



Australia's most imperilled vertebrates

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ABSTRACT

The likelihood of extinction within the next 20 years was determined for 47 Australian mammal, bird, reptile, frog and freshwater fish taxa previously identified as being highly imperilled. A 14-member expert elicitation panel, consisting of a mix of taxon experts and government managers of threatened species, estimated that there was a > 50% chance that nine taxa would be extinct by 2041. The panel estimated that there was a > 50% likelihood that a further 16 taxa (considered extant under Australian legislation), for which there are no recent independently verified records, are already extinct, with four almost certainly extinct. For five of these taxa, there was a > 50% chance that they would persist for 20 more years if they are currently extant, notwithstanding the lack of recent records. Most of the taxa considered occur within conservation areas and in south-eastern Australia, where human population density is highest. All the highly imperilled taxa occur wholly or partly in conservation reserves, within a total reserved area of 1994 km², 0.13% of the total area conserved in Australia. Highly imperilled taxa also occur on 313 km² of non-conservation government-owned land, and 242 km² of private land. The total area that needs management intervention to prevent extinction of Australia's most imperilled vertebrate taxa in the next 20 years represents 0.06% of the area of Australia's terrestrial and freshwater environments.

1. Introduction

Modern extinctions are occurring at a rate comparable in magnitude to the five mass extinction events of Earth's history (Johnson et al., 2017). A review undertaken in 2019 by the United Nations estimated that up to one million species are threatened with extinction as a result of human impacts, and that the overall health of ecosystems is deteriorating more rapidly than ever (IPBES, 2019). However, extinction,

even of highly imperilled species, need not be inevitable (Bolam et al., 2021), and lessons learnt from the many examples of local conservation success demonstrate that losses can be halted, and in some cases reversed (e.g. see Garnett et al., 2018; Grace et al., 2021). Reducing the rate of biodiversity loss requires, in part, an understanding of which species are at greatest risk of extinction so that remedial management can be taken in time.

Extinction risk is broadly described by the International Union for

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the Conservation of Nature (IUCN) Red List of Threatened Species. The IUCN assigns conservation status categories to species based on criteria relating to distribution, population size, decline and threats, with categories ranging from “Least Concern” to “Extinct”. To date, more than 124,000 species have been assessed against the IUCN criteria globally (IUCN, 2021), and it has long been the most widely used tool for measuring extinction risk (Rodrigues et al., 2006). However, despite its wide application, the approach has limitations for identifying and prioritising species at the very edge of extinction. First, assessments are biased towards some taxonomic groups. Among vertebrates, 87–100% of all described species of birds, mammals and frogs had been evaluated as of March 2021, compared to 75% of reptiles and 61% of fish (IUCN, 2021). The proportions are far lower for plants (13% of all described taxa), invertebrates (2%), fungi and protists (0.3%). Second, the IUCN categories were not designed to distinguish species on a rapid trajectory towards extinction from those with very small populations that may persist for long periods, even though their extinction risk is high should circumstances change (Geyle et al., 2018). This is particularly true for predicting imminent extinction in taxa with long generation times where individuals may survive beyond the period of interest even if recruitment has ceased. There is therefore value in undertaking an additional process that more explicitly estimates extinction likelihood over a specified time period, as this can assist timely allocation of adequate resources targeted directly at preventing extinction.

Previous research has found that adapting standard extinction risk models to forecast imminent extinction does not produce plausible results, at least for some species (Geyle et al., 2018). This is in part because the data required for individual population viability models (based on life history parameters and population growth rates) are not available for most threatened species (Coulson et al., 2001), and often there is not enough time to obtain additional data for such purposes, even if funds were available (Martin et al., 2012a). Given that the most imperilled species often include multiple taxonomic groups with varying levels of data deficiency, a useful alternative source of knowledge may come from experts (Hemming et al., 2018a). Experts have acquired learning and experience that allows them to provide valuable insight into the behavior of environmental systems (McBride et al., 2012), and they are able to synthesize multiple risks and probabilities in ways that may be intractable for numerical models (Geyle et al., 2018). Furthermore, the variation in experience and risk perception among experts allows for the development of multiple “mental models” from the same empirical data, where integrating the opinions of multiple experts may be seen as an exercise in model averaging (Symonds and Moussalli, 2010). Several studies have found that a diverse group of experts with varied experience and backgrounds produced more accurate results than did a single ‘expert’ or small group of ‘experts’ (Budescu and Chen, 2014; Burgman et al., 2011; Hemming et al., 2018a, 2018b; Martin et al., 2012b).

Such approaches do, however, have limitations. The current status and threat milieu may be a poor predictor of future risks, especially if novel threats are encountered, or if existing threats rapidly become magnified to unprecedented levels. For example, three endemic lizard species on Christmas Island (Indian Ocean) were considered secure and common in the 1980s but declined thereafter precipitously to extinction or extinction in the wild over the next few decades, because of the inadvertent introduction of a new predator (Emery et al., 2021). Another example is the exceptional wildfires in Australia in 2019–20, that caused abrupt deterioration in the conservation status and population trajectories of hundreds of species, including the sudden imperilment of many species not formerly considered threatened (Legge et al., in press).

Furthermore, experts may be subject to cognitive and motivational biases that impair their ability to report their true beliefs accurately (Morgan, 2014). For example, expert judgements may be influenced by individual values and conflicts of interest, and they are sensitive to a number of subjective biases (McBride et al., 2012). Structured expert elicitation has been developed in an attempt to counter some of these known biases (Hemming et al., 2018b). Structured approaches employ a

formal, documented, and systematic procedure for expert elicitation that encourages experts to cross-examine evidence, resolve unclear or ambiguous language and think about where their judgements may be at fault or superior to those of others (Hemming et al., 2018b; McBride et al., 2012). While performance-weighted aggregation may be useful for improving pooled judgements relating to ecological questions, this approach is likely to be significantly more time consuming with no guarantee that it will lead to improvements (Hemming et al., 2020). Given the time sensitive nature of extinctions, especially in relation to taxa categorised by the IUCN as “Critically Endangered (Possibly Extinct)” CR(PE), some of which are assessed here, it is more prudent to estimate extinction risk in a timely manner to inform and prioritise management actions aimed at preventing extinctions, than to undertake significantly lengthier processes that may or may not improve estimates.

