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S. T. Garnett <sup>1\*</sup>, S. H. M. Butchart <sup>2,3</sup>, G. B. Baker <sup>4</sup>, E. Bayraktarov,<sup>5</sup> K. L. Buchanan <sup>6</sup>, A. A. Burbidge,<sup>7</sup> A. L. M. Chauvenet <sup>8</sup>, L. Christidis <sup>9</sup>, G. Ehmke,<sup>5,10</sup> M. Grace <sup>11</sup>, D. G. Hoccom,<sup>12</sup> S. M. Legge <sup>5,13</sup>, I. Leiper <sup>1</sup>, D. B. Lindenmayer <sup>13</sup>, R. H. Loyn <sup>14,15,16</sup>, M. Maron <sup>5,17</sup>, P. McDonald <sup>18</sup>, P. Menkhorst <sup>19</sup>, H. P. Possingham <sup>5,20</sup>, J. Radford <sup>21,22</sup>, A. E. Reside <sup>5</sup>, D. M. Watson <sup>15</sup>, J. E. M. Watson <sup>5,17,23</sup>, B. Wintle <sup>24</sup>, J. C. Z. Woinarski <sup>1</sup> and H. M. Geyle <sup>1</sup>

<sup>1</sup>Threatened Species Recovery Hub, National Environmental Science Program, Research Institute for the Environment and Livelihoods, Charles Darwin University, Northern Territory, 0909, Australia

<sup>2</sup>BirdLife International, David Attenborough Building, Pembroke Street, Cambridge, CB2 3QZ, U.K.

<sup>3</sup>Department of Zoology, The University of Cambridge, Downing Street, Cambridge, CB2 3EJ, U.K.

<sup>4</sup>Institute for Marine and Antarctic Studies, The University of Tasmania, Hobart, Tasmania, 7005, Australia

<sup>5</sup>Threatened Species Recovery Hub, National Environmental Science Program, Centre for Biodiversity and Conservation Science, The University of Queensland, St Lucia, Qld, 4072, Australia

<sup>6</sup>School of Life and Environmental Sciences, Deakin University, 75 Pigdons Road, Geelong, Victoria, 3216, Australia

<sup>7</sup>87 Rosedale Street, Floreat, Western Australia, 6014, Australia

<sup>8</sup>School of Environment and Science & Environmental Futures Research Institute, Griffith University, Gold Coast, Queensland, 4222, Australia

<sup>9</sup>National Marine Science Centre, Southern Cross University, Lismore, New South Wales, 2480, Australia

<sup>10</sup>BirdLife Australia, Carlton, Victoria, 3053, Australia

<sup>11</sup>Department of Zoology, The University of Oxford, Oxford, OX1 3PS, U.K.

<sup>12</sup>Royal Society for the Protection of Birds, Bedfordshire, SG 19 2DL, U.K.

<sup>13</sup>Threatened Species Recovery Hub, National Environmental Science Program, Fenner School of Environment and Society, The Australian National University, Canberra, Australian Capital Territory, 2601, Australia

<sup>14</sup>The Centre for Freshwater Ecosystems, School of Life Sciences, La Trobe University, Wodonga, Victoria, 3690, Australia

<sup>15</sup>Institute for Land, Water and Society, Charles Sturt University, Albury, New South Wales, 2640, Australia

<sup>16</sup>Eco Insights, Beechworth, Victoria, 3747, Australia

<sup>17</sup>School of Earth and Environmental Sciences, The University of Queensland, St Lucia, 4072, Australia

<sup>18</sup>Zoology, School of Environmental and Rural Science, University of New England, Armidale, New South Wales, 2351, Australia

<sup>19</sup>Arthur Rylah Institute for Environmental Research, Department of Environment, Land, Water and Planning, Heidelberg, Victoria, 3084, Australia

<sup>20</sup>The Nature Conservancy, Arlington, VA, 22203-1606, U.S.A.

<sup>21</sup>Department of Ecology, Environment and Evolution, La Trobe University, Bundoora, Victoria, 3086, Australia

<sup>22</sup>Research Centre for Future Landscapes, La Trobe University, Bundoora, Victoria, 3086, Australia

<sup>23</sup>Wildlife Conservation Society, Bronx, NY, 10460-1068, U.S.A.

<sup>24</sup>School of Bioscience, The University of Melbourne, Parkville, Victoria, 3010, Australia

**Abstract:** *Although evidence-based approaches have become commonplace for determining the success of conservation measures for the management of threatened taxa, there are no standard metrics for assessing progress in research or management. We developed 5 metrics to meet this need for threatened taxa and to quantify the need for further action and effective alleviation of threats. These metrics (research need,*

\*Address correspondence to S. T. Garnett, email [stephen.garnett@cdu.edu.au](mailto:stephen.garnett@cdu.edu.au).

