Raking over the ashes: assessing the impact of fire on native fauna in the aftermath of Australia's 2019-2020 fires

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ABSTRACT

The 2021 annual forum of the Royal Zoological Society of NSW raked over the ashes of the unprecedented "Black Summer" bushfires of 2019–2020 in eastern and southern Australia to assess how forest ecosystems and their constituent fauna had fared. This paper provides an overview of the 21 studies that were presented at the forum, now as papers in this theme edition of *Australian Zoologist*. All the authors were unanimous in their agreement about the unparalleled extent and severity of the fires and the magnitude of their ecological impacts. Whereas much of the focus of the 2019–2020 fires was on vertebrates, significant research was also carried out on a diverse range of invertebrate taxa. The studies of the invertebrate groups found that different taxa respond variably to fire and also emphasised the difficulties in judging the full impact of the fires due to taxonomic impediments. An underlying theme in almost all studies was that long-term and broad-scale monitoring of fauna and faunal habitats is essential if we are to build a robust understanding of how animals respond to fire, and in turn how managers can mitigate the impacts of fire in future. Such monitoring will need to incorporate the effects of other disturbance factors, such as habitat fragmentation, drought, salvage logging and longwall mining, that interact with fire, and also trial new methods to track and assist fauna to cope with the changing fire regimes. Several studies advocated the use of novel and emerging technologies to achieve better monitoring of fauna, while others proposed mapping of large scale, as well as micro-refuges, to maximise fire resilience, or the use of supplementary resources such as nest boxes and artificial roosts to replace those lost in fires. We concur with all the authors that a critically important way to protect and manage our native fauna is through expanded and sustained research and monitoring programs, and by making the key results available to managers and policy makers via peer-reviewed publication.

Key words: bushfire, climate change, fauna monitoring, greater glider, invertebrates, long-term studies, threatened species, tree hollows, vertebrates, wildfire.

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Introduction

The extensive fires in 2019–2020 in eastern Australia and on Kangaroo Island in South Australia have become known as the "Black Summer wildfires". In north-eastern Australia, the fires took hold in early spring and significant, but less extensive fires swept through parts of Western Australia, as well as through parts of northern and inland Australia (Dickman 2021). New South Wales was the most severely affected state with 5.3 million hectares of forest burnt (DPIE 2020, 2021), representing 25% of the native forest area in the state (Davey and Sarre 2020). The country lived and breathed the devastation, with residents who were not directly affected by the destruction or smoke impacted by the memories that occupied the daily news from spring 2019 to autumn 2020.

Prior to the "Black Summer wildfires", the country had seen record temperatures and had been in severe drought for several years, as captured by Smith and Smith (2022): "Much of eastern Australia had been in drought since January 2017, with conditions becoming drier with each year (BOM 2020). The drought peaked in 2019, which was the hottest and driest year on record in Australia (Abram *et al.* 2021). The extreme drought and heatwave conditions in 2019 culminated in the 'Black Summer' fires of spring and summer 2019–20."

The fires directly affected many people. By March 2020, when the fires in eastern Australia had been extinguished by heavy rain - triggered by an east coast

low, 33 people had lost their lives in the flames, some 417 people had perished due to respiratory problems caused by particulate matter in the smoke, while many more people continued to experience post traumatic stress and poor health (Borchers Arriaga *et al.* 2020; Filkov *et al.* 2020). Over 3000 houses were destroyed by the fires, communities displaced, and roads, power lines and other key infrastructure damaged. Media coverage was extensive during the fires, both in Australia and internationally, focusing on the plight of the human population and also on the impacts of the fires on wildlife. Footage of, and interviews with, heroic fire-fighters and fire chiefs were daily fare, as were distressing images of animals fleeing oncoming fire-fronts. Estimates of the numbers of animals in the path of fires were reported widely, and grave concerns were expressed for the fate of threatened (and non-threatened) species of animals and plants whose geographical ranges overlapped the areas that burned (Dickman and McDonald 2020; Gallagher *et al.* 2021). Inappropriate fire regimes threaten 88% of Australia's threatened land mammals, with frequent severe fires the primary cause of population declines (Santos *et al.* 2022).

