Ten years on – a decade of intensive biodiversity research after the 2009 Black Saturday wildfires in Victoria's Mountain Ash forest

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ABSTRACT

The catastrophic 2009 wildfires in the Mountain Ash (*Eucalyptus regnans*) forests of the Central Highl&s of Victoria provided an opportunity to gain new insights into the responses to fire by various elements of the biota. Ongoing long-term monitoring at a large number of permanent field sites for up to 25 years prior to the fire, together with 10 years of post-fire monitoring, has provided an unparalleled series of datasets on mammal, bird, & plant responses on burned & unburned sites. The empirical studies briefly summarized in this paper show patterns of steep declines in large old trees & declines in site occupancy by arboreal marsupials & birds. These changes contrast markedly with the responses of the two most common species of small mammals (the Agile Antechinus [*Antechinus agilis*] & Bush Rat [*Rattus fuscipes*]), which recovered within two generations after the fire. Declines in arboreal marsupials, birds & large old trees have also occurred on unburned sites, indicating an ecosystem-wide trend. In general, logging had a greater impact than fire on the majority of groups of birds & plants, particularly post-fire salvage logging that occurred in some areas following the 2009 wildfires. Beyond interactions between fire & post-fire (salvage) logging & their effects on forest biota, we have uncovered evidence of other kinds of interactions in Mountain Ash forests. These include interactions between: **(1)** the severity of fires & logging history, **(2)** post-fire bird population recovery & long-term climate & short-term weather conditions, & **(3)** impacts on forest soils. The structure & l&scape composition of the Mountain Ash ecosystem has been radically altered over the last century. This has resulted from the combined impact of several large fires, including the 2009 fires as well as widespread clearfell logging that has been conducted within state forests over the last 50 years. The ecosystem now supports old growth cover that is 1/30th to 1/60th of what it was estimated to have been prior to European settlement. The ongoing decline of key components of the Mountain Ash ecosystem has led to it being classified as Critically Endangered & at high risk of ecosystem collapse. We argue that current forest policy & practices need to better mitigate the effects of fire on this already highly disturbed forest & enhance the possible persistence of species in this ecosystem. Several key strategies are required to do this. First, there is a need to significantly exp& the extent of old growth within the Mountain Ash forest estate. This is because fire severity is diminished in such areas. Spatial contagion across old-growth dominated l&scapes also may be suppressed relative to l&scapes composed primarily of young forest. Allied management strategies include the protection of more mesic parts of Mountain Ash l&scapes as these are less likely to burn or at least burn at high severity. Such enhanced protection should include an exp&ed network of buffers around drainage lines & waterways as these are where fire severity is likely to be lowest & also where old growth elements like large old hollow-bearing trees are more abundant. In addition, all existing living & dead hollow-bearing trees need to be protected by buffers of unlogged forest within wood production forests to promote their st&ing life & better conserve cavity-dependent fauna such as the Critically Endangered Leadbeater's Possum (*Gymnobelideus leadbeateri*) & other declining taxa like the Greater Glider (*Petauroides volans*).

Key Words: Ecosystem collapse, long-term monitoring, hollow-bearing trees, wildfire, logging, biodiversity conservation, Leadbeater's Possum, forest policy.

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INTRODUCTION

The February 2009 Victorian Black Saturday fires were the most destructive in Australian history in terms of loss of human life and property (Gibbons *et al.* 2012). These fires burned 78 300 ha of 157 000 ha of Mountain Ash (*Eucalyptus regnans*) forest in the Central Highlands of Victoria.

At the time of the 2009 fires, we had already conducted 25 years of pre-fire research in these forests (Lindenmayer 2009a) and have continued to monitor their recovery thereafter. Intensive and extensive pre-fire and post-fire research, including ongoing research in unburned areas, logged and unlogged areas has provided an unprecedented opportunity for learning about key aspects of fire ecology, forest management and biodiversity conservation in the ten years since Black Saturday. In this paper, we provide an overview of some of the insights from work completed in the past decade, primarily as they relate to biodiversity conservation and forest ecosystem process. We aim to bring together key findings from published and recently gathered information that are relevance to aspects of forest management that can influence the abundance and persistence of biodiversity, either directly or indirectly. Such a synthesis is timely given current Victorian Government plans to modernize forest management policies like those associated with the Regional Forest Agreement for the Central Highlands of Victoria (Government of Victoria and Commonwealth of Australia 1997).

