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Your story
I am an internationally recognised expert in dynamic bushfire behaviour and extreme bushfire development. I am currently Professor of Bushfire Dynamics at the University of New South Wales, where I lead the UNSW Bushfire Research Group. I am also an active member of the Applied and Industrial Mathematics Research Group and the Computational Science Initiative in the School of Science at UNSW Canberra. I have worked in the field of bushfire science since 2006 and have led research projects into various aspects of fire science, fire weather and bushfire risk management since 2011. I am currently the Project Leader of two Australian Research Council Discovery Indigenous projects and a Bushfire and Natural Hazards Cooperative Research Centre project. I am also an invited participant in two international research projects that involve research teams from the United States, Portugal, China and New Zealand. All these projects involve research into various aspects of dynamic fire behaviour, fire-atmosphere

interactions and extreme bushfire development.

I have also been a volunteer firefighter with the ACT Rural Fire Service since 2003 and have been actively involved with firefighter training in the ACT, NSW, Victoria and Tasmania, where I've delivered training to basic and advanced firefighters, crew leaders and fire behaviour analysts. Moreover, I have revised and developed new firefighter training materials for national curricula. I acted as an expert witness at the 2014 Coronial Inquiry into the Wambelong Campground Fire, and during the 2019/20 bushfire season I provided in-house and remote support to the NSW Rural Fire Service.

Terms of Reference (optional)

The Inquiry welcomes submissions that address the particular matters identified in its Terms of Reference.

1.1 Causes and contributing factors
See attached document

1.2 Preparation and planning
See attached document

1.3 Response to bushfires
See attached document

1.4 Any other matters
See attached document

Supporting documents or images

Attach files

- Sharples_NSWIndependent.pdf

Submission to the NSW Independent Bushfire Inquiry

Prepared by:

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Background – scientific expertise

I am an internationally recognised expert in dynamic bushfire behaviour and extreme bushfire development. I am currently Professor of Bushfire Dynamics at the University of New South Wales, where I lead the UNSW Bushfire Research Group. I am also an active member of the Applied and Industrial Mathematics Research Group and the Computational Science Initiative in the School of Science at UNSW Canberra. I have worked in the field of bushfire science since 2006 and have led research projects into various aspects of fire science, fire weather and bushfire risk management since 2011. I am currently the Project Leader of two Australian Research Council Discovery Indigenous projects and a Bushfire and Natural Hazards Cooperative Research Centre project. I am also an invited participant in two international research projects that involve research teams from the United States, Portugal, China and New Zealand. All these projects involve research into various aspects of dynamic fire behaviour, fire-atmosphere interactions and extreme bushfire development.

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1.1 Causes and contributing factors

The major impacts experienced during the 2019/20 bushfire season can be understood in terms of two phases of fire activity. The first phase of fire activity started in late August/early September in southern Queensland and northern NSW (above a latitude of about 33°S) and involved a number of large wind-driven fires. The second phase started in late October/early November and involved very large fires in the forested regions below 33°S. It was in this second phase that the most disastrous impacts arose from a number of fires that episodically escalated into 'extreme bushfires'. The names of these second phase fires are well-known: Currowan, Gospers Mountain, Green Wattle Creek, Dunn's Road, Badja, etc. The causes and contributing factors that are of most relevance to the Inquiry, therefore, are those that led to the most damaging fire events in each of the two phases of fire activity.

Wind-driven fires, foehn winds and isentropic drawdown

In the first phase of fire activity, the combination of strong winds and dry fuels led to the development of several large wind-driven fires. As the name suggests, wind-driven fires largely spread in response to wind speed and direction, and form a typical elliptical shape. However, the severity of these fires was exacerbated by extreme drought – the Bureau of Meteorology rated the rainfall deficiency from April 2018 – January 2020 as 'Severe Deficiency' or 'Lowest on Record' for most of the affected area. In addition, the winds that drove the episodes of significant fire growth in this first phase exhibited foehn characteristics (Sharples et al. 2010). While foehn winds have been recognised as a potential factor in driving the development of large fires, and have been covered in some firefighter training materials, recent research (going back to about 2008) has identified the key processes that drive these winds in eastern Australia and have highlighted areas prone to their effects (Sharples et al. 2010, Fox-Hughes 2015).

Notably, the main mechanism driving foehn winds in eastern Australia was found to be different to the one espoused in existing training resources. Specifically, the main mechanism driving foehn winds in eastern Australia was found to be *isentropic drawdown*. In this mechanism, the low-level air flow upwind of a mountain range is blocked and drier and potentially warmer air aloft is drawn down to replace it on the leeward side of the mountain range. These leads to substantially drier and warmer conditions in the lee of many parts of the Great Dividing Range, and these warmer and drier conditions result in lower fuel moisture contents. In the fires experienced in the first phase of fire activity, this effect combined with the extreme drought produced critically low fuel moisture content, which led to very rapid and extensive fire spread and greatly enhanced the spotting process. As will be described in a later part of my submission, mass spotting involves dynamic fire interactions that can increase fire intensity, even in moderate fuel loads. It was this sort of fire that resulted in the devastation of Rappville, for example.

