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Estimating the number of wild animals affected by Australia's 2019–20 wildfires

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Summary

Context and challenges

- The 2019–20 wildfires in Australia were unprecedented in their extent and severity, affecting individuals and populations of many fauna species.
- We sought to assess these impacts by estimating the numbers of native vertebrate animals likely to have been present within the fire impact area.
- For several major taxon groups, datasets on pre-fire population densities were limited so we were necessarily conservative in the estimates that we made for these groups.
- Similarly, limited available data on the ability of different taxon groups to survive fire meant that we could not estimate mortality rates.
- Robust, consistent and targeted long-term monitoring is required to inform assessments of the impacts of fire on individual animals and populations, to identify key resources needed by fire-susceptible species and to assess the effectiveness of management interventions.

Main findings

- Our estimate of the numbers of reptiles, birds, mammals, and frogs affected by the 2019–20 wildfires rose from over 1 billion individuals in January 2020 while the fires still raged to 2.8 billion individuals after the fires were extinguished.
- The magnitude of the estimates stimulated huge interest from national and global media about the impacts of these fires upon biodiversity. Media focus on numbers of animals killed, rather than affected, by the fires made nuanced messaging difficult, but perhaps helped to catalyse management action, liberation of funds and subsequent inquiries into the impacts of the fires on wildlife.

Introduction

Fire is a common feature of Australian landscapes, with many plant and animal species evolving adaptations that allow them to survive, benefit from and even depend on fire. However, fire extent, frequency and intensity have increased in recent decades due to the changing global climate (Bowman *et al*. 2020). As such, Australian ecosystems are experiencing fires that may have long-term consequences for flora and fauna, with detrimental impacts to conservation of biodiversity (Lindenmayer and Taylor 2020). The wildfires that occurred in 2019–20 were unprecedented in their extent and severity (Bowman *et al*. 2020; Wintle *et al*. 2020; Collins *et al*. 2021; Chapter 2), including burning vegetation types such as rainforest that are not normally exposed to fire. It was quickly recognised that these fires were having major impacts on native fauna and flora, both on the survival of individual animals and on the resilience of populations and communities of conservation concern.

As the fires burnt across increasingly large areas of temperate forest and woodland, news of the impact of the fires on Australia's wildlife focused on a subset of charismatic fauna in both print and digital media. Most graphically, harrowing images of burnt koalas (*Phascolarctos cinereus*) and kangaroos captured attention in Australia and then globally (Fig. 12.1), as did the rescue efforts being made for these animals. This prompted us to think about the impacts of the fires on individual animals, recognising that there were vastly more individuals of many more species behind these icons that were also being affected. We wondered whether it was possible to estimate numbers of *all* vertebrates affected by the fires (not just the icons) to more fully appreciate the potential toll and to explore whether numbers of individuals in the path of the fires could translate to impacts at the population and species levels, or even to the ecological communities to which they belonged.

One of us (CD) made preliminary estimates in January 2020 that hundreds of millions of vertebrate animals had been impacted by the fires, with the numbers rising rapidly to

Fig. 12.1. Emotive scenes showing the direct impacts of fire on the welfare of charismatic fauna, such as koalas, generated international media interest in the Australian wildfires and their impacts on wild animals. (Photo: The Footage Company/Nine Network Australia)

more than 1 billion animals as the fires continued to rage (Box 12.1). The fires burnt for many weeks following this estimate, finally being extinguished in eastern Australia in March 2020. Although the notion that over a billion animals could have been in the path of the fires was shocking (Dickman and McDonald 2020), this figure was based on population density estimates that had been collected previously to assess the impacts of land clearing on wildlife in New South Wales (Johnson *et al*. 2007) and was clearly rough.

