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RESEARCH ARTICLE

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Rapid assessment of the biodiversity impacts of the 2019–2020 Australian megafires to guide urgent management intervention and recovery and lessons for other regions

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Abstract

Aim: The incidence of major fires is increasing globally, creating extraordinary challenges for governments, managers and conservation scientists. In 2019–2020, Australia experienced precedent-setting fires that burned over several months, affecting seven states and territories and causing massive biodiversity loss. Whilst the fires were still burning, the Australian Government convened a biodiversity Expert Panel to guide its bushfire response. A pressing need was to target emergency investment and management to reduce the chance of extinctions and maximise the chances of longer-term recovery. We describe the approach taken to rapidly prioritise fire-affected animal species. We use the experience to consider the organisational and data requirements for evidence-based responses to future ecological disasters.

Location: Forested biomes of subtropical and temperate Australia, with lessons for other regions.

Methods: We developed assessment frameworks to screen fire-affected species based on their pre-fire conservation status, the proportion of their distribution overlapping with fires, and their behavioural/ecological traits relating to fire vulnerability. Using formal and informal networks of scientists, government and non-government staff and managers, we collated expert input and data from multiple sources, undertook the analyses, and completed the assessments in 3 weeks for vertebrates and 8 weeks for invertebrates.

Results: The assessments prioritised 92 vertebrate and 213 invertebrate species for urgent management response; another 147 invertebrate species were placed on a watchlist requiring further information.

Conclusions: The priority species lists helped focus government and non-government investment, management and research effort, and communication to the public. Using multiple expert networks allowed the assessments to be completed rapidly using the best information available. However, the assessments highlighted substantial gaps in data availability and access, deficiencies in statutory threatened species listings, and the need for capacity-building across the conservation science and management sectors. We outline a flexible template for using evidence effectively in emergency responses for future ecological disasters.

KEYWORDS
ecological disturbance, emergency response, fire impacts, fire management, megafire, rapid assessment, wildfire

1 | INTRODUCTION – THE 2019–2020 AUSTRALIAN MEGAFIRES

Fire has shaped ecosystems globally for hundreds of millions of years (Bowman et al., 2009; He et al., 2019). However, the combination of anthropogenic climate and land use change is increasing the likelihood of major fires, often termed 'megafires' (Bowman, Kolden, et al., 2020; Jolly et al., 2015). Fire seasons are lengthening, and fires are becoming more frequent and severe, in ecosystems as diverse as the Arctic (McCarty et al., 2020) to the forests of western North America (Higuera & Abatzoglou, 2020), and the tropical wetlands of the South American Pantanal (Garcia et al., 2021). Much biodiversity may be lost as fire regimes change, especially if conservation managers are poorly prepared, responding after the event slowly, without well-established objectives and priorities, and without adequate resources.

The 2019–2020 fires in the forests of eastern and southern Australia were extraordinary, even in the context of the increasing global occurrence of major fires. A 3-year drought, culminating in record-setting dry and hot temperatures, created extreme fire weather conditions (King et al., 2020; Nolan et al., 2020; Van Oldenborgh et al., 2021). Between September 2019 and March 2020, fires killed 33 people, destroyed 3000 houses, and burned over 10 million hectares of habitat for native plants and animals (Bowman, Williamson, et al., 2020; Ward et al., 2020). Many aquatic habitats within and downstream of burnt areas were also impacted when post-fire rain washed heavy sediment and nutrient loads into waterways (Lyon & O'Connor, 2008; Silva et al., 2020). Ecosystems that rarely, if ever, experience fire burned, including World Heritage-listed subtropical Gondwanan rainforests (DPIE, 2020a; Kooyman et al., 2020). Over 20% of Australia's eucalypt forests burned, which is much higher than the annual average for this biome (2%), and much higher than forest biomes on any other continent over the past 20 years (Boer et al., 2020; Bowman, Williamson, et al., 2020). The 2019–2020 fires burned over a period that was longer, and at severities that were higher, than previously experienced for Australia's forested biomes (Collins et al., 2021; Lindenmayer & Taylor, 2020; Wintle et al., 2020), setting a precedent for the new fire future under hotter and drier conditions (Pyne, 2020).

Australia is the most fire-prone continent, contributing an average of over 14% of the world's total annual fire extent despite comprising just 6% of the land area excluding Antarctica (Murphy et al., 2019). Much of Australia's biota has evolved to co-exist with fire (Bowman et al., 2012; Gill et al., 1999), but larger high severity fires with shorter inter-fire intervals will exceed the tolerances of some species, and likely cause population declines and extinctions (Williams et al., 2009). Severe fires can directly kill individuals and cause elevated mortality for months after the fire due to a lack of resources (food, water, shelter), increased sedimentation and deteriorating water quality in waterways, and heightened exposure to other threats such as introduced predators, herbivores, and disease (Whelan et al., 2002). In some circumstances, fires can cause key habitat resources (e.g. large tree hollows) to be rare for decades after the fire event, potentially hastening declines and local extinctions for species depending on those resources (Haslem et al., 2011; Lindenmayer et al., 2020).

After fire, populations usually recover by dispersal from nearby unburnt areas as well as in-situ reproduction (Banks et al., 2017). In 2019–2020, the extent and severity of the fires was such that mortality during and after the fire was potentially higher than usual: early analyses estimated that three billion mammals, birds and reptiles were killed, displaced, or otherwise affected (van Eeden et al., 2020). The scale of the fires was such that unburnt refuges within largely burnt landscapes were absent, or very small in contrast to the areas burnt (Collins et al., 2021), diminishing the potential for nucleated recovery (sensu Banks et al., 2017). Compounding this issue, many species were already declining, fragmented, or had reduced populations before the fires due to extended drought, and from ongoing threats such as previous fires, habitat loss, introduced species and disease (Geyle et al., 2018, 2020; Gillespie et al., 2020; Lintermans et al., 2020).

1.1 | Developing a strategic national response

By December 2019, the mid-point of the fire season, the scale of the unfolding catastrophe in southern Australia was apparent. State governments began emergency operations for a very small proportion of threatened species that were in the fire's path. This included suppressing fire around stands of the iconic and critically endangered wollemi pine (*Wollemia nobilis*) (Morton, 2020); emergency rescue of threatened freshwater fish, crayfish, mussels, and birds; and collecting cuttings from highly endangered plants (Clarke et al., 2020; Lintermans, 2020; Soebridge & Marciniak, 2020). Animal rescue groups were working at capacity to reduce the suffering of injured animals, and food and water were provided to species with high public appeal (e.g. brush-tailed rock-wallabies [*Petrogale penicillata*]; koala [*Phascolarctos cinereus*]) (DPIE, 2020b). A preliminary spatial analysis revealed that 327 (of the ca. 1800) nationally threatened plants and animals were potentially affected by the fires (DAWE, 2020e). The fire-affected areas were so large, that even species previously considered secure were now the subject of concern. The Victorian Government''s preliminary assessment estimated that 176 previously non-threatened species had distributions that overlapped with fires by at least 50%, and their status was now uncertain (DELWP, 2020a).

There were no pre-existing contingency plans or response packages for fires of this scale and duration (Dickman et al., 2020), which met the criteria to be recognised as a 'catastrophic disaster' as defined by the Australian Institute for Disaster Resilience (e.g. impacts greater than previous experience, multi-jurisdictional, causing severe disruption to community and environment, AIDR, 2009). By early January 2020, state and territory governments were, to varying degrees, initiating processes to develop strategic responses within their jurisdictions (DELWP, 2020a, 2020b; DPIE, 2020a, 2020b; Threatened Species Operations, 2020). However, the scale of the fires meant that a national perspective and coordination was also crucial: the fires occurred over seven states and territories, affecting species with distributions that extended across multiple jurisdictions. In addition, the Australian Government has legislative responsibilities to protect species listed as nationally threatened.

In early January 2020, the Australian Government convened a Wildlife and Threatened Species Bushfire Recovery Expert Panel (whose membership included this paper's co-authors) to help guide the national response for fire-affected biodiversity. The panel comprised eight independent environmental scientists representing a broad range of ecological and conservation management expertise, including fire ecology and management, conservation of threatened species, structured decision-making and ex situ conservation, and an Indigenous environmental expert. Senior representatives from the fire-affected states and territory were present as observers, and the Australian Government staff administered the Panel. It provided a mechanism for developing, prioritising and coordinating responses across governments and regional management delivery structures and integrating these efforts with the broader conservation and science community. The Expert Panel set objectives to guide immediate recovery efforts (Expert Panel, 2020) and began identifying the fire-affected biodiversity in greatest need of emergency actions and advising on what those actions should be. The Expert Panel commissioned rapid assessments of fire impacts on animals (reported here), plants (Gallagher, 2020), ecological communities (Keith et al., 2020) and World Heritage Areas (DAWE, 2020e), from experts in their fields who are well networked to other experts. The assessments covered species and communities within temperate and subtropical bioregions that experienced highly anomalous fire (DAWE, 2020c).

