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Quantifying extinction risk and forecasting the number of impending Australian bird and mammal extinctions

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Abstract. A critical step towards reducing the incidence of extinction is to identify and rank the species at highest risk, while implementing protective measures to reduce the risk of extinction to such species. Existing global processes provide a graded categorisation of extinction risk. Here we seek to extend and complement those processes to focus more narrowly on the likelihood of extinction of the most imperilled Australian birds and mammals. We considered an extension of existing IUCN and NatureServe criteria, and used expert elicitation to rank the extinction risk to the most imperilled species, assuming current management. On the basis of these assessments, and using two additional approaches, we estimated the number of extinctions likely to occur in the next 20 years. The estimates of extinction risk derived from our tighter IUCN categorisations, NatureServe assessments and expert elicitation were poorly correlated, with little agreement among methods for which species were most in danger – highlighting the importance of integrating multiple approaches when considering extinction risk. Mapped distributions of the 20 most imperilled birds reveal that most are endemic to islands or occur in southern Australia. The 20 most imperilled mammals occur mostly in northern and central Australia. While there were some differences in the forecasted number of extinctions in the next 20 years among methods, all three approaches predict further species loss. Overall, we estimate that another seven Australian mammals and 10 Australian birds will be extinct by 2038 unless management improves.

Additional keywords Anthropocene mass extinction crisis, biodiversity conservation, threatened species

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Introduction

Although extinctions occur naturally, the rate of extinction is currently ~1000 times the background rate (Pimm *et al.* 2014). At least three endemic vertebrate species were rendered extinct in Australia in the last decade (Woinarski *et al.* 2017), continuing an ongoing pattern of high rates of extinction for at least some segments of our fauna. This is most evident in the loss of an average of one to two mammals per decade since the 1850s, amounting to a total loss of 30 endemic species (Woinarski *et al.* 2015). Twenty-nine Australian birds have also become extinct over the last 200 years (Szabo *et al.* 2012). At least some of these extinctions may well have been prevented with adequate forewarning followed by appropriate management responses (Woinarski *et al.* 2017).

Extinction risk is broadly captured in the International Union for the Conservation of Nature (IUCN) Red List categories and criteria (IUCN 2012). The category 'Critically Endangered' is applied to those species at greatest risk, suggesting that action needs to be taken immediately to prevent their loss. However, some species can be Critically Endangered for many decades while others move rapidly through categories to Extinct, meeting the criteria for Critically Endangered only briefly before the last individual dies, thus allowing little time for management action. Also, even recently, some species have not been assessed until it was too late to act. For example, the forest skink (*Emoia nativitatis*), which was endemic to Christmas Island, remained unassessed by the IUCN until 2010 when it was listed as Critically Endangered. This was evidently too late, as the last wild reporting of this species took place in 2009 (Woinarski *et al.* 2017). The last captive individual died in 2014, marking the species' extinction (Woinarski *et al.* 2017).

General models capable of forecasting which species are at imminent risk of extinction do not yet exist. Population viability models can be useful, but require detailed data that are not available for most species, especially those most threatened with extinction, and those from groups for which there is generally a high proportion of species lacking extensive background data (i.e. invertebrates: Schultz and Hammond 2003). One alternative is to apply and extend existing systems conventionally used to assess extinction risk. Additional to the IUCN Red List categories and criteria, NatureServe provides a system for assessing extinction risk, using broadly analogous criteria to the IUCN (Master *et al.* 2009). Both systems lend themselves to tailored modification for more precisely predicting the likelihood of imminent extinction.

Extinction risk can also be assessed using expert elicitation. Experts are able to synthesise multiple risks and probabilities in ways that may be intractable for numerical models. Furthermore, variation in experience and risk perception among experts allows the development of multiple mental models from the same raw empirical data. Thus, integrating the opinions of multiple experts is essentially an exercise in model averaging (Symonds and Moussalli 2011) and produces better results than can be obtained from a single expert (Martin *et al.* 2012). Expert elicitation techniques are becoming increasingly sophisticated as inherent biases in judgement are better understood (Martin *et al.* 2012).

In this paper, we aim to predict which Australian bird and mammal taxa (encompassing species and subspecies) are most likely to be lost in the next 20 years under current management. The rationale for this assessment is that such forecasting may improve prioritisation, direction and resourcing of management aimed at averting losses. We combine three approaches to identify the taxa in most immediate danger: (1) a nominal tightening of the IUCN Red List criteria; (2) application of the NatureServe protocol; and (3) expert elicitation. We compare each method to identify overlaps and limitations, recognising that each may miss some highly imperilled taxa or exaggerate extinction risk in others.

We then map the distributions of the 20 most imperilled birds (using data provided by BirdLife Australia) and mammals (using data compiled for Woinarski *et al.* 2014) to allow identification of the regions in which prioritisation of extinction prevention should be focussed. Finally, we aggregate and model our estimated extinction risks for individual taxa to derive estimates of the number of Australian birds and mammals likely to become extinct in the next two decades unless management is enhanced or directed more appropriately. We compare these outputs with two other approaches used to forecast the number of extinctions: (1) probability of extinction thresholds under IUCN Red List Criterion E, and (2) projection of the rate of change through IUCN conservation status categories based on rates of change observed over the past two decades.

Materials and methods

Identifying the taxa most at risk of extinction

Initial selection

All birds listed as Vulnerable, Endangered or Critically Endangered under relevant Australian legislation (*Environment Protection and Biodiversity Conservation Act 1999*) or in the

2010 Action Plan for Australian Birds (Garnett *et al.* 2011) were considered in this study. Because mammals were recently assessed against the IUCN Red List criteria for the 2012 Action Plan for Australian Mammals (Woinarski *et al.* 2014), terrestrial taxa listed as Endangered or Critically Endangered in the Action Plan were considered in this study, along with subsequent assessments for a small set of taxa described since then, and updated assessments for two subspecies of nabarlek (*Petrogale concinna*) based on more recent information. We excluded four birds and two mammals flagged as 'Possibly Extinct' as the available evidence indicates that each of these taxa had already been lost (Table S1, available as Supplementary Material to this paper). In total, 235 birds and 39 mammals were assessed.

