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Corrigendum to: Australian Fire Danger Rating System: implementing fire behaviour calculations to forecast fire danger in a research prototype

B. J. Kenny, S. Matthews, S. Sauvage, S. Grootemaat, J. J. Hollis and P. Fox-Hughes

This article corrects *International Journal of Wildland Fire* 33, WF23142.
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On Page 3 of the published paper, in discussion of the fire behaviour models used in the Australian Fire Danger Rating System, the publication related to the grass model was cited incorrectly as McArthur (1973) which is regretted. The citation should, in fact, be Cheney *et al*. (1998), which is correctly cited in Table 1 on page 4 of the published paper and also provided in the References list.

Therefore, the incorrect paragraph below:

Fire spread models

Eight models of rate of forward spread were used, as recommended by Cruz *et al.* (2015*a*), including those specific to forest (Cheney *et al.* 2012), grassland (McArthur 1973), spinifex (Burrows *et al.* 2017), pine (Cruz *et al.* 2008), northern grassland (savanna woodland) (Cheney and Sullivan 2008), mallee-heath (Cruz *et al.* 2013), shrubland (Anderson *et al.* 2015) and buttongrass (Marsden-Smedley and Catchpole 1995*a*) fuel types.

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This has made the below reference redundant as not being cited anywhere else in the paper.
McArthur AG (1973) 'Grassland fire danger meter MkIV.' (Forest Research Institute, Forestry and Timber Bureau: Canberra, ACT)

Kenny BJ *et al.* (2024) *Corrigendum to*: Australian Fire Danger Rating System: implementing fire behaviour calculations to forecast fire danger in a research prototype. *International Journal of Wildland Fire* **33**, WF23142_CO. doi:10.1071/WF23142_CO

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Australian Fire Danger Rating System: implementing fire behaviour calculations to forecast fire danger in a research prototype†

B. J. Kenny[A,C], S. Matthews[A,D], S. Sauvage[B], S. Grootemaat[A,E], J. J. Hollis[A,F,*] and P. Fox-Hughes[B]

For full list of author affiliations and declarations see end of paper

***Correspondence to:**
J. J. Hollis
New South Wales Rural Fire Service, 4 Murray Rose Avenue, Sydney Olympic Park, NSW 2127, Australia
Email: jennifer.hollis@dbca.wa.gov.aus

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ABSTRACT

Background. The Australian Fire Danger Rating System (AFDRS) was implemented operationally throughout Australia in September 2022, providing calculation of fire danger forecasts based on peer-reviewed fire behaviour models. The system is modular and allows for ongoing incorporation of new scientific research and improved datasets. **Aims.** Prior to operational implementation of the AFDRS, a Research Prototype ($AFDRS_{RP}$), described here, was built to test the input data and systems and evaluate the performance and potential outputs. **Methods.** Fire spread models were selected and aligned with fuel types in a process that captured bioregional variation in fuel characteristics. National spatial datasets were created to identify fuel types and fire history in alignment with existing spatial weather forecast layers. **Key results.** The $AFDRS_{RP}$ demonstrated improvements over the McArthur Forest and Grass Fire Danger systems due to its use of improved fire behaviour models, as well as more accurately reflecting the variation in fuels. **Conclusions.** The system design was robust and allowed for the incorporation of updates to the models and datasets prior to implementation of the AFDRS.

Keywords: AFDRS, Australian Fire Danger Rating System, fire behaviour calculations, fire behaviour models, fuel attributes, fuel classification, fuel type map, interactive forecast display, research prototype.

Introduction

The five articles that comprise this Special Section of the International Journal of Wildland Fire introduce the Australian Fire Danger Rating System (AFDRS):

Article 1 (Hollis *et al.* 2024*b*) introduces the AFDRS and provides a short history of fire danger in Australia together with requirements to make advancements;

Article 2 (Hollis *et al.* 2024*a*) identifies and presents a framework for identification and categorisation of fire danger;

Article 3 (this paper, Kenny *et al.* 2024) describes a system for implementing fire danger calculations to forecast fire danger;

Article 4 (Grootemaat *et al.* 2024) evaluate the performance of the AFDRS Research Prototype during a live trial in the 2017–18 southern Australian fire season; and

Article 5 (Sauvage *et al.* 2024) presents a climatology of the AFDRS Research Prototype.

Background

Fire danger 'is an expression of probable fire behaviour in relation to a particular set of fuel and weather conditions' (McArthur 1977). Fire danger rating (FDR) expresses fire danger in descriptive categories (e.g. low to extreme) indicating levels for appropriate actions. FDR is an important tool for fire management, driving fire and land management agency preparedness (including suppression, ignition management and resource

Collection: Australian Fire Danger Rating System
†This article is number three in a series of five.

allocation) and communicating risk to the community (Taylor and Alexander 2006). The AFDRS program included the development of a Research Prototype platform to demonstrate the feasibility of developing a fire danger forecasting system based on contemporary fire behaviour models that was national, modular and open to continuous improvement.

Prior to 2022, the operational fire danger forecasting system within Australia used the Forest and Grass Fire Danger Indexes (FFDI and GFDI) derived from the fire behaviour models of McArthur and Dwyer (1958), McArthur (1960). Identified limitations in the McArthur system, such as the inability to incorporate contemporary fire behaviour knowledge (e.g. Cruz *et al.* 2015*a*) without changing the way users interacted with the system, complex weather effects such as stability (e.g. Dowdy and Pepler 2018) and local fuel variation (e.g. Duff *et al.* 2013) led to the development of the Australian Fire Danger Rating System: Research Prototype ($AFDRS_{RP}$) (Hollis *et al.* 2024*b*). This formed part of a broader program to introduce the AFDRS as the operational fire danger rating system nationally in Australia. Within this system, individual fire behaviour models could be implemented then retired as scientific progress occurred.