In this study, we used structured expert elicitation to identify the Australian vertebrates at greatest risk of extinction, focusing on five taxonomic groups: mammals, birds, reptiles, frogs and freshwater fish. Australia has one of the worst records globally for recent extinctions (Ritchie et al., 2013), most evident in the average loss of ca. 1.5 mammal species per decade since European colonisation in 1788 (Woinarski et al., 2017), amounting to a total loss of 34 endemic mammal species (Woinarski et al., 2019). Thirty-one Australian bird taxa (i.e., including subspecies) have also become extinct in the last 200 years, of which 30 were Australian endemics (Garnett and Baker, 2021). While fewer extinctions have been recorded among Australian frogs, reptiles and fish (Woinarski et al., 2019), undetected extinctions may well have occurred in each of these groups. For example, no Australian frog extinctions were recorded before 1970 (Hero et al., 2006), but there was limited work on Australian frogs before the 1950s (Shea, 2015). High levels of cryptic diversity have recently been found among frogs (Mahony et al., 2020, 2021a, 2021b), reptiles (Melville et al., 2021) and freshwater fish (Adams et al., 2014; Hammer et al., 2007, 2018; Oliver et al., 2009; Raadik, 2014; Shelley et al., 2017; Unmack et al., 2017), meaning some species are almost certain to have become extinct without formal description (Adams et al., 2014; Oliver et al., 2009). To date, four Australian frog species, three Australian reptiles and one Australian freshwater fish are formally recognised as having become extinct, or extinct in the wild, over the last ca. 200 years (Woinarski et al., 2019).

The Australian Government has identified risk of imminent extinction as a key principle for prioritising recovery action, particularly in response to natural disasters and other emergency events (Department of Agriculture, Water and the Environment, 2021a), which first requires identification of the taxa at most immediate risk. In this paper, we build on previous class-specific studies aimed at identifying taxa at risk of imminent extinction, focusing on taxa estimated in the earlier studies to have a > 50% likelihood of extinction in the next 20 years (Geyle et al., 2018, 2021a, 2021b; Lintermans et al., 2020). There are three major differences in this new work. First, we forecast extinction risk for vertebrates of all five taxonomic classes at the same time based on structured elicitation from a single panel of experts. Secondly, over half of the elicitation panel used here consisted of government managers of threatened species with direct responsibility for ensuring species recovery, with the remainder being lead experts from each of the targeted groups. Our approach therefore allows direct comparisons to be made of the most threatened taxa across vertebrate classes, and consequently will assist with prioritisation, direction and resourcing of management aimed at preventing future Australian vertebrate extinctions. Thirdly, we consider the tenure of the land on which each highly imperilled taxon now survives, to determine which of these taxa now rely on conserved areas, both public and private (Jonas et al., 2021), or on other government-managed lands.

2. Methods

2.1. Data collection and preparation

2.1.1. Taxon selection

We considered all Australian birds, mammals, reptiles, frogs and freshwater fish for which there was a modelled likelihood of extinction greater than 50% from recent expert elicitation studies (Geyle et al., 2018, 2021a, 2021b; Lintermans et al., 2020). This resulted in the inclusion of an initial 44 taxa. We then consulted experts with knowledge on each vertebrate group to determine if any additional taxa warranted inclusion based on new information obtained since the earlier assessments were completed, resulting in the addition of a further 19 taxa (see Supplementary Material S1 for list of taxa considered). This included taxa that were not considered in the previous elicitation exercises, but for which recent events (e.g., the 2019–2020 wildfires) were likely to have elevated their risk of extinction, and one taxon that was recently recognised as taxonomically distinct (*Gadopsis* sp. South-East; Unmack et al., 2017). We also included two species of turtle thought to be at high risk that had not previously been assessed (because the previous reptile assessment included only squamates): the Bellinger River Snapping Turtle (*Myuchelys georgesi*) and the Western Swamp Turtle (*Pseudemys umbrina*). The set of taxa also included 16 taxa for which there has been no recent (typically >20 years), independently verified sightings, and consequently, taxa for which there is uncertainty regarding their status as extant. We label these taxa Critically Endangered (Possibly Extinct) (CR(PE)) but note that only five are currently assessed in the literature as such (Department of Environment and Energy, 2018; Garnett and Baker, 2021; Shea et al., 2018; Woinarski et al., 2018), with the others being assessed as Extinct (EX, 1 taxon), Critically Endangered (CR, 5 taxa), Endangered (EN, 3 taxa) or not assessed (2 taxa). For birds and mammals, we used subspecies as our unit of assessment, as comprehensive treatments are available for both these classes at the subspecific levels (Garnett and Baker, 2021; Woinarski et al., 2014). For reptiles (including the turtles), freshwater fish and frogs, we assessed taxa at the species level because extinction risk has only been assessed consistently at the species level for these classes, in line with global IUCN policy (Chapple et al., 2019; Gillespie et al., 2020; Lintermans et al., 2020; Tingley et al., 2019). For freshwater fish, this included several newly recognised genetically distinct species of *Galaxias*, *Gadopsis* and *Melanotaenia* (Majtánová et al., 2020; Raadik, 2014; Unmack et al., 2017) which lack formal description. In all our assessments, we considered the probability of *extinction from the wild*: we did not include two reptile species and one fish species that are already Extinct in the Wild (see Geyle et al., 2020, Geyle et al., 2021b, Lintermans et al., 2020).

2.1.2. Expert selection

We invited threatened species managers from state/territory and federal government departments across Australia to participate in this assessment, given their responsibility for the management of the threatened taxa considered here. We also asked five researchers considered to be leading experts in at least one of the taxonomic groups assessed. Taxon leads, selected on the basis of their contributions to recent elicitation assessments, provided an expert perspective on extinction risk for the taxa considered. Any confirmation bias that might have arisen from using the same experts in the current and previous assessments was assumed to be offset by the value derived from their continued contributions and the dilution of any one opinion in a panel of 14 people. In addition to the taxon experts, our expert panel had representatives of the governments of the Northern Territory, South Australia, Victoria, Queensland, Tasmania and Western Australia, and the Australian Commonwealth (all but one of whom are listed as authors here). Managers from the sixth Australian state, New South Wales, participated in the analysis and interpretation of results. All participants had a history of working with threatened species in both a research and

management capacity, and had relevant knowledge of distributions, ecology and populations of taxa considered as part of this study.

2.1.3. Structured expert elicitation

We used structured expert elicitation to obtain estimates of extinction risk (Burgman et al., 2011; McBride et al., 2012). We adapted the process to suit the purpose of the study, which involved four main steps, all of which were conducted remotely via email or teleconference.

