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RESEARCH ARTICLE

The conservation impacts of ecological disturbance: Time-bound estimates of population loss and recovery for fauna affected by the 2019–2020 Australian megafires

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Abstract

Aim: After environmental disasters, species with large population losses may need urgent protection to prevent extinction and support recovery. Following the 2019–2020 Australian megafires, we estimated population losses and recovery in fire-affected fauna, to inform conservation status assessments and management.

Location: Temperate and subtropical Australia.

Time period: 2019–2030 and beyond.

Major taxa: Australian terrestrial and freshwater vertebrates; one invertebrate group.

Methods: From > 1,050 fire-affected taxa, we selected 173 whose distributions substantially overlapped the fire extent. We estimated the proportion of each taxon's distribution affected by fires, using fire severity and aquatic impact mapping, and new distribution mapping. Using expert elicitation informed by evidence of responses to previous wildfires, we estimated local population responses to fires of varying severity. We combined the spatial and elicitation data to estimate overall population loss and recovery trajectories, and thus indicate potential eligibility for listing as threatened, or uplisting, under Australian legislation.

Results: We estimate that the 2019–2020 Australian megafires caused, or contributed to, population declines that make 70–82 taxa eligible for listing as threatened;

and another 21–27 taxa eligible for uplisting. If so-listed, this represents a 22–26% increase in Australian statutory lists of threatened terrestrial and freshwater vertebrates and spiny crayfish, and uplisting for 8–10% of threatened taxa. Such changes would cause an abrupt worsening of underlying trajectories in vertebrates, as measured by Red List Indices. We predict that 54–88% of 173 assessed taxa will not recover to pre-fire population size within 10 years/three generations.

Main conclusions: We suggest the 2019–2020 Australian megafires have worsened the conservation prospects for many species. Of the 91 taxa recommended for listing/uplisting consideration, 84 are now under formal review through national processes. Improving predictions about taxon vulnerability with empirical data on population responses, reducing the likelihood of future catastrophic events and mitigating their impacts on biodiversity, are critical.

KEYWORDS
conservation status, ecological disturbance, expert elicitation, megafire, population decline, Red List Index

1 | INTRODUCTION

Changes to fire regimes, driven by anthropogenic climate change (Bowman, Kolden, et al., 2020; Goss et al., 2020), imperil much of the world's terrestrial and freshwater biota (Kelly et al., 2020). These changes include an increased frequency of 'megafires' in diverse biomes from boreal forests to tropical wetlands (Duane et al., 2021). As well as causing greater immediate impacts on species, these extensive, severe or rapidly spreading fires tend to leave fewer unburnt refuges within the fire footprint (Collins et al., 2021), constraining population recovery by both in-situ reproduction and recolonization from elsewhere (Banks et al., 2017). Key resources, including habitat structures (e.g., large tree hollows, leaf litter, deep pools, submerged woody habitat) as well as food, can be rare for many years after such fires (Gresswell, 1999; Haslem et al., 2011; Jones et al., 2021). Therefore, megafires can cause large, sudden, and enduring changes in population size for affected species that need to be recognized swiftly by legislative and policy review to ensure that investment, management, and research activities are prioritized to reduce extinction risk.

Australia experienced an unprecedented series of megafires in 2019–2020, amplified by a 3-year drought and record high temperatures across the continent (Abram et al., 2021; Van Oldenborgh et al., 2021). Between September 2019 and March 2020, > 100,000 km^2 of native vegetation in eastern and southern Australia burned in a fire season of longer duration, with severe fires of greater spatial extent, than ever recorded for these temperate and subtropical regions (Collins et al., 2021; Nolan et al., 2020). Over 20% of Australia's eucalypt forests burned, 10-fold higher than the annual average for these biomes (Boer et al., 2020; Bowman, Williamson, et al., 2020), representing suitable habitat for 69% of all Australian plant species (17,197 species, Gallagher et al., 2021). Aquatic habitats within and downstream of burnt areas were also heavily impacted (Silva et al., 2020), and ecosystems that rarely experience fire burned, including subtropical rain forests (Collins et al., 2021; Godfree et al., 2021).

Rapid desktop assessments showed that the 2019–2020 Australian megafires overlapped with the distributions of hundreds of vertebrate species and thousands of invertebrate species, including numerous threatened species (Legge et al., 2020; Legge, Woinarski, Scheele, et al., 2021; Marsh et al., 2021; Ward et al., 2020). Fire overlap offers a rapid means of identifying *potentially* impacted species (e.g., Feng et al., 2021), but does not account for variability in how fire affects species. For example, greater gliders (*Petauroides volans*) almost disappeared from areas of the Victorian central highland forests that burned severely in 2009, whereas mountain brushtail possums (*Trichosurus cunninghami*) persisted in those same areas, experiencing little to no mortality (Banks et al., 2011; Lindenmayer et al., 2013). Such differences in fire responses reflect interspecific differences in ability to escape or shelter from fire, and to survive in post-fire environments that have experienced abrupt changes to habitat structure, resource availability, and predation risk (Engstrom, 2010; Nimmo et al., 2021; Whelan et al., 2002). Likewise, species differ in their capacity to recover from population loss due to differences in habitat and resource specificity, fecundity, and dispersal capacity. Although there is some evidence from previous studies of impacts of fire (e.g., Fox, 1982; Friend, 1993; Johnston et al., 2014; Lindenmayer et al., 2021; Loyn, 1997; Lyon & O'Connor, 2008; Westgate et al., 2018) there is limited or no information on the fire responses of most species, especially in relation to fires of the scale and severity of the 2019–2020 Australian megafires (Jolly, Dickman, et al., 2022; Pausas & Parr, 2018; Rowley et al., 2020). Severe deficiencies in documenting the pre-fire population status for most species, even our most-studied species (e.g., Cristescu et al., 2021), compounds this difficulty.

Here, we combine different data sources to predict the immediate and longer-term effects of the 2019–2020 Australian megafires on fire-affected vertebrates and one invertebrate group. We then use the results to indicate which species may be eligible for conservation status review. Our analysis contains two components: first, we intersect fire severity and aquatic impact severity maps with species distribution data to estimate the proportions of each species' range that overlapped with each fire/aquatic severity class. Second, we use structured expert elicitation, informed by the available evidence from on-ground studies of responses to previous fires, to estimate the proportional population change caused by different fire/aquatic severity classes, and the ensuing rate of population recovery to 10 years/three generations (whichever is longer) after the fires.

Structured expert elicitation protocols (Hemming et al., 2018) are increasingly used to bridge knowledge gaps that impede conservation planning and management (Geary et al., 2021; Geyle et al., 2018; Gillespie et al., 2020; Lintermans, 2020; Scheele, Pasmans, et al., 2019). In the context of our focus on the 2019–2020 Australian megafires, expert elicitation was required given the many species considered; the limited evidence base for most of those species; and the need to understand uncertainty around future population trends. This approach also allowed us to estimate population response to fire as consistently as possible across all species, rather than only those subject to the most research (Legge, Woinarski, Scheele, et al., 2021). By using estimates of population loss and recovery for each species, relative to population loss thresholds for conservation status assessments, we identify species that merit formal and more detailed consideration for listing assessment or reassessment under Australian threatened species legislation (*Environment Protection and Biodiversity Conservation Act 1999*: EPBC Act). We also indicate those species least likely to recover, without additional management, and hence those that are priorities for additional management investment. The incidence of mega-disturbances is increasing globally, and the approach we describe could be applied to estimate impact, and to inform management that supports recovery, after other comparable disturbances.

2 | METHODS

2.1 | Study area and species

Our analysis considered taxa with distributions that overlapped with the fire extent (*c*. 104,000 km^2) in the bioregions of southern and eastern Australia most affected by the 2019–2020 megafires (Figure 1; Boer et al., 2020; Bowman, Williamson, et al., 2020; DAWE, 2020b). It covered all vertebrate groups and one group of invertebrates (freshwater spiny crayfish *Euastacus* spp.) to align with an earlier prioritization of fire-affected fauna that informed recovery investment by the Australian Government (Legge et al., 2020; Legge, Woinarski, Scheele, et al., 2021), and to help to assess the applicability of the approach across diverse animal taxa. We considered fire impacts on species, and (for birds and mammals) on subspecies when they were differentially impacted by fire; detail in Supporting Information Appendix S1. From here, we use 'taxa' when referring to a mix of species and subspecies, and 'species' when referring only to that taxonomic rank.

We identified over 1,050 vertebrate and spiny crayfish taxa with distributions that overlapped the fire extent, including the downstream impact extent for aquatic taxa (Legge, Woinarski, Garnett, et al., 2021). In a preliminary spatial analysis, we shortlisted this set to threatened taxa likely to have over 10% of their distributions overlapping the fire extent and non-threatened taxa with over 25% of their distributions overlapping the fire extent. Eight threatened taxa (one bird, four reptiles, three spiny crayfish; Supporting Information Appendix S1) with fire overlaps < 10% were retained because these taxa have small, poorly defined distributions where a small adjustment to their mapped distribution could increase the fire overlap substantially. The application of these filters resulted in a shortlist of 288 taxa (240 species) for further assessment (Table 1).

