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Red hot frogs: identifying the Australian frogs most at risk of extinction

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Abstract. More than a third of the world's amphibian species are listed as Threatened or Extinct, with a recent assessment identifying 45 Australian frogs (18.4% of the currently recognised species) as 'Threatened' based on IUCN criteria. We applied structured expert elicitation to 26 frogs assessed as Critically Endangered and Endangered to estimate their probability of extinction by 2040. We also investigated whether participant experience (measured as a self-assigned categorical score, i.e. 'expert' or 'non-expert') influenced the estimates. Collation and analysis of participant opinion indicated that eight species are at high risk (>50% chance) of becoming extinct by 2040, with the disease chytridiomycosis identified as the primary threat. A further five species are at moderate–high risk (30–50% chance), primarily due to climate change. Fourteen of the 26 frog species are endemic to Queensland, with many species restricted to small geographic ranges that are susceptible to stochastic events (e.g. a severe heatwave or a large bushfire). Experts were more likely to rate extinction probability higher for poorly known species (those with <10 experts), while non-experts were more likely to rate extinction probability higher for better-known species. However, scores converged following discussion, indicating that there was greater consensus in the estimates of extinction probability. Increased resourcing and management intervention are urgently needed to avert future extinctions of Australia's frogs. Key priorities include developing and supporting captive management and establishing or extending *in-situ* population refuges to alleviate the impacts of disease and climate change.

Keywords: amphibian, anthropogenic mass extinction crisis, Australia, biodiversity conservation, climate change, Delphi, expert elicitation, frog, IDEA, IUCN criteria, threatening processes.

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Introduction

Environmental change from human activities has had devastating effects on global biodiversity, leading to an increase in the number of species lost to extinction over recent decades (Pimm *et al.* 2014; Ceballos *et al.* 2015; Johnson *et al.* 2017). There has been considerable public and scientific concern over the nature and rate of decline in amphibians. This is primarily because high rates of species loss over the past 40 years have occurred in habitats that were considered to be intact, and because there was much uncertainty about the underlying causes of declines (Fisher and Garner 2020). However, over the past two decades, a marked increase in our understanding of the threats facing amphibians has led to consensus on the broad factors driving global patterns of decline (Grant *et al.* 2020). Some of the primary threats facing amphibians globally include habitat loss (Cushman 2006), disease (Bower *et al.* 2017; Scheele *et al.* 2019), contaminants (Hayes *et al.* 2010), climate change (Laurance 2008; McCaffery and Maxell 2010), invasive species (Kats and Ferrer 2003) and over-exploitation (Warkentin *et al.* 2009), with the relative importance of each of these factors varying depending on species, populations and regions (Grant *et al.* 2020). Notably, the amphibian disease chytridiomycosis, caused by the fungal skin pathogen *Batrachochytrium dendrobatidis* (Berger *et al.* 1998) has been implicated in the global decline of over 500 species, and the presumed extinction of up to 90 species over the past 50 years (Scheele *et al.* 2019).

Enigmatic, rapid declines and disappearances of some Australian amphibian species began in the 1970s, continued through the 1980s and 1990s, and were most prominent in stream-breeding rainforest frogs in eastern Australia (Tyler and Davies 1985; Czechura and Ingram 1990; McDonald 1990; Laurance *et al.* 1996; Hero *et al.* 2006). These declines were later attributed to *B. dendrobatidis* (Murray *et al.* 2010). The first record of *B. dendrobatidis* in Australia is from a museum specimen collected in 1978 near Brisbane (Berger *et al.* 1998). *Batrachochytrium dendrobatidis* has since been implicated in the decline of 43 Australian species, representing nearly one fifth of the country's amphibian diversity (Scheele *et al.* 2017). Additionally, a recent review has identified *B. dendrobatidis* as the primary cause of expected future declines and extinction risk in Australian frogs (Gillespie *et al.* 2020). Climate change has also been identified as an emerging major threat, especially for range-restricted montane frogs (Gillespie *et al.* 2020). Habitat loss and invasive species (e.g. predatory fish, feral pigs (*Sus scrofa*) and cats (*Felis catus*)) have also caused significant range reductions for some Australian frog species (Gillespie *et al.* 2020; West *et al.* 2020). However, no frog extinctions to date have been attributed to these factors alone (Scheele *et al.* 2017).

More than a third of the world's amphibian species are now listed as Threatened or Extinct against IUCN criteria, the largest proportion of any vertebrate class (IUCN 2020). Amphibians are consequently well represented on the IUCN Red List, with 84% of all described species having been evaluated as of September 2020 (IUCN 2020). The IUCN Red List is the most widely used tool for measuring extinction risk to biodiversity on a global scale (Rodrigues *et al.* 2006), but it has limitations for identifying and prioritising species at immediate risk of extinction. This is because some species may meet Extinct criteria, after only a brief listing as Critically Endangered (CR), whereas others may be CR for decades before the last individuals are lost (Geyle *et al.* 2018). For this reason, there is value in undertaking an additional process that more explicitly estimates extinction probability over a specified time period, as this will assist allocation of limited resources to prevent extinction.

A recent review by Gillespie *et al.* (2020) re-evaluated the conservation status of all Australian frog species, finding that 45 of the 244 currently recognised species (18.5%) are now considered to be threatened based on IUCN criteria. Here, we extend and complement this work by identifying which Australian species are most likely to go extinct in the next 20 years. We used structured expert elicitation to forecast which, and how many, Australian frog species are at imminent risk of extinction, with the aim of improving prioritisation, direction and resourcing of management aimed at preventing future extinctions. Our approach follows comparable methodology to estimate imminent extinction risk among Australian birds and mammals (Geyle *et al.* 2018), freshwater fish (Lintermans *et al.* 2020), terrestrial squamates (Geyle *et al.* 2020) and butterflies (Geyle *et al.* 2021).

