Fire, Forests and Fauna

(The 2020 Krebs Lecture)

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This is personal perspective on fire in Australia, but I am deeply indebted to my friend and colleague Charley Krebs for suggesting that I deliver his named lecture. I hope that he felt I did his request justice. I thank the University of Canberra for hosting the talk and Denis Saunders and Mike Calver for encouraging me to write this article. Importantly, many of my insights into the effects of, and recovery from, wildfire could not be derived without the benefit of long-term ecological monitoring – something that Charles Krebs is passionate about and something that he has maintained diligently in his extraordinary career. I am deeply indebted to a vast number of people with whom I have had the great good fortune to have worked with over the past 37 years; scientists, statisticians, field ecologists (who are also scientists), field volunteers, and many others too numerous to mention (but are not forgotten). My lecture and this associated paper are dedicated to the memory of the late Marjorie Lindenmayer who lived with great dignity and grace and died the same way.

ABSTRACT

This article discusses some of the key themes on wildfires in forests and their effects on fauna, that I explored in the 2020 Krebs lecture at the University of Canberra. The lecture examined my personal perspectives on such topics as: **(1)** climate change and fire, **(2)** the role of hazard reduction burning in mitigating house loss from wildfires, **(3)** how logging can elevate the risks of high-severity wildfire, **(4)** the ways in which the structure and age of a forest at the time it is burnt has marked impacts on post-fire recovery, **(5)** the ecological damage caused by post-fire (salvage) logging, and **(6)** aspects of post-fire species recovery. Perspectives on these topics are informed largely by long-term work in the wet forests of Victoria and the coastal forests and woodlands in the Jervis Bay Territory and neighbouring southern New South Wales. Some key policy and land management responses to wildfires are outlined, including: **(1)** the urgent need to tackle climate change, **(2)** better targeting of hazard reduction burning close to human infrastructure, **(3)** the removal of conventional logging and post-fire (salvage) logging from native forests, **(4)** the substantial expansion of the old growth forest estate, and **(5)** the establishment of dedicated long-term monitoring to gather the empirical data needed to quantify responses to wildfires.

KEYWORDS: Wildfire, logging, salvage logging, hazard reduction burning, climate change, forest biodiversity, south-eastern Australia

INTRODUCTION

Australia has just experienced an unparalleled (2019-2020) fire season in terms of the extent of areas burned and losses of biodiversity (Boer et al. 2020; Shine 2020). When I was first asked to deliver the 2020 Charles Krebs lecture at the University of Canberra, scheduled for mid-February 2020, I initially framed a talk around landscape transformation and its impacts on biodiversity. I changed tack given the number of public and media requests during the 2019-20 fire catastrophe for scientific information about wildfires, and reworked the lecture to become an overview of some of the key aspects of science of fire. This paper is a brief overview of the key points in that lecture and is arranged around several themes including the importance of climate and weather in fire behaviour, how logging influences fire severity, and critical perspectives on post-fire recovery of biodiversity. The insights in this paper draw heavily on work in our large-scale, long-term work, especially the past ~four decades of research and monitoring in the montane ash forests of the Central Highlands of Victoria and almost two decades of research and monitoring in various vegetation types at Booderee National Park in the Jervis Bay Territory (coastal southern New South Wales). This article is not a comprehensive review of fire science in Australia – that would take entire volumes to write (e.g. Bradstock et al. 2012; Cary et al. 2003; Whelan 1995). Rather, it is a series of personal perspectives on what I consider to be key perspectives on fire sciences and inter-relationships with forest management and biodiversity conservation.

THE DIFFICULTY IN STUDYING FIRE – COMPLEXITY RULES

Fire is arguably one of the most complex topics in ecology and is notoriously difficult to study. There are many reasons for this, but primary amongst them is the array of factors that can influence fire behaviour and fire effects, including post-fire recovery. Such complexity is embodied in the concept of a fire regime (*sensu* Gill 1975; Keeley 2009), that includes (among others), fire severity, fire intensity, fire patchiness, the timing of fire (including seasonality), the number of past fires in an area, and time since the previous fire (Driscoll et al. 2010). Importantly, such complexity will often mean that robust scientific solutions to problems with fire management will be best informed by long-term research and monitoring. This is because insights from not just one fire but many fires in a location will be most instructive for management (Driscoll et al. 2010). Yet, as discussed below, Australia's record on maintaining long-term ecological research and monitoring is nothing short of appalling, with some recent spectacularly short-sighted decisions (Lindenmayer et al. 2017) drastically undermining the accumulation of critical knowledge and understanding about fire.

