Fire Behaviour Index Technical Guide

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1 Introduction

The AFDRS aims to provide information that is simple and consistent by using four public rating categories and a numerical fire behaviour index that applies to all fuels across the entire country. These simple products are built on considerable complexity in the underlying fire behaviour models, aiming to use accurate predictions based on a detailed understanding of fire spread and fuel structure.

This document explains the structure of the fire behaviour index, its relationship to fire danger rating levels and provides a detailed an up to date description of the fire behaviour models used in the calculations. The sections on fire behaviour index and ratings (2.1-2.3) have not previously been documented. Section 3 documents the fire behaviour models, this material is an update to Chapter 3 in Matthews et al. (2019) and includes improvements resulting from testing of AFDRS outputs since the Research Prototype phase of the program (2017-19). Finally, computer code implementing the models is included in Section 4.

2 Fire Behaviour Index and Fire Danger Ratings

2.1 Fire behaviour index for each model

The Fire Behaviour Index (FBI) is an index that can be used consistently across all eight models, allowing users to make decisions that require more detail than the four rating categories allow and to identify conditions where the index is near the top or bottom of a rating category.

Thresholds between columns in the (up to) six FBI definitions (https://fdv.afdrs.org.au/definitions) translate to memorable, round numbers similar to those used in the current FFDI/GFDI system

- For each fuel type, index values corresponding to definitions are:
    - Dark purple: 0-6
    - Mid purple: 6-12
    - Light purple: 12-24
    - Yellow: 24-50
    - Orange: 50-100
    - Red: 100+
- For index values from 0 to 100, linear scaling between threshold values is used.
- For index values above the top threshold, a scale that gives a similar increase in FBI with fire behaviour metric to that used in the next highest range is sued, aiming to have known 'reasonable worst case' historical fires around 200.
- FBI values are based on continuous quantities such as rate of spread. This means that the assignment of threshold values (6, 12, 24, 50, 100) defined FBI ranges is ambiguous. To avoid this ambiguity in published FBI products, calculated values are rounded down to the nearest whole number. In published tables, the rounding down is expressed by lowering the listed upper bound for each FBI range:
    - Dark purple: 0-5
    - Mid purple: 6-11
    - Light purple: 12-23
    - Yellow: 24-49
    - Orange: 50-99
    - Red: 100+

2.1.1 Grassland

For grass the fire behaviour metric is fire line intensity measured in kW m^{-1}. For the six fire behaviour index ranges:

Intensity range (kW/m)	FBI range	
0-50	0-6	
50-2000	6-12	
2000-9000	12-24	
9000-17500	24-50	
17500-25000	50-100	
25000+	100+	

An intensity value of 90,000 kW/m (Kilmore East fire) is used to provide an upper anchor at FBI=200.

2.1.2 Savanna

For savannas the fire behaviour metric is fire line intensity measured in kW m^{-1}. Four FBI ranges are defined for Savanna in the tables: 0-6,6-12,12-50 and over 50. An additional level is inserted at 25,000 to allow Catastrophic ratings to be calculated.

Intensity range (kW/m)	FBI range	
0-100	0-6	
100-4000	6-12	
4000-17500	12-50	
17500-25000	50-100	
25000+	100+	

An intensity value of 90,000 kW/m (Kilmore East fire) is used to provide an upper anchor at FBI=200.

2.1.3 Spinifex

For spinifex fuels the fire behaviour metric is rate of spread measured in m h^{-1}. For the five fire behaviour index ranges:

Spread index	Rate of spread range (m h^{-1})	FBI range	
<=0	0	0	
>0	0-50	0-6	
>0	50-1300	6-12	
>0	1300-7500	12-50	
>0	7500-10750	50-100	
>0	10750+	100+	

A rate of spread value of 20 km h^{-1} is used to provide an upper anchor at FBI=200.

