection reference

INCIDENT DATA COLLECTION REFERENCE

Observations of the behaviour and response to fire incidents will be used to evaluate the ability of the NFDRS Research Prototype to predict fire danger. To record incident observations, use the 'Incident fire danger form.xls' spreadsheet.

Because fire danger changes during the day, the spreadsheet can be used to make repeated observations of the same incident as it escalates and de-escalates. Please use a separate column for each time period that you nominate for multiday incidents.

Your observations will be used to help us understand how you have assigned a rating category to the incident and also why the Research Prototype performed well or poorly for this incident. If information for some sections is not available (e.g. fire ground observations of fuel and fire behaviour may be difficult to obtain) please feel free to leave the field blank. It is important however, to complete as much of the form as possible and the more information you provide, the better we can understand the strengths and weaknesses of the Research Prototype. Incomplete observations are still valuable provided at least Sections 1, 2, and 3a are completed.

NFDRS Research Prototype forecast products are available from:

- Daily ratings page: https://reg.bom.gov.au/reguser/by_user/bomw0415/ username: bomw0415 password: uscu25mT
- Interactive web page: https://fireweather.uat.rfs.nsw.gov.au/nfdrs An individual username and password will be issued to you

Common Questions Answered:

Which fires should I complete an observation for?

Observations can be completed for any prescribed burn, burn escape or wildfire and can represent any type of fire danger. The full spectrum of fire danger is required for evaluation, including those fires that typically fall into the lower ends of fire danger (e.g. categories 1 and 2) however because of the limited numbers of fires likely to occur that represent the upper end of the fire danger, fires in categories 5 and 6 should be prioritised.

When should I complete my observation?

Observations should be completed within 24 hours of the time period you have nominated. The fire danger forecast, as well as all the other spatial layers and information for a point, are available going back the previous 24 hours only.

What should I do if I simply don't have time to complete the observation within 24 hours?

If you find yourself stuck for time (and let's face it…we know this will sometime happen!), you can quickly and easily download the forecast within 24 hours of your selected time period (instructions for how to do this are outlined below), which allows you to complete your observation at a later time. Please remember that observations are best done while your memory is fresh and you can track down any information you need, so we prefer that you don't do this too often.

If more than 24 hours have passed and the forecast is no longer available on the interactive website for your nominated time period, you can contact the NFDRS team (E: nfdrs@rfs.nsw.gov.au) and request the forecast. You will need to provide the team with the fire coordinates (Lat/Lon) and your nominated time period.

How do I select the best time period for my observation?

The time period that you select to do an observation on a fire is likely to be a time when you have sufficient information to complete an observation. For example, you may have received information on fire behaviour and fire area/perimeter from the field, or perhaps a linescan was performed, or you've just received photographs or information regarding suppression and resourcing. Alternatively, you may choose to nominate a time period where there were significant consequences observed, for example property or house losses. Even if nothing really notable happened, your observations for this time period are important!

How do I download the forecast?

At any time, you can download the forecast for a particular point by right-clicking on the point of interest. You'll see a location pin come up on your map at this point and under the 'details' tab on the left side of the screen, the forecast for the last 24 hours can be seen on a series of graphs. Above the graphs is a 'download forecast' button. When you select 'download forecast' a .csv file is created and you will see this download at the bottom left of your screen. It typically opens easily in Excel, where you will see all the data for that forecast point for the current 24 hours.

How do I work out what type of fuels a fire is burning in and also what FDR Table is best to be used?

Under the 'menu' tab on the left of your screen, you can display these spatially by choosing 'fuel type' from the 'select forecast layer' list, which can then be identified by various colours on the map. You can also determine these for any point by placing your mouse on the point of interest and the value at the mouse pointer is displayed underneath the colour bar on the left hand side of the screen.

How to I determine the fuel age, drought factor, grass curing or grass fuel load for a given point?

Under the 'menu' tab on the left of your screen, you can select any of these as the 'select forecast layer' which can then be identified by various colours on the map. These can also be determined for any point by placing your mouse on the point of interest and the value at the mouse pointer is displayed underneath the colour bar on the left hand side of the screen.