In this paper, we describe the approach taken to prioritise animal species for urgent management intervention. The available information was imperfect, yet the task was extremely pressing: extinctions were possible if populations of already imperilled species were not rescued or immediately buffered from post-fire threats. The assessments were completed in 3 weeks for vertebrates and 8 weeks for invertebrates, and involved inputs from 34 vertebrate species experts, 35 invertebrate species experts, 15 spatial analysts, and 13 scientists with additional relevant expertise. These experts were drawn from government, universities, and non-government organisations and accessed through the connections of a team of 7 lead scientists with expertise across the animal taxa in the assessment. Throughout the work, we also engaged with 33 staff from state and Australian governments who coordinated the emergency response for their agencies (see author list and acknowledgements), some of whom helped develop the assessment framework. In the Discussion, we summarise how the information has been used in the fire recovery effort, and we reflect on what made the task possible, what the barriers were, and how such a process could be improved and better-enabled in the future. Our assessment reveals important lessons for incorporating evidence into emergency responses to minimise biodiversity loss following major and catastrophic ecological disasters.

2 | METHOD – RAPID ASSESSMENT APPROACH

The purpose of our rapid assessment was to identify the animal species (and for some taxonomic groups, subspecies) that were likely most affected, and potentially brought closer to extinction because of the fires, and the actions that would limit further decline and support recovery in the year after fire. Below, we separately describe how the information for vertebrates and invertebrates was gathered, categorised and used in a vulnerability assessment framework. More detailed information is available in the Supporting Information and in DAWE (2020e).

2.1 | Vertebrates

We assessed vertebrate species (including some cryptic taxa not yet formally described, but for which there is unpublished genetic evidence to support recognition) with distributions that overlapped with the fire extent, whether listed as threatened or not, because the fires were so extensive that even non-threatened species with relatively large distributions could now be potentially at risk. We collated information on three factors that contribute to the relative vulnerability of a species to the immediate and short-term (0–12 months) impacts of fire: pre-fire conservation status; the proportion of its distribution that overlapped with fire; and the physical, behavioural and ecological traits that influence mortality during and after fire.

1. *Pre-fire conservation status*. Species at greater risk of extinction before the fires were considered more likely to need intervention than non-threatened species. We used conservation assessments from several sources, including those from Australia's national environmental legislation, the Environment Protection and Biodiversity Conservation Act 1999 (EPBC Act); the IUCN Red List of Threatened Species; action plans for Australian reptiles, birds and mammals (Chapple et al., 2019; Garnett et al., 2011; Woinarski et al., 2014); and reviews carried out by expert groups including the Australian Society for Fish Biology (Lintermans, 2019) and a recent review of Australian frogs (Gillespie et al., 2020), as measures of pre-fire imperilment, as these listings consider extinction risks across multiple features (e.g. area of occupancy, rate of decline, population size). Given the discrepancies in data sources and the large number of species to assess, the leads of each vertebrate class scored each species from 0 to 4, with the higher scores given to species with poorer conservation status (Critically Endangered [4], Endangered [3], Vulnerable [2], Data Deficient [2], Near Threatened [1], Migratory [1], not listed or Least Concern [0]). However, threatened species listings do not always match the true status of species, particularly for some groups such as fish and frogs, where comprehensive listing assessments are less current, or taxonomic revisions have been frequent (Lintermans et al., 2020). The conservation status for five species was therefore adjusted based on expert input. In addition, many fish and frog species are highly range-restricted, with populations in rapid decline, potentially increasing vulnerability to fire events; we scored these species higher than species whose populations were not declining and not range-restricted (details in Supplementary Information).
2. *Proportion of distribution overlapping the fire extent*. We regarded the spatial overlap between the fires and a species geographic range as a rough but readily measurable surrogate for the potential scale of impact of the fires on a given species. Species whose distributions overlapped more substantially with fires were considered likely to need management intervention. For fire extent, we used the National Indicative Aggregated Fire Extent Dataset (DAWE, 2020b) within the subtropical and temperate bioregions affected by the fires (DAWE, 2020c) (Figure 1a). This dataset describes the boundaries of fire-affected areas, without providing information on the severity of fire, nor whether unburnt refuges exist within the boundaries. Overlapping this dataset with

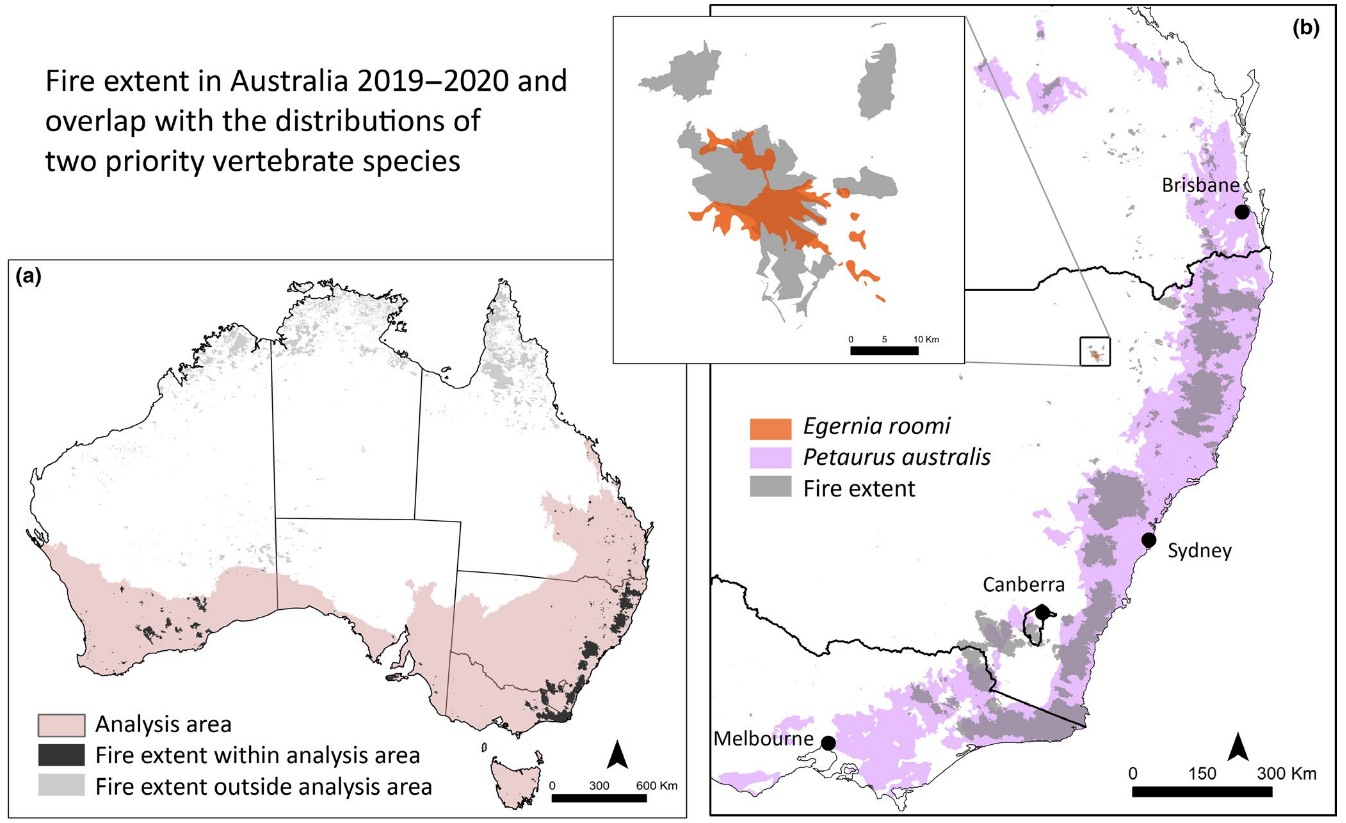


FIGURE 1 (a) The fire extent in Australia for 2019–2020; and the analysis area, which includes the temperate and subtropical forested biomes, and where the 2019–2020 fires were highly anomalous in terms of extent and severity. Species with distributions within or overlapping the fire extent in the analysis area were the focus of the rapid assessment. (b) The extent of the 2019–2020 fires in south-eastern Australia over the distributions of two priority species, one with a small range, the Mt. Kaputar rock skink (*Egernia roomi*), and the other with a much larger range, the yellow-bellied glider (*Petaurus australis*), demonstrating that priority species had a range of distribution sizes

species distributions could overestimate potential impacts on species; however it was the only nationally consistent fire extent data available at the time. There is no single source of distribution data for Australian species; thus we collated species distribution information from multiple sources (Table S1.1), including species distribution models developed by the Australian Department of Agriculture, Water and the Environment (DAWE), range maps from recent IUCN Red List assessments, species observation records from DAWE's Species Observation System (SOS), the Atlas of Living Australia (ALA), and BirdLife Australia. For fish, we also considered the potential impacts of sedimentation arising from burnt landscapes up to 80 km upstream (Lyon & O'Connor, 2008). The leads for each vertebrate class worked with 13 spatial analysts across universities and governments to complete these analyses.

