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Indirect effects of climate change on forests and their fires – pitfalls for modellers

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Abstract:

This paper discusses some issues to be considered in assessments of the impact of climate change on forest fires. Climate change modelling typically makes assumptions, often implicitly, about the state of some key elements of fire behaviour being static. These do indeed change, and some changes are significant for climate change impacts.

Data from Black Summer showed that forested sites' weather failed to pass a fuel-drying threshold, implying that active evapotranspiration was in play. This infers that forests are not passive components of the landscape. The same effect was not seen from other weather observation sites in that dataset.

The effect of drought on fire behaviour and fire risk is estimated through one of two commonly used Drought Indices. Both are calibrated by a key, variable, parameter. Those parameters – average annual rainfall for one and forest canopy type for the other - could be altered by climate change, whose effect on Drought Index could have an impact on model results of a similar magnitude to the impact of changes in temperature. The balance of weather and drought impacts is complex.

Forest stand structure affects winds and their effects on flame geometry. The stand structure varies with time after a fire, either planned or unplanned. This can alter both the wind profile within the stand and the geometry of fire behaviour in complex ways.

Thus, if we are to achieve accurate modelling of the impact of climate change on future forest fires, we need to consider how the forest itself may need to be treated as a variable in the models. The effect of climate change on extreme wildfires may not be sensitive to this as those fires are less sensitive to stand characteristics.

***Keywords**:*

Climate change, modelling, forest, drought, wildfire

1. INTRODUCTION

Operational fire spread models treat weather as a fine-scale temporal variable, fuels as a medium-scale temporal variable (typically semi-annual or real-time) and other aspects as long-scale variables, including some set on an as-needs basis, such as amending forest type after clearing or logging. While climate change modelling may use the same indices, the temporal scales need to differ. Weather may be on a coarser temporal scale, fuel loads may lose relevance, and other elements may be held constant or become implicit. This paper addresses issues with the treatment of some of those other elements.

These need to be considered as variables and may have effects on the model outputs of a magnitude comparable to climate change. Unless the balance is optimised, the true scale of climate change's impact on wildfire risks may not be fully elucidated.

Put another way, it is standard practice to consider that a forest stand is the subject of a forest fire. It is typically said to be "adapted" to burning, and a fire is something that happens to it. In this paper I will use widely used indices of forest fire behaviour to explore how aspects of that framework may be wrong.

This paper does not consider the direct impacts of climate change on forest dynamics, rather it addresses how forest dynamics should be considered in climate change modelling.

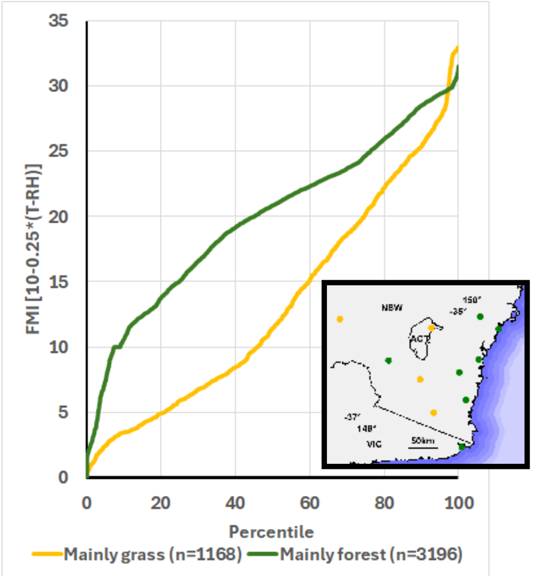

Figure 1. Comparison of the distribution of calculated FMI values for forested and grassland weather observation sites (inset map) across Black Summer. Note how the forest set asymptotically approaches zero.

2. FUEL MOISTURE FROM THE AIR

Fuel moisture from the air is universally described by some function of air temperature (T) and the water content of the air. There is currently some variation in the literature about how these should be described. To discuss this, it is useful to refer to an aerological diagram – the traces of temperature and water content measured as a weather balloon ascends through the profile. As its data are plotted using temperature and height axes, the water content is described by the dewpoint temperature (DP), the temperature to which an air parcel would need to be cooled to become saturated. In rising dry air, T drops by the Dry Adiabatic Lapse Rate of about 10°C per kilometre, while DP rises by about 1.5°C per kilometre. These converging traces meet at the Lifted Condensation Level (LCL) and form an inverted triangle.

