Title: Continental-scale assessment reveals inadequate monitoring for threatened vertebrates in a megadiverse country

Authors: Ben C. Scheele[1,2*], Sarah Legge[1,2,3], Wade Blanchard[1], Stephen Garnett[4], Hayley Geyle[4], Graeme Gillespie[5,6], Perter Harrison[7], David Lindenmayer[1,2], Mark Lintermans[8], Natasha Robinson[1,2], and John Woinarski[4]

[1] Fenner School of Environment and Society, The Australian National University, Canberra, ACT 2601, Australia.

[2] Threatened Species Recovery Hub, National Environmental Science Program, Fenner School of Environment and Society, The Australian National University, Canberra, ACT 2601, Australia.

[3] Threatened Species Recovery Hub, Centre for Biodiversity Conservation Research, University of Queensland, St Lucia, Queensland 4072, Australia.

[4] Threatened Species Recovery Hub, Research Institute for the Environment and Livelihoods, Charles Darwin University, Darwin, Northern Territory 0909, Australia.

[5] Department of Environment and Natural Resources, Palmerston, Northern Territory 0831, Australia

[6] School of Biosciences, University of Melbourne, Melbourne, Victoria 3010, Australia.

[7] Marine Ecology Research Centre, Southern Cross University, Lismore, NSW 2480, Australia.

[8] Institute for Applied Ecology, University of Canberra, Canberra, ACT 2601, Australia.

* Corresponding author: Ben Scheele (ben.scheele@anu.edu.au)

Building 141, Fenner School of Environment and Society, Linnaeus Way, Acton, ACT 2601, Australia

Abstract

Monitoring threatened species is essential for quantifying population trends, understanding causes of species' declines, and guiding the development and assessment of effective recovery actions. Here, we provide a systematic, continental-scale evaluation of the extent and quality of monitoring for threatened species, focussing on terrestrial and freshwater vertebrates in Australia. We found marked inadequacies: one in four threatened taxa are not monitored at all; for taxa that are monitored, monitoring quality, as assessed across nine metrics, was generally low. Higher quality monitoring was associated with policy recognition, in the form of species recovery plans, and for species having a more imperilled conservation status. Across taxonomic classes, the proportion of species monitored was highest for mammals and then birds, whereas monitoring quality was greatest for birds. Improving monitoring quality requires setting clear objectives, direct integration with management, incorporating explicit management triggers, long-term resourcing, and better communication and accessibility of monitoring information. While our results revealed that overall monitoring efforts are inadequate, the positive relationship between improved monitoring outcomes and national policy support highlights that, when resources are available, good monitoring outcomes can be achieved. Quality monitoring programs for threatened species, and biodiversity more generally, should be recognized as vital measures of a nation's progress, analogous and complementary to more widely-used economic and human health indicators.

Key words: adaptive management; conservation; conservation policy; extinction, management; monitoring; threatened species

Introduction

Monitoring threatened species is crucial to halting biodiversity loss (Legge et al., 2018; Primack, 2006). Information on species population trajectories is essential for assessing extinction risk, determining species' responses to threatening processes, prioritizing remedial management, evaluating management effectiveness (Balmford et al., 2005; Legge et al., 2018; Marsh and Trenham, 2008), and improving understanding and management of threats (Garnett et al., 2018). In contrast, absence of robust information on species' trajectories can lead to poor allocation of conservation resources (Campbell et al., 2002; Marsh and Trenham, 2008; Robinson et al., 2018), sub-optimal conservation outcomes, and potentially leads to preventable extinctions (Lindenmayer et al., 2013; Woinarski et al., 2017). Aggregation of adequate monitoring data and synthesis of trends across species is also a pivotal requirement for assessment of policy performance (Loh et al., 2005; Tittensor et al., 2014).

Despite recognition that monitoring is crucial to conservation, it is rarely prioritized in threatened species management, and may be absent or of poor quality (Field et al., 2007; Legg and Nagy, 2006; Lindenmayer and Likens, 2018). For example, while endangered species recovery plans in the United States commonly provide for monitoring of target species' population trajectories, few consider threat, demographic or habitat trends (Campbell et al., 2002). Likewise, many monitoring programs have limited power to detect changes in abundance (Marsh and Trenham, 2008), or are not linked to management actions, resulting in situations where species are monitored to extinction (Lindenmayer et al., 2013).

Frameworks and principles to guide development of effective biodiversity monitoring programs have been proposed (e.g. Lindenmayer and Likens, 2009; Reynolds et al., 2016; Robinson et al., 2018). Key recommendations include ensuring monitoring: (1) aims to answer clearly defined questions; (2) has clearly stated objectives and links to policy and management; (3) is underpinned by rigorous statistical design; and (4) can evolve iteratively in response to new information, research questions and technology (Lindenmayer and Likens, 2009; Reynolds et al., 2016; Robinson et al., 2018). Here we provide the first continental-scale systematic evaluation of the extent to which current monitoring complies with these recommendations for all threatened terrestrial and freshwater vertebrates in Australia.

We focused on Australia for two reasons. First, Australia is a megadiverse continent-country, with a broad range of species and ecosystems. Second, Australia has a poor track-record of halting species decline and extinction (Woinarski et al., 2015; Woinarski et al., 2017). Given the key role of monitoring in threatened species management (Legge et al., 2018), an assessment of current monitoring against the attributes that characterise high quality monitoring is an important step towards reversing declines. Our analysis identifies key deficiencies in current monitoring efforts for threatened species and their consequences, differences in monitoring extent and quality across taxonomic groups, and factors that are associated with higher quality monitoring. Building on these insights, we provide recommendations for improving monitoring for threatened species.

Material and methods

Framework to assess monitoring extent and quality

We used an assessment framework to consistently score the extent and quality of monitoring programs for each threatened species (Woinarski 2018; Table 1). The framework comprised nine metrics, each scored on a 0 (no monitoring) to 5 (optimal monitoring) scale (see Tables S2-S10 for scoring criteria). Monitoring was defined as targeted, repeated survey efforts. Where multiple monitoring programs were identified for a taxon, the evaluation metrics were scored from a national perspective on the aggregated/combined monitoring effort, so each taxon received a single monitoring score for each metric. Our assessment of monitoring was undertaken from July 2016 to July 2017.

Collating information

We assessed monitoring for all Australian threatened vertebrates, excluding marine fish and marine mammals, listed as Critically Endangered, Endangered, or Vulnerable under the Australian Government's *Environment Protection and Biodiversity Conservation Act* 1999 (EPBCA). We also assessed monitoring for some taxa that are not currently EPBCA-listed, but are assessed as threatened under State/Territory legislation, or by the International Union for Nature Conservation (IUCN), or other non-statutory listings. We refer to the conservation status of these taxa as 'Other'. For example, for fish, 19 taxa were categorised as 'Other'; these taxa have been assessed by the Australian Society for Fish Biology as nationally threatened, using IUCN listing criteria. For information on the number of taxa from each taxonomic group in each EPBCA listing category, and the number of Other taxa assessed, see Table S1.

Species in each taxonomic class were assessed by one or more of the authors with expertise for that class, using published information, personal communications with individuals involved in management, and information from relevant government agencies and non-government conservation organizations. Our assessments of monitoring for each taxonomic group was largely based on information collated during recent reviews of the conservation status of Australian birds (Garnett et al., 2011), mammals (Woinarski et al., 2014a), reptiles (Chapple et al., in press), frogs (unpubl.) and fish (unpubl.). These reviews included inputs from all relevant researchers, state agencies and conservation NGOs about population status and trends, and for older reviews, was updated for this paper. Information was based on monitoring programs, with the characteristics of these programs described by their practitioners. Where contributors to these accounts indicated that no trend information was available, we contacted all relevant experts to confirm the absence of monitoring programs, or for details of any monitoring programs that were present, but could not provide such trend information. Notwithstanding our efforts, some monitoring activity for some taxa may have been overlooked, as information on monitoring is often not published and is sometimes obscure, potentially resulting in underestimation of monitoring effort. However, we believe it is unlikely that any such missing information would substantially alter our analyses and conclusions. To ensure consistency in scoring across taxonomic groups, the assessors thoroughly discussed the assessment framework before commencing assessment to ensure consistent interpretation and implementation.