CLIMATE AND FIRE

Climate and weather are the key drivers of fire behaviour (Luke and McArthur 1977) (Sullivan et al. 2012). It has long been recognised that climate change will significantly increase the risk of more frequent, more intense, more severe, and more extensive wildfires in Australia (Cary et al. 2012; Mackey et al. 2002; Williams et al. 2009). Indeed, most recent global analyses show that Australia is at high risk of a major increase in future fire conditions (Jones et al. 2020). Importantly, there is now good evidence to show that the impacts of fires have been made significantly worse by the effects of climate change, with weather conditions such as long runs of extreme temperatures (that promote wildfire problems) highly unlikely to have occurred in the absence of climate change (Lewis et al. 2020). The fact that 2019 was the driest and hottest year on record in Australia and, at the same time, a period of unprecedented fire extent and impact should be sobering for even the most ardent climate change denialists. Given that the evidence of links between climate change and wildfires are compelling (Jones et al. 2020), discussions about wildfires in Australia (and indeed elsewhere in the world) cannot be divorced from the need to tackle climate change.

Beyond the effects of climate change, other factors can (and do) influence fire behaviour and fire regimes, including hazard reduction burning, and the condition of ecosystems such as forests before and after fire. These topics are the focus of much of the remainder of this article.

HAZARD REDUCTION BURNING

Hazard reduction burning is a key part of management efforts to protect human lives and property. Prescribed burning will have some effect on fire risk reduction for house loss if it is done close to houses and done frequently (Gibbons et al. 2012). That is, the quality (rather than the quantity or sheer spatial extent) of burning is important. Given this, extensive prescribed burning in remote areas will not prevent house loss or damage to infrastructure. Furthermore, as the main driver of fire behaviour is climate and weather (see above), property damage will be inevitable under extreme conditions. For example, extensive house loss and loss of life was apparent at Marysville in the 2009 wildfires even though prescribed burning was completed around the town approximately eight weeks prior to the conflagration on 7 February 2009 (D. Lindenmayer, personal observation).

Simple metrics, such as a target for the area of a jurisdiction to be treated by hazard reduction burning, can have a highly perverse effect. For example, a recommendation from the Royal Commission into the 2009 Black Saturday fires in Victoria was to burn 5% of the State every year. The only way to achieve such a high target was to burn remote areas with limited human infrastructure. Yet, as outlined above, the areas that need to be subject to regular hazard reduction burning are actually those close to human settlements (Gibbons et al. 2012). This kind of perverse application of flawed metrics is well known in many fields (from economics to education as well as fire management) and is called Goodhart's Law. It is most commonly expressed as: "*When a measure becomes a target, it ceases to be a good measure*" (Oxford Reference 2020). Notably, more recently, fire management has switched to risk reduction as opposed to a target-based approach.

Calls for more prescribed burning of recently burned forests are misguided. Many forests, such as those in East Gippsland in north-eastern Victoria, have been subject to up to four fires in the past 25 years –when they should burn no more than once every 50-100 years or even longer (Lindenmayer and Taylor 2020). These ecosystems need less (not more) fire if they are to recover. Some forest ecosystems, such as tall wet forests, sub-tropical rainforests, and southern conifer forests, should not be subject to any prescribed burning, otherwise the ecosystems are at risk of collapse. Repeated fires at short return intervals in these environments take fire regimes outside the bounds of natural variation and undermine the ecological integrity of these ecosystems. Better understanding of this problem demands extensive mapping of appropriate fire regimes for particular ecosystems at local, regional, State and National levels – a key resource which is currently lacking.

Efforts to reduce property damage and loss during wildfires must extend beyond hazard reduction burning. They must include (among others) more considered urban planning with houses not established in highly fire-prone areas, better house design, and clearing of vegetation within 30 m of homes (Cary et al. 2003; Gibbons et al. 2012). There is also a need to ensure that logging is not conducted near rural settlements because harvesting operations can increase the severity of wildfires (see below).