How do I determine the forecasted fire behaviour index, intensity, rate of spread, flame height, spotting distance, FFDI/GFDI, temperature, RH, dew point, wind speed for a given point?

As above.

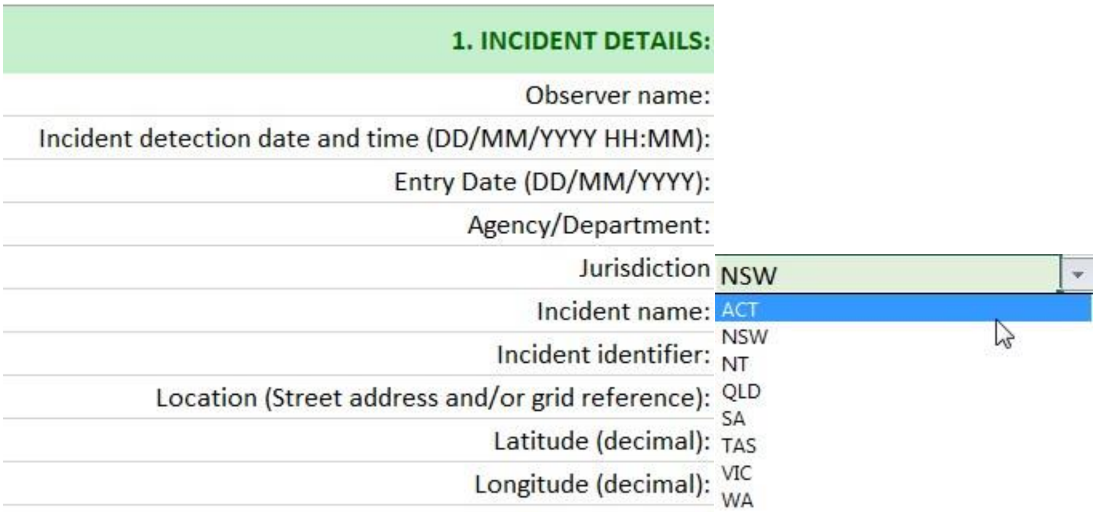
What if I forget my FDR Tables or observation forms?

You can download a copy of the FDR Tables (as a .pdf) or the observation form (.xls) at any time on the interactive web page. To download an FDR Table, simple select the 'fuel type' forecast layer and then use your mouse to click on the 'Fire Danger Table' that you require in the table on the left hand side of the screen. To download an observation form, select the 'INFO' menu at the top of the left side of the screen and use your mouse to click on 'data collection form' under the useful documents header.

Who do I contact if there is some nasty fire danger weather forecast?

If you're aware that there is some 'extreme' or 'catastrophic' fire danger forecast within your state, please contact the NFDRS team (E: nfdrs@rfs.nsw.gov.au) as soon as you can to ensure that observations will be able to be conducted should any fires be ignited under these conditions. The NFDRS team are aware you are likely to be extremely busy in an operational capacity under these conditions and can provide you with support (either remotely or within your fire control centre) to ensure observations are able to be completed.

The Evaluation Form



Jurisdiction is selected using a dropdown list (click the triangle on the right to open it). All other values can be typed.

For the **incident identifier** please use:

- ACT: incident number, e.g. 033058-14092017
- NSW: six-digit incident id, e.g. 274023
- NT: name and date notified, e.g. GREGORY PL, JABIRU 2017-09-14 20:11
- QLD: incident id, e.g. QF3-17-099469
- SA: incident number, e.g.1233569
- TAS: incident number, e.g. 254532
- VIC: incident id, e.g. 1646306
- WA: DFES unique identifier, e.g. 371297

Coordinates (Latitude/Longitude) can be easily obtained on the interactive web page, by placing your mouse at the fire location and recording the coordinates that are displayed at bottom right corner of the map. Note that fire coordinates are also recorded for you when you choose to download the forecast.

Use the remainder of the form to record information about the incident. For short incidents a single entry may be sufficient, for longer incidents use multiple columns or forms. There are no set time periods expected but as a guide it is expected that separate entries would be used for periods where the observed fire danger rating is different or significant escalation/de-escalation of the incident occurs.