We also collated information for each taxon's EPBCA recovery plan status. In Australia, threatened species recovery plans (typically lasting five years) are developed to facilitate and coordinate the recovery and conservation of threatened taxa. They have legislative powers but are not automatically mandatory for listed threatened taxa (see Walsh et al., 2013 for an overview of recovery planning in Australia). Taxa were categorized into three groups: (1) 'current recovery plan', (2) 'lapsed recovery plan' or (3) 'never had a recovery plan'.

Statistical analysis

First, we quantified the proportion of taxa that receive some form of monitoring. We then investigated whether presence or absence of monitoring was associated with taxonomic class (amphibian, bird, fish, mammal and reptile), conservation status (EPBCA listing: Critically

Endangered, Endangered or Vulnerable, or 'Other'), or EPBCA recovery plan status ('current', 'lapsed', or 'none'). Our outcome variable was binary (presence (scores 1-5) or absence of monitoring (score 0)). We employed Bayesian logistic regression with the main effects of taxonomic class, conservation status, and recovery plan status as potential predictor variables. We constructed a set of eight potential models, which were then compared using the Leave-One-Out-Cross-Validation Information Criteria (LOOIC) (Vehtari et al., 2017). The most parsimonious model within two LOOIC of the best fitting model was selected as the best model. We report 95% credible intervals for model estimates and differences between the various levels of the categorical predictor variables.

In the second phase of our analysis, we focused only on taxa that received some form of monitoring identified in the first stage of our analysis. We investigated which of the above mentioned predictor variables (class, conservation status, and recovery plan status) influenced monitoring scores assessed for each of the nine metrics, and the total score summed across the nine metrics. We modelled scores using Bayesian linear models assuming a Gaussian distribution, and considered the same set of eight potential models, which were compared using LOOIC.

All analyses were conducted using Bayesian regression models in Stan (brms) package (Bürkner, 2016) in R (R Development Core Team, 2017). We used default priors (improper flat prior over the real line) for the regression parameters and a half Student-t with 3 degrees of freedom for the residual standard deviation in the linear model and Cauchy distribution with location zero and scale five for the logistic regression model parameters to avoid potential issues with complete separation. For each model, we ran four Markov Chains for 2000 iterations after discarding the burn-in of 1000 iterations. All chains showed good mixing, as measured by the Gelman and Rubin convergence diagnostic (Gelman and Rubin, 1992).

Results

We assessed monitoring for 408 threatened Australian vertebrates (excluding marine mammals and marine fish), representing ~ 5.5% of the total number of described species in these classes (~7358: Walsh et al., 2013). We found that 303 (74%) threatened taxa received some monitoring, with the remainder not monitored at all. The proportion of species monitored was highest among mammals (89%), then birds (76%), amphibians (75%), reptiles (62%) and fish (53%). For monitored taxa, the average summed score across the nine metrics was 29 out of 45, with the highest average score for birds (32), followed by amphibians (31), fish (27), reptiles (25), and mammals (25). The mean scores for each assessment metric are summarized in Fig. 1.

Extent and quality of threatened species monitoring

The best ranked model for presence/absence of monitoring contained all three predictor variables: taxonomic class, conservation status, and recovery plan status (Table S11, Fig. S1). The predicted probability of monitoring was highest for mammals, followed by birds, reptiles, amphibians and fish (Fig. 2a). A higher proportion of taxa with current or lapsed recovery plans were monitored than for taxa that had never had a recovery plan (Fig. 2b). Likewise, Critically Endangered and Endangered taxa were more likely to be monitored than Vulnerable or Other taxa (Fig. 2c).

For taxa that were monitored, the best ranked model for total monitoring score also contained the three predictor variables: taxonomic class, conservation status, and recovery plan status (Table S11, Fig. S2). Predicted mean monitoring score was highest for birds, followed by amphibians, fish, mammals and reptiles (Fig. 3a). Species with lapsed recovery plans had the highest predicted scores, followed by species with current recovery plans, while scores were lowest for species with no recovery plan (Fig. 3b). Critically Endangered species had the highest predicted scores, followed by Other, with Vulnerable taxa having the lowest predicted scores (Fig. 3c; Fig. S3-S11 for the model predictions for each of the nine metrics).

Discussion

We conducted the first continental-scale evaluation of monitoring for a diverse array of threatened taxa, to identify the strengths and weaknesses of current monitoring efforts, and thus guide key improvements that could be made to prevent species loss. Our assessment revealed inadequacies in both the extent and quality of threatened species monitoring in Australia. One in four threatened taxa receives no monitoring. Where monitoring does occur, its quality (as assessed across nine metrics) is generally poor, with a low overall average score (29, out of a maximum of 45).

Key deficiencies and consequences

That one quarter of threatened Australian taxa are not monitored is symptomatic of a broader ad-hoc approach to threatened species conservation in Australia (Scheele et al., 2018), and is consistent with inadequate environmental monitoring in Australia (Cresswell and Murphy, 2016). Notably, although not specifically targeting threatened species, the Australian Long Term Ecological Research Network was decommissioned in 2018 (Lindenmayer, 2017), further eroding Australia's capacity to accurately access species trajectories. Without monitoring, we are unable to assess extinction risk robustly, identify causes of decline, evaluate management effectiveness, identify species/population trends or trajectories, identify research priorities, or fully engage stakeholders and the community (Legg and Nagy, 2006; Lintermans, 2013b; Marsh and Trenham, 2008). Given our results, it is unsurprising that efforts to halt species declines in Australia have met with idiosyncratic and limited success.

Where taxa were being monitored, average scores were relatively low across the nine assessment metrics. Although scores for each metric were highly variable, four stood out as having particularly low values: (1) Design quality, meaning that monitoring had limited statistical power to detect changes in species abundance or site occupancy; (2) Demographic parameters, meaning that causes of decline, and critical life stages, would be hard to discern; (3) Data availability, meaning that any information collected was typically not publicly available, and (4) Management linkage, meaning the monitoring was not integrated with, nor informing management (Fig. 1). These metrics are those most likely to be severely limited by resource availability, and/or lack of expertise. Poor quality monitoring fails to deliver detailed knowledge of threat impacts and how they vary across environmental space and over time; information that is essential in successful recovery programs (Scheele et al., 2017).

We found that there was little publicly available information about, or data from, monitoring programs funded using public monies. Notwithstanding commitments in Australia's national biodiversity strategy (Commonwealth of Australia, 2016), there is no integrated monitoring program for biodiversity or threatened species in Australia, and no central location for storing monitoring information, or making such information publicly accessible (Legge et al., 2018). Consequently, the public has limited awareness of the trajectories of Australian threatened species (typically negative), and hence relatively little reason for engagement and concern. In stark contrast, monitoring information on the performance of other public programs such as education or health are increasingly made available to the public, and the absence of monitoring is viewed as evidence of poor program governance (Lindenmayer et al., 2012).

Our assessment also highlights that current EPBCA lists of threatened terrestrial vertebrates and freshwater fish under-represent the number of taxa requiring recovery/conservation action (e.g. of the 56 fish considered in this review, only 38 are EPBCA listed). No or minimal monitoring for many, potentially most, non-listed taxa represents a hidden threat to biodiversity conservation in Australia. For some taxa with immediate and severe threats (e.g. >10 unlisted small-bodied galaxiid and rainbowfishes threatened by alien invasive species), extinction is possible before taxa are listed (Moy et al., 2018; Raadik, 2014). In many other cases, insufficient data inhibits assessment of conservation status (Walsh et al., 2013; Woinarski et al., 2014b). To overcome these limitations and provide early warnings of emerging declines, we also must monitor non-listed taxa (Lindenmayer et al., 2012). In particular, monitoring is needed for data-deficient species that are likely to be impacted by current or emerging threats. Citizen science, new technologies, and improved statistical analyses may help meet the challenge of increasing monitoring coverage for both threatened and non-threatened species (Lahoz-Monfort and Tingley, 2018).