There are useful lessons in the application of fire management that can be gained from exploring indigenous uses of fire (Bowman 2003). However, the notion of indigenous fire management is complex for a wide range of reasons (Perry et al. 2018). First, different First Nations burnt country in different ways and for different purposes, making the selection of which fire regimes to employ context dependent (Bowman 2003). Second, cultural burning was often conducted for reasons other than asset protection and often not to control subsequent wildfires. Third, there have been almost no empirical studies of the effectiveness of cultural burning, especially in south-eastern Australia and western science studies are urgently required, although these must be done in suitably culturally-sensitive partnerships with Traditional Owners. Indeed, there is a need to be careful with the maintenance of intellectual property and the misappropriation of cultural knowledge. Finally, the widespread existence of even-aged forests prior to European settlement shows that extreme wildfires occurred even during the era where indigenous people were the sole land managers of the Australian continent.

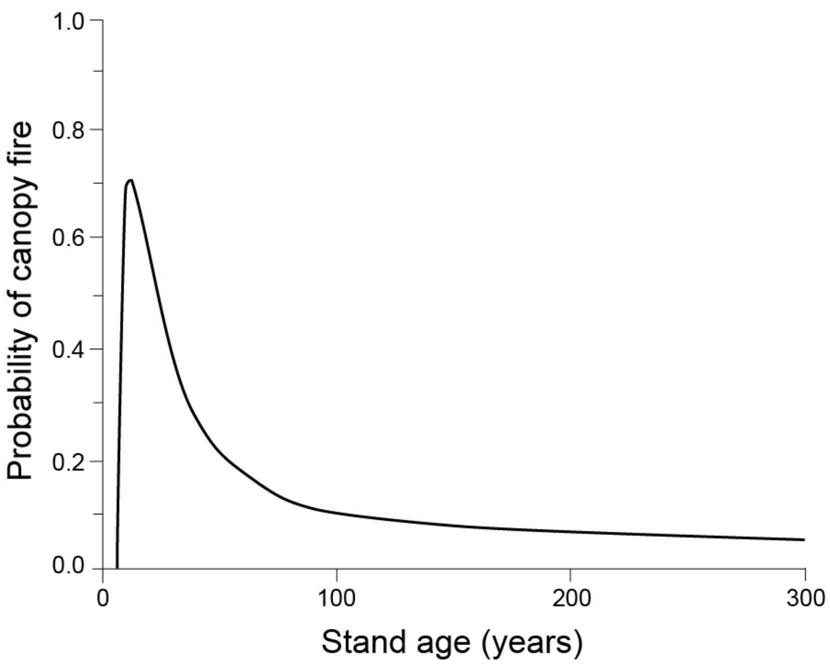
In summary, hazard reduction burning is useful but it needs to be conducted close to human infrastructure and conducted frequently (Gibbons et al. 2012). Many ecosystems do not need more fire (particularly given their recent exposure to fire, including areas subject to several fires in the past 25 years (Lindenmayer and Taylor 2020)). Some ecosystems such as tall wet ash-type forests and rainforests should not be subject to any prescribed fire at all. Australian governments at all levels must invest more in natural resource management agencies so that they can conduct hazard reduction burning in areas where it matters most – that is, close to the peri-urban interface.

BEFORE THE FIRE - LOGGING MAKES FORESTS MORE PRONE TO HIGH SEVERITY FIRE

A series of studies has shown that the severity of wildfires is influenced by the condition of the forest at the time of the fire (Bradstock and Price 2014; Lindenmayer et al. 2009; Taylor et al. 2014; Tiribelli et al. 2018; Winoto-Lewin et al. 2020; Zylstra 2009; Zylstra 2018) . A detailed empirical study after the 2009 Black Saturday wildfires in Victoria showed that logged in wet eucalypt forests that had been regenerated after harvesting were at seven times greater risk of burning at high severity than older, unlogged forests (Taylor et al. 2014). The shape of the fire response curve is based on probit regression analyses fit to point data for 9934 sites (Taylor et al., 2014) and is distinctly non-linear (Taylor et al. 2014) (Figure 1). Therefore, the elevated risk of high severity fire in forests that have been logged and regenerated lasts for more three decades after timber harvesting (Taylor et al. 2014) when forests can be up to 50 m tall and flame heights somewhat higher again.