Materials and methods

Initial selection of species

Our assessment considered 26 Australian frog species. This included all 22 species proposed for listing as CR or Endangered (EN) under IUCN criteria by Gillespie *et al.* (2020). Each of these species is known to be extant based on current surveys and monitoring. We also included two CR species that may possibly be Extinct; the yellow-spotted bell frog (*Litoria castanea*) and the northern tinker frog (*Taudactylus rheophilus*), and two species generally considered to be Extinct, the mountain mist frog (*Litoria nyakalensis*) and the northern gastric-brooding frog (*Rheobatrachus vitellinus*). These four species were included because surveys have not been undertaken in some important parts of their potential ranges, and thus there is a small possibility of persistence of remnant populations (Gillespie *et al.* 2020). Three other Australian frog species classified as Extinct in Gillespie *et al.* (2020), the southern gastric-brooding frog (*Rheobatrachu silus*), the southern day-frog (*Taudactylus diurnus*) and the sharp-snouted day frog (*Taudactylus acutirostris*), were not considered because survey effort has been comprehensive enough to be confident that they are extinct (Newell 2018).

Expert selection

Key researchers were invited to participate in this study based on their knowledge of threatened frog species in Australia and/or based on their specialist skills (e.g. familiarity with Australian threatened species listing processes, substantive general ecological knowledge, or previous experience with structured expert elicitation processes). This included individuals from academic institutions, state and federal government agencies, consulting agencies, museums, zoos, and non-government organisations. The majority (>80%) of those invited agreed to be involved, making up a panel of 28 participants (all of whom are co-authors on this paper).

Structured expert elicitation

We used structured expert elicitation (based largely on the Delphi and 'Investigate, Discuss, Estimate and Aggregate' (IDEA) approaches, e.g. Burgman *et al.* 2011; McBride *et al.* 2012; Hemming *et al.* 2018*a*) to estimate the probability of extinction of each of the 26 species included in our assessment. These approaches seek to reduce the incidence of some commonly encountered biases (either cognitive or motivational) in expert elicitation processes. Our adapted elicitation procedure involved four main steps, all of which were conducted remotely via email or phone:

(1) Participants were provided with a summary of the available information on the ecology, threats and population trends for each species, based largely on material collated from recent Australian Government conservation assessment documents, and published and unpublished literature. Additional input was provided by at least one authority on each species (and in some cases by several authorities) to ensure that any relevant unpublished information was also captured. Much of this information is sensitive, and hence has not been included as Supplementary material (available at the journal website). All participants had the same written information available to them when making assessments about the extinction risk of a given species. All participants were then asked to estimate the probability of extinction in the wild by 2040, *assuming current levels and direction of management* ('Round 1' scores). For the four possibly extinct species, we asked participants to assume that one or more undiscovered populations persist (i.e. the species is 'extant') when making their assessments about future extinction probability. We also asked participants to estimate the probability that each of these species was already extinct. Twenty years was chosen as a period over which extinction risk might reasonably be assessed given uncertainties about the pace and severity of some major threats (particularly climate change). Likewise, two decades was seen as a period in which extinction risk might reasonably be influenced by policy and management changes made today. We asked participants to provide a level of confidence in their estimates, choosing from five pre-defined categories: very low (<20%); low (21–40%); moderate (41–60%); high (61–80%); and very high (>80%). We also asked participants to provide a measure of their experience with each species, selecting from three pre-defined categories: 'expert' (i.e. I consider myself an expert on the species – I

personally work on it, undertake fieldwork, write reports); 'intermediate' (i.e. I am not an expert but believe I have a useful insight into the species' ecology – I have some direct experience with it and/or work on a similar species or similar threats); and 'little/none' (i.e. I know little about the species beyond what I have read or been told – I have no direct field experience, or do not work on this group). Participants were able to use additional resources to inform their estimates but were asked not to discuss their scores with any others participating in the elicitation, as each individual assessment was to be treated as independent.

(2) Individual estimates of extinction probability and their associated confidence were compiled, and then modelled using a linear mixed-effects model (package 'nlme' for R ver. 3.6.0, Pinheiro *et al.* 2020; R Core Team 2019), where estimates were logit-transformed prior to analysis. Systematic participant-to-participant variations in estimates of extinction probability were modelled by specifying their identity as a random intercept. We specified a variance structure in which the variance increased with the level of uncertainty associated with each estimate of probability of extinction. Confidence classes of 'very low', 'low', 'moderate', 'high' and 'very high' were converted to uncertainty scores of 90, 70, 50, 30 and 10%, respectively. This model allowed us to predict the probability of extinction (with 95% confidence intervals) for each species. Summary statistics (including mean, median, range and outliers) were also calculated, and participants were provided with figures displaying both the summary statistics and their individual estimates so that they could see where their estimates lay relative to the rest of the group (an example is provided in Supplementary material S1).

(3) Participants were asked to review the results, and note any concerns about the spread of estimates given for a particular species, outliers or the rankings of extinction probability. Where concerns were present, participants were invited to provide an anonymous written statement (which was then distributed to the rest of the group). Participants were then encouraged to take part in a teleconference, during which a facilitator drew attention to any marked discrepancies in the Round 1 scores and individual concerns. This triggered a general conversation about the interpretation and context of species background information, as well as the underlying questions. All participants were given the opportunity to clarify information about the presented data, introduce further relevant information that may have justified either a greater or lesser risk of extinction, and to cross-examine new information. A recording of the teleconference and detailed minutes were provided to all participants, including four participants who were unable to attend.

(4) Participants were then asked to provide a second, final assessment of the probability of extinction (and associated confidence) for each species from which the results were finalised ('Round 2' scores).

Testing for concordance among participant assessments

We measured the level of agreement among participants in the relative rankings of the species using Kendall's Coefficient of Concordance (W) (Kendall and Babinton Smith 1939). This test allows for comparison of multiple outcomes (i.e. assessments made by multiple participants), 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, and ranks were compared only for participants who assessed all 26 species ($n = 19$).

Estimating the number of species likely to become extinct in the next 20 years

The predicted probabilities of extinction for each of the 26 species (assessed by all participants) were summed to estimate the number of these species likely to become extinct by 2040 (as per Geyle *et al.* 2018).