Extreme bushfires

The second phase of fire activity, which produced most of the fire season's destructive impacts, involved more complex fire development. In particular, the major fire impacts resulted from episodic development of 'extreme bushfires'. Here, the term 'extreme bushfire' refers to the phenomenon defined by Sharples et al. (2016) as: a fire that exhibits deep or widespread flaming in an atmospheric environment conducive to the development of violent pyroconvection, often manifesting as towering pyrocumulus (pyroCu) or pyrocumulonimbus (pyroCb) storms. A distinguishing feature of these types of fires is that they involve a coupling of the fire with the atmosphere well above the mixed layer, which modifies or maintains the fire's propagation (e.g. through mass spotting, blustering winds and lightning).

Fires escalate into extreme bushfires through the occurrence of one or more blow-up events. Blow-up events involve a sudden increase in fireline intensity or rate of spread sufficient to preclude direct control or to upset existing suppression plans (AFAC 2012). Traditionally, fire blow-up has been attributed to a relatively broad set of drivers including strong winds, wind changes, heavy fuels, and upwardly sloping terrain. Recent research, however, has identified several additional specific processes that can contribute to blow-up events – these processes are distinctly dynamic in nature.

Quasi-steady vs dynamic fire behaviour

Traditional approaches to modelling fire spread have focused on observation and prediction of an equilibrium, or quasi-steady, rate of spread; that is, the rate of spread attained by a fire propagating under constant and uniform environmental conditions (fuel, weather, topography) after it has finished its growth phase. Of course, unavoidable variations in environmental conditions will result in fluctuations in the rate of spread of a fire, but these fluctuations are assumed to be relatively small, and to occur around a well-defined average; i.e. the quasi-steady rate of spread. Hence, the traditional fire behaviour modelling paradigm (the dominant paradigm since the 1950s) posits that if environmental conditions are unchanging, then the rate of spread of a bushfire (typically the head fire rate of spread) will also be unchanging. While this quasi-steady assumption is valid for a large proportion of bushfires, there are now many documented cases where the assumption does not hold (Viegas 2005, Sharples et al. 2012, Raposo et al. 2018). In these instances, the rate of spread of the fire can vary significantly, even to the point that no equilibrium exists, despite unchanging environmental conditions. Such behaviour is referred to as *dynamic fire propagation*; the fire's spread is driven not only by the ambient environmental conditions, but also by dynamic interactions between the fire and the atmosphere and even between different parts of the fire itself. Quasi-steady fire behaviour models are manifestly unable to account for dynamic fire propagation.

Dynamic fire propagation and extreme bushfire development

Historically, our understanding of how extreme bushfires develop has been couched mainly in terms of atmospheric drivers. Specifically, this has focused on hot, dry and windy surface meteorological conditions and lower atmospheric conditions. Surface meteorological conditions are typically assessed using the Forest Fire Danger Index ($FFDI$), which was designed to directly relate to the quasi-steady rate of spread of a bushfire; indeed, the quasi-steady rate of spread is given by[1]:

$$R_{qs} = 0.0012 \times w \times FFDI, \quad (1)$$

where w is the fuel load, measured in tonnes per hectare.

In Australia, lower atmospheric conditions are assessed via the continuous Haines (cHaines) index, which combines information on the stability and dryness of the lower atmosphere – less stable and drier conditions are associated with a greater chance of extreme bushfire development.

However, even though extreme bushfires manifest as coupled fire-atmosphere events, there has been much less attention paid to the role played by the dynamics of the fire in driving extreme bushfire development. Recent research has revealed this as a critical oversight. Indeed, McRae et al (2015) demonstrated the link between blow-up fire behaviour and the formation of deep or widespread zones (i.e. 10s to 100s of hectares) of active flaming. While research is still underway to fully understand the physical processes underpinning this association, Badlan et al. (2017, 2019, 2020a, 2020b) have shown that large areas of active flame are more likely to produce plumes that penetrate high into the atmosphere. Plumes that reach high into the atmosphere are then more likely to involve secondary processes such as cloud formation and latent heat release, which can trigger towering pyroCu or pyroCb (i.e. 'fire thunderstorm') development. It was these sorts of bushfire events that were repeatedly reported in the media during the 2019/20 season as "creating their own weather".

Research has identified several likely triggers for the formation of deep flaming. These include previously known factors such as strong winds, wind changes and mass spotting, as well as novel factors: eruptive fire behaviour and vorticity-driven lateral spread (Viegas 2005, Sharples et al. 2012). In addition, deep flaming can arise due to the overzealous, or ill-informed, use of incendiaries.

Notably, eruptive fire behaviour, vorticity-driven lateral spread and mass spotting all involve dynamic fire propagation, and all are highly likely to have played a part in the escalation of the 2019/20 fires into extreme bushfires. Indeed, feedback from the NSW Rural Fire Service confirmed the occurrence of vorticity-driven lateral spread and other dynamic fire behaviours such as junction fires during many of the 2019/20 bushfires (S. Heemstra, NSW RFS, Pers. Comm.).

Vorticity-driven lateral spread (VLS) involves rapid lateral fire propagation across the tops of steep, leeward-facing slopes (Sharples et al. 2012, Simpson et al. 2013, 2016), which has the effect of widening the lateral expanse of the fire. In addition to this, the highly turbulent nature of VLS means that ember production is enhanced, and often results in mass spotting downwind of the lateral spread zone. The dense spot fires so formed then interact, coalesce, and form deep flaming zones (see Figure 1).