2. INCIDENT OBSERVATIONS:
Start of time period (DD/MM/YYYY HH:MM):
End of time period (DD/MM/YYYY HH:MM):
Status at the end of the time period (select):
Status at the end of the time period (select):
Fire type (select) i.e. P/B, wildfire or P/B escape:
Fire size at the beginning of time period (ha):
Fire size at the end time period (ha):
Closest (or most representative) BoM AWS:
Have you made an observation on this fire incident previously? (If yes, please provide date):
Was the fire contained within 1 hr of suppression commencing? (i.e. initial attack success) (yes/no):
Maximum Forecast FFDI during time period:
Maximum Forecast NFDRS FIRE BEHAVIOUR INDEX for fuel type (number):
Maximum Forecast NFDRS FIRE DANGER RATING for fuel type (number):
Fuel type (i.e. FIRE DANGER RATING Table used) (select):

A variety of terminology is used to describe the **status** of incidents. Some synonyms for the terms used here are:

- Out of control: Going, Responding, Not Yet Under Control □ Being controlled:
- Under control: Contained, Patrolled, Patrol, Controlled.
- Out: Closed, Complete, Safe.

Fire size may be estimated if mapping is not available. Please note when fire size has been estimated (e.g. 10ha (estimated)).

FFDI, NFDRS rating and **index**, **fuel type and the location of the closest BoM AWS** can be obtained from the NFDRS Research Prototype website. Because fuel type mapping is presented at a course scale it may be necessary to use a pixel near the fire that is most representative of the incident, e.g. for a heath fire mapped in an area with a mix of forest and heath choose one of the heath pixels even if the fire location is mapped as forest. For a fire that covers multiple fuel types choose the type that is most representative for the remainder of the form, e.g. the head fire.

3 (a) FIRE DANGER OBSERVATIONS (for all fuel types):
Your observed NFDRS FIRE DANGER RATING (based on your own opinion/observations using the appropriate FDR TABLE) (number):
If the Forcasted NFDRS FIRE DANGER RATING does not match your Observed NFDRS FIRE DANGER RATING, what was the main reason in your opinion:
How confident are you in your observations? (Please rate):

Use the fire danger rating definition table to determine what you think the FDR rating should have been. This is your observation and should be based on the fire behaviour, prescribed burn implications, fire suppression and containment, and consequences descriptors.

If the forecasted NFDRS fire danger rating doesn't match your observation, please try to specify what the main reason was.

Some examples of why the NFDRS fire danger rating might not match your observation are included below:

- *Fire behaviour, specifically rate of spread, was over- or under-estimated in the FDR table (and therefore in the NFDRS FDR rating).*
- *Grassland curing used in the NFDRS FDR was more (or less) than actual observations and has therefore had an impact on the rate of spread prediction (and FDR).*
- *The descriptions of prescribed burn implications were over- or underestimated.* The descriptions of potential consequences hadn't sufficiently identified actual consequences that occurred.

3 (b) GRASS FIRE DANGER OBSERVATIONS (only to be completed for grassfires):
Maximum Forecast GFDI during time period:
Predicted grassland curing (%):
Your observed grassland curing (%)

Forecast **GFDI** and **Curing** can be obtained from the Research Prototype website. Visual estimates for observations of grassland curing may be obtained from field guides, field personnel or photographs. Please state what method you used to derive your observation and if using photographs, please attach them to your email when returning the form.

4. FIRE BEHAVIOUR OBSERVATIONS:
Mean rate of spread during time period (m/hr):
Mean flame height during time period (m):
Spotting distance and frequency (describe):
Did the forecasted FIRE BEHAVIOUR DESCRIPTORS within the FDR Table broadly represent your observations of POTENTIAL fire behaviour (Yes, No-underestimated, No-overestimated):
How confident are you in your observations? (Please rate):

The Research Prototype uses calculations based on modelled head fire behaviour to calculate fire danger rating. Observations of fire behaviour are useful for validating these calculations. Values may be obtained from field personnel or estimated from maps or photographs. If using maps or photographs, please attach them to your email when returning the form.