2.1.4 Buttongrass

For button grass the fire behaviour metric is rate of spread measured in m h^{-1}. For the five fire behaviour index ranges:

Rate of spread range (m h^{-1})	FBI range	
0-30	0-6	
30-480	6-12	
480-2040	12-24	
2040-4200	24-50	
4200-8400	50-100	
8400+	100+	

A rate of spread value of 16.8 km h^{-1} is used to provide an upper anchor at FBI=200.

2.1.5 Forest

For forests the fire behaviour metric is fire line intensity measured in kW m^{-1}. For the six fire behaviour index ranges:

Intensity range (kW/m)	FBI range	
0-100	0-6	
100-750	6-12	
750-4000	12-24	
4000-10000	24-50	
10000-30000	50-100	
30000+	100+	

An intensity value of 90,000 kW/m (Kilmore East fire) is used to provide an upper anchor at FBI=200.

2.1.6 Mallee-heath

For mallee-heath fuels three fire behaviour metrics are combined: spread probability, crown fire probability and fire line intensity measured in kW m^{-1}. Five FBI ranges are defined for Mallee-heath in the tables: 0-6,6-12,12-24, 24-50 and over 50. An additional level is inserted at 40,000 to allow Catastrophic ratings to be calculated. For display, all values over 50 are shown as orange.

Spread probability	Crown fire probability	Intensity range (kW/m)	FBI range	
0-0.5*			0-6	
>0.5	0-0.33*		6-12	
>0.5	0.33-0.66*		12-24	
>0.5	>0.66	0-20000*	24-50	
>0.5	>0.66	20000-40000*	50-100	
>0.5	>0.66	>40000*	50-100	

Linear interpolation is performed on the item with an asterisk. An intensity value of 90,000 kW/m (Kilmore East fire) is used to provide an upper anchor at FBI=200.

2.1.7 Shrubland

For shrublands the fire behaviour metric is fire line intensity measured in kW m^{-1}. Five FBI ranges are defined for Shrublands in the tables: 0-6,6-12,12-24, 24-50 and over 50. An additional level is inserted at 40,000 to allow Catastrophic ratings to be calculated. For display, all values over 50 are shown as orange.

Intensity range (kW/m)	FBI range	
0-50	0-6	
50-500	6-12	
500-4000	12-24	
4000-20000	24-50	
20000-40000	50-100	
40000+	100+	

An intensity value of 90,000 kW/m (Kilmore East fire) is used to provide an upper anchor at FBI=200.

2.1.8 Pine

For forests the fire behaviour metric is fire line intensity measured in kW m^{-1}. For the six fire behaviour index ranges:

Intensity range (kW/m)	FBI range	
0-100	0-6	
100-750	6-12	
750-4000	12-24	
4000-10000	24-50	
10000-30000	50-100	
30000+	100+	

An intensity value of 90,000 kW/m (Kilmore East fire) is used to provide an upper anchor at FBI=200.

2.2 Fire Behaviour Index Quantization

To remove any ambiguity about which FBI range threshold values belong to, the FBI is converted to a whole number. Following current Bureau of Meteorology practice for the FFDI/GFDI, FBI values are rounded down to the nearest whole number. This means that for example an FBI of 5.9999 will be rounded down to 5 and belong to the lowest FBI range.

FBI range	FBI output
0<=FBI<6	0-5
6<=FBI<12	6-11
12<=FBI<24	12-23
24<=FBI<50	24-49
50<=FBI<100	50-99
100<=FBI	100+

2.3 Fire danger rating

For fire danger rating a simple threshold is applied, using the FBI thresholds of 12, 24, 50 and 100. The same table is used for all fuel types:

FBI range	Rating	
0-11	No rating	
12-23	Moderate	
24-49	High	
50-99	Extreme	
100+	Catastrophic	

Exact colour shades for rating levels are yet to be determined. No rating should be shown as white on maps.