Factors associated with better monitoring

Despite the poor overall monitoring scores in our assessment, we found that some species (e.g. Tasmanian devil, Leadbeater’s possum, western swamp tortoise, orange-bellied parrot, red-finned blue-eye, orange-bellied frog) had exemplary monitoring for almost all metrics in our framework, demonstrating that good monitoring programs are achievable. National policy and legislative support was associated with better monitoring: taxa with EPBCA recovery plans (either current or lapsed) were more likely to be monitored, and that monitoring was likely to be of higher quality. Taxa with lapsed plans still scored highly for monitoring quality, suggesting an enduring legacy of recovery planning; or that earlier plans, which were better supported by Australian government funding (Walsh et al., 2013), incorporated more rigorous monitoring. Monitoring quality was also higher for species with more imperilled conservation status, indicating that management and monitoring effort has been focused on species at highest risk of extinction. The snapshot nature of our assessment means that it is not possible to tease apart cause and effect between policy support and monitoring. For example, more imperilled species may elicit better monitoring; or more imperilled species may be easier to monitor (e.g. range-restricted, fewer to count); or good monitoring programs that provide robust information on extinction risk may support prompt and accurate listings.

Variation across taxonomic classes and countries

Mammals and birds are more likely to be monitored, and monitored well, than other taxonomic groups, especially fish; a similar pattern of monitoring bias exists in Europe (Schmeller et al., 2009). There are several possible explanations for taxonomic biases. First, conservation resources and research are unevenly distributed across classes, with biases towards mammals and birds (Lawler et al., 2006; Walsh et al., 2013). In particular, reptiles and fish are underrepresented in EPBCA threatened species listings, meaning their monitoring may be under-resourced (Walsh et al., 2013). Second, some taxonomic classes are easier to monitor than others. For example, many threatened amphibians (which scored higher, on average, than mammals, fish and reptiles) have restricted distributions and form conspicuous breeding aggregations, making them easier to monitor. Third, the currency and comprehensiveness of EPBCA lists varies among classes; for example, one third of fish taxa assessed as threatened by the Australian Society for Fish Biology are not listed under national legislation, which might contribute to lack of monitoring in this class (Lintermans, 2013a). Fourth, taxonomic groups have varying levels of buy-in from the public; birds are especially amenable to monitoring by community groups and have well-established public involvement in and programs for monitoring (e.g. Birdlife Australia's Birdata program). Our assessment focused on vertebrates, which are given disproportionately high attention in conservation management (Walsh et al. 2013): the status of monitoring for threatened invertebrates is likely to be even more parlous.

Comparing monitoring efforts among countries is challenging because publicly available, synthesised information on monitoring is limited (Schmeller et al., 2009). Notwithstanding, monitoring efforts for threatened species in Australia fall short of those undertaken in some countries. For example, in the United Kingdom, *State of Nature* reporting provides publicly available information on the trajectory of thousands of species (Hayhow et al., 2016). Similarly, monitoring actions are mandatory in recovery plans for threatened species in the United States (Campbell et al., 2002). More broadly, a general pattern of inadequate biodiversity monitoring has been reported across the majority of regions worldwide (Balmford et al., 2005).

Improving threatened species monitoring

Broad deficiencies in threatened species monitoring in Australia highlight a critically important and urgent need for a more robust and integrated approach. Improving both the extent and quality of threatened species monitoring is a necessary first step in efforts to redress

Australia's poor conservation record. Globally, under-funding remains an inescapable conservation challenge (Waldron et al., 2017). This challenge is particularly acute in Australia, where environmental spending is disproportionately low, with Australia one of only four developed countries featuring in the top 40 underfunded countries for conservation spending (Waldron et al., 2013). Further, biodiversity conservation has experienced sharp reductions in funding over the past decade, receiving less than five cents for every $100 of Australian government spending in 2018 (ACF, 2018). To achieve effective conservation outcomes, Australia must increase spending on biodiversity conservation (Scheele et al., 2018). As long as recovery plans are the critical mechanism for guiding species recovery, then all recovery plans should include quality-assured and funded monitoring, as legislated in the United States under the USA Endangered Species Act (Campbell et al., 2002). The value of investing in monitoring is clearly demonstrated by the positive association between good-quality monitoring and the level of understanding and management of threats for threatened species (Garnett et al., 2018).

At the scale of individual monitoring programs, there is much that can be done to increase monitoring extent and quality, despite limited resources. (1) Monitoring needs to be closely linked with management, with clear objectives, and explicit triggers for responsive management actions. (2) Specified monitoring objectives should guide the methodological design of fit-for-purpose monitoring programs (Robinson et al., 2018). (3) Monitoring must be recognised as a long-term activity with secure resourcing, rather than an occasional ad-hoc activity undertaken when surplus resources become available, or after it has become apparent that management actions have failed. This could be achieved by prioritizing and mandating an adequate monitoring program within any recovery plan or equivalent management document. (4) Monitoring should be a mechanism for communication and engagement with all stakeholders, with responsible agencies recognising an obligation to provide, interpret and disseminate monitoring results to all stakeholders, including the broader public. (5) Adequate attention must be given to data management and metadata collection. (6) A national program to facilitate the storage, analysis, interpretation of, and public accessibility to, monitoring data, is urgently needed (Legge et al., 2018). (7) Information from monitoring programs for threatened species, and biodiversity more generally, should be recognized as a vital measure of a nation's progress, analogous and complementary to the more widely-used economic and health indicators.

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Supplementary material

Table S1. Information on the number of species included in the assessment.

Tables S2-S10. Scoring criteria for each of the nine metrics used to assess monitoring quality.

Table S11. Leave-One-Out-Cross-Validation Information Criteria for each of the eight models considered for each of the 11 response variables.

Figures S1-S11. Model predictions for: presence/absence of monitoring, total score, and each of the nine metrics.

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Table

Table 1. Description and rationale for each of the nine metrics used to evaluate the quality of threatened taxa monitoring adopted from Woinarski (2018). For each metric, taxa were scored 0-5 (see scoring criteria, Tables S2-S10).

Metric	Description	Rationale
1. Fit-for-purpose	The use of methodologies designed to optimize detection of the target species.	To provide robust information, species-specific methods that consider the ecology and detectability of the target species are needed.
2. Coverage	The spatial extent of monitoring efforts across the target species' distribution.	A species' abundance and threat milieu can vary markedly across its distribution. As such, monitoring across a species distribution is needed to provide representative information on the species' trajectory.
3. Periodicity	Frequency of monitoring.	Timely information on a species' trajectory is needed. Monitoring should be undertaken frequently enough to be able to detect rapid changes and inform management.
4. Longevity	Longevity of monitoring.	Monitoring needs to be undertaken over sufficient timeframes to differentiate short-term variability from longer-term trends. Monitoring also needs to be able to identify small, incremental changes that may not be apparent where monitoring duration is limited.
5. Design quality	The statistical power of monitoring to detect trends in the occupancy/ abundance of the target species.	Sufficient replication and detection frequency is needed to identify robust trends in the occupancy/ abundance of the target species.
6. Coordination	The coordination of monitoring efforts among relevant jurisdictions and stakeholders.	When monitoring is performed by multiple organizations, its design, analysis and reporting needs to be effectively integrated to ensure comparable data are obtained.
7. Data availability and reporting	The availability and reporting of monitoring information.	For the value of monitoring data to be maximized, it must be readily accessible and well-curated, with adequate metadata and secure long-term storage.
8. Management linkage	Integration of monitoring and management actions.	Monitoring should inform the design and implementation of management, as well as be able to evaluate effectiveness.
9. Demographic parameters	The inclusion of demographic parameters in monitoring efforts.	In most cases, monitoring should involve assessment of critical demographic parameters, rather than just abundance. Information on life-history parameters can provide important ecological insights and help refine management.