EXAMPLE: In line number 45, please compare your observations of fire behaviour with the descriptions within the appropriate FDR table. For example, if you've observed rates of spread that are faster, and/or flame heights that are higher, and/or spotting distances are further than those described within the FDR table, you would record that the FDR table has 'underestimated' fire behaviour.

5. FUEL OBSERVATIONS:
Estimated fine fuel load (t/ha):
Please describe which fuel layers are represented in above figure (e.g. surface, elevated, bark, canopy):
Fuel age (years):
How confident are you in your observations? (Please rate):

Please include any information on the fuels driving the fire derived from field intelligence or situation reports.

6. PRESCRIBED BURN IMPLICATIONS (only to be completed for prescribed burns):
Prescribed burn type (e.g. hazard reduction, pile burn, wind row, silvicultural, agriculatural etc):
Were there any burn escapes associated with prescribed burn (yes/no):
Did the PRESCRIBED BURN DESCRIPTORS within the FDR Table broadly represent your expectations and fire applications (Yes, No-underestimated, No-overestimated):

If the incident was a prescribed burn please indicate the type of burn and if there were any escapes related to the burn.

EXAMPLE: In line number 57, please compare your experience and knowledge of the prescribed burn with the descriptions of prescribed burn implications within the appropriate FDR table. For example, if there was difficulty getting the fire ignited and spreading while the FDR table had suggested that conditions were suitable, you would record that the FDR table has 'overestimated' prescribed burn conditions.

7. RESOURCES, STRATEGIES and SUPPRESSION/CONTAINMENT DIFFICULTY:
Number of field personel operational during time period:
Number of tankers/trucks operational during time period:
Number of heavy plant operational during time period:
Number and type of aerial resources operating during time period:
What width fuel break (i.e. road networks, buffers etc) proved to be adequate in containing fire (m):
Was there any active fire suppression during time period:
If there was active fire suppression, describe any OFFENSIVE strategies used during the time period (e.g. direct, indirect, parallel attack):
If there was active fire suppression, describe any DEFENSIVE strategies used during the time period (e.g. property protection, evacuation, public notifications):
Did the SUPPRESSION/CONTAINMENT DESCRIPTORS within the FDR Table broadly represent the difficulty of containment and the strategies used (Yes, No-underestimated, No-overestimated):

Describe the resources working on the fire, and the strategies being applied. If this information is described in a situation report in more detail than the form allows, please attach the situation report to your email when you return then form.

OFFENSIVE strategy: Offensive strategies are used when the fire can safely and effectively be attacked or extinguished, and include direct attack, parallel attack and indirect attack.

DEFENSIVE strategy: A firefighting strategy used where the protection of life and assets is a priority when a fire is: (i) located in inaccessible or remote location OR (ii) too intense to be safely or effectively attacked directly.

EXAMPLE: In line number 68, please compare the suppression strategies that were used on the fire during the period of observation with the descriptions of fire suppression and containment within the FDR table. For example, if the strategies that were used on the fire were mostly 'defensive' strategies because 'offensive strategies were not appropriate, however descriptions within the FDR table suggested that direct approaches would have been suitable and effective, you would record that that FDR table has 'underestimated' fire suppression and containment.

8. CONSEQUENCES:
Number of injuries during time period:
Number of deaths during time period:
Estimated houses threatened (number):
Houses lost (number):
Estimated other assests threatened e.g. mining infrastructure, electrical infrastructure, fence lines, machines, sheds, livestock) etc (describe):
Other sssests lost (describe):
Did the CONSEQUENCE DESCRIPTORS within the FDR Table broadly represent the POTENTIAL effects of the fire (Yes, No-underestimated, No-overestimated):

Describe any losses (deaths, injuries, property) or threats to values that occurred. Estimates of losses can be uncertain during an incident. If better information such as building impact analysis data is collected after the incident we would be happy to receive it. Please indicate in the **Other Comments** below if the incident is sensitive or likely to be subject to an enquiry.