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 modelsl used for the AFDRS

Fire behaviour model	Short name	Reference	Fuel type
CSIRO Grassland fire spread meter	Grassland	Cheney et al. (1998) and Cruz et al. (2015b)	Continuous grasslands
CSIRO Grassland for northern Australia	Savanna	Cheney et al. (1998) and Cruz et al. (2015b)	Grassy woodlands and open forests
Desert spinifex model	Spinifex	Burrows et al. (2018)	Hummock grasslands
Buttongrass moorlands model	Buttongrass	Marsden-Smedley and Catchpole (1995b)	Buttongrass moorlands
Dry Eucalypt Forest Fire Model (DEFFM or “Vesta”)	Vesta	Cheney et al. (2012)	Shrubby dry eucalypt forests
Mallee heath model	Mallee heath	Cruz et al. (2013)	Semi-arid mallee heath
Heathland model	Shrubland	Anderson et al. (2015)	Temperate shrublands
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. In addition, 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 Matthews et al. (2019, chapter 4).

3.1 Measures of fire behaviour

All fire behaviour models available for use in the AFDRS produce rate of spread 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 area available in the AFDRS, 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.
- 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. 2007, K. Tolhurst pers. comm.[1]). 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, are correlated. However, because flame dimensions and intensity include fuel 'twice' in their calculation, they are more sensitive to fuel parameters. As it is relatively simple to calculate these four variables (spotting for forests only), all are available as AFDRS outputs.

How the fire danger rating thresholds were defined based on the above mentioned fire behaviour variables is described in Matthews et al (2019, chapter 2).

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 not suitable for use in the AFDRS 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. If power was 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 house loss.

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, 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. Research by Plucinski et al. (2020) using a variety of FFDI measures showed that daily maximum fire danger is most useful.

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 contribute to fire danger 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

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

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 AFDRS, 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. In future CHaines may be replaces with a more accurate PyroCb outlook product (Tory and Kepert 2021).

- 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 is 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 is included in the AFDRS as an index and 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 (2018)	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 is not currently feasible and the model requires more work to improve accuracy across a range of conditions (Zhao et al. 2021, 2022). 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 fuel availability modifier for dry forests is (Fig. 3.1a):

$$Fuel\_availability = 0.1DF \tag{3.1}$$

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 (Cruz et al. 2021):

$$C1 = 0.1(KBDI(0.0046W^2 - 0.0079W = 0.0175) - 0.9167W^2 + 1.5833W + 13.5) \tag{3.2}$$

$$Fuel\_availability = \frac{1.008}{1 + 104.9e^{-0.9306DF*C1}} \tag{3.3}$$

Where:

KBDI is the Keetch-Byram drought index (mm)

W is wind reduction factor $\in$[3,5]

C1 is the stand structure adjustment $\in$[0,1]

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.

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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 use the wet forest fuel availability, eqns3.2 and 3.3.

Foliar moisture content was also modified:

$$Foliar\ moisture\ content = 150 - 5 * DF \qquad (3.4)$$

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 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, the AFDRS calculates the maximum potential rate of spread, assuming that the fire has reached its quasi-steady state. Consequently, it might be over-predicting in cases where the fire is still in an initial state, or when fuels are damp.

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):

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

For downhill slopes (Sullivan et al. 2014):

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

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. The AFDRS does not include topographic effects. The system was built to allow inclusion of slope as a variable in future if required, depending on the outcomes of the AFDRS Ignition, Suppression and Impact research project.

3.3 Detailed model descriptions

In the sections below, the eight selected fire behaviour models are discussed in detail. We have 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 was necessary 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 AFDRS 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. For development of the AFDRS, grass condition was estimated from fuel load:

1. Grass fuel load ≥ 6 t ha^{-1} = natural grasslands
2. Grass fuel load between 3 and 6 tha^{-1} = grazed grasslands
3. 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. The operational AFDRS uses grass condition reported by field observers.