Figures

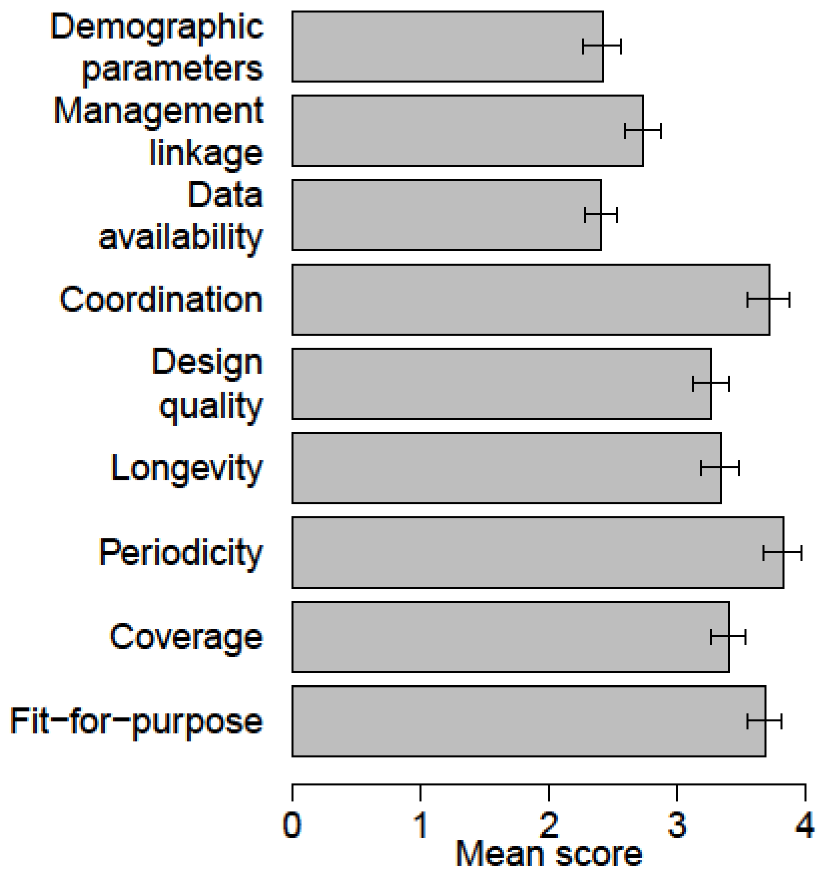

Figure 1. Mean scores for each of the nine assessment metrics for monitored taxa. Error bars show the 95% credible intervals.

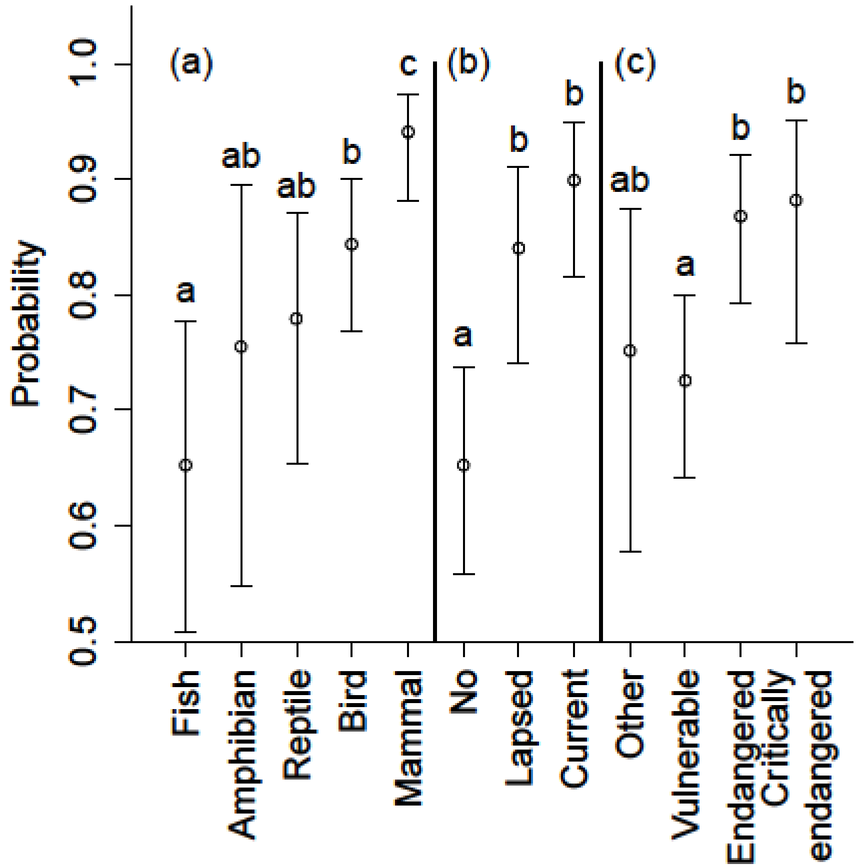

Figure 2. Probability of presence/absence of monitoring for Australian threatened taxa by (a) taxonomic class, (b) recovery plan status, and (c) conservation status. In each case, the probability of monitoring was predicted at average values for the other two predictors in the model. Different letters (within a panel) indicate significant differences between predicted values where the 95% credible interval for the log odds ratio does not cross zero.

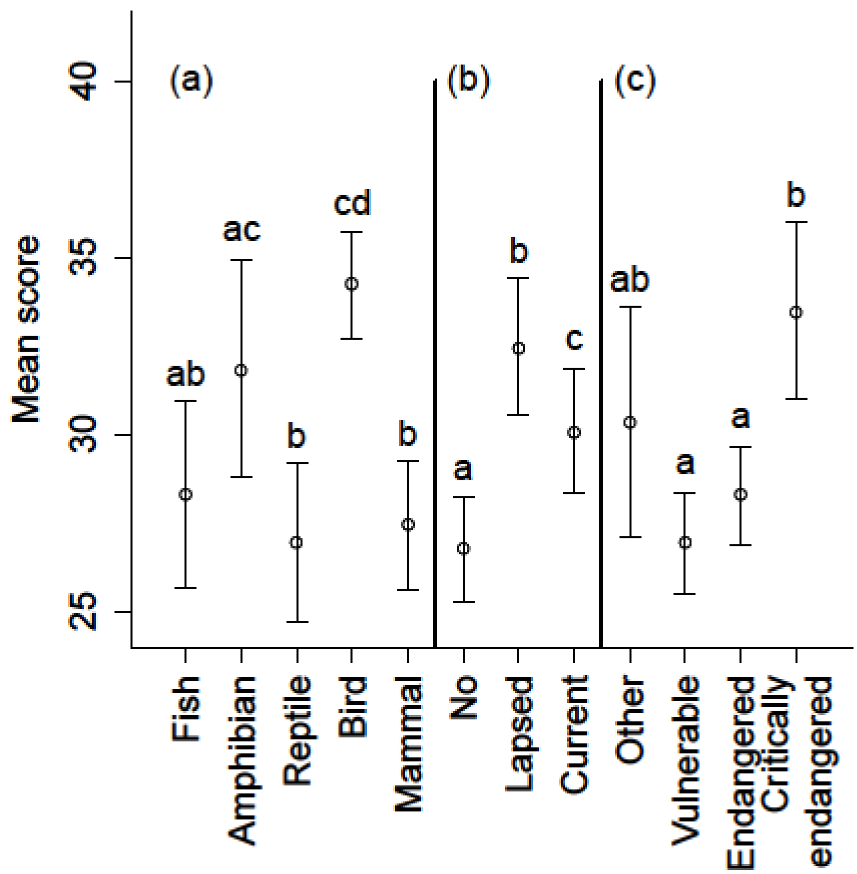

Figure 3. Predicted mean total score for monitoring quality for Australian threatened taxa by (a) taxonomic class, (b) recovery plan status, and (c) conservation status. In each case, predictions were made at average values for the other two predictors in the model. Different letters (within a panel) indicate significant differences between predicted values where the 95% credible interval for the difference does not cross zero.

Supplementary material

Article: Continental-scale assessment reveals inadequate monitoring for threatened vertebrates in a megadiverse country

Table S1, Information on the number of taxa in: (1) each taxonomic class; (2) each *Environmental Protection and Biodiversity Conservation Act 1999* (EPBCA) conservation status category; and (3) non-EPBCA listed taxa, that are considered threatened in non-statutory lists such as the International Union for the Conservation of Nature Red List of threatened species ('Other').

Taxonomic class	Critically Endangered	Endangered	Vulnerable	Total	Other	Total
Fish (freshwater)	5	15	17	37	19	56
Amphibian	5	14	10	29	0	29
Reptile	10	18	33	61	9	70
Bird	15	54	73	142	12	154
Mammal	5	33	57	95	4	99
Total	40	134	190	364	44	408

Notes on sub-species, undescribed taxa and non-EPBCA listed species

Freshwater fishes: Includes 19 taxa (including recognised but currently undescribed taxa) listed on the Australian Society for Fish Biology national list of threatened fish species, assessed in accordance with the International Union for the Conservation of Nature (IUCN) Red List criteria for threatened species listing http://www.asfb.org.au/assets/ASFB/Threatened-Species-Committee/ASFB-2016-Threatened-Fishes-Committee-report.pdf. Includes one sub-species currently listed by EPBCA. EPBCA listed marine species excluded.