THE 2009 FIRE

The February 2009 wildfires were the most damaging fires in Australian history in terms of loss of human life and property (Gibbons *et al.* 2012) but also burned extensive areas of Mountain Ash forest. The severity of these fires in Mountain Ash forest varied substantially, with some areas remaining unburned, others subject to moderate severity fire, and some fire-affected areas reputed to have experienced among the most intense fires ever recorded, reaching 88,000 kW/m (Cruz *et al.* 2012). In addition, the effects of the fires varied spatially, with some landscapes almost completely burned, whereas others experienced either patchy fire or no fire (Lindenmayer *et al.* 2015).

SUMMARY OF KEY FINDINGS

Since beginning our research in 1983, we have established more than 180 long-term monitoring sites across the range of ecological conditions that characterize the Central Highlands region. These sites encompass both wood production forests (49% of sites) and ecological reserves (51% of sites), including those in closed water catchments where logging operations have been excluded. Of the sites, 16.6% were burned at high severity in 2009, where the Mountain Ash overstorey was killed by canopy scorch or consumption. A similar number (17.1% of sites) were burned at moderate or low severity. A total of 53.6% of the sites were unburned. The remaining 12.7% burned at variable severity, with the majority of these being unburned/low severity burned.

Time series data on various groups of biodiversity, vegetation structure and plant species composition provided the empirical datasets for a large number of different and often multi-faceted analyses of post-fire responses with many of these studies published in the international peer-reviewed scientific literature. These long-term monitoring studies have been supplemented with an array of other inter-related investigations, including true experiments, natural experiments and observational studies (*sensu* Cunningham and Lindenmayer 2016).

Responses of arboreal marsupials

Analyses of time series data has indicated a strong decline in populations of arboreal marsupials in Mountain Ash forests. Levels of site occupancy by Leadbeater's Possum have declined by 50% since 1997 (Blair *et al.* 2018; Lindenmayer and Sato 2018). More substantial declines have been documented for the Greater Glider for which levels of site occupancy in 2017 were more than 80% lower than in 1997 (Lindenmayer and Sato 2018). The extent of declines have been pronounced on sites burned in the 2009 fire (Lindenmayer *et al.* 2013), but are also occurring on unburned sites, particularly where there has been a marked reduction in the number of large old hollow-bearing trees (which are nest and denning sites for arboreal marsupials). Declines of arboreal marsupials have occurred in both wood production forests as well as in ecological reserves.

Surveys since the fires of 2009 indicate that many of our long-term monitoring sites where species such as Leadbeater's Possum previously occurred are no longer occupied. In some cases, this is likely due to the direct effects of fire, whereas in other it is likely due to deteriorating habitat quality and the loss of hollow-bearing trees. Prior to the 2009 fires, 73 of 164 long term monitoring sites had been occupied by Leadbeater's Possum, while in the ten years since (with all sites having been surveyed a minimum of two times), 38% of those sites (28 sites) have supported Leadbeater's Possum. Of the 73 sites that had Leadbeater's Possum at some time in the past, 48 remained unburnt following the 2009 fires. (Lindenmayer *et al.*, unpublished data). These sites have typically been subject to rapid rates of loss of large old trees, (Lindenmayer *et al.* 2016; 2018a; 2018b). Ongoing declines in populations of hollow-bearing trees, coupled with the very limited recruitment of these trees (see below), will likely drive further marked declines in site occupancy by arboreal marsupials in the coming decades (Blair *et al.* 2018).

Population Viability Analyses indicate that the existing reserve system for Leadbeater's Possum and other species of arboreal marsupials is insufficient to ensure their persistence in the medium to long term, particularly in the advent of additional fires in the Central Highlands region (Todd *et al.* 2016; Taylor *et al.* 2017). The analyses by Todd *et al.* (2016) and Taylor *et al.* (2017) both indicate the protection of substantial additional areas of Mountain Ash forest will be required to adequately protect populations of arboreal marsupials.