Box 12.1. Your number's up: media interest in the effects of the fires on wildlife

Anyone walking along an Australian forest trail on a hot summer day would be likely to see small lizards scuttling among the leaf litter, chance upon a sun-baking snake, and enjoy the sounds and sights of many birds before flushing a kangaroo or spotting a sleeping koala. Yet intense media focus on the marsupials gave the impression that they were the primary casualties of the 2019–20 megafires; other wildlife was ignored. Just after Christmas 2019 one of us (CD) brooded about this imbalance in reporting and used some readily available information on animal densities, contained in a 2007 report for WWF-Australia (Johnson *et al*. 2007), to estimate that some 480 million mammals, birds and reptiles would have been in the path of fires that had raged in New South Wales to that time. With some trepidation, and several caveats, CD provided the estimate in an interview with *The Times* on the 27 December 2019. The number appeared in *The Times* on the same day and swiftly went viral, appearing in stories about the impacts of the fires in Australia and globally in the days before the New Year. When the University of Sydney switchboard opened on 2 January 2020, the operators were inundated with calls from concerned people, including wildlife carers who had been rescuing animals from fire fronts, and especially from journalists from radio, television, podcasters, social media and other news outlets requesting updates and interviews. On 3 January 2020, CD issued a media release to outline the background rationale for his estimate of 480 million animals, updating this 5 days later to acknowledge the greatly increased area burnt by the fires since the original estimate to more than 800 million animals affected in New South Wales and more than a billion animals if burnt areas in Victoria were also included. Despite the continuing passage of the fires, no further updates were made: the estimate of 'over a billion' fire-affected animals was more than enough to sustain media attention. On 3 January 2020 there were 242 media articles quoting CD in 41 countries; on 9 January this peaked at 907 media articles, and by the end of January 2020 the numerical toll of Australia's wildlife had been noted in at least 6495 media articles in 115 countries (Fig. 12.2). Over 100 interviews were given in that month. Although media attention diminished when no further updates on numbers were provided, there were further peaks in interest when our preliminary updated numbers became available in July 2020 and later in the year when our final report was published (van Eeden *et al*. 2020). By year's end the estimates of animal numbers affected by the 2019–20 fires had been reported in at least 7539 media articles, in 36 languages, and reached an estimated audience of 25.6 billion people – more than three times the global population (V. Reiner, Media Office, University of Sydney, *pers. comm*.).

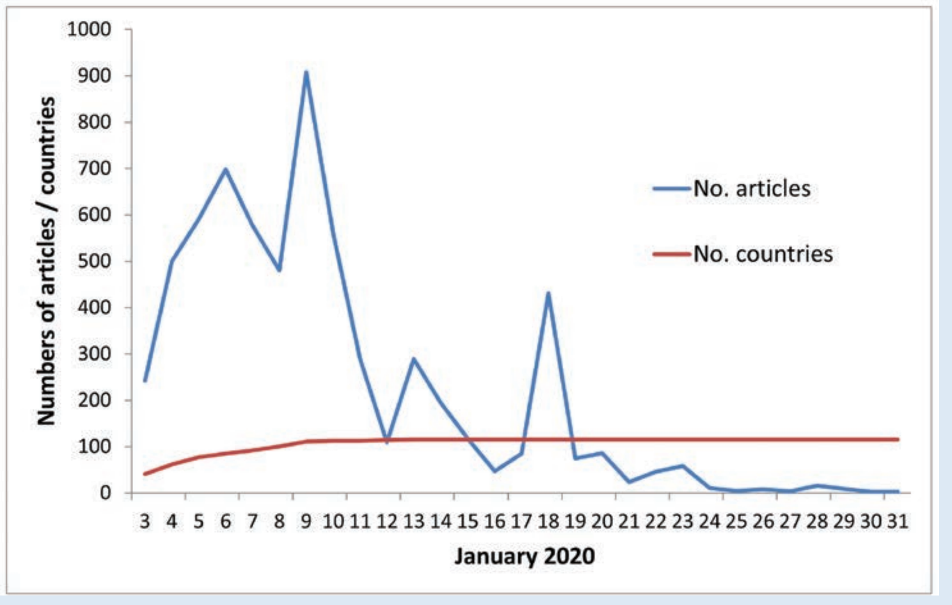

Fig. 12.2. Daily numbers of articles reporting estimates of animal numbers affected by Australia's fires, and cumulative number of countries in which the reports appeared, in January 2020. (Source: V. Reiner, Media Office, University of Sydney)

Communicating nuance to the media is sometimes difficult. Our observation of the media interest was that it was hard to maintain the clear message that our estimates were not a death toll but rather represented an estimate of the number of animals within the fire impact area that might have been affected in a variety of ways (e.g. direct mortality, displacement, increased competition for resources). The media's (and public's) black-and-white interpretation of our estimate as a death toll probably contributed to the incredible extent of the media interest.