The various distribution datasets, and the spatial analyses that were possible given the nature of those datasets, suffer from idiosyncratic biases and limitations, which made comparing fire overlaps across and even within taxonomic groups, difficult. To increase our confidence in the results, we estimated fire overlaps using alternative distribution datasets and spatial analyses (Supporting Information). Where alternative fire overlap estimates diverged markedly, we considered the likely biases of the respective methods and made judgement calls (vertebrate class leads with relevant species experts) on the most appropriate method(s). Finally, to address issues of multiple data sources of varying quality, we categorised the fire overlap estimate for each species from 1–4, with high overlaps receiving the highest score, as follows: >80% (4); 50%–80% (3); 30%–50% (2); 10%–30% (1). These groupings were based on the thresholds for population decline used in Criterion A of IUCN Red List assessment guidelines (where an 80% decline is a threshold value for CR, a decline of 50%–80% is EN, 30%–50% is VU, and approaching 30% is NT).

Pre-fire conservation status and fire overlap were categorised so that the assessment could rapidly use different data sources and encompass uncertainty.

3. *Physical, behavioural and ecological traits*. The survival of individuals through fire events partly depends on their ability to flee the fire front (or sediment event), or to shelter from it, for example in a deep burrow (Whelan et al., 2002). After fires, surviving individuals of species with specialised requirements for habitat, shelter, or food may be at greater risk of

mortality. Depending on the taxonomic group, we collated information on traits relating to their ability to flee or shelter from fire; traits relating to dietary or habitat specialisation (including reliance on unburnt habitat); traits relating to their ability to persist in the post-fire environment, such as area requirements and ability to disperse, reliance on social groups, and susceptibility to introduced species. For fish and crayfish, in addition to dietary and habitat specialisations, movement and spawning ecology, we considered sensitivity to dissolved oxygen, sediment inputs, and degradation to riparian vegetation caused by introduced species (Table S1.2). The trait information was assembled by the leads for the 5 vertebrate classes, using published sources and grey literature, supplemented by input from some of the additional 28 vertebrate experts (details in Supporting Information). The information for each trait was scored, with higher scores inferring greater vulnerability to fire. For each species, we summed scores across all traits. Thus, within taxonomic groups, species with high summed trait scores were considered relatively more vulnerable to fire than species with low scores.

2.1.1 | Assessment framework

The vulnerability assessment framework relied on the collation of continuous and discrete data from different sources, of varying quality. Of the three factors we considered, we were most confident about the conservation status, variably confident about the overlap of fires with species distribution (because of variability in quality of species distribution data), and least confident about the strength of the relationship between species traits and fire impacts. We therefore designed the framework to have discrete steps, where conservation status and fire overlap were afforded greater leverage than the trait score (Figure 2). First, we limited the species set to those with fire overlaps greater than defined thresholds (≥10% for threatened species, ≥30% for non-threatened species). These thresholds were chosen because a 30% population decline could cause a previously secure species to be eligible under Criterion A of IUCN Red List guidelines; a 10% population decline could push a listed species into a higher threat category. Second, in this species set, we considered their pre-fire conservation status and fire overlap and immediately prioritised species that were highly threatened before

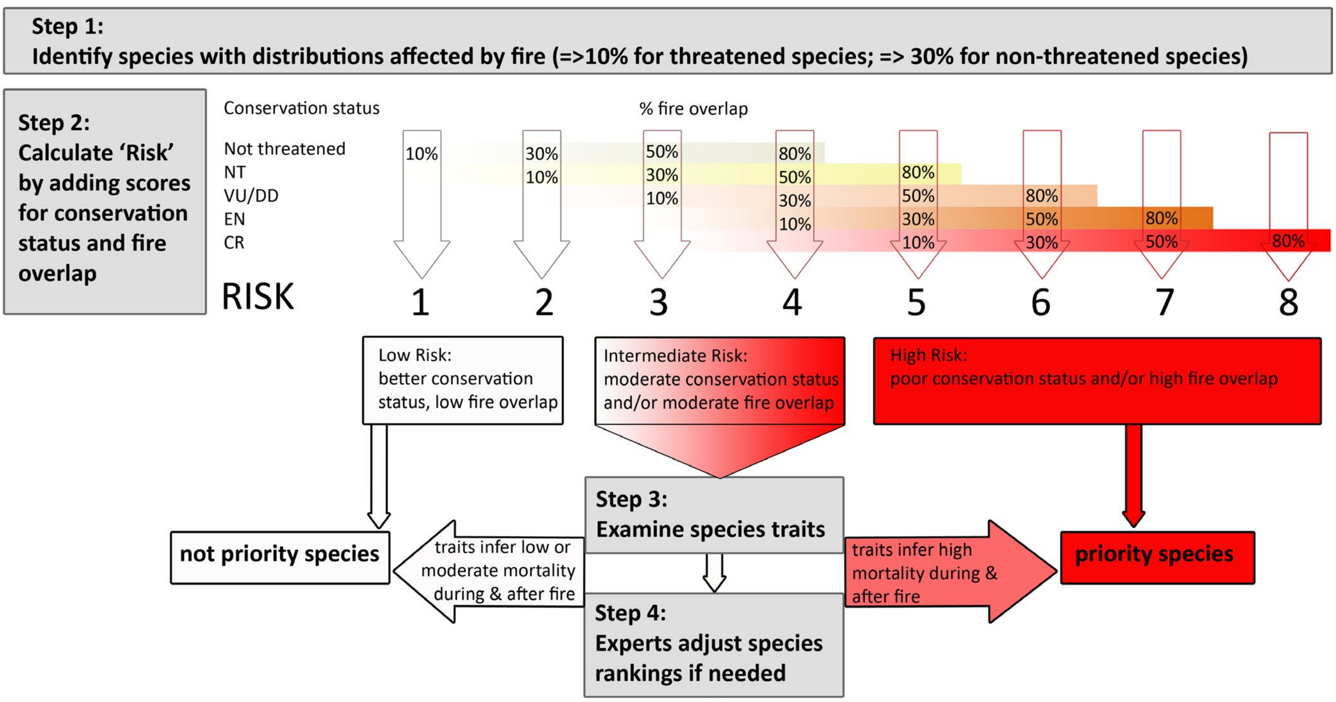


FIGURE 2 The diagram illustrates how the combination of conservation status, fire overlap, and species traits were used to prioritise species for emergency intervention (0–12 months after fire). Step 1: Identify species with distributions affected by fire (≥10% for threatened species; ≥30% for non-threatened species). Step 2: Add scores for conservation status and fire overlap to calculate 'risk' score. Species that were highly threatened before the fire, and had large proportions of their distribution burnt, had the highest risk scores and were immediately prioritised for urgent management intervention. Conversely, species that were not threatened and had <50% of their distribution burnt were not prioritised. Although such species may still benefit from actions to support recovery, they were less at risk from extinction than other fire-affected species. Step 3: Species with intermediate risk scores (indicating moderate pre-fire conservation status and/or moderate fire overlap values) were ranked within their taxonomic groups according to their trait score for fire vulnerability. Species with trait scores greater than the mean for the taxonomic group were also prioritised for immediate action. Step 4: The ordering of species, especially near the threshold for inclusion as a priority species, was checked by taxon experts for rankings that seem misplaced (species ranked too high, or too low), who could argue for adjustments to the rankings, or for the inclusion of borderline species on precautionary grounds

the fire, with large proportions of their distribution overlapping the fire extent. Third, of the species not immediately prioritised, we considered those with moderate pre-fire imperilment and/or moderate fire overlap scores and prioritised those species with relatively high trait scores (i.e. trait scores exceeding the mean for the taxonomic group), inferring relatively greater vulnerability during and immediately after the fire. Last, the list of species was checked by the lead for each class, who consulted with other experts and could argue for adjustments, or for the inclusion of borderline species on precautionary grounds (Figure 2). This was done, for instance, in instances where narrowly distributed but unlisted species had very high overlap with the fires, even if their traits would suggest resilience to fire.

We released the original assessment results in early February 2020, followed by a revised version in mid-March after the fires were mostly extinguished (Legge et al., 2020). The revision included updates to the fire extent and additional input from management agencies on fire overlap, fire vulnerability, or pre-fire conservation status for a few species. We report on the revised assessment in this paper.

2.1.2 | Guidance for priority activities for each species

Appropriate management inventories did not exist for most priority species, partly because the 2019–2020 fires were of a severity and extent outside the experience of conservation managers, and partly because species not normally exposed to fire were impacted (e.g. species in temperate and subtropical rainforests). The Expert Panel identified a set of priority activities required in the 0–12 months post-fire (Expert Panel, 2020). In this rapid assessment, we used the species trait collation to infer which of these activities were in scope for each species. For example, if a species had high susceptibility to introduced predators after fire, then predator control or exclusion was in-scope. If a species scored highly for dietary specialisation, then supplementary feeding could be an option (Figure 3). We also identified additional actions that were critical for a species but did not fall into one of the activity classes originally identified by the Panel.