Insights from a long-term study of the Mountain Brushtail Possum (*Trichosurus cunninghami*) at Cambarville showed that, as a single fire, the Black Saturday conflagration had a relatively small effect on the survival and abundance of this large and long-lived possum that dens in hollows within large Mountain Ash trees. In fact, the impacts of fire on mortality were lower in magnitude than the effects of rainfall variability over 22 years of research (Banks *et al.* 2015). However, the abundance of this species is closely linked to the availability of hollow-bearing trees and our research showed that the dead or previously fire-damaged trees favoured as dens by this species were particularly prone to collapse after the 2009 fires (Banks *et al.* 2013). Therefore, the inter-related impacts of climate change on rainfall and fire frequency may affect this species through lower resource availability and survival rates under future climate scenarios. Our research to date indicates that topographic climate and fire refuges play an important role in buffering populations against climatic variability and fire and these parts of the landscape will become increasingly important for species persistence in the future (Berry *et al.* 2015). These climate and fire refuges (termed 'ecosystem greenspots'; Mackey *et al.* 2012) should be protected from logging or other human disturbance.

Responses of small terrestrial mammals

The small ground-dwelling mammal assemblage inhabiting Mountain Ash forests is relatively species poor, but three species in particular can be extremely abundant – the Bush Rat (*Rattus fuscipes*), Agile Antechinus (*Antechinus agilis*), and Dusky Antechinus (*Antechinus swainsonii*) (Cunningham *et al.* 2005). Ecological and genetic research conducted immediately post the 2009 fire revealed that these species can persist in burned areas, including those subject to very high severity fire. These residual populations acted as nodes of population recovery (Banks *et al.* 2011). Subsequent work showed that population recovery of the Agile Antechinus and the Bush Rat occurred within two generations. The local persistence and recovery of the Bush Rat was associated with minimum vegetation cover within drainage lines in burned forest. In the case of the Agile Antechinus recovery was largely through animals that persisted within the boundaries of areas affected by the fire (Banks *et al.* 2017). Therefore, neither species was dependent on populations from outside the boundary of the fire for recolonization of the burned areas.

Responses of birds

The 2009 wildfires have had marked negative effects on forest birds, with levels of site occupancy by many species being significantly depressed relative to both pre-fire levels and on unburned sites (Lindenmayer *et al.* 2014b). Only one species – the Flame Robin – has responded in a significant positive way to the effects of fire with numbers of birds far higher on sites subject to high severity fire relative to other parts of Mountain Ash landscapes, including unburned stands (Lindenmayer *et al.* 2014b). More recent analyses have suggested that many (24 of 49 modelled species) are not showing signs of post-fire recovery, with most continuing to decline (Lindenmayer and Sato 2018; Lindenmayer *et al.* unpublished data).

The combined effects of fire and logging (i.e. salvage logging) are particularly marked for the avifauna in Mountain Ash forests, with overall bird species richness on salvage logged sites typically half that of unburned areas (Lindenmayer *et al.* 2018c). Bird species richness on salvage logged areas is also significantly less than forests subject to conventional clearfelling operations (Lindenmayer *et al.* 2018c). The extent of declines in some bird species extend well beyond burned sites to encompass areas remaining unburned (Lindenmayer *et al.* 2014b). Such patterns of temporal change are associated with factors such as the amount of burned or logged forest in the surrounding landscape (Lindenmayer *et al.* 2014b; unpublished data) as well as long-term climate and short-term weather conditions in Mountain Ash forests (Lindenmayer *et al.*, unpublished data).

Responses of large old hollow-bearing trees

Large old hollow-bearing trees are a key component of stand structure in Mountain Ash forests. They are an essential habitat resource for a range of cavity-dependent fauna. They also store large amounts of carbon (Keith *et al.* 2009). Stands of old growth (where large old hollow-bearing trees are most abundant (Lindenmayer *et al.* 2000b)) play key roles in the water cycle (Vertessy *et al.* 2001).

A population of 1129 large old trees has been monitored since 1997 and the extent of decline has been substantial during this time. Between 1997 and 2015, on unburned sites we found 84.8% of hollow-bearing trees had deteriorated in condition and in areas affected by the 2009 fires, we measured a decline in condition of 96.1% of hollow-bearing trees. Of great concern was prevalence of trees that completely collapsed, rendering them unable to support arboreal marsupials. In the same period, 41% of hollow-bearing trees that were standing in 1997 had collapsed by 2015. Since 1997, hollow-bearing tree density on our long term monitoring sites has declined from a median of seven (average of 8.4) hollow-bearing trees per hectare to a current median of two (average 4.6) hollow-bearing trees per hectare. This has meant that many sites have no or very few hollow-bearing trees. As of 2019, there are no hollow-bearing trees on almost 18% of sites with 47% of sites supporting two or fewer large old hollow-bearing trees (Lindenmayer *et al.* unpublished data).

