Climate Systems

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Things to consider when using fire-behaviour models to understand changes to future bushfire risk

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- **Fire indices and behaviour models were not designed to consider longer-term climate implications:** Modelling the effect of climate on fire danger is particularly difficult, due to the highly complex processes that affect fuel distribution, structure, amount and flammability. These processes also vary substantially between vegetation species, and with local geology and micro-climate.

- **Careful interpretation and communication is needed:** Given the limitations of applying future climate projections in fire-behaviour models, the interpretation and communication of future bushfire risk based on these models requires careful attention to detail. A clear explanation of how projections might vary when using different weather functions is needed, along with an acknowledgement of the limitations of the underpinning climate functions in the models.

With increasing global temperatures, climate change is increasing the risk of bushfires in Australia. There are, however, significant complexities and nuances as to how bushfire danger will change. This doesn't make it easy for researchers or decision makers trying to interpret changes to fire risk in a future climate.

The effect of weather, that is, the immediate short-term conditions, and climate, the longer-term conditions, on fire danger is highly complex. Effects on the fuel structure, amount of fuel and dryness, as well as on ignitions and the ability for fires to spread and cause damage are all part of this complexity (see this article from The Conversation). There are various tools or fire behaviour models that we can use to examine fire danger, including simple fire threat measurement indices, and ratings systems.

This discussion paper outlines some of the challenges and limitations of using climate projections in these fire-behaviour models. It highlights some of the assumptions which prevail and the implications of those assumptions, which can confound the results if not interpreted correctly. This document provides insights to deal with the limitations of the current tools and inform potential future improvements.

What is a fire behaviour model and what tools do we currently use to understand future bushfire risk?

Fire-behaviour models are mathematical models used to predict fire characteristics as a fire spreads across the landscape. They have been used for decades to assess fire threat, not only for public messaging but also operational procedures, such as fire suppression, planned burning and resource allocation.

There are numerous models that have been used around the world for assisting fire-agency operations over the last half-century and longer (Cruz et al., 2015; Kenny et al., 2024; Fire Weather Indices WIKI). For example, in Australia, the McArthur Forest Fire Danger Index (FFDI) is a commonly used model. There is also a Canadian Forest Fire Weather Index (FWI) system, and the United States has its own National Fire Danger Rating System (NFDRS). The majority of models have inputs that can be characterised as weather inputs or climate inputs, and some contain both. Figure 3 is a simple illustration of a generic fire behaviour model and its components, including climate and weather inputs.

As above, the Forest Fire Danger Index (FFDI) is commonly used by climate scientists to convey the likely increase in fire risk due to a changing climate. FFDI is calculated using a combination of weather inputs known to influence dangerous bushfire conditions in Australia: temperature, humidity and wind speed. It's a convenient metric that is relatively simple to implement, with a long history of use for assessing forest fire danger in Australia.

One challenge with fire behaviour models like the FFDI is that they were designed for use in predicting fire threats to inform operational response. Due to their reliance on accurate weather inputs, fire behaviour models used in operations have a short-term focus, a period of one to currently about seven days. In this period, other inputs such as the type of vegetation, how much vegetation and how dry it is, can be reliably used, as they are assumed to be approximately constant.

These tools were not designed for use in providing an understanding of the long-term future fire risk, for example, out to the 2050s. And with climate models projecting increases in temperature and changes in precipitation for Australia, this long-term understanding of fire risk is crucial for future planning and adaptation.

More recently, the Australian Fire Danger Rating System (AFDRS) (Kenny et al., 2024) has addressed some of these issues by developing specific fire behaviour models for different vegetation types, that is, ‘fuel’ types (e.g., grasslands, heathland and a range of forest types). The AFDRS is now utilised across Australia by fire and emergency services. It uses eight different fire-behaviour models to represent the diversity of vegetation or fuel types across the continent. Those eight models and the vegetation types they represent are shown in Figure 1. Through modifications to the eight models, their application and use were expanded to 22 different fuel types across Australia.

Figure 1*. The eight fire behaviour models used in the Australian Fire Danger Rating System (AFDRS) and the specific Australian vegetation (fuel) types they represent. (Source: AFDRS Fire Behaviour Index and Model Guides)*

What happens when we use climate projections in these tools?

Applying climate projections in fire behaviour models requires assumptions to be made about the next few decades, and as above, this longer-term outlook is generally outside the design scope of these tools (Benger et al., 2026). Any longer-term assumptions, about future vegetation type/amount/dryness are primarily driven by, and connected to, the climate, not just short-term weather conditions. For example, if there are trees in a local reserve, there can be a fair amount of certainty that they will be there in one week, but what about in 20 years' time, if there is a long drought or land use changes?

So with the changing climate in Australia expected to bring increases in the number of hot days, the duration and intensity of heatwave events, and changes in rainfall patterns, decision-makers (bushfire managers, planners) require a robust understanding of future bushfire risk in Australia. While we are doing the best with the tools we have, it needs to be recognised that those tools were not designed to be used with climate projections. And this means careful application and interpretation is needed.