For natural grasslands (class (i)):

- If 10 m wind speed < 5 km h-1, the rate of spread is calculated as:

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

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

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

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:

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

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

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

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

For eaten-out grasslands:

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

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

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

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

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

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

$$MC = 9.58 - 0.205 * T + 0.138 * RH \quad (3.13)$$

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 calculating 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[2], assumed 18,600 kJ kg^{-1}
w = fuel load, as reported or estimated from the best data available, in kg m^{-2}.
ROS = rate of spread (m s^{-1})

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

For natural grasslands (class (i)):

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

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

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

[2] 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}.

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. For some arid fuel types with low, open canopies, wind reduction factors between 0.5 and 1.0 were used.

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. 2018)

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:

$$SI = 412 * U_e + 0.311 * Cov_{ns} - 0.676 * MC - 4.073 \qquad (3.21)$$

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:

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

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:

$$ROS = 40.982 * {U_e}^{1.399} {Cov_{ns}}^{1.201} MC^{-1.699} \quad (3.23)$$

Where:

ROS = head fire rate of spread (m h^{-1})
U_e = wind speed at 1.70m (eye-level) (km h^{-1}) this is achieved by dividing the 10 m wind speed by a factor 1.35
Cov_{ns} = live and dead spinifex fuel cover (%)
MC = clump profile moisture content (%)

For estimating fuel load we used:

$$FL_{ns} = \begin{cases} 2.046\, TSF^{0.42} & productivity = 1 \\ Table\ 3.6 & productivity > 1 \end{cases} \quad (3.24)$$

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

Productivity is derived from fuel type mapping with 1 denoting arid fuels and 2 or 3 denoting more productive fuels based on Carbon Farming Initiative mapping (CFI 2013).

Table 3.7 Fuel class, time since fire and load as reported in CFI (2013)

TSF (years)	Productivity = 2 Open spinifex	Productivity = 2 Spinifex woodland	Productivity = 3 Open spinifex	Productivity = 3 Spinifex woodland
<1	1.28	2.01	3.58	3.78
1-2	2.39	3.4	5.25	5.11
2-3	3.36	4.38	6.73	5.95
3-4	4.21	5.06	8.05	6.49
4-5	4.96	5.53	9.21	6.84
>5	5.6	5.86	13.34	7.38

For estimating fuel cover we use:

$$COV_{ns} = \begin{cases} 26.20\, TSF^{0.227} & productivity = 1 \\ 39.3\, TSF^{0.227} & productivity > 1 \end{cases} \quad (3.25)$$

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 fuel classes are defined based on time since fire (Table. 3.7; Burrows et al. 2015). The classification in Burrows et al. (2015) does not allow fuels less than 6 years old to burn. However, it has been observed that fuels in large parts of the Northern Territory typically burn after 3 years. Accordingly the threshold between classes one and two has been lowered to 3 years.

Table 3.7 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	< 3	15 – 20	0
2	3 - 10	30 – 40	< 5
3	11 - 15	35 – 45	5 - 10
4	16 - 20	40 – 50	10 - 15
5	>20	30 – 40	30 - 40

For class 1 (0-3 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 is not applied.

For class 2 the following equation is used to calculate clump moisture content:

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

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:

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

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

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

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%.

Where

RH = relative humidity (%)
(Pers. comm. N. Burrows 16/10/2017)

Finally, to account for water absorption effects in dead materials, a dead fuel moisture content based on adjustment (J. Parker pers comm.) of Simard (1968) model B moisture content was calculated:

$$FMC = 2.279 + 0.160107RH - 0.014784T + 7 \tag{3.30}$$

The higher of the moisture contents calculated using eqns 3.26-32.9 and 3.30 was then used.