Geographic distribution of the most imperilled Australian frogs

We mapped the distribution of the frog species under consideration according to their presence in each Interim Biogeographic Regionalisation for Australia (IBRA) bioregion (DAWE 2015). This included occurrence data compiled from various sources, including the Atlas of Living Australia, state and territory government biodiversity databases, published literature, researchers, community groups, or individuals working in government agencies or on local conservation initiatives (Gillespie *et al.* 2020). The data were vetted for spurious records (such as implausible geographic outliers) in consultation with authorities on each species (Gillespie *et al.* 2020).

Assessing the impact of participant experience on estimates of extinction probability

To assess the impact of experience on extinction probabilities, we first pooled the data into two categories, combining self-assessed 'expert' and 'intermediate' scores (hereafter referred to as experts), and comparing these with the self-assessed 'little/none' scores (hereafter referred to as non-experts). The pooling of expert and intermediate scores was necessary due to the typically small sample sizes obtained for the categories of highest experience (see Supplementary material S2). Furthermore, although people with intermediate experience had not directly worked on a given species, they still had some direct experience with the genus or habitat.

We then investigated four specific questions.

(1) Does experience level (expert vs. non-expert) affect the ranking of species?
(2) Is the effect of experience on species ranking more pronounced for poorly known species?
(3) Are experts more likely to be confident in their assessments?
(4) Are non-experts more likely to revise their estimates following open discussion with experts?

We tested for differences in averages, rank and confidence (taking the mid-range of each confidence category, i.e. 10, 30, 50, 70 and 90) between experts and non-experts using two-tailed Wilcoxon signed-rank tests. To assess whether species were likely to be scored differently depending on expertise, we tested whether there was a difference in the average probability score for each species between the experts and the non-experts.

For visualisation, we also plotted this as the differential scores (i.e. the expert score minus the non-expert score). To test whether 'poorly known' species (i.e. those with relatively few participants who identified as experts, see Supplementary material S2) were scored differently depending on expertise, we tested for a difference in the scores for species with <10 participants in the expert category (equivalent to <42% of all participants). This represented 16 of the 26 species. We also used Wilcoxon signed-rank tests to determine if there were differences in scores between Round 1 and Round 2 for experts and non-experts, and to test for differences in confidence of scoring between the two expertise groups.

Threats, management and research actions

When assessing the conservation status for all Australian frogs, Gillespie *et al.* (2020) identified key threats and associated management and research actions. Each action was scored based on the IUCN status assigned to the relevant species, as well as the actions' relative conservation value, feasibility and current level of implementation (for more information see Gillespie *et al.* 2020). All plausible management and research actions were grouped into sets of generic (umbrella) actions – in some cases specific actions for each species were unique but could still be classified more broadly (Supplementary material S3, Gillespie *et al.* 2020). For each of the 26 species considered in this study, we extracted the threats, management and research actions from Gillespie *et al.* (2020). We considered this approach appropriate, given the timing of publication of that study, and because the authors, many of whom are also authors here, had much of the same information available to them when conducting their assessment. We then replaced the IUCN ranked value with estimated extinction probabilities (to avoid double-counting extinction risk) to identify key conservation priorities for averting future Australian frog extinctions.

Results

Expert elicitation, extinction probabilities, and the number of species likely to go extinct

An average of 24 estimates was received for each species (ranging from 22 to 27). Nineteen participants provided estimates for all 26 species, whereas others chose to assess only species for which they had first-hand experience. All 28 participants adjusted some of their Round 1 scores following the teleconference discussion, with each participant adjusting scores for an average of 58% of the species they assessed (ranging from 8 to 100%). This resulted in changes to the modelled probabilities for every species under consideration (a comparison of Round 1 and 2 modelled outputs are provided in Supplementary material S4). The predicted probability of extinction decreased following discussion for most species (69%), and in some cases by a considerable amount. On average there was an 8% decrease in modelled probability of extinction (ranging from 0.5% for the Howard River toadlet (*Uperoleia daviesae*) to 34% for the white-bellied frog (*Geocrinia alba*)). The predicted probability of extinction for eight species (31%) increased by an average of 3.9% (ranging from 0.8% for the Kroombit tinker frog (*Taudactylus pleione*) to 10% for the mountain top nursery frog (*Cophixalus monticola*)).

Collation and analysis of the final (Round 2) scores indicated that eight of the 26 species are at high risk (>50% chance) of becoming extinct in the next 20 years (Table 1). However, it is important to note that the four top ranked species may be extinct already (Table 1). The set of eight species considered most likely to become extinct in 20 years (if extant) included *Rheobatrachus vitellinus*, *Litoria nyakalensis*, *Litoria castanea*, *Taudactylus rheophilus*, *Taudactylus pleione*, the southern corroboree frog (*Pseudophryne corroboree*), the Baw Baw frog (*Philoria frosti*) and the armoured mist frog (*Litoria lorica*). An additional five species – all of which are currently extant – were scored at moderate–high risk (30–50% chance) of becoming extinct in the next 20 years (Table 1). This included *Cophixalus monticola*, the beautiful nursery frog (*Cophixalus concinnus*), the northern corroboree frog (*Pseudophryne pengilleyi*), the spotted tree frog (*Litoria spenceri*) and the Kroombit tree frog (*Litoria kroombitensis*).

There was a significant degree of conformity among participants (of those who provided estimates for all 26 species, $n = 19$) in their assessments of extinction risk ($W = 0.47$, $P < 0.01$) (i.e. a high level of agreement among participants in the relative rankings of species).

Assuming the first four species in our list are indeed extinct, summed probabilities across the remaining extinction risk values assigned by participants suggests that an average of 6.7 additional species could be lost in the wild by 2040 unless there are changes to resourcing, monitoring and management.

On average, 23 participants (ranging from 22 to 25) assessed extinction probability for the four possibly extinct species (*Litoria castanea*, *Litoria nyakalensis*, *Rheobatrachus vitellinus* and *Taudactylus rheophilus*), with most experts estimating very low probabilities (≤10%, Table 1) that undiscovered populations persist (i.e. the consensus among experts was that these four species are highly likely to be extinct already). If undetected populations do persist, participants also considered the near-future outlook to be very poor, with probabilities of extinction >90% by 2040 for all four species (Table 1).