2.2 | Estimating fire overlaps with taxon distributions

We assembled comprehensive distribution data by collating taxon range maps and records from multiple sources [including Australian government mapping of nationally threatened species; International Union for Conservation of Nature (IUCN) range maps for globally threatened species; species-specific range maps developed by taxon experts; range maps based on observations collated by BirdLife Australia]. We also created new distribution models for a subset of 132 taxa (Supporting Information Appendix S1). Maps were adjusted based on feedback from taxon experts, and where more than one mapping product for a taxon was available (e.g., a pre-existing range map and predictions from a new distribution model; 120 taxa), experts selected the map they deemed most accurate.

To estimate spatial variation in fire severity, we used the Australian Google Earth Engine Burnt Area Map (AUS GEEBAM; DAWE, 2020a), defining 'severe' fires as those with substantial effects on the canopy (i.e., the canopy is scorched or consumed), and 'mild' fires as those with no or moderate effects on the canopy (Figure 1; Supporting Information Appendix S1).

Fires cause influxes of nutrients, ash, and sediment into waterways, with impacts extending downstream, weeks to months after fire (Lyon & O'Connor, 2008; Silva et al., 2020). These impacts are influenced by topography, soil features, fire severity, and the timing, scale, intensity, and duration of rain and runoff after fire (Neary et al., 2005; Rieman et al., 2012). For the 45 aquatic species in our assessment, we developed an 'aquatic impact risk' model for waterways (Legge, Woinarski, Garnett, et al., 2021) by modifying an existing soil erosion risk model based on topography and soil features (Teng et al., 2016) to incorporate spatial variation in fire severity,

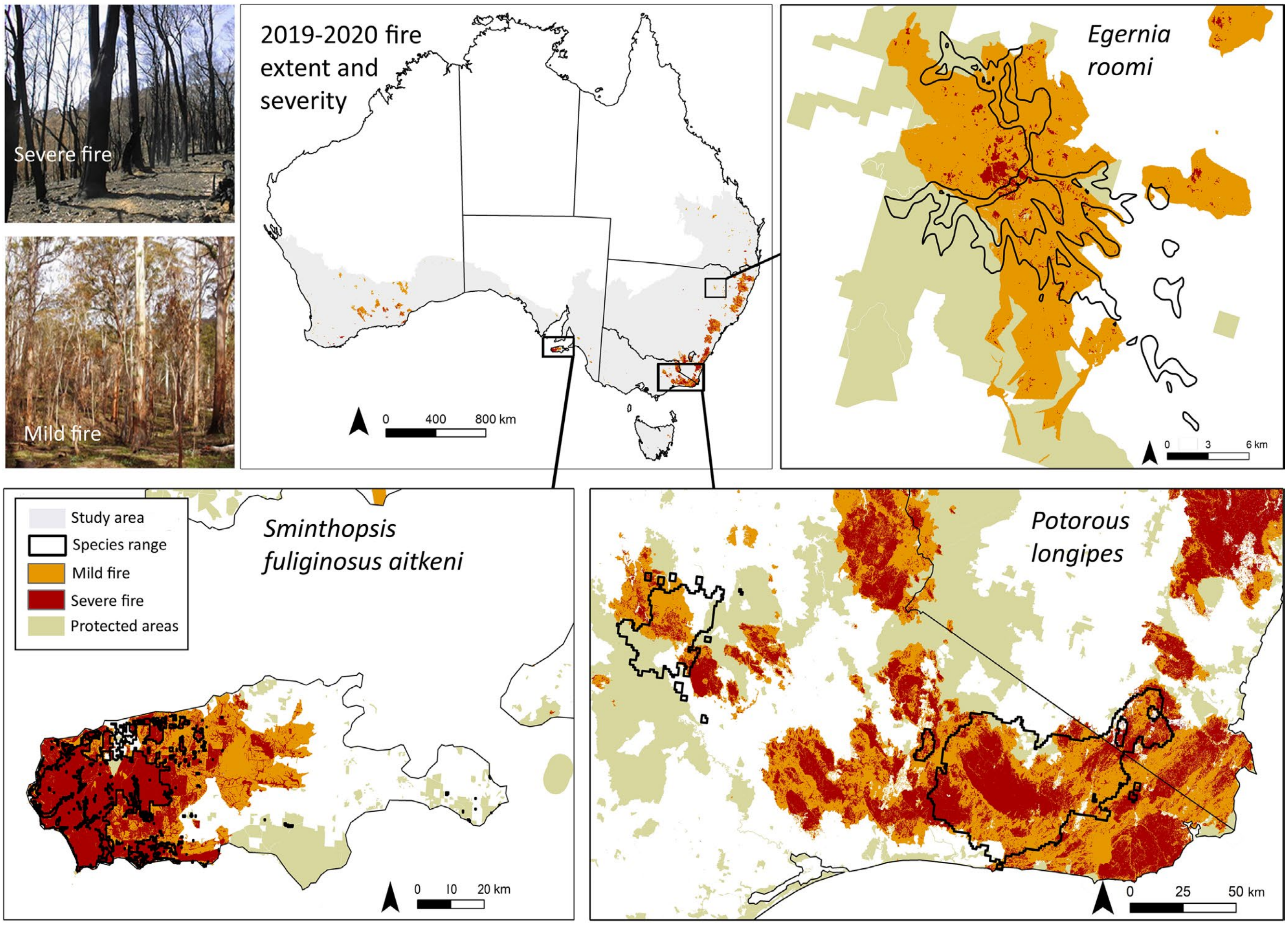

FIGURE 1 Maps showing (top left) the overall fire extent and severity of the 2019–2020 Australian megafires within the 'study area' (the temperate and subtropical bioregions with anomalous fire patterns); and examples of species with distributions that overlapped substantially with fire, yet experienced marked variation in the ratio of mild to severe fire: (top right) Kaputar rock skink (*Egernia roomi*): 67% of the range was burnt, but mostly in mild fire (63%); (bottom right) long-footed potoroo (*Potorous longipes*): 81% of its range burnt, almost half of it in severe fire (38%); and (bottom left) Kangaroo Island dunnart (*Sminthopsis fuliginosus aitkeni*): 95% of its range burnt, mostly in severe fire (90%). The two photos in the top left show forest after severe (canopy scorched or consumed) or mild fire (canopy not, or moderately, affected by fire)

and daily and fortnightly rainfall events occurring to mid-March 2020 in the catchment above each stream node (using the Bureau of Meteorology's Australian Hydrological Geofabric raster). The aquatic impact risk model was applied to 50 km downstream from the fire extent edge (with that distance based on observations in Lyon & O'Connor, 2008; Silva et al., 2020). Aquatic impact risk index scores were divided into three classes of risk (no risk, mild risk, severe risk) to align with the fire severity mapping categories (Legge, Woinarski, Garnett, et al., 2021).

Taxon distribution, fire severity and aquatic impacts risk maps were projected to equal area projection Australian Albers (Geocentic Datum of Australia 94) at 250-m resolution. For each of the 288 short-listed taxa, we used a Python script in QGIS to calculate the proportion of its distribution that was unburnt (or no risk of aquatic impacts for aquatic fauna), or overlapped with mild fire/aquatic impacts, or severe fire/aquatic impacts in 2019–2020, with these three proportions summing to 100.

2.3 | Expert elicitation to estimate local population response to fire

We used structured expert elicitation (Hemming et al., 2018) to estimate local proportional population change after mild and severe fire. The use of expert data in this context was critical, as spatially and temporally representative data on the impacts of the fires across species are not yet available, pre-existing long-term data on population status and trends are at best limited for even the most well-studied species, and the future is uncertain. The specification of uncertainty about the future is a clear advantage here, as it can be used to explore lower bounds (worst case scenarios) and inform a precautionary approach to listing advice. The use of structured expert elicitation is a well-established tool when data are scarce and decisions are urgent (Martin et al., 2012) that has been used in similar contexts (for examples see Drescher et al., 2013; Hemming et al., 2018), including IUCN Red List assessments (IUCN, 2019).

TABLE 1 Summary of the number of shortlisted taxa for assessment, and the number currently listed in various conservation status assessments

Group	Number of taxa in assessment (species)	Taxa listed by EPBC Act (species)	Species listed by IUCN (species)	Taxa listed by an Action Plan or another expert assessment (species)
Birds	68 (54)	11 (7)	9 (5)	15 (9)
Mammals	56 (46)$^+$	21 (17)	22 (17)	26 (21)
Frogs	66 (47)	21 (15)	34 (25)	18 (18)
Reptiles	45 (40)	9 (9)	16 (16)	17* (17)
Fish	21 (21)	9 (9)	19 (19)	13 (13)
Spiny crayfish	32 (32)	0	22 (22)	4 (4)
Total	288 (240)	71 (57)	122 (104)	93 (82)

Note: EPBC Act, *Environment Protection and Biodiversity Conservation Act 1999*; IUCN, International Union for Conservation of Nature. Sources for taxonomies and the full list of taxa are in Supporting Information Appendix S1. The tallies for *taxa* in the table include accepted subspecies for birds and mammals, and candidate species for mammals, reptiles and frogs identified in Catullo et al. (2021). The tallies for *species* exclude the potential updates noted by Catullo et al. (2021), and where two or more recognized subspecies are fire-affected, only the species is counted. For bird species that migrate out of Australia ($n = 2$), we considered only their Australian range. Four bird taxa migrate within Australia, and we considered the fire overlap with their seasonal breeding range. The relevant action plans or equivalent assessments are Chapple et al. (2019); Garnett et al. (2011), Gillespie et al. (2020), Lintermans (2019), Lintermans et al. (2020), Woinarski et al. (2014). Note that the EPBC Act can list species or subspecies; IUCN assesses at species level; bird and mammal action plans assess subspecies, and expert assessments for other groups assess at species level.