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

$$I_B = h * w * ROS \tag{3.31}$$

Where:

I_B = fireline intensity (kW m^{-1})
h = heat yield[3], 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})

Flame height

$$F\_height = 0.097 * ROS^{0.424} + 0.102 * FL_{ns} \tag{3.32}$$

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[4]), where probability of sustained buttongrass moorland fires was

[3] This value needs further investigation.
[4] 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, the correct equation was given.

added (see also Marsden-Smedley 2009, 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:

$$Probability = \frac{1}{\left(1 + e^{\left(-\left(-1+0.68*\frac{U_{10}}{1.2}-0.07*MC-0.0037*\frac{U_{10}}{1.2}*MC+2.1*productivity\right)\right)}\right)} \quad (3.33)$$

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

In case sustained fire spread is likely, 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):

$$ROS = 0.678 * (U_{10}/1.2)^{1.312} * e^{(-0.0243*MC)} * \left(1 - e^{(-0.116*TSF)}\right) * 60 \quad (3.34)$$

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):

$$MC = Rf + Hf \quad (3.35)$$

$$Rf = 67.128 * \left(1 - e^{(-3.132*rain)}\right) * e^{(-0.0858*t)} \quad (3.36)$$

$$Hf = e^{(1.660+0.0214*RH-0.0292*Tdew)} \quad (3.37)$$

Where:

MC = dead fuel moisture (%)
R_f = rainfall factor
H_f = 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 (%)
T_{dew} = 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 AFDRS, we use 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):

$$Fuel_{low} = 11.73 * (1 - e^{(-0.106*TSF)}) \tag{3.38}$$

$$Fuel_{med} = 44.61 * (1 - e^{(-0.041*TSF)}) \tag{3.39}$$

$$Dead_{low} = \left(0.873 * \left(1 - e^{(-0.036*TSF)}\right)\right) * Fuel_{low} \tag{3.40}$$

$$Dead_{med} = \left(0.950 * \left(1 - e^{(-0.054*TSF)}\right)\right) * Fuel_{med} \tag{3.41}$$

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

$$I_B = h * w * ROS \tag{3.42}$$

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):

$$F\_height = 0.148 * {I_B}^{0.403} \tag{3.43}$$

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.

DEFFM/Vesta incorporates the fuel structure of a forest, 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.

For the AFDRS we use 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 Matthews (2019, chapter 4).

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

$$ROS = \Phi 1(\text{wind}) * \Phi 2(\text{fuel attributes}) * \Phi 3(\text{moisture content}) * \Phi 4(\text{slope}) \quad (3.44)$$

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

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.

Giving

$$ROS = 30 + 1.5308(U_{10} - 5)^{0.8576} * FHS_s^{0.9301} * (FHS_{ns} * H_{ns})^{0.6366} * 1.03 \quad (3.45)$$

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). The equation then becomes:

$$ROS = 30 + 1.5308(U_{mod} - 5)^{0.8576} * FHS_s^{0.9301} * (FHS_{ns} * H_{ns})^{0.6366} * 1.03 \quad (3.46)$$

Where:

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

Testing during the Research Prototype phase showed over prediction of rate of spread in forests with high near-surface heights. As this parameter was uncertain for many fuel types, the default value used was changed from 25 cm to 20cm. 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).

For moisture content in dry eucalypt forests, we used (Cheney et al. 2012) with upper and lower limits estimated from Cruz et al (2021):

$$\Phi 3(\text{moisture content}) = \begin{cases} 2.31 & MC \le 4 \\ 18.35\, MC^{-1.495} & 4 < MC \le 20 \\ 0 & MC > 20 \end{cases} \quad (3.47)$$

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

$$MC = 2.76 + 0.124 * RH - 0.0187 * T \tag{3.48}$$

Period 2: overcast, day light hours

$$MC = 3.60 + 0.169 * RH - 0.0450 * T \tag{3.49}$$

Period 3: night time hours

$$MC = 3.08 + 0.198 * RH - 0.0483 * T \tag{3.50}$$

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}:

$$Spotting\ distance = |176.969 * \arctan(FHS_s) * \left(\frac{ROS}{{U_{10}}^{0.25}}\right)^{0.5} + 1568800 * {FHS_s}^{-1} * \left(\frac{ROS}{{U_{10}}^{0.25}}\right)^{-1.5} - 3015.09| \tag{3.51}$$