Geographic distribution of the most imperilled Australian frogs

Twenty-one of the 26 species assessed are endemic to a single state or territory. The majority (67%) occur only in Queensland. The biogeographic regions with the most at-risk species are the Wet Tropics (nine species), South Eastern Queensland (three species), Australian Alps (three species) and Central Mackay Coast (two species) (Fig. 1). Several species are known from a single locality (e.g. Mt Elliot nursery frog (*Cophixalus mcdonaldi*), *Cophixalus concinnus*, *Cophixalus monticola*, *Philoria frosti*, *Litoria lorica*, *Litoria kroombitensis and Taudactylus pleione*), whereas others (e.g. Sloane's froglet (*Crinia sloanei*), *Geocrinia alba* and *Litoria spenceri*) are known only from highly fragmented and isolated populations.

Assessing the impact of participant experience on estimates of extinction probability

There was no evidence to suggest that experts and non-experts scored differently when tested across all species in Round 1 ($W = 156$, $Z = -0.50$, $P = 0.617$) or Round 2 ($W = 153$,

Table 1. The probability of extinction by 2040 (EX (2040)) (in the wild) for the 26 Australian frogs considered to be most imperilled
Likelihoods of extinction are based on structured expert elicitation (with lower/upper 95% confidence intervals) and are ranked from highest to lowest probability of extinction. Current IUCN refers to the current conservation status (as of 2004), and proposed IUCN refers to the proposed revised conservation status in Gillespie *et al.* (2020): EX, Extinct; CR, Critically Endangered; EN, Endangered; VU, Vulnerable; NA – Not Assessed (i.e. described after 2004). For the four possibly extinct taxa, we also provide the average estimate (range in parenthesis) that the species is already extinct (EX (present))

Rank	Species	EX (present)	EX (2040)	Lower 95% CI	Upper 95% CI	Current IUCN	Proposed IUCN
1	Northern gastric-brooding frog (*Rheobatrachus vitellinus*)	0.95 (0.75–1)	0.95	0.92	0.97	CR	EX
2	Mountain mist frog (*Litoria nyakalensis*)	0.93 (0.75–1)	0.94	0.89	0.97	EX	EX
3	Yellow-spotted tree frog (*Litoria castanea*)	0.92 (0.70–1)	0.93	0.89	0.96	CR	CR
4	Northern tinker frog (*Taudactylus rheophilus*)	0.90 (0.70–1)	0.92	0.86	0.95	CR	CR
5	Kroombit tinker frog (*Taudactylus pleione*)	Extant	0.70	0.57	0.81	CR	CR
6	Southern corroboree frog (*Pseudophryne corroboree*)	Extant	0.66	0.54	0.76	CR	CR
7	Baw Baw frog (*Philoria frosti*)	Extant	0.65	0.52	0.76	CR	CR
8	Armoured mist frog (*Litoria lorica*)	Extant	0.57	0.42	0.71	CR	CR
9	Mountain top nursery frog (*Cophixalus monticola*)	Extant	0.47	0.32	0.62	EN	CR
10	Beautiful nursery frog (*Cophixalus concinnus*)	Extant	0.45	0.30	0.60	CR	CR
11	Northern corroboree frog (*Pseudophryne pengilleyi*)	Extant	0.38	0.26	0.51	EN	CR
12	Spotted tree frog (*Litoria spenceri*)	Extant	0.36	0.24	0.49	CR	CR
13	Kroombit tree frog (*Litoria kroombitensis*)	Extant	0.31	0.19	0.45	NA	CR
14	Mt Elliot nursery frog (*Cophixalus mcdonaldi*)	Extant	0.29	0.18	0.44	EN	EN
15	Kuranda tree frog (*Litoria myola*)	Extant	0.29	0.17	0.43	NA	CR
16	Eungella day frog (*Taudactylus eungellensis*)	Extant	0.27	0.17	0.40	CR	EN
17	Bellenden Ker nursery frog (*Cophixalus neglectus*)	Extant	0.26	0.16	0.40	EN	EN
18	Rattling nursery frog (*Cophixalus hosmeri*)	Extant	0.20	0.11	0.32	VU	EN
19	Tapping nursery frog (*Cophixalus aenigma*)	Extant	0.16	0.09	0.26	VU	EN
20	White-bellied frog (*Geocrinia alba*)	Extant	0.15	0.09	0.24	CR	CR
21	Littlejohn's tree frog (*Litoria littlejohni*)	Extant	0.12	0.07	0.19	LC	EN
22	Sloane's froglet (*Crinia sloanei*)	Extant	0.10	0.06	0.17	DD	EN
23	Richmond Range mountain frog (*Philoria richmondensis*)	Extant	0.09	0.05	0.16	EN	EN
24	Howard river toadlet (*Uperoleia daviesae*)	Extant	0.08	0.04	0.14	NA	EN
25	Giant burrowing frog (*Heleioporus australiacus*)	Extant	0.08	0.04	0.14	VU	EN
26	Mahony's toadlet (*Uperoleia mahonyi*)	Extant	0.04	0.02	0.08	NA	EN