$^+$One taxon is the listed population of the koala.

*Includes *Egernia roomi*, listed by New South Wales government.

To reduce the elicitation burden for experts, we selected 173 taxa (143 species) from the 288 taxa included in the spatial analyses. This included 119 taxa that had been identified as priorities for conservation attention in an earlier analysis (Legge et al., 2020; Legge, Woinarski, Scheele, et al., 2021) supplemented with taxa with high fire overlap estimates, or about which experts expressed concern. We assumed that subspecies of a single species had similar population responses to fire, and thus undertook the elicitations on species, unless the subspecies were expected to respond differently to fire (relevant for only two bird species: *Pezoporus wallicus*, *Calyptorhynchus lathami*).

Fifty-one experts participated overall, with separate panels of seven to 10 experts assessing the taxa in each taxonomic group (mammals, birds, reptiles, frogs, fish, spiny crayfish). Some experts assessed two groups. In a few cases, experts did not complete elicitations for all species in their taxonomic group; but we ensured that no species had fewer than seven independent elicitors. Expert groups were deliberately diverse in terms of gender, age, and experience, because drawing on such group judgements has been shown to produce more reliable estimates than relying on the most experienced or regarded experts (Burgman et al., 2011). However, experts were not novices, and were selected so that the expert group had field experience with the majority of the assessed taxa, and because they had conducted previous studies on impacts of fire (having collectively published » 100 papers or reports on the impacts of fire; Drescher et al., 2013). Species for which none of the experts had direct field experience were in all cases closely related to, or ecologically similar to, species for which the experts had field experience.

Elicitations were facilitated by the same (experienced) team members, to ensure consistency across groups. For the species in their taxonomic group, experts were provided with summaries of pre-fire population status and trend, species ecological traits, current management conditions, and any relevant existing information on fire responses and recovery. Experts were free to conduct their own research prior to the elicitation but we deliberately did not provide an extensive summary of existing literature to avoid biases such as anchoring, and because we expected that participants would be aware (or be authors) of relevant literature that could be shared in the discussion phase. Experts were also provided with detailed elicitation instructions that outlined assumptions when considering 'typical habitat', fire severity, the application of management, and future climate change scenarios, so that they had clearly specified bounds for the questions and were answering the same question (see Supporting Information Appendix S1).

Experts were asked to estimate the proportional local population change for each species at a hypothetical site (with habitat typical for the species, and of undefined size) at three time points (1 week, 1 year, and 10 years or three generations post-fire, whichever was longer for the taxon in question, in line with IUCN criteria); for three scenarios: (a) the site remained unburnt, (b) the site was burned by mild fire, and (c) the site was burned by severe fire (or, for aquatic species: no, mild, or severe aquatic impacts). The experts were instructed to consider their estimates on the premise that after the fire, management was the same as that prevailing before the fire, because we aimed (a) to estimate the immediate decline caused by fire (which is unaffected by management subsequent to the fires); (b) to provide advice to governments seeking to prioritize their post-fire management investment. We hope that enhanced management investment post-fire, for some of the considered species, has provided additional benefit, but quantifying that was not the primary purpose of this study. We also asked experts to assume there were no further *extreme* drought or fire events of the same magnitude as in 2019–2020 for the next 10 years/three generations. This assumption may be unrealistic, especially for long-lived species. However, we aimed to estimate population trajectories as a result of the 2019–2020 megafires, rather than the prospective impacts of multiple permutations of future drought and fire events.

Using the structured four-step IDEA protocol (Investigate, Discuss, Estimate, Aggregate: Hemming et al., 2018), experts provided their most plausible estimates for each time point (i.e., 1 week, 1 year and 10 years/three generations post-fire) and fire scenario (unburnt, mild fire and severe fire), with upper and lower bounds, and their confidence in those bounds (i.e., 36 judgements per expert per species). This four-step approach has been demonstrated to result in improved judgements, through mitigation of biases in experts, particularly overconfidence (Hemming et al., 2018). Confidence bounds were then standardized to 80% confidence, and anonymized results were then discussed (in an online meeting) within each taxonomic group. During this discussion, experts provided interpretations of the evidence base from previous studies (including their own) of the response of the considered species to fire. Following group discussions, experts could revise their estimates, which were then aggregated for use in further analysis. Though multiple aggregation methods are possible (Hanea et al., 2021), quantile aggregation is an accepted and intuitive method that does not rely on assuming and fitting a particular distribution to the data (Hemming et al., 2018; Lyon et al., 2015) and was used to obtain the arithmetic mean of the best, lower and upper estimates. Across the combinations of species, fire/aquatic impact classes and time points, there were 3,861 aggregated estimates.

2.4 | Overall population changes

For each of the 173 taxa, we multiplied the averaged expert estimates for local proportional population change at each time point, with the proportion of that taxon's distribution exposed to each of the three fire (or aquatic) severity levels (i.e., unburnt/none, mild, severe), to generate an overall estimate for proportional population change immediately after the fire, 1 year after fire, and 10 years/three generations after fire, relative to a standardized population estimate of 100 immediately before fire, as:

$$OP_{\text{immed}} = \left(U \times P_{\text{none\_immed}}\right) + \left(M \times P_{\text{mild\_immed}}\right) + \left(S \times P_{\text{severe\_immed}}\right). \tag{1}$$

where *OP* is the overall population; *U*, *M* and *S* are the proportions of the distribution that are unburnt, mildly burnt and severely burnt (or impacted, for aquatic systems), respectively, with these summing to 100; and *P* is the elicited local population proportional change for each severity level and time point (shown in subscript). This formula was also used as the conceptual basis for both other time points (1 year and 10 years/three generations post-fire), and the lower and upper confidence bounds.

2.5 | Conservation status review

To assess how the fires could impact the conservation status of the 173 taxa, we used the IUCN Red List guidelines (IUCN, 2019), which form the basis for listing taxa as threatened under the Australian EPBC Act. We determined whether taxa were likely to be *eligible* for listing/uplisting; or *could be eligible* for listing/uplisting, based on their most plausible estimates and the lowest 80% confidence bounds for population loss (i.e., a precautionary approach), respectively, in the context of their pre-fire status in the EPBC Act and other expert assessments (Supporting Information Appendix S1). Our analysis provides evidence for such listing assessments, but where possible any relevant additional information, such as post-fire surveys, should be (and is) considered in the formal legislative listing process.

As well as the 173 taxa included in the elicitation, we considered an additional 17 taxa in the conservation status review; 13 with distributions that were so extremely fire-affected that population losses would easily exceed eligibility thresholds for listing, and four fire-impacted species already recognized as highly threatened (IUCN Red List, Gillespie et al., 2020), and that are overdue for assessment under Australian legislation (details in Supporting Information Appendix S1).

To examine the likely magnitude of changes in conservation status for assessed fauna groups due to the megafires, we: (a) estimated the proportional increase to the national statutory list of threatened species if the taxa recognized in our analysis as likely to be eligible for listing were indeed subsequently listed as threatened; and (b) then used the Red List Index (RLI) approach to chart changes in the overall extinction risk for the groups assessed (Butchart et al., 2007). This approach allows for fire-driven changes in conservation status to be contextualized against underlying trends arising from other factors; illustrates differences among taxonomic groups in the relative impacts of the fires; and provides a template that can be used to report on the impacts of comparable events. The RLI varies from 1 if all taxa in a taxonomic group are Least Concern, to 0 if all taxa are Extinct. We used EPBC Act conservation status at 2000, 2005, 2010, 2015 and 2019 to describe underlying trends for the vertebrate groups examined, omitting spiny crayfish because most species have not had their conservation status assessed under the EPBC Act. We then calculated the Red List Index for 2020, assuming the listing changes suggested by our analysis (Supporting Information Appendix S1).

3 | RESULTS

3.1 | Overlaps of fire impacts with taxon distributions

Of the 288 shortlisted taxa, 255 had distributions that overlapped with the fire or aquatic impact extents by at least 10%; 199 taxa by at least 25%; 76 taxa by at least 50%; and 16 taxa had distributions that were at least 80% fire-affected. Severe fire/aquatic impacts covered > 10% of the distributions of 202 taxa; > 25% of the distributions of 64 taxa; > 50% of the distributions of 30 taxa; and > 80% of the distributions of eight taxa (Figure 2). Among the assessed species, birds had the largest number of taxa affected by fire, partly because many bird subspecies are endemic to Kangaroo Island, which was extensively and severely burned (Figure 1). Fish and spiny crayfish had relatively higher proportions of assessed taxa with distributions that substantially overlapped fire/aquatic impact extents, including by severe impact extents (Figure 2).