Where:
Spotting distance is 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 the overstorey height, 50% of the canopy fuels are included as well. Fuel loads are calculated based on Olson (1963) curves:

$$Fuel\_load_{surface} = FL_s * (1 - e^{-k_s * t}) \tag{3.52}$$

$$Fuel\_load_{near\ surface} = FL_{ns} * (1 - e^{-k_{ns} * t}) \tag{3.53}$$

$$Fuel\_load_{elevated} = FL_{el} * (1 - e^{-k_{el} * t}) \tag{3.54}$$

$$Fuel\_load_{bark} = FL_b * (1 - e^{-k_b * t}) \tag{3.55}$$

$$Fuel\_load_{canopy} = FL_o * (1 - e^{-k_o * t}) \tag{3.56}$$

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 section 3.2.1 (equation 3.1 and 3.2). Fuel load available for combustion, and therefore intensity calculations, then becomes:

$$Fuel\_load_{combustion} = Fuel_{availability} * Fuel\_load_x \qquad (3.57)$$

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

$$I_B = h * w * ROS \qquad (3.58)$$

Where:

I_B = fireline intensity (kW m^{-1})
h = heat yield[5], assumed 18,600 kJ kg^{-1}
w = $Fuel\_load_{combustion}$, converted to kg m^{-2}
ROS = rate of spread (m s^{-1})

For forests with high litter fuel loads, the contribution of the surface litter to intensity was capped at 10 t ha^{-1}, to represent the process of fire burning across then down into the fuel bed. Flame height was calculated using surface ROS and elevated fuel height:

$$F\_height = 0.0193 * ROS^{0.723} * e^{(0.64 * H_{el})} * 1.07 \qquad (3.59)$$

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 section 3.2.1, 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.
- Rate of spread is determined for either a surface or a crown fire (or a weighted average of the two).

[5] This value needs further investigation.

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:

$$MC = MC_1 + MC_2 \quad (3.60)$$

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

$$MC_1 = 4.79 + 0.173 * RH - 0.1\ (T - 25) - \Delta 0.027 * RH \quad (3.61)$$

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):

$$MC_2 = 67.128 * (1 - e^{(-3.132 * rain)}) * e^{(-0.0858 * t)} \quad (3.62)$$

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:

$$ProbSpread = \frac{1}{(1 + e^{[-(14.624 + 0.2066 * U_{10} - 1.8719\, MC - 0.30442 * Cov_o)]})} \quad (3.63)$$

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:

$$ProbCrown = \frac{1}{(1 + e^{[-(-11.138 + 1.4054 * U_{10} - 3.4217 * MC)]})} \quad (3.64)$$

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 use the surface fire spread model.

$$ROSs = \left(3.337 * U_{10} * e^{(-0.1284*MC)} * H_o^{-0.7073}\right) * 60 \tag{3.65}$$

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.

$$ROSc = \left(9.5751 * U_{10} * e^{(-0.1795*MC)} * \left(\frac{Cov_o}{100}\right)^{0.3589}\right) * 60 \tag{3.66}$$

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.

$$ROSe = (1 - ProbCrown) * ROSs + ProbCrown * ROSc \tag{3.67}$$

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:

$$Fuel\_load_{surface} = FL_s * (1 - e^{-k_s*t}) \tag{3.68}$$

For crown fires, the fuel load is calculated as:

$$Fue\_load_{crown} = Fuel\_load_{surface} + FL_o * (1 - e^{-k_o*t}) \tag{3.69}$$

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

$$Fuel\_load_{ensemble} = Fuel\_load_{surface} + ProbCrown * Fuel\_load_{crown} \tag{3.70}$$

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

$$I_B = h * w * ROS \tag{3.71}$$

Where:

I_B = fireline intensity (kW m^{-1})
h = heat yield, 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):

$$F\_height = e^{-4.142} * I_B^{0.633} \tag{3.72}$$

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 use (i) the height-model for the AFDRS.