Amphibians: Only *Environmental Protection and Biodiversity Conservation Act 1999* (EPBCA) listed species included. The conservation status of all Australian amphibians is currently being revised (as of June 2018).

Reptiles: Includes four species listed as threatened by the IUCN, but not included under the EPBCA. EPBCA listed marine species excluded.

Birds: Includes 12 species listed as threatened by the IUCN, but not included under the EPBCA. EPBCA total includes 11 sub-species that were assessed separately in our monitoring evaluation, but that are not independently listed under the EPBCA.

Mammals: Includes four species listed as threatened by the IUCN, but not included under the EPBCA. EPBCA listed marine species excluded.

Tables S2-S10. Scoring criteria for each of the nine metrics used to assess monitoring quality. Adopted from Woinarski (2018) A framework for evaluating the adequacy of monitoring programs for threatened species, In S. Legge, D.B. Lindenmayer, N.M. Robinson, B.C. Scheele, D.M. Southwell, B.A. Wintle editors. Monitoring Threatened Species and Ecological Communities. CSIRO Publishing, Melbourne.

Table S2. Metric 1: Fit-for-purpose

Score	**Score basis**
5	sampling protocol effectively applies all relevant methods that have been demonstrated to optimise detectability and population estimation at sampled sites
4	sampling protocol is based on one or more methods that can reliably detect species
3	sampling protocol is likely to detect species if present, but will provide limited information on abundance
2	not known if sampling protocol will reliably detect species if present
1	sampling protocol is an unreliable approach to demonstrating occurrence or abundance
0	no monitoring

Table S3. Metric 2: Coverage

Score	**Score basis**
5	monitoring undertaken comprehensively across range
4	monitoring undertaken representatively at many sites across range
3	monitoring undertaken at several sites across range, but significant components not monitored
2	monitoring at a few sites, not necessarily representative
1	monitoring at one site only (except where this is the only site of occurrence)
0	no monitoring

Table S4. Metric 3: Periodicity

Score	**Score basis**
5	monitoring at least annually at major site(s)
4	monitoring at 2–3 year intervals
3	monitoring at 4–9 year intervals
2	monitoring at >10 year intervals
1	no repeat sampling
0	no monitoring

Table S5. Metric 4: Longevity

Score	**Score basis**
5	monitoring extending back for >30 years, and there is an assurance of ongoing commitment
4	monitoring extending back for >20 years, and there is some indication of ongoing commitment
3	monitoring extending back for >10 years
2	monitoring extending back for >5 years
1	monitoring established only in last 1–5 years, no consideration of future sampling
0	no monitoring

Table S6. Metric 5: Design quality

Score	**Score basis**
5	high statistical power to detect small (e.g. 5%) change in population size over a timeframe relevant to conservation context
4	sufficient statistical power to reliably detect moderate (e.g. 30% change) in population size
3	reasonable design but low statistical power (e.g. unlikely to reliably detect 50% change in population size)
2	rudimentary design but resulting in sufficient records to suggest broad changes in abundance
1	typically *ad hoc* with few records
0	no monitoring

Table S7. Metric 6: Coordination

Score	**Score basis**
5	monitoring activities tightly integrated across sites with unambiguous overall responsibility and consistent sampling methodologies
4	broad consistency in sampling protocols across sites; some linking of results across sites
3	some links established between monitoring projects at different sites
2	range of monitoring projects compiled, but no linking of results, and inconsistent sampling protocols across sites
1	no apparent coordination in monitoring activities, design or reporting
0	no monitoring

Table S8. Metric 7: Data availability

Score	Score basis
5	all relevant data are collated, readily available and up to date on well-established and publicly accessible sites, with robust analysis and interpretation
4	all relevant data readily available and up to date on publicly accessible sites
3	reasonably easy to find some information on monitoring results, either through websites or published reports or scientific papers
2	some information may be available, but difficult to access readily
1	monitoring information largely unobtainable by others
0	no monitoring

Table S9. Metric 8: Management linkage

Score	Score basis
5	monitoring closely linked to adaptive management, providing an explicit measurement of threat impacts and/or management performance; monitoring includes inbuilt triggers or review that prompt management responses
4	monitoring design explicitly assesses different threat impacts and management responses, and has some links to management agency; triggers (if existing) are weakly defined and do not necessarily provoke management response
3	monitoring programs provide some consideration of effects of different management regimes; no defined triggers
2	monitoring program may provide weak inference about management, but no clear links to adaptive management; no triggers
1	monitoring program not capable of assessing management effectiveness
0	no monitoring

Table S10. Metric 9: Demographic parameters

Score	Score basis
5	monitoring program includes detailed assessment of relevant life history parameters (such as reproductive success, mortality rates and their causes), which can identify weak points in biology and interventions for management action, and monitoring data allow predictive population modelling
4	monitoring includes reliable information on at least one relevant life history parameter
3	monitoring includes some consideration of at least one relevant life history parameter
2	monitoring parameters are restricted to incidence or abundance, but in a manner that may allow reasonable inference about some life history parameters
1	monitoring parameters are restricted to incidence or abundance
0	no monitoring

Table S11. Leave-One-Out-Cross-Validation Information Criteria for each of the eight models considered for each of the 11 response variables (monitoring presence/absence, total score and individual score for each of the nine metrics). Best ranked model highlighted with bold text.

	Null	**Class(C)**	**Recovery Plan (RP)**	**EPBCA Status**	**RP + EPBCA**	**C + EPBCA**	**C + RP**	**CP + RP + EPBCA**
Monitoring (pre/abs)	467.4	444.1	436.1	449.6	431.4	431	420.3	**416**
Total across nine metrics	2145.3	2095.4	2127.6	2135.6	2112.9	2085.2	2076.8	**2061.4**
1. Fit for purpose	916.2	897.2	892.2	915.6	885.5	897.4	874.3	**868.5**
2. Coverage	955.5	926.3	948.5	935.5	919.8	911.7	921.2	**899.9**
3. Periodicity	1022.2	953.5	1014.9	1021.2	1013	950.7	945.6	**943.3**
4. Longevity	1016.3	997	997.5	1020.1	1003.3	1002.8	**974.9**	980.2
5. Design quality	988.6	913.6	977.6	981.1	970.7	904.5	901	**892.5**
6. Coordination	1093	939.9	1092.8	1078.2	1076.8	**918.8**	939.3	918.7
7. Data availability	897.8	898.1	891.1	891.8	883.4	890.1	891.1	**880.9**
8. Management linkage	999.8	1002.6	999	994.8	**988**	1000.2	1000.7	993.3
9. Demographic parameters	1006.5	993.3	995.9	1001.9	989.8	991.7	984.1	**980.5**

Figures S1-S11. Model predictions

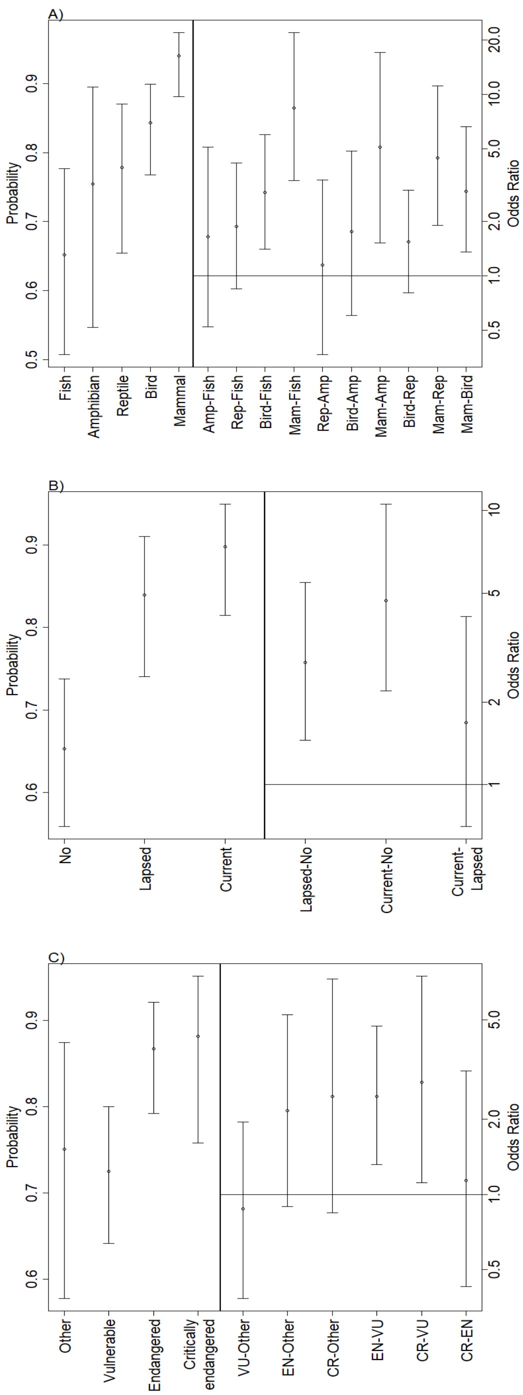

Figure S1. Probability of presence/absence of monitoring for Australian threatened taxa by (A) taxonomic class, (B) recovery plan status, and (C) conservation status. In each case, the probability of monitoring was predicted at average values for the other two predictors in the model. The right side of each panel depicts the odds ratio and 95% credible interval comparing each level of the factor.