Notably, recent analyses across a broader part of the 2009 fire footprint have confirmed earlier relationships quantified by (Taylor et al. 2014) between logging history, stand age, and fire severity (Taylor et al., in re-review). These new analyses also indicate that the logging-fire relationships quantified for wet eucalypt forests also extend to drier mixed species forests, demonstrating that the problem is more widespread that previously recognized. Moreover, in north-eastern New South Wales, there is evidence that Gondwanic relict rainforests (which are not logged) are particularly vulnerable to being badly burnt when adjacent areas have been subject to relatively recent logging (Lindenmayer et al. 2020). That is, the effects of elevated fire severity have a spatial contagion dimension in which neighbouring areas can be damaged even though they are exempt from logging (Lindenmayer et al. 2011). For example, pyro-cumulonimbus events can be initiated by large, fast-spreading flames that create a deep-flaming zone. They can develop as a result of crown fires and increased landscape flammability, amplifying the severity of fires (Sharples et al. 2016). Disturbances such as logging increase the likelihood of crown fires and therefore also increase the severity of fire in surrounding, unlogged forest, and promote the formation of pyro-cumulonimbus events (Sharples et al. 2016).

Figure 1. Relationship between the probability of canopy fire and stand age in ash-type forests (modified from Taylor et al. (2014))



There are several likely reasons for elevated fire severity in logged and then regenerated forests. These include: **(1)** The extensive amount of logging slash that is left behind (which contributes to forest fuel). The amount of logging slash after logging can be as high as 450 tonnes per ha (Lindenmayer and Taylor 2018). Some of this is consumed in a subsequent burn lit to promote the regeneration of cutover stands (Lindenmayer and Taylor 2018) but a substantial amount remains in recovering forests. **(2)** The loss of mesic understorey plants such as tree ferns in logged areas (Blair et al. 2016; Ough and Murphy 1996) (which may lead to a drying of the forest, although empirical work is needed to test this premise). And, **(3)** The creation of densely stocked stands created by reseeding after logging. Rapid self-thinning and self-pruning in these stands (e.g. see Cunningham 1960) add significantly to the fine and medium fuels in regrowth forests.

Relationships between logging and subsequent elevated fire severity is controversial and some people have claimed there is no link between forestry operations and fire risk (e.g. Attiwill et al. 2014). However, evidence presented in (Attiwill et al. 2014) actually showed that crown fires had occurred twice as frequently in regrowth when compared to old growth forests. Similarly, (Price and Bradstock 2012) and (Winoto-Lewin et al. 2020) also found that the likelihood of crown fire declined in ash-type forests as they age. Attiwill et al. (2014) have elected to ignore the broader body of evidence on relationships between logging and fire, including data in their own study.

In summary, there is compelling empirical evidence for an interaction between past logging history and subsequent elevated fire severity, with such effects prominent for several decades after harvested stands have been regenerated (Figure 1). Therefore, human disturbance and natural disturbance can interact with one another even though they may occur many years apart (Taylor et al. 2014). In essence, the past history of logging in many

Australian landscapes has created an additional fire burden that will be experienced for many decades to come.

BEFORE THE FIRE - THE EFFECTS OF PRE-FIRE FOREST STRUCTURE ON FIRE BEHAVIOUR AND POST-FIRE RECOVERY

As outlined in the preceding section, the condition of a forest prior to a wildfire can have a profound impact on key aspects of fire regimes such as fire severity. However, the condition of forest, such as stand age at the time of a fire can have other important impacts, particularly through the biological legacies that are left in a recovering forest. Biological legacies are the living and dead components of the original stand (trees, shrubs, seeds, eggs, whole animals) that can be incorporated into new areas of forest regrowing in a burned area (Franklin et al. 2000). The presence of biological legacies can have marked effects on the ability of species to persist in a disturbed area as well as the rate at which species can recolonize such places (Lindenmayer et al. 2019).

The types, prevalence, and diversity of biological legacies in a burned forest are strongly associated with the age of a forest at the time it was disturbed. A fire in an old growth forest will have profoundly different impacts relative to a fire in a young, logged and regenerated forest. Work from the wet ash-type forests in Victoria has shown that the abundance of large old trees is significantly greater in burned old growth forests than in young burned stands (Lindenmayer et al. 2012). In addition, more trees survive fire in old growth stands than when young stands are burned. Similarly, the prevalence of post-fire seedling germination and rate of post-fire animal recolonization is far greater when old forest is burned than when young stands are burned (Lindenmayer et al. 2019). Indeed, some species of arboreal marsupials of conservation concern occur in stands of regrowth forest only if there are biological legacies of previous old growth stands (in this case the large old hollow-bearing trees that are critical denning and nesting sites) (Lindenmayer et al. 2019).