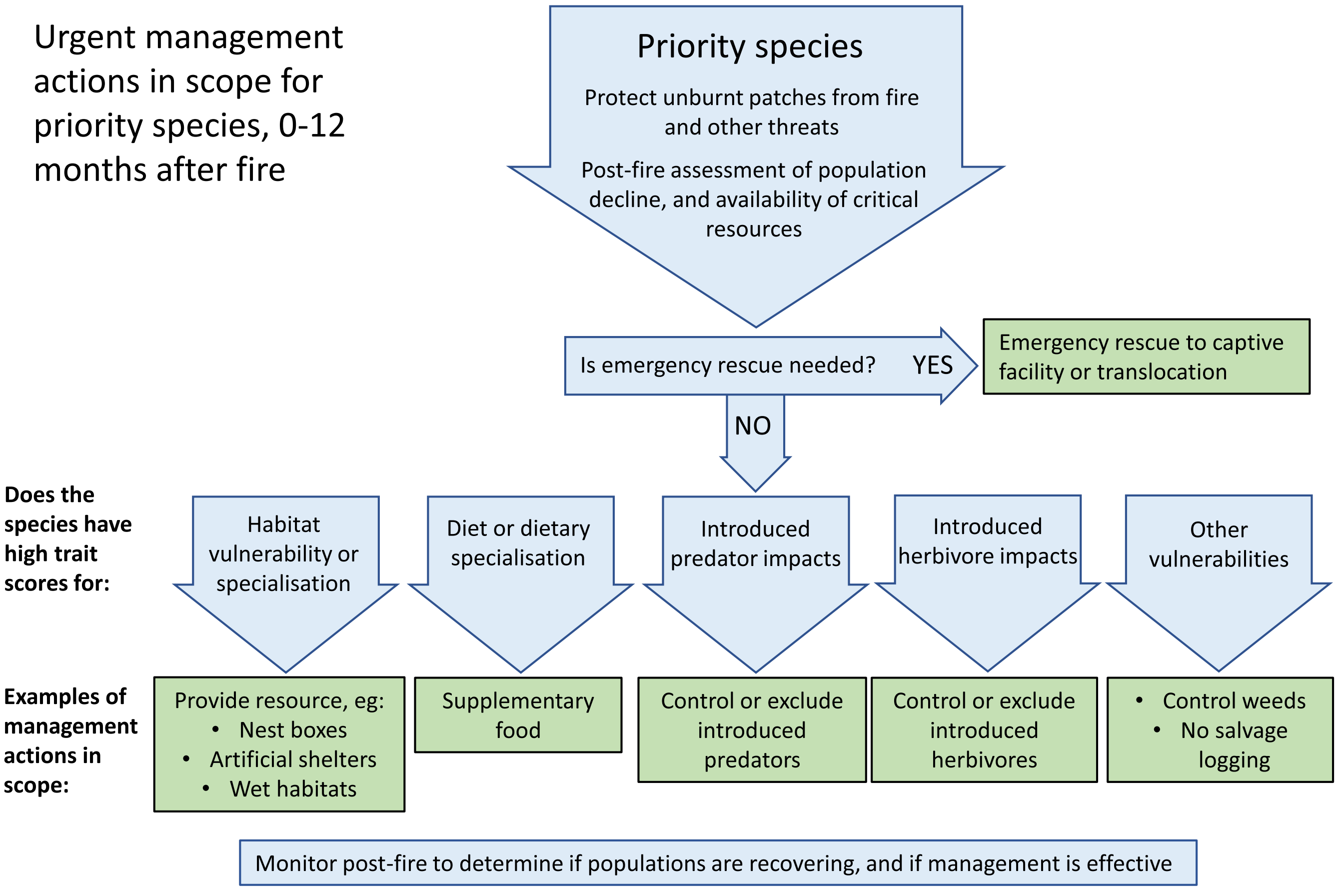


FIGURE 3 Schema illustrating how the trait analysis was used to identify actions in scope for each priority species. Protecting unburnt areas and rapid post-fire assessment of population decline and resource availability were in-scope for all priority species. Other actions varied across species and were usually related to the species' traits. Funding was focussed towards in-scope actions for each priority species

2.2 | Invertebrates

2.2.1 | Assessment framework

Invertebrate groups with sufficient information readily available on their population status, distribution and ecologies were assessed similarly to vertebrates; this included invertebrate species listed as nationally threatened and spiny crayfish (*Euastacus* spp.), one of the most threatened genera in the world (Richman et al., 2015). For other invertebrates, we considered conservation status and fire overlap alone.

We could not assess fire impacts comprehensively across all invertebrate species in the time required to prioritise urgent management response, because there are a much larger number of species (>300,000 Australian invertebrate species); many species are undescribed; distributional information for most named invertebrates is scant and scattered; and there is limited information on the vulnerability of most invertebrates to fire. Furthermore, many invertebrate species have complex life histories that meant that fire impacts could have varied substantially depending upon the proportion of the population in particular life stages at the time of fire.

More pragmatically than for vertebrates, we adopted several complementary approaches in developing a priority list of fire-affected invertebrate species. First, we assessed fire overlap for all invertebrates listed as threatened by the IUCN, Australian government or by state and territory governments (ca. 800 species). Second, we assessed invertebrate species considered significantly fire-affected by state and territory agencies and by a suite of experts, with this set of candidate species developed in part through an expert workshop. Third, we used expert networks to derive priority species lists for particular fire-affected regions (Kangaroo Island and Stirling Range) known to host high numbers of short-range endemics. Fourth, we assessed some invertebrate groups that were unusually data-rich, including butterflies, landsnails and some beetle groups. Thirty-five invertebrate experts contributed to this information gathering, supplemented by additional advice on the assessment framework from eight experts, and with active engagement from the group of 33 government representatives involved in delivering the emergency on-ground response.

As for vertebrates, we estimated the proportion of the distribution that was burnt using several analytical approaches (Appendix S1, DAWE, 2020e). Distributional data were also collated from multiple sources, including the Atlas of Living Australia, Species Observation System (mostly for nationally listed species) and some other institutional sources (e.g., the Australian Museum). Invertebrate species experts worked with six spatial analysts on this task.

Results were grouped based on the pre-fire conservation status, the number of observation records available (reflecting confidence in the analysis) and the extent of the fire overlap of those observations. We included in the priority list all threatened species known or presumed to have had at least 30% of their distributions overlapping the 2019–2020 fires and non-threatened species with at least 50% of their known or presumed distributions overlapping the 2019–2020 fires. We also compiled a list of invertebrate species that were priorities for further assessment, because although they had probably experienced substantial fire overlap the very limited distributional data (typically fewer than five records) lowered our confidence in the results. Results were collated and published in April 2020, ca. 4–6 weeks after extinguishment of the last fires of the season (Woinarski, 2020).

2.2.2 | Guidance for priority activities for each species

There is little guidance available for post-fire recovery actions for most invertebrate species. Although we developed a set of priority management responses for fire-affected invertebrate species in one area, Kangaroo Island, through a broader workshop process, we did not compile such a catalogue of recovery actions across all priority invertebrates.

3 | RESULTS – ASSESSMENT OUTCOMES

3.1 | Vertebrates

In the first step of the assessment, focusing on the temperate and subtropical bioregions that experienced major fires in 2019–2020, we found that 70 threatened vertebrate taxa had distributions with fire overlaps of ≥10% and 80 non-threatened vertebrate taxa had distributions with fire overlaps of ≥30%.

Of the set of 150 vertebrate taxa, we prioritised 92 taxa (17 bird, 20 mammal, 23 reptile, 16 frog and 16 fish taxa) for urgent management intervention (Table S1.3). Half of these were prioritised because they had a high risk score, 30 were prioritised because they had intermediate risk scores and high trait scores, and 16 were added because they were on the borderline for inclusion and experts took a precautionary approach and recommended to provisionally include until further information could be obtained (e.g. from on-ground surveys or new spatial datasets; Figure S1.1). Priority vertebrates included species with large and small ranges (Figure 1b), but prioritised species that were considered secure before the fires tended to have higher fire overlap estimates than threatened species (Table 1). Priority vertebrate species were distributed all around the southeast coast, with different classes more or less represented in different regions (Figure 4).

3.1.1 | Guidance for priority activities for each species

The in-scope priority activities varied across the vertebrate groups (Figure 5). Emergency rescue (into ex situ or to other habitat) was most frequently indicated as a priority for aquatic species.

TABLE 1 Summary of the fire overlaps for the priority animal species in each vertebrate group

Vertebrate group	Status	% fire overlap				Group total
		10%–30%	30%–50%	50%–80%	>80%	
Fish	Threatened	0	0	3	13	16
	Non-threatened	0	0	0	0	
Frogs	Threatened	5	5	6	0	16
	Non-threatened	0	0	0	0	
Reptiles	Threatened	8	2	5	0	23
	Non-threatened	3	4	0	1	
Birds	Threatened	4	6	2	0	17
	Non-threatened	0	3	1	1	
Mammals	Threatened	8	5	5	1	20
	Non-threatened	0	1	0	0	
Total	Threatened	25	18	21	14	92
	Non-threatened	3	8	1	2	

Sedimentation events in waterways were considered to have a high risk of causing rapid extinction in aquatic taxa when populations occur in just one or two waterways, and the most feasible intervention to prevent extinction in such cases was judged to be emergency salvage. Controlling introduced herbivores and predators was most commonly indicated for mammals and reptiles, both groups having high proportions of ground-dwelling species that rely on vegetation cover for resources and to avoid predation. Common additional actions across species included weed control, avoiding salvage logging, and, to a lesser extent, preventing human disturbance, suggesting these actions should be included as priority activities in future fire responses (Figure 5).