On a bad fire day, the triangle will be large. The size of the triangle can be described by mathematical equations or by ecological concepts such as the cloud base height (at the LCL). This is important because while the mathematics of the triangle appear immutable, there is nevertheless a valid possibility that the forest can play a role in deforming the shape of the triangle.

Some literature refers to the Vapour Pressure Deficit (VPD) (e.g. Clarke et al. 2022). T, DP, and the gap between them at any pressure level can all be expressed in degrees Celsius, as g/m^3, or by pressure in hPa. The pressure difference is the VPD. Some meteorological literature refers to Dew Point Depression (DPD) – the gap between T and DP in °C (e.g. Dowdy and Mills, 2012). Most fire literature typically refers to T and

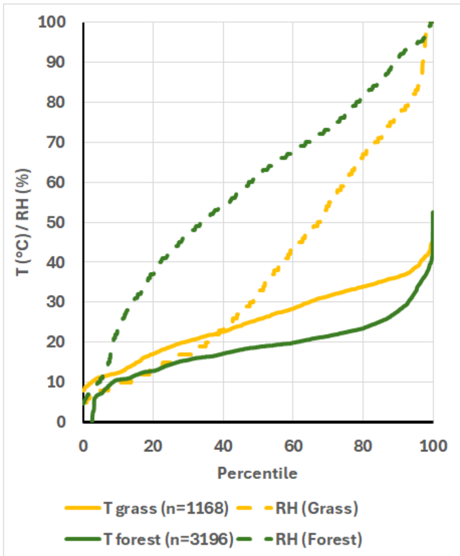

Figure 2. Comparisons of the distributions of observed T & RH values for forested and grassland weather observation sites across Black Summer. Note that the RH lines are similar to those of FMI, while there is a large difference with the T lines. The traces for forest RH and for FMI in Figure 1, have a strong inflection at the 15th. This allows the potential that evapotranspiration may have a role, which becomes stressed at low values.

Relative Humidity (RH). Starting at saturation, with both traces equal, RH roughly halves for every 10 °C difference between T and DP (making it a function of DPD). Importantly, many fire indices use T and RH, and can be directly measured in the field using portable equipment widely used by fire crews. All three describe the size of the triangle, but VPD and f(T, RH) also reflect how far along the T (X) axis the triangle is.

A large set of weather observations from part of the Black Summer fire season was used to examine this. (Data were from Bureau of Meteorology.) This used the simple Fuel Moisture Index (FMI) (Sharples, et al., 2008) [FMI = 10-0.25*(T-RH)]. Roughly put, fire danger is wind speed divided by FMI. So, if (T-RH) nears or exceeds 40 the resulting FMI value loses any real-world meaning, beyond “things are really bad” (which has serious consequence for a forest stand). At that stage it is likely that dynamic fire behaviour would dominate, with different drivers (McRae, 2024),

Figure 1 and Figure 2 show the distribution of the values for observation sites from both forest and grassland settings. Two key deductions arise from these:

Firstly, forest sites have, overall, higher RH and FMI values. With far higher live overall biomass, this could be expected if the biomass is metabolically altering the values.

Secondly, very few sites have any negative values for the FMI function. There is no obvious meteorological reason for (T-RH) not exceeding 40. A reasonable hypothesis is that the vegetation’s metabolic processes are preventing such values. Testing that is outside the scope of this paper.

Of note there are two negative values for forest in this dataset: both corresponded to catastrophically severe fire behaviour. If the hypothesis were true, then it must be assumed that if climate change raises temperatures, then an increasing metabolic effort is required to limit the value of (T-RH). There may be a limit to this effort, beyond which catastrophic fire impacts could jump in frequency.

It must be noted that forest sites were considered unsuitable for agriculture in the past, and this may result in a bias in the result. However, the difference is sufficiently large that there may be multiple factors in play. This requires further investigation.

So, there is some indication that a forest stand is not a passive participant but could be modifying the fire danger through altering an environmental parameter that is involved in fuel moisture, and therefore also in fire danger. The active role is speculative, and needs to be confirmed by further, detailed evapotranspiration studies.

3. FUEL MOISTURE FROM THE SOIL

As a rule of thumb, Forest Fire Danger is a linear function of Drought Factor (DF), which is a measure of how well fine fuel is dried by the soil.