By late 2021 the fires had been long extinguished, much work had been undertaken to examine the effects of the fires on wildlife and on the extent of initial recovery of individual species and forest ecosystems, providing an opportunity to reflect on the impact—or rake over the ashes—of the Black Summer wildfires. "Raking over the ashes" means to revisit something unpleasant, and a close examination of the impact of the extensive fires of 2019–2020 in eastern Australia and Kangaroo Island in South Australia on our fauna may indeed seem to be unpleasant. However, it is our view as zoologists, that understanding how fire affects our fauna is an essential step in drawing out lessons to better manage our wildlife to cope with the unpleasant reality of inevitable future fires. This theme edition of *Australian Zoologist* addresses this matter. This closing paper synthesizes the 21 individual papers, makes some pointed observations, and draws some painful lessons.

Extent and severity of the 2019–2020 wildfires

In assessing the potential effects of the 2019–2020 fires on forest and woodland ecosystems, and in particular the impacts of the fires on fauna, an initial question is how much of the forest estate was burnt, and how severely? Australia-wide estimates range from 30.4–39.8 million hectares affected by the fires, but these estimates included fires in regions across the Top End and the continental interior that burn regularly (Bowman *et al.* 2020). By contrast, the fires in the eucalypt forests in eastern Australia were unusually—even unprecedentedly—expansive. Some 5.67 million hectares of eucalypt forest burned in this region, representing some 20% of the forest cover in the south-east (and 25% of that in NSW), a figure over 7.5 times higher than the average area burnt each year over the previous 18 years (Bowman *et al.* 2020). In addition to the fire extent, fire severity was high over large areas due to the accumulated fuel and extremely dry and hot conditions throughout 2019 leading up to the main fire season that began in November 2019 (Nolan *et al.* 2020; Smith and Smith 2022). The speed of fire spread, the coalescing of fire fronts and the invasion of fire into vegetation types that seldom burn, such as rainforest, left few fire-free refuges in many areas, leading to grave concern for the fate of many plant and animal species, as well as ecological communities (van Eeden *et al.* 2020; Wintle *et al.* 2020).

Beyond the sheer areal coverage of the 2019–2020 fires, a further key question that arose, even as these fires were raging, was how badly affected were sites that are most important for biodiversity and other protected area values? Using Australian Google Earth Engine Burnt Area Maps (Commonwealth of Australia 2020), Ward *et al.* (2022) evaluated the severity of the 2019–2020 fires and the extent to which they burnt protected areas such as National Parks, Wilderness Areas, World Heritage Listings and Key Biodiversity Areas within a total burn area of ~10 million hectares. The results showed that some 3.2 million hectares were burnt within protected area estate, with 1.4 million hectares burning with low to moderate severity and 1.8 million hectares burning with high to very high severity. Fires in some areas, such as the World Heritage Listed Greater Blue Mountains Area, were particularly extensive with very large areas being severely burnt. Intriguingly, the analyses of Ward *et al.* (2022) also showed that—except, anomalously, in World Heritage Areas—degraded forests within the protected area estate experienced burns of higher severity than less disturbed forests, thus feeding into current debates about how disturbance from logging operations affects fire severity (Bowman *et al.* 2021; Lindenmayer *et al.* 2022a; Zylstra *et al.* 2022).

Krogh *et al.* (2022) examined how fire severity interacts with disturbance. The massive Gospers Mountain wildfire significantly affected Newnes Plateau shrub swamps, which had predominantly been impacted previously by mining. All the swamps on the plateau were burnt, some severely, but only vegetation on swamps that were not located near longwall coal mining activity recovered quickly. In contrast, swamps already impacted by longwall mining were severely impacted by the fires which caused extensive combustion and oxidization of the peat soils. The coal mining, which is ongoing, has changed the hydrology of the swamps. Sites that had been catastrophically impacted by the longwall mining hydrological impacts before the fires showed

no recovery of the plant communities and returned no records of the endangered populations of the Blue Mountains Water Skink *Eulamprus leuraensis* or the Giant Dragonfly *Petalura gigantea*. Reference sites that had not been impacted by mining recovered quickly and the Water Skink and the Giant Dragonfly remained present. Importantly, this study highlighted the fact that the effects of fire are influenced by conditions that prevail before the fire, and include not only severe drought, but disturbance activities such as longwall coal mining.