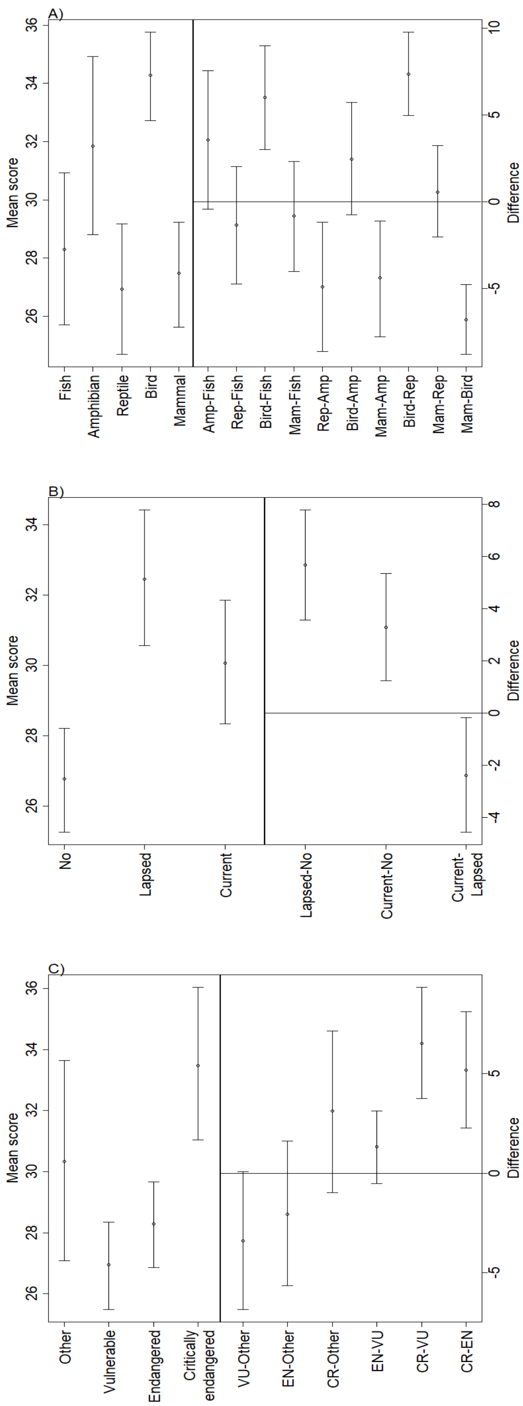

Figure S2. Predicted mean total score for monitoring quality for Australian threatened taxa by (A) taxonomic class, (B) recovery plan status, and (C) conservation status. In each case, predictions were made at average values for the other two predictors in the model. The right side of each panel depicts the mean difference and 95% credible interval comparing each level of the factor.

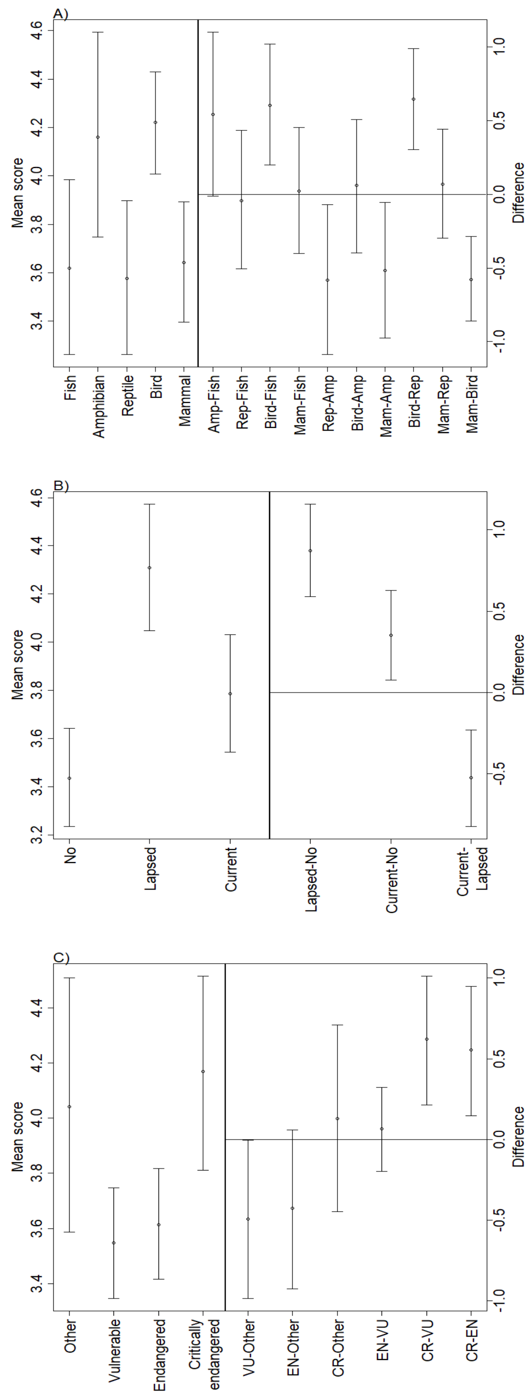

Figure S3. Predicted score for fit-for-purpose for monitoring programs for Australian threatened taxa by (A) taxonomic class, (B) recovery plan status, and (C) conservation status. In each case, predictions were made at average values for the other two predictors in the model. The right side of each panel depicts the mean difference and 95% credible interval comparing each level of the factor.

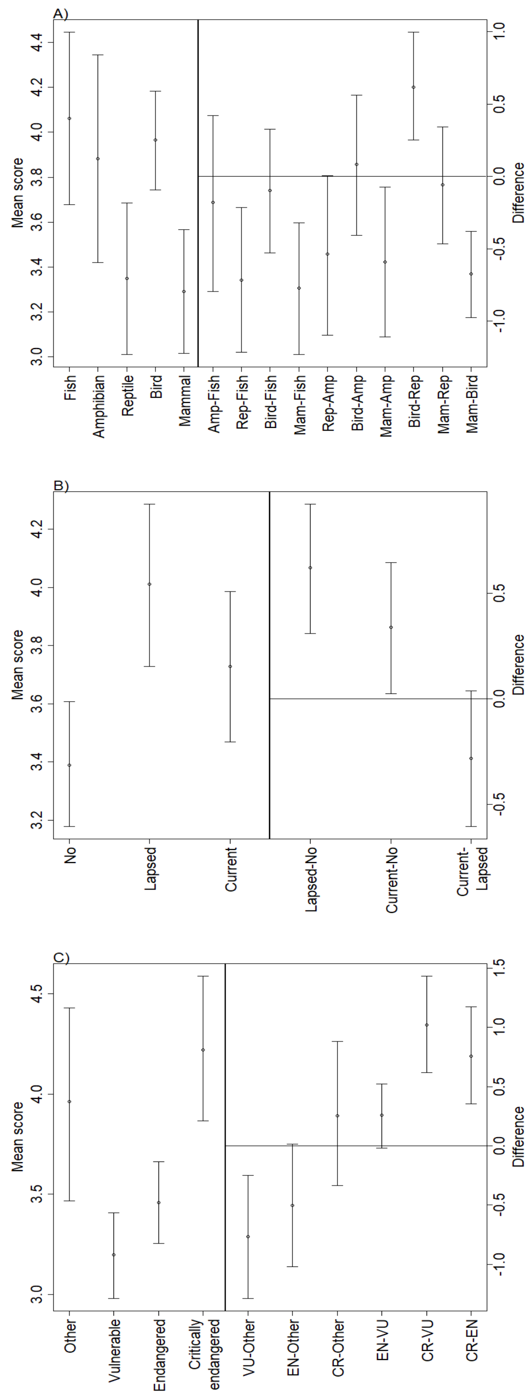

Figure S4. Predicted score of monitoring coverage for Australian threatened taxa by (A) taxonomic class, (B) recovery plan status, and (C) conservation status. In each case, predictions were made at average values for the other two predictors in the model. The right side of each panel depicts the mean difference and 95% credible interval comparing each level of the factor.