Since the pioneering work of McArthur in fire behaviour and fire danger, new fire spread models have been developed for both grassland (Cheney *et al.* 1998) and dry sclerophyll forests (Cheney *et al.* 2012). Additional models have been developed for other vegetation types: temperate shrublands (Anderson *et al.* 2015); semi-arid mallee-heath shrublands (Cruz *et al.* 2013); spinifex hummock grasslands (Burrows *et al.* 2018); buttongrass moorlands (Marsden-Smedley and Catchpole 1995*a*); and pine plantations (Cruz *et al.* 2008). These models cover the major vegetation types in Australia, but gaps remain in the knowledge of fire behaviour in less fire-prone vegetation types (e.g. rainforests, arid shrublands, wetlands and alpine herblands) and vegetation in disturbed and developed areas (e.g. crops, invasive weeds, agricultural/rural landscapes, urban areas) (Cruz *et al.* 2015*a*; Plucinski *et al.* 2017; Cruz *et al.* 2018).

Implementing spatially explicit fire management systems (e.g. fire danger ratings, fire spread simulation) requires full spatial coverage of all elements (e.g. fuel types, fire behaviour calculations, environmental data, weather forecasts) (Loveland 2001; Taylor and Alexander 2006). The lack of fire behaviour models for some vegetation types needs to be accounted for, e.g. by the application or modification of an existing model based on similarity of fuel types (Plucinski *et al.* 2017).

Fuel types are used to group and map vegetation in a manner relevant to fire management (Keane *et al.* 2001; Keane 2013; Cruz *et al.* 2018). In Australia, operational fuel type mapping is usually based on existing vegetation and land use mapping (Tolhurst *et al.* 2013; Lynch *et al.* 2015; Kenny and Roberts 2016); however, there is a lack of consistency in fuel type classification and the level of fuel attribute detail documented between jurisdictions. The Australian Bushfire Fuel Classification (BFC) was proposed to provide this consistency at a national scale (Hollis *et al.* 2015; Cruz *et al.* 2018) but had not been implemented at the time of $AFDRS_{RP}$ development.

Vegetation classification and mapping itself has variable purposes and focus, e.g. structure, floristics, climatic zone, bioregion or conservation status (Groves 1981; Specht and Specht 1999). From a fuels and fire behaviour perspective, the vegetation stratum that will carry the fire (such as surface litter, grasses or understorey plants) is the most important factor (Sullivan *et al.* 2012); therefore, structural vegetation classification is the most useful for broad fuel type classification (Lynch *et al.* 2015). However, additional information can be gained from other aspects of vegetation mapping. For example, climatic and bioregional variation influence ecosystem productivity (and hence fuel condition and dynamics) within broad vegetation types (Walker 1981; Watson 2009; Duff *et al.* 2013). Additionally, floristic information can provide data on some specific fuel attributes, e.g. bark type (Horsey and Watson 2012). These details help to define local fuel types that have the same broad fuel structure (i.e. use the same fire behaviour model) but will have different fuel attributes (e.g. height, bark, fuel load) that drive specific fire behaviour (e.g. flame height, spotting distance, intensity).

Aims

A Fire Behaviour Index (FBI – see description below in the 'Fire Behaviour Outputs' section), together with fire danger ratings, were computed daily by the Bureau of Meteorology (the Bureau) at hourly intervals on a 1.5×1.5 km resolution grid across Australia using gridded forecast weather. The 6×6 km gridded weather data were interpolated to the 1.5 km FBI grid. Each grid cell was assigned a fuel type that allowed the selection of the appropriate fire behaviour model and provided fuel attribute details. Weather and fuel inputs were then used to calculate fire behaviour metrics (rate of spread, intensity, flame height and spotting distance) that were classified into rating categories (Hollis *et al.* 2024*a*).

A live trial using data collected between October 2017 and March 2018 was conducted to test the performance of the system (Grootemaat *et al.* 2024). Live trial output was made available to fire agency staff via a specifically developed website for assessment. Given that the output was developmental during the live trial, it was not made available to the public at that time, to avoid any potential for confusion.

Methods

We describe the construction of the AFDRS Research Prototype following the system architecture as implemented in the prototype, i.e. fuel state, fire danger calculations, then visualisation.

Fuel types

For the purpose of the $AFDRS_{RP}$, fuel type classification was driven by the need to select an appropriate fire behaviour model and to capture the range of variation in fuel characteristics that provide the required fuel attributes and parameters for the fire behaviour models. Because the BFC had not been implemented when developing the $AFDRS_{RP}$, the lack of commonality between jurisdictional fuel classifications drove development of an $AFDRS_{RP}$ fuel type classification that would fit this purpose, using three tiers of increasing detail in fuel information within the $AFDRS_{RP}$:

1. Broad fuel types = primary fire behaviour models (n = 9 as per Table 1);
2. $AFDRS_{RP}$ fuel types = to suit application of fire behaviour models (n = 23 as per Table 1); and
3. Local fuel types = regionally defined fuel types with fuel attribute and parameter information (n = 430).

Broad fuel types are defined by fire spread models (Table 1; Cruz *et al.* 2015*a*). At this level, fuel types reflect broad vegetation structure in a way that indicates the primary fuel strata for fire propagation and closely resembles the fuel types implemented in the CSIRO-developed fire behaviour decision support system *Amicus* (Plucinski *et al.* 2017).

Many vegetation types don't have a specifically developed fire behaviour model (e.g. rainforests, arid shrublands, wetlands, rural and urban areas); therefore, these have been allocated to the fire spread model with the most similar fuel structure. 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 (Plucinski *et al.* 2017). Thus, some modifications (e.g. fuel availability function, wind factor, grass condition) must be made to the fire behaviour calculations to reflect these limitations. These are documented in the 'Model Application' column in Table 1 and described in the 'Fire Spread Models' subsection above.

At the most detailed level, the definition of local fuel types describes the spatial variation in fuel attributes and parameters (e.g. bioregional and floristic influences) and allows for the use and adaptation of existing agency fuel maps and fuel datasets.