3.2 | Invertebrates

Of the invertebrates assessed using the vertebrate framework, fire overlaps exceeded 10% for 25 crayfish species listed by the IUCN Red List; another 7 unlisted crayfish species had fire overlaps exceeding 30%. Of these 32 species, 22 species were prioritised on the basis of either a high risk score (15 species) or an intermediate risk score coupled with concern that the extent of fire overlap was higher than suggested by the desktop analysis (7 species) (Table S1.4). In the broader invertebrate analysis, 191 invertebrate species (including 49 species listed as threatened pre-fire) were identified as priorities for post-fire management, typically with fire overlaps of over 30% (if threatened) and over 50% (if not threatened) (Table S1.5). A further 147 species were prioritized for further assessment because of concern about possible high fire impact (Table S1.6). Most of the priority invertebrates were short-range endemics with high fire overlap: at least five threatened invertebrate species had their entire known range burnt, as had many species not yet listed as threatened. This pattern (high fire overlap for many short-range invertebrate species) has also been reported in a subsequent independent analysis, at a more local scale (the state of New South Wales) (Hyman et al., 2020), reinforcing a well-recognised conservation concern for such species (Harvey, 2002; Harvey et al., 2011; Taylor et al., 2018). Further to our preliminary assessment, fires in Western Australia are thought likely to have caused the loss of the only known population of one short-range host-specific species, judging from the fire impacts on the few known individuals of the host plant (Moir, 2021).

4 | DISCUSSION

Faced with an ecological disaster in the form of the 2019–2020 Australian megafires, the Expert Panel needed to rapidly identify a priority list of taxa for urgent management intervention and commissioned a rapid assessment from the author group. The author group developed assessment frameworks for vertebrates and invertebrates, then worked with many experts to collate, analyse and integrate large amounts of disparate data within 3 weeks for vertebrates and 8 weeks for invertebrates. The process began whilst fires were still burning, and the assessment was updated after the fires had extinguished. Below, we summarise how the rapid assessments were used in the fire recovery effort. We then discuss key lessons from the assessments that could inform responses to future ecological disasters. Where there were challenges, we present recommendations to address these. We focus here on the specific task of gathering and using ecological evidence to inform a conservation response, not on operational elements of an emergency response such as managing a fire (or another ecological disaster) itself.

4.1 | How was the rapid assessment used?

The lists of national priority animal species and priority activities were used immediately to focus and coordinate investment towards

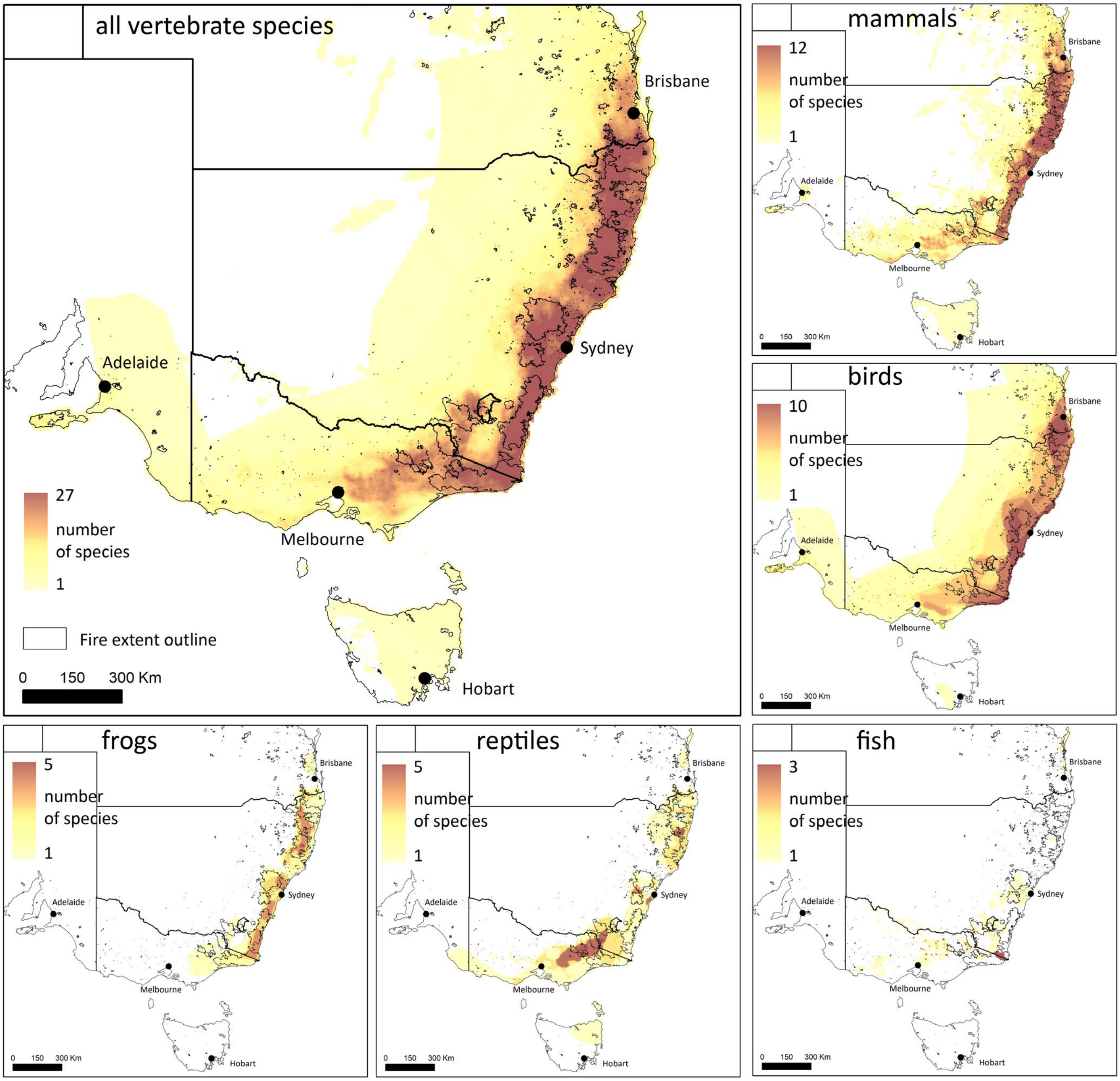
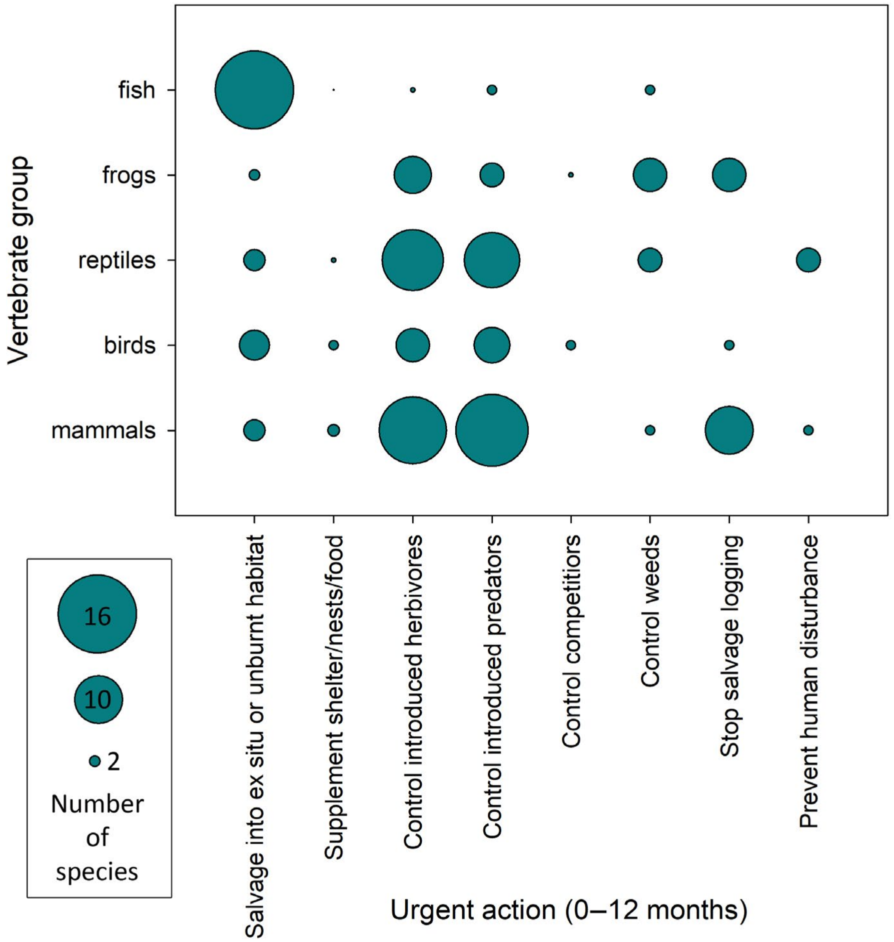


FIGURE 4 The distributions (overlaid, with shading indicating number of species) of all priority vertebrate species, priority mammals, birds, frogs, reptiles and fish, in relation to the fire extent. There was only one priority vertebrate in Western Australia, Western ground parrot (*Pezoporus occidentalis*), not shown here

on-ground management response (Figure 6). To date, the Australian Government has committed $200 million to help native wildlife and their habitats recover; the majority is being directed towards actions to support priority species and ecological communities; as of September 2021, the funding has been committed, targeting 91% of the 92 priority vertebrate species and 57% of the 213 priority invertebrates (DAWE, 2021). The national perspective on which species are priorities for action may differ from priorities set at state, territory and regional scales. The national priority list is therefore not intended to be definitive nor to over-ride local priorities, but to complement action and investment by state and territory governments and by non-government organisations.