- i. We provided participants with a dossier of information on each taxon, including taxonomic status, conservation status, distribution and population estimates, ecology, threats, and past and current conservation management actions. Respondents could read dossiers in any order, so sequence order is unlikely to have biased responses. The information was collated from IUCN Red List assessments, Recovery Plans and Conservation Advices for taxa listed as threatened under Australian threatened species legislation (*Environment Protection and Biodiversity Conservation Act 1999*), relevant literature and unpublished information provided by taxon-specific experts. All participants were asked to review the information provided and estimate the likelihood of extinction in the wild within the next 20 years (i.e., to 2041) assuming current levels and directions of management (“Round 1” scores). For the taxa we considered to be CR(PE), we asked participants to estimate two parameters: (1) the likelihood the taxon was already extinct, and (2) if extant, the likelihood the taxon will go extinct in the next two decades. Participants were asked to provide a level of confidence for each of their estimates (i.e., (very low <20%, low 21–40%, moderate 41–60%, high 61–80%, very high >80%)). Participants were able to use additional resources to inform their estimates but were asked not to discuss their scores with any other expert to ensure that each individual assessment of extinction risk was derived independently.
- ii. From the individual estimates of extinction likelihood and their associated confidence estimates from Round 1, we calculated summary statistics (mean, median, range and outliers) and modelled extinction probabilities (see statistical analyses section below for details). The summary statistics and model outputs were then provided to participants, along with anonymised individual scores to show how each estimate compared to the group averages (an example is provided in Supplementary Material S2).
- iii. Participants were asked to review the results, focusing on the most disparate estimates, outliers, and on the relative rankings of extinction likelihood among taxa. Participants were then encouraged to take part in a teleconference, during which a facilitator systematically stimulated discussion on each taxon. This discussion allowed participants to clarify information about the presented data, introduce new information on a taxon that had not been included in the background material, and cross-examine information and interpretations presented by other experts. A recording and detailed minutes of the teleconference were provided to all participants following the teleconference.
- iv. Finally, experts were asked to provide a second (final) estimate of the likelihood of extinction (and in the case of the CR(PE) taxa, the likelihood they were already extinct), as well as updated confidence measures in their estimates from which the results were finalised (“Round 2” scores). This final estimate was adopted for analysis without further discussion.

2.2. Statistical analyses

2.2.1. Estimating extinction risk

Likelihood estimates of extinction risk were logit-transformed and analysed using generalized linear mixed-effects models (GLMMs; ‘lme’ in package ‘nlme’) in R 4.0.3 (R Core Team 2021). To control for

consistent over- or under-estimation of extinction likelihood, we specified expert identity as a random intercept.

The likelihood that a taxon was already extinct was modelled as:

$$AE \sim \text{taxon} + (1|\text{expert})$$

where AE is the likelihood that the last individual has died, taxon refers to the species or subspecies and $1|\text{expert}$ is the random intercept for individual participant scores.

The risk of extinction by 2041 was modelled as:

$$E_{2041} \sim \text{taxon} + (1|\text{expert})$$

where E_{2041} is the likelihood that the last individual will die in the wild by 2041.

We incorporated participant uncertainty in the models by specifying a variance structure, where variance increased with the associated level of uncertainty in each individual's estimates. Confidence classes of 'very low', 'low', 'moderate', 'high' and 'very high' were converted to uncertainty scores of 88, 75, 50, 25 and 13% respectively (Geyle et al., 2018, 2021a, 2021b; Lintermans et al., 2020). This approach was applied to both the Round 1 estimates, in order to provide preliminary results to the expert panel to consider during the teleconference (step 3 above), and the Round 2 scores to obtain a final estimate of likelihood of extinction in the next 20 years for each taxon and, for the CR(PE) taxa, the likelihood that the taxon was already extinct.

Confidence in the likelihood of extinction in the next 20 years, or the likelihood that a taxon was already extinct (CR(PE) taxa), was considered high if the 95% confidence intervals around coefficient estimates were greater than zero. Taxa with coefficient estimates and error bars below zero were assumed to have a lower likelihood of extinction.

We compared extinction probabilities obtained for taxa from previous elicitation assessments to the estimates obtained as part of this study using a Spearman Rank Correlation test. For visualization, we plotted back-transformed modelled extinction likelihood estimates using bar charts.

2.2.2. Testing for concordance among expert assessments

We measured the level of agreement among participants in the relative rankings of the taxon extinction probabilities using Kendall's Coefficient of Concordance (W) (Kendall and Smith, 1939). This test allows for comparison of multiple outcomes (i.e., assessments made by multiple experts), whilst making no assumptions about the distribution of the data. Average ranks were used to correct for the large number of tied values in the dataset. Ranks were compared for all extant taxa, and all CR(PE) taxa. For the CR(PE) taxa, we excluded ranks for one participant who did not assess all 16 taxa considered.

2.2.3. Geographic distribution and tenure

We mapped the distribution of the species considered in this study according to their presence in each Interim Biogeographic Regionalisation for Australia (IBRA) region (Department of the Environment, 2013). Occurrence data collected after 2000 were compiled from various sources, including the Atlas of Living Australia, museums, State and Federal Government biodiversity databases, published literature (including conservation advices and Action Plans), citizen science and community programs, and academic researchers (Geyle et al., 2018, 2021a, 2021b; Lintermans et al., 2020).

We also estimated, using expert knowledge of the distributions of each taxon, the proportion of the distribution of each taxon on government tenures or conserved areas (using definition of Jonas et al., 2021).

3. Results

3.1. Extinction probabilities of animals with no recent verified records

For all the 16 taxa (5 reptiles, 4 birds, 4 frogs, 2 mammals, 1 fish; Supplementary Material S1) for which there were no recent independently verified records, the expert panel concluded there was a high likelihood (>50%) that they were already extinct (Fig. 1a) with only Coxen's Fig-Parrot *Cyclopsitta coxeni* and Buff-breasted Button-quail *Turnix olivii* having error bars just overlapping the 50% estimate. When experts were instructed to assume the CR(PE) taxa had persisted undetected, five taxa were considered to have a < 50% likelihood of going extinct within the next 20 years, although this was significant only for the fig-parrot (Fig. 1b). If considered currently extant, four taxa, the Christmas Island Shrew *Crocidura trichura*, Victorian Grassland Earless Dragon *Tympanocryptis pinguicollis*, the Kangaroo River Macquarie Perch *Macquaria* sp. (Kangaroo River) and the Northern Gastric-brooding Frog *Rheobatrachus vitellinus*, had probabilities of extinction in the next 20 years significantly >50%. No taxonomic class stood out as having taxa more or less likely to go extinct if still extant.

3.2. Extinction probabilities and the number of taxa in imminent danger of extinction

Of the 47 most highly imperilled Australian vertebrate taxa known to be extant (21 fish, 12 birds, 6 mammals, 4 frogs and 4 reptiles) in our sample, participants estimated that the risk of extinction within the next 20 years was >50% for nine taxa, being significantly greater for four taxa: Yalmy Galaxias (*Galaxias* sp. 'Yalmy'), West Gippsland Galaxias *Galaxias longifundus*, Baw Baw Frog *Philoria frosti* and Mukarrthippi Grasswren *Amytornis striatus striatus* (Fig. 2). Although all taxa were considered highly threatened, the likelihood of extinction in the next 20 years was considered to be <50% for the remaining 38 taxa, being significantly so for 26 of the taxa.