Nonetheless, this high visibility may have benefitted the post-fire conservation cause. After the release of our initial numerical estimates and later report, recovery funds were set up by different levels of government and further funds were donated to many non-government organisations; there was a senate inquiry and Royal Commission into National Natural Disaster Arrangements (with a focus on bushfires), and further inquiries in New South Wales and Victoria.

Following the release of the preliminary estimate, we were commissioned by WWF-Australia to extend our analyses to cover the final impact area of the fires and include a more comprehensive suite of faunal groups (van Eeden *et al.* 2020). We defined the impact area to include the National Indicative Aggregated Fire Extent Dataset (NIAFED, Feb 2020 release: DAWE 2020) and an additional 120 000 ha of rainforest burnt in northern Australia. This excluded areas where fires would not be considered unusual (e.g. in savanna or grassland ecosystems in northern and central Australia). We initially explored whether we could estimate mortality rates based on existing faunal mortality data post-fire and mapping of fire severity. However, we soon found that data on mortality rates in and immediately after fire were limited and, where available, dominated by mammal species (Jolly *et al.* 2022). Similarly, at the time we conducted our analysis, fire severity mapping was available only for New South Wales. Such mapping has since been made available for the entire extent of the 2019–20 wildfires (DAWE 2020), but still has not been ground-truthed. As such, our scope was limited to estimating the number of individuals likely to have been present within the fire-impact area (in our analysis, 11.46 million ha), and precluded estimates of actual mortality. Nonetheless, although we could not ascribe rates of mortality, we note that many observers have recorded at least some instances of many animals being killed in previous Australian wildfires (e.g. Hood 1941; Fox 1978).

The methods by which we generated our density estimates differed between the four major groups that we focused on: amphibians, reptiles, birds and mammals. All were based largely on known estimates of population densities of native species within fire-affected bioregions. These methods are summarised briefly below, and greater detail can be accessed in van Eeden *et al.* (2020):

- For frogs, Michael Mahony mapped the distributions of 67 species to stream and non-stream (e.g. wetland) habitats. Population densities for these species were then estimated based on a literature review and expert knowledge, with these estimates then used to calculate the number of individual frogs within the fire impact area. This estimate was confined to Victoria and New South Wales (which encompassed most of fire-affected regions) due to lack of available data on frog densities for other fire-impacted areas.
- A modelling approach was taken for reptiles, led by Dale Nimmo. The model predicted squamate (i.e. snake and lizard) reptile densities as a function of broad-scale environmental variables and species body size, and was informed by a global database of reptile population densities (Santini *et al.* 2018).
- BirdLife Australia generated estimates for birds using population density estimates from almost 104 000 standardised bird count surveys from their Birdata database. These density estimates were stratified by vegetation type and bioregion to calculate estimates of the numbers of individuals by bioregion and within the overall fire impact area.
- For mammals, we began with an existing database on species population densities in forest and woodland habitats that was used to assess the effects of land clearing in New South Wales (Johnson *et al.* 2007). We then added to this database with new estimates sourced from a literature review and contact with taxon experts. Population density estimates for mammals were categorised into 11 species groups and then averaged per group for each of the fire-affected bioregions to generate estimates of population numbers per hectare within the fire impact area.

We aimed to include as many faunal groups as possible; however, there were many species and groups for which too few data were available to inform our estimates. For example, we were not able to make estimates for invertebrates because population density estimates for invertebrates are lacking in Australia. As invertebrates represent by far the majority of animal species (Chapman 2009; Chapter 11), this is a major omission in our estimates. Indeed, Chris Reid estimated in January 2020 that up to 240 trillion arthropods were likely to have been impacted in 8 million ha of burnt habitat (C. Reid, Australian Museum, *pers. comm.*). There is little known about how invertebrates are impacted by wildfire and taxonomic biases in the data that are available, hindering our ability to understand the impacts of major fire events on invertebrates and the predicted increases in frequency and severity of fires under future climate scenarios (Chapter 11; Saunders *et al*. 2021).

Similarly, we did not make estimates for several other vertebrate groups, including fish, flying-foxes, platypus, and all non-squamate reptiles (e.g. turtles) due to lack of available density estimates.