3.2 | Elicited estimates of local population response to fire

Experts estimated that there was marked variability among species in the local population loss after fire, and the impacts of mild versus severe fire (Supporting Information Table S2.1). For example, 1 week after severe fire, the estimated local proportional population loss (relative to the pre-fire benchmark) varied from 8% (confidence limits: 1.5–38%) for the Manning River turtle (*Wollumbinia purvisi*) to 85% (confidence limits: 69–94%) for the greater glider. However, 1 week after mild fire, although the Manning River turtle again had the smallest estimated local population loss (2%; confidence limits: 0.5–4.7%), the mainland dusky antechinus (*Antechinus mimetes*), a species reliant on dense understorey, leaf litter and woody debris, had the greatest estimated local population loss of 50% (confidence limits: 31–59%), and the greater glider, a canopy-dependent species, was estimated to have a local population loss of only 25% (confidence limits: 7–45%).

Expert elicitation indicated that, of all taxa assessed, mammals and birds were most likely to be immediately susceptible to severe fire (Figure 3). Of the 20 taxa with the largest estimates of local population losses immediately after severe fire, 14 were mammals, five were birds, and one was a reptile. However, the relative rankings of taxa changed over time: by 1 year post-fire, nine mammal taxa and 11 bird taxa comprised the 20 highest ranked taxa; by 10 years/three generations post-fire, the 20 taxa with the largest estimated local population losses comprised nine mammals, five frogs, four fish, and two bird taxa (Supporting Information Table S2.1). Thus, mammal taxa were predicted to suffer sustained impacts at all three post-fire time periods; recovery was anticipated for most bird taxa; frog and fish taxa were projected to either fail to recover, or continue to decline; and reptiles were generally estimated to be the least fire-affected taxa at any time point.

For each taxonomic group, the average (across species in that group) estimated proportional local population loss varied from 17 to 25% at 1 week after mild fire, and 34 to 61% after severe fire, depending on the group (Figure 3). In all groups except reptiles, estimated population loss worsened from 1 week to 1 year after fire (Figure 3). By 10 years/three generations post-fire, most groups were predicted to partially recover. Frogs changed little, and fish continued to decline over 10 years/three generations; these two groups were also predicted to have the greatest downward trajectories over time even in the absence of fire (12 and 25%, respectively; Figure 3), reflecting the effects of other threatening processes.

3.3 | Estimated overall population losses due to megafires

The overall population loss from the 2019–2020 Australian megafires was estimated for 173 taxa (from 143 species) by combining the spatial overlap of fires/aquatic impacts of varying severity over a taxon's range with the taxon's predicted local population response to fires/aquatic impacts of varying severity.

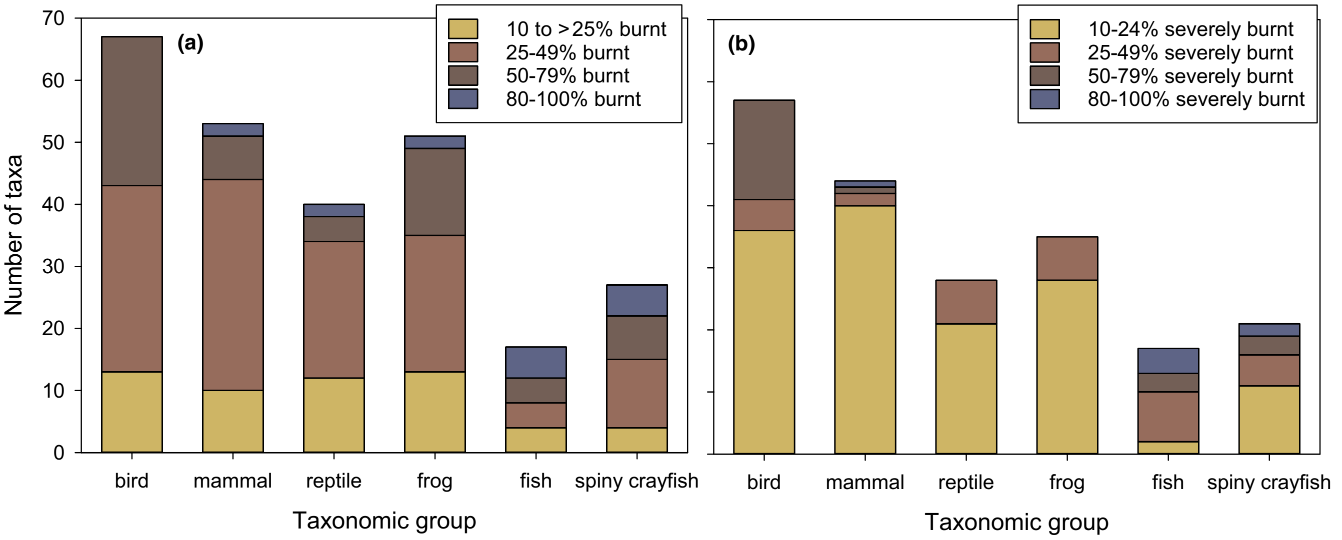

FIGURE 2 Number of taxa in each taxonomic group whose distributions were affected by increasing (a) fire extents; and (b) severe fire extents during the 2019–2020 Australian megafires

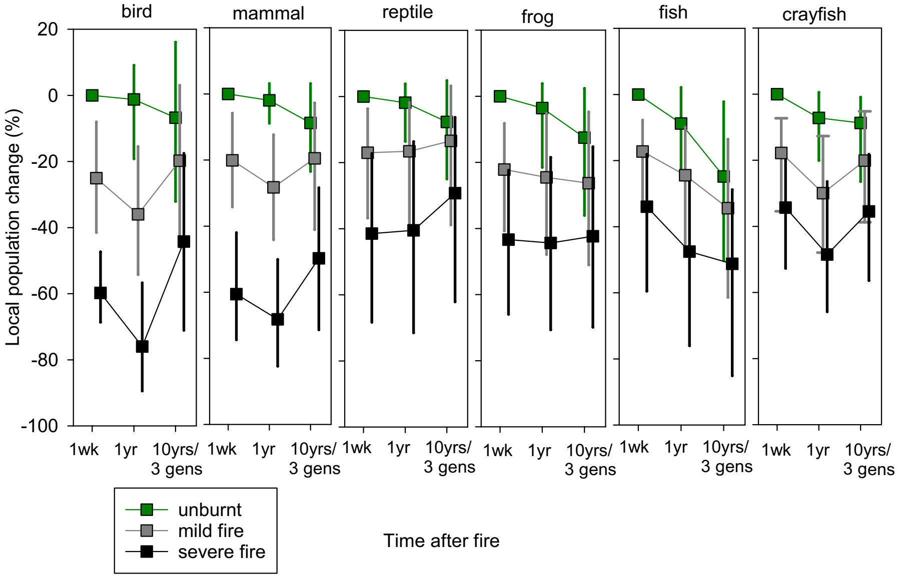

FIGURE 3 Estimates for local population change at three time points, after exposure to severe, mild, or no fire (or severe, mild, or no aquatic impacts), under current conservation management conditions. Data shown are the averaged most plausible, upper and lower 80% confidence bounds, across species in each group. Estimates for each taxon are available in Supporting Information Table S2.1

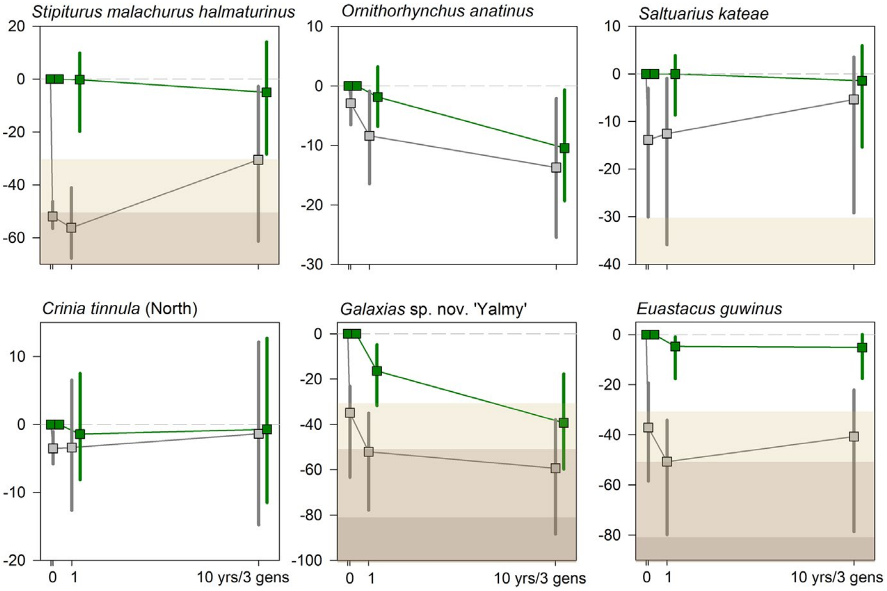

FIGURE 4 Examples of the population changes predicted after fire (grey line) versus if no fire occurs (green line) for 6 out of 173 assessed taxa. Similar graphs for all 173 taxa are in Supporting Information Figure S3.1. Data show estimates of overall population change relative to pre-fire, with 80% confidence bounds, at three time points after fire. Background shading indicates population decline thresholds for listing categories under Criterion A of the International Union for Conservation of Nature (IUCN) Red List Guidelines (lightest brown is 30%; mid-brown is 50%; darkest brown is 80%). All taxa shown here are currently unlisted in national legislation. Our assessment suggests that the Kangaroo Island emu-wren (*Stipiturus malachurus halmaturinus*), Yalmy galaxias (*Galaxias* sp. nov. 'Yalmy'), and Tianjara crayfish (*Euastacus guwinus*) meet criteria for listing based on population loss. Moreover, in each of these three taxa, recovery by 10 years/three generations seems unlikely, as the confidence bounds at this time fail to cross zero. In contrast, recovery seem likely for the wallum froglet [*Crinia tinnula* (North)], and possible for Kate's leaf-tailed gecko (*Saltuarius kateae*). The platypus (*Ornithorhynchus anatinus*) is an example of a taxon experiencing some background decline that fire impacts have compounded in the short term, but the overall population change appears insufficient to warrant listing