3.3. Comparison with previous extinction risk estimates

The likelihood of imminent extinction of 79% (50/63) of the taxa considered here had been assessed in the last five years by separate groups of taxon experts (Geyle et al., 2018, 2021a, 2021b; Lintermans et al., 2020), with seven participants in the current assessment having participated in the earlier panels. Overall, the elicited values for extinction risk were lower in the current assessment than the previous assessment (fish 19/20, birds 9/11, frogs 8/8, reptiles 5/6, mammals 4/5; Fig. 3; see also Supplementary Material S3 and S4), although there was a substantial overlap in the spread of values for birds (Fig. 3c), reptiles (Fig. 3e) and mammals (Fig. 3b). Spearman Rank Correlation coefficient scores suggested consistent ranking between assessments for fish ($R_s = 0.59$, $P < 0.01$) but not for reptiles (0.71, $P > 0.1$), frogs (0.67, $P > 0.05$), mammals (0.20, $P > 0.5$), or birds (-0.11, $P > 0.1$). The largest differences in estimates of extinction risk were most evident for three frog species (Yellow-spotted Tree Frog *Litoria castanea*, Northern Gastric-brooding Frog *Rheobatrachus vitellinus*, Mountain Mist Frog *Litoria nyakalensis*) and two fish species (the Swan Galaxias *Galaxias fontanus* and the Shaw Galaxias *Galaxias gunaikurnai*), all of which exhibited lower scores of absolute extinction likelihood in the second assessment compared to the previous assessment (Fig. 3b, c).

3.4. Testing for concordance among expert assessments

There was a reasonable and significant degree of conformity among participants in their assessments of extinction risk for the 47 extant taxa assessed ($W = 0.53$, $p < 0.01$). For the 16 CR(PE) taxa, the participants showed high concordance in their assessment of the likelihood that they were already extinct ($W = 0.38$, $p < 0.01$) or, if extant, the likelihood that they would go extinct by 2041 ($W = 0.32$, $p < 0.01$).

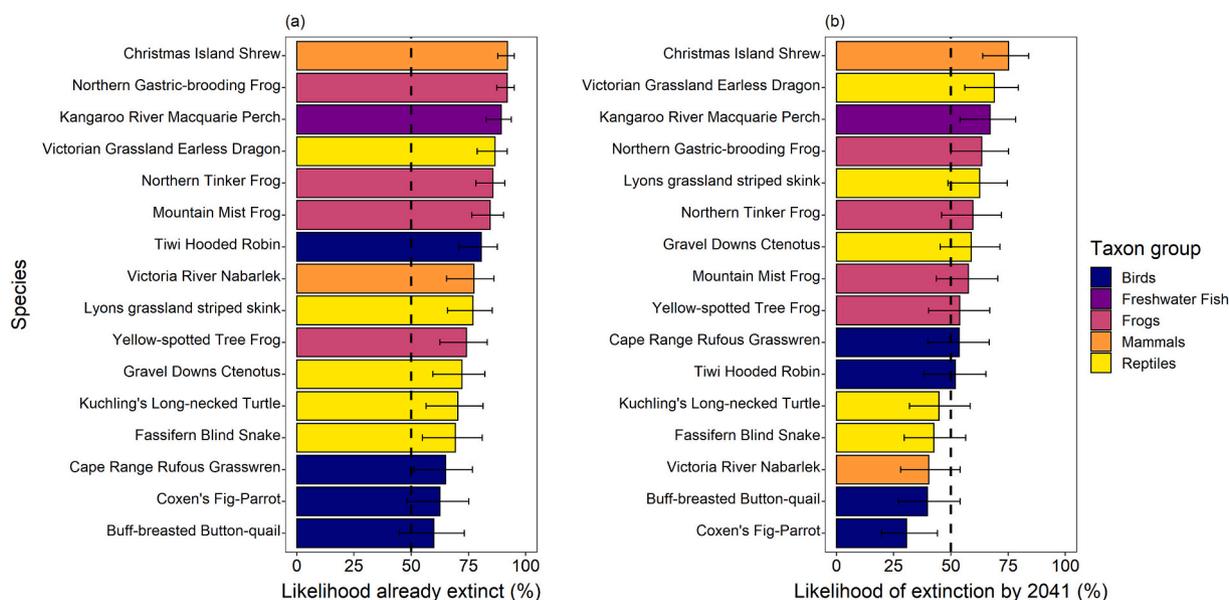


Fig. 1. (a) Modelled likelihood that taxa for which there are no recent, independently verified records are already extinct, and (b) modelled likelihood of extinction for the same taxa by 2041 should undiscovered populations remain. Both coefficient estimates have 95% confidence intervals weighted by expert uncertainty. Dashed vertical line represents a 50% likelihood. Deep blue: birds; purple: freshwater fish; pink: frogs; orange: mammals; yellow: reptiles. See Supplementary Material S1 for scientific names.

3.5. Geographic distribution of the most imperilled taxa

A high proportion of the highly imperilled taxa known to be extant (~79%) are endemic to a single bioregion, including all four taxa of reptile and frog. The three bioregions with the highest number of highly imperilled taxa occur along the Victorian-New South Wales (NSW) border (South Eastern Highlands (10), Australian Alps (9) and South East Corner (5; Fig. 4). The Australian Alps and South Eastern Highlands have the highest number of imperilled freshwater fish (5 each) while the largest number of imperilled birds (4) occur in the King bioregion (King Island in Bass Strait, Tasmania). Seven bioregions (all in South-East Australia) had three imperilled birds. All but one of the at-risk mammals occur in different bioregions, with only the Australian Alps containing two taxa. Other bioregions containing imperilled mammals include the Arnhem Coast and MacDonnell Ranges in the Northern Territory (NT), Esperance Plains and Jarrah Forest in Western Australia (WA), the South Eastern Highlands and the Wet Tropics of Queensland, making the mammals the most widely distributed group. The reptiles and frogs are each known from different bioregions. The reptiles occur in Arnhem Plateau (NT), NSW North Coast, South Eastern Highlands and Swan Coast, while the frogs occur in Australian Alps, South Eastern Highlands, South Eastern Queensland and Wet Tropics.

Most highly imperilled vertebrates occur entirely on, or within the catchments of, protected areas, both privately and publicly owned (Table 1). For nearly half the taxa, including all four frog species and four out of the six mammal taxa, the entire range is now within lands dedicated to biodiversity conservation, highlighting the importance of these areas. For 16 taxa some of their distribution occurs on government-owned land allocated to resource extraction, with four fish and one bird occurring entirely on government owned tenures allocated either to forestry or grazing. At least half the distribution of 14 taxa is on non-conservation, non-government lands, with the Malanda Rainbowfish *Melanotaenia* sp. (Malanda) and the Bathurst Grassland Earless Dragon *Tympanocryptis mccartneyi* thought to have their entire distribution on private non-conservation tenures.

A high proportion (85%) of the taxa we considered occur within conserved areas, including three on private conservation reserves. Collectively, the AOO of these conservation areas occupied by highly imperilled taxa is 1994 km². The total AOO of taxa occurring on non-

conservation government-owned land is 313 km² and that of those on private land 242 km². The nine most imperilled extant taxa occupy 292 km² (of which the Western Ground Parrot *Pezoporus wallicus flaviventris* occupies 140 km²). There is effectively no overlap in the ranges of any of the 47 extant taxa considered, even for the two bird subspecies on King Island.