Impacts of the 2019–2020 wildfires on fauna

The extent and high severity of many fires during the 2019–2020 fire season led to significant concern about the impacts of the fires on wildlife. Images on commercial and social media of kangaroos fleeing from flames or Koalas *Phascolarctos cinereus* being rescued stoked fears of catastrophic losses of these marsupials. In January 2020, estimates made by one of us (CD) of the numbers of all terrestrial vertebrates in the path of the fires were widely reported in at least 6495 articles in 115 countries, reaching by year's end 25.6 billion views (V. Reiner, pers. comm.; van Eeden and Dickman 2022). Final estimates of the number of individual vertebrates affected by the fires—almost three billion—were astonishing (van Eeden *et al.* 2020), as were estimates that the fires burnt greater or lesser parts of the geographical ranges of 832 vertebrate species (Ward *et al.* 2020). But how many animals actually succumbed to the flames or smoke suffocation? Although there are no definitive answers to this question, some intriguing insights were obtained by Nimmo *et al.* (2022) using an eco-evolutionary approach.

Direct fire-induced mortality of vertebrates may in general be much lower than expected (Nimmo *et al.* 2022). Pointing to a recent review showing low mortality of animals (average 3–7% depending on fire severity) that were radio-tracked before and after fire (Jolly *et al.* 2022), Nimmo *et al.* (2022), then raised the intriguing possibility that mega-fires and other severe or moderate to large scale fires may act as mass selection events that filter and remove 'fire-naïve' individuals from populations. Many species respond to fire cues in ways that increase their chance of survival. For example, some species of mammals, birds and reptiles become more active in response to smoke and may move away from the cue or seek safety in secure refuges underground or in tree hollows (Nimmo *et al.* 2019, 2021). Individuals that respond so proactively to oncoming fire fronts are more likely to survive than individuals that respond slowly or not at all, thus setting up a 'Darwinian guillotine' (*sensu* Lunney *et al.* 2008) that favours fire-savvy animals over those that are fire-naïve. By extension, animals that occur in vegetation types that seldom burn are likely to be naïve to fire and are unlikely to survive large fire events, whereas animals in fire-prone vegetation types would have been filtered by natural selection to show some level of response to fire. This proposal echoes current thinking in predator-prey theory, where naïve prey species are expected to be at greater risk to novel predators than are prey species that have co-evolved with their predators (e.g., Banks and Dickman 2007; Carthey and Banks 2014). Fire has been viewed as a global herbivore in that it consumes vegetation in most parts of the world (Bond and Keeley 2005). By analogy, the proposal of Nimmo *et al.* (2022) is that fire might be seen also as a global predator that has strong selection effects on its animal prey.

Animals may survive the immediate passage of a fire, but then must navigate the profound changes that have been wrought by the fire to the structure of the habitat, to roosts and shelters, and to food and water resources. Several papers in this theme issue explore how different animal species fare post-fire. Greater Gliders *Petauroides volans* in the Blue Mountains World Heritage Area were not found on two transects burnt at high to extreme severity (100% of eucalypt foliage killed in the canopy) but remained present on transects burnt at low to moderate severity, although in significantly lower numbers (Smith and Smith 2022). The authors put forward seven recommendations for not only conserving Greater Gliders, but also other native fauna and flora in the region. They highlighted the need to reduce greenhouse gas emissions, citing the IPCC (2021) report that if the impacts of climate change are not reduced, then other recommendations will not succeed. Other recommendations included more strategic hazard reduction burning programs; protecting post-fire fauna and flora refuges; and providing more resources for long-term monitoring programs to track changes in native fauna and flora populations as a basis for adaptive biodiversity management in bushland areas.