Dynamic modes of fire propagation like eruptive fire behaviour and VLS are subject to specific environmental thresholds such as sufficiently strong winds and sufficiently steep terrain. This means that rugged terrain; that is, areas with local topographic relief >300m, is particularly prone to dynamic fire behaviour. This is consistent with recent research findings that extreme bushfires occur almost exclusively in rugged, forested terrain (Di Virgilio et al. 2019), and is also consistent with the spatial

[1] This model for rate of spread is no longer recommended for use in Australian forests; rather, the Dry Eucalypt Forest Fire Model (Cruz et al. 2015) is preferred. However, it is important to note that the Dry Eucalypt Forest Fire Model is still a model for predicting quasi-steady rate of spread.

patterns of the most damaging of the 2019/20 bushfires, which exhibited a high correlation with rugged terrain. This can be clearly seen in Figure 2.

Rugged areas are also typically remote and difficult to access. Hence, when a fire is ignited (almost exclusively by lightning in the 2019/20 fires), initial attack is extremely challenging and dangerous, and is more likely to fail (even with extensive aerial firefighting resources) as these fires escalate quickly due to the action of dynamic modes of fire propagation.

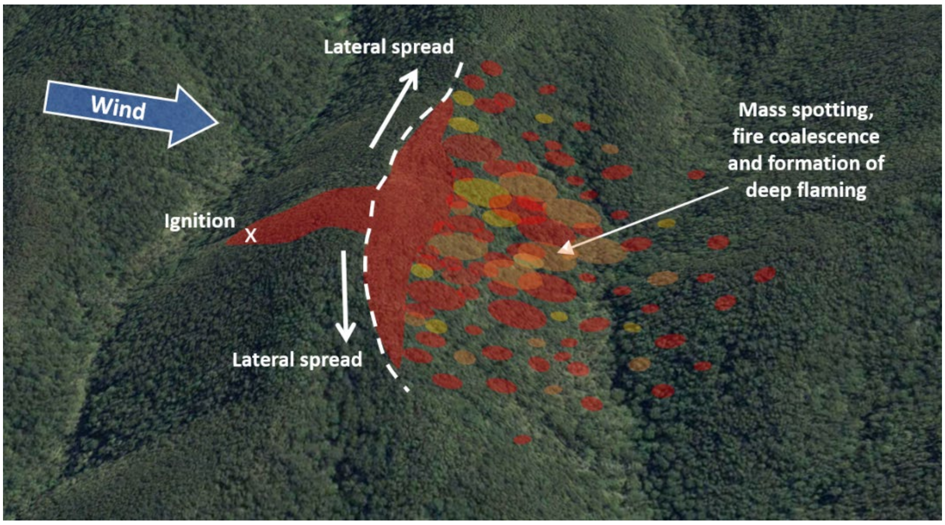

Figure 1. Schematic diagram illustrating VLS and associated downwind spotting, spot-fire coalescence and formation of deep flaming. The fire has ignited mid-slope on a windward facing slope and initially spreads up the slope with the wind. As the fire encounters the ridge line (white dashed line), dynamic fire-atmosphere interactions drive the fire laterally (VLS). The regions of lateral spread act as an enhanced source of embers, which are deposited downwind as a dense ember attack.

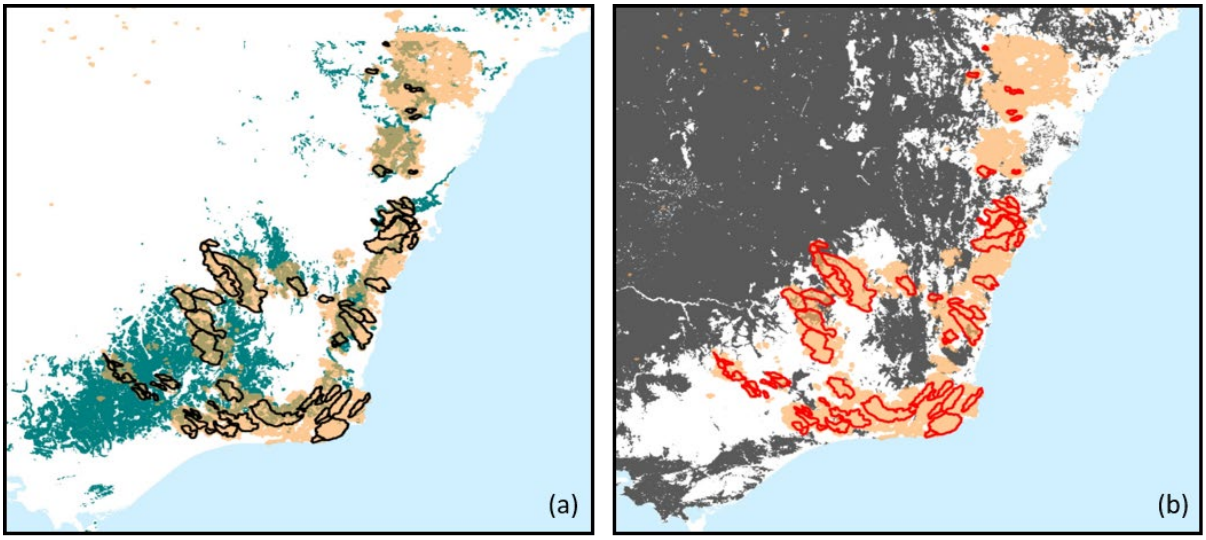

Figure 2. (a) Rugged terrain (green shading) in southeastern Australia. The orange shading represents MODIS Hotspots and the black outlines indicate the extreme/blow-up fires. (b) Forested landscape (white) in southeastern Australia. The orange shading represents MODIS hotspots and the red outlines indicate the extreme/blow-up fires.