IUCN 'Extinction Imminent' assessments

To be threatened under the IUCN Red List, a species must meet defined criteria (Table S2, see Supplementary Material; IUCN 2012). Here, we nominally tighten those categories and criteria to further highlight the most imperilled species by subdividing the existing Critically Endangered category. The more extreme of these subdivisions we consider to be *Extinction Imminent,* with the definition of this class based on a logical extrapolation of the existing Critically Endangered thresholds (Table S2). We assessed all birds and mammals (identified above) against these new thresholds, using information on population size, geographic range and trends (obtained from Garnett *et al.* 2011 and Woinarski *et al.* 2014).

NatureServe assessments

The NatureServe protocol uses point scoring and logical rules with a mixture of quantitative, qualitative, and subjective criteria to assess extinction risk (Master *et al.* 2009, 2012). This method has five categories of threat, ranging from G1 (Critically Imperilled) to G5 (Secure and Abundant). While similar data inputs are used for allocating a threat category under both IUCN and NatureServe protocols (Tables S2 and S3, see Supplementary Material), the latter system categorises and assigns number codes (which may be positive or negative, depending on the parameter), which are then weighted and summed to give an overall conservation status score (Regan *et al.* 2005) (See Table S3 for details on the data inputs and weights). All birds and mammals identified above were evaluated against the NatureServe criteria using the conservation status factors outlined in Table S3 and then ranked according to conservation status score. Two scores were derived for each taxon: the *pessimistic* score (calculated using the lower bound of the conservation status factors) and the *optimistic* score (calculated using the upper bound of the conservation status factors) (Table S3). Lower and upper data bounds, derived from Garnett *et al.* (2011) and Woinarski *et al.* (2014), reflect the uncertainty of data input estimates.

Expert elicitation

We used expert elicitation to assess extinction risk in all 39 mammal taxa selected using the procedures described above. Due to the large number of threatened birds considered, we reduced the number of birds to be assessed to 34 by choosing only taxa that (1) were assessed as Extinction Imminent under our extension of the IUCN protocol, and/or (2) ranked in the top 20 most at risk of extinction under the NatureServe protocol (for both pessimistic and optimistic assessments).

We then asked 13 experts for each of the mammal and bird lists to make a judgement about the likelihood of extinction (in the wild) of each taxon (scaled from 0 to 100%) in the next 20 years, assuming current levels and character of management. Experts were selected on the basis of their contributions to Garnett *et al.* (2011) and Woinarski *et al.* (2014). We also obtained a level of confidence for each of their estimates (very low, low, moderate, high, or very high). Some experts decided to score taxa only if confident in their ability to ascribe extinction risk. We then asked experts to determine whether there were any taxa missing from the lists that they also considered to be at high risk of imminent extinction; this resulted in the inclusion of six additional birds for assessment (Gawler Range short-tailed grasswren, *Amytornis merrotsyi pedleri*; western bristlebird, *Dasyornis longirostris*; mallee emu-wren, *Stipiturus mallee*; Gulf St Vincent slender-billed thornbill, *Acanthiza iredalei rosinae*; Norfolk Island scarlet robin, *Petroica multicolor*; western partridge pigeon, *Geophaps smithii blaauwi*) and two additional mammals (bridled nailtail wallaby, *Onychogalea fraenata*; New Holland mouse, *Pseudomys novaehollandiae*). Following the initial round of expert elicitation, feedback was provided, email discussions took place, and some experts adjusted their judgement (as per the Delphi process, see McBride *et al.* 2012).

Statistical analysis

We controlled for individual experts consistently underestimating or overestimating likelihood of extinction by analysing each expert's estimates (logit-transformed before analysis) using a linear mixed-effects model ('lme' in package 'nlme') in R 3.2.1 (R Core Team 2015), with the identity of the individual experts specified as random intercepts. We specified a variance structure in which variance increased with the level of uncertainty associated with each estimate of likelihood 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. We used the linear mixed-effects model to predict the probability of extinction (with 95% confidence intervals) for each taxon.

The set of experts involved in evaluating extinction risk were largely different for birds compared with mammals. If a major difference in attitude to risk evaluation was evident between these two taxonomic groups, then a comparison of extinction risk may be inappropriate. To test for such an artefactual result, we compared the extinction risk ratings for the 20 birds and 20 mammals ranked most in danger of extinction (using Mann–Whitney U tests) for each of three experts who provided scores for both taxonomic groups.

We used Pearson's correlation coefficient to test for correlation between NatureServe scores and expert elicitation extinction probabilities (log-transformed). To test for concordance with Extinction Imminent status, we ran linear regression models where NatureServe score or expert extinction probabilities were modelled as response variables and Extinction Imminent status was modelled as a binary predictor.

We report the P-values (considered significant if $P < 0.05$) of these models for inference.

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

Expert elicitation

The predicted probabilities of extinction for each of the 40 birds and 41 mammals (assessed by the experts) were summed to estimate the number of taxa (from this subset of birds and mammals) likely to become extinct in the next 20 years.