Madani *et al.* (2022) focussed on the impact of the 2019–2020 fires on a species that could be expected *a priori* to be 'fire-naïve' – the Golden-tipped Bat *Phoniscus papuensis*. This species occurs in rainforest in eastern Australia and is dependent on the dense understorey 'clutter' that is characteristic of long-unburnt rainforest habitats. These habitats provide both the roosting requirements and specialised diet—orb-weaving spiders—that the species needs to persist. The extensive fires of 2019–2020 led to marked reductions in the species' occupied habitat. Importantly, Golden-tipped Bats roost in suspended bird nests within the rainforest understorey, and the removal of these nests by fire most likely leads to the post-fire loss of bats. Because of the importance of these unusual roost sites, Madani *et al.* (2022) trialled the deployment of artificial roost structures—

the heads of floor mops—to determine whether these facilitated rapid recovery of Golden-tipped Bats in burnt habitat. Unfortunately, despite the inventiveness of this approach, no bats were found to use the mop heads, although these structures were damaged by heavy rains after deployment and thus rendered unattractive as potential roost sites.

The plight of Koalas was well documented by popular media during the Black Summer bushfires. Using the records of the licensed wildlife rehabilitation groups in NSW that rescued Koalas during the fires, Lunney *et al.* (2022) documented 209 Koalas that came into rehabilitation due to the effects of fire and a further 307 that were admitted to rehabilitation over the same period for reasons other than fire. Just over half (106) of the fire-affected animals were euthanised or died after being admitted to care, while 74 had been released at the time of writing. The high rate of release can be taken as a rehabilitation success story. If many thousands of Koalas were in the path of the fires (e.g., van Eeden *et al.* 2020) or an estimated 5000 Koalas were killed by the fire (Parliament NSW 2020), the relatively small number admitted to rehabilitation might suggest that the fires had little impact on Koalas or, in reality, that many animals died *in situ* due to the flames or to post-fire threats such as dehydration, starvation or exposure. Certainly, an expert elicitation by Legge *et al.* (2022) identified that the fires would have had marked effects on Koala populations, and that these effects would be sufficient to warrant a review and potential upgrade of its status under the Commonwealth's *Environment Protection and Biodiversity Conservation Act 1999* from Vulnerable to Endangered in NSW, Queensland and the ACT. Following review, the Koala was uplisted to Endangered in February 2022 (DAWE 2022).

While most studies of severe fire are opportunistic in that they are usually unplanned, Dickman and Happold (2022) were able to take advantage of a small scale but high severity fire that was planned as part of a broader experiment. Population fluctuations and diets of three species of small mammals were monitored before and after the fire and simultaneously sampled in a nearby site that was not burnt. The populations of two species of *Antechinus* declined in the burnt site but not in the control (unburnt) site in the year of the fire, but recovered quickly just 1–2 years later, probably due to high *in situ* survival or immigration from adjacent unburnt forest. The Bush Rat *Rattus fuscipes*, by contrast, appeared to be largely unaffected by the fire, with populations in the burnt and control sites tracking each other closely. Diets of the insectivorous *Antechinus* spp. contracted sharply in the immediate wake of the fire, with ground-dwelling invertebrates being notably absent, but rebounded 12–16 months post-fire when leaf litter and other ground cover had recovered sufficiently to allow the restoration of invertebrate populations. By contrast, Bush Rats ate a wider range of food groups post-fire, including ferns and grasses that were otherwise seldom consumed, returning to their usual diet within 12–16 months. Dietary flexibility was proposed as a potentially important—but seldom invoked—mechanism that facilitates maintenance of species populations in the post-fire environment.