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research achievement, management need, management achievement, and percent threat reduction) can be aggregated to examine trends for an individual taxon or for threats across multiple taxa. We tested the utility of these metrics by applying them to Australian threatened birds, which appears to be the first time that progress in research and management of threats has been assessed for all threatened taxa in a faunal group at a continental scale. Some research has been conducted on nearly three-quarters of known threats to taxa, and there is a clear understanding of how to alleviate nearly half of the threats with the highest impact. Some management has been attempted on nearly half the threats. Management outcomes ranged from successful trials to complete mitigation of the threat, including for one-third of high-impact threats. Progress in both research and management tended to be greater for taxa that were monitored or occurred on oceanic islands. Predation by cats had the highest potential threat score. However, there has been some success reducing the impact of cat predation, so climate change (particularly drought), now poses the greatest threat to Australian threatened birds. Our results demonstrate the potential for the proposed metrics to encapsulate the major trends in research and management of both threats and threatened taxa and provide a basis for international comparisons of evidence-based conservation science.

**Keywords:** avian, conservation performance, recovery planning, threat reduction, threatened species

### Medidas de Progreso en el Entendimiento y el Manejo de las Amenazas que Enfrentan las Aves Australianas

**Resumen:** Aunque los métodos basados en evidencias se han vuelto muy comunes para la determinación del éxito de las medidas de conservación del manejo de los taxones amenazados, hoy en día no existen medidas estandarizadas para la evaluación del progreso de la investigación o el manejo. Desarrollamos cinco medidas para cumplir con esta necesidad que tienen los taxones amenazados y para cuantificar la necesidad de una mayor acción y un alivio efectivo de las amenazas. Estas medidas (falta de investigación, éxito de la investigación, falta de manejo, éxito del manejo y porcentaje de reducción de amenazas) pueden agregarse para examinar las tendencias de un taxón individual o las tendencias de las amenazas para múltiples taxones. Probamos la utilidad de estas medidas por medio de su aplicación en aves australianas amenazadas, que parece ser la primera vez que se evalúa el progreso en la investigación y en el manejo de amenazas para el caso de varios taxones amenazados dentro de un grupo faunístico a escala continental. Se ha realizado algún tipo de investigación sobre casi tres cuartas partes de las amenazas conocidas para los taxones, y hay un claro entendimiento de cómo aliviar casi la mitad de las amenazas con el impacto más alto. Se ha intentado algún tipo de manejo con casi la mitad de las amenazas. Los resultados del manejo variaron desde ensayos exitosos hasta la mitigación completa de la amenaza, incluso para un tercio de las amenazas de alto impacto. Tanto el progreso en la investigación como en el manejo tendió a ser mayor para los taxones que estaban siendo monitoreados, o que ocurrían en islas oceánicas. La depredación por gatos tuvo el puntaje más como amenaza potencial. Sin embargo, ha habido poco de éxito en la reducción del impacto de la depredación por gatos, así que ahora el cambio climático (particularmente la sequía) es la mayor amenaza para las aves amenazadas en Australia. Nuestros resultados demuestran el potencial que tienen las medidas propuestas de encapsular las tendencias más importantes en la investigación y en el manejo tanto de las amenazas como de los taxones amenazados y de proporcionar una base para comparaciones internacionales de la ciencia de la conservación basada en evidencias.

**Palabras Clave:** aviar, desempeño de la conservación, especies amenazadas, planeación de la recuperación, reducción de amenazas

**摘要:** 虽然受威胁物种的管理中常常用到基于证据的方法来确定保护措施的功效,但还没有统一的标准来评估受威胁物种研究或管理的进展。我们为受威胁物种制定了五个指标,并量化分析了深入行动和有效减缓威胁的需求。这些指标(研究需求、研究成果、管理需求、管理成果和威胁减少的百分比)可以共同用于分析单个类群的趋势或跨类群的威胁。我们通过澳大利亚受胁迫鸟类上的应用检验了这些指标的效用,这是首次在大陆尺度上评估一个动物区系中所有受胁迫类群面临威胁的研究和管理进展。该类群已知的威胁中有四分之三已有一些研究,且影响最大的威胁中有一半已被清楚地指出应如何减缓这种威胁。针对近一半的威胁因素已有相应管理措施。管理成果包括成功的尝试到完全减缓威胁,这涉及了三分之一影响较大的威胁。那些受到监测、或分布在海岛上,或的类群的研究和管理往往有更多进展。被猫捕食的鸟类受到的潜在威胁最大。不过,在减轻被猫捕食的影响方面已取得一些成功,而气候变化(特别是干旱)才是目前澳大利亚鸟类面临的巨大威胁。我们的结果表明,我们制定的指标可以概括受威胁类群及其面临威胁的研究和管理的主要趋势,并为全球范围内基于证据的保护科学的比较分析提供了基础。【翻译:胡怡思; 审核:聂永刚】