Key findings

In total, we estimated that around 2.8 billion individuals among the included taxa were likely to have been present within the 2019–20 wildfire impact area. This estimate comprised 52 million frogs, 2.5 billion reptiles, 180 million birds and 143 million mammals (Table 12.1). The methods used and nature of the density data available meant that confidence intervals could not be calculated for all groups and that, even for reptiles and birds, the confidence intervals are large.

As noted above, these numbers are not estimates of the death toll, but rather of how many individuals were likely to have been present within the fire impact area. Differences in species mobility, ability to shelter or escape from fire, landscape characteristics (e.g. availability of shelter), and fire intensity and severity would all shape mortality rates (Nimmo *et al*. 2019, 2021). Animals present within the fire impact areas would have been affected in a variety of ways, including direct mortality, indirect mortality due to post-fire succession processes (e.g. increased predation due to lack of available shelter), heat stress and smoke inhalation, displacement to neighbouring unburnt areas, and increased competition for resources. Lack of available data on population densities pre-fire and different species' ability to survive different fire severities meant that we could not estimate rates of direct mortality, indirect mortality, or non-lethal impacts. Nonetheless, using assessments in Garnett and Baker (2021), Garnett *et al*. (Chapter 15) estimated that 1.53 million individual threatened or Near Threatened birds died in the fires; much greater numbers of individuals of common (non-listed) bird species would also have been killed.

There are several limitations to these estimates and their interpretation. For all taxa, there were few data available on population densities, and what was available was often decades old and thus may over- or under-represent population sizes at the time of the fires. There were no available density estimates for some taxa in some bioregions where they are known to occur, and thus conservative estimates were made which are likely to under-represent species prevalence and abundance. In contrast, density estimates are more likely to have been collected in areas where taxa were targeted because they were known to be more abundant than elsewhere within a bioregion. The model for reptiles relied largely on density estimates from overseas (Santini *et al*. 2018) and estimates for some frog species were based on expert knowledge due to lack of available published data. For birds and

Table 12.1. Number of individuals estimated to have been present within the 2019–20 wildfire impact areas (from van Eeden *et al*. 2020). CI = confidence interval.

Taxon group	Estimate (millions)	Lower CI (millions)	Upper CI (millions)
Frogs	52	N/A	N/A
Reptiles	2457	779	9622
Birds	180	151	207
Mammals	143	N/A	N/A
Total	2832		

mammals, we assumed that each taxonomic group present in a bioregion occurred throughout at the same average density. While necessary, this simplification does not account for variation in densities that would occur both spatially and temporally (e.g. seasonally), nor for population densities that would have been lower in the predominantly dry conditions that had affected ecosystems in eastern Australia in the 3 years leading up to the wildfires.

Overall, we consider that the estimates for each taxon group are likely to be conservative. Each bioregion contains a range of land uses, but the fires occurred primarily in areas that probably provided good habitat for wildlife. Furthermore, we confined our estimates to burnt areas, but impacts are likely to have extended into unburnt areas – for example, through soil run-off into waterways, heat stress and smoke inhalation, and influxes of animals fleeing from neighbouring burnt areas.

Given this range of limitations, largely centred on a lack of available data, we consider that making estimates about future fire impacts would be significantly improved by implementing a systematic monitoring program of population sizes and densities for a diverse range of species. This would also provide a framework to facilitate and capture data from incidental monitoring of species populations before and after fire to assess mortality rates under different fire severities. The current paucity of data has been identified by a range of authors as limiting conservation knowledge and recovery estimates and has prompted calls to expand the network of national monitoring sites (Legge *et al*. 2018; Lindenmayer *et al*. 2014). A greater and more reliably sustained flow of biodiversity data could be collated by a centralised national information system and then used to guide management actions, support decision makers, and gain and maintain public confidence. Such a system could be set up as a biodiversity analogue of Australia's federal Bureau of Meteorology. Indeed, a 'Bureau of Biodiversity' has been advocated by the Australian Academy of Science (Academy of Science 2020) and the idea elaborated by Dickman (2021).