This reinforces the importance of old growth forest for biodiversity, even when (and after) such areas have been burned. However, the rapid and ongoing loss of old growth forest is a major concern. In Victoria there has been a 77% reduction in old growth in the past 25 years (Lindenmayer and Taylor, 2020, in press). The dearth of current old growth forest will significantly impair the recovery potential of a large number of forest-dependent species after future fires (Lindenmayer et al. 2019).

AFTER THE FIRE - THE IMPACTS OF POST-FIRE (SALVAGE) LOGGING

Many forest ecosystems were extensively damaged by the wildfires that occurred in 2019-2020. New South Wales and Victoria have embarked on post-fire logging (sometimes called salvage logging) following the 2019-2020 fires (e.g. VicForests (2020)). Extensive work from around the world (e.g. Hutto et al. 2016; Leverkus et al. 2018; Lindenmayer et al. 2008; Thorn et al. 2018) shows that post-fire logging has major negative impacts on forest ecosystems. Some of the key effects include:

- Bird populations are severely reduced in salvage logged areas (Lindenmayer et al. 2018b).
- Soils remain highly depleted of key soil nutrients for up to 80 years (and possibly longer) (Bowd et al. 2019).
- Plant communities are radically altered, with moist forest elements like tree ferns highly reduced (Blair et al. 2016; Bowd et al. 2018).
- The recovery of natural forest vegetation is impeded (Blair et al. 2016; Bowd et al. 2018).
- Habitat suitability for threatened cavity-dependent mammals is set back by up to 170 years (Lindenmayer and Ough 2006).
- Populations of insects and other key forest biota are detrimentally affected (Leverkus et al. 2018; Thorn et al. 2018).

- Salvage logged and regenerated areas can be prone to further fire (Donato et al. 2006).

Post-fire logging makes no ecological sense in the vast majority of Australia's forest types because many of the overstorey eucalypt trees are not killed by fire and begin resprouting between one and six months after being burned. Logging such recovering systems serves only to impair recovery.

In summary, all available data indicate that post-fire salvage logging is a highly detrimental form of forest logging. Effects are also long lasting. Importantly, populations of some species that may persist in burned areas (including those burned at very high severity and intensity) can subsequently be eliminated from such places if they are subject to salvage logging operations (Blair et al. 2016). Given such negative impacts, there is no place for continued post-fire (salvage) logging in Australian forests. However, a conundrum exists when there are long-term commitments to supply timber under contractual arrangements. Difficult decisions may be required concerning whether to source wood from burnt forests or to log intact (unburnt) forests which may otherwise have acted as refugia for biodiversity. The solution to this problem will be context specific and depend on a number of factors such as how quickly the quality of burnt timber deteriorates, the spatial extent of fire (and hence the size and location of refuges) and opportunities to obtain timber from alternative sources (such as plantations).

SPECIES PERSISTENCE DURING WILDFIRES AND POST-FIRE RECOVERY

The conventional portrayal of fire-damaged areas in the media is of "destroyed" environments. This is undoubtedly and tragically often the case for human infrastructure. However, it is rarely the case for the natural environment. In some cases, entire populations of animals persist in burned areas, even those subject to high intensity and high severity wildfire. For example, at one of our long-term field sites in Victorian Mountain Ash forests, all 15 individual Mountain Brushtail Possums (*Trichosurus cunninghami*) fitted with radio transmitters prior to the 2009 wildfire survived that conflagration (Banks et al. 2011b). Similarly, ecological and genetic research conducted immediately after the 2009 fire in Victorian ash-type forests revealed that small mammals such as the Bush Rat (*Rattus fuscipes*) and Agile Antechinus (*Antechinus agilis*) persisted in many burned areas and these residual populations acted as nodes of population recovery (Banks et al. 2011a). Subsequent work showed that population recovery of the Agile Antechinus and the Bush Rat occurred within two generations and largely through animals that persisted within the boundaries of areas affected by the fire (Banks et al. 2017). Neither the Bush Rat nor the Agile Antechinus was dependent on populations from outside the boundary of the fire for recolonization of the burned areas (Banks et al. 2017).