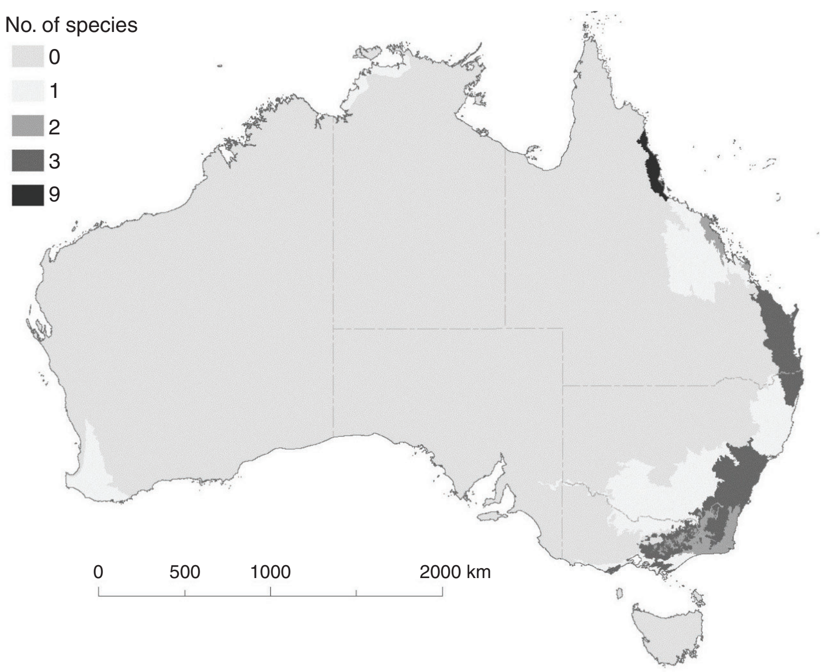

Fig. 1. The number of imperilled Australian frog species (based on structured expert elicitation) that occurs in each Interim Biogeographic Regionalisation for Australian (IBRA) bioregion (DAWE 2015).

$Z = -0.57$, $P = 0.569$). However, there was evidence of differences between experts and non-experts for some species (Fig. 2). For species with <10 participants in the self-assessed expert category, expert scores of extinction probability were generally higher than non-expert scores in Round 1 ($W = 32$, $Z = -1.86$, $P = 0.063$) and in Round 2 ($W = 24.5$, $Z = -2.02$, $P = 0.043$), with a few exceptions (Fig. 2). In contrast, for species with ≥10 experts, the non-expert scores were generally higher than expert scores in both rounds, again with a few exceptions (Fig. 2). The scores for 16 of 26 species converged in Round 2 (Fig. 2), indicating that there was greater consensus in the estimates of extinction probability following open discussion.

Average expert confidence was consistently higher than non-expert confidence in Round 1 ($W = 2.0$, $Z = -4.32$, $P < 0.001$) and Round 2 ($W = 0$, $Z = -4.46$, $P < 0.001$). Investigation of the raw data suggests that non-experts were more likely to revise their scores in Round 2 (~72% of all scores revised) than experts (~59% of all scores revised). However, the average non-expert extinction probabilities did not change significantly between Rounds 1 and 2 ($W = 115.5$, $Z = -1.52$, $P = 0.129$). In contrast, average expert probabilities decreased in Round 2 compared with Round 1 ($W = 85$, $Z = -2.30$, $P = 0.021$).

Threats, management and research actions

The most prevalent threats facing the 26 frogs assessed included climate change (19 species), *B. dendrobatidis* (15 species), changing fire regimes (13 species), habitat loss (11 species) and invasive species (primarily introduced fish and feral pigs; 10 species) (Supplementary material S5; Gillespie *et al.* 2020). *Batrachochytrium dendrobatidis* was the primary threat for the

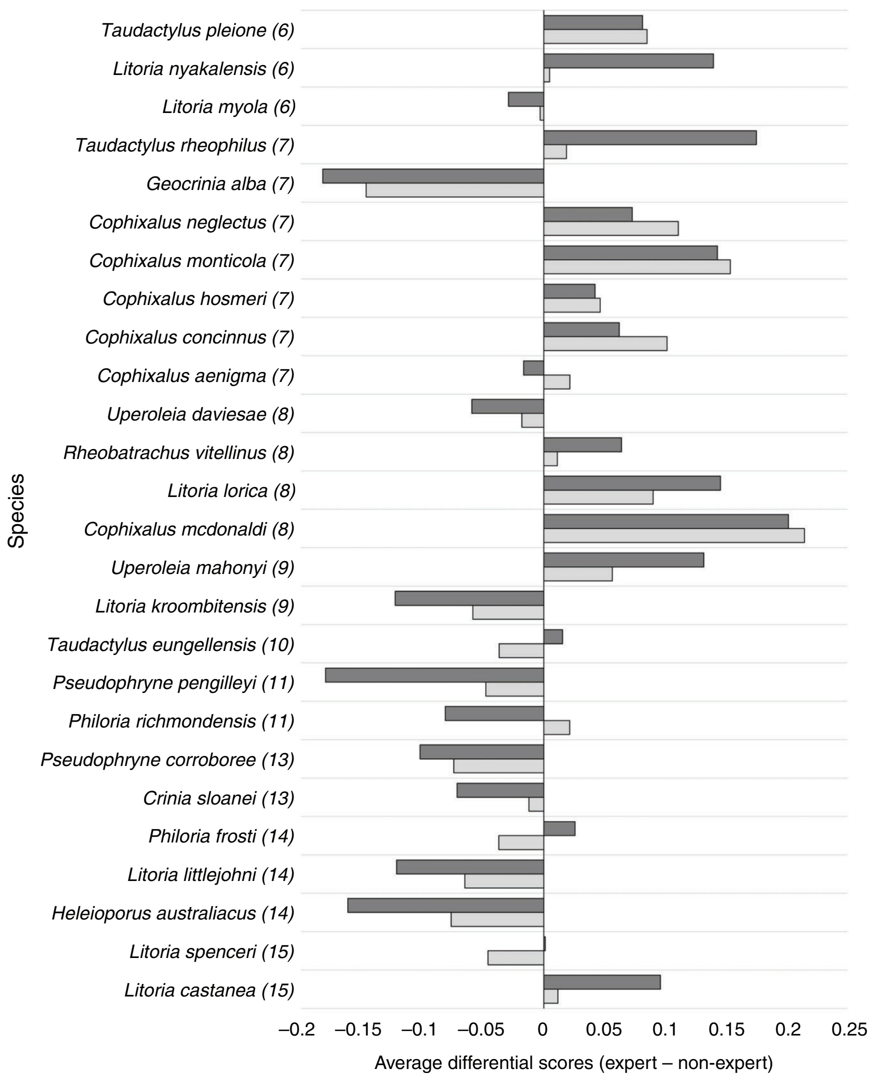

Fig. 2. Plot showing the differential scores (i.e. average expert scores minus average non-expert scores) for Round 1 (dark grey) and Round 2 (light grey) of the structured expert elicitation. A positive score indicates that the expert scores were higher, while a negative score indicates that the non-expert scores were higher. A score of zero indicates no difference between the expert and non-expert scores. The number of self-assigned experts for each species is provided in parenthesis.

top eight species on our list (all species with >50% probability of becoming extinct in the next 20 years). For the next five species on our list (those with 30–50% likelihood of extinction by 2040), the primary threats were climate change (*Cophixalus monticola*, *Cophixalus concinnus* and *Litoria kroombitensis*), *B. dendrobatidis* (*Pseudophryne pengilleyi* and *Litoria kroombitensis*) and introduced fish (*Litoria spenceri*) (Supplementary material S5; Gillespie *et al.* 2020).