**关键词:** 保护成效, 减少威胁, 鸟类, 受胁迫物种, 恢复计划

## Introduction

Robust, unbiased, transparent, and broadly applicable measures of how much has been achieved in conservation and how much is still needed are key to ensuring ongoing support (Sutherland et al. 2004), efficient resource allocation, and development of sound policy (Ferraro & Pattanayak 2006). Existing metrics, such as the Red List Index (Butchart et al. 2005, 2007) or the U.S. Fish and Wildlife Service's (1983) favorability scores, are insufficiently sensitive to understand the effectiveness of management or to compare management effectiveness across threats and taxa. Assessments of success and impact for species recovery projects (Kapos et al. 2008) are not standardized and, as such, not suitable for comparison of large numbers of taxa.

General measures of conservation progress are made available through the conservation action planning process (Schwartz et al. 2012). However, the Royal Society for the Protection of Birds (RSPB) seems to be the only organization to have developed a set of defined categories for assessing progress toward an explicit final conservation target (RSPB 2017). Under their system, the lowest level of progress is associated with taxa with no monitoring, research, or management, and the highest level applies when population or range targets have been met and the conservation status of the species has been secured. These categories allow ready comparison of progress toward whatever targets are deemed appropriate for a taxon and can be translated into a traffic light system for visualization and interpretation.

However, the process by which the RSPB applies aggregated information to assign the category of progress for each species is not widely known. Given that the key to progress in the conservation of threatened taxa is threat reduction (Meredith et al. 2018), measuring progress in alleviating each threat (Salafsky & Margoluis 1999) can illuminate the components of such progress.

Threat management has 2 phases: research and implementation. The research phase (equivalent to the diagnosis phase of Westwood et al. [2014]) aims to understand the nature of a threat (i.e., how it is affecting a taxon and the actions required to alleviate it). This phase commonly has few direct benefits in terms of threat reduction or population increase. Implementation involves managers applying research findings and ends when a taxon can maintain a self-sustaining population (Redford et al. 2011; Westwood et al. 2014; RSPB 2017).

There is a need for metrics that will allow measurement of progress in alleviating threats across multiple taxa and to facilitate their management. Alleviation of high-impact threats benefit taxa more than will easing of threats with low or negligible impacts, particularly if existing management is negligible. Combining these ideas into standardized metrics allows retrospective assessment of how

effective past interventions have been and can help direct resources to the most pressing targets across demands for research and management. We applied standardized metrics to threatened Australian bird taxa to quantify the effectiveness of threat alleviation and provide the means to allocate resources in a manner that maximizes the benefits of threat reduction to threatened taxa.

## Methods

Our approach to assessing and understanding progress in threat alleviation among Australian threatened birds had 5 components: identifying threats affecting different taxa; assessing the timing, scope, and severity of those threats to create weighted threat impact scores that were then assigned to weighted categories; assessing the level of understanding about how to manage each threat; determining success in managing the threat; and assembling threat impacts, understanding, and management success into metrics of progress for an individual taxon or threat. To illustrate application of the metrics, we compared them with characteristics of the taxa and of the threats.

### Taxa Assessed

To demonstrate our method, we assessed 238 Australian bird taxa (species and subspecies). This included all those listed as threatened or near threatened at any time in the last 25 years (Garnett et al. 2015) or taxa currently listed under Australia's Environment Protection and Biodiversity Conservation Act 1999 (EPBC Act; Department of the Environment and Energy 2017). Taxonomy followed Garnett et al. (2015). We updated passerine taxonomy to account for taxonomic revisions published in del Hoyo and Collar (2016).

### Threats

All threats ( $t$ ) known to have affected the selected taxa ( $x$ ) were first identified from Garnett et al. (2011) because these threat assessments have undergone multiple iterations over the last 20 years. Threat assessments were then updated and validated by experts. Multiple viewpoints were elicited wherever possible (see Supporting Information). Threats were then categorized using the IUCN Red List threat classification scheme (IUCN 2012) down to the most specific level possible. Extra detail was provided where available on invasive species, fishing type, mining target, recreational activity and climate impact. Then, following IUCN (2012), we assessed the timing of each threat (i.e., ongoing, may occur or return in the short term, may occur or return in the distant future); its extent or scope (i.e. the proportion of the total population affected); and its severity (i.e., the rate of population

**Table 1.** Indicators of progress in understanding threats or implementing management and weights used to characterize needs and achievements in research or management.