We also estimated the likely number of extinctions, in the next 20 years, of taxa not in this subset, i.e. those lower-extinction-risk taxa not assessed by the experts. To do this, we first established that there was no significant difference between the distributions of predicted probabilities of extinction for the subset of 40 birds and 41 mammals, using a non-parametric Kolmogorov–Smirnov test ($P > 0.05$). We then modelled the linear relationship between the logarithm of predicted probability of extinction for each taxon and rank order of likelihood of extinction (based on expert elicitation in both cases) for birds and mammals combined ($R^2 = 0.99$).

To estimate the probability of extinction of the 1199 birds and 380 mammals not included in the subset of taxa assessed by the experts, we summed predicted probabilities of extinction for each rank to approximate the total number of taxa not assessed by experts that are likely to become extinct in the next 20 years.

IUCN Red List Criterion E

The number of taxa expected to become extinct in the next 20 years can also be estimated on the basis of assumptions underlying IUCN Criterion E extinction probability thresholds, which are based on population viability analyses. Under the IUCN Red List categories and criteria, Critically Endangered taxa are considered to have at least a 50% probability of extinction within 10 years or three generations (whichever is longer); Endangered taxa are considered to have >20% probability of extinction within 20 years or five generations; and Vulnerable taxa are considered to have >10% probability of extinction within 100 years. Following Brooke *et al.* (2008), we assumed that taxa listed in a threatened Red List category (Vulnerable, Endangered or Critically Endangered) under any criterion other than E will have comparable extinction risk to taxa listed within that status under Criterion E.

On the basis of this assumption, we calculated the minimum number of bird and mammal taxa *expected* to become extinct (N_{ex}) in the next 20 years as:

$$N_{ex} = N_{th}\left(1 - (1 - EX)^{\left(\frac{1}{T}\right)^{t}}\right)$$

Where N_{th} refers to the number of taxa in each threatened category (hereby referred to as N_{cr}, N_{en} and N_{vu} for respective categories), EX is the probability of extinction (i.e. 50%, 20% 10% for Critically Endangered, Endangered, and Vulnerable respectively), T is the time corresponding to the minimum period for each of the extinction probabilities (i.e. 10, 20 and 100 for Critically Endangered, Endangered and Vulnerable respectively), and t is the period of interest (i.e. 20 years). We were thus able to calculate the number of expected extinctions as:

$$N_{ex} = N_{cr}\left(1 - (1 - 50)^{\left(\frac{1}{10}\right)^{20}}\right) + N_{en}\left(1 - (1 - 20)^{\left(\frac{1}{20}\right)^{20}}\right) + N_{vu}\left(1 - (1 - 10)^{\left(\frac{1}{100}\right)^{20}}\right)$$

Trajectories in IUCN Red List categories over the last 20 years

Using Garnett *et al.* (2011) and Woinarski *et al.* (2014), we assessed changes in the conservation status of all Australian birds and all terrestrial Australian mammals from 1990 to 2010 and from 1992 to 2012, respectively. We identified the number of taxa moving between different conservation status categories owing to genuine improvement or deterioration in status (as in Brooke *et al.* 2008) to estimate how many could move into the Extinct category based on historical trends. We analysed these data using proportional odds logistic regression models ('polr' in package 'MASS') in R, whereby the response is an ordered multinomial. In our case, the response was the most recent (2010 for birds, 2014 for mammals) IUCN Red List category for each taxon (i.e. Least Concern < Near Threatened < Vulnerable < Endangered < Critically Endangered < Extinct). We modelled these as a function of the IUCN category for each taxon 20 years earlier (1990 for birds, 1992 for mammals). To approximate the total number of taxa likely to become extinct in the next 20 years, we multiplied the proportion of taxa in each category moving into the Extinct category over a 20-year period predicted using the proportional odds logistic regression model by the number of taxa currently in each category. This analysis assumes that the historical rate (i.e. over the last 20 years) of movement of individual taxa across Red List conservation status categories will continue over the next 20 years.

Results

Taxa most likely to become extinct

IUCN 'Extinction Imminent' category

Of the 40 birds assessed, 23 (~58%) triggered Extinction Imminent status under our nominally tighter IUCN thresholds, with most triggering either Criteria A1–4 (population size reduction), Criteria B1 (extent of occurrence and accompanying subcriteria) or B2 (area of occupancy and accompanying subcriteria) (Table S2). Of the 41 mammals assessed, nine taxa (~22%) triggered Extinction Imminent status – all based on Criteria A1–4 or B1–2 (and accompanying subcriteria) (Table S2). Taxa with Extinction Imminent status are listed in Tables 1 and S4 (see Supplementary Material).

NatureServe assessments

Of the birds assessed by the experts, NatureServe scores ranged from −1.2 (for the Critically Imperilled orange-bellied parrot, *Neophema chrysogaster*) to 2.7 (for the western bristlebird, *Dasyornis longirostris*) based on pessimistic estimates, and from −0.7 to 3.5 based on optimistic assessments (Tables 1 and S4). Most of the top 20 ranked pessimistic NatureServe scores (85%) were <1.5, corresponding to allocation to the highest

Table 1. The likelihood of extinction (EX) in the next 20 years for the 20 birds and 20 mammals considered most imperilled

Likelihoods of extinction are based on expert elicitation (with lower/upper confidence intervals) and are ranked from highest to lowest probability of extinction. Also shown: whether they met intensified IUCN Red List Criteria (EI), their pessimistic (pes) and optimistic (opt) NatureServe (NS) scores (i.e. scores calculated using the *lower* and *upper* bound of NatureServe conservation status factors – see Table S3) and their pessimistic (pes) and optimistic (opt) NatureServe ranks respective to the total number of birds ($n = 235$) and mammals ($n = 41$) assessed. CI, confidence interval