Given our rapid assessment highlighted key data inadequacies, the Expert Panel recommended that the Australian Government's bushfire response funding should include support for projects with strong knowledge-gathering, monitoring, and adaptive management components. Together with other funding sources, this means that state government agencies, non-government organisations, university researchers, community groups and citizen scientists are all contributing to an increased level of data-gathering than what

FIGURE 5 Mapping of priority actions for priority vertebrate species



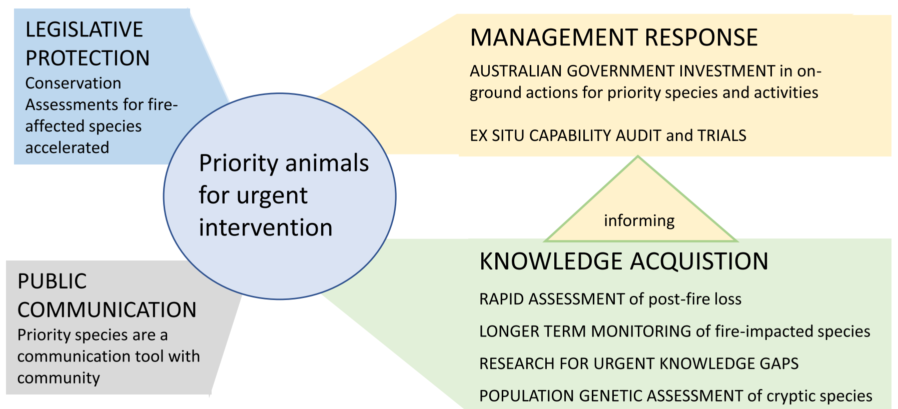


FIGURE 6 The list of priority species was used to guide management investment, research, legislative processes and public communication. The Australian Government directed $200 million from February 2020 to state/territory governments, regional delivery organisations, and via a competitive grants scheme, for actions to support priority species (DAWE, 2020d). The Zoo and Aquaria Association conducted an audit of existing and priority captive breeding facilities and expertise (ZAA, 2020). Additional investment via the National Environmental Science Program aimed to fill key knowledge gaps, including guidance for post-fire population surveys and long-term monitoring programs for priority species (Southwell et al., 2020), and evaluations of existing population genetic data to identify fire-affected cryptic taxa (Catullo & Moritz, 2020). Processes to provide legislative protection and enable recovery planning under the EPBC Act were fast-tracked for priority species (TSSC, 2020). Priority species were the focus for many articles in print and online outlets

existed before the 2019–2020 fires. Whilst recognising that poor baseline data remain a constraint, we anticipate that new data on population status across many taxa will soon make it possible to evaluate whether our assessment correctly identified the species as most heavily impacted by the fires and their priority management needs. Exploring where our assessment predicted impacts poorly will be important for improving prioritisations to future fire events. Predicting impacts on invertebrates will remain particularly challenging, because of the limited level of information on their taxonomy, distribution and status.

Priority animal species were also the focus of Australian Government funding for urgent research to fill key knowledge gaps impeding effective post-fire action, delivered through the National Environmental Science Program (https://www.nespthreatenedspecies.edu.au/research/theme-8-0). This research includes optimising the design for post-fire surveys; carrying out such surveys for key groups like frogs; identifying the ranges of cryptic species based on population genetic analyses; a global assessment of fire-induced mortality in vertebrates; and assessing the post-fire density or compounding impacts of introduced species (e.g. feral cats, large herbivores, myrtle rust). Processes to provide legislative protection and enable conservation planning under the EPBC Act were fast-tracked for priority species (TSSC, 2020). The priority animal lists were also important communication tools with the public: non-government organisations used the priority lists in their public appeals (e.g. https://www.birdlife.org.au/projects/bushfire-recovery), and the general media broadened their coverage from fire impacts on a few iconic species to the wider range of priority taxa (Batsakis & Mountain, 2020). The authoritative communication possibly helped to organise public attention in a way that eased the sense of chaos and loss felt by many (Bogard, 2020).

4.2 | Lessons for responding to future ecological emergencies

4.2.1 | Organisation

In our view, the organisational elements that underpinned the assessment worked well. The response of the Australian, state and territory governments, who began instigating strategic, evidence-based responses before the fires were extinguished, was key to coordinating efforts across many stakeholders. Assembling an Expert Panel and defining the objectives of the national response early on were critical steps that ensured clarity of purpose and brought evidence into the heart of the response. The diverse membership of the Expert Panel facilitated consultation and engagement across many stakeholders, built a community with shared objectives, and ensured rapid access to networks of scientists, managers, non-government organisations, Indigenous groups, and others. There was undoubtedly further expert opinion and insight that could have been drawn upon; however, when time is short, standard approaches to developing collaborative work based on comprehensive consultation and shared understandings developed over time are infeasible. Alternatively, using pre-existing formal and informal networks can lead to a type of dynamic self-organisation that is known to be swift and effective in emergency situations (Bodin et al., 2019; Harrald, 2006).

Lessons

- In ecological disasters, an evidence-based response helps to target investment, management and research effectively and transparently, coordinate actions across levels of government, inform legislative processes, and communicate with the broader public.
- Establishing an expert group, or networks of linked expert groups, is an effective mechanism for accessing relevant information and expertise rapidly. Where possible, the expert group(s) should be formed swiftly, before the disaster is finished (if feasible), even if this means advice will be updated, in order to engage people who are willing to help and focus efforts.

4.2.2 | Data availability - Fire mapping

The rapid assessment was hindered by the lack of timely data on the extent and severity of fires. There is no national facility in Australia for collating and making accessible information on fires. Instead, this information is held by a range of departments within each state and territory government; the information is collected using a variety of methods and used to create maps of varying accuracy and resolution (Bowman, Williamson, et al., 2020). The Australian Government worked rapidly with state and territory counterparts to create, and then maintain, the National Indicative Aggregated Fire Extent Dataset from these multiple sources (DAWE, 2020b). This dataset described the boundary of the fire-affected areas with varying accuracy across jurisdictions, but without information on the locations of pockets of unburnt or lightly burnt vegetation within the fire footprint (potential refuges for fire-affected species), nor on fire severity. Information on fire severity—the effects of fire on vegetation and soil, ranging from unburned/low to very high impacts—is critical for estimating impact, as species' fire responses vary considerably depending on severity (Chia et al., 2015; Lindenmayer et al., 2013) and how that interacts with the habitat and soil that is burnt. Information on the locations of unburnt refuges and fire severity was not available until July 2020 because methods to map fire severity variation at a national scale needed to be developed from scratch (DAWE, 2020a).

Delineating the boundaries of fire impacts was particularly difficult for aquatic species, because they can be affected by heavy rainfall and run-off events from burnt areas far upstream (Lyon & O'Connor, 2008). Our understanding of when and where these sedimentation events occur is poor, yet such information is critical for informing pre-emptive salvage interventions.

Lessons

- Given the increasing frequency of large fires extending across jurisdictional borders, Australia and other fire-prone continents or regions need national (or international) facilities for rapidly assembling and displaying data on fire extent and severity, as well as other fire-related information (Binskin et al., 2020; Bowman, Williamson, et al., 2020).

- Understanding is required of how fire affects erodibility of soils in different landscape contexts, and how to predict high-magnitude, post-fire instream sedimentation events that threaten aquatic fauna, for example by modifying water chemistry (Emelko et al., 2016) and existing soil erosion models (Teng et al., 2016).