Three further studies examined how suites of vertebrate species respond to fire. Lothian *et al.* (2022) explored the impacts and recovery of several species of mammals following a fire at Newnes Plateau in 2013. Comprehensive surveys showed that even with high severity fire over a large portion of the landscape, habitat recovery was relatively quick. Small mammal responses were species-specific, but again, most returned to pre-fire (or at least control site) levels within six years. In a second broad-scale survey of vertebrates, Spencer *et al.* (2022) used camera traps to undertake a rapid fauna assessment after the Gospers Mountain fire, which burnt 79% of the Greater Blue Mountains World Heritage Area. Relative abundance of the Eastern Grey Kangaroo *Macropus giganteus*, Common Wombat *Vombatus ursinus* and Australian Magpie *Gymnorhina tibicen* were higher in burnt than in unburnt sites, while small mammals (< 500 g) had higher relative abundance in unburnt sites. There was no difference in the relative abundance of the Superb Lyrebird *Menura novaehollandiae* across burnt and unburnt sites. Analysis of Red Fox *Vulpes vulpes* scats revealed that invertebrates and plant material were the dominant prey items in both burnt and unburnt sites. The authors concluded that rapid survey was an effective tool to gain preliminary data on species responses to the 2019–2020 megafires. But like so many others in this forum, they emphasised the critical importance of faunal monitoring

Mahony *et al.* (2022) used expert elicitation to analyze the traits of frogs that potentially influence their fire sensitivity or resilience. Species restricted to cool, moist habitats are less exposed to the threat of wildfire, but they also had the highest sensitivity scores. The group considered to be the least sensitive comprised those species which occupy riparian zones as macro-refuges, and include species with wide geographic distributions, general reproductive strategies, high fecundity, and moderate physiological capacity. Management actions were proposed for frogs, such as protection and enhancement of micro-refuge components of the landscape, which are used as shelter during times of heat and moisture stress, and provision of buffer zones around macro-refuge habitats, such as streams.

Whereas much of the focus of the 2019–2020 fires was on vertebrates, significant research was carried out also on a diverse range of invertebrate taxa. Three

papers on the invertebrates of the forest floor in NSW (Cassis *et al.* 2022; Foon *et al.* 2022; Reid *et al.* 2022) took advantage of baseline surveys undertaken by the Australian Museum on behalf of NSW National Parks and Wildlife Service in 1993 as well as follow-up surveys in 1998 and 1999. Along with the ALA (Atlas of Living Australia) plus other databases, inventories of the invertebrates were compiled before the 2019–2020 fires, thus providing an opportunity to assess the impacts of the fires. However, unlike for the vertebrates, it is important to stress that we lack a complete database on invertebrates, with many taxa collected during these surveys not having been identified to species level, although all material has been lodged in the Australian Museum. Only 25% of Australia's invertebrate fauna has been described, of which the majority occur in marine and terrestrial environments (Taxonomy Decadal Plan Working Group 2018). However, in May 2020 the Australian Government released a "Provisional list of priority invertebrate species requiring urgent management or on-ground assessment" (DAWE 2020a) and provided funding to undertake these assessments.

Reid *et al.* (2022) undertook a survey of beetles, predominantly dung beetles (Scarabaeinae), consisting of 12 species, which had been highlighted by DAWE (2020a). Despite limited sampling, their results indicate that most of the target species were present in both burnt and unburnt sites in the 2021 survey, although some species were present only in low numbers. The authors also found some evidence that the loss of tree canopy led to invasion by open woodland species.

Cassis *et al.* (2022) looked at the impact of the Black Summer wildfires on the true bug species that had been identified as priority species in north-eastern NSW forests. They targeted seven species belonging to three families, which are primarily phytophagous and associated with a broad range of trees, woody shrubs and monocotyledonous plants. They suggested that while some of these species were not found, this may reflect inadequate sampling or that their host plants had been burnt and not regenerated, and so they had been killed during the fires. As such, these bugs are vulnerable to co-extinction if their host plants are at risk, particularly if they are narrowly distributed.

Nationwide, 56 species of land snails were identified as needing priority assessments, with respect to possible impacts of bushfires (Legge *et al.* 2020). Twenty-six of these were the focus of the study by Foon *et al.* (2022), and an additional five species identified by Hyman *et al.* (2020) were added because more than half of their known occurrences were located within the fire zone in north-eastern NSW. From mid-March to late May 2021, the authors sampled 70 sites in north-eastern NSW, which differed in burn severity and included unburnt sites. Damper landscape pockets were relatively less affected than the surrounding dry sclerophyll forests, which in turn provided greater micro-habitat refuge. Limestone outcrops are also critically important habitats and support a large number of narrowly distributed endemic species (Hyman and Stanisic 2005). The authors stressed the need for more long-term monitoring using standardized techniques (Parkyn and Newell 2013). Such surveys are critical for the management of narrow range endemics as these species may become critically endangered due to localized threats which are not easy to identify before it is too late.