Since our report (van Eeden *et al*. 2020) was released, several studies have documented reductions in the abundance of some species from before to after fire, or reduced abundance in burnt areas relative to matched unburnt areas (e.g. Box 12.2); although not conclusive, these observations are strongly indicative of substantial mortality during the fire or in its aftermath. There have been several assessments targeting arboreal marsupials such as the greater glider (*Petauroides volans*) and yellow-bellied glider (*Petaurus australis*) (see also Chapter 16). In one survey in the Blue Mountains in New South Wales, for example, these species were reported to have disappeared in some areas where fires reached the tree canopy (Smith and Smith 2021). Surveys in Victoria detected greater gliders at 57% (DELWP 2021), 29% (Rutter and Blake 2020) and 8% (Burns and Atkins 2021) of sites where they were previously known to occur pre-fire. Yellow-bellied gliders have been detected at around 50% (DELWP 2021), 47% (Burns and Atkins 2021) and 42% (Rutter and Blake 2020) of sites where they were previously known to occur in Victoria, again pre-fire.

Box 12.2. Assessing the extent of wildlife population loss in Victoria

South-eastern Australia experienced some of the most severe fires of the 2019–20 fire season. In Victoria, more than 1.5 million ha burnt across the eastern side of the state. The Victorian Government invested in monitoring and recovery efforts, seeking to assess the impacts of the fires on species and communities most at risk and to maximise recovery efforts where they were most needed. The government estimated that 244 species of flora and fauna had more than 50% of their modelled habitat burnt, and species and locations were then prioritised for monitoring based on the degree of fire impact, conservation status, and logistics such as seasonal detectability and site access (DELWP 2021). Where monitoring was possible, the existence of contemporary pre-fire data for species was vital for effectively assessing the impacts of fire on species populations.

Post-fire population monitoring found reductions in species persistence for most species assessed (DELWP 2021). These included:

- *Mammals*: In the Eastern Alpine National Park, broad-toothed rats (*Mastacomys fuscus*) persisted at 67% of unburnt sites but only at 25% of burnt sites where they had occurred in the past decade. Among 104 sites assessed, 41 of which had been burnt, spotted-tailed quolls (*Dasyurus maculatus*) were detected at only two sites in the Alpine National Park, both of which were unburnt. Greater gliders persisted at 57% of sites and yellow-bellied gliders persisted at 48–53% of sites within and adjacent to burnt areas in highland forests of East Gippsland where they were known to have occurred previously. Gliders were more frequently detected in unburnt forest or forest that experienced low or medium severity fire than high-severity fire.
- *Birds*: Within highland forests of East Gippsland, there were generally low detection rates for sooty owls (*Tyto tenebricosa*) at surveyed burnt sites (detected at three of 37 sites),

Fig. 12.3. Monitoring before and after the 2019–20 wildfires allowed researchers to document a reduction of local glossy black-cockatoo populations in Victoria to less than a fifth of pre-fire levels (DELWP 2021). (Photo: Peter Menkhorst, DELWP)

powerful owls (*Ninox strenua*) (two of 37 sites), and masked owls (*Tyto novaehollandiae*) (no confirmed detections). Pre-fire surveys of randomly selected habitat identified feeding sign for glossy black-cockatoos (*Calyptorhynchus lathami*) (Fig. 12.3) at 35.7% of sites. This reduced to 6.4% detection in burnt areas after the fires, less than a fifth of pre-fire detection rates. Cockatoo frequency did not change at unburnt sites, suggesting that birds did not disperse from burnt to neighbouring unburnt areas.

- *Frogs*: Spotted tree frogs (*Litoria spenceri*) were detected at three of seven sites where they were previously known to occur and Booroolong frogs (*Litoria booroolongensis*) were detected at both surveyed sites. Martin's toadlet (*Uperoleia martini*) was detected at 36% of sites, green and golden bell frogs (*Litoria aurea*) were detected at 63% of sites, and Keferstein's tree frog (*Litoria dentata*) was not detected at the three surveyed wetlands where each species was known to occur. Blue Mountains tree frogs (*Litoria citropa*) and leaf-green tree frogs (*Litoria nudidigita*) were detected at 57% and 73%, respectively, of sites at which they were previously known to occur, including severely burnt sites.
- *Fish, crayfish and mussels*: All targeted aquatic species in moderate to high intensity burn areas persisted but were affected, with some galaxiids declining in abundance by up to 70%.