Our initial surveys in 1997 focused on standing large old hollow-bearing trees and by 2015 a total of 57% of these trees had collapsed on sites where the surrounding forest was young (< 30 years old). The corresponding values for old growth stands was 16% (Lindenmayer *et al.* 2016).

The 98.8% of the Mountain Ash forest estate which is 120 years or younger is where rates of decline in condition and rate of tree collapse are fastest (Lindenmayer *et al.* 2016). Rates of decline are also elevated on sites with increasing amounts of logging and fire in the surrounding landscape (Lindenmayer *et al.* 2018b). During the past two decades of monitoring, there has been extremely limited recruitment of new hollow-bearing trees on our long-term sites (Lindenmayer *et al.* 2012b; Lindenmayer *et al.* unpublished data).

The ecosystem-wide decline in populations of hollow-bearing trees appears to be associated with at least three factors. First, as outlined above, tree fall has been considerable on sites subject to fire (Lindenmayer *et al.* 2012a) as well as in places where large parts of the surrounding landscape have been burned and/or logged (Lindenmayer *et al.* 2018b). Second, climate appears to be having an impact of tree mortality; more than 25% of living large old hollow-bearing trees on unburned sites died between 1997 and 2015 (Lindenmayer *et al.* 2018a). Third, rates of deterioration and collapse of large old trees are significantly elevated in young logged and regenerated forests (Lindenmayer *et al.* 2016; 2018b) that are increasingly common and widespread throughout Mountain Ash landscapes.

Responses of other plants

We have explored the responses of plants in the Mountain Ash ecosystem to the 2009 wildfires in a number of studies (e.g. Pharo *et al.* 2013; Smith *et al.* 2014; Blair *et al.* 2016; Smith *et al.* 2016; Blair *et al.* 2017b; Bowd *et al.* 2018).

In the first year after high severity fire, regenerating Mountain Ash seedlings were found to be more numerous under burned old growth stands with fewer than 50 trees/ha than under 70 years or younger regrowth with 300 trees/ha (Smith *et al.* 2014). We also found that the density of natural regeneration diminished at lower elevations relative to stands located in cooler and higher elevation (Smith *et al.* 2016). These patterns are possibly as a result of changes to an increasingly drier and warmer climate, and are consistent with modelling indicating that such responses will become common over the next 50+ years (Mok *et al.* 2012). However, Mountain Ash forests undergo significant natural self-thinning (Florence 1996) and the long-term impacts of reduced regeneration on stand density remain unclear.

In our studies comparing forest recovery after fire and logging, we found important differences in the abilities of plants to regenerate. We found that plants which recover by re-sprouting (including most of the ferns and midstorey trees) were significantly less common in conventional clearfelled and salvage logged areas than in forests burned by wildfire (Blair *et al.* 2016; Bowd *et al.* 2018). This can be explained by the combination of physical disturbance from logging machinery (which can destroy plant resprouting structures), and pre-logging wildfire or post-logging 'slash' burning in which fires are deliberately lit to consume slash remaining after timber harvesting (Blair *et al.* 2016; Bowd *et al.* 2018). Furthermore, salvage logging had the greatest impact on forest composition with salvaged stands being greatly simplified relative to conventionally clearfelled areas as well as stands burned but not logged (Blair *et al.* 2016).

In other vegetation studies, bryophytes were heavily impacted by high severity fire whereas refuges in low severity burnt areas retained most species (Pharo *et al.* 2013). We also found that tree ferns had non-linear growth rates after the 2009 wildfire. Taller tree ferns exhibited the greatest rates of growth in height over the five year study. The reasons for these results remain unclear, but a plausible explanation was shading of tree ferns (which were up to 6m tall) as dense canopy trees regenerated (Blair *et al.* 2017b).

Landscape structure and old growth extent

The 2009 wildfires have contributed to major changes in the age class composition of Mountain Ash forest landscapes. These fires, coupled with earlier conflagrations over the past century, as well as extensive past logging operations, have resulted in the loss of large amounts of old growth forest with just 1.16% of the forest estate now older than 120 years (Lindenmayer *et al.* 2012a). Historically, the extent of old growth forest was estimated to comprise 30-60% of the ecosystem (Lindenmayer and McCarthy 2002).