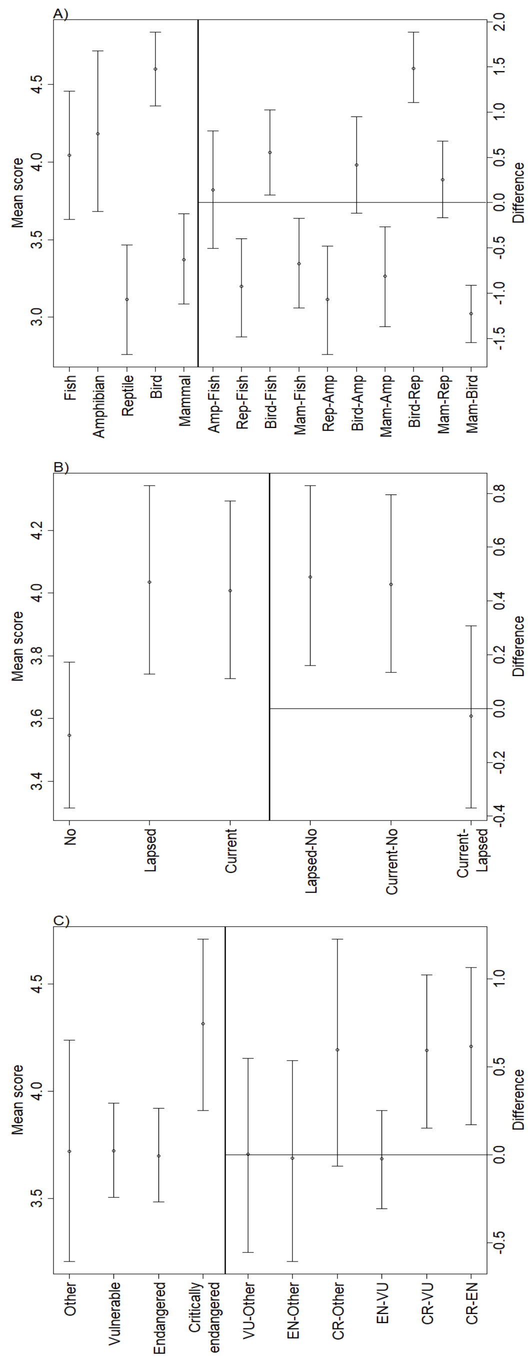

Figure S5. Predicted score for periodicity of monitoring for Australian threatened taxa by (A) taxonomic class, and (B) recovery plan status, and (C) conservation status. In each case, predictions were made at average values for the other two predictors in the model. The right side of each panel depicts the mean difference and 95% credible interval comparing each level of the factor.

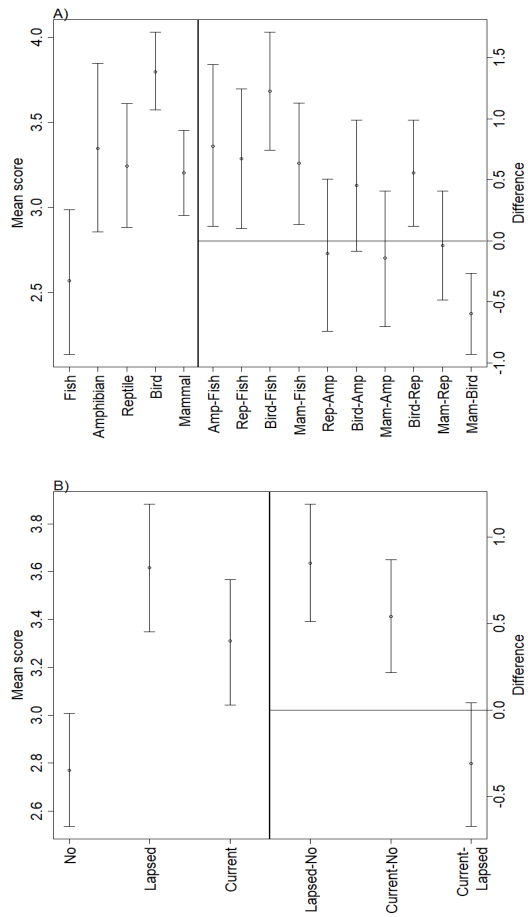

Figure S6. Predicted score for longevity of monitoring for Australian threatened taxa by (A) taxonomic class, and (B) recovery plan status. In each case, predictions were made at average values for the other predictor in the model. The right side of each panel depicts the mean difference and 95% credible interval comparing each level of the factor.

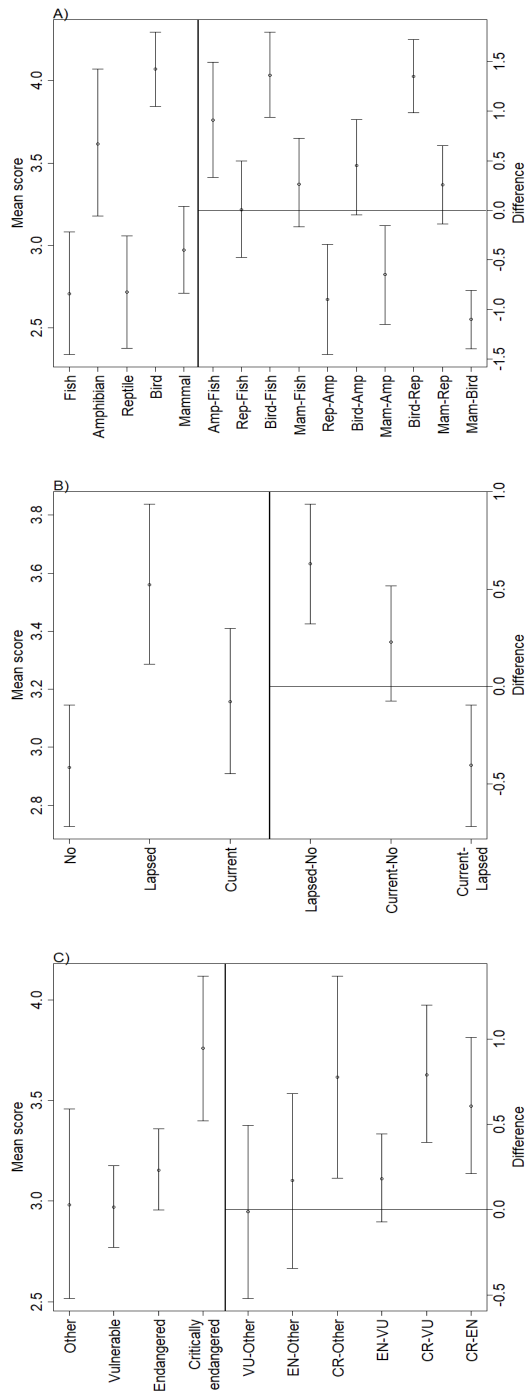

Figure S7. Predicted score for monitoring design quality for Australian threatened taxa by (A) taxonomic class, (B) recovery plan status, and (C) conservation status. In each case, predictions were made at average values for the other two predictors in the model. The right side of each panel depicts the mean difference and 95% credible interval comparing each level of the factor.