4. Discussion

We used structured expert elicitation to refine understanding of the extinction risk of 63 highly threatened Australian vertebrate taxa which had either recently been identified as having a > 50% likelihood of extinction within the next 20 years (Geyle et al., 2018, 2021a, 2021b; Lintermans et al., 2020) or were subsequently considered to warrant consideration by threatened species managers. To prevent further extinctions of vertebrates in Australia, these are the taxa in most urgent need of attention. While the earlier works assessed groups separately by individual taxonomic class, the current analysis is the first to be undertaken across vertebrate classes. Using new information gathered since the earlier studies, and combining expert knowledge of each class with the collective knowledge of conservation managers, our study concluded: (i) a very low likelihood that the 16 taxa considered here, for which there are no recent verified records, are still extant; (ii) an additional nine taxa are more likely to go extinct in the next decade than to persist; and (iii) all of the highly imperilled taxa have small ranges, with most on conserved or government-managed lands, particularly government conservation reserves.

4.1. Taxa for which attention may have come too late

We assessed 16 taxa that have had no recent, independently verified records, indicating that they may already be extinct. Several Australian vertebrate species have been rediscovered recently despite many years without records (e.g. Armoured Mist Frog *Litoria lorica*, Puschendorf et al., 2011, Night Parrot *Pezoporus occidentalis*, Leseberg et al., 2021), so there may still be some hope for some of these taxa. However, for the 16 nominally or formally listed CR(PE) species assessed here, the panel of experts were not optimistic: all taxa were assessed as having a > 50% likelihood of already being extinct. Furthermore, even if they have

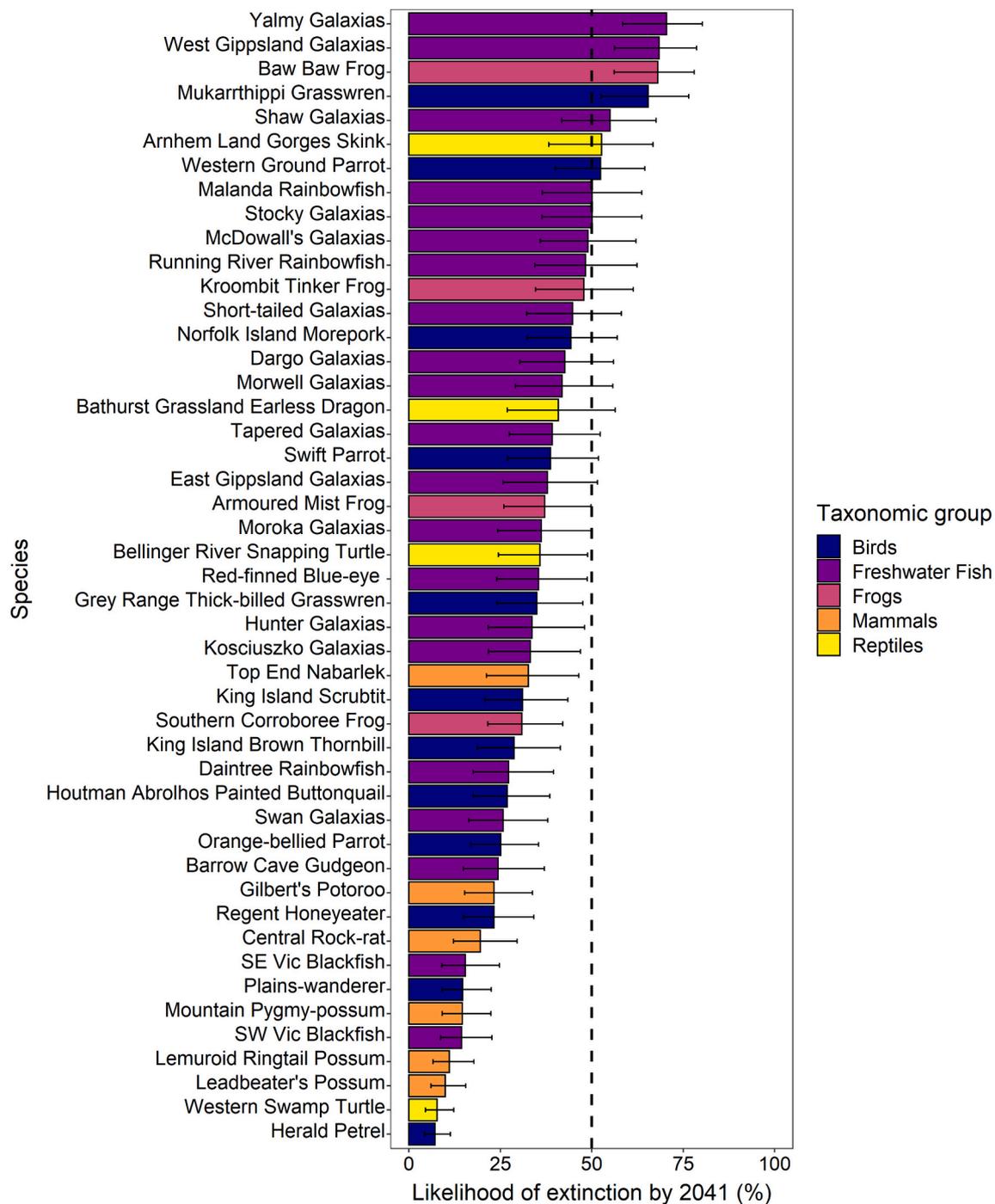


Fig. 2. Modelled likelihood of extinction for the 47 highly threatened taxa known to be extant and the associated coefficient estimates with 95% confidence intervals weighted by expert uncertainty. Dashed vertical line represents a 50% likelihood of extinction. Deep blue: birds; purple: freshwater fish; pink: frogs; orange: mammals; yellow: reptiles. See Supplementary Material S1 for scientific names.

survived undetected, 11 of the 16 taxa considered were assessed as having a > 50% likelihood of going extinct by 2041. All such taxa warrant urgent surveys to determine whether any do in fact survive. Thirteen of the 16 are full species so, if all have indeed gone, the number of Australian vertebrate species known to have gone extinct since European colonisation (1788) would increase by over 25% from the 51 known to have been lost already (Woinarski et al., 2019). Kangaroo River Macquarie Perch would be the first documented extinction of an Australian freshwater fish.

4.2. Taxa needing immediate attention

Of the 47 taxa considered and known to be extant, nine were assessed as having >50% likelihood of extinction by 2041 under current management, with two freshwater fish, one frog, one bird and one reptile having a significantly higher likelihood of extinction than the other highly threatened taxa. Were just the eight full species in this group to go extinct in the next two decades, it would be at a rate of one extinction every 2.5 years, or 4.0 per decade, nearly double the already high background rate of extinctions of Australian vertebrates of 2.2 per decade from 1788 to the present (Woinarski et al., 2019).