EXAMPLE: In line number 77, please compare your observations of POTENTIAL consequences with the decriptions of potential consequences within the FDR Table. This can be particularly tricky to do because we are specifically asking you to compare what has and may have actually happened with the descriptions of what may have happened in the FDR table. Please keep in mind that the descriptions of fire size in the FDR tables relate to the maximum potential spread of fire within a 4 hour period under the maximum forecasted FDR, so if the period you are observing is less than 4 hours, you'll need to take this into account. For example, if there were no known property losses and no known impacts on infrastructure and there was no comments relating to community or infrastructure loss within the FDR table, you could record 'Yes', that FDR table has broadly reflected potential consequences.

9. OTHER:
Other comments:
Attachments (eg. Spread maps, photos, incident reports):

Please add any other comments and list attachments that accompany your report.

Submit your observation

Once the spreadsheet is complete, please save the file as *yourname_firename_yyyymmdd.xls* and email it along with any attachments to: nfdrs@rfs.nsw.gov.au

Appendix F. Prototype review comments from Paulo Fernandes

Comments on the Australian NFDRS by P.M. Fernandes (October 10, 2017)

The intent to standardize the fire danger rating process and criteria across Australia is commendable but not devoid of complexity and difficulties given the variety of vegetation types, climates, fire regimes and (to my understanding) fire management practices.

The proposed approach intends to better integrate variation in fuels and fire behaviour such that the assessment of fire danger is in better agreement with suppression difficulty and wildfire impacts. However, I was under the impression, perhaps wrong, that the scale of application is spatially too fine, i.e. excessively detailed and more close to fire behaviour quantification than to classical fire danger rating. This can result in increased difficulty of interpretation for fire preparedness and operations, putting a burden on agencies planning procedures and making communication to the public more difficult.

Minor remarks:

- Given that NFDRS is the U.S. fire danger rating system a more distinctive acronym is warranted, e.g. ANFDRS or, even better, AFDRS;

- One of the documents refers Portugal as having adopted a fire danger rating classification in which the fire danger index threshold separating fire danger classes is based on the correlation between fire activity and the index. In fact the current practice by agencies (since 2006) adopts thresholds defined as a function of potential fireline intensity (hence fire suppression difficulty) for the worst-case fuel scenario of a typical pine (Pinus pinaster) stand.

I did appreciate the completeness and level of detail of the NFDRS Categories table. The description of relevance, especially for increasingly higher classes (categories), is different from what is usually seen (solely based on fire control difficulty). I also liked the red flag warnings. Four remarks:

- You might want to revise the maximum flame height for category 2, as 4m is clearly too high for a fireline intensity of 750 kW/m;

- There are partial overlaps between rate of spread and flame height among categories (but not between fire intensity). This might create confusion and doubts in the users, or is it to accommodate the possible variation in fire behaviour inherent to fuel variability and local conditions?

- Finally, it is excellent that the red flag warnings include both atmospheric instability and forecasted wind change. However, and regarding the latter, it is my opinion that there should be no restriction regarding the period for which a change has been forecasted. Catastrophic fire behaviour in relation to changes in wind direction and speed often occurs latter in the day when dead fuel moisture contents are increasing, especially when thunderstorms and PyCb formation are involved.

- The use of C-Haines index is an incomplete (although undeniably useful) way of assessing atmospheric instability. I am not sure whether this is operationally feasible in terms of forecasts and their interpretation, but it would be interesting to supplement it with CAPE (energy available for convection in the atmosphere) and DMAPE (maximum energy available in the atmosphere for downdrafts).

Appendix G. Prototype review comments from Marty Alexander

Comments on the Australian NFDRS by M.E. Alexander (Sept. 30, 2017)

1. Perhaps it would be useful to know "why is a national system is needed" (i.e. what's the purpose?). For example, is there a statutory requirement by the Federal government? Is it for consistency of communication across the nation. I think this should be clearly spelled out as I can help but think there are very definite regional (individual state/territory) vs. national needs that are very different.