Fuel characteristics and temporal fuel state variation

The fundamental physical characteristics of fuel particles and fuelbeds (fuel attribute; Hollis *et al.* 2015), as well as the characteristics required as direct input into existing fire behaviour models (fuel parameter; Hollis *et al.* 2015), were collated to enable calculation of rate of spread, flame height and intensity in the various fire behaviour models (Supplementary Table S2). Examples of the fuel attributes include fuel hazard score and fuel height. Most fuel attributes were recorded per local fuel type in a look up table, and a few were applied directly in the model code (e.g. grass condition, fuel load equations for spinifex and buttongrass).

Fuel attribute tables were primarily collated from operational fuel tables for each jurisdiction, as well as additional published values. Where there was no known value for a required fuel attribute, data were converted from another format (e.g. from fuel hazard rating (McCarthy *et al.* 1999; Hines *et al.* 2010) to DEFFM fuel hazard score (Gould *et al.* 2007*b*) or to fuel load), or generic values were applied (e.g. values from the published fire behaviour models).

Temporal fuel state data were acquired from additional spatial layers (grass curing, reported grass fuel load and time since last fire). Grass curing and grass fuel load are existing ADFD layers (provided by agencies to the Bureau) used in GFDI calculation and were used in the $AFDRS_{RP}$ to vary fuel availability, grass condition and fuel load (Table 1). A time since fire spatial layer was created from jurisdictional fire history data to allocate certain fuel attributes (fuel load, fuel hazard scores and near-surface height) in recently burnt areas. Fuel load was estimated using the time since fire layer and the fuel accumulation curve of Olson (1963), with fuel curve parameters (maximum and constant) either in the fuel attribute table (forest, mallee-heath, shrubland) or built into the model code (spinifex and buttongrass).

Fire spread models

Eight models of rate of forward spread were used, as recommended by Cruz *et al.* (2015*a*), including those specific to forest (Cheney *et al.* 2012), grassland (McArthur 1973), spinifex (Burrows *et al.* 2017), pine (Cruz *et al.* 2008), northern grassland (savanna woodland) (Cheney and Sullivan 2008), mallee-heath (Cruz *et al.* 2013), shrubland (Anderson *et al.* 2015) and buttongrass (Marsden-Smedley and Catchpole 1995*a*) fuel types. Table 1 lists the fire spread models used within the $AFDRS_{RP}$. Most models were implemented as recommended by (Cruz *et al.* 2015*a*), with the addition of fuel availability modifiers where these were lacking, as described below and in Table 1.

Dead fuel moisture is an important determinant of the potential for fires to start and spread (Matthews 2014). Two main approaches have been used for including the effect of rainfall on operational fire spread models: (1) increasing moisture content above the fibre saturation point, e.g. Marsden-Smedley and Catchpole (1995*b*); or (2) reducing the amount of fuel available to burn, e.g. the McArthur drought factor (Noble *et al.* 1980). Below, we describe the approaches used to evaluate fuel availability within the

Table 1. Fuel type descriptions and fire behaviour model application in AFDRS Research Prototype.

Broad fuel type	Fire behaviour model	$AFDRS_{RP}$ fuel type	Fuel type description	Limitations	Model application
Forest	Dry Eucalypt Forest Fire Model (DEFFM); Cheney *et al.* (2012)	Forest	Dry eucalypt forest and temperate woodland with a shrubby understorey and litter surface fuel	n/a	Fuel availability function applied (Eqn 1)
		Wet forest	Forests with high moisture content due to structure (closed forest cover >70%, tall forest >30 m), topography or inundation, e.g. rainforest, wet sclerophyll forest, swamp forest	Fuel availability limited by moisture content	Fuel availability function applied (Eqn 2)
Grassland	CSIRO Grassland fire spread meter; Cheney *et al.* (1998)	Grass	Continuous and tussock grasslands	n/a	Cruz *et al.* (2015*b*) curing function; fuel condition from reported grass fuel load
		Pasture	Modified or native pasture where primary land use is grazing	Fuel availability variable with management	
		Crop	Non-irrigated cropping land (cereals, hay, sugar, etc.)		
		Low wetland	Wetland with low or no overstorey, e.g. low swamp heath, sedgeland, rushland	Fuel availability limited by moisture content	Cruz *et al.* (2015*b*) curing function; fuel condition set to eaten-out
		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	
Northern grassland (savanna)	CSIRO Grassland northern Australia; Cheney *et al.* (1998), Cheney and Sullivan (2008)	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 grass understorey	n/a	Cruz *et al.* (2015*b*) curing function; fuel condition from reported grass fuel load
		Gamba	Grassland, woodland or rural area invaded by gamba grass (*Andropogon gayanus* Kunth.) or similar high fuel load invasive grass	Higher than standard grass fuel loads	Cruz *et al.* (2015*b*) curing function; fuel load applied via attribute table
		Arid woodland	Arid/semi-arid woodland or shrubland with an ephemeral grass understorey; fuel connectivity only when grass cover occurs after sufficient rain. Mostly *Acacia* dominated (e.g. Mulga) but also includes *Eucalyptus*, *Casuarina*, *Callitris*, etc.	Fuel connectivity limited and variable with ephemeral grass growth	Cruz *et al.* (2015*b*) curing function; fuel condition set to eaten-out
		Woody horticulture	Perennial woody horticulture, likely managed (mown, irrigated) grass understorey, e.g. orchards, vineyards	Fuel availability variable with management	
		Rural	Rural residential areas. Typically continuous grass with variable tree cover. Note fuel management (e.g. grazing, mowing) may be highly variable	Fuel availability variable with management	Cruz *et al.* (2015*b*) curing function; fuel condition set to grazed

(*Continued on next page*)

Table 1. (*Continued*)