When weighted against extinction probability, the most important management action assigned was 'develop and/or undertake and support captive management' (action M3 of Gillespie *et al.* 2020; Supplementary material S3). This action was the most commonly assigned management action across the species considered, the highest ranked management action for all of the mountain top *Cophixalus* species, and one of two top ranked management actions for *Litoria castanea*, *Taudactylus eungellensis*, *Taudactylus pleione* and *Taudactylus rheophilus* (the other being M5, 'establish and/or extend *in situ* population refuges from detrimental emergent disease impacts') (Fig. 3; Supplementary materials S3 and S6; Gillespie *et al.* 2020). Neither of the corroboree frog species (*P. corroboree* or *P. pengilleyi*) ranked highly for captive management, primarily because they had high scores for implementation. In both cases, captive management is currently underway and well resourced, so any additional resources may be better spent on other actions, or on other taxa that do not currently have resourcing for captive management, but for which it is a high priority.

When weighted against extinction probability, the most important research action was 'investigate options and potential feasibility of *in-situ* refugia for populations from disease' (action R3 of Gillespie *et al.* 2020; Supplementary material S3). This was the top ranked research action for *Litoria spenceri*, *Philoria frosti* and the two corroboree frogs, and one of two top ranked actions for *Litoria kroombitensis* (the other being R4, 'investigate potential locations and feasibility of potential *in situ* refuges for populations from detrimental climate impacts') (Supplementary materials S3 and S6; Gillespie *et al.* 2020). The second most important research action (when weighted against extinction probability) and the most common action (i.e. a priority for 23 of the species considered) was 'undertake surveys and/or modelling to improve knowledge of species distribution, ecological requirements and conservation status' (action R1 of Gillespie *et al.* 2020; Supplementary material S3). This includes surveys to find populations of missing species (logically the most important action for the four possibly extinct species) or to improve knowledge of the distribution and population status of an extant species. For those species which are demonstrably extant, R1 was the top priority research action identified for Littlejohn's tree frog (*Litoria littlejohni*), the Eungella day frog (*Taudactylus eungellensis*), *Uperoleia daviesae*, Mahony's toadlet (*Uperoleia mahonyi*) and one of two top ranked actions for *Crinia sloanei* (Fig. 3; Supplementary material S6).

Discussion

Our results indicate a dire situation for Australia's most threatened frogs. First, participants in our expert elicitation suggested, with universally high probabilities, that four of the 26 frogs we considered – *Litoria nyakalensis*, *Rheobatrachus vitellinus*, *Litoria castanea* and *Taudactylus rheophilus* – are already

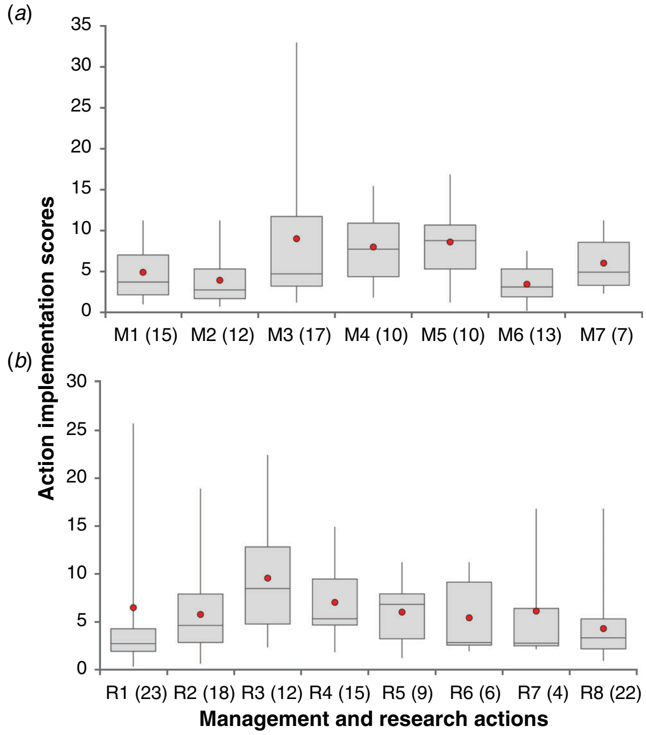

Fig. 3. A summary of the management (*a*) and research (*b*) actions (refer to Supplementary material S3 for action descriptions) that are likely to support the recovery of the 26 most imperilled Australian frog species. Management and research actions were taken from Gillespie *et al.* (2020). A higher action implementation score indicates a higher priority action, based on estimated extinction probability, conservation value, feasibility and current levels of implementation and resourcing. Lower and upper box boundaries are the first and third quartiles respectively, the line inside the box is the median, the red circle is the average, and the lower and upper error bars are the minimum and maximum values respectively. The number in parentheses refers to the total number of species for which each action was assigned.

extinct. Second, a further four species (which are currently extant) were considered more likely to go extinct than to persist over the next 20 years (estimated chance of extinction >50%). Third, our results suggest that an additional five species are at a moderate–high risk (30–50% chance) of extinction in the next two decades without improvements to current management practices. These results are alarming, especially given the relatively short timeframes for which this assessment was conducted, and that for many species, these probabilities may not be indicative of the scale of threat they face over longer time-periods.