2. I've always felt that agency systems (i.e. those that use national system outputs such as fireline intensity but for which the agency has decided how they will be applied for IA readiness and dispatching for example) are external to the national system. See the CFFDRS structure diagrams in the papers by Alexander et al. (1996) and Taylor & Alexander (2006). What you don't want to have happen is for what I would call "random modifications" to a NFDRS; see footnote 2 on Page 9 in my thesis (Miguel has a copy) with respect to the KBDI and MSDI (what a mess!); I see that folks are still monkeying with this (http://www.publish.csiro.au/WF/WF16217). This has happen a lot in Australia and probably because there has been no real national "authority" in Australia following Alan McArthur's death in 1978.

3. Have you seen the following (I view these FDR principles as highly important)? Alexander, M.E. 2012. The Science and Art Behind Fire Danger Ratings: An Historical and International Perspective, Invited presentation in the Australian Bushfire Cooperative Research Centre Professional Development Event Series, June 18, 2012, Sydney, New South Wales. (http://www.bushfirecrc.com/research/event/2012-marty_seminar)

4. I was recently asked by a University of Toronto student about the origin of the head fire intensity classes in Canada. I note in the documentation you sent along that the various state and territorial agencies have a wide view with regards to the fireline intensity classes. How will you resolve that or do you not intend to do so? Other than Project Aquarius and Wilson's (1988) grass fire break breaching that there hasn't been any formal study of fire suppression effectiveness in relationship to fireline intensity in Australia has there? You may be interested to know that as the section editor for fire for Current Forestry Reports that I have asked Matt Plucinski to undertake a review on this topic.

5. Regarding the higher end of the fire danger classes – is it not academic from a direct attack standpoint?

6. Did you meet Al Beaver when he was over in Australia? I think it would be worthwhile running your documents for comment at some point.

7. Regarding your Evaluation matrix (Simon and Stuart recent ppt), see Alexander and Thomas (2004, Fig. 2) article in Fire Management Today.

8. It's good that you plan to undertake a fire danger rating climatology.

9. Regarding the statement "One of the main limitations of the current McArthur FFDI and GFDI based fire danger ratings is that they are not adequately aligned to community loss or the destructiveness of a fire" – what about Andrew Wilson's probably of house survival (Wilson 1988 Aust. For. 51: 119-123)?

10. I think we all (wildland fire community) need to acknowledge that fire behaviour research and in turn fire danger rating is evolutionary in nature.

11. In your development work, readily acknowledge the shortcomings (known or suspected).

12. Luke and McArthur (1978) give a good rationale for writing wildland fire behaviour case studies, even on small incidents:

- *Inquiries should be made into all fires as soon as possible after they have been controlled. Even short descriptions of very small fires have a value. Recording the details of large fires is vital because success in the future depends largely on knowledge gained in the past.*

- *A map showing the perimeter of a fire at progressive time intervals provides the best basis for a case history analysis. This should be accompanied by descriptions of fire behaviour related to weather, fuel and topography, and details of the manning arrangements, strategy and tactics employed during each suppression phase. Particular attention should be given to initial attack action.*
- *At the conclusion of the analysis it should be possible to prepare a précis of the reasons for success or failure, not for the purpose of taking people to task for errors of judgment, but solely to ensure that the lessons that have been learnt contribute to the success of future suppression operations.*

13. How is slope steepness going to be handled if at all?
14. How will you incorporate atmospheric stability into the NFDRS? Obviously thru the C-Haines Index what are the specifics (do indirectly via weather forecast)? See p. 36 of the CFFDRS Weather Guide (http://cfs.nrcan.gc.ca/pubwarehouse/pdfs/29152.pdf).
15. What about incorporating probabilistic prediction (e.g. Cruz 2010 IJWF) into the NFDRS?