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:

$$ROS = 5.6715 * (WRF * U_{10})^{0.9102} * {H_{el}}^{0.227} * e^{(-0.0762*MC)} * 60 \tag{3.73}$$

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}.

The Anderson et al. (2015) does not include a spread probability function. Testing during the AFDRS Research Prototype project showed that this resulted in unrealistically high rates of spread outside of typical wildfire conditions, especially when winds are light and/or fuels are moist. To compensate for this a rate of spread reduction function is applied based on results from Cruz et al. 2010:

$$ROS_{adj} = \frac{ROS}{1+e^{-(16.57+1.188U_{10}-2.705MC)}} \tag{3.74}$$

Dead fuel moisture content was described as

$$MC = MC_1 + Mc_2 \tag{3.75}$$

with the following equations (Cruz et al. 2015a, Marsden-Smedley et al. 1999):

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

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

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}):

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

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:

$$I_B = h * w * ROS \tag{3.79}$$

Where:

I_B = fireline intensity (kW m^{-1})
h = heat yield[6], 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):

$$F\_height = e^{-4.142} * I_B^{0.633} \tag{3.80}$$

Where:

[6] This value needs further investigation.

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 a simplified equation based on Rothermel (1983) (Cruz pers comm):

$$m_{litter} = 4.3426 + 0.1188RH - 0.0211T \qquad (3.81)$$

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

$$W_{stand\_height} = W_{10m}\frac{\ln\frac{0.36h}{0.13h}}{\ln\frac{10+0.36h}{0.13h}} \qquad (3.82)$$

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

$$W_{mid\_flame} = W_{stand\_height}e^{-0.48} \qquad (3.83)$$

A wind coefficient is then calculated:

$$C_{wind} = C\left(54.68W_{mid\_flame}\right)^{B}\left(\frac{P}{P_o}\right)^{-E} \qquad (3.84)$$

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:

$$ROS_{surface} = 18.288\frac{R\chi(1+C_{wind})}{\rho N_h h_p} \qquad (3.85)$$

Where:

ρ is the litter bulk density

N_h is the effective heating number

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:

$$I_{critcal} = \left(0.01 H_{canopy\_base} h_i\right)^{1.5} \tag{3.86}$$

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

$$h_i = 460 + 25 m_{foliar} \tag{3.87}$$

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:

$$CAC = \frac{ROS_{active}}{60f/\rho_{canopy}} \tag{3.88}$$

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

$$ROS_{active} = 661.26 W_{stand\_height}^{0.8966} \rho_{canopy}^{0.1901} e^{-0.1714 m_{litter}} \tag{3.89}$$

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

$$ROS_{passive} = ROS_{passive} e^{-CAC} \tag{3.90}$$

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

$$ROS = \begin{matrix} ROS_{surface} & r_c \le 1 \text{ or } r_c > 1, CAC < 1, ROS_{passive} \le ROS_{surface} \\ ROS_{active} & r_c > 1, CAC \ge 1 \\ ROS_{passive} & r_c > 1, CAC < 1, ROS_{passive} > ROS_{surface} \end{matrix} \tag{3.91}$$

Where the crowning ratio, r_c is:

$$r_c = \frac{I}{I_{critical}} \tag{3.92}$$

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

$$F_{height} = 0.07755 I^{0.46} + \Delta h \tag{3.93}$$

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

Because information about time since harvesting and silvicultural management is not available in the AFDRS, fire behaviour in pine plantations is calculated using an ensemble of 6 different stages from Cruz and de Mar (2011), listed in Table 3.8.