Rank	Taxon	EX	Lower 95% CI	Upper 95% CI	IUCN (EI)	NS score (pes)	NS rank (pes)	NS score (opt)	NS rank (opt)
Birds									
1	King Island brown thornbill, *Acanthiza pusilla archibaldi*	0.94	0.84	0.98	Yes	0.9[B]	12	1.2[B]	7
2	Orange-bellied parrot, *Neophema chrysogaster*[A]	0.87	0.76	0.94	Yes	−1.2[B]	1	−0.7[B]	1
3	King Island scrubtit, *Acanthornis magna greeniana*	0.83	0.66	0.93	Yes	0.3[B]	5	0.6[B]	3
4	Western ground parrot, *Pezoporus wallicus flaviventris*[A]	0.75	0.56	0.87	Yes	−0.5[B]	2	0.3[B]	2
5	Houtman Abrolhos painted buttonquail, *Turnix varius scintillans*	0.71	0.42	0.90	No	0.6[B]	8	1.1[B]	5
6	Plains-wanderer, *Pedionomus torquatus*[A]	0.64	0.40	0.82	Yes	−0.1[B]	3	1.7	12
7	Regent honeyeater, *Anthochaera phrygia*[A]	0.57	0.37	0.75	Yes	0.6[B]	6	1.8	14
8	Grey range thick-billed grasswren, *Amytornis modestus obscurior*	0.53	0.27	0.78	Yes	0.9[B]	12	1.2[B]	6
9	Herald petrel, *Pterodroma heraldica*[C]	0.52	0.27	0.76	Yes	2.0	73	2.1	22
10	Black-eared miner, *Manorina melanotis*	0.47	0.05	0.93	No	0.9[B]	16	2.2	27
11	Northern eastern bristlebird, *Dasyornis brachypterus monoides*[A]	0.39	0.17	0.67	No	1.2[B]	19	1.7	13
12	Mallee emu-wren, *Stipiturus mallee*[A]	0.34	0.11	0.67	No	1.3[B]	21	2.8	66
13	Swift parrot, *Lathamus discolor*[A]	0.31	0.16	0.50	Yes	0.8[B]	10	2.2	24
14	Norfolk Island boobook, *Ninox novaeseelandiae undulata*[A]	0.27	0.13	0.46	Yes	0.9[B]	12	1.4	11
15	Mount Lofty Ranges chestnut-rumped heathwren, *Calamanthus pyrrhopygia parkeri*	0.24	0.08	0.51	No	0.6[B]	7	1.9	18
16	Fleurieu Peninsula southern emu-wren, *Stipiturus malachurus intermedius*	0.17	0.05	0.44	No	1.3[B]	20	1.9	15
17	Helmeted honeyeater, *Lichenostomus melanops cassidix*[A]	0.17	0.08	0.32	Yes	1.0[B]	17	1.1	4
18	Cocos buff-banded rail, *Hypotaenidia philippensis andrewsi*	0.17	0.07	0.34	Yes	1.9	62	2.2	25
19	Western bristlebird, *Dasyornis longirostris*	0.16	0.05	0.40	No	2.7	149	3.5	142
20	Alligator Rivers yellow chat, *Epthianura crocea tunneyi*[A]	0.15	0.04	0.40	No	0.7[B]	9	1.9	16
Mammals									
1	Central rock-rat, *Zyzomys pedunculatus*[A]	0.65	0.48	0.79	Yes	−0.58[B]	1	−0.58[B]	1
2	Northern hopping-mouse, *Notomys aquilo*[A]	0.48	0.30	0.67	No	0.39[B]	6	0.55[B]	7
3	Carpentarian rock-rat, *Zyzomys palatalis*	0.44	0.24	0.66	No	0.84[B]	15	1.0[B]	15
4	Christmas Island flying-fox, *Pteropus natalis*[A]	0.41	0.23	0.62	Yes	0.26[B]	4	0.26[B]	3
5	Black-footed tree-rat (Kimberley and mainland NT), *Mesembriomys gouldii gouldii*	0.39	0.22	0.59	No	1.10[B]	18	1.27[B]	18
6	Gilbert's potoroo, *Potorous gilbertii*[A]	0.36	0.21	0.58	Yes	−0.52[B]	2	0.36[B]	2
7	Leadbeater's possum, *Gymnobelideus leadbeateri*[A]	0.29	0.15	0.52	Yes	0.42[B]	7	1.27[B]	4
8	Nabarlek (Top End), *Petrogale concinna canescens*	0.29	0.13	0.51	No	0.49[B]	9	0.65	10
9	Brush-tailed phascogale (Kimberley), *Phascogale tapoatafa kimberleyensis*	0.28	0.13	0.49	No	1.58	31	1.7	31
10	Brush-tailed rabbit-rat (Kimberley, Top End), *Conilurus penicillatus penicillatus*[A]	0.25	0.11	0.47	No	0.92[B]	16	1.37[B]	22
11	Western ringtail possum, *Pseudocheirus occidentalis*[A]	0.25	0.11	0.46	Yes	0.26[B]	3	0.45[B]	5
12	Northern brush-tailed phascogale, *Phascogale pirata*	0.23	0.10	0.44	No	1.59	32	1.88	32
13	Mountain pygmy-possum, *Burramys parvus*[A]	0.22	0.09	0.42	No	1.28[B]	23	1.43[B]	24
14	Kangaroo Island dunnart, *Sminthopsis griseoventer aitkeni*[A]	0.22	0.09	0.44	No	1.33[B]	26	1.48[B]	26
15	Brush-tailed rabbit-rat (Tiwi Islands), *Conilurus penicillatus melibius*[A]	0.21	0.09	0.41	No	0.06[B]	11	1.06[B]	17
16	Silver-headed antechinus, *Antechinus argentus*	0.20	0.08	0.42	No	1.71	33	3.17	39
17	Southern bent-winged bat, *Miniopterus orianae bassanii*	0.18	0.07	0.37	No	1.14[B]	20	1.31[B]	20
18	Black-tailed antechinus, *Antechinus arktos*	0.17	0.06	0.37	No	2.3	39	4.89	41
19	Northern bettong, *Bettongia tropica*	0.14	0.05	0.31	No	1.48[B]	29	1.63	28
20	Tasman Peninsula dusky antechinus, *Antechinus vandycki*	0.14	0.05	0.31	No	2.23	38	4.75	40

[A]Included in the priority list of 20 birds and 20 mammals under the National Threatened Species Strategy (Department of the Environment and Energy 2016).
[B]Critically Imperilled based on NatureServe criteria.
[C]Refers to Australian breeding population.