An alternative approach to estimating faunal losses in the 2019–20 wildfires was provided by Legge *et al*. (in press). These authors estimated the proportional population loss in the wildfires for many vertebrate species, based on spatial overlap with fires of varying severity and expert elicitation of proportional population loss in fires of varying severity. For the few vertebrate species with plausible total population estimates, this proportional loss can be used to estimate the numbers of individuals killed in the 2019–20 wildfires. One of the few such examples is for the koala. Legge *et al*. (in press) reported that 16.9% of the koala's distribution was burnt in the 2019–20 wildfires (with 6.9% burnt in fires of high severity); they then estimated that, as a consequence, the pre-fire total population of koalas was reduced by 7.15% (with lower and upper bounds of 4.3% and 9.4%). Given that Adams-Hosking *et al*. (2016) estimated the total koala population in 2012 to be 330 000 individuals, it follows that the estimated number of koalas killed in the fires is 23 595 (14 169 to 31 020). Although it is highly likely that an ongoing declining trend for koalas (Woinarski and Burbidge 2020) meant that the population was smaller immediately before the fires than the estimated population in 2012, an estimate of at least 10 000 koalas killed in the fires is plausible. Given that several hundred mammal species occur in the fire-affected regions (Chapter 16), many of which would have far larger population sizes than the koala, and many of these had a higher proportion of their range burnt, it is likely that at least hundreds of thousands, and probably millions, of mammals were killed directly by these fires.

Nonetheless, for these species and most others, there are still not enough available data to make generalisations about immediate or post-fire mortality that might support or conflict with our estimates. Overseas, attempts have been made to assess direct mortality due to fire by systematically counting carcasses immediately after fire, with the magnitude of these tallies demonstrating that wildlife mortality can be very high; for example, extrapolation of transect sampling of corpses after fire estimated that > 15 million vertebrates were killed in a single recent fire event in the Pantanal, South America (Tomas *et al*. 2021).

However, this approach would provide reliable estimates of mortality only for larger and more conspicuous vertebrate species. Otherwise, the existence of pre-fire monitoring data complemented by post-fire assessments is the only way to accurately assess the magnitude of population loss due to fire on resident fauna.

Conclusion

The megafires that ravaged Australian landscapes in 2019–20 focused national and international attention on the causes of the fires and, particularly, their impacts on people and wildlife. Initial concern for wildlife was directed mostly at large charismatic animals such as koalas and kangaroos, but after our estimates that over a billion vertebrates could have been in the path of the fires, much attention focused on the magnitude of the numbers across a broad suite of species. Owing to the paucity of pre-fire surveys the actual impact of the fires on animal mortality could not be quantified directly, and our estimates therefore were based on extrapolations of average animal densities in the habitats that burnt. Restrictions imposed by the COVID–19 pandemic slowed the roll-out of post-fire surveys, but results from current work suggest that the occupancy and abundance of many vertebrate species is much less in burnt than in unburnt forest, and less than before the fires at sites where pre-fire information was available, with this reduction especially pronounced in areas burnt at high severity (Box 12.2). The reduced numbers probably result from animal deaths in the fires and from mortality afterwards in the open and resource-depleted post-fire environment, although the relative contribution of each source of mortality is not known. A key lesson to emerge from our 'critter counts' and attendant media is that wildlife monitoring in much of Australia is sadly lacking, and that a greatly expanded program of ongoing general and targeted surveys must be established if we are to understand and effectively manage the effects of fires and other disturbances, and measure the extent of recovery, in future. In addition to the specific recommendations listed below, we suggest that a dedicated Bureau of Biodiversity be set up to receive, curate and interpret survey and monitoring data so that our management of wildlife can be informed and proactive.

Recommendations

The following recommendations derive mainly from Dickman (2021) and van Eeden *et al.* (2020):

- Undertake long-term species monitoring, including invertebrates, using nationally standardised measures (which may differ for different taxa) in all bioregions, prioritising areas and species or populations at greatest risk of future wildfires, and recovering from past fires.
- Develop strategies to reduce the likelihood of fires of high severity in these areas along with plans to protect these species and communities if such fires occur. This might include improving habitat connectivity to ensure access to fire refuges for mobile species or retrieving threatened species for conservation in captivity until post-fire induced threats are abated (e.g. Ayres *et al.* 2012, DELWP 2021, Lamont *et al.* 2021).
- Identify key resources necessary for the survival of prioritised species and communities (e.g. food or shelter) and compounding threats to these species and communities during post-fire succession (e.g. increased predation risk). We should then be prepared to manage these threats or provide necessary resources to mitigate fire risks and post-fire mortality.