PyroCb occurrence

One of the most remarkable features of the 2019/20 fire season was the sheer number of pyrocumulonimbus (pyroCb, or fire thunderstorm) events that were recorded. At the time of writing, there are still several events that are suspected pyroCb events but are still under review. Definitive identification of a pyroCb event requires collation of a number of complementary data feeds and is complicated by the presence of ambient (i.e. non-fire induced) thunderstorm events. It can be difficult to distinguish a pyroCb from an ambient thunderstorm that just happens to form in the vicinity of a major fire. Presently, there is an informal collaboration amongst international scientists (e.g. from NASA, US Naval Research Labs, etc.) known as "the pyroCb group" that identifies, assesses, confirms and catalogues pyroCb events around the world. While the analyses are still incomplete, it is very likely that the majority of unconfirmed pyroCb cases will be confirmed as pyroCb events. Noting this, Figure 3 shows the cumulative total of pyroCb events in southeastern Australia since the start of the satellite record in 1978. There was a 50% jump in the cumulative total of pyroCbs in the 2019/20 season – from 60 at the end of 2018/19, to 89 at the end of 2019/20, hence the number of pyroCb events in the 2019/20 season was absolutely unprecedented.

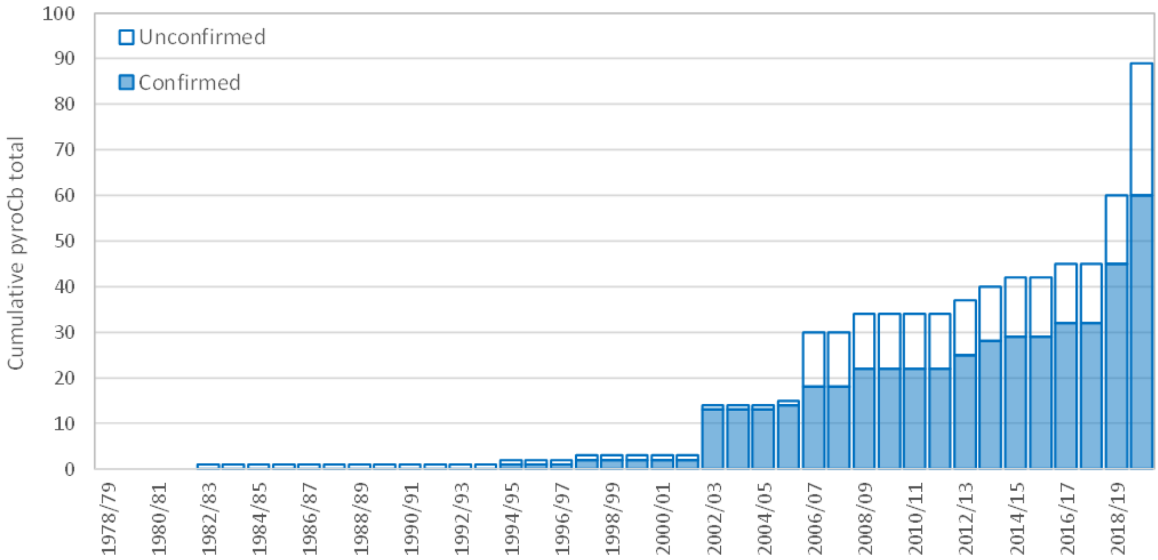

Figure 3. Cumulative total of pyroCb events over southeastern Australia plotted against fire season.

Heat waves and critically low fuel moisture content

As mentioned in my discussion of the first phase of fire activity, the extreme drought primed the landscape with very high levels of fuel availability (i.e. the portion of the fuel below the extinction moisture content). In the grasslands, this led to very low fuel loads, but in the forests die-back led to significant amounts of fully available fuel. Also, as mentioned in my discussion of the first phase of fire activity, the fires were driven by successive episodes of strong foehn-like winds. As pointed out by Sharples et al. (2010), foehn winds are driven by the passage of low-pressure cells across the Great Australian Bight and accompanying trough/frontal systems. These weather systems are well-known to produce heat waves in southeastern Australia as the prefrontal trough funnels hot air from the centre of the continent towards the southeast.

Indeed, another remarkable feature of the 2019/20 season was the number of successive heatwaves associated with prefrontal activity. These resulted in 'Extreme' and 'Catastrophic' fire weather almost on a weekly basis at times during the season. Recent research (yet unpublished) has highlighted the effect that heatwaves occurring in close succession can have on lowering fuel moisture content; particularly that of larger fuel elements designated as '10-hour fuels' (small dead branches).