Broad fuel type	Fire behaviour model	$AFDRS_{RP}$ fuel type	Fuel type description	Limitations	Model application
		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 cover and management may be highly variable	Fuel availability variable with management	Cruz *et al.* (2015*b*) curing function; fuel condition set to eaten-out
Spinifex	Spinifex grassland model; Burrows *et al.* (2018)	Spinifex	Spinifex hummock grassland	n/a	Modelled soil moisture (AWRA)
		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	Modelled soil moisture (AWRA); wind factor applied via attribute table
Mallee-heath	Semi-arid mallee-heath model; Cruz *et al.* (2013)	Mallee-heath	Semi-arid mallee-heath woodland and shrubland, specifically with a shrubby understorey. Note that mallee with a spinifex understorey is included in Spinifex woodland; mallee with a chenopod or ephemeral grass understorey is included in Arid woodland	n/a	Fuel availability function applied Marsden-Smedley *et al.* (1999)
Shrubland	Temperate shrubland model; Anderson *et al.* (2015)	Heath	Temperate shrublands. Primarily heathland; may also include tall closed shrubland, low closed forest or open woodland with heath understorey where the structure is dominated by a single shrub layer (cf. multiple strata of forest). Note that arid and semi-arid shrublands are included in other fuel types (e.g. mallee-heath, arid woodland, spinifex woodland, chenopod shrubland)	n/a	Fuel availability function applied Marsden-Smedley *et al.* (1999)
		Wet heath	Wetlands with a medium to tall shrubland structure, e.g. swamp heath, melaleuca shrubland. Note that buttongrass moorlands of Tasmania have a separate fuel type	Fuel availability limited by moisture content	
Buttongrass	Buttongrass moorlands model; Marsden-Smedley and Catchpole (1995*a*)	Buttongrass	Buttongrass moorland of Tasmania: largely treeless sedgeland/low heath containing the hummock-forming tussock sedge *Gymnoschoenus sphaerocephalus* (R.Br.) Hook.f.	n/a	Fuel availability function applied Marsden-Smedley *et al.* (1999)
Pine	Adjusted Cruz *et al.* (2008) Pine model; M. Cruz, pers. comm.	Pine	Pine plantation	n/a	Fuel availability function applied (Eqns 3 and 4)
Non-combustible	n/a	Horticulture	Seasonal horticulture, very low flammability, e.g. vegetables, herbs and irrigated crops	Minimal flammable material	Nil fire behaviour calculations
		Built up	Non-combustible urban areas and intensive land use, e.g. business districts, industrial areas, infrastructure, mining		
		Non-combustible	Non-combustible areas of water, sand, rock, etc. Includes saline wetlands		

models used in the $AFDRS_{RP}$. Note that observed values of grass curing were used in grassland calculations, as occurred in operational fire weather forecasts.

The Dry Eucalypt Forest Fire Model (DEFFM: Cheney *et al.* 2012) assumes dry summer conditions and as such, does not include fuel availability or rainfall effects in its fuel moisture models. The DEFFM does not specify recommendations for treatment of these effects on either fuel moisture or fuel quantity. The process-based fuel moisture model of Matthews (2006) was considered too complex to implement within the $AFDRS_{RP}$. Instead, simple fuel availability curves were implemented as functions of drought factor, loosely based on fire occurrence observations presented by (Cawson *et al.* 2017). Fuel quantity values (fuel hazard scores (Gould *et al.* 2007*b*) and fuel loads) were multiplied by the fuel availability factor

For dry forests:

$$\text{Fuel\_availability} = (\text{DF} \times 0.1) \quad (1)$$

For wet forests, a logistic function was used:

$$\text{Fuel\_availability\_WF} = (1.135 / (1 + e\hat{}(2 \times (9 - \text{DF})))) \quad (2)$$

where Fuel_availability is the fraction of fuel available for combustion and DF is the drought factor, calculated by the Bureau of Meteorology at the same resolution as the weather parameters (6 × 6 km, downscaled to 1.5 × 1.5 km), using the method of Griffiths (1999). A different fuel availability function was developed for wet forests in order to account for the more limited fuel availability in these forest types compared with the dry forests for which the DEFFM model had been developed (Matthews *et al.* 2018).

Similar to the DEFFM, fuel availability and rainfall effects are not accounted for in the Cruz *et al.* (2013) mallee-heath and Anderson *et al.* (2015) shrubland models. Because these fuel types are expected to become flammable more rapidly after antecedent rainfall than a forest fuel type, we applied the Marsden-Smedley *et al.* (1999) fuel moisture modifier function, originally developed for buttongrass fuels, to derive fuel availability for the mallee-heath and shrublands models. Although these fuel types are structurally dissimilar and occur in different climatological zones, 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. We note that very little rainfall is required for fire to be extinguished in buttongrass moorland fuel, a characteristic which may not be ideally suited to mallee-heath and shrubland fuels.

For pine plantation, the recommended Cruz *et al.* (2008) fire behaviour model and fine fuel moisture code (Van Wagner 1987) were considered too complex to implement in the $AFDRS_{RP}$. Instead, we used a simplified fire behaviour model originally developed for use with the Commonwealth Scientific and Industrial Research Organisation (CSIRO)-developed SPARK fire spread simulation software (Hilton *et al.* 2015; Miller *et al.* 2015), with the following functions to modify dead fuel amount and foliar moisture content (M. Cruz pers. comm.):

$$\text{Fuel load (in kg} \times \text{m}^{-2}) = 0.3 + 0.075 \times \text{DF} \quad (3)$$

$$\text{Foliar moisture content} = 150\text{–}5 \times \text{DF} \quad (4)$$

where DF is the drought factor.

Fuel type modifications to fire behaviour model application

The CSIRO grassland models (Olson 1963; Cheney *et al.* 1998) have separate rate of spread equations depending on grass condition (natural/undisturbed, grazed/cut, eaten-out). Australian grass fuel reporting protocols record fuel load and curing only, so reported fuel load was used as a proxy for condition. Ideally, information on grass condition would be used in these calculations. The use of load instead is a pragmatic decision, and does not suggest that the two quantities are coupled in the model. For the standard grassland fuel types (grass, woodland), the reported grass fuel load layer was used to select the grass condition (where fuel load of 3 t ha^{-1} or less was set to eaten-out; between 3 and 6 t ha^{-1} was set to grazed; 6 t ha^{-1} and above was set to natural). For fuel types where the grass fuel is limited by ephemeral grass growth (chenopod shrubland, arid woodland), inundation (low wetland) or human management (pasture, crop, rural, urban, woody horticulture), the grass condition was set by fuel type (reported grass fuel for pasture and crop; grazed for rural; eaten out for all others; see Table 1). For all grassland and northern grassland fuel types, fireline intensity was calculated using the reported grass fuel load.