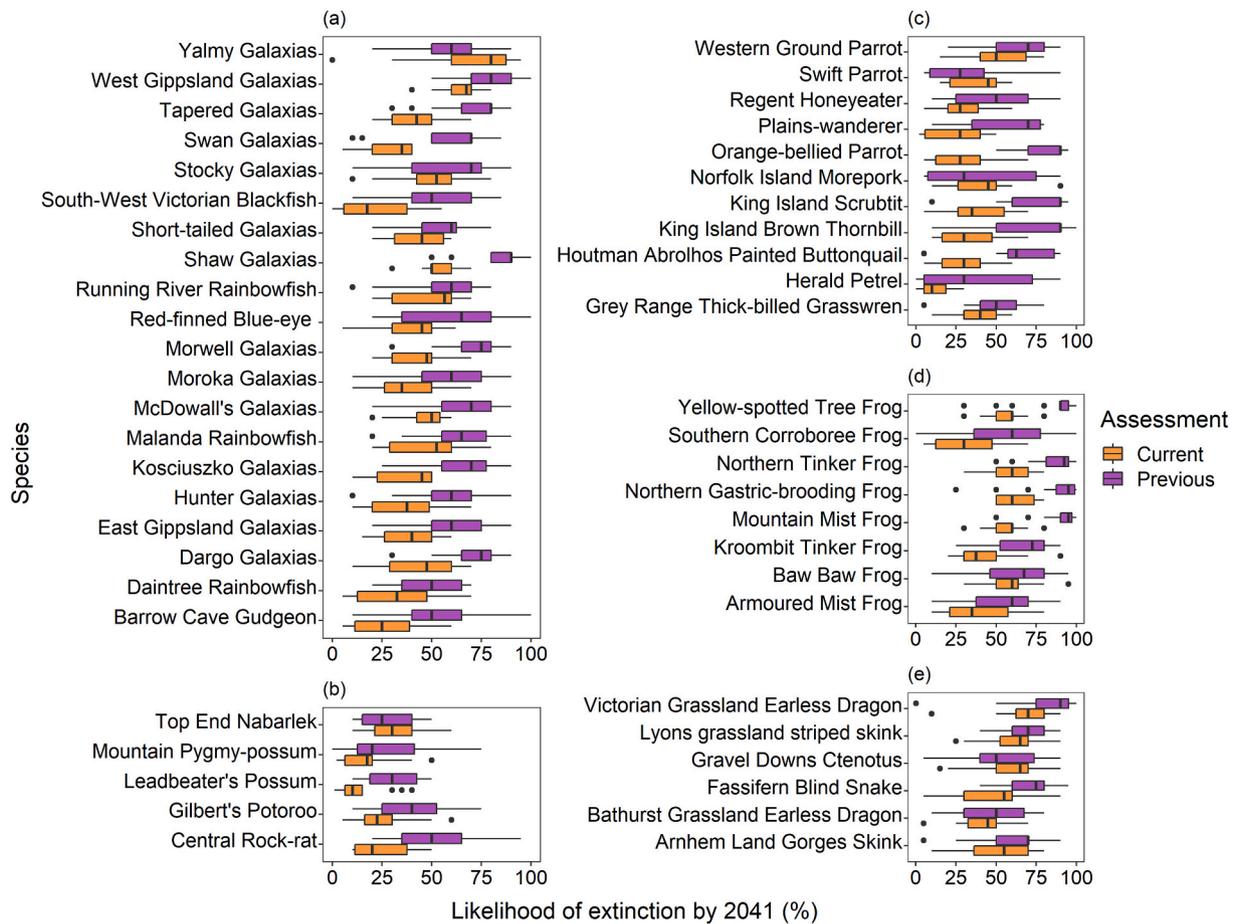


Fig. 3. Likelihood of extinction by 2041 as directly assessed by the expert panel in this current assessment (orange), and previous assessments of the same nature (blue; Geyle et al., 2018; 2021a, 2021b; Lintermans et al., 2020) by taxon group. Does not include species that were assessed in the second assessment, but not the first assessment.

Some threats are specific to particular classes, such as the amphibian disease chytridiomycosis, which has driven frog declines (Scheele et al., 2019), or predation of small native freshwater fish by introduced salmonids (Raadik, 2014). However, almost all the most imperilled taxa have very small ranges (Garnett and Baker, 2021; Geyle et al., 2021a, 2021b; Lintermans et al., 2020; Woinarski et al., 2014), making them highly susceptible to stochastic events (Murray et al., 2017; Pritt and Frimpong, 2010; Purvis et al., 2000) such as the megafires of 2019–2020 (Legge et al., 2022; Ward et al., 2020; Wintle et al., 2020).

4.3. Uncertainty around extinction risk

We incorporated expert uncertainty in the model explicitly through the variance structure, giving more weight to the estimates that had lower uncertainty. Uncertainty reflects the amount of information available on a taxon (Gillespie et al., 2011). A problem with uncertainty is that it can lead to procrastination (Chakraborty et al., 2020), potentially because of fear of failure (Meek et al., 2015). Reducing uncertainty around the status of the highly imperilled taxa (e.g. through further surveys and assessments of the efficacy of management responses), as well as around the nature and severity of the threats facing them, is among the most urgent steps in their recovery.

4.4. Comparison with recent class-based assessments

Extinction risk was generally deemed lower for most taxa in this study than the earlier class-specific studies (Geyle et al., 2018, 2021a, 2021b; Lintermans et al., 2020). The differences were surprising given

the occurrence of prolonged drought culminating in catastrophic wildfires in 2019–2020 which burned habitat of at least nine of the considered species, particularly six species of Galaxiid fish which were affected by heavy siltation of streams (Legge et al., 2022). Of these nine species, the only one with a higher likelihood of extinction in the second than the first study was the Yalmy Galaxias, of which the entire known distribution was first burnt and then smothered with sediment when rain fell immediately after the fire; the population has declined from 3 to 4 individuals per 150 linear m of stream length to 0–1 individuals (T. Raadik, pers. comm.).

There are two possible reasons for the differences between the earlier class level estimates of extinction risk and the current study. First, taxon specific experts tend to have higher estimates of extinction risk than non-specialists (Montibeller and von Winterfeldt, 2015), such as the managers who made up the majority of elicitors in the current assessment. We currently cannot tell whether that means the assessments made by the conservation biologists will prove more or less accurate than the current estimates (dominated by managers). If this and similar papers elicit no consequent management action, a test of which group was most accurate will become increasingly possible leading up to 2041.