The effect of fuel moisture content on the development of extreme bushfires can be assessed through consideration of the fuel moisture index (Sharples et al. 2009). The fuel moisture index (FMI) is a dimensionless index defined as follows:

$$FMI = 10 - 0.25 \times (T - RH), \tag{2}$$

where T is the temperature in °C and RH is the relative humidity in %. Previous studies have shown that $FMI < 5$ marks a critical point in the way fires behave, as when $FMI < 5$, the fuels become exceedingly dry so that process like spotting will dominate the propagation of the fire. Formation of deep flaming also becomes much more likely, and so critically low fuel moisture content is a pre-requisite for extreme bushfire development. This is illustrated in Figure 4. Figure 4a shows the daily values of the critical FMI anomaly ($FMI - 5$) at Canberra Airport (broadly representative of conditions during NSW pyroCb events), while Figure 4b shows the same at Omeo (broadly representative of conditions during Victorian pyroCb events). The figure demonstrates that for the 28 pyroCb events shown, 24 (86%) of them occurred on days with $FMI < 5$ while the other 4 occurred on days with $FMI < 6.4$.

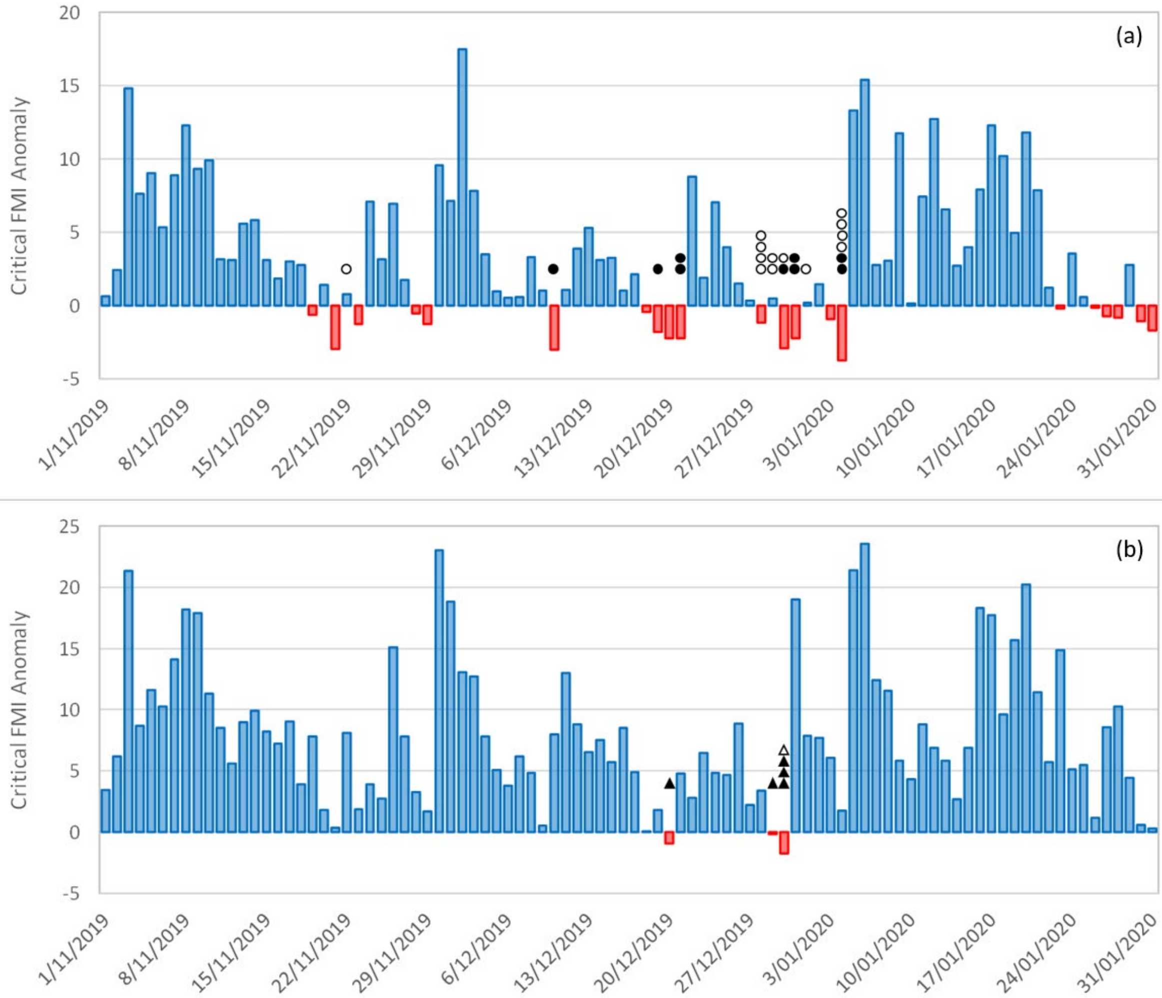

Figure 4. (a) Daily critical FMI anomaly calculated using data from Canberra Airport (negative anomalies are red). The circles represent pyroCb occurrences in NSW – solid circles represent confirmed events and open circles are unconfirmed events. (b) Daily critical FMI anomaly calculated using data from Omeo (negative anomalies are red). The triangles represent pyroCb occurrences in Victoria – solid triangles represent confirmed events and open triangles are unconfirmed events.