Table 2. NatureServe scores and associated status descriptions

NS score range	NS status description
≤1.5	G1: Critically Imperilled
1.6–2.5	G2: Imperilled
2.6–3.5	G3: Vulnerable
3.6–4.5	G4: Apparently Secure
≥4.6	G5: Secure

category afforded by the NatureServe protocol, Critically Imperilled (Table 2). Less than half of the top 20 ranked optimistic scores (30%) were categorised as Critically Imperilled, while the remaining scores corresponded to an Imperilled or Vulnerable status (i.e. scores ranging from 1.6 to 3.5: Table 2).

Of the mammals assessed, NatureServe pessimistic scores ranged from −0.58 (for the Critically Imperilled central rock rat, *Zyzomys pedunculatus*) to 3.34 (the vulnerable yellow-bellied glider (wet tropics), *Petaurus australis* undescribed subspecies). Optimistic scores ranged from −0.58 to 4.89 (Critically Imperilled to Secure and Abundant) (Tables 1 and S4).

Expert elicitation and extinction probabilities

Table 1 presents the probability of extinction and 95% confidence intervals for the 20 birds and mammals at greatest risk of extinction based on the expert elicitation, and application of the linear mixed-effects model. Collation and analysis of expert opinion indicated that nine birds (see Table 1) and one mammal (the central rock-rat, *Zyzomys pedunculatus*) were more likely than not to become extinct in the next 20 years. This result may reflect real differences between these two groups in likelihood of extinction or attitudinal difference in the experts who assessed birds relative to those who assessed mammals. The former is more likely, as all three experts who assessed both birds and mammals rated extinction-risk higher for bird taxa than mammal taxa, with this difference highly significant in two out of three cases (Table 3).

Concordance among the three approaches in ranking the taxa at highest extinction risk

Of the 20 birds and mammals listed in Table 1, just over half (60%) of the birds and one-quarter (25%) of the mammals were also categorised as Extinction Imminent in our nominal tightening of IUCN criteria. More than three-quarters of the birds (80%) and just over half of the mammals (60%) had NatureServe scores ranking in the top 20 (based on pessimistic calculations). A greater proportion (85% of birds and 75% of mammals) obtained NatureServe scores <1.5, corresponding to allocation of Critically Imperilled status.

For the remaining mammals, Extinction Imminent birds, and those birds with high-ranking NatureServe scores, the experts considered the probability of extinction in the next 20 years to be relatively low (≤12%, Table S4). The overall probability of extinction for the entire subset of taxa was loosely correlated with whether a taxon had a high-ranking NatureServe score ($r_{80} = -0.5$, $P < 0.01$) (Fig. 1). There was no significant effect of Extinction Imminent status on the probability of extinction

Table 3. Comparison of the average scores derived from three individual experts' estimated likelihoods of extinction (±standard error) for the 20 birds and 20 mammals most in danger of extinction

All three experts provided assessments for most of the bird and mammal taxa considered as part of this study. Z-scores and associated *P*-values (considered significant if $P < 0.05$) are provided for comparisons between the individual expert's scores, based on Mann–Whitney U tests

	Expert 1	Expert 2	Expert 3
Birds	0.46 (±0.08)	0.49 (±0.06)	0.52 (±0.11)
Mammals	0.31 (±0.06)	0.17 (±0.03)	0.17 (±0.04)
Comparison: Z (P)	1.22 (0.22)	3.47 (0.0005)	2.53 (0.0011)

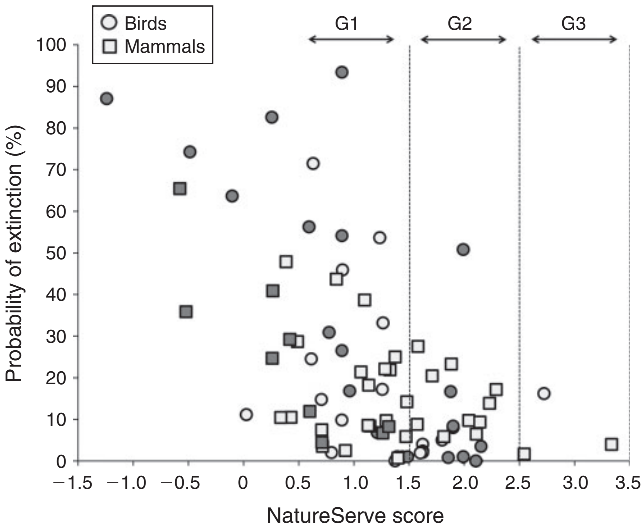

Fig. 1. The relationship between expert elicitation probabilities of extinction, NatureServe pessimistic scores (i.e. those calculated using the *lower* bound of NatureServe parameters – see Table S3) and whether bird and mammal taxa met the intensified IUCN Red List 'Extinction Imminent' criteria (dark shaded symbols). G1, Critically Imperilled; G2, Imperilled; G3, Vulnerable (see Table 2).

($P = 0.72$), but Extinction Imminent taxa were more likely to have lower NatureServe scores ($P = 0.028$) (Fig. 1).