The responses of the Mountain Brushtail Possum and species of small mammals to the 2009 wildfire in Victorian Mountain Ash forest contrast markedly with those of other taxa such as Critically Endangered Leadbeater's Possum (*Gymnobelideus leadbeateri*) and the Vulnerable Greater Glider (*Petauroides volans*). Populations of both species of arboreal marsupials have declined significantly over the past 20 years (Lindenmayer and Sato 2018), particularly where there has been a large amount of fire in the surrounding landscape (Lindenmayer et al. 2020a). Such declines are continuing more than a decade after the 2009 wildfires, in part because of the loss of nesting and denning sites in large old hollow-bearing trees that are badly damaged or completely consumed by fire (Lindenmayer et al. 2020a) . Declines of animals have been particularly pronounced in regrowth forest where the abundance of hollow-bearing trees is low and rates of collapse of these trees is most rapid relative to old growth stands (Lindenmayer et al. 2018a).

In summary, media descriptions of forests and forest biodiversity as having been destroyed by fire are overly simplistic. Populations of some species persist and then quickly recover in burned areas. Conversely, the notion that Australian ecosystems and their associated biodiversity will quickly return to pre-fire conditions because they are well adapted to fire is also overly optimistic in the context of the legacy effects of human land use and ongoing disturbance, with some species continuing to decline long after wildfires have occurred (Lindenmayer et al. 2020a). Of course, old growth forests subject to stand-replacing wildfires may require centuries to recover (Lindenmayer and Taylor 2020).

TACKLING FIRE PROBLEMS IN AUSTRALIA

This paper has touched on a subset of the perspectives on, and issues associated with, the effects of wildfires on forests and forest biodiversity. Some key, strongly inter-related policy and land management changes are required to deal with the challenges generated by large-scale, widespread wildfires in Australia.

First, Australian State and Commonwealth Governments must deal with climate change. This is because climate and weather are fundamental drivers of fire weather. This is easier said than done because addressing climate change (which is a global issue) requires high levels of international co-operation to catalyze effective action. It is also essential to recognize that solutions to climate change problems have several important dimensions. For example, whilst there has been much focus on bringing down carbon emissions, at the same time there is an urgent need to substantially increase the amount of carbon stored in the land sector, including forests (Keith et al. 2017). Reducing or halting logging of native forests will be an important part of boosting levels of carbon storage – even in the event of recurrent wildfires (because comparatively only limited amounts of carbon within the total carbon stock are lost, even when severe wildfires occur; (see Keith et al. 2014).

If timber can no longer come from native forests, where should be it sourced? The answer in an Australian context is clear – from plantations. In States such as Victoria and New South Wales, almost all the sawn timber (~ 88%) already comes from plantations

(ABARES 2018). Almost all jobs (> 92%) in forest industries also are in the plantation sector (Schirmer et al. 2018). Moreover, in States like Victoria, where 87% of all native forest that is logged is directed into the paper pulp and woodchip streams, it is readily feasible to replace that feedstock with plantation-generated feedstock. Ironically, plantation feedstock is preferred in paper manufacturing. This is because, in part, levels of pulp recovery from plantation timber are higher than from trees cut from native forest. In 2017, Victoria produced 3.9 million tonnes of plantation eucalypt pulp logs but then exported almost three-quarters of this (2.9 million tonnes) for processing overseas (ABARES 2018). The reality is that plantation eucalypt pulp logs could readily be processed in Victoria to make paper, thereby obviating the need to cut trees from native forests to manufacture the same product (i.e. paper). Native forests could then be managed for the best and highest economic values such as carbon storage, water production and tourism (see the accounting work by Keith et al. 2017).

Second, reducing fire risks requires removing logging from native forests because such operations significantly increase the risks of high-severity conflagrations (Attiwill et al. 2014; Bradstock and Price 2014; Taylor et al. 2014; Winoto-Lewin et al. 2020) . The long-term objective of such an action would be to remove the additional fire burden that arises from logging. This heightened risk currently threatens Australian rural communities and landscapes and will continue to do so for many decades to come. Given that the protection of human lives is of paramount importance, logging near rural and regional settlements is no longer acceptable. Native forests must be protected from post-fire salvage logging because of the highly detrimental impacts that it has on forest ecosystems, and the increased risk of future fire that it engenders. Indeed, the term “salvage” is a misnomer given that little is being “saved” or “recovered”. Rather, ecosystems are being badly damaged and recovery is impaired.