While many of the papers in this theme edition of *Australian Zoologist* focus on the impacts of the fires in eastern Australia, especially NSW, Marsh and Glatz (2022) reported how the Black Summer fires on Kangaroo Island in South Australia affected the invertebrates. Almost 50% of the island was burnt, impacting large areas of high-quality native vegetation that is home to many rare, endemic invertebrate species plus many more which remain to be described. Invertebrates with low dispersal ability, endemics with narrow ranges, or habitat specialists, were most likely to be severely impacted by fires.

Marsh and Glatz (2022) conducted habitat assessments at 67 sites within burnt and adjacent unburnt areas, and 38 sites were ranked as high priority for the faunal surveys of one of more of the priority species. During these surveys they were able to find eight of the priority species within the burnt and unburnt sites, even recording range extensions for some – although this may simply have reflected limited data on the distributions of these species pre-fire. The authors highlighted the variability of species' responses to fire and the conservation status of some limited-range endemics, including a couple of spider species.

The four papers on terrestrial invertebrates, all at the base of the food chain, focus on taxa that play a critical role in the different environments that were severely burnt. The papers based on surveys in NSW all relied on previous faunal surveys without which it would not have been possible to develop the lists (DAWE 2020a, b) that prioritized the species that should be most urgently surveyed. Even so, the surveys represent only a subset of the insect and molluscan fauna (i.e., taxa that have been sampled and identified, even if only to Sp. 1, Sp. 2, etc). Many more invertebrates remain to be sampled and identified and added to inventories. Much of the invertebrate fauna probably exhibits long term fluctuations due to shifts in weather and climate change, with many likely to be collected only during certain times of the year, and many that are restricted in distribution to particular species of plants or habitats. Also, it should be stressed that all the invertebrate papers from NSW were restricted to

studies in north-eastern NSW, meaning that we lack studies for the other areas of NSW and Victoria that were severely burnt.

Looking back, looking forward: monitoring and other lessons

Several papers in this theme issue highlight the way forward to provide improved assessments of fire impacts and biodiversity responses, noting that one of the key themes of the forum was the lack of rigorous pre-fire data for many species. Laidlaw *et al.* (2022) found that bushfire severity mapping and analysis for Queensland's Gondwana Rainforests World Heritage Area properties under-predicted the ecological impact of fire within closed-canopy rainforests, thereby biasing against giving priority to rainforest-dependent threatened fauna for assessment and the allocation of recovery resources. By incorporating the fire tolerance of vegetation communities mapped within the bushfire extent, bushfire severity models can be extended to predict the potential ecological impact of each severity class both on ecosystems and priority species.

Hayward *et al.* (2022) pointed out that conservation managers cannot manage what they do not know, and highlighted that existing biodiversity monitoring is idiosyncratic and small in scale. Commitment to monitoring biodiversity is one of the great challenges that we should all be supporting. They proposed a need for technological development using sensors and machine learning to achieve coordinated, comprehensive and continuous monitoring across large scales. Dubbed the BIOMON project, they outlined the kind of work still needed to achieve these goals.

Howard *et al.* (2022) suggested that nest boxes can be used as a restoration tool after fire, as they are often deployed in an attempt to offset the loss of natural tree hollows. However, nest boxes can experience more variable and extreme microclimates than natural hollows, thereby harming animals that use them. Temperatures inside nest boxes with more than one side insulated took longer to increase and decrease in a convective heat chamber, but importantly, never reached the heat extremes (> 40°C) of less insulated nest boxes. Fully insulated nest boxes also maintained heat longer than any other nest box type in a cold room. Understanding how different construction materials influence nest box temperature profiles and identifying designs that minimise thermoregulatory costs for animals are important considerations for the safe implementation of nest box programs.