Geographical distribution of the taxa at highest extinction risk

Four of the 20 birds with highest extinction risk breed only on small islands (<40 km^2), with a further two from King Island, a large island (1098 km^2) in Bass Strait, and two others in Tasmania, a larger island again (64 519 km^2). The latter two are both migratory parrots (*Neophema chrysogaster* and *Lathamus discolor*) that spend the non-breeding season in mainland Australia. All of the other birds with mainland distributions occur in southern Australia, mostly in intensively modified regions (Fig. 2*a*).

Five of the 20 most imperilled mammals occur only on islands (ranging in size from 137 to 5786 km^2), but none of these islands also support a highly threatened bird (i.e. ranking

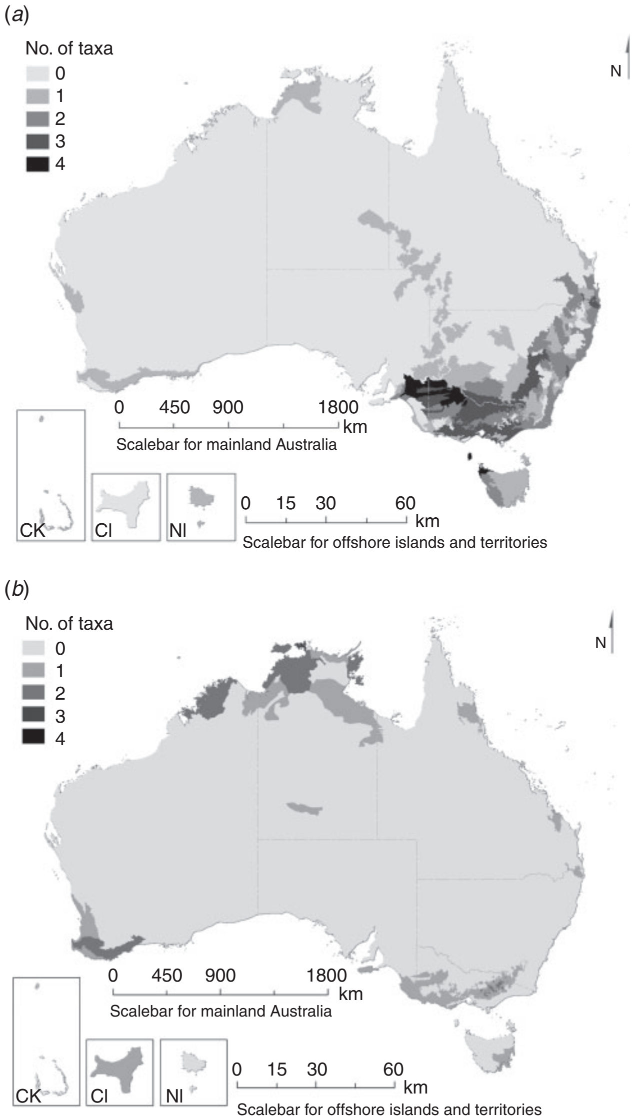

Fig. 2. The number of (*a*) bird and (*b*) mammal taxa occurring in each Interim Biogeographic Regionalisation for Australia (IBRA) subregion (SA Department of Environment Water and Natural Resources 2015). Data are presented for the 20 most imperilled birds and the 20 most imperilled mammals (obtained from expert elicitation). CK, Cocos (Keeling) Islands; CI, Christmas Island; NI, Norfolk Island.

in the top 20) (Table 1). In contrast to the birds, half of the most imperilled mammals occur mostly or only in northern or central Australia (Fig. 2*b*).

Number of taxa likely to become extinct in the next 20 years

From extinction-risk values assigned by experts to the 40 bird and 41 mammal taxa assessed, we estimate that 9.9 birds and 7.2 mammals will become extinct in the next 20 years. On the basis of the extrapolation of the distribution of scores for likelihood of extinction (from expert opinion) of these taxa, we estimate that a further 0.02 birds and 0.02 mammals, not assessed by experts, will become extinct over this period, bringing the total to ~10 birds (0.82% of 1239 extant taxa) and ~7 mammals (1.76% of 421 extant taxa) (Table 4).

Table 4. The number and percentage of Australian bird and terrestrial mammals expected to become extinct in the next 20 years, if current levels of management are assumed

Numbers are estimated using three methods: (1) expert elicitation (selected high-risk taxa directly assessed by experts, and additional taxa not assessed); (2) IUCN Red List Criterion E extinction probability thresholds; and (3) trends and trajectories in IUCN statuses observed during recent 20-year periods (1990–2010 for birds and 1992–2012 for mammals)

Estimation method	Birds	Mammals
Extant taxa	1239	421
Proportion extinct in next 20 years		
Experts	0.82%	1.76%
Directly estimated	0.80%	1.71%
Additional taxa	0.02%	0.05%
Red List Criterion E	2.20%	3.50%
Trajectories over last 20 years	0.27%	1.01%
Absolute number extinct in next 20 years		
Experts	10.16	7.41
Directly estimated	9.91	7.20
Additional taxa	0.25	0.21
Red List Criterion E	27.26	14.74
Trajectories over last 20 years	3.35	4.25

Table 5. The number of birds in each IUCN Red List category in 1990, on the basis of current knowledge regarding population parameters (see Brooke *et al.* 2008) and the number of taxa changing category by 2010 owing to genuine improvement (below diagonal ~) or deterioration (above diagonal ~) in status

LC, Least Concern; NT, Near Threatened; VU, Vulnerable; EN, Endangered; CR, Critically Endangered; EX, Extinct

1990 category	No. of spp.	2010 category					
		LC	NT	VU	EN	CR	EX
LC	1063	~	16	7	7	1	
NT	56		~	5	6	1	
VU	60		1	~	11		
EN	47	1	1	3	~	1	
CR	16				1	~	3
EX	1						~

Application of IUCN Red List Criterion E to all extant taxa suggests that ~27 birds (2.2% of extant taxa) and ~15 mammals (3.5% of extant taxa) can be expected to become extinct in the next 20 years (Table 4).