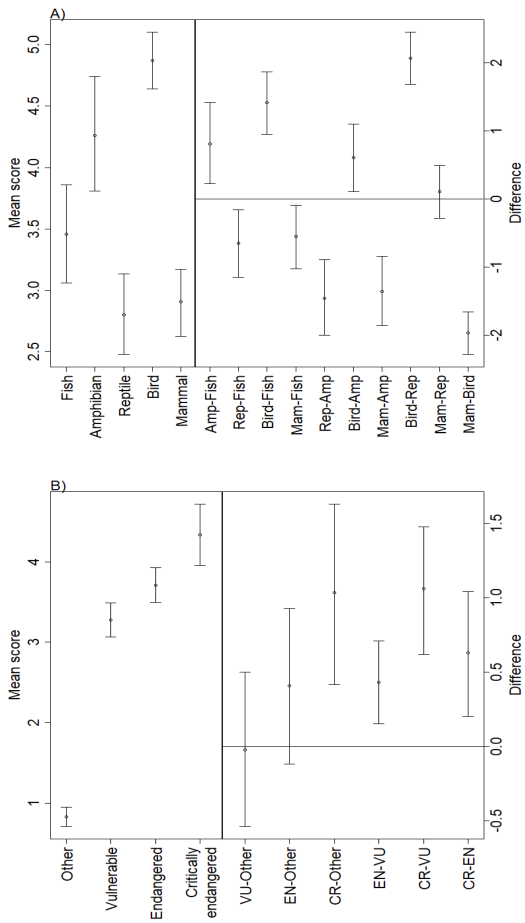

Figure S8. Predicted score for monitoring coordination for Australian threatened taxa by (A) taxonomic class, and (B) conservation status. In each case, predictions were made at average values for the other predictor in the model. The right side of each panel depicts the mean difference and 95% credible interval comparing each level of the factor.

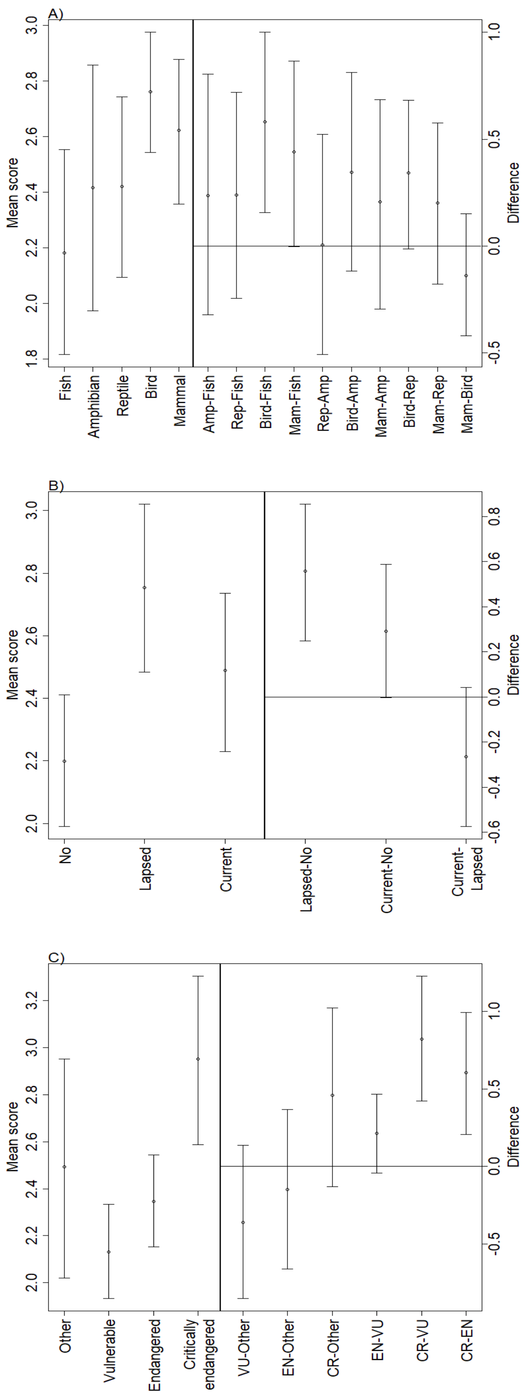

Figure S9. Predicted score for monitoring data availability for Australian threatened taxa by (A) taxonomic class, (B) recovery plan status, and (C) conservation status. In each case, predictions were made at average values for the other two predictors in the model. The right side of each panel depicts the mean difference and 95% credible interval comparing each level of the factor.

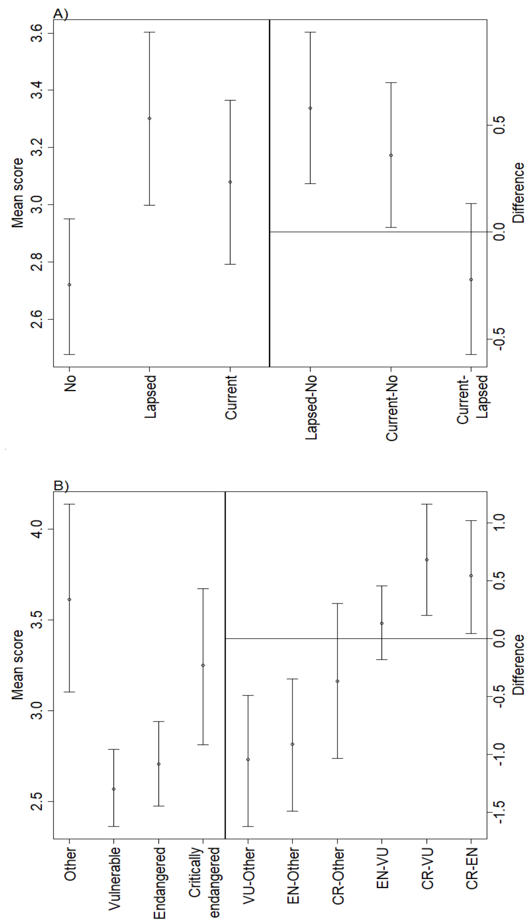

Figure S10. Predicted score for management linkages for Australian threatened taxa by (A) taxonomic class, and (B) conservation status. In each case, predictions were made at average values for the other predictor in the model. The right side of each panel depicts the mean difference and 95% credible interval comparing each level of the factor.

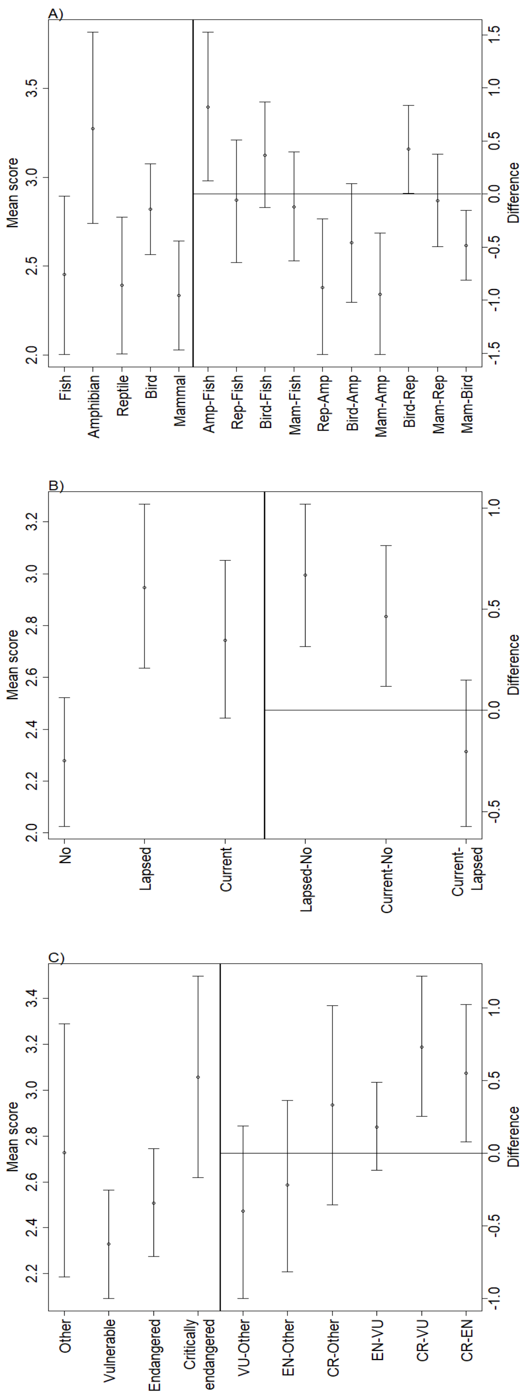

Figure S11. Predicted score for consideration of demographic parameters in monitoring for Australian threatened taxa by (A) taxonomic class, (B) recovery plan status, and (C) conservation status. In each case, predictions were made at average values for the other two predictors in the model. The right side of each panel depicts the mean difference and 95% credible interval comparing each level of the factor.