The extent of old growth forest matters for a range of reasons. First, old growth is where populations of some key species such as the Greater Glider and Yellow-bellied Glider (*Petaurus australis*) are highest (Lindenmayer *et al.* 1990; 1999). Second, old growth forests support the greatest abundance of large old hollow-bearing trees (Lindenmayer *et al.* 2000a) which are a key limiting resource for many species of cavity-dependent fauna in Mountain Ash forests. Third, as outlined above, rates of decay and collapse of hollow-bearing trees are slowest in old growth forests (Lindenmayer *et al.* 2018a) and hence these areas are increasingly important habitat refugia for cavity-dependent fauna. Fourth, fire severity is lowest in old growth forests (Taylor *et al.* 2014) and hence such stands will be critical fire and faunal refugia in the event of future fires in Mountain Ash forests. Finally, in the event of fires in the next 50 years, areas of old growth forest that are burned will be those most likely to result in a pulse of dead standing trees large enough to provide suitable cavities for hollow-dependent animals.

Effects on soils and soil nutrients

Some of the most striking recent findings following the 2009 wildfires have come from work on the structure and composition of Mountain Ash forest soils. A study on the effects of fire, and clearfell and post-fire salvage logging found significant disturbance impacts on a number of vital key soil measures with effects that can persist for at least 80 years post-fire, 34 years post-clearfell logging, and possibly much longer (Bowd *et al.* 2019). For instance, relative to long-undisturbed areas, forest soils burned and/or logged were characterized by significantly lower levels of soil nutrients including nitrate and available phosphorus (key nutrients that plants need for growth) in stands aged 8, 34 and 78 years (Bowd *et al.* 2019). Further, soils in forests that were clearfelled or burned in multiple fires (including those on Black Saturday), were characterized by significantly lower amounts of these nutrients, and had a higher pH (in fire-only sites) and sand content, relative to forests burnt once, and those unlogged (Bowd *et al.* 2019). The impacts of fire and logging are also experienced by biological communities in the soil microbiome, with pronounced impacts recently observed on mycorrhizal fungal communities that may influence plant growth (Bowd *et al.*, unpublished data).

INTERACTIONS BETWEEN FIRE AND OTHER DRIVERS OF CHANGE

We have employed considerable effort to quantifying the effects of fire on various groups of biota or factors influencing the occurrence of biota (such as populations of large old trees or the extent of old growth forest). However, fire can interact with other factors to affect the forest and biodiversity. For example, the severity of the 2009 wildfire was elevated by past logging operations with crown-scorching fires more likely to occur in forests 7-36 years after stand regeneration (Taylor *et al.* 2014). Notably, similar effects have been documented for Alpine Ash forests (Zylstra 2018).

Fire and logging can interact in other ways, especially through their combined negative effects (i.e. post-fire salvage logging) on groups such as birds and plants with these effects more pronounced than the effects of either fire or logging in isolation (Blair *et al.* 2016; Lindenmayer *et al.* 2018c).

Recent work has shown there are important interactions between fire and long-term climate and short-term weather on key groups of biota such as birds (Lindenmayer *et al.*, unpublished data). Post-fire recovery is impaired on sites within the Central Highlands region characterized by long-term cool and wet conditions (Lindenmayer *et al.*, unpublished data).

A further form of fire-environment interaction concerns the inter-relationships between fire, the age of a stand at the time it is burned, and the development of new cohorts of hollow-bearing trees. While past fires have produced pulses of habitat for species such as Leadbeater's Possum (Lindenmayer *et al.* 1991), future conflagrations are unlikely to do so. The reason is that past fires burned large areas of old forest with a subsequent pulse of large old fire-scarred living and dead hollow-bearing trees. Future fires will burn primarily young forest with small-diameter trees that lack the internal decay within the trunk that makes the older trees suitable habitat for hollow-dependent fauna. Moreover, fires in these younger forests are also likely to be of greater severity than in older stands (Taylor *et al.* 2014) and rates of tree fall will be faster (Lindenmayer *et al.* 2018a). This will, in turn, have negative impacts on a range of cavity-dependent species.

GENERAL DISCUSSION

Large areas of the Mountain Ash forests of the Central Highlands of Victoria have been extensively altered by the 2009 fires. Following ten years of detailed research, we have documented fire effects on soils, plants, large old trees, small mammals, birds, and arboreal marsupials. Fires like those in 2009 undoubtedly have huge impacts on ecosystems but these forests do recover from fire (and have likely done for many thousands of years) especially if the recovery processes are not impaired by logging, either before a fire (leading to much elevated subsequent fire severity; (see Taylor *et al.* 2014) or after fire (*viz* salvage logging) (Blair *et al.* 2016; Bowd *et al.* 2018; Lindenmayer *et al.* 2018c).