Although many birds can flee the direct effects of fire, Milledge and Soderquist (2022) examined the impacts of the 2019 wildfires on large trees and stags in Barking Owl *Ninox connivens* territories in the lower Richmond River district, north-eastern New South Wales. The loss of, or severe damage to, 22.6% of large trees and stags recorded by this one wildfire event is unsustainable for Barking Owls. Monitoring the condition of large trees and stags across areas impacted by the 2019 wildfires in north-eastern NSW, together with their dependent populations of hollow-dwelling large owls, gliders and other arboreal marsupials, is imperative if we are to avert dire predictions of the fate of southern and eastern Australia's native fauna species, including hollow-dependent species.

In their long-term monitoring of an endangered population of Yellow-bellied Glider *Petaurus australis* on the Bago Plateau, NSW, Bilney *et al.* (2022) found that their susceptibility is exacerbated by severe wildfire, which impacted the Bago Plateau during the Black Summer fires of 2019–2020. It was the first significant fire event on the plateau in almost a century. The long-term monitoring program found that pockets of unburnt and low-severity fire-affected forests may serve as refuges from wildfire, and the authors added that this observation highlights the ecological value of these pockets and the need to prioritize them as sites for fauna conservation. They added that the importance of hollow-bearing trees for the Yellow-bellied Glider was demonstrated by the probability of colonisation being strongly and positively associated with the density of hollow-bearing trees at a site. This observation is one of the common findings in post-fire studies. The authors concluded with the strongly-expressed view that long-term monitoring programs are paramount for detecting and understanding population trends, particularly when species are facing pressure from a changing climate, increasing exposure to novel biota and live within forests susceptible to wildfire–which now includes both wet forests and rainforest.

In their study of the interacting impacts of drought and fire on bird populations—insights from a long-term study in the Warrumbungles, Stevens and Watson (2022) identified that the interacting effects of drought and fire on ecological communities are poorly understood. Their long-term study allowed them to conclude that "no suite of birds is exempt from these environmental stressors, and predict that, as droughts reduce populations at regional scales and fires diminish carrying capacity of critical habitats at landscape scales, rarer species will decline to local extinction while more commonly observed species will be reduced in abundance." The authors underlined the seemingly obvious, but important point, that droughts typically occur over multiple years across entire regions, whereas bushfires typically occur over multiple days or weeks across landscapes. In citing Nimmo *et al.* (2021), they added that the consequence is that droughts allow many organisms to either leave or enter a quiescent stage, whereas

bushfires are rapid, and large numbers of plants and animals are killed directly.

The study of Stevens and Watson (2022) was conducted in the Warrumbungles about 33 km west of Coonabarabran, NSW. Six of their survey sites were on the private property "Chitty" in the Warrumbungle Mountains, and six were in the Warrumbungle National Park. Two droughts (2001–2006 and 2017–2019) affected the whole region, whereas the 'Wambelong' fire of January 2013, as it is known, affected some parts of their study area more than others. This study, along with those of Dickman and Happold (2022) and Lothian *et al.* (2022) were of fires that preceded the 2019–2020 fires. Stevens and Watson (2022) highlighted that the relatively rapid decreases in numbers after the 2013 fire contrast with the long slow decline from drought. With their long-term perspective, these authors were able to demonstrate that fire added to drought-mediated declines for some species. Both sets of sites showed similar patterns of bird declines, with relatively little change in species richness, but an overall halving of abundances for all groups. The halving of the numbers for most groups, on and off the National Park, they identified as a serious concern, and as a stage in biodiversity loss – declines in numbers before local and regional extinction.

In the view of Stevens and Watson (2022), the future of this lower rainfall region largely depends on what happens under climate change, with longer and more severe droughts and worsening fire conditions likely. As they demonstrate, the early manifestations of these conditions have been severe declines in a group of birds, the honeyeaters, not previously identified in earlier studies on fragmentation and extinction debt, where ground-dwelling insectivores were those most at risk. The authors then commented on the recent fires and observed that the severe fires that affected huge areas of southern and eastern forests of NSW and Victoria in 2019–2020 underline the importance of large refuges for the continuing survival and genetic diversity of many bird species.