It is possible that these results could be an artefact of the general attitudes of participants; all were conservation biologists, and thus may have been subject to the bias of overestimating extinction risk (Montibeller and von Winterfeldt 2015). However, an increase in the rate of extinction is not unreasonable, particularly given that some frog species have been lost to extinction recently (and so there is an empirical basis for concern). The already diminishing population sizes of many species, and increases in the intensity of many threats, augmented by the ongoing and emerging threats of disease and climate change are also concerning (Cohen *et al.* 2019; Scheele *et al.* 2019). Furthermore, it is likely that many threatening processes have compounding and interacting effects on threatened frogs (e.g. West *et al.* 2020), and this was a common concern among participants.

Management and research priorities for averting future Australian frog extinctions

The greatest conservation management gains are likely to be made through two broad actions: by (1) developing and supporting captive management and head-starting (i.e. where egg clutches are collected from the wild and reared in captivity to increase their chances of reaching adulthood), and (2) establishing and/or extending *in-situ* population refuges to alleviate the detrimental impacts from emergent diseases. This result was unsurprising, given that many of the species we considered here are already close to extinction, and because ongoing impacts associated with *B. dendrobatidis* are likely to lead to further declines (Gillespie *et al.* 2020). Ideally, captive management would incorporate gene banking from founder animals and assisted reproductive technologies to minimise costs and avoid inbreeding depression, enabling re-introduction and supplementation of genetically diverse wild populations (Clulow *et al.* 2019; Howell *et al.* 2021). However, for captive management to be successful, it must be accompanied by specific actions aimed at ameliorating the threats responsible for the initial declines across the species' range (Griffiths and Pavajeau 2008). There has been great progress in developing and implementing captive breeding programs for frogs in Australia, which has been demonstrated through population supplementations, re-introductions, and provision of insurance populations for several threatened species (Canessa *et al.* 2016; Skerratt *et al.* 2016; McFadden *et al.* 2018; Silla and Byrne 2019; Hoffmann *et al.* 2021). In addition, gene banking technologies have been developed and implemented for threatened frogs, providing a toolkit for optimised *ex-* and *in-situ* conservation programs (Clulow and Clulow 2016; Upton *et al.* 2018; Browne *et al.* 2019).

The most frequently high-ranking research action (and the second most important action when weighted against extinction probability) was 'improving knowledge of species distribution, ecological requirements, and conservation status', which, as expected, was the top ranked research action for the four possibly extinct species, *Litoria nyakalensis*, *Rheobatrachus vitellinus*, *Litoria castanea* and *Taudactylus rheophilus.* It is important to note that participants scored these four species as having a very high probability of already being extinct. Nevertheless, there remain some poorly surveyed areas within their range, and so there is a small possibility that remnant populations may be discovered (Gillespie *et al.* 2020), particularly in light of other rediscoveries of Australian frogs previously presumed to be extinct, such as *Litoria lorica* (Puschendorf *et al.* 2011). Targeted surveys for these species are thus of high priority, particularly in areas likely to provide refuge from disease-driven declines (Hoskin and Puschendorf 2014; Gillespie *et al.* 2020; Meyer *et al.* 2020). Additionally, there were several extant species likely to benefit from this research action; it was assigned to an additional 19 species (of the remaining 22 considered) and was the top-ranking research action for five of these. This is no surprise, given that information on distribution, ecology and conservation status provides the foundation for successful management programs (Gillespie *et al.* 2020).

For extant frogs, climate change and *B. dendrobatidis* were considered the major threats (Gillespie *et al.* 2020). Although there are currently limited options for directly mitigating the impacts of either of these (Garner *et al.* 2016; Skerratt *et al.* 2016), there are some notable exceptions for *B. dendrobatidis* (e.g. see Clulow *et al.* 2018; Heard *et al.* 2018) on which research could be built to provide management solutions for multiple taxa. Some of the other threatening processes are more feasible to manage with existing knowledge (e.g. introduced predatory species, see West *et al.* 2020), and thus should be prioritised, at least until feasible wide-scale management options for climate change and *B. dendrobatidis* can be identified. Doing so may make it more likely that populations can persist despite disease or climate change impacts (Shoo *et al.* 2011; Scheele *et al.* 2014; West *et al.* 2020).

Comparison of frog extinction risk to other taxonomic groups

Our estimated extinction probabilities for frogs are similar to results for Australian birds (Geyle *et al.* 2018) and terrestrial squamates (Geyle *et al.* 2020), higher than for Australian mammals (Geyle *et al.* 2018), and lower than for Australian freshwater fishes (Lintermans *et al.* 2020) using the same methods over a similar timeframe. This may reflect, in part, differences in risk perception among participants who assessed extinction probability in frogs compared with those who assessed the other taxa. However, given that Australian mammals have had the highest historic rates of extinction (Woinarski *et al.* 2019), one explanation could be that many of the most vulnerable mammal taxa have already been lost. Additionally, a common management response for mammals is the exclusion of predators or translocation to predator-free islands (Legge *et al.* 2018). This approach has had substantial recent success in stabilising and recovering many threatened mammal species (e.g. see Kanowski *et al.* 2018; Moseby *et al.* 2018), and consequently, participants of the mammal study may have had some confidence that those species at greatest risk of extinction can be secured, and are unlikely to become extinct over the predictive timeframe considered (20 years) (Geyle *et al.* 2018). By contrast, participants of the present study may be more pessimistic due to the limited options currently available for managing some of the key threats to frogs (e.g. *B. dendrobatidis* and climate change). Translocation approaches used for mammals have also been less successful for the other taxonomic groups, although with some notable exceptions (e.g. Harley *et al.* 2018).

The similar levels of imperilment predicted for frogs, birds and terrestrial squamates may be a result of these species occupying very restricted ranges, and consequently being highly susceptible to stochastic events (such as the 2019–2020 mega fires across the eastern Australian coast and range). They are also vulnerable to many of the same threats (e.g. climate change and invasive species, Gibbons *et al.* 2000), although we emphasise that one of the most important threats considered here (*B. dendrobatidis*), is unique to amphibians. The higher predicted rates of extinction for freshwater fish compared with all other taxonomic groups is likely due to several factors: (1) many of the highly imperilled freshwater fish species have smaller distributions than species assessed in other taxonomic groups; (2) many species have experienced far more rapid and recent declines; (3) many species have few prospects for recovery or protection; and (4) freshwater fishes have generally received limited management investment, particularly when compared with birds, mammals and frogs (Lintermans *et al.* 2020).