Following the 2009 fires, our empirical studies contain evidence of steep declines in patterns of site occupancy by arboreal marsupials and birds. We have also found compelling evidence for a rapid collapse in populations of large old hollow-bearing trees. There is limited evidence of post-fire recovery for many species of birds or of large old trees on burned sites. Given the strong relationships between the occurrence of cavity-dependent arboreal marsupials and the presence of hollow-bearing trees (Lindenmayer *et al.* 2014a), ongoing declines in populations of hollow-bearing trees, coupled with the very limited recruitment of these trees, will likely drive further declines in occupancy by arboreal marsupials at our long-term sites in the coming decades (Blair *et al.* 2018). These changes contrast markedly with the responses of the two most common species of ground-dwelling small mammals in Mountain Ash forests, which recovered within two generations.

Declines in arboreal marsupials, large old trees and many species of birds extend beyond burned sites and have also occurred on unburned sites. Our studies suggest there is a landscape-scale effect of the amount of burned forest and the amount of logged forest in the landscape on declines of these groups of organisms (Lindenmayer *et al.* 2013; 2014a; 2018a). There is also evidence of long-term climate and/or short-term weather effects on declines in large old trees (Lindenmayer *et al.* 2012a), patterns of natural regeneration in overstorey trees (Smith *et al.* 2014), and bird responses (Lindenmayer *et al.*, unpublished data).

A key outcome of the fires, together with ongoing clearfell logging, is that the Mountain Ash ecosystem and many of the species it supports are under considerable ecological and management pressure. Indeed, the Mountain Ash ecosystem has been classified as Critically Endangered under the IUCN Red Listed Ecosystem process (Burns *et al.* 2015) and there are high risks of ecosystem collapse (Lindenmayer and Sato 2018). We argue that it is important to make a distinction between the threats to Mountain Ash as a species (or local population) and the Mountain Ash ecosystem.

The key threat to the population of Mountain Ash trees in the Central Highlands of Victoria relates to the shortening of inter-fire intervals and the time required for Mountain Ash to mature and produce viable seed. Recent published work shows the minimum period between disturbances before Mountain Ash have sufficient seed in the canopy to regenerate is ~20 years, although there is some environmentally-associated intraspecific variation (von Takach Dukai *et al.* 2018). Like many eucalypts, Mountain Ash hybridises readily with other species including Messmate (*Eucalyptus obliqua*) and Red Stringybark (*Eucalyptus macrorhyncha)* (Ashton and Sandiford 1988). This, and the high gene flow within the species, should give it a strong capacity to adapt to environmental change (although it is still at risk).

The threat to the Mountain Ash ecosystem is primarily associated with the age structure of Mountain Ash stands, which are almost exclusively dominated by areas that are 80 years old or younger. We can easily lose much of the forest ecosystem simply by losing the older cohort of Mountain Ash trees, and not the species itself (Lindenmayer and Sato 2018).

The need for strengthened fire management strategies

A major issue for the Mountain Ash ecosystem is the ongoing impacts of widespread wildfire. Indeed, the area of forest burned by wildfire in our study region has been increasing over time (Victorian Environmental Assessment Council 2017). Moreover, as outlined above, repeated wildfires at intervals of less than 20 years has the potential to trigger the collapse of the Mountain Ash ecosystem. Ways need to be found to reduce both the number and the extent of wildfires and their impacts. This is critical for conserving both the ecosystem *per se* and the array of species that it supports. We propose the following key strategies to tackle fire issues in Mountain Ash forests.