Projection of the rate of movement of taxa between conservation status categories during the last 20 years indicates that 0.27% of birds (i.e. ~3 taxa) and 1.01% of mammals (i.e. ~4 taxa) are likely to become extinct by 2038 (Tables 4, 5, 6).

Discussion

Conservation status assessments aim to identify the extinction risk of species (Mace *et al.* 2008). Accurate characterisation of extinction risk is crucial, given ambitions of national governments and non-government organisations to prevent further

Table 6. The number of mammals in each IUCN Red List category in 1992, on the basis of current knowledge regarding population parameters (see Brooke *et al.* 2008) and the number of taxa changing category by 2012 owing to genuine improvement (below diagonal ~) or deterioration (above diagonal ~) in status

LC, Least Concern; NT, Near Threatened; VU, Vulnerable; EN, Endangered; CR, Critically Endangered; EX, Extinct

1992 category	No. of spp.	2012 category					
		LC	NT	VU	EN	CR	EX
LC	260	~	13	2	1	2	
NT	90	4	~	27	2	1	
VU	41		7	~	4		
EN	19		1		~	3	1
CR	12			1	2	~	3
EX	35						~

species loss (United Nations 2015; Department of the Environment and Energy 2016). Here, we apply and extend two global protocols that assess conservation status and extinction risk, and use expert elicitation, to forecast which, and how many, Australian birds and mammals are in imminent danger of extinction.

Typically, extinction probabilities are calculated by formulating mathematical models based on life-history parameters and population growth rates. For example, population viability analysis estimates the future risk of extinction (Coulson *et al.* 2001). However, for most threatened taxa, the extensive and high-quality data required to ensure reliable outputs from this approach are not available. For taxa requiring urgent intervention, managers can rarely afford delays until appropriate data become available (O'Grady *et al.* 2004*b*; Martin *et al.* 2012). An alternative approach is to use expert judgements obtained via elicitation processes (e.g. McBride *et al.* 2012). While expert judgements tend to overestimate risks, can show considerable bias, and are sometimes not considered scientifically rigorous (Morgan 2014), expert predictions can be of comparable quality to those of modelled predictions, particularly when the data and outputs relate to a short timeframe such as 20 years (McCarthy *et al.* 2004). Compared with population modelling, expert elicitation is cost-effective, requiring far less time and resources, and can be conducted with limited ecological data (McCarthy *et al.* 2004); the latter aspect is important when dealing with taxa at imminent risk of extinction, and threatened taxa more generally, particularly when considering the biases associated with allocation of conservation resources. Fleming and Bateman (2016) found that most Australian mammalian research is focussed on larger, widely distributed taxa, or on managing the threat caused by introduced eutherian mammals. As a result, many native species (particularly those generally considered to be the least charismatic, i.e. rodents and bats) have attracted little research effort, recognition and funding.

For such taxa where high-quality data are lacking, there is a temptation to use rubrics based on whatever data are available. In such cases it may be useful to combine multiple approaches for forecasting extinction risk, particularly given that experts are able to add knowledge on some aspects that are not explicitly considered by risk-ranking protocols (for example dispersal ability, susceptibility to fire and low reproductive success). Our study supports this suggestion, evident by the overall poor correlation between extinction risk determined using IUCN and NatureServe thresholds compared with expert elicitation. The NatureServe scores were loosely correlated with expert estimates of extinction risk, but we found no significant association between the likelihood of species extinction derived from expert elicitation and whether or not a species was categorised as Extinction Imminent. Extinction Imminent taxa were, however, more likely to be accorded higher extinction-risk (i.e. lower scores) under our assessment against NatureServe criteria; this concordance is consistent with a previous study that found a significant correlation between IUCN and NatureServe status assessments (O'Grady *et al.* 2004*a*).

The differences in how data are combined and weighted, and the thresholds that delineate categories, make consistent assessment among protocols difficult (Regan *et al.* 2005). For example, the Australian breeding population of herald petrel (*Pterodroma heraldica*), which nests on just 32 ha of Raine Island, meets Extinction Imminent status based on IUCN Red List Criteria B2 (area of occupancy <10 km^2 and accompanying subcriteria) (Table S2), yet does not rank highly based on NatureServe assessments due to the taxon's large non-breeding extent of occurrence ($\sim$1 500 000 km^2), the apparent lack of high-impact threats (leading to allocation of a 'low' score), and the subsequent weight afforded to each of these parameters in the final calculation of status. The experts ranked the Australian breeding population of herald petrel as having the 9th highest probability of extinction of the bird taxa considered (with likelihood of extinction in the next 20 years of 52%), thus suggesting that the IUCN Red List assessment is more likely to reflect the true extinction risk to this species when compared with the NatureServe assessment.

Geographic range is a key criterion for both IUCN and NatureServe protocols, with taxa occupying a greater geographic range generally considered to be more secure than those with restricted ranges (although this can mask population declines: see Ceballos *et al.* 2017). The relationship between distribution and extinction risk is not always straightforward (Runge *et al.* 2015). Nomadic taxa (e.g. regent honeyeaters) often occupy a small part of their maximum distribution in response to fluctuating resources. In contrast, sedentary taxa with a restricted range may be locally common (Williams *et al.* 2006) and face no immediate threats, yet be allocated to a higher threat category due to their limited extent of occurrence or area of occupancy. Furthermore, the restricted distribution of such taxa may lead to more tractable and effective management responses and outcomes. For example, noxious weeds, introduced predators and fire can be readily controlled on small islands, an outcome much harder to achieve on mainland Australia. In this study, several locally common and stable populations of birds were classified as Critically Imperilled or Extinction Imminent (e.g. the Lord Howe Island subspecies of pied currawong, *Strepera graculina crissalis*; golden whistler, *Pachycephala pectoralis contempt*; and silvereye, *Zosterops lateralis tephropleurus*). In each of these examples expert elicitation readily justified a lower extinction risk.