4.2.3 | Data availability - Species distribution, traits, status, and trends

The quantity and quality of distribution data vary substantially across taxa. For example, some bird species have thousands of well-curated observation records, and their distributions are well-delineated. In contrast, some species of frogs and reptiles and most invertebrates have very few records, and delineating their distributions is challenging. Furthermore, records for many species are not evenly spread across their ranges, often being clustered around human population centres. For taxa with small distributions and/or few records, the potential errors stemming from data limitations could be material, as small inaccuracies in the fire extent or distributional estimate could result in large differences in estimates of fire overlap. This problem was especially marked for invertebrates, which was partly why the assessment was limited to a subset of a species (i.e. threatened species, taxonomic groups such as butterflies and spiny crayfish, and species nominated by experts as likely to have been fire-affected) where sufficient information was available. However, there are hundreds of thousands of unlisted invertebrate species, many of which have very small distributions that may have been almost or entirely burnt in the 2019–2020 fires. We recognise that for invertebrate species with narrow host plant specificity, it could be useful to reinforce the meagre distributional information about the invertebrate species through inference from distributional data available for host plants. Such an approach would also highlight the effects of fire on ecological connectivity. However, we also recognise that this may add a further dimension of uncertainty and bias because only some invertebrate species have a narrow host plant specificity; such host specificity is imperfectly documented, and host plant occurrence does not guarantee the presence of the host-specific invertebrate species. Uneven knowledge quality across taxonomic groups compounds existing biases in conservation effort (Brito, 2010; Diniz-Filho et al., 2013; Hortal et al., 2015; Walsh et al., 2013).

The rapid assessment also faced hurdles assembling the available data on species distributions. No single, national facility holds comprehensively curated and readily accessible distribution data on all Australian species. Instead, data are held by many state and territory agencies and museums, university scientists, citizen scientists, Indigenous ranger groups, and non-government organisations, with some of that data partly aggregated (but not curated) by platforms such as the Atlas of Living Australia. This meant that, in order to estimate species' distributional overlaps with fire, we had to aggregate distribution data from many sources, each with their own access arrangements, and rapidly develop workarounds for duplicate records held by different institutions.

The pre-fire conservation status of fire-affected species is critical for evaluating and contextualising fire impacts, especially for species with ongoing distributional declines, but our knowledge of species status and trends is uneven. For example, although some threatened species are monitored well, overall, one in four vertebrate species listed as nationally threatened under the EPBC Act have no monitoring program, and where monitoring exists its quality is often poor (Scheele et al., 2019). Even fewer monitoring data are available for non-listed species in Australia, and virtually none are available for invertebrates. Taxonomic uncertainty (especially in frogs, reptiles and invertebrates) also complicated our assessment; we incorporated likely taxonomic updates that we were aware of and carried out spatial analyses of fire overlaps on both recognised and candidate species, but sometimes the distributional limits of candidate species were unclear.

For assessment of the impacts of fire on invertebrate species, we were also constrained by limited and uneven data for individual species about ecological and other traits that could be related to susceptibility in fires. In the absence of such data for individual species, where possible and appropriate, we sought to apply such knowledge from broader taxonomic groupings: for example, for those invertebrate taxonomic groups that are characteristically short-range endemics (Harvey, 2002). However, even this shortcut approach was constrained, because there was no established data base that comprehensively catalogued a broad array of relevant traits across higher-order invertebrate taxonomic groups.

Lessons

- Gaps in fundamental information such as species distribution, status, trends, traits relating to susceptibility, and taxonomy need to be filled with substantial data acquisition programs (Scheele et al., 2018). These could encompass policy initiatives, such as increased funding to data-deficient taxonomic groups or disciplines, or even legislative reforms. For example, in Switzerland, national biodiversity surveys are mandated under the Ordinance on the Protection of Nature and Cultural Heritage (NCHO Art. 27a), with reporting required by law every three years. The surveys cover several components of biodiversity, including threatened species as well as common and widespread species, and the condition of natural habitats and agricultural land (FOEN, 2017).
- A national facility is needed to collect, curate, analyse and provide access to biodiversity data collected by multiple contributors. Existing platforms, such as the Atlas of Living Australia, could be enhanced (for example, by incorporating systems to ingest and curate data) to achieve this functionality. A national facility for storing biodiversity data would serve many purposes, including enabling the regulatory and decision-making functions of the EPBC Act, and is long overdue (AAS, 2020; Binskin et al., 2020).

- Software tools that can combine biodiversity information (species distributions, ecological traits, conservation status) with fire-related information (fire extent, fire severity, fire history) to aid future rapid assessments are also needed.
- Where appropriate data (e.g. concerning distribution or factors relating to susceptibility) for individual species are lacking (e.g. for many poorly known invertebrate species), some judicious use of data from associated (e.g. host) species or from higher taxonomic levels, may be a pragmatic and efficient approach to filling gaps, and may provide useful inference.

4.2.4 | Taking stock – research priorities

The rapid assessment highlighted several critical knowledge gaps; addressing these research priorities will improve responses to future ecological disasters. For example, losses during fires could be reduced through research and planning to ensure key biodiversity assets are protected during fire suppression and standard fire management activities (e.g. prescribed burning, firebreak maintenance, retardant application). To achieve this, we need to identify the species and ecosystems most at risk from changed fire regimes and single extreme fire events (because of vulnerabilities caused by their distribution, population size or ecological traits) and consider whether, where and how they can be protected with careful fire management and fire suppression approaches (Bowman, Kolden, et al., 2020; Wilkin et al., 2016) and how their recovery can be supported.

Our knowledge about species responses to fire is generally poor, especially for some taxonomic groups (e.g. frogs Rowley et al., 2020). Moreover, very large fires are likely to cause greater mortality and constrain recovery more profoundly than smaller fires, but we have very little data to confirm this. We attempted to bridge this information gap in the assessment by using behavioural and ecological traits to infer fire vulnerability. However, trait information is more readily available for better-studied taxonomic groups such as birds and mammals, patchier for other groups like reptiles, fish and frogs, and scant for invertebrates. Moreover, the relationships between traits and fire response are clearer in some taxa (e.g. mammals) than others (e.g. frogs) (Friend, 1993; Rowley et al., 2020; Westgate et al., 2012).

Co-occurring threats can greatly amplify impacts from fire, but we are usually unable to map threats at a fine-enough scale to inform site-based management. For example, predation by introduced predators is a key driver for post-fire mortality in native small mammals (McGregor et al., 2016). Variation in cat density has been mapped at a national scale (Legge et al., 2017), but such models are poor at predicting cat density at site scales, especially after severe fire. Post-fire control of introduced predators can be carried out at massive scales (e.g. DPIE, 2020b), but smaller actions could potentially achieve the same benefit if well-targeted, leaving funds for other management priorities. The rapid assessment included species' susceptibilities to introduced species in the traits collation, but this information could have been more effectively used if fine-scale spatial variation in introduced species density after fire was known or predictable. For other co-occurring threats, our understanding of how and to what extent they affect taxa was too patchy to be used across species in the assessment. For example, the impact of the extended drought that preceded the 2019–2020 fires on the status of aquatic species was unclear.

Finally, the assessment necessarily focussed on estimating the immediate (0–12 months) impacts of fire, but extending the focus to consider the capacity of species to recover, with and without different management interventions, is necessary. To achieve this, we will need the capacity to deploy extra research and monitoring effort quickly and at scale (Lindenmayer et al., 2010). In addition, we note that the conservation management response (triggered largely by the assessment described here) following the 2019–2020 Australian fires was exceptional in scale. It is critical to evaluate in the near- and mid-future how successful this response has been and where it could have been improved. Such evaluation is essential to allow for a more robust evidence base to inform responses to any future comparable events.

Lessons

- Identify the species and ecosystems most at risk from ecological disasters, so that their locations and needs can be built into management and emergency response planning.
- Understand how antecedent conditions and species' traits drive fire vulnerability within taxonomic groups, to improve assessments of impacts, and guidance for management response.
- Establish processes to rapidly deploy people and resources to assess impacts, monitor recovery, and measure the contribution of management interventions, after ecological disasters.
- Evaluate the response, and use this information to guide future responses to ecological disasters.

4.2.5 | Capacity-building

The 2019–2020 fires stretched the capacities of government departmental staff, fire scientists, conservation ecologists and managers, and community groups to the limit, and many of these individuals and organisations are still operating under extreme workloads and pressure, two years on. We know that ecological crises will recur with increasing frequency, and we need to plan for this new future. Massive ecological disturbances, like mega-fires, also disrupt prevailing social and professional practices and norms and can be an opportunity for significant change (Buma & Schultz, 2020). The 2019–2020 fires should trigger a state shift in strategic planning and preparedness, creative adaptation, and new models of collaboration. For example, the fires have generated substantial interest in reinvigorating Indigenous fire practices and supporting Traditional Owners to integrate cultural burning into fire management planning and implementation frameworks (Robinson et al., 2021). In a world increasingly prone to ecological disasters, the government and non-government conservation sector needs to reorganise itself, establishing structures and processes that can swing rapidly into action after ecological crises, accessing a substantially enhanced information base, whilst maintaining a culture of creativity and agility to accommodate unexpected events and impacts (Crosweller & Tschakert, 2020; Gustafsson et al., 2019; Lindenmayer et al., 2010).

Substantial resourcing is needed to realise national facilities for data acquisition and management, increased applied research to fill critical knowledge gaps, adaptive conservation and fire management, and to expand the capacity of environmental scientists and managers. However, these costs are dwarfed by the socioeconomic impacts of megafires. The 2019–2020 fires caused over $100 billion in tangible costs to the economy, without even considering the costs of biodiversity impacts to the human economy, people's wellbeing, and the longer term consequences of an unravelling natural world (Read & Denniss, 2020).