Third, land management agencies must work harder to significantly expand the old growth forest estate. This is critical for several reasons: **(1)** Old growth forest is where fire severity is lowest (Lindenmayer et al. 2020b; Taylor et al. 2014; Winoto-Lewin et al. 2020; Zylstra 2018). **(2)** The old growth forest estate has declined dramatically in recent decades (Lindenmayer and Taylor 2020) and this will have major negative impacts on biodiversity, including after wildfire (through a scarcity of key biological legacies such as large burned trees). And, **(3)** Old growth is where the most carbon is stored in forest landscapes (Keith et al. 2009) and thus where efforts to tackle climate change will be most effective. Expanding the old growth estate will be particularly challenging given the climatic conditions that have led to increased risks of frequent, large-scale wildfires. However, some targeted actions can be taken such as to protect key parts of landscapes with particular environmental and other attributes where old growth forests are most likely to develop (e.g. see Mackey et al. 2002).

Of course, the three recommendations listed above are strongly inter-related as removing logging would result in more old growth and, in turn, less severe fire and well as greater carbon storage (that is central to addressing concerns about climate change).

Fourth, prescribed burning is a key part of efforts to limit the impacts of wildfires on human life and property, although under extreme conditions it may have limited effect and result in limited levels of risk reduction. The "window" in which to conduct prescribed burning is increasingly limited as the length of fire seasons are expanding – a problem that has been recognized for many decades (see Whelan 1995). Therefore, it is essential that prescribed burning is as effective as possible where and when it is practiced. As indicated by Gibbons et al. (2012), this will be in such places as peri-urban areas that are close to human infrastructure.

Fifth, understanding the effects of, and recovery from, wildfires demands long-term monitoring information (Lindenmayer et al. 2012). This is essential to determine impacts from a sequence of multiple fires in a given region and/or ecosystem. Long-term work is also essential for understanding how to best mitigate fire effects (Driscoll et al. 2010; Lindenmayer and Likens 2018). Australia currently has limited capacity to adequately quantify bushfire risks. However, it has inexplicably further reduced capacity because the long-term ecological monitoring network was axed in 2017 (Lindenmayer and al. 2017). Without long-term data, Australia will have no predictive capability to forecast the impacts of fire on any aspect of the environment (Lindenmayer 2018). The costs of maintaining an effective long-term ecological research network is ~ $1.5m per annum. This is a small fraction of the estimated $100 billion that the 2019-2020 wildfires have cost the Australian economy (https://edition.cnn.com/2020/01/10/perspectives/australia-fires-cost/index.html).

CONCLUSIONS

This paper is based on a series of personal perspectives as they were presented in the 2020 Krebs Lecture at the University of Canberra. These perspectives make it clear that the impacts of, and recovery from, fire are far more complex than portrayed in the media. Beyond climate and weather, several aspects of fire dynamics in forests can be influenced by conditions prior to a fire (such as the age of a forest at the time of a fire and whether it has been logged), and what occurs after fire (e.g. whether salvage logging takes place). The widespread loss of old growth forests is likely having substantial impacts on fire behaviour in some ecosystems. Young forests are more flammable and more prone to high severity fire than old forests. Indeed, the legacy of past forest management that has replaced old forest with young stands will be felt as an increased fire burden for many decades to come. Finally, improved understanding of wildfire in Australia requires long-term empirical field data, but the nation no longer has the environmental infrastructure to facilitate the collection of such data. This problem is easily rectified with a limited investment that will yield a major and crucial return.

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This is personal perspective on fire in Australia, but I am deeply indebted to my friend and colleague Charley Krebs for suggesting that I deliver his named lecture. I hope that he felt I did his request justice. I thank the University of Canberra for hosting the talk and Denis Saunders and Mike Calver for encouraging me to write this article. Importantly, many of my insights into the effects of, and recovery from, wildfire could not be derived without the benefit of long-term ecological monitoring – something that Charles Krebs is passionate about and something that he has maintained diligently in his extraordinary career. I am deeply indebted to a vast number of people with whom I have had the great good fortune to have worked with over the past 37 years; scientists, statisticians, field ecologists (who are also scientists), field volunteers, and many others too numerous to mention (but are not forgotten). My lecture and this associated paper are dedicated to the memory of the late Marjorie Lindenmayer who lived with great dignity and grace and died the same way.

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