This result suggests that critically low fuel moisture content was a necessary condition for extreme bushfire development in the 2019/20 season. This is an example of how very simple indices can be used to provide insights into complex fire development. I note that $FMI < 5$ is currently one of the thresholds used within the Blow-Up Fire Outlook (BUFO) model of McRae and Sharples (2013, 2014). This model was used to successfully predict the blow-up of the 2017 Sir Ivan fire (although this was not reflected in the subsequent Coronial proceedings).

cHaines and atmospheric instability

Unfortunately, due to the short time frame for submissions and the disruption caused by COVID-19, it was not possible to perform analyses of the role of atmospheric instability in the development of the extreme bushfires during the 2019/20 season. No doubt these analyses will be done, and I'm sure some groups have analysed these aspects of the fire environment already. I do know that a number of fires burnt under upper atmospheric conditions that prevented them from developing into pyroCbs. For example, on the day a firefighter was killed near Jingellic, the Green Valley fire only developed into a towering pyroCu, not a pyroCb, due to the presence of a strong convective cap.

It is also clear that many of the pyroCbs formed in pre-frontal environments, which are typically associated with enhanced atmospheric instability, and so it is highly likely that requisite levels of instability were present. There are several open questions about whether the escalation of a fire in association with a cold front is due to the passage of the trough or the passage of the front, which can be separated by several hours. This is an important problem for future research, and the events of 2019/20 will form an extremely useful set of case studies.

Role of fuel load

There has been much said in the media (and the wider community) about the role of fuel loads and hazard reduction in relation to the 2019/20 bushfires. Exasperatingly, a lot of what has been said (even by 'experts') have failed to make the critical distinction between 'ordinary' bushfires and extreme bushfires or bushfires exhibiting dynamic behaviours. This is perhaps symptomatic of the continued influence of the traditional (quasi-steady) fire modelling paradigm on the way the public and some scientists think about fire spread and intensity.

The most common view that has been forwarded is that fire intensity increases quadratically with fuel load, and so reducing fuel loads results brings about a significant reduction in fire intensity. This view is based on quasi-steady principles – like that embodied in equation (1) – and the well-known concept of Byram's fireline intensity, which states that the intensity I of a fire is given by:

$$I = HwR_{qs}, \tag{3}$$

where H is the heat yield of combustion (a constant). Combining equations (1) and (3) gives $I \propto w^2$ for a particular value of the $FFDI$; that is, if the $FFDI$ is held constant, doubling the fuel load quadruples the fire intensity, or alternatively, halving the fuel load leads to a four-fold reduction in intensity.

However, as noted by Dold and Zinoviev (2009) (alluding to earlier work by Albini (1982)), equation (3) is only applicable to the case of a fire spreading in a quasi-steady state. As such, the assumed quadratic relationship between intensity and fuel load should not be considered as valid in general. In particular, the relationship is unlikely to hold for fires burning under extreme conditions and exhibiting dynamic fire behaviour. Indeed, a recent study by Hilton et al. (2017) demonstrated how dynamic interactions between multiple spot-fires can increase fire intensity and lead to significantly higher peak fire power than would have otherwise occurred. Specifically, they found that the coalescence of multiple spot fires can produce fire intensities much higher than what would be produced by a single fire in the same fuel load.

Hence, it is not surprising that in many instances during the 2019/20 season extreme bushfires were seen to propagate essentially unabated over areas than had been subject to hazard reduction burning only a few years prior. I have heard testimony of such from firefighters and helicopter pilots who worked on the fires and observed this myself while working on the Gospers Mountain fire in the NSW State Operations Centre in November 2019. In this case, I was receiving linescan data showing the fire burning intensely through four-year-old fuels – according to the available fuel maps the area had been burnt in a wildfire in 2015. A similar instance can be found in the Werri Berri fire, which burnt through the region burnt in the Yankees Gap fire in September 2018.

In fact, researchers have known for some time that under extreme conditions hazard reduction burning is of diminishing effectiveness in slowing fires. Tolhurst and McCarthy (2016) studied the effects of fuel reduction burning (FRB) on the 2003 Victorian fires and noted that fuel discontinuities created by FRB become substantially less important to the spread of large-scale fires. Moreover, their data showed that when $FFDI > 50$, and particularly when the width of the fire reached 5-10 km, reductions in fire severity due to any recent prescribed burns were minimal. This means that while a previous burn may result in a local reduction in fire intensity, it will have a negligible effect on the overall propagation of a large bushfire. Collins et al. (2019) also found that severe weather conditions and intense drought can overrule the effects of fuel age, with implications for the preservation of wildlife fire refugia.

McCaw (2010) arrived at similar conclusions from his study of the effect of FRB on the behaviour and severity of the 2009 Black Saturday fires. For fires burning under the NW winds prior to the passage of the cold front, there was some indication that the presence of one-year-old fuels reduced the severity of the fire in some case. For example, during the initial stages of the Beechworth fire the presence of one-year-old fuels reduced the fire intensity but did not prevent the fire from spreading further. However, the presence of one-year-old fuels in the Kilmore fire had no effect in reducing fire severity. McCaw noted that since the fuel reduced areas were of a relatively small size (<300 ha), they would have been easily outflanked and breached by spotting. It is worth mentioning that McCaw (2010) did highlight the valuable role that extensive areas of one-year-old fuels played in providing anchor points for fire suppression operations (e.g. back-burning).

In the Bunyip fire, McCaw (2010) found that the presence of four-year-old fuels did not result in any clear amelioration of the behaviour or overall severity of the fire. He also noted that while there was some indication that the severity of the Murrundindi fire was reduced by one-year-old fuels (after the passage of the cold front), they did not prevent the fire from spreading further. Regions of younger fuels (burnt in 2004) also played an important role as anchor points for fire containment operations as the fires burnt under more benign post-frontal conditions.