Appendix H. Live trial participants

Jurisdiction	Agency	Name
ACT	ACT Rural Fire Service	Chris Condon
ACT	ACT Rural Fire Service	Rohan Scott
ACT	Parks and Conservation Service	Brian Levine
NSW	NSW Rural Fire Service	Belinda Kenny
NSW	NSW Rural Fire Service	Jen Hollis
NSW	NSW Rural Fire Service	Saskia Grootemaat
NSW	NSW Rural Fire Service	Stuart Matthews
NT	Bushfires NT	Maggie Towers
NT	Bushfires NT	Mark Gardener
QLD	Queensland Fire and Emergency Services	Andrew Sturgess
QLD	Queensland Fire and Emergency Services	Ben Twomey
QLD	Queensland Fire and Emergency Services	Casey Scholten
QLD	Queensland Fire and Emergency Services	Russell Stephens-Peacock
QLD	Queensland National Parks, Sports and Racing	Chris White
QLD	Queensland National Parks, Sports and Racing	Ian Holloway
QLD	Queensland National Parks, Sports and Racing	Jack Hargreaves
SA	Department of Environment, Water and Natural Resources	Anne Mclean
SA	Department of Environment, Water and Natural Resources	Damon Ezis
SA	Department of Environment, Water and Natural Resources	Simeon Telfer
TAS	Tasmania Fire Service	Daniel Hoar
TAS	University of Tasmania	Jon Marsden-Smedley
VIC	Country Fire Authority	Musa Kilinc
VIC	Country Fire Authority	Tim McKern
VIC	Department of Environment, Land, Water and Planning	Darcy Prior
VIC	Department of Environment, Land, Water and Planning	Greg McCarthy
WA	Department of Biodiversity Conservation and Attractions	Dave Atkins
WA	Department of Biodiversity Conservation and Attractions	Dave Turnbull
WA	Department of Biodiversity Conservation and Attractions	Glen Daniel
WA	Department of Biodiversity Conservation and Attractions	Lachie McCaw
WA	Department of Biodiversity Conservation and Attractions	Lance Jackson
WA	Department of Biodiversity Conservation and Attractions	Pedro Palheiro
WA	Department of Biodiversity Conservation and Attractions	Rob Towers
WA	Department of Biodiversity Conservation and Attractions	Ryan Butler
WA	Department of Biodiversity Conservation and Attractions	Tammy-Ann Cole
WA	Department of Biodiversity Conservation and Attractions	Trevor Howard
WA	Department of Fire and Emergency Services	Agnes Kristina
WA	Department of Fire and Emergency Services	Jackson Parker
WA	Department of Fire and Emergency Services	Jonathon Palmer
WA	Department of Fire and Emergency Services	Rachael Parkes
WA	Landgate	Adrian Allen
WA	Office of Bushfire Risk Management	Tim McNaught

Appendix I. Acronyms

Acronym	Description
ABARES	Australian Bureau of Agricultural and Resource Economics and Sciences
ACCESS	Australian Community Climate and Earth-System Simulator
ACLUMP	Australian Collaborative Land Use and Management Program
ACT	Australian Capital Territory
ADFD	Australian Digital Forecast Database
AEDT	Australian Eastern Daylight Time
AEMC	Australian Emergency Management Committee
AFAC	Australasian Fire and Emergency Service Authorities Council
ALUM	Australian Land Use and Management classification
ANZEMC	Australia New Zealand Emergency Management Committee
AWAP	Australian Water Availability Project
AWRA	Australian Water Resources Assessment
AWRA-L	Australian Water Resources Assessment Landscape model
AWS	Automatic Weather Station
BARRA	Bureau of Meteorology Atmospheric high-resolution Regional Reanalysis for Australia
BFC	Bushfire Fuel Classification
BOHM	Bushfire Operational Hazard Model (Tasmania)
BoM	Bureau of Meteorology
BRAM	Bushfire Risk Assessment Model (Tasmania)
BRAN	Bushfire Risk Analysis (WA)
BRIMS	Bushfire Risk Information Management System (NSW RFS)
BVG	Broad Vegetation Group (Queensland)
CDU	Charles Darwin University
CFA	Country Fire Authority (Victoria)
CFFDRS	Canadian Forest Fire Danger Rating System
CFI	Carbon Farming Initiative
CFS	Country Fire Service (SA)
cHI	Continuous Haines Index
CRC	Cooperative Research Centre
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DBCA	Department of Biodiversity Conservation and Attractions (WA)
DEFFM	Dry Eucalypt Forest Fire Model (i.e. Vesta)
DELWP	Department of Environment, Land, Water and Planning (Victoria)
DEWNR	Department of Environment, Water and Natural Resources (SA)
DF	Drought factor
DFES	Department of Fire and Emergency Services (WA)
DPIPWE	Department of Primary Industries, Parks, Water and Environment (Tasmania)
ERA-I	European Re-analysis – Interim
EVC	Ecological Vegetation Community (Victoria)
FBP	Forest Fire Behaviour Prediction (Canada)
FDR	Fire Danger Rating
FFDI	Forest Fire Danger Index
FFDM	Forest Fire Danger Meter
FHS	Fuel hazard score (as per Vesta Fuel Guide)
FHR	Fuel hazard rating (as per Overall Fuel Hazard Guide)
FNSW	Forestry NSW
FOP	Fire Occurrence Potential system (Canada)
FRNSW	Fire and Rescue NSW