For the spinifex model, a wind factor was added as per the northern Australia grassland model (Cheney and Sullivan 2008), to allow for the effect of overstorey cover on the 2 m wind speed. This was implemented using the fuel attribute tables, where the wind factor for spinifex was set to 1, whereas the wind factor for spinifex woodland was a value less than 1 depending on the level of overstorey cover. Note that as specified in Table 1, spinifex woodland is a distinct fuel type from other woodland types or mallee-heath.

Weather data

Weather parameters (such as wind speed, air temperature and relative humidity) are primary inputs to all of the fire behaviour models. Most weather parameters (Supplementary Table S1) were acquired from the Australian Digital Forecast Database (ADFD: Bureau of Meteorology 2023*b*).

The Wind Change Danger Index was calculated from ADFD layers (surface wind gust strength, wind direction) using the algorithm of Huang and Mills (2006).

The soil moisture input required to calculate spinifex fuel availability came from the Australian Water Resource Assessment (AWRA) (Frost *et al.* 2018) data available through the Bureau.

Spatial data processing

For the purpose of fire behaviour calculations, the ~6 km resolution of the ADFD weather forecast grids was considered too broad to capture the spatial variability in fuel type and fire history data, and the native resolution of the original data (30–250 m) was too fine for efficiently processing in the forecast calculation system. Therefore, a ~1.5 km grid was built to nest within the ADFD grids. The fuel type and fire history spatial data were post-processed to this $AFDRS_{RP}$ resolution. Spatial analyses were performed on the input data to produce layers of dominant fuel type (the local fuel type with the maximum area coverage within a grid cell) and average time since fire.

Forecast calculation system

A calculation system was built and run by the Bureau to take the fuel and daily weather forecast inputs and run the various fire behaviour model calculations to produce a range of fire danger outputs. Calculations ran within the Bureau's development environment, entirely separate from operational forecasting systems. The FDR was calculated per grid cell and summarised at the Fire Weather District (Bureau of Meteorology 2023*a*) scale as the highest rating with at least 10% coverage of the Fire Weather District (i.e. 90th percentile). Calculations were primarily performed using the Python programming language using the NumPy (van der Walt *et al.* 2011), Pandas (McKinney 2011) and xarray (Hoyer and Hamman 2017) libraries to efficiently perform scientific calculations using the large meteorological datasets required. A Jenkins (https://jenkins.io) automation server was used to control data processing tasks.

To support the ability of the system to include continuous improvement by allowing the safe inclusion of changes to the model code, Git (Blischak *et al.* 2016) was used for version control, and all code updates were tested using the pytest framework (Okken 2017) through GitLab's (https://gitlab.com/) continuous integration tools. These tests were conducted prior to deployment.

The system collected ADFD forecast data and AWRA soil moisture data at 0200 hours Australian Eastern Daylight Time (AEDT) daily. The data for each jurisdiction were unified by transforming them onto a common grid at hourly intervals. At 0500 hours AEDT, the unified data were then passed through the fire behaviour model calculations for the relevant fuel types for each jurisdiction. Computations were performed in parallel, with a maximum calculation time of 15 min. Results were stored and published as netCDF grids (Rew and Davis 1990) through existing Bureau data delivery infrastructure. Summary products such as area rating tables and images of daily maximum rating values were also produced.

Red flag warnings

Not all weather (or weather-related) quantities that might affect the occurrence or spread of a fire were amenable to direct inclusion in fire spread model calculation (and therefore of fire danger in the $AFDRS_{RP}$). For this reason, fire agency managers wished to have additional red flag warnings calculated, to identify conditions where fire danger was likely to be increased by a wind change, atmospheric instability or long-distance spotting. A Daily Wind Change Danger Index (Huang and Mills 2006) was included together with a value for the 90th percentile daily maximum spotting distance (Gould *et al.* 2007*a*) and maximum CHaines (Dowdy and Pepler 2018) above the 95th percentile climatological value displayed in the output websites. These red flags are described in more detail by Hollis *et al.* (2024*b*). The Red flag warnings did not modify the rating categories, but are noted here because they formed part of the implemented $AFDRS_{RP}$.

Fire behaviour outputs

All of the fire spread models used within the $AFDRS_{RP}$ use a combination of weather parameters and fuel characteristics, including fuel moisture to calculate rate of spread. Some models also produce flame height/length and spotting outputs.

Fireline intensity was calculated from rate of spread and fuel load using the Byram (1959) fireline intensity equation, assuming a heat yield of 18 600 $kJ\,kg^{-1}$ (Albini 1976) for all fuel types except buttongrass and spinifex, where 19 900 $kJ\,kg^{-1}$ (Marsden-Smedley and Catchpole 1995*b*) and 16 700 $kJ\,kg^{-1}$ (M. Possell, pers. comm.) were used respectively. Total fuel load was modified by the fuel availability (e.g. as in Eqn 3) and was then used to calculate fireline intensity for most fuel types, but fuel load of different strata was added incrementally for forest (based on flame height) and mallee-heath (based on probability of crown fire).

A Fire Behaviour Index (FBI) was determined using a linear interpolation based on the fire behaviour metric (e.g. rate of spread, fireline intensity) and the table of Fire Behaviour Index values and intensity thresholds (Hollis *et al.* 2024*a*). From this, a forecast was produced that included a Fire Behaviour Index as well as Fire Danger Rating categories (FDR) (Hollis *et al.* 2024*a*).

Website outputs

An interactive website was produced to display the hourly forecasts of the Fire Behaviour Index and Fire Danger Rating, including the input weather forecasts and the output fire behaviour calculations (Supplementary Table S3). The main features of the website include: an interactive map display of FBI (Supplementary Fig. S1*a*) and other variables for the current and previous days at hourly intervals; the ability to view and download time series graphs for all variables at any location; and incident markers and information from agency incident feeds.