McRae and Sharples (2015) specifically considered the effect of FRB on extreme bushfires through analysis of MODIS hotspot data. They found that fuel reduction mainly occurred near the edges of forested areas, while extreme bushfires were relatively much more frequent in the interior. Moreover, they found that fuel reduction occurred more frequently in flatter landscapes, while extreme bushfires are most common on rugged landscapes, where they present greater operational challenges. Hence, most extreme bushfires are statistically unlikely to encounter previously burnt areas. McRae and Sharples (2015) further found that where extreme bushfire did encounter previously burnt areas, there was little indication of an interaction.

It is worth noting that the framework developed by McRae and Sharples (2013, 2014) for prediction of extreme bushfires has no explicit role for fuel load, other than acknowledging the generally heavier fuel loads that are associated with rugged forested landscapes. McRae and Sharples (2015) note, however, that more research is required to better understand the role of fuel loads in extreme bushfire development, or to confirm that no such role exists. Nevertheless, the weight of research into the effects of FRB on the propagation of extreme bushfires, indicates that as conditions deteriorate, FRB is of diminishing effectiveness, and may have no appreciable effect under extreme conditions.

Impacts of climate change

Climate change had a clear impact on the 2019/20 fire season in general, and on the development of extreme bushfires in particular. During the 2019/20 bushfire I was a co-author and a leading signatory of the open letter: https://australianbushfiresandclimatechange.com/

The contents of the open letter provide a good summary of how climate change is adversely influencing the drivers of bushfires, including those experienced during the 2019/20 season – there is no need for me to repeat those points here. Sharples et al. (2016), Di Virgilio et al. (2019) and Dowdy and Pepler (2018) provide further details of how climate change is increasing, and will continue to increase, the potential for extreme bushfires. There is no doubt that if climate change continues unabated, then fire seasons will lengthen and become more severe, and the potential for extreme bushfires will increase. The significant increases in pyroCb occurrence in recent years evident in Figure 3, suggests that we are already beginning to see this potential fulfilled.

It is also worth noting recent climate change attribution studies relating to bushfires. Lewis et al. (2019) showed that the high temperatures that contributed to the 2018 Queensland fires were four times more likely due to climate change, while van Oldenborgh et al. (2020) concluded that the extreme conditions experienced during the 2019/20 season were at least 30% more likely due to influence of human caused climate change.

1.2 Preparation and planning

Mitigation of the risks arising from extreme bushfires through fuel management, ignition prevention or response arrangements, must take account of the nature of these fires, and recognise that their drivers differ from those of 'ordinary' bushfires (McRae and Sharples 2015). Dynamic fire propagation, coupled fire-atmosphere effects and massive ember attack present distinct management challenges compared to the majority of bushfires experienced in Australia.

McRae and Sharples (2015) suggest that a more extensive hazard reduction program that produces a larger coverage of hazard reduced areas might be effective. Indeed, there is some indication that extensive areas of very young fuels (1-2 years old) can assist with the suppression of extreme fires, especially as anchor points for fire containment. However, there will be obvious issues with funding and resourcing such an extended program. More targeted hazard reduction burning in remote and rugged areas that produce larger hazard reduced areas in those regions, or that specifically treats terrain that is prone to dynamic modes of fire propagation, might be effective in mitigating the risk from extreme wildfires. Again, the costing and resourcing needs to be addressed, and the perceptions of lower concentration of effort close to life and property could have political ramifications. However, the fact that many extreme bushfires are only stopped after leaving rugged landscapes, suggests there may be no consistently effective fuel treatment for risks related to extreme bushfires in remote and rugged areas.

McRae and Sharples (2015) also suggest that a greater emphasis on ignition prevention may reduce the risk. This risk treatment is limited, however, as it would not affect lightning ignitions, which were the sources of ignition for almost all of the extreme bushfires during the 2019/20 season. Fire agencies could augment their initial response capabilities, with the aim of preventing newly ignited fires from escalating, though budgetary constraints and the logistic challenges of working in remote and rugged terrain may limit this risk treatment.

The general rule arising from the research described above is that a proactive approach to managing the risk of extreme bushfires is necessary – the best time to fight these fires is five years before they start. However, there remain significant gaps in our knowledge about the best way to implement such approaches, and these will need to balance a wide range of often competing values (ecological, cultural, hydrological, public health, etc.).

One possible way of implementing more widespread FRB is to reinstate widespread cultural burning. Small-scale cultural burning programs are already being implemented by some fire management agencies, and it is possible that extension of these programs would ameliorate the risk of extreme bushfires. It must be realised, however, that Country will have changed considerably since colonisation, and that the significant disruption to cultural practices that has occurred across southeast Australia means that reinstating cultural burning to the 'whole-of-society' practice it once was will require care, effort, time and resources.

Of course, climate change complicates the ability for fire managers to prepare and plan for extreme bushfires (or indeed bushfires of any scale). The window of time suitable for prescribed burning in each year is narrowing as a consequence of a warming climate. The climate projections of Di Virgilio et al. (2020) indicated that the number of days suitable for burning in March-May will significantly decrease by 2060-79, although this may be offset by increases in the number of days suitable for burning in the June-August period.