The complexities in understanding future bushfire risk: An illustration from the AFDRS

Most Australians are now familiar with the AFDRS, with fire danger ratings expressed using the green, yellow, orange and red colour categories, seen throughout the country on roadside signs (see figure 2). These ratings are informed by a Fire Behaviour Index (FBI), which provides a scale of potential fire danger (should a fire ignite), based on the predicted fire intensity or rate of spread. The FBI is made up of step-ups or transitions, where an increase in category is triggered by a change in: i) fire behaviour, ii) suppression response, or iii) potential impacts. The FBI runs from 0 to 100 and provides decision makers with a finer level of detail for responding and planning than the four fire danger rating categories.

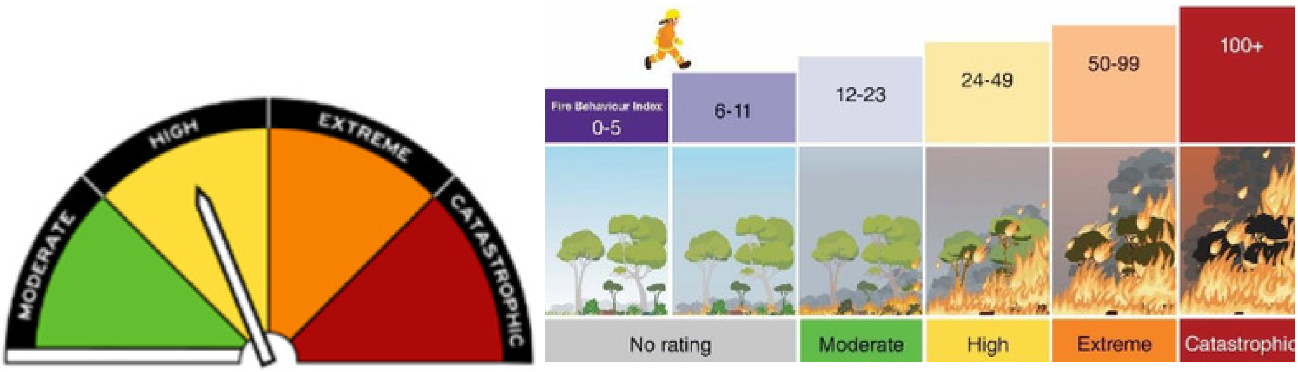

Figure 2. *The Australian Fire Danger Ratings System categories, and the Fire Behaviour Index values that underpin the ratings.*

What is fireline intensity?

For many vegetation types in the AFDRS the dominant fire characteristic that underpins the FBI is fireline intensity, which indicates how intensely a fire is burning along its front. Figure 3 shows the generic components of a fireline intensity model (a type of fire behaviour model) illustrating the dominant effects of weather and climate on fire danger.

The schematic shows that in general, fireline intensity is proportional to the amount of fuel available to burn and how fast it can burn, represented by how fast the fire spreads (Byram, 1959). In technical terms, fireline intensity is the rate heat energy is released per metre across the fire front (Figure 3, red box). It is the product of: the mass of burning vegetation (green box); its calorific value, that is, the amount of heat energy present in the fire fuel (yellow box); and the rate the fire is spreading (orange box). Figure 3 also illustrates how some fireline intensity components are climate-influenced, and others are weather-influenced.

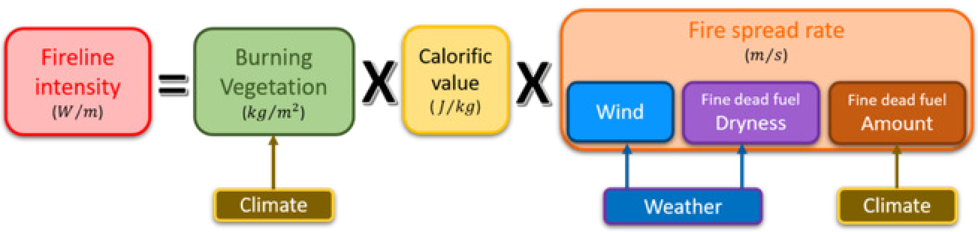

Figure 3: *A schematic of a generic fireline intensity model, a type of fire behaviour model, illustrating the core components, how they fit together and whether they are predominantly weather or climate influenced.*

What is fire spread rate?

The rate the fire spreads depends on how rapidly fuels near the ground ignite. Fuels that rapidly ignite tend to be fine (they have a small cross section) and dead – they are the fuels that 'carry the fire'. There are three main factors (e.g., Cruz et al., 2015) shown in Figure 3 that affect how fast these fine, dead, near-ground fuels ignite: wind speed (blue box), fuel dryness (purple box), and fuel amount (brown box).

What role do weather and climate play and how does this impact fire danger?

Weather can be understood as the atmospheric state at a particular point in time, and climate as the atmospheric state over a longer time period. In the bushfire context, this 'longer time period' could be weeks for grass curing (part of the life cycle of grasslands, where after flowering, the plant dies or becomes dormant and dries out). It could be several seasons or years for the development of drought conditions in forests, or it could be decades to centuries if changing climate causes plant species transition.