3.3.1 | Population loss at 1 week and 1 year post-fire

Of the 173 assessed taxa, 126 had estimated population losses exceeding 10% at either 1 week or 1 year post-fire (Supporting Information Table S2.2, Figure S3.1); estimates exceeded 30% population decline for 28 taxa (nine bird, seven spiny crayfish, four mammal, six fish, two frog, no reptile taxa). Eight taxa (one bird, one mammal, three fish, three spiny crayfish) had estimated population declines that exceeded 50% at either 1 week or 1 year post-fire. Considering the lower 80% confidence bounds, 96 taxa had overall population declines that could exceed 30% at 1 year post-fire (Supporting Information Table S2.2, Figure S3.1).

3.3.2 | Population loss at 10 years/three generations post-fire

Of the 35 taxa (10 fish, six mammal, six frog, six bird, five spiny crayfish, two reptile taxa) with overall estimated population losses exceeding 30% at 10 years/three generations, 23 were among the 28 taxa with population losses exceeding 30% within 1 year of fire. The six taxa with the worst population predictions at 10 years/three generations were all fish. Considering the lower 80% confidence bounds, the population sizes of 130 taxa could decline by at least 30% at 10 years/three generations post-fire (Supporting Information Table S2.2). The overall population changes for each of the 173 taxa after the 2019–2020 fires, together with the estimated population changes had the fires not occurred, are available in Supporting Information Figure S3.1 and Table S2.2, with examples of calculations for six taxa in Figure 4.

3.4 | Population recovery

We predicted most taxa would continue to decline between 1 week and 1 year after fire. Reptiles were most likely to be exceptions, with 20% of taxa predicted to have recovering population trajectories over this period. Between 1 year and 10 years/three generations, predicted population trajectories varied considerably across taxonomic groups, being positive in 6% of the fish taxa, 26% of frog, 42% of mammal, 53% of reptile, 64% of bird and 92% of spiny crayfish taxa (Table 2; Supporting Information Figure S3.1).

Population recovery to within 5% of pre-fire levels was predicted for only 19 of the 173 taxa (11%), ranging from 0% in mammals and fish to 37% in reptiles (Table 2; Supporting Information Figure S3.1). In 79 of the 173 taxa (46%), the upper 80% confidence bound overlapped 100 at 10 years/three generations, indicating that recovery was considered possible, at least in some circumstances. Reptiles were the group with the largest proportion of taxa with predictions indicating possible recovery (87%), followed by birds (71%), frogs (45%) and mammals (37%), whereas fish and spiny crayfish had the lowest proportion of taxa with predictions indicating at least some possibility of recovery (19 and 4%, respectively). Fish were also disproportionately represented in the 50 taxa with the worst population predictions at 10 years/three generations (Figure 5). Some taxa have underlying trends that are unrelated to the fires, with trajectories being influenced by other threats. For example, both the platypus *Ornithorhynchus anatinus* and Yalmy galaxias, *Galaxias* sp. nov. 'Yalmy', were predicted to decline even in the unburnt scenario (Figure 4).

3.5 | Ground-truthing elicitation estimates

Ideally, these elicited assessments should be tested through on-ground evaluations of actual population change. However, it is not possible to do this consistently across species, because there was no relevant sampling following the 2019–2020 wildfires for many species, and because results have not yet been published for most sampling that has been done. Nonetheless, there has been some post-fire monitoring of some species at some sites. Examples of these results, along with examples of previous work that informed expert estimates, are compared with our elicited estimates in Supporting Information Appendix S4 (including Tables S4.1–S4.6), indicating reasonable concordance of the predicted and actual extent of population losses, and suggesting no directional or systematic bias in our elicitations.

3.6 | Conservation status review

From reviewing estimated population declines in the context of the pre-fire status and projected trends of each taxon, we conclude that 21–27 taxa (13–19 species), or 8–10% of the 271 terrestrial and freshwater taxa currently listed as Vulnerable or Endangered, are likely to be eligible for uplisting to a higher threat category under the EPBC Act (Table 2, Figure 6a). We also estimate that the status of another 44–50 listed taxa (38–44 species) has deteriorated, but either not enough to meet thresholds for uplisting, or these taxa (n = 8) already have the highest possible conservation status (Critically Endangered). Our estimates indicate that 70 to 82 currently unlisted taxa (from 68–80 species) are potentially eligible for listing as threatened under the EPBC Act (Table 2, Figure 6b); if these are indeed listed, they would represent an increase of 22–26% over the current list of threatened terrestrial and freshwater vertebrates and spiny crayfish. Most of the currently unlisted taxa are recommended for assessment on the basis of predicted population declines that exceed thresholds in Criterion A, B or C (43–45 taxa). The remaining 27–37 taxa are recommended for assessment because the 2019–2020 fires deepened a pre-existing discrepancy between threatened status under the EPBC Act and more recent assessments by IUCN or other expert groups. Most uplistings are recommended because fire impacts are estimated to have accentuated underlying declines not yet recognized under the EPBC Act (Table 2). These suggested conservation status changes are sufficient to result

TABLE 2 Summary of (a) patterns of recovery for species included in the elicitation; and (b) the conservation status review; based on the estimates for fire-caused population loss and conservation status leading up to the fires

	Birds	Mammals	Reptiles	Frogs	Fish	Spiny crayfish	Total
(a) Recovery (population changes for each species displayed in Supporting Information Figure S3.1)							
n taxa (species) in elicitation	28 (19)	43 (34)	30 (27)	31 (22)	16 (16)	25 (25)	173 (143)
n taxa where population increases between 1 week and 1 year post-fire; % of group	0; 0%	0; 0%	9; 20%	1; 3%	0; 0%	0; 0%	10; 6%
n taxa where population increases between 1 year and 10 years/3 generations post-fire; % of group	18; 64%	18; 42%	16; 53%	8; 26%	1; 6%	25; 92%	86; 50%
n taxa where population recovery by 10 years/3 generations is likely (mean estimate within 5% of pre-fire size); % of group	4; 14%	0; 0%	11; 37%	4; 13%	0; 0%	1; 4%	20; 12%
n taxa where population recovery by 10 years/3 generations is possible (80% confidence includes pre-fire size); (% of group)	20; 71%	16; 37%	25; 83%	14; 45%	3; 19%	1; 4%	79; 46%
(b) Conservation status review							
Number of taxa (and species) potentially eligible for uplisting							
Estimated population loss exceeds a threshold of Criterion A	0	0	0	0	0	0	0
Estimated population loss may exceed a threshold of Criterion A, AND there is evidence of poor pre-fire conservation status	1 (1)	9–11 (5–7)	1–4 (1–4)	4 (2)	0	0	15–20 (9–14)
Estimated population loss contributes to eligibility under Criterion B or C	0	0	0–1	5 (3)	1	0	6–7 (4–5)
Totals	1 (1)	9–11 (5–7)	1–5 (1–5)	9 (5)	1 (1)	0; none listed	21–27 (13–19)
Species already listed as CR	2	0	2	3	1	0	8
Number of taxa (and species) potentially eligible for listing							
Estimated population loss exceeds a threshold of Criterion A	17[#](17)	0	1	2 (2)	9 (9)	8 (8)	37 (37)
Estimated population loss may exceed a threshold of Criterion A, AND there is evidence of poor pre-fire conservation status	6–7 (4–5)	1–5 (1–5)	0–2 (0–2)	4–6[+] (4–6)	1	15–16* (15–16)	27–37 (25–35)
Estimated population loss contributes to eligibility under Criterion B or C	0	0	4–6 (4–6)	1	0	1	6–8 (6–8)
Totals	23–24[#] (21–22)	1–5 (1–5)	5–9 (5–9)	7–9[+] (7–9)	10 (10)	24–25[*] (24–25)	70–82 (68–80)

(Continues)

TABLE 2 (Continued)

	Birds	Mammals	Reptiles	Frogs	Fish	Spiny crayfish	Total
Total number of listed terrestrial and freshwater taxa (excludes marine, seabirds, waders) under EPBC Act at Jan 2021; % increase to statutory lists after 2019–2020 fires (based on species)	92	98	52	35	35	3	315 (44 CR; 271 EN, VU)
	25–26%	5%	10–17%	20–26%	29%	800–833%	22–26%

Note: EPBC Act, *Environment Protection and Biodiversity Conservation Act 1999*; CR, Critically Endangered; EN, Endangered; VU, Vulnerbale. Where there is a range, the lower value counts taxa that our assessment indicates *are likely* to be eligible; the upper value also counts taxa that our assessment indicates *could be* eligible. The tallies for *taxa* in the table include accepted subspecies for birds and mammals, and candidate species for mammals, reptiles and frogs (identified in Catullo et al., 2021). The tallies for *species* exclude the potential taxonomic updates, and where two or more recognized subspecies are fire-affected, only the species is counted.