All jurisdictions in Australia publish a live, web-based feed of active, going fire incidents. These data were displayed on the interactive website and stored in a database for analysis of reported incidents during the $AFDRS_{RP}$ live trial.

A daily summary website was produced to display the daily FBI calculations and associated FDR and delivered using the Bureau's registered-user's websites. A national map of daily maximum FDR by Fire Weather District was generated (Supplementary Fig. S1*b*), as well as state-based maps of daily maximum fire danger rating and index displayed on both the $AFDRS_{RP}$ grid and by Fire Weather District. Tables were generated summarising daily maximum FDR per Fire Weather District and displaying the red flag warnings for wind change, instability and spotting. Additional weather demonstration products (weather products not yet fully operational, but with potential for future incorporation into the AFDRS) were presented, including a link to JASMIN (Dharssi and Vinodkumar 2017) soil moisture data and images of pyrocumulonimbus and dry lightning potential (produced by the Bureau Extreme Weather Desk).

Re-calculation system

The forecast calculation system was built in a modular structure to allow changes as the underlying scientific knowledge improves. However, each module or node was sufficiently complex that the effect of changes to model code on model performance may not have been immediately obvious. To ensure the effect of changes are clear and can be reproduced in a transparent way, we developed a system for re-calculating and evaluating the performance of the $AFDRS_{RP}$ models. The re-calculation system was built as a self-contained virtual machine using an Amazon Web Services EC2 instance (https://aws.amazon.com/ec2/). This allowed the system to be duplicated if required and allowed snapshots of the system at various points in time to be archived. The same Python modules that are used in the forecast calculation system are also used in the re-calculation system, ensuring consistency between both systems (with code changes tracked using the Git version control system). The system included a set of interactive Jupyter (Kluyver *et al.* 2016) notebooks for comparing the performance of the $AFDRS_{RP}$ among versions to ensure that changes improve predictive skill before they are incorporated into the operational forecast system.

Results and discussion

The $AFDRS_{RP}$ successfully demonstrated that it is possible to build a fire danger rating system that is national, modular and open to continuous improvement. The requirements for an improved fire danger rating system are outlined by Hollis *et al.* (2024*b*). Some principles relating to these requirements are discussed here, with further details covered by Grootemaat *et al.* (2024) and Hollis *et al.* (2024*a*).

System performance

The forecast calculation system and the two output websites were fully functional and available to users around Australia during the period of the live trial and remained functional for ongoing evaluation up to implementation in September 2022. Minor outages occurred, but automated error checking and alerts enabled rapid identification of calculation or display errors. As detailed in the accompanying 'Live Trial' article in this series describing the $AFDRS_{RP}$, the overall performance of the $AFDRS_{RP}$ was superior to the McArthur system, with a tendency to over-predict rather than under-predict fire danger potential (Grootemaat *et al.* 2024).

An example of an hourly $AFDRS_{RP}$ rating for a day with elevated fire danger (4 January 2019 at 1400 hours) on the $AFDRS_{RP}$ forecast grid (interactive website output) is included in Supplementary Fig. S1*a*. The daily maximum FDR for the same day by Fire Weather District (summary website output) is also provided in Supplementary Fig. S1*b*.

Fuels

A major improvement that the $AFDRS_{RP}$ introduced was the use of fire behaviour models for a wider range of fuel types and the use of detailed fuel attributes allowing for regional variation. The McArthur derived Forest Fire Danger Index (FFDI; McArthur and Dwyer 1958) and Grass Fire Danger Index (GFDI; McArthur 1960) were used to determine fire danger ratings within Australia, so all vegetation was classified as either forest or grass. The calculation of GFDI incorporates variation in grass fuel state through reported grass curing and grass fuel load, but FFDI calculation assumes forest fuels to be static both spatially and temporally.

The mapping of forest fuel types between the McArthur systems and the $AFDRS_{RP}$ is roughly equivalent (Fig. 1 and Supplementary Fig. S2). Although forest only covers a small portion of Australia, it coincides with the areas of greatest population (including around Australia's three biggest cities: Sydney, Melbourne and Brisbane), and forest is the fuel type most likely to impact on residential areas. This human influence is seen in the discrepancy between overall area covered (6%), reported incidents (20%) and the distribution of forest within Fire Weather Districts (Table 2). Forest is the dominant fuel type (greatest area coverage) in 18% of Fire Weather Districts, and significant (at least 10% area coverage, i.e. enough to set the fire danger rating) in 38% of Fire Weather Districts. Note that Fire Weather Districts are variable in size, generally reflecting population density.