Fire behaviour models generally treat the short and long-term atmospheric effects separately. Weather, that is, immediate conditions, affects the wind speed (blue box) and how dry the fine dead fuels are (purple box). Consequently, weather primarily affects fire-danger by modulating the fire spread rate, and thus the *rate* heat energy is released. Climate, that is, longer term conditions, affects the total amount of vegetation available to be burned (green and brown boxes). Consequently, climate affects fire-danger by modulating the *amount* of heat energy that can be released (green box), but also impacts the rate the energy is released through the amount of fine dead fuel (brown box). More fine dead fuel will generally result in a greater fire spread rate.

How does weather affect fire spread rate?

Fires spread when sufficient energy from burning fuel ignites adjacent fuel. The amount of energy required to ignite neighbouring fuel varies with the amount of water in the fuel that needs to be vaporised before it can ignite or catch fire. Fine, dead fuels dry out in dry (low humidity) and windy conditions, especially when exposed to direct sun, which reduces the necessary ignition energy, leading to more rapid ignition and faster fire spread rates. Windy weather causes flames to tilt over towards unburned fuel, increasing the rate energy is transferred from the burning fuel to neighbouring fuel, which also increases ignition and fire spread rates (e.g., Sullivan, 2017).

How does climate affect the amount and flammability of vegetation?

Climatic conditions such as prolonged wet or dry spells lead to different changes. For example, prolonged wet spells may promote vegetation growth, increasing vegetation mass or amount. Prolonged dry spells can lead to vegetation stress, drying out and then dying of vegetation. This not only increases overall flammability (how easy it is for a fire to ignite or start), but the shedding of leaves and twigs adds to the fine dead fuels that 'carry the fire'. Heatwaves may accelerate and exaggerate this process.

For many grasses with shallow roots, this pattern describes typical seasonal cycles of growth and curing (drying out and dying or dormancy), due to short time lags between seasonal precipitation/evaporation cycles and shallow soil moisture. In contrast, due to their deeper roots, vegetation stress in shrublands and forests may be limited to more extreme seasonal cycles, or consecutive dry years.

The limitations of fire-behaviour models in assessing changing fire threat in the future

Changing fire weather and fire climate can be assessed by extracting weather data (for example, temperature, wind speed, humidity) from past observations (historical data) and/or climate models, and then applying these data to the weather and climate functions in fire behaviour models. This approach provides quantitative measures of changing fire weather, fire climate and fire behaviour that can be used to make projections of future fire danger.

However, care needs to be taken when drawing conclusions from projections based on fire behaviour models, as these models were not designed to consider the long-term implications of a changing climate.

Further, weather functions can vary substantially between models, and the climate functions are typically highly simplistic. For both weather and climate, the models are unable to reflect the complex processes and interactions described above.

For example, some older fire-behaviour models, including the FFDI, are commonly used to produce projections of changes in these measures, up to the year 2100. This is often expressed as an increase in the number of 'fire days', that is, days when there is a high likelihood of fire. However, there are key limitations with the index; for example, in some regions, the climate function reaches a maximum value nearly every fire season. This makes it difficult to distinguish potential fire severity between regular and extreme seasons. The FFDI was not designed to capture the longer-term hydroclimate influences, such as those experienced through the Tinderbox drought that preceded the 2019–2020 bushfires. Further, with climate change comes anticipated changes to vegetation type, amount, and dryness. These elements are fundamental to bushfire risk but are not incorporated into projections made based on individual fire behaviour models, such as the FFDI.

The more complex design of the AFDRS does address some of these issues, but solutions to others are still being explored. As a fire danger rating system, it is still providing the best insights we have for immediate-term operational purposes. However, at this point in time, trying to extend its use with climate projections to understand longer-term bushfire risk is challenging as the underpinning fire behaviour models cannot simulate some of the more complex interactions between weather, climate and fire risk.

How is research in this area progressing and what still needs to be done?

To address the issues outlined, significant effort is required to construct more physically realistic and accurate climate functions in fire-behaviour models.

Some progress has been made over the past decade with studies considering new ways to assess drought state or conditions using soil moisture (Vinodkumar & Dharssi, 2019; Vinodkumar, et al., 2021) and vegetation moisture (e.g. Nolan et al., 2018). Other studies have looked at historical observational data and correlated long periods of high evaporation potential with extreme fire events (e.g., Seager et al., 2015). However, these studies only confirm qualitative relationships between drought and fire that apply generally across the landscape, e.g., severe forest fire events are preceded by prolonged dry spells. But fire behaviour models require quantitative relationships between drought state and fire behaviour (e.g., for a specific drought value, the model needs to predict how much fuel is available to burn and how readily it will burn in a range of forest types). This means the most challenging task of converting these learnings into useful climate functions, necessary to improve fire behaviour models, is yet to be achieved.

For more information on understanding and assessing bushfire risk, see this Developing a simple fire-weather index factsheet produced by the Climate Systems Hub.

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