#Includes 13 taxa not in the elicitation, endemic to Kangaroo Island, with distributions mostly (> 50%) severely burnt.

*Includes three fire-affected taxa not in the elicitation, listed as Endangered by International Union for Conservation of Nature (IUCN) Red List, and highly likely to be eligible for listing under the EPBC Act.

+Includes one fire-affected taxon not in the elicitation, listed as Endangered by a recent expert assessment (Gillespie et al., 2020), and highly likely to be eligible under the EPBC Act.

in a steepening of the underlying trajectory of decline in RLI for all vertebrate taxonomic groups (Figure 7).

4 | DISCUSSION

Megafires are unique in their capacity to rapidly drive changes in the conservation status of many species across large geographical areas. Our study suggests that after the 2019–2020 Australian megafires, 91–109 vertebrate and spiny crayfish taxa (from 81–99 species) may be eligible for listing as threatened, or uplisting, under national environmental legislation; and that most assessed taxa are unlikely to recover fully over the next 10 years/three generations, even in the absence of further megafires or droughts. Given the predictions of increasing frequency of extensive, severe fires driven by climate change (Di Virgilio et al., 2019), the long-term prospects for these taxa appear poor. Below, we discuss key findings from the expert elicitation on local population response to fire, before covering the implications of the estimates of overall population declines and recovery, and conservation status assessments. Finally, we discuss the limitations of our study and outline recommendations for further research.

4.1 | Local population response to fire

Across most taxa, we estimated marked local population losses within a week of fire, with losses varying among species and groups, and being more pronounced in severe than in mild fires. For most taxa, we predicted that the local population losses would worsen for at least 1 year following fire. Changes to food, shelter, predation risk, and other effects of fire can increase mortality for weeks, months, and even years after fire (Engstrom, 2010; Whelan et al., 2002). For aquatic fauna, impacts can manifest well after fires, due to rainfall events that transport and deposit sediment and ash into waterways (Rieman et al., 2012; Silva et al., 2020). Overall, mammals and birds were considered more susceptible to the short-term impacts of severe fire than other groups.

By 10 years/three generations after fire, we predicted many mammal species would remain heavily impacted, but birds would recover more strongly (Figures 3, 4; Supporting Information Figure S3.1). We predicted that frogs and fish would not recover, or may even continue to decline, over this period. Conversely, we predicted many spiny crayfish would show signs of recovery, and most reptiles would recover by 10 years/three generations after fire, with exceptions including the riverine turtles (*Wollumbinia* spp.) and the Blue Mountains water skink (*Eulamprus leuraensis*). Between 1 week, 1 year, and 10 years/three generations, the shuffling in rankings of taxa according to their estimated population losses reflects differences among species in their recovery trajectories post-fire. This could be driven by variation among species in their exposure to other threats (e.g., the turtles and Blue Mountains water skink are strongly affected by threats unrelated to fire); the time taken for critical resources to recover for some species; and life-history traits. For example, the greater glider and yellow-bellied glider (*Petaurus australis*) both depend on large tree hollows, a resource that could be reduced for decades after severe fire (Haslem et al., 2011; Jones et al., 2021; Lindenmayer & Taylor, 2020; Parnaby et al., 2010). Both glider species had the highest estimates for local population loss at 1 week, 1 year and also at 10 years/three generations after fire. The predicted poor recovery of many fish species reflects the persistence of changes to stream and habitat architecture following fire, such as infilling of pools by coarse sediment with residence times of > 100 years (Lyon & O'Connor, 2008; Moody & Martin, 2001); low dispersal capacity (many are small-bodied species, Kopf et al., 2017; Olden et al., 2007), and constrained recolonization opportunities (such as when linear environments are fragmented by anthropogenic barriers, Crook et al., 2015).

We note that populations were predicted to decline over the next 10 years for many species, even at sites that were not burnt in the

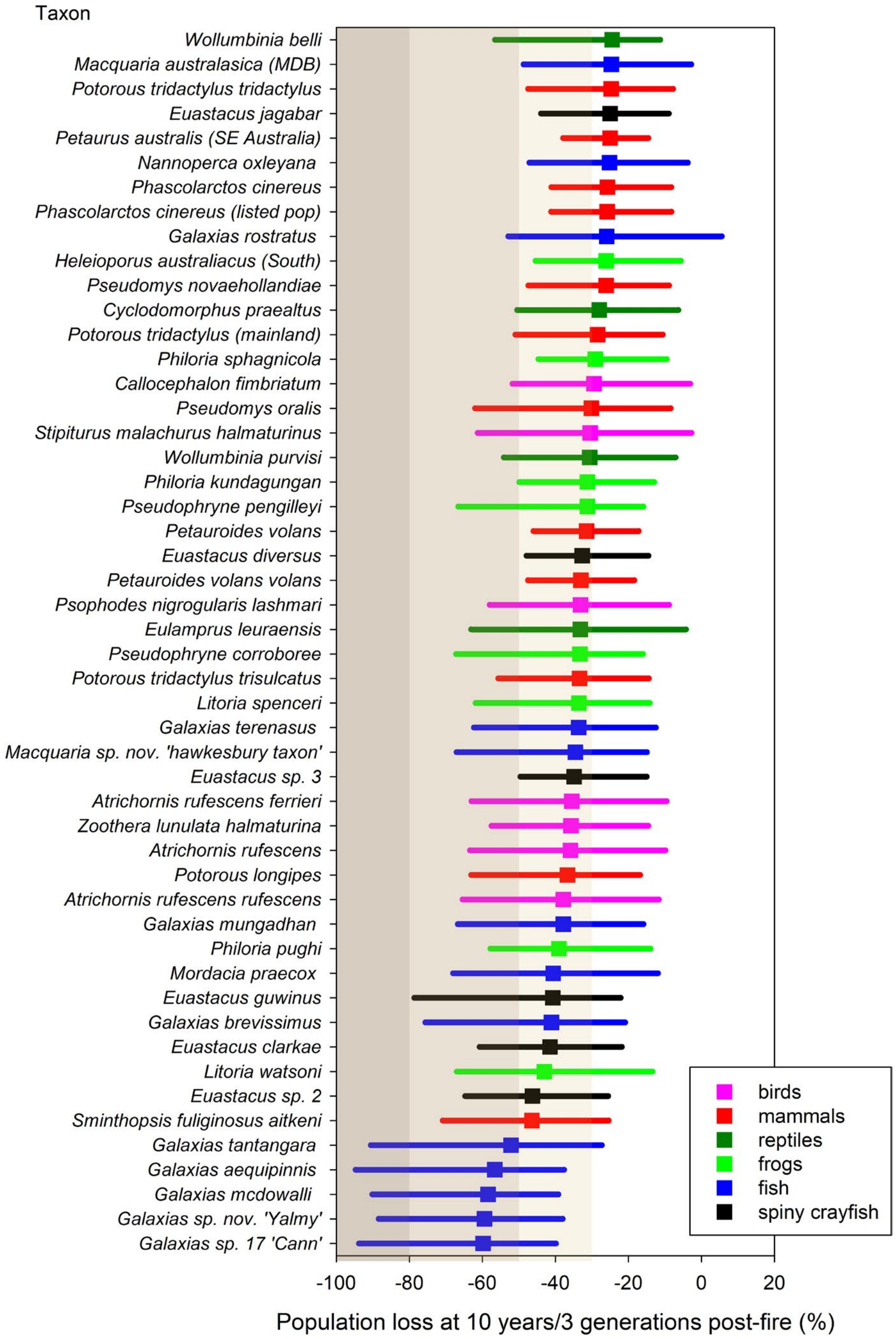

FIGURE 5 The 50 taxa with the largest estimated population losses at 10 years/three generations, arranged in order of loss using most plausible estimates, and colour-coded to show their taxonomic group. The shading indicates population declines of 30% (lightest brown), 50% (mid-brown), and 80% (darkest brown)

2019–2020 fires (Figures 3, 4; Supporting Information Figure S3.1), reflecting underlying declines caused by other threats. However, notwithstanding such expected losses at unburnt sites, in general (Figure 3) populations were expected to be lower 10 years post-fire at sites that were severely burnt in the 2019–2020 fires, than at sites that were burnt mildly, and at unburnt sites; that is, experts predicted an enduring impact of the 2019–2020 fires.