Second, the first class-specific assessment, on birds and mammals (Geyle et al., 2018), spawned surveys that provided new information and new conservation actions for some species that are likely to have led to decreases in extinction risk. For example, there have been further surveys and concerted threat abatement action to conserve the Central Rock-rat (McDonald et al., 2018a, 2018b), which was considered the mammal at greatest risk of extinction in the 2018 assessment (Geyle et al., 2018). Surveys of some of the most threatened birds identified

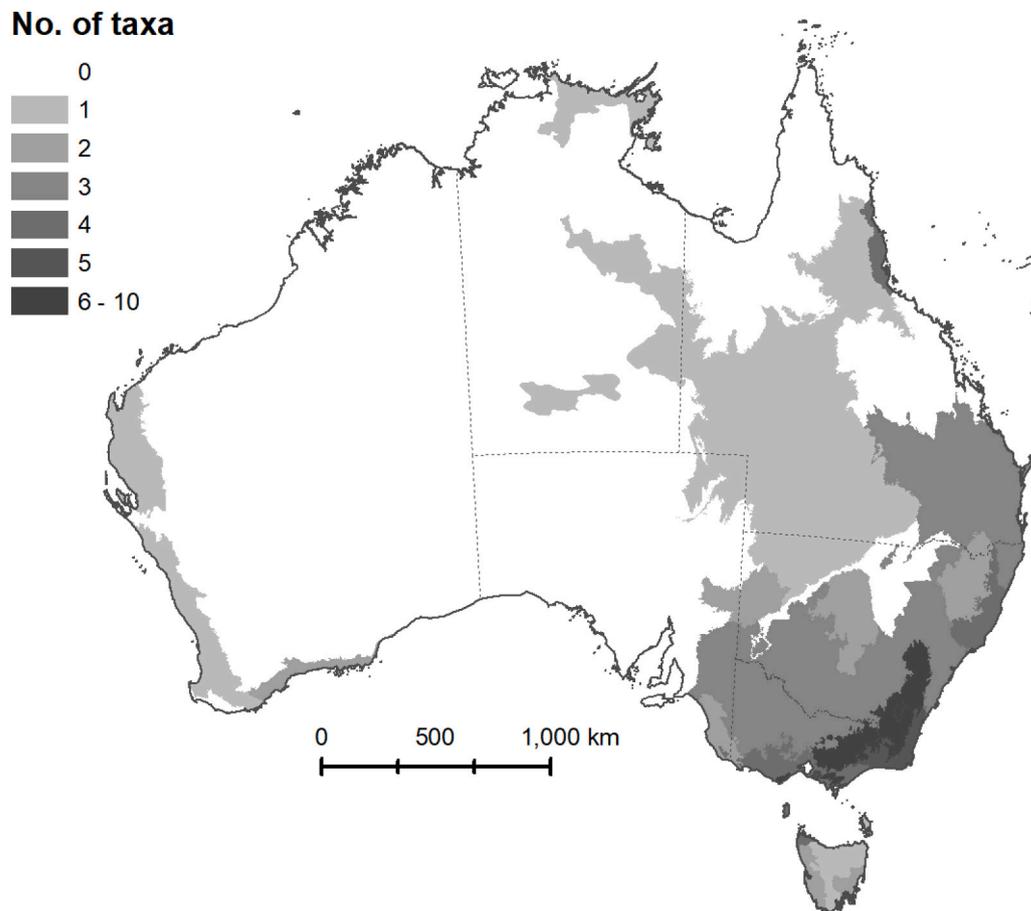


Fig. 4. The number of extant highly imperilled Australian vertebrates occurring in each Australian bioregion. Norfolk Island (not shown) has one.

Table 1

Number of extant Australian vertebrate taxa in imminent danger of extinction in each class with 0, ≥ 50 and 100% of their ranges on conservation (public and private) tenures, the number with $\geq 50\%$ of their ranges on other government and on other tenure types, and the summed Area of Occupancy of all taxa in each class.

Class	Conservation lands			$\geq 50\%$ on non-conservation government lands	$\geq 50\%$ on other tenures	no. taxa	Total Area of Occupancy (km ²)
	0%	$\geq 50\%$	100%				
Birds	1	6	5	1	6	12	2342
Freshwater fish	7	11	7	6	7	21	456
Frogs	0	4	4	0	0	4	20
Mammals	0	6	6	0	0	6	1318
Reptiles	1	3	2	0	1	4	130
All	8	30	24	7	14	47	4266

new populations (e.g. Holdsworth et al., 2021), reducing the estimated likelihood of extinction. Similarly, prioritisation of several fire-affected fish species included in the original elicitation for freshwater fish (Lintermans et al., 2020) has resulted in new records and new ecological information that can improve management of these species (e.g. Stocky Galaxias, Short-tail Galaxias).

The new knowledge and the actions taken since the first class-based assessments also partly explain why there were differences in the rankings within animal classes. The classes with the longest time since assessment (birds and mammals, assessed 2017) had lower rank correlation coefficients than those for fish (assessed originally in 2018), reptiles and frogs (in 2019). Notwithstanding differences in rankings within groups, the rankings of the classes were similar, with the set of fish species having higher overall likelihood of extinction, reflecting the sensitivity of freshwater ecosystems (Collen et al., 2014; Reid et al., 2019).

While additional knowledge, including traditional knowledge held

by Indigenous people (Reyes-García and Benyei, 2019; Ogar et al., 2020), will undoubtedly influence further perceptions of imminent extinction risk, managers need to respond to the state of knowledge at any moment. Currently, the taxa considered here must be considered at greatest risk unless and until such new contradictory knowledge becomes available.

5. Management implications

Among the first steps towards retaining populations of the most imperilled taxa is listing them as threatened under relevant legislation so they can be appropriately recognised and protected under law. At the time of writing, 25 of the taxa considered here, of which 18 are fish and five are considered CR(PE), were not listed as threatened under Australia's *Environmental Protection and Biodiversity Conservation Act*. However, as a result of this paper, all of these are now under consideration. Listing under legislation can influence prioritisation of funding, which

leads to research and management and must be a priority action for the unlisted taxa in this assessment. Urgent investment and strategic conservation effort are fundamental to preventing extinction (Woinarski et al., 2017).

Secondly, in addition to listing, there is a need for surveys for the taxa with no recent reliable records to attempt to locate any populations that have so far eluded earlier searches. This needs to be combined with best practice monitoring (Legge et al., 2018) of those known to be extant.

Thirdly, for taxa with known extant populations, a set of urgent management actions needs to be initiated, or expanded, to reduce the risk. Although several species, such as Orange-bellied Parrots and Northern Hairy-nosed Wombat *Lasiorhinus krefftii*, would now be extinct if it were not for strategic interventions and substantial investment (Bolam et al., 2020), in general Australia has a poor record with conserving species (Scheele et al., 2018). The imminence of likely extinction for these taxa should provide an incentive to improve this record, potentially with policy settings and dedicated funds specifically for preventing extinction, particularly for rapid responses to emergencies (Martin et al., 2012a).