Lessons

- Train a new and larger generation of agency staff, scientists and managers who are experts in ecological disturbance and can work creatively to trial new adaptive approaches for disaster management and biodiversity conservation in a volatile and uncertain environment.

5 | CONCLUSIONS

By using formal and informal networks to assemble disparate datasets and expert opinion, we completed species assessments rapidly and helped people with diverse skills to feel engaged in the recovery effort. However, easier access to datasets (on fire extent and severity, taxonomy, species distributions, species status and trends, and

TABLE 2 Checklist of 10 key lessons for using evidence-based approaches to respond to major and catastrophic ecological disasters, grouped under the four phases of emergency management recognised by the Australian National Disaster Risk Reduction Framework

Phase 1. Prevention and Mitigation: reduce risk of ecological disasters	
1	Environmental scan • What ecological disturbances are most likely, and where?
2	Identify and mitigate drivers of ecological disasters
Phase 2. Preparedness: before ecological disaster	
3	Assess risks: • Identify and spatially delineate components of biodiversity at greatest risk from ecological disaster and ensure their locations and needs are built into standard management and emergency response operations (e.g. as priorities for protection during fire-fighting operations) • Identify components of biodiversity that may be susceptible to disaster-control operations (e.g. application of fire retardants) and identify options (e.g. alternative control actions) to reduce such impacts • Where risks of catastrophic losses are extreme, establish insurance populations (through captive breeding, seed storage or translocations)
4	Gather accessible information and establish systems for data curation and ready access for: • Major ecological disturbance data collection and dissemination (e.g. for fire, flood, drought) • Fundamental data on species distributions, ecologies, traits, threats • Status and trends across species and ecosystems, and their response to management actions • Husbandry and translocation techniques across species, in case captive breeding/emergency salvage or translocations are required
5	Build capacity (in people, infrastructure, knowledge) to manage ecological disturbances and disasters.
Phase 3. Response during ecological disaster	
6	Form expert advisory group (embedded within, and reporting to, responsible authorities) with an appropriate mix of skills/experience and colleague networks, to access the best available information rapidly, and engage widely, as quickly as possible (i.e. don't wait until the disaster is over).
7	Scalability: develop an organising hierarchy of lead organisations to coordinate communication and response at the right scale and to foster collaborative and coordinated responses across that hierarchy (national, state/territory, regional, community)
8	Mobilise funding and organise investment according to priorities and to complement investment by other government and non-government organisations.
Phase 4. Recovery after ecological disaster	
9	Monitor the extent and timescale of post-disaster recovery and the effectiveness of management interventions. Report publicly
10	Review the emergency response and improve the model: • Review response efficacy; build or refine blueprints for responding to future ecological disasters • Identify key knowledge gaps; instigate research or reform to address those gaps. • Recognise opportunities for innovative conservation management that ecological disaster may provide (e.g. drought or post-fire sediment events could extirpate populations of aquatic predators, proving habitat for reintroductions of native species)

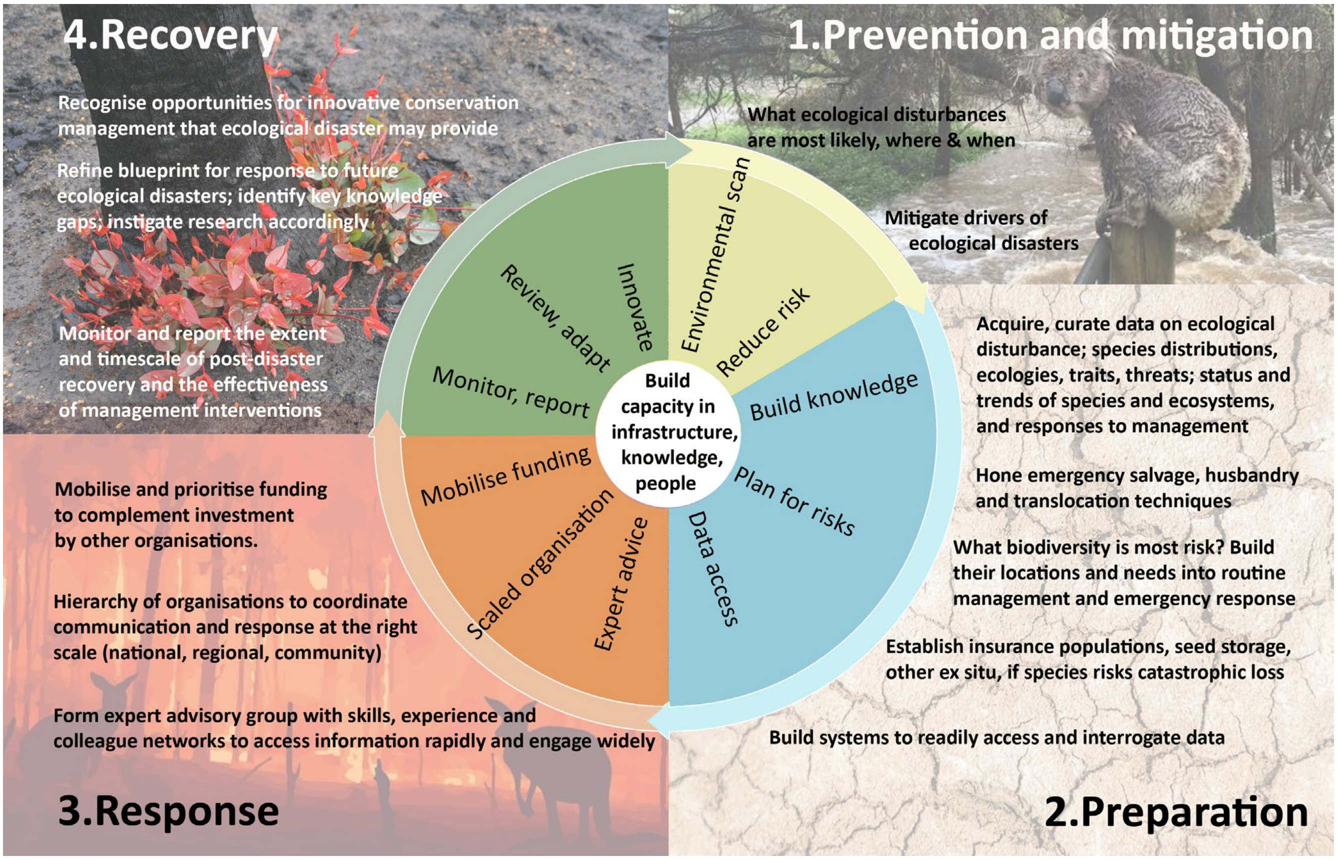


FIGURE 7 Key lessons for enhancing the use of evidence in the responses to major and catastrophic ecological disasters, following the four phases of emergency management recognised by the Australian National Disaster Risk Reduction Framework (Photos: Pixabay, R. Latter, R. Kerton, C. London)

species' traits) of consistently high quality would have made the process faster, improved interoperability across species and taxonomic groups, and increased our confidence in the results.

Major and catastrophic ecological disasters (sensu AIDR, 2009) are expected to occur with increasing frequency, in Australia and globally (Binskin et al., 2020). The exact nature, location, scale and impacts of such disasters are much less predictable, meaning that emergency responses need to be flexible and tailored for the specifics of each event. Nevertheless, it is possible to consider the optimal process for using evidence in ecological disasters in the context of standard emergency response planning structures. The Australian National Disaster Risk Reduction Framework recognises four phases of emergency management: Prevention and Mitigation; Preparedness; Response; and Recovery (AIDR, 2009). The lessons arising out of the rapid assessment outlined earlier can be grouped and generalised under each of these four phases (Table 2; Figure 7), providing a template for responding flexibly but effectively to any ecological disaster, in Australia or elsewhere in the world.

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CONFLICT OF INTEREST

The authors declare no conflicts of interest.

PEER REVIEW

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DATA AVAILABILITY STATEMENT

Data available at: https://www.environment.gov.au/biodiversity/bushfire-recovery/research-and-resources.

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BIOSKETCH

In early January 2020, the Australian Commonwealth Minister for the Environment asked the Threatened Species Commissioner (a position within the Government's environment department) to convene an Expert Panel to help guide and coordinate the national response to support recovery of fire-affected biodiversity, particularly threatened species, ecological communities, other natural assets and their Indigenous cultural values. The Expert Panel comprised eight independent scientists, government and zoo scientists, and an Indigenous expert, with senior representatives from the fire-affected states and territory present as observers, and was supported by Commonwealth government staff. The Panel provided a mechanism for developing, prioritising and coordinating responses across governments and regional management delivery structures and integrating these efforts with the broader conservation and science community. The Panel collaborated with spatial analysts and species experts to undertake the rapid assessment described in this paper; key members of the assessment team are the authors.

SUPPORTING INFORMATION

Additional supporting information may be found in the online version of the article at the publisher's website.

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