4.2 | Conservation impact and taxon recovery

The 2019–2020 Australian megafires have potentially increased the extinction risk of many animal taxa. At least one taxon, Yalmy galaxias, which was restricted to one small stretch of river, faces imminent extinction as a direct consequence of the megafires (only two males have been detected since the fires despite intensive field sampling; T. Raadik, personal communication). We estimate that the 2019–2020 Australian megafires have caused or amplified extinction risks sufficiently to cause a change in conservation status for 70–82 currently unlisted taxa, potentially increasing the statutory lists of threatened terrestrial and freshwater vertebrates and spiny crayfish by 22–26%. In addition, of the 49 taxa in our assessment that are listed as Vulnerable or Endangered under the EPBC Act, our assessment indicates that over one third may require uplisting to a higher threat category, which would cause a change in status for 8–10% of the currently listed terrestrial and freshwater vertebrates and

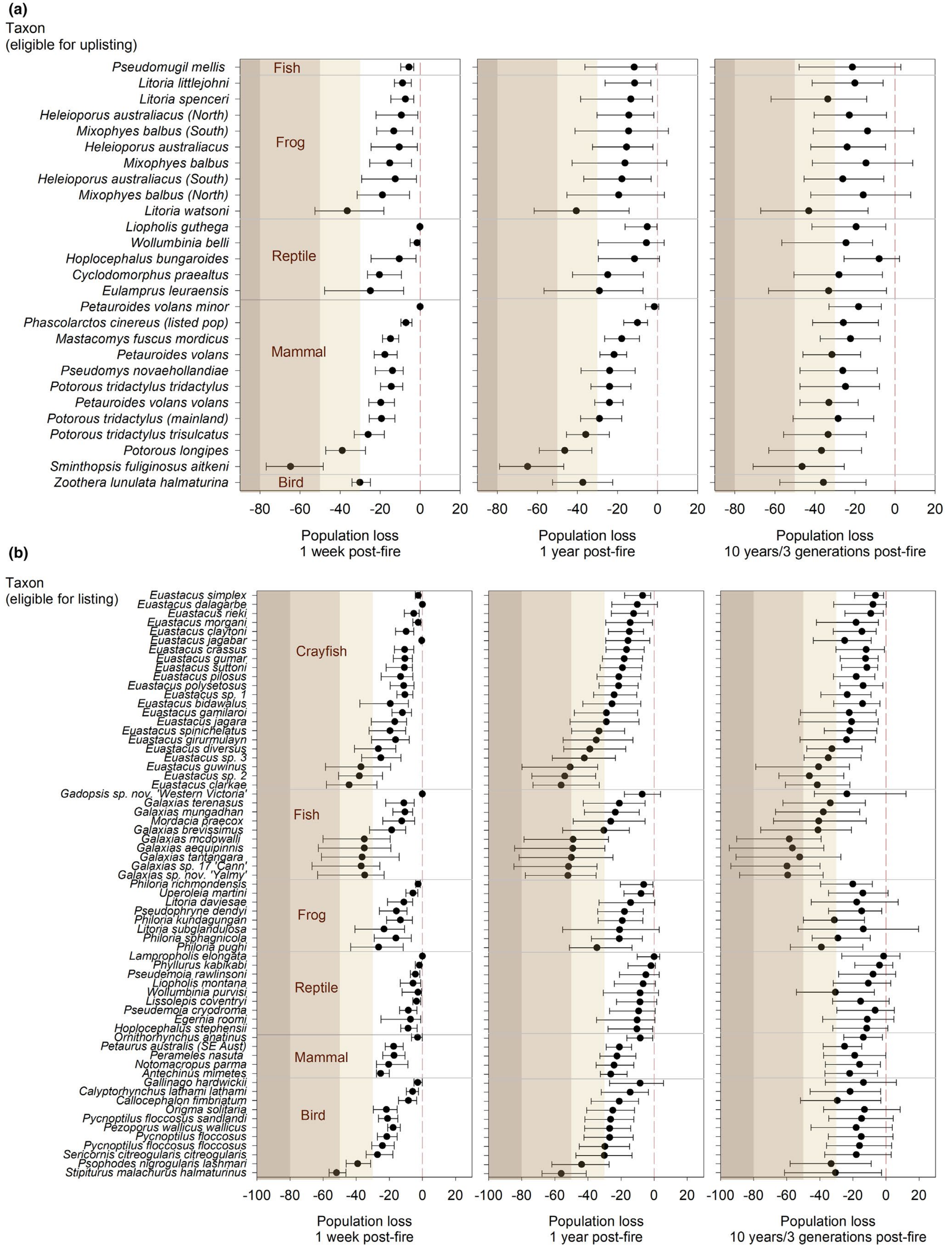
(a)
Taxon
(eligible for uplisting)
Fish
Frog
Reptile
Mammal
Bird
Pseudomugil mellis
Litoria littlejohni
Litoria spenceri
Heleioporus australiacus (North)
Mixophyes balbus (South)
Heleioporus australiacus
Mixophyes balbus
Heleioporus australiacus (South)
Mixophyes balbus (North)
Litoria watsoni
Liopholis guthega
Wollumbinia belli
Hoplocephalus bungaroides
Cyclodomorphus praealtus
Eulamprus leuraensis
Petauroides volans minor
Phascolarctos cinereus (listed pop)
Mastacomys fuscus mordicus
Petauroides volans
Pseudomys novaehollandiae
Potorous tridactylus tridactylus
Petauroides volans volans
Potorous tridactylus (mainland)
Potorous tridactylus trisulcatus
Potorous longipes
Sminthopsis fuliginosus aitkeni
Zoothera lunulata halmaturina
-80 -60 -40 -20 0 20
Population loss
1 week post-fire
Population loss
1 year post-fire
Population loss
10 years/3 generations post-fire
(b)
Taxon
(eligible for listing)
Crayfish
Fish
Frog
Reptile
Mammal
Bird
Euastacus simplex
Euastacus dalagarbe
Euastacus rieki
Euastacus morgani
Euastacus claytoni
Euastacus jagabar
Euastacus crassus
Euastacus gumar
Euastacus suttoni
Euastacus pilosus
Euastacus polysetosus
Euastacus sp. 1
Euastacus bidawalus
Euastacus gamilaroi
Euastacus jagara
Euastacus spinichelatus
Euastacus girurmulayn
Euastacus diversus
Euastacus sp. 3
Euastacus guwinus
Euastacus sp. 2
Euastacus clarkae
Gadopsis sp. nov. 'Western Victoria'
Galaxias terenasus
Galaxias mungadhan
Mordacia praecox
Galaxias brevissimus
Galaxias mcdowalli
Galaxias aequipinnis
Galaxias tantangara
Galaxias sp. 17 'Cann'
Galaxias sp. nov. 'Yalmy'
Philoria richmondensis
Uperoleia martini
Litoria daviesae
Pseudophryne dendyi
Philoria kundagungan
Litoria subglandulosa
Philoria sphagnicola
Philoria pughi
Lampropholis elongata
Phyllurus kabikabi
Pseudemoia rawlinsoni
Liopholis montana
Wollumbinia purvisi
Lissolepis coventryi
Pseudemoia cryodroma
Egernia roomi
Hoplocephalus stephensii
Ornithorhynchus anatinus
Petaurus australis (SE Aust)
Perameles nasuta
Notomacropus parma
Antechinus mimetes
Gallinago hardwickii
Calyptorhynchus lathami lathami
Callocephalon fimbriatum
Origma solitaria
Pycnoptilus floccosus sandlandi
Pezoporus wallicus wallicus
Pycnoptilus floccosus
Pycnoptilus floccosus floccosus
Sericornis citreogularis citreogularis
Psophodes nigrogularis lashmari
Stipiturus malachurus halmaturinus
-100 -80 -60 -40 -20 0 20
Population loss
1 week post-fire
Population loss
1 year post-fire
Population loss
10 years/3 generations post-fire

FIGURE 6 (a) Taxa that could be considered for uplisting under the *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act), based on the estimated fire-caused population declines and their pre-fire population status and trends. Taxa are arranged in order of their most plausible estimated declines 1 year post-fire, within their taxonomic groups. Taxa with population loss estimates and bounds that do not exceed thresholds [e.g., the broad-headed snake (*Hoplocephalus bungaroides*) does not exceed 30% population loss] are generally fire-impacted taxa that are eligible for uplisting on criteria other than Criterion A. The shading indicates thresholds for population declines of 30% (lightest brown), 50% (mid-brown), and 80% (darkest brown). (b) Taxa that could be considered for listing as nationally threatened under the *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act), based on the estimated fire-caused population declines and their pre-fire population status and trends. Taxa are arranged in order of their most plausible estimated declines 1 year post-fire, within their taxonomic groups. Taxa with population loss estimates and bounds that do not exceed 30% [e.g., small mountain crayfish (*Euastacus simplex*)] are fire-impacted taxa that are eligible for listing on criteria other than Criterion A. The shading indicates thresholds for population declines of 30% (lightest brown), 50% (mid-brown), and 80% (darkest brown)