- Experimentally evaluate the effectiveness of different post-fire management methods to ensure effective management of prioritised species and communities in the event of fire.
- Adopt population viability analysis (PVA) for selected species as a useful tool for modelling the effects of disturbance events (in this case, wildfire) where basic demographic traits are known (Glen and Dickman 2013). At present, we make assumptions about the impacts of fires on species based on their habits and the extent of their range that has been burnt, but PVA would allow stronger quantification. PVA appears to be as yet underutilised for assessments of fire impacts.

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References

Academy of Science (2020) Environment reform must include a 'Biodiversity BOM'. Australian Academy of Science, <https://www.science.org.au/files/userfiles/support/position-statements/environment-reform-must-include-biodiversity-bom.pdf>.

Adams-Hosking C, McBride MF, Baxter G, Burgman M, De Villiers D, *et al.* (2016) Use of expert knowledge to elicit population trends for the koala (*Phascolarctos cinereus*). *Diversity & Distributions* **22**, 249–262. doi:10.1111/ddi.12400

Ayres R, Nicol M, Raadik T (2012) *Establishing New Populations for Fire-affected Barred Galaxias (*Galaxias fuscus*): Site Selection, Trial Translocation and Population Genetics. Black Saturday Victoria 2009 – Natural Values Fire Recovery Program*. Arthur Rylah Institute for Environmental Research, Department of Sustainability and Environment, Heidelberg,. <https://www.ari.vic.gov.au/__data/assets/pdf_file/0023/34952/VBRRA-P14b-web.pdf>.

Bowman D, Williamson G, Yebra M, Lizundia-Loiola J, Pettinari ML, *et al.* (2020) Wildfire: Australia needs a national monitoring agency. *Nature* **584**, 188–191. doi:10.1038/d41586-020-02306-4

Burns PA, Atkins ZS (2021) 'Gliding from the ashes: Post-fire surveys for the greater glider and yellow-bellied glider in Far East Gippsland'. Unpublished report for Aussie Ark Australian Endangered Species Recovery Fund.

Chapman AD (2009) 'Numbers of living species in Australia and the world. Report for the Australian Biological Resources Study, 2nd edition'. Department of the Environment, Water, Heritage, and the Arts. Australian Government, Canberra, <https://www.environment.gov.au/system/files/pages/2ee3f4a1-f130-465b-9c7a-79373680a067/files/nlsaw-2nd-complete.pdf>.

Collins L, Bradstock RA, Clarke H, Clarke MF, Nolan RH, *et al.* (2021) The 2019/2020 mega-fires exposed Australian ecosystems to an unprecedented extent of high-severity fire. *Environmental Research Letters* **16**, 044029. doi:10.1088/1748-9326/abeb9e

DAWE (2020) *Australian Google Earth Engine Burnt Area Map: A Rapid, National Approach to Fire Severity Mapping.* Department of Agriculture, Water and the Environment (DAWE), Canberra.

DELWP (2021) *Biodiversity Bushfire Response Supplementary Report: Bushfire Impacts on Species in Victoria*. Department of Environment, Land, Water and Planning (DELWP), Melbourne.

Dickman CR (2021) Ecological consequences of Australia's 'Black Summer' bushfires: managing for recovery. *Integrated Environmental Assessment and Management* **17**, 1162–1167. doi:10.1002/ieam.4496

Dickman CR, McDonald T (2020) Some personal reflections on the present and future of Australia's fauna in an increasingly fire-prone continent. *Ecological Management & Restoration* **21**, 86–96. doi:10.1111/emr.12403

Fox A (1978) The '72 fire of Nadgee Nature Reserve. *Parks & Wildlife* **2**, 5–24.

Garnett ST, Baker GB (Eds) (2021) *The Action Plan for Australian Birds 2020*. CSIRO Publishing, Melbourne.