First, active efforts must be made to significantly expand the amount of old growth forest as these areas have a lower probability of burning at high severity (Taylor *et al.* 2014). Old growth stands have a well developed tree fern layer and a greater presence of rainforest elements (Lindenmayer *et al.* 2000a; Lindenmayer *et al.* 2000b) that are likely to create more mesic conditions in Mountain Ash ecosystems. Greater areas of old growth forest mean that, in the advent of future fires, more key biological legacies (*sensu* Franklin *et al.* 2000) such as large old fire-damaged hollow-bearing trees will be created than if young stands are burned (Lindenmayer 2009b). Larger areas of old growth forest mean that there is a greater chance that more forest will escape the impacts of future fires. Indeed, we argue that the substantial negative current impacts of fire are strongly related to the extent of past disturbances that have removed a large amount of previous old growth forest from the landscape. Greater levels of forest protection and the creation of more old growth forest is also essential because existing reserves are insufficient to ensure the persistence of key species of conservation concern such as arboreal marsupials (Todd *et al.* 2016; Taylor *et al.* 2017). To meet goals such as a minimum target for 30% of the Mountain Ash forest being old growth (see Lindenmayer *et al.* 2013 which is also a goal of government (LPAG recommendations 2014)), all existing areas of the next nearest age cohort of forest to old growth (forest that regenerated following the widespread 1939 fires) will need to be exempt from timber harvesting (Blair *et al.* 2017a), lest this target not be met for over a century.

Second, there is a need for a major reduction in the amount of logging in the landscape. This is critical, not only to boost the amount of forest that will potentially become old growth (Lindenmayer *et al.* 2013), but also to reduce the amount of fire-prone, post-harvested forest in the landscape (Taylor *et al.* 2014). There is also a need to halt thinning of young forest stands, given that it too can promote fire proneness by elevating fuel loads, drying the understorey, and increasing wind incursion (Buckley and Cornish 1991; Forestry Tasmania 2001). We argue that the high level of ecological damage that comes as a result of salvage logging burned forest after wildfires cannot be justified.

Third, there is a need for greatly expanded riparian buffers as the wetter parts of landscapes are where fire frequency and fire severity is likely to be lowest; it is also where the abundance of existing large old hollow-bearing trees is highest (Lindenmayer *et al.* 1991).

Fourth, there is a need to complete analyses of landscape-level environmental conditions to identify the most mesic parts of the Mountain Ash ecosystem. These should be targeted for protection (i.e. exclusion from logging) as they are the areas with the greatest probability of developing into old growth stands (Mackey *et al.* 2002). Notably, recent assessments have shown areas targeted for clearfell logging are characterized by both the highest levels of rainfall (Taylor *et al.* 2018) and have the highest values for the predicted occurrence of threatened species (Taylor and Lindenmayer unpublished data).

Fifth, the Government of Victoria needs to strengthen its capacity for rapid response to suppress fires as quickly as possible after ignition, including in remote areas. This is particularly important given the fire proneness of the existing Mountain Ash landscape that is dominated by young forest (Taylor *et al.* 2014).

Sixth, in the event of wildfire, there should be no salvage logging. This is because of its substantial negative effects on key biological legacies such as large old trees, resprouting plants like tree ferns, and the majority of understorey and midstorey species that are in a vulnerable state as young seedlings at the time when salvage logging is conducted.

Seventh, there is an urgent need to tackle climate change as it is one of the major underlying drivers of changes in fire regimes, including in Mountain Ash ecosystems (Williams *et al.* 2009). A warming climate will result in more frequent, more severe, and more widespread fires in the Central Highlands region (Williams *et al.* 2009). Climate change also will have significant effects on key components of the life cycle of Mountain Ash forests such as the regeneration niche (Smith *et al.* 2016) and also accelerated mortality of large old living trees (Lindenmayer *et al.* 2012a). Notably, some analyses indicate that up to 80% of the area currently occupied by Mountain Ash forest will support unsuitable climatic conditions for the species to be able to regenerate naturally by seed by 2080 (Mok *et al.* 2012; Victorian Environmental Assessment Council 2017). Addressing the effects of climate change is obviously a national and global challenge that extends well beyond regional environments such as wet eucalypt forests dominated by Mountain Ash stands.

We argue that it is essential to implement the strategies outlined above quickly given the rate of decline of species such as Leadbeater's Possum and the Greater Glider (Blair *et al.* 2018; Lindenmayer and Sato 2018). Recovering small populations of threatened species is notoriously difficult and can be extremely expensive (Garnett *et al.* 2018). In the case of Leadbeater's Possum, catastrophic declines have recently occurred in small populations such as those at Yellingbo Nature Reserve (D. Harley, personal communication) and the species has not bred successfully in captivity despite intensive efforts for eight years by some of Australia's leading zoos such as the Melbourne Zoo and Healesville Sanctuary.