The geographic spread of imperilled frogs was found to be similar to that of the terrestrial squamates, with a majority of the most imperilled species occurring only in Queensland, especially in upland rainforest habitats (Geyle *et al.* 2020). This is partly because there is a greater diversity of reptiles and frogs in Queensland compared with other states (Cogger 2018), but also reflects the greater impact of *B. dendrobatidis* in cooler, wetter habitats (e.g. Scheele *et al.* 2019) and the projected impacts of climate change in this region (Williams *et al.* 2012). In contrast, future Australian bird extinctions are predicted to occur in island endemics or in taxa that occupy environmentally degraded parts of southern Australia, whereas future mammal extinctions are likely in the less developed parts of northern and central Australia (Geyle *et al.* 2018). Additionally, we can expect future freshwater fish extinctions from southern Australia, particularly in the Australian Alps (Lintermans *et al.* 2020).

The historical pattern of frog declines in Australia is very different to that of the other taxonomic groups. Birds and mammals have experienced near constant rates of extinction over the past two centuries (Scheele and Gillespie 2018; Woinarski *et al.* 2019), which has been largely attributed to habitat loss and introduced predators (Szabo *et al.* 2012; Woinarski *et al.* 2015). Both these threats have contributed substantially to Australian frog declines, but they have not been directly and exclusively implicated in any amphibian extinctions to date (Scheele *et al.* 2017). Additionally, there were no amphibian extinctions recorded in Australia before 1970 (Hero *et al.* 2006; Andrew *et al.* 2018), although work on Australian frogs was limited prior to the 1950s (Shea 2015), and so we have only a rudimentary understanding of the status of many species before that time. Nevertheless, for those extinctions that have occurred to date, other threatening processes have played the major role, particularly disease (Scheele *et al.* 2017). The historical pattern of decline in frogs is also very different to that observed for reptiles and freshwater fish. In the past few decades, several frog species have become extinct (attributable to *B. dendrobatidis*). By contrast, the first documented Australian reptile and freshwater fish extinctions were recorded only recently; the Christmas Island forest skink (*Emoia nativitatis*) and the Kangaroo River Macquarie Perch (*Macquaria* sp.), both of which were attributed to invasive species (Woinarski *et al.* 2019; Lintermans *et al.* 2020).

The influence of participant experience on estimated extinction probability

Average expert and non-expert scores were generally similar across all of the species considered, although we found some differences in the extinction probabilities given for poorly known species. For example, all six *Cophixalus* species (all with ≤8 experts) were estimated to have higher probabilities of extinction by experts than non-experts, and in some cases the estimates were substantially different (e.g. over 20% for *Cophixalus mcdonaldi*). This could be due to differences in risk perception among participants, particularly relating to the timing of climate change impacts, or due to a lack of understanding of the level of threat these species face, apparent to experts but not to non-experts. Experts may also be emotionally engaged with the species they study, and consequently could have inflated the probability of extinction relative to non-experts. Intriguingly, the opposite was true for better known species – the non-expert scores were significantly higher than the expert scores. One possible explanation could be that non-experts were more likely to score in a conservative range (e.g. not too high and not too low). Alternatively, it could be that more long-term data are available for better-known species, leading to greater confidence among experts in projections of persistence, compared with poorly known species where uncertainty is likely to be a major contributing factor. Nevertheless, the reason for the differences in scores is difficult to disentangle, particularly given the inherent biases associated with expert judgements (Martin *et al.* 2012).

We remain confident that our results provide a robust estimate of relative extinction risk for the 26 species of Australian frogs assessed. Several studies on structured expert elicitation demonstrate that equally weighted aggregations, taken from a diverse group of participants with varying experience and backgrounds, produce results that are closer to the truth than can be obtained from a single 'expert', or from a small group of 'experts' (Burgman *et al.* 2011; Martin *et al.* 2012; Budescu and Chen 2014; Hemming *et al.* 2018*a*, 2018*b*). This is further supported by the convergence of non-expert and expert scores for most species in Round 2 of the elicitation, and that every participant revised some of their scores following the group discussion. Other approaches, such as performance-weighted aggregation, may be useful for improving pooled judgements relating to ecological questions (Budescu and Chen 2014; Mellers *et al.* 2015). However, this approach is likely to require significantly more time and effort, comes with several additional challenges (e.g. developing questions about future events for which data can be obtained within a reasonable timeframe for validating participant performance), and there is no guarantee that it will improve estimates (Hemming *et al.* 2020). We consider the approach we used here provides an effective means for assessing extinction risk relative to selecting one or a few seemingly well-credentialed experts.

Conclusions

The probability of further extinctions of Australian frogs is unacceptably high, especially given commitments made by the Australian Government to avoid further extinctions (Department of Environment and Energy 2016). Our study, coupled with the research and management actions identified in Gillespie *et al.* (2020), provide a solid foundation from which to prioritise future conservation efforts for Australian frogs. Some extinctions may be averted using well-established approaches to threat management such as invasive animal control in key habitats. Others will potentially be alleviated with greater investment in research, particularly in areas where existing research is promising and could be developed further (e.g. efforts to alleviate the impacts of *B. dendrobatidis*). Climate change is more intractable, but solutions might include assisted colonisation or targeted gene flow

(Rudin-Bitterli *et al.* in press). Fundamentally, urgent investment and more strategic conservation effort are required to avert the impending extinction of Australia's most imperilled frogs. Given current trends, a contingency plan should be developed to ensure adequate monitoring, and to identify thresholds for action and planning for interventions that might be required, such as *ex-situ* conservation of additional species beyond those already maintained successfully in captivity.

Data availability

Sensitive data used in this study are not provided (including species summaries containing unpublished information, participant identities and their individual estimates of extinction). All other data (including threats, research and management categorisations) are provided as supplementary material.

Conflicts of interest

The authors declare no conflicts of interest.

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