1.3 Response to bushfires

The escalation of a fire to an extreme bushfire requires re-evaluation of the sorts of incident action plans traditionally applied in fire control operations. The dynamic nature of extreme bushfires and the effects of fire-atmosphere interactions make them exceptionally dangerous to firefighters and the community. The death of a firefighter, whose truck was flipped by strong winds in an extreme bushfire (towering pyroCu) near Jingellic on the 30th of December 2019 stands as a tragic case in point.

Extreme bushfires are generally not suppressed while they remain in rugged terrain. However, McRae and Sharples (2015) note that 7 out of 18 extreme bushfires they considered stopped soon after leaving rugged landscapes. This transition corresponds to changes in access, vegetation, FRB intensity and weather-terrain interactions. More research is required to understand the mechanisms at play, but a more comprehensive understanding of these mechanism could be used to improve the likelihood of success of fire control operations.

Regarding the best way to respond to extreme bushfires more generally, my colleagues and I have been advocating of a type of bushfire 'triage'. By this I mean developing improved methods that permit early identification of the fires most likely to develop into extreme wildfires. On a given day there may be hundreds of fires burning across the landscape, and so the ability to identify the ones that are likely to pose the most serious threat allows for more accurate community warnings and more targeted deployment of resources. This was the case with the 2017 Sir Ivan fire, which was identified as the main threat using the BUFO framework of McRae and Sharples (2013, 2014). Having said this, however, the sheer number of fires that developed into extreme bushfires over the course of an afternoon during the 2019/20 season would have undermined the utility of such a system of triage. Again, climate change is likely to confound things further into the future, in this respect.

The question of how firefighting crews should respond in the face of an extreme bushfire is an important one. Once an extreme bushfire has been confirmed or predicted to develop, it is possible to define a broad 'threat footprint'; that is, a region that is likely to be impacted in the next few hours. Based on this threat footprint, firefighting resources should be deployed defensively – essentially, crews should locate defendable assets within the threat footprint and do their best to defend them. Of course, this should be done with crew safety absolutely at front of mind. It

Special consideration must also be given to back-burning operations during extreme bushfires. Given that extreme bushfires develop in association with zones of deep or widespread flaming, the introduction of more fire into the landscape while an extreme bushfire is active can result in further escalation of the event. Note that I listed 'overzealous use of incendiaries' as a trigger for deep flaming earlier in my submission. Moreover, strong pyrogenic winds and other fire-atmosphere interactions can exacerbate the risk associated with back-burning, which is already a very risky practice. As such, back-burning under such extreme conditions can often fail – and fail catastrophically in some cases. Indeed, the fires that impacted Binna Burra, Rappville and Lake Conjola appear to be cases in point.

In large fires, back-burning often presents itself as the only available option for fire control. However, in certain cases it will not be the right option. More research involving fully coupled fire-atmosphere modelling is required to better understand when back-burning is a sensible option, and more training is required to help firefighters understand that back-burning has the potential to do more harm than good.

1.4 Any other matters

Education and Training

Most of the research into extreme bushfires that has been described above has only taken place over the last ten years or so. As such, much of the critical knowledge that has been created has not made its way into formal firefighting education and training materials – this situation needs to be remedied posthaste. I made this same comment in my report to Deputy Coroner Dillon in the Coronial Inquiry into the Wambelong Campground Fire (Sharples 2014). It should be mentioned that certain initiatives are presently underway:

- The Bushfire and Natural Hazards CRC has funded a number of utilisation projects aimed at delivering better education and training resources to the firefighting industry. I am working on one related to VLS and enhanced ember production;
- The Bushfire and Natural Hazards CRC is in the process of developing a 'Fire-pedia' that will provide explanations of many of the concepts relating to dynamic fire behaviour and extreme bushfire development;
- I am co-authoring a book entitled "Extreme Bushfire", a reference for firefighters;
- Discussions with AFAC about how to incorporate the latest research findings into national training modules.

It is important that newly generated training materials form part of a genuinely national firefighting curriculum. Bushfire events of the magnitude experienced in the 2019/20 season require a national response (at least), and so interstate deployment of fire crews is a necessity; indeed, it has become routine practice over the last 10-20 years. A nationally consistent understanding of extreme bushfire concepts is therefore important for a coordinated national response to such events.

Building Standards

Another measure for mitigating the impacts of extreme bushfires is the imposition of a national standard for construction in bushfire prone areas. The current national standard is AS 3959, which stipulates building requirements for a number of Bushfire Attack Levels or BAL ratings, has been criticised by a number of researchers. In AS 3959, the BAL is calculated based on the concept of a 'design fire' and predicated almost entirely on the assumption that the radiant heat from a fire is responsible for burning down houses and other structures. The characteristics of the design fire itself are determined based on quasi-steady fire behavioural principles, and are used to determine a level of radiant heat from a standing flame based on fireline intensity (equation 3), distance of the vegetation from the structure and the local topographic slope. However, in extreme bushfires the bushfire attack mechanism is predominantly ember attack, not radiation from flames. In addition, AS 3959 does not account for the presence of pyrogenic winds that often arise from fire-atmosphere interactions. These winds can often lift tiles, or deform the structure in other ways, which creates openings for ember incursion. As pointed out by Sharples (2017), the current standard AS 3959 is not consistent with the state of the science of extreme bushfires.

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