In the Keetch-Byram Drought Index (Keetch & Byram, 1968), rainfall totals for every rain event are used. A rain event is totalled over all contiguous rain days, with the first 5mm ignored as it does not penetrate the soil. The event value is then divided by the Average Annual Rainfall (AAR). A 30mm event in a tropical rainforest will be divided by a large number and will have little impact on the overall drought status, while the same rain on a semi-arid woodland will be divided by a smaller number and

Figure 3. Severe die-back due to drought in an unburnt forest stand, Black Mountain, Canberra, at end of Black Summer. This could have mathematically reduced fire danger using Mount’s SDI, due to reduced canopy interception of rainfall. This canopy condition is what would typically be expected early in recovery after a wildfire. [Photo: McRae]

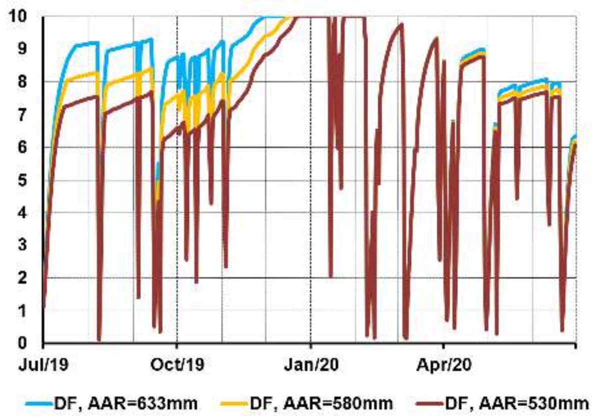

Figure 4. Plots of the effect of varying AAR on a fixed recorded set of annual rain events. There was no difference in the core of Black Summer and little difference afterwards. However large differences in the lead-up may have affected preparedness options.

will have a greater field effect.

Mount's Soil Dryness Index (Mount, 1972) is a widely used alternative Drought Index (DI). It uses canopy intercept classes instead. It is a widespread phenomenon that forest stands are experiencing extreme stress. This can come in many forms: crown fires; insect attack on foliage or bark; root rot fungus; or carbohydrate shortage. In the long term it is expected that through these stressors stands will change their canopy intercept classes (Figure 3), altering the dynamics of DI, DF and fire danger. This has an advantage of being based on field observations.

Canopy class can be assigned in the field or using remote sensing. It is important for administrative decisions on the values to be applied uniformly through all stakeholders' systems.

Meteorology services are tending to keep AAR constant, due to serious difficulties were AAR to become a variable reflecting climate change. So, if we used static AAR, and we took, for example, all rain records for a forested area over year, we could see the year's range of values for DI, and subsequently those for DF and for fire danger. Figure 4 shows this for the 2019/2020 fire year

We can explore what a change to AAR means by a simple analysis. If, for a forested area, we hold all sets of inputs to fire danger (over that year) the same, but only reduce AAR, then the equations reduce DI. Figure 4 shows that during the lead-up to Black Summer there was roughly a 20% reduction of DF (and thus also of fire danger) due to reducing AAR from 633mm to 520mm. A variation of this magnitude makes this worth exploring for its role in climate change studies.

The constant baseline values for AAR may have differing origins. BoM uses Climate Normals which are averages over three decades (1/1/1961 - 31/12/1990). The Global ECMWF Fire Forecast model uses the ERA-Interim protocol (1980-2014 average, Di Giuseppe, et al. 2016).

It must be noted that observations of T are not subject to this issue. Therefore, if climate change were making conditions hotter and drier, the T changes would raise fire danger, while the AAR changes might act to reduce fire danger. Thus, the balance is important and needs assessment on a site-by-site basis.

In principle the same argument applies to SDI, however there is rarely enough scrutiny of canopy class values to support such an analysis. However, an analogous dynamic should be expected.

This would be another case where a forest is an active driver of fire danger.

4. WIND PROFILE

Another key driver of fire impacts in forests is the wind profile under the canopy, which can vary over time.

As biomass burns it produces a flame. A fire can spread when new biomass is contacted by such a flame. The amount of biomass burning at any one time determines the flame length. If wind is driving the flames, they will lean downwind (with, perhaps, a loss of maximum height). By keeping the flames in a single layer for longer, this can increase the amount of biomass involved and make the flames longer – fire intensity goes up.

Figure 5. A hot-burnt stand of Snow Gums, seen 4 years and 11 years post-fire. In between, the eucalypt canopy layers (shown by white lines) have lifted up out of the shrub layer and has formed an initial canopy gap. [Photos: McRae]

There is a balance – more biomass means more flame, but it also means more friction and so lower wind speeds. There may be a disconnect between fire intensity and fire rate of spread.