Finally, we believe that current forest management policies are deficient because they maintain an extensive and intensive native forest logging industry in Mountain Ash forests that are already heavily disturbed by extensive wildfires and past logging. Indeed, these forests are already classified as Critically Endangered. Moreover, some policies have deliberately eroded efforts to conserve suitable habitat for at-risk species like Leadbeater's Possum (Blair *et al.* 2018). On this basis, urgent policy reform is essential to accommodate the major impacts that fire and logging have had in Mountain Ash forests and to better conserve the biota associated with this ecosystem.

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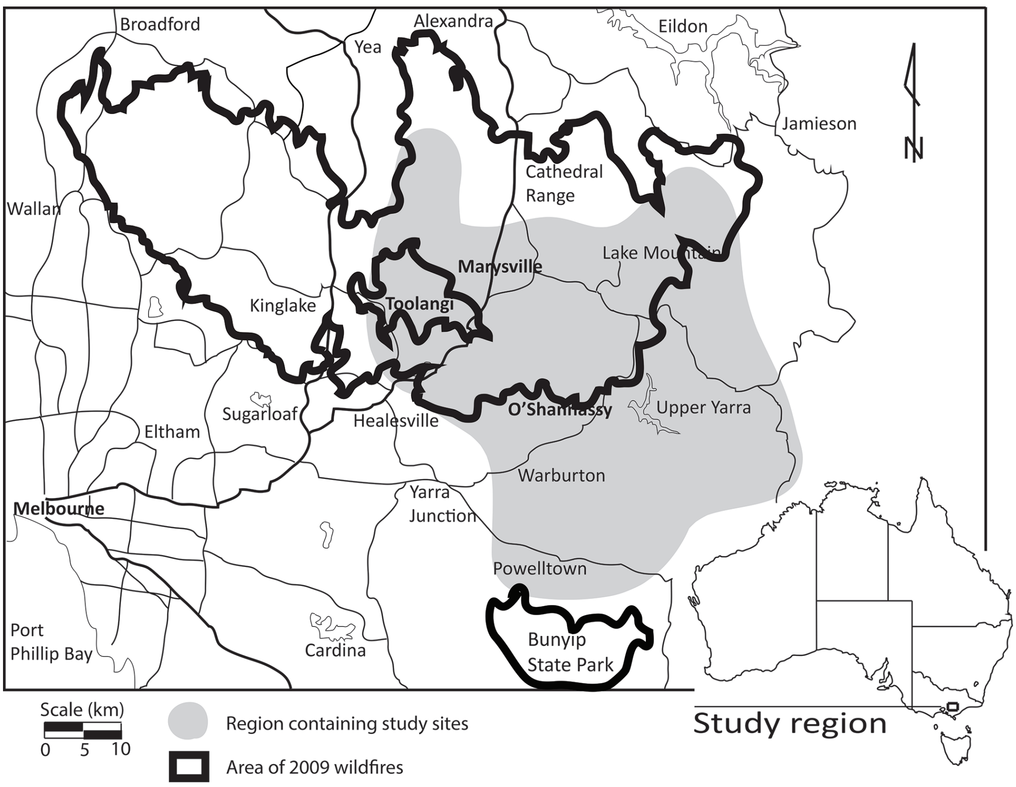
APPENDIX I



Caption for photo montage, top to bottom, left to right

1. Old growth forest, rich with tree ferns which are a group of resprouting plants for which patterns of site abundance are severely reduced following clearfell logging.

2. Leadbeater's Possum, the faunal emblem of Victoria and for which levels of site occupancy halved between 1997 and 2017.

3. The Greater Glider, a species for which levels of site occupancy have declined significantly in the past 20 years.

4. Crested Shrike-tit, one a suite of bird species most commonly associated with old growth forests and which are undergoing significant declines in montane ash forests.

5. Logging coupe immediately after a high-intensity regeneration burn lit on a clearfelled logging coupe.

6. The Flame Robin, the only bird species in montane ash forests that is most abundance in young forests immediately following wildfire.

7. Clearfelling operation (pre-regeneration burn) in the Toolangi State Forest.

8. Stand of young, post-logged montane ash forest that was burned in the 2009 wildfires. This forest is characterized by an absence of tree ferns and other resprouting plants as well as large old trees.

Photograph credits: 1, 5, 6, 8 David Blair; 2, 3 Tim Bawden; 5 Julie Burgher; 7 Tabitha Boyer

APPENDIX I