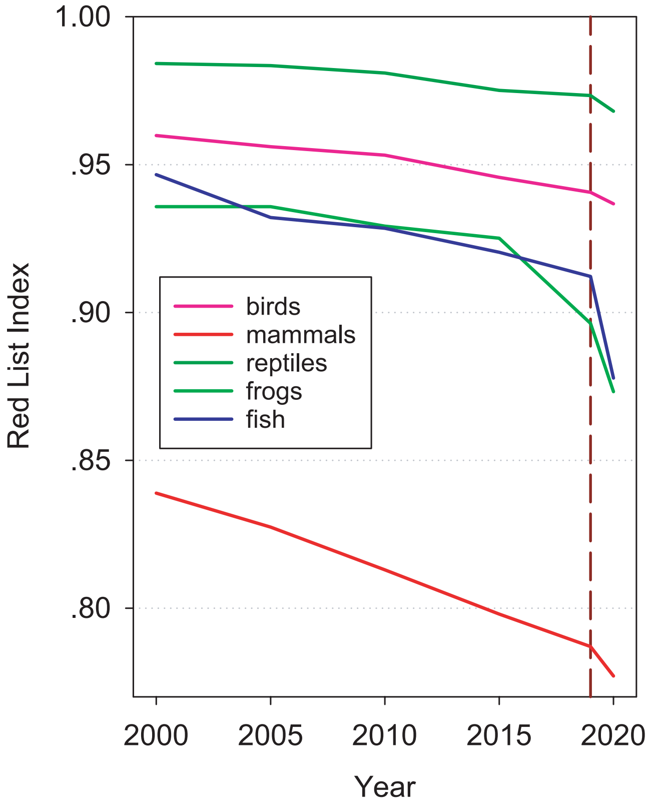

FIGURE 7 Changes in the Red List Index since 2000 for the five vertebrate groups, based on the assumption that taxa assessed here as likely to be eligible for threatened species listing are so-listed. The vertical dashed line shows when, in the timeline, the 2019–2020 megafires occurred

spiny crayfish taxa. In some taxa, the fires have likely compounded declines that were previously below thresholds for listing as threatened, or that were substantial but yet to be recognized by the formal Australian threatened species listing process. This is particularly the case for fish and spiny crayfish, many of which are narrow-ranged endemics and already threatened by factors such as climate change (drought) and invasive species (Furse & Coughran, 2011; Lintermans et al., 2020). In other taxa, we estimate that the fires have caused substantial population loss when pre-fire population trajectories were stable, such as the Kangaroo Island southern emu-wren (*Stipiturus malachurus halmaturinus*, estimated population loss 1 year post-fire: 56%, confidence limits: 41–68%).

The evidence arising from this study is being used to prioritize and inform conservation assessments under Australian legislation: of the 91 taxa predicted to warrant listing/uplisting, 84 are already in various stages of review under national processes. If the changes to the statutory lists recommended by our study are made, the 2019–2020 fires will cause a notable inflection to underlying patterns of decline in the vertebrate groups assessed, as measured by the Red List Index. Overall, around half of this steepening is solely due to estimated fire impacts, with the remainder due to fire impacts compounding declines that had yet to be recognized under Australian legislation. Our analysis considered terrestrial and aquatic vertebrates and one invertebrate group; we anticipate similar consequences for other taxa, such as plants and other invertebrates (Gallagher et al., 2021; Marsh et al., 2021).

The sudden increase in extinction risks across many taxa may be a new and recurring feature of megafires. Similar effects from single fire seasons have been reported from the Amazon, where megafires in 2019 potentially increased the extinction risk for up to half the listed threatened plant taxa in the region (Mortara et al., 2020), and contributed to the broad-scale conversion of some forest types to savanna (Armenteras et al., 2021). Some invasive species and diseases have impacted biodiversity at comparable scales. For example, chytrid fungus has caused the largest vertebrate biodiversity loss of any pathogen, causing declines (including extinctions) in 6.5% of frog species globally (Scheele, Pasmans, et al., 2019), and 18% of frog species (i.e., 43/238) in Australia (Scheele et al., 2017) but this impact has been realized, and is potentially still being realized, over an extended period of time.

Although the immediate impacts of megafires may be large, the longer-term effects of increases in fire frequency, size and severity, driven by a changing climate (Di Virgilio et al., 2019; Goss et al., 2020), could be greater. The structure and composition of some ecosystems are shifting, with areas becoming uninhabitable for some species (Armenteras et al., 2021; Bergstrom et al., 2021). Moreover, populations of some taxa may be unable to recover between fire events, leading to a ratchet of progressive decline (Lindenmayer et al., 2021). In our assessment, only 12% of taxa were predicted to recover to pre-fire levels by 10 years/three generations (noting that some of these were undergoing declines before the fires). Recovery was possible for an additional 34% of taxa, meaning that over half the taxa assessed were considered unlikely to recover to pre-fire levels within 10 years or three generations. We estimated that the groups with poorest recovery prospects were spiny crayfish, fish, and mammals, while recovery was possible in a greater proportion of reptile and bird taxa. The predicted lack of recovery over a decadal scale to pre-fire population levels for most species here is consistent with the limited or lack of recovery observed for species of forested environments after previous severe fires (Bergstrom et al., 2021).

Our recovery projections may be optimistic, because our predictions assumed no further extreme drought or fire events during the recovery period, which is unrealistic across the broad geographical region captured in our assessment (Abram et al., 2021). Furthermore, the scale of severe fires that occurred in 2019–2020 could affect processes of recolonization and resource recovery more strongly than observed in other fires, upon which our expert judgments were based. Conversely, expert predictions assumed that the management effort in place before the fires would continue, but additional targeted efforts post-fire could improve recovery. Such efforts are underway for some taxa at some sites, although future resourcing to prolong this remedial management is not guaranteed.

4.3 | Recommendations for further research

We refined previous work that estimated fire overlaps with taxon distributions (Feng et al., 2021; Legge, Woinarski, Scheele, et al., 2021; Ward et al., 2020) by incorporating improved distribution data, new fire severity and aquatic impact mapping, and the expert estimates of taxon susceptibilities to fires/aquatic impacts of varied severity. Our study nevertheless has limitations that can inform future research priorities. First, the fire severity dataset and the aquatic impacts spatial model both require further validation. Second, considering the estimated population trajectories in the context of alternative fire frequency scenarios, as well as interactions with the changing climate and other threats, would help identify vulnerable taxa and guide conservation efforts to mitigate or spread risk (e.g., through translocation, captive breeding and targeted fire management). Third, estimates of overall population loss is an important but blunt metric, and more refined estimates could be produced by considering spatial variation in population density and population genetics, as well as the spatial variation in fire severity (Jolly, Moore, et al., 2022). Fourth, our analysis estimated population losses across the entire distribution of a taxon in order to inform a national assessment of conservation status. It would be possible to devolve these results to regional and local levels to identify priority sites for recovery actions and long-term monitoring across multiple taxa, and our estimates for population recovery rates could inform the sampling design of such monitoring (Southwell et al., 2021).

Finally and most importantly, our assessments of population responses to fire are estimates and predictions; empirical data on taxon response to fires of different severity across their range are urgently needed to calibrate expert judgements (Kahneman & Klein, 2009). It is not currently possible to do this consistently across species, because there has been no relevant sampling following the 2019–2020 wildfires for many species, and because results have not yet been published for some sampling that has been done. Nonetheless, the fragmentary data available so far, together with monitoring of some species, at some sites, before and after previous fire events (Supporting Information Appendix S4) indicate reasonable concordance with the expert elicitations. Ideally, time series monitoring is needed to assess trends (including responses to major disturbance events) for many more species and their threats than is currently the case: the poor state of biodiversity and threat monitoring in Australia has been repeatedly recognized as a major impediment to conservation management (Lindenmayer et al., 2012; Scheele, Legge, et al., 2019). This enhanced research and management attention is needed across all species, given that declines related to climate change and associated stochastic events are predicted for many non-threatened as well as threatened species (Lunney, 2017).

The extent of the 2019–2020 Australian megafires also provides an exceptional opportunity to build evidence from on-ground studies about population impacts, the rate and extent of recovery, and the effectiveness of post-fire management actions. Some such studies are currently underway; many of these should be maintained to describe longer-term recovery trajectories, and responses to recurrent fire. Such work will provide a stronger platform for future conservation assessments and recovery planning. Critically, for taxa with poor recovery prospects, evaluating whether additional management intervention could facilitate recovery and enhance resilience is an important next step.

Our study was a pragmatic attempt to assess the magnitude and uncertainty around potential impacts of the 2019–2020 megafires across a large suite of species. The process we describe here, of combining measurements of distributional overlap with fires of varying severity, with expert-based estimates of local population loss in fires of varying severity, allows for rapidly estimating population losses and recovery across many taxa when empirical data are limited. Most importantly, the approach can rapidly help to prioritize species that need legislative protection, surveys to establish status, and remedial management (such as threat abatement, habitat protection and restoration, ex situ and translocation actions) after future megafire or other environmental catastrophes that affect many species. Unfortunately, there is likely to be growing global need for the development and application of such responses.

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CONFLICT OF INTEREST

The authors have no conflicts of interest to declare.

ETHICAL APPROVAL

This desktop study did not require ethics permits.

DATA AVAILABILITY STATEMENT

Data are available as Supporting Information.

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BIOSKETCH

The 2019–2020 Australian megafires had such extensive effects on biota that prioritizing management attention and legislative protection has been critical for mounting an effective response. This research aimed to support that prioritization, by estimating population declines across many taxa using the best information available at the time. The research team comprises 51 ecologists who are experts in one or more of the taxonomic groups included in the study, plus 11 ecologists with expertise in expert elicitation, species distribution modelling, spatial analysis, and application of IUCN listing criteria.

SUPPORTING INFORMATION

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

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