This argument can be applied separately to ground cover, shrub layer and tree canopy layers. These form a basic structural description of the forest stand. The way the vegetation grows affects the way the vegetation burns.

If climate change causes a change in the forest type over time, then, as noted above, that can change the canopy intercept class, but it also changes the way fire moves through the stand. There is a broad literature on wind profiles and fire (see for example Sutherland et al., 2023 and Hung, et al. 2024). Many sites with open canopies – woodlands – include dense shrub layers which can be particularly important in this respect.

Another dynamic structural feature is the crown gap (Figure 5). This is the space underneath the canopy and above the shrub layers. Resistance to wind moving through the crown gap is weak and primarily comes from tree trunks and main limbs. If wind can enter this space, then it is stronger at flame level. If the canopy is closed, then the winds are reduced at the flames.

It is important to note that stand structures often reflect the impact of hazard reduction burning. These are planned to reduce fine fuel loads but may influence stand structure in ways that alter future wildfire behaviour. In other words, human intervention may alter a stand's dynamics in ways that alter future fire behaviour, doing so in ways that are difficult to predict, and which may be time-dependent. An example of the complexity and non-linearity of stand recovery after fire can be seen at https://www.highfirerisk.com.au/papers/bmf/index.htm

A frequently observed feature of post-fire regeneration in forests of south-east Australia is a tall shrub layer dominated by Fabaceous species, often colloquially called 'Kerosene Bush'. The assumed concept is that these induce more frequent unwanted fire. A more holistic approach allows possibilities like a tall shrub layer keeps the crown gap closed for years longer, preventing certain types of fire spread.

5. RESULTS & CONCLUSIONS

Comparing weather data across Black Summer from observation sites linked to forest and grassland produced different distributions. Forest sites produced higher FMI, with a small handful of exceptions (where catastrophic fire behaviour occurred). While other factors may have been in play, the difference is large enough to indicate that forest might be actively evapo-transpiring moisture, with the effect of moistening fuels and reducing fire danger.

A valid question is whether weather models can account for the effect of forests on FMI. If not, then there are implications for the validity of the outputs. Another allied issue is the use of FFDI across the Australian continent in climate studies. This has been done in a number of papers (see, for example, Dowdy, 2018, Dowdy & Pepler, 2018, Richardson, et al. 2021). Clearly, even if the various equations (AFDR Implementation Team, 2023) could be suitably "rebalanced" the climate change dynamics inferred may still be invalid. A further difficulty for this is the lag-time for changes. A grass sward can adapt to changes on an almost annual basis, while a forest stand may take many decades to reach stability after change.

The equations used for Drought Factor – the input of moisture into fuels from the soil – allow for changes due to climate change. The common indices include changes to average annual rainfall and changes to canopy type. Either can have real impacts on the resulting fire danger values. Both are associated with changes to the forest composition and structure. A drying climate may at times affect fire conditions in a way that reduces fire danger.

An issue that exists only due to administrative decisions is the use of KBDI instead of Mount's SDI as the operational drought model for bushfire. It has long been known that the latter is superior in Australian conditions (Sullivan, 2001). For climate change the canopy intercept value poses challenges. However, AAR is equally challenging. If it were made a variable, the normalisation function would need to reflect the adaptation time of local forest types – a spatial variable.

The dynamics of stand recovery after fire can produce a wide range of potential future fire behaviours. A key element of this is the wind profile across the stand, which affects fire intensity and rate of spread independently. Thus, future fire potential is not just dependent on fuel age and fuel recovery since the last fire. This must have a large impact on planning for fuel reduction burns. Repeat extreme wildfires and climate change may shrink the window for planned burns.

Are these elements in some way optimised or random? It is easy to just assume that the stand structure is what it is for no apparent reason. It is more likely that it is optimised for whatever might influence stand persistence, and thus survival of the species on the stand. If the main risk faced is wildfire, then climate change and ill-informed human intervention may negate that optimisation. After that, a new equilibrium may be difficult to achieve unless subsequent human actions are far better informed. If that is not allowed to happen then climate impacts may be chaotic.

These concepts need to be incorporated into research into climate change's impacts of future wildfire risks and ecological impacts. Nothing in this study states that climate change will not increase risk from wildfires. Those risks are simply more complex than is often stated. Fine fuel moisture, drought factor and inter-stand wind profiles may have little role in Blow-Up Fire Events, and so may have little effect on either the resulting risks from such fires or the effect of climate change on those risks.

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