The fundamental difference among the protocols lies in the structure of each method; thus, combining multiple approaches provides an opportunity to overcome instances where one method may be performing better than another. Regan *et al.* (2005) found that a rule-based approach (i.e. the IUCN criteria) typically performed better when data are scarce, as rule-based approaches have more robust strategies for dealing with unknown data than a point-scoring system (i.e. NatureServe). Furthermore, parameter weightings that are implicit in particular protocols may suit some purposes more than others (Regan *et al.* 2004). The importance of knowledge of related taxa and experience of experts is valuable in such cases, where subjective decisions are made using a combination of logic, common sense, skill, experience and judgement (Regan *et al.* 2004). While the known biases in elicitation methods can only partially be overcome (Morgan 2014; Montibeller and Winterfeldt 2015), using multiple experts to assess the probability of extinction independently, discussing discrepancies among assessors, and reconciling inconsistencies and differences in interpretation can produce robust estimates of extinction probability, particularly when used in conjunction with the outputs of different risk-ranking protocols.

A notable feature of our results is the generally higher risk of extinction predicted for the most at-risk birds relative to the most at-risk mammals (Table 1). This appears to be a real result rather than an artefact of largely different sets of individual experts rating these groups (Table 3). We consider that this may be because there has been substantial recent success by managers in stabilising and recovering many of the most imperilled mammal species through the use of predator exclosures and translocations (Kanowski *et al.* 2018; Moseby *et al.* 2018), thus giving assessors relative confidence that the most imperilled mammals can be at least secured and unlikely to become extinct over the predictive timeframe considered in this study. In contrast, although with some notable exceptions (e.g. Harley *et al.* 2018), there has been less success in recent management efforts for highly imperilled birds. This may be because the most successful approach for securing threatened mammals (i.e. predator exclusion) is less relevant for the threats affecting the most imperilled birds, or alternatively is far less tractable.

We predict that substantial numbers of Australian birds and mammals are likely to become extinct in the next two decades unless current management effort and approaches are greatly enhanced. Our three independent approaches all predict further extinctions of birds and mammals in the next 20 years, with the highest predicted number of extinctions derived solely from the application of Criterion E threshold probabilities of extinction for Vulnerable, Endangered, and Critically Endangered categories. The lowest estimates of predicted extinctions follow trajectories of conservation status changes reported in recent decades, and reflect the efforts made over that time to prevent extinctions. More taxa would almost certainly have gone extinct in the last few decades had there not been concerted efforts to prevent this (Garnett *et al.* 2011; Woinarski *et al.* 2014). Nevertheless, there have been some notable failures (Martin *et al.* 2012; Woinarski *et al.* 2017), and more can be expected in the next two decades without substantial increase in the effort and commitment by governments and society more broadly (Visconti *et al.* 2016) and unless urgent attention is directed to those taxa identified to be at greatest risk. While there is some overlap in the distributions of the most imperilled birds and mammals, most taxa will require individual attention. Without interventions, future Australian bird extinctions are likely to occur in island endemics, or in taxa that occupy the more developed parts of southern Australia. In contrast, we can expect future mammal extinctions to occur in the less developed parts of central and northern Australia.

The predicted numbers of extinct taxa derived from the expert elicitation fell between the estimates obtained using Criterion E and trajectories through time, further suggesting that the expert elicitation process was a reasonable approach. Experts expect the rate of extinction to increase over the next 20 years compared with 20-year periods in the recent past. This may be attributed to the fact that all experts were conservation biologists, and thus may have been subject to the known bias of overestimating extinction risk (Montibeller and Winterfeldt 2015), but this estimate is lower than that obtained using Criterion E thresholds and thus should not be ignored. The average of their estimates is that 10 birds and seven mammals will become extinct in the next 20 years without purposeful intervention. This estimate is about five times higher than the 1–2 taxa per decade that has been occurring historically for the Australian mammal fauna (Woinarski *et al.* 2015). However, an increase in extinction rate is not unreasonable given the increase in intensity of many threats, augmented by the novel threat of climate change.

We recognise that each of the approaches used in this study has inherent limitations. While previous studies have shown that risk-ranking protocols are useful for forecasting extinction (Keith *et al.* 2004), they are prone to some errors, and can sometimes fail to acknowledge the extent to which taxa are in danger or, conversely, overestimate extinction risk. Furthermore, the differences in the way that parameters are weighted and combined can lead to inconsistent assessments between protocols (Regan *et al.* 2005). Experts may be subject to biases that vary somewhat unpredictably depending on their interests in the outcome, but increasing the number of participants can increase confidence in predictions. We thus highlight the importance of integrating multiple approaches in an attempt to overcome some of the challenges associated with forecasting species extinction in the face of data and resource constraints, presenting a simple and transferable framework that may be applied to different taxonomic groups and regions globally.

Regardless of these methodological constraints, our forecasting of high (and increased) numbers of extinctions of Australian bird and mammal taxa over the next 20 years is consistent across three different approaches. If such a high rate of extinctions is to be averted, then a more resolute, strategic and better-resourced conservation response is required than that now prevailing.

Conflicts of interest

The authors declare no conflicts of interest.

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