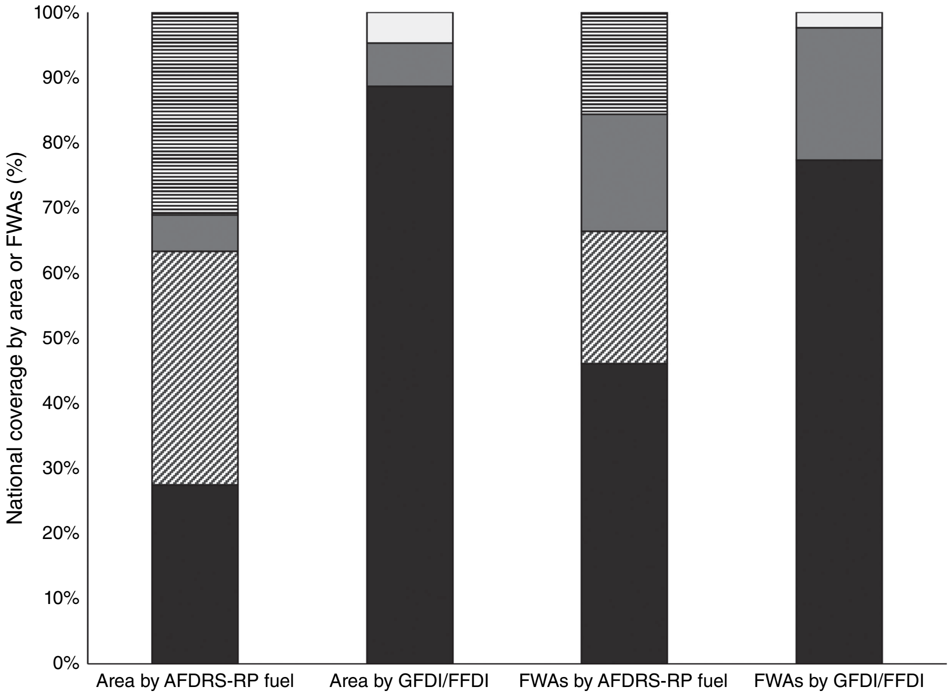

Fig. 1. Comparison of fuel type coverage between $AFDRS_{RP}$ and GFDI/FFDI, shown as both percentage of national area covered and percentage of Fire Weather Districts with dominant fuel type. Black, grassland; diagonal lines, northern grassland ($AFDRS_{RP}$ only); grey, forest; horizontal lines, other $AFDRS_{RP}$ fuel types (see Table 2 for detailed breakdown); light grey, combined (where both GFDI and FFDI are calculated).

Table 2. Coverage of broad fuel types and distribution of incidents across fuel types.

Broad fuel type	Area covered (% national)	Dominates FWD (% national)	Significant in FWD (% national)	Reported incidents (%)	Evaluations live trial + case studies (%)
Forest	5.5	18.0	38.3	20.2	55.7
Grassland	27.5	46.1	75.8	33.2	22.9
Northern grassland (savanna)	35.9	20.3	50.8	37.0	5.4
Spinifex	25.7	12.5	28.9	1.7	3.0
Mallee-heath	2.2	1.6	14.1	0.6	4.5
Shrubland	1.0	1.6	7.8	0.9	5.4
Buttongrass (% Tasmania)	0.1 (10)	0.0 (0.0)	0.8 (9.1)	0.01 (0.3)	1.8
Pine	0.2	0.0	0.0	0.6	1.5
Non-combustible	1.8	0.0	0.0	5.7	0.0

Fuel type coverage is given as a percentage of the total national area (calculated from the $AFDRS_{RP}$ 1.5 km grid) and by Fire Weather District. Dominates Fire Weather District (FWD) means the fuel type with greatest area coverage of an FWD; 'significant' in an FWD means that a fuel type has at least 10% coverage within an FWD (i.e. could set the fire danger rating) (note that multiple fuel types may meet this criterion per FWD, hence the total of this column exceeding 100). Incidents reported through fire agency incident feeds (n = 31 945) and evaluations received (n = 336) (Grootemaat *et al.* 2024) during the live trial (October 2017–March 2018) are shown by percentage per fuel type.

Bioregional variation and disturbance (e.g. fire history), which have a significant influence on the distribution and condition of forest fuels (Duff *et al.* 2013), are not accounted for in the FFDI. The influence of variable fuel attributes was seen in the $AFDRS_{RP}$ calculated fire behaviour (and hence forecast FBI and FDR), both between different forest fuel types and within a fuel type as fire history changed between sites (example shown in Fig. 2).

Although grass-like fuels cover the largest area of Australia (Cheney and Sullivan 2008; Sullivan *et al.* 2012), this includes a variety of fuel types: tussock grassland; pasture and crop land (all included in $AFDRS_{RP}$ grassland broad fuel type); tropical grasslands ($AFDRS_{RP}$ northern grassland) and hummock grass ($AFDRS_{RP}$ spinifex).

The classification of grass fuels is where the difference between the McArthur based fire danger forecasts and the $AFDRS_{RP}$ becomes most apparent (Fig. 1 and Supplementary Fig. S2). McArthur fire danger ratings are primarily set by GFDI, with 89% area coverage and 77% of Fire Weather Districts dominated by fuel classified as grass (Fig. 1). Under

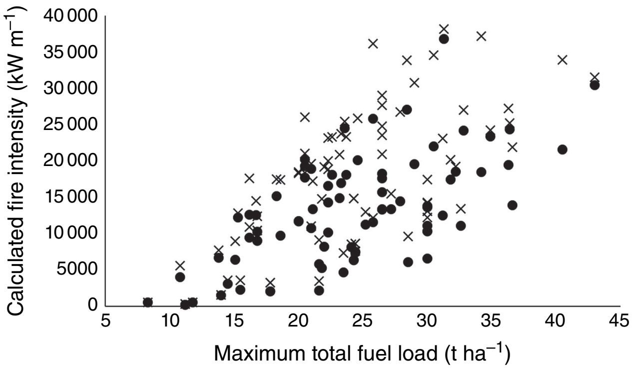

Fig. 2. Variation in fuel load and $AFDRS_{RP}$ calculated fire intensity for Forest fuel types. Circle = calculated at a time since fire of 5 years; crosses = calculated at a time since fire of 25 years. The *x*-axis shows maximum total fuel load for each local level forest fuel type (*n* = 82); note that all other fuel attributes used to calculate intensity also vary per fuel type. Weather parameters used: wind speed 35 km h^{-1}; temperature 30°C; relative humidity 20%; drought factor 9. Equivalent FFDI = 35 (very high).

the $AFDRS_{RP}$ classification, Grassland and Northern Grassland (allowing for a tree canopy over a grassy understorey) are still the primary fuels in terms of area covered (28 and 36% respectively), Fire Weather Districts influenced (46 and 20%), and reported incidents (33 and 37%) (Table 2). Between Grassland and Northern Grassland, the latter covers a greater physical area but in less populated areas, hence Grassland influences more Fire Weather Districts.

The other fire behaviour models (i.e. spinifex, mallee-heath, shrubland, buttongrass and pine), which are not considered when calculating fire danger in the McArthur System, collectively cover a substantial portion (29%) of Australia (Table 2).

Spinifex covers a large area of inland Australia, but coincides with the most arid, remote and sparsely populated areas. In the FFDI/GFDI forecast system, this is all treated as grass. Fire behaviour in spinifex hummock grasslands is very different to that in continuous grasslands, due to the different structure, continuity and life cycle of spinifex (Cruz *et al.* 2015*a*; Burrows *et al.* 2018). The influence of recent fire on the calculation of probability and rate of fire spread in the spinifex model was observed as obvious patterns in forecast fire danger (Supplementary Fig. S1*c*). This is in contrast with the GFDI in continuous grasslands, which is driven by weather-dependent grass curing and condition (Cheney *et al.* 1998; Cruz *et al.* 2015*a*).