Acronym	Description
FWA	Fire Weather Area
FWI	Fire Weather Index (Canada)
GFDI	Grass Fire Danger Index
GFE	Graphical Forecast Editor
KBDI	Keetch-Byram Drought Index
ICON	Incident Control and Operational Management System (NSW RFS)
IMT	Incident Management Team
JASMIN	JULES Australian Soil Moisture Information (JULES = Joint UK Land Environment Simulator)
LAT	Large air tanker
L:B	Length to breadth ratio
LPI	Land and Property Information (NSW)
MC	Moisture content
NAFI	North Australia and Rangelands Fire Information
NFDRS	National Fire Danger Rating System
NPWS	National Parks and Wildlife Service (NSW)
NSW	New South Wales
NT	Northern Territory
NVIS	National Vegetation Information System
OEH	Office of Environment and Heritage (NSW)
OFH	Overall Fuel Hazard
PCA	Principle component analysis
PPPY	Pine Plantation Pyrometrics model
PSG	Predictive Services Group (AFAC)
PWS	Parks and Wildlife Service (Tasmania)
QFES	Queensland Fire and Emergency Services
RFS	Rural Fire Service (NSW)
RH	Relative humidity
ROS	Rate of spread
RS	Relative sensitivity
SA	South Australia
SDI	Soil Dryness Index
SI	Spread index
TASVEG	Vegetation of Tasmania
TFB	Total Fire Ban
TFS	Tasmanian Fire Service
TSF	Time since fire
UoW	University of Wollongong
UTC	Coordinated Universal Time
VLAT	Very large air tanker
WA	Western Australia
WCDI	Wind Change Danger Index
WRF	Wind reduction factor

Appendix J. Author contributions

The development of the NFDRS Research Prototype was a major collaborative effort involving the contributions of many people both in establishing the need for and direction of the project and the development of the Research Prototype. Importantly, there have been many people that have provided their time and support through observations, workshops, guidance, suggestions and ideas, as noted in the Acknowledgements at the start of this report.

This report has been prepared by the Research Prototype project team consisting of: Dr Stuart Matthews, Dr Saskia Grootemaat, Dr Jennifer Hollis and Dr Belinda Kenny from the NSW Rural Fire Service, Dr Paul Fox Hughes and Sam Sauvage from the Bureau of Meteorology, with additional contributions from Dr Miguel Cruz of the CSIRO. This project has been a coordinated team effort. We note these particular contributions:

Dr Stuart Matthews was the project manager and principal investigator. Stuart also led development of the interactive website and collection and analysis of public incident data.

Dr Paul Fox-Hughes led the preparation and analysis of weather data, including data for the case studies and the use of reanalysis data to investigate the climatology of Research Prototype ratings.

Dr Saskia Grootemaat led implementation of the fire behaviour models and the analysis of live trial incident data.

Dr Jennifer Hollis led the development of the fire danger rating definitions, led the development of the live trial evaluation process, and analysed the degree of potential bias within the observations.

Dr Belinda Kenny led the development of the base data and analysis of the spatial distribution of fuels and the implications for determining ratings.

Sam Sauvage led the development and support of computer systems to implement the Research Prototype including the calculation and daily ratings display system, as well as calculating ratings using weather reanalysis data.

Dr Miguel Cruz from the CSIRO Bushfire Dynamics and Applications team provided a sensitivity analysis of fire behaviour models (Chapter 13).

Everyone contributed to the preparation of case studies and the successful operation of the live trial.