Table 3.8 Fuel class, time since fire and estimated cover as reported in Burrows et al. 2015

Fuel class	Model	Ensemble weight (%)	Surface load (t/ha)	Canopy load (t/ha)	Canopy base height (m)	Canopy bulk density (kg m^{-3})
1	Grass	9.1				
2	Pine	15.1	4	11.5	0.7	0.17
3	Pine	15.1	5	12	1.5	0.18
4	Pine	12.1	8.5	12	2.5	0.18
5	Pine	9.1	10	8	6	0.12
6	Pine	39.4	7	10	14	0.15

3.4 Application of models to fuel types

For the AFDRS, 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 AFDRS (Figure 3.2).

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 3.8). A comparison between the AFDRS fuel types and other fuel and vegetation classifications is provided in Matthews et al. (2019, Supplementary Table 4.7.1).

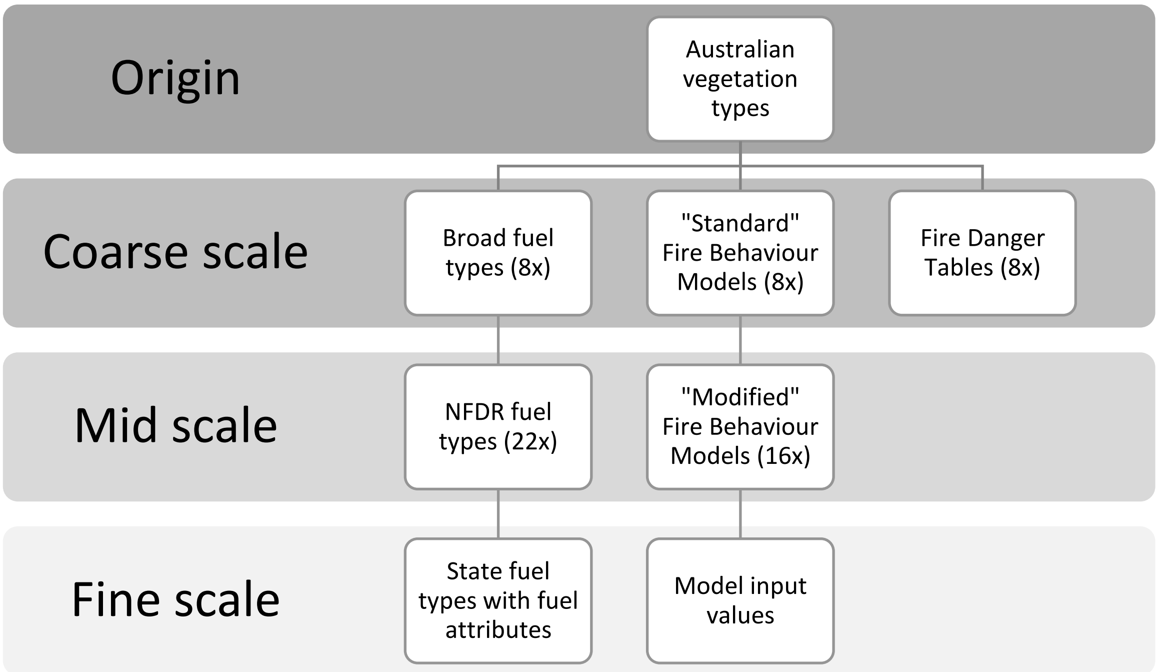

Figure 3.2 Fuel classification hierarchy

Fire Behaviour Model	Fuel Type	Description	Limitations to Fire Behaviour Model Use	Fire Behaviour Model Modifications
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
Grassland or Savanna	Gamba grass	Invasive Andropogon gayanus grasses introduced for grazing in tropical areas	Fuel loads and fuel height outside the range of application for the grassland model	Always natural condition, fixed fuel loads per fuel type
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

Fire Behaviour Model	Fuel Type	Description	Limitations to Fire Behaviour Model Use	Fire Behaviour Model Modifications
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

4 Model code

Python code to implement fire behaviour and danger calculations is maintained by the NSW RFS in a Gitlab repository. To request access to the code please contact afdrs@afac.com.au

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