In contrast to almost all the papers in this theme edition of detailed, species-specific, site-specific studies leading to well-founded conclusions, the paper by Lindenmayer *et al.* (2022b), entitled "Perspectives on biotic responses to repeated wildfires from decades of long-term empirical studies" is principally comprised of conclusions based on the authors' insights and long experience. Of course, these insights are worth repeating, but that should not stop the reader going to their paper and see the results of such a major contribution to this theme of forest fires and wildlife.

One light note arose during the Royal Zoological Society of NSW zoom meeting of this forum in September 2021. David Lindenmayer was presenting his paper and the audience of 200 registrants were all ears. Silence. David was talking, but there was no sound. The technical hitch was soon sorted out, but not before some minutes had passed. Can you imagine how frustrating it is to have the answers to so many of the problems of forest fauna management and be silenced. It was symbolic: Lindenmayer's voice is among the most powerful in Australia in advocating for better management of forests and their dependent fauna. When you read the paper by Lindenmayer and co-workers, you appreciate their logic, and are more than likely to support their advice and recommendations. Their final conclusion echoes so many other researchers and it bears repeating because of its universality: "Finally, many of the insights discussed in this article have emerged only through long-term studies. More long-term monitoring and research is needed to truly understand and better manage fire in Australian ecosystems." The conclusions in Lindenmayer *et al.* (2022b) are replete with such strong statements as: "One of the key lessons from the long-term work in the wet forests of Victoria and at Booderee National Park is that fire often interacts with other stressors in ecosystems such as human disturbances (e.g. logging) and natural disturbances like herbivory (e.g. by macropods or exotic taxa such as Sambar Deer *Rusa unicolor*...)." To that conclusion, add the further observation by the authors that, "Beyond the undoubted importance of the impacts of a single fire, what can be even more critical is the sequence of fires in an area and over time."

Lindenmayer *et al.* (2022b) argue that it is important to quantify the total disturbance impacts on species and ecosystems, pointing out that fire is just one of several stressors, such as elevated herbivory and rates of predation as well as further human disturbances. Lindenmayer *et al.* (2022b) highlight post-fire salvage logging in this context, one of Lindenmayer's bugbears.

While it is tempting to make a long series of concluding remarks and recommendations, it would be little more than a reiteration of the points made study by study that have been covered already. However, several common themes emerged, beginning with the conclusion that the fires of 2019–2020 were of unprecedented scale and severity. The findings were that the impacts of the fires on fauna were dramatic, especially in forests that were severely burnt, including rainforest. It is more apparent than ever that long-term monitoring of fauna and habitat condition must be initiated and then maintained consistently and systematically across the forest estate. The underpinning of any successful monitoring and assessments of impact and recovery will depend on research to better understand the basic biology and resource requirements of forest fauna, particularly the invertebrates. Research must accompany long-term monitoring to elucidate the

interactive effects of fire with other disturbance factors, including invasive species, habitat fragmentation, and other anthropogenic disturbances, such as mining, logging, droughts, floods and other manifestations of climate change. Refuges at the landscape and smaller (micro) scales will be crucial for the long-term persistence of many fauna species, and need to be identified and protected. The magnitude of the task ahead means that we need to embrace new thinking and new technologies to ensure effective management of our fauna.

There is one further key point that is more than apparent to every author, but sadly not apparent to some planners, policy makers and managers, and that point is that all the fauna matters, not just the threatened vertebrates, and that one of the most effective ways to protect and manage all the fauna is through research, and making it available to managers and policy makers via peer-reviewed publication. Indeed, that has been the underpinning of the Royal Zoological Society's forum on fire and our efforts to see the papers published.

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APPENDIX 1

Kiwarrak State Forest, mid-north coast NSW, a) February 2020, three months post-wildfire, and b) June 2022, recovering 31 months post-wildfire. The site was the focus of Koala and eucalypt flowering surveys. Photos: B. Law.