One of the striking features of the results is the relatively tiny area over which intensive management needs to occur, largely because all but a few scarce but mobile taxa are largely sedentary and would not be highly-imperilled if their ranges were not quite so small. The cumulative total AOO occupied by the set of highly imperilled taxa of 4266 km², fits within a circle of radius of just 36 km² and constitutes 0.06% of Australia's land area. Because the IUCN guidelines for estimating AOO allocate a minimum of 2 km × 2 km to any occupied location (Keith et al., 2018), the actual area occupied may be considerably smaller. As it is, the 1994 km² of conserved lands occupied by highly imperilled taxa represents just 0.13% of the total area allocated to conservation in Australia (Department of Agriculture, Water and the Environment, 2021b). For these reserves, a primary goal could be preventing the extinction of these taxa. The management of the 16 taxa that occur on the 313 km² of non-conservation government-owned land, including seven that occur only on such tenures, could also have a high priority in land management even though the primary purpose is commercial use. The remaining 242 km² of highly imperilled taxa AOO on private land represents a logical target for conservation extension and partnerships, especially for the two taxa found only on such lands.

Despite the small area, the wide dispersion of threatened taxa across Australia represents a major opportunity for Indigenous Peoples to become involved in extinction prevention should they so choose. Many threatened taxa are known to occur on Indigenous lands (Renwick et al., 2017), and many Indigenous people are involved in the management of threatened species and ecological communities (Leiper et al., 2018). Indigenous Peoples are also increasingly becoming involved in threatened species planning (Duncan et al., 2018). While logistic constraints and the urgency to act precluded consultation with the 150 Indigenous Peoples with connection to the lands and waters occupied by the taxa considered here (Supplementary Material 5), the opportunity for traditional owner involvement should be maximised in the future.

While the current study is confined to taxa in Australia, the approach we have taken can be applied at multiple scales, from global to regional. In many ways this analysis complements the global aspirations of the Alliance for Zero Extinction to conserve sites that contain ≥95% of the population of all Endangered and Critically Endangered species (Parr et al., 2009) but local knowledge and priorities meant that we could include subspecies, which are given equal standing with full species for some groups, as well as taxa that are too mobile and dispersed to fit within defined sites. Just as relevant to any context was the involvement of threatened species managers in the assessment exercise, allowing them to be across the latest information not just for their jurisdiction but also providing an awareness of issues facing others in their position across the country.

Inclusion of the threatened species that are the most difficult to

assess, those that are now so scarce that they are considered Critically Endangered (Possibly Extinct), increased the value of the exercise by identifying knowledge gaps that most urgently need filling if any of these taxa are to be rediscovered and recovered. Knowledge gaps for other taxa also became evident through the assessment exercise, allowing managers to target survey and research investment. Although the approach we used deals with uncertainty, it still may be challenging to overcome critical knowledge gaps and biases. For example, of Australia's ca. 320,000 invertebrate species, most are undescribed (Chapman 2009), and there is no information on the status, population size and trajectory or threats for most species (Taylor et al., 2018), rendering elicitation of extinction risk almost impossible for the vast majority of Australian animal species. The extinction rate of Australian invertebrates is very poorly resolved (Woinarski et al., 2019), but it is plausible that invertebrates comprise the majority of Australian extinctions to date and are likely to do so for the future time period considered in the assessment here.

6. Conclusion

Our results represent the most recent representation of the extinction risk of what we consider to be the 63 most threatened Australian freshwater and terrestrial vertebrate taxa using a formal elicitation of a diverse group of experts, including managers with responsibility for ensuring that the predictions of extinction do not eventuate.

The number of vertebrate species that have become extinct in Australia since European colonisation may be over 25% higher than the 51 taxa known to have gone if all those without recent records have indeed become extinct; the expert panel considered that there is a > 50% likelihood this is the case. Nevertheless, surveys may allow this forecast to be downgraded, if followed by effective conservation management of any populations found to have persisted. Such surveys are urgent – even if taxa have survived until now, the panel think many will go in the next 20 years as threats continue, and many intensify.

Also urgent is action for the nine taxa known to be extant that the panel concluded have a > 50% likelihood of extinction by 2041, as well as others that are highly imperilled. Most have tiny ranges on lands entirely or largely dedicated to biodiversity conservation. By making an explicit list of the taxa at greatest risk, time, money, skills and other resources can be directed at proving the predictions wrong. Earlier assessments have already contributed to this process – the current study highlights that action is needed urgently across vertebrate classes.

A first step will be ensuring all the taxa considered here are listed as threatened under appropriate legislation at all levels of government. However, listing alone will not be sufficient. Such processes take time and little time is available to retain the most threatened of the taxa considered here. Thus, simultaneously, action must be taken to secure remaining populations, reduce or mitigate threats and begin the systematic task of reducing extinction risk to less perilous levels.

Finally, we end on a note of caution because the predictions made by elicitors in this study are based largely on current status and threats, and hence could not consider novel threat factors, unexpected increasing magnitudes of some threats or exceptional instances of existing threats. They may therefore be conservative, and we recommend that such assessments be made at least every five years to incorporate new knowledge and the results of management aiming to conserve the taxa we consider here.

CRedit authorship contribution statement

Conceptualization, S.T.G. & H.M.G.; methodology, S.T.G., J.C.Z.W., S.L. & H.M.G.; formal analysis, S.T.G., B.K-H-B., R.K.K. & H.M.G.; expert knowledge: S.T.G., B.K-H-B., R.K.K., J.C.Z.W., K.A.C., D.G.C., P.C., A.F., G.G., P.L., S.L., M.L., A.M., M.P., J.R., J.B. & D.K.; writing—original draft preparation, S.T.G., B.K-H-B., R.K.K., J.C.Z.W. & H.M.G.; writing—review and editing, S.T.G., B.K-H-B., R.K.K., J.C.Z.W., K.A.C., D.G.

C., P.C., G.G., S.L., M.L., M.P. & J.R.; visualization, S.T.G., B.K-H-B., R.K. K. & H.M.G; project administration, S.T.G. All authors have read and agreed to the published version of the manuscript.

Declaration of competing interest

This statement is to certify that:

The work is all original research carried out by the authors. All authors agree with the contents of the manuscript and its submission to the journal.

No part of the research has been published in any form elsewhere, unless it is fully acknowledged in the manuscript.

Authors should disclose how the research featured in the manuscript relates to any other manuscript of a similar nature that they have published, in press, submitted or will soon submit to Biological Conservation or elsewhere.

The manuscript is not being considered for publication elsewhere while it is being considered for publication in this journal.

Any research in the paper not carried out by the authors is fully acknowledged in the manuscript.

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The authors will not gain any direct financial benefits from publication. While many of the authors are embedded in the government agencies responsible for threatened species management, and an objective of this research is to increase state investment in the threatened species concerned, the authors will not obtain personal financial benefits from such investment.

No ethics and other approvals were necessary for the research.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.biocon.2022.109561>.

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