Glen AS, Dickman CR (2013) Population viability analysis shows spotted-tailed quolls may be vulnerable to competition. *Australian Mammalogy* **35**, 180–183. doi:10.1071/AM12045

Hood JB (1941) Birds and bushfires. *South Australian Ornithologist* **15**, 125–127.

Johnson C, Cogger H, Dickman C, Ford H (2007) 'Impacts of landclearing: the impacts of approved clearing of native vegetation on Australian wildlife in New South Wales'. Report prepared for WWF-Australia, Sydney.

Jolly CJ, Dickman CR, Doherty TS, van Eeden LM, Geary WL, *et al*. (2022) Animal mortality during fire: a global systematic review. *Global Change Biology* **28**, 2053–2065. doi:10.1111/gcb.16044

Lamont A, Parrott M, Wicker L, Banks C, Lang M, *et al*. (2021) Building wildlife resilience in disasters. *Australian Journal of Emergency Management* **36**, 12–14.

Legge S, Lindenmayer DB, Robinson NM, Scheele BC, Southwell DM, *et al*. (Eds) (2018) *Monitoring Threatened Species and Ecological Communities*. CSIRO Publishing, Melbourne.

Legge S, Rumpff L, Woinarski JCZ, Whiterod NS, Ward M, *et al*. (in press) The conservation impacts of ecological disturbance: time-bound estimates of population loss and recovery for fauna affected by the 2019–20 Australian megafires. *Global Ecology and Biogeography*, doi:10.1111/geb.13473.

Lindenmayer DB, Burns E, Thurgate N, Lowe A (Eds) (2014) *Biodiversity and Environmental Change: Monitoring, Challenges and Direction*. CSIRO Publishing, Melbourne.

Lindenmayer DB, Taylor C (2020) New spatial analyses of Australian wildlife highlight the need for new fire, resource, and conservation policies. *Proceedings of the National Academy of Sciences of the United States of America* **117**, 12481–12485. doi:10.1073/pnas.2002269117

Nimmo DG, Avitabile S, Banks SC, Bliege Bird R, Callister K, *et al*. (2019) Animal movements in fire-prone landscapes. *Biological Reviews of the Cambridge Philosophical Society* **94**, 981–998. doi:10.1111/brv.12486

Nimmo DG, Carthey AJR, Jolly CJ, Blumstein DT (2021) Welcome to the Pyrocene: animal survival in the age of megafire. *Global Change Biology* **27**, 5684–5693. doi:10.1111/gcb.15834

Rutter N, Blake B (2020) 'Post-fire assessment of Greater Gliders in East Gippsland: interim report'. WWF-Australia, Sydney.

Santini L, Isaac NJB, Ficetola GF (2018) TetraDENSITY: a database of population density estimates in terrestrial vertebrates. *Global Ecology and Biogeography* **27**, 787–791. doi:10.1111/geb.12756

Saunders ME, Barton PS, Bickerstaff JRM, Frost L, Latty T, *et al*. (2021) Limited understanding of bushfire impacts on Australian invertebrates. *Insect Conservation and Diversity* **14**, 285–293. doi:10.1111/icad.12493

Smith P, Smith J (2021) 'Post-fire survey of arboreal mammals at Wombeyan and Jenolan – interim report. Report prepared For Glideways'. The Great Eastern Ranges and WWF-Australia, Sydney.

Tomas WF, Berlinck CN, Chiaravalloti RM, Faggioni GP, Strussmann C, *et al*. (2021) Counting the dead: 17 million vertebrates directly killed by the 2020's wildfires in the Pantanal Wetland, Brazil. *Scientific Reports* **11**, 23547. doi:10.1038/s41598-021-02844-5 van Eeden LM, Nimmo D, Mahony M, Herman K, Ehmke G, *et al*. (2020) 'Impacts of the unprecedented 2019–2020 bushfires on Australian animals'. Report prepared for WWF-Australia, Sydney.

Wintle BA, Legge S, Woinarski JCZ (2020) After the megafires: what next for Australian wildlife? *Trends in Ecology & Evolution* **35**, 753–757. doi:10.1016/j.tree.2020.06.009

Woinarski J, Burbidge AA (2020) *Phascolarctos cinereus* (amended version of 2016 assessment). The IUCN Red List of Threatened Species 2020: e.T16892A166496779, <https://www.iucnredlist.org/species/16892/166496779>.