The other broad fuel types (mallee-heath, shrubland, buttongrass and pine) are generally represented by FFDI calculations in the McArthur system. Spatially, these fuel types have a small national area coverage and do not influence many Fire Weather Districts (Table 2, Supplementary Fig. S2). However, these fuel types all have unique characteristics influencing their fire behaviour (Marsden-Smedley and Catchpole 1995*a*; Cruz and Fernandes 2008; Cruz *et al.* 2013; Anderson *et al.* 2015). For example, buttongrass moorlands are known to burn rapidly with high fuel moisture levels and low–moderate forecast FFDI (Marsden-Smedley and Catchpole 1995*a*), when surrounding rainforest and wet eucalypt forest are unlikely to be flammable under those conditions (Marsden-Smedley *et al.* 1999). Such differences became apparent in the $AFDRS_{RP}$ where these fuel types occur in proximity to each other, resulting in considerably different forecast FBI in adjacent forecast grid cells (Supplementary Fig. S1*d*). An evaluation of the performance of the $AFDRS_{RP}$ across the range of fuel types is presented by Grootemaat *et al.* (2024).

System improvements

Various improvements were made to the system during the live trial period, demonstrating the importance of the modular nature of the system and its ability to support continual improvement.

Updates to the spinifex model provide an example of successful updates to the $AFDRS_{RP}$. During development of the $AFDRS_{RP}$ model code, the spinifex model was under revision (released as Burrows *et al.* (2018)). A draft version was initially implemented in discussion with the authors, then updated once the latest version was published. This update occurred successfully during the live trial period. Equations for accumulation of spinifex fuel load and cover were implemented in the spinifex module via code rather than the fuel attribute tables. The equations used describe spinifex growth in the arid and semi-arid zones (N. Burrows, pers. comm.). Spinifex growth and cover follow a rainfall gradient from arid to tropical zones (Allan and Southgate 2002); therefore, more appropriate fuel values (the late dry season tables from the Carbon Farming Initiative methodology (Australian Government 2015)) have now been applied, with a productivity code in the fuel attribute table to determine which fuel values to use.

Limitations

During the development of the $AFDRS_{RP}$, a list of knowledge gaps, limitations and potential improvements was compiled (Matthews *et al.* 2018). Many of these items were addressed and revisions made prior to implementation of the AFDRS. The major issues are discussed below.

The fire spread models adopted in the $AFDRS_{RP}$ were designed for calculating the forward rate of spread of fully developed fires. Using them at a broader scale to predict fire danger (i.e. potential fire behaviour if an ignition were to occur) creates some limitations. The lack of incorporating a build-up phase may lead the system to over-predict fire potential (Cruz *et al.* 2015*a*; Plucinski *et al.* 2017). Local terrain effects (e.g. slope, alignment with wind direction), which can have a significant impact on potential rate of spread (McArthur 1967; Sullivan *et al.* 2014), are not accounted for due to the scale of calculations.

The simple fuel availability function applied for wet forests was identified as requiring revision (Grootemaat *et al.* 2024). This is a topic of ongoing research (Cawson *et al.* 2017; Duff *et al.* 2018), so improvements are expected when this research can be collated into an operational solution. Similar limitations of fuel availability apply to other fuel types, for example mallee-heath and shrublands, for which the buttongrass moorland fuel availability calculation has been used in this work.

A limitation seen in other applications of fuel classification (Plucinski *et al.* 2017; Cruz *et al.* 2018) is that some vegetation types (e.g. rainforests, arid shrublands, wetlands) do not have an established fire spread model, nor do disturbed and developed areas. When building a spatial system with full national coverage, these must be accounted for. The approach taken here was to use the fire spread model most likely to represent the fuel structure and make modifications based on fuel characteristics (as per Plucinski *et al.* 2017). Some of these modified models worked well, but most have not been adequately tested through the evaluations conducted to date. Although fire spread models may be developed for some of these fuel types in the future (e.g. crops, Cruz *et al.* 2020), most are of low priority due to the low flammability (Cruz *et al.* 2018) and/or remote distribution. Of these, the ephemeral grass fuel types (arid woodland and chenopod shrublands) cover the greatest area. Several solutions could be implemented to more accurately reflect ephemeral grass condition, including remote sensing (Tindall *et al.* 2015), rainfall monitoring (Bastin 2014), grass growth modelling (Stone *et al.* 2010) or improved jurisdictional reporting.

Implementation of the AFDRS

The full operational AFDRS was implemented nationally in September 2022, based on the foundation for calculating fire danger developed in the $AFDRS_{RP}$. The system architecture for the AFDRS is based on four modules: (1) a fuel state editor (an interactive tool for capture, upload and approval of the fuel inputs); (2) fire danger calculations (implementation of the fire behaviour models and forecast calculations); (3) a fire danger viewer (interactive visualisation of the weather and fire danger forecasts, including red flags); and (4) seasonal outlooks (visualisation products of seasonal forecasts of fire danger).

Supplementary material

Supplementary material is available online.

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Author affiliations

[A]New South Wales Rural Fire Service, 4 Murray Rose Avenue, Sydney Olympic Park, NSW 2127, Australia.

[B]Research Program, Bureau of Meteorology, 7/111 Macquarie Street, Hobart, Tas. 7000, Australia.

[C]Present address: Nature Conservation Council of NSW, Sydney, NSW, Australia.

[D]Present address: Nova Systems, 100 William Street, Woolloomooloo, NSW 2011, Australia.

[E]Present address: NSW National Parks and Wildlife Service, 4PS, 12 Darcy Street, Parramatta, NSW 2150, Australia.

[F]Present address: Department of Biodiversity, Conservation & Attractions, Brain Street, Manjimup, WA 6258, Australia.