Indicator	Weighting	
	need	achievement
Management understanding		
i. no knowledge and no research	6	0
ii. research being undertaken or completed; limited understanding on how to manage threat	5	1
iii. research has provided strong direction on how to manage threat	4	2
iv. solutions being trialled; work initiated recently	3	3
v. trial management under way; no clear evidence yet that it can deliver objectives	2	4
vi. trial management is providing clear evidence that it can deliver objectives	1	5
vii. research complete and being applied or ongoing research associated with adaptive management of threat	0	6
Management implementation		
i. no management	6	0
ii. management limited to trials	5	1
iii. work has been initiated to roll out solutions where threat applies across the taxon's range	4	2
iv. solutions have been adopted; too early to demonstrate success	3	3
v. solutions are enabling achievement but only with continued conservation intervention	2	4
vi. good evidence available that solutions are enabling achievement with little or no conservation intervention	1	5
vii. threat no longer needs management	0	6

decline caused by the threat within its scope), each with reference to Garnett et al. (2011) before review and validation by 1 or more experts on the taxon. To measure progress in alleviating threats, we estimated the timing, scope, and severity of threats for the existing impact, which accounts for any management and for the potential threat impact under the counterfactual assumption that no management of the threat had been undertaken (Ferraro & Pattanayak 2006; Ferraro 2009) since 1900.

The timing, scope, and severity of each threat were translated into a weighted impact score ( $I_t$ ) for both the actual situation ( $I_{ta}$ ) and the counterfactual scenario ( $I_{tc}$ ). Impact scores reflect the total population decline over ten years or 3 generations (whichever longer) likely to be caused by that threat (i.e., the product of scope and severity), weighted by threat timing (IUCN 2012) (see Supporting Information for greater detail). Where no action had been undertaken,  $I_{ta} = I_{tc}$ .

### Progress in Understanding Threats or Implementing Management

The extent of progress in alleviating each threat to each taxon was divided into 2 parts: management understanding (MU), which represented the current level of knowledge of how to manage threat  $t$  for taxon  $x$ , and management implementation (MI), which represents the extent to which threat  $t$  has been alleviated for taxon  $x$ . For MU there were 7 mutually exclusive categories ranging from no knowledge and no research to research complete and being applied or ongoing research associated with adaptive management of threat (Table 1). For MI there were another 7 mutually exclusive categories ranging from no management to threat no longer needs man-

agement. Each step was scored from 0 to 6 for both MU and MI. Both metrics were derived from RSPB categories of progress in species conservation (RSPB 2017) (see Supporting Information for categories and data) but, unlike that framework, research and management were separated. We did not assume initiation of management action for a threat was contingent on complete knowledge of how to undertake management.

Weighted data were assembled into 5 metrics applied both to individual taxa and to specific threats: 2 for progress in understanding (research need and research achievement), 2 for progress in management (management need and management achievement), and 1 for assessing overall progress in threat reduction (percent threat reduction). These metrics help highlight gaps in understanding and management and identify achievements.

### Basic Metrics

For each threat ( $t$ ) faced by each taxon ( $x$ ), we calculated research need (RN) and management need (MN) such that

$$RN_{xt} = I_{xtc} \times \left( 1 - \frac{MU_{xt}}{MU_{(\max)}} \right) \quad (1)$$

and

$$MN_{xt} = I_{xtc} \times \left( 1 - \frac{MI_{xt}}{MI_{(\max)}} \right), \quad (2)$$

where  $MU_{xt}$  and  $MI_{xt}$  are management understanding and implementation respectively,  $MU_{(\max)}$  and  $MI_{(\max)}$  are both 6, and  $I_{xtc}$  is threat impact under the assumption there has been no management.

**Table 2.** Weights accorded to the impact<sup>a</sup> of continuing threats based on their extent (i.e., the proportion of the total population affected) and their severity (i.e., the rate of population decline caused by the threat within its extent).

Extent	Severity				
	very rapid decline	rapid decline	slow, significant decline <sup>b</sup>	negligible decline	no decline
Whole	63.0**	23.5*	10.4*	1.4 <sup>†</sup>	0.0 <sup>†</sup>
Majority	52.0**	18.0*	9.0 <sup>^</sup>	1.1 <sup>†</sup>	0.0 <sup>†</sup>
Minority	24.9*	7.3 <sup>^</sup>	4.8 <sup>^</sup>	0.5 <sup>†</sup>	0.0 <sup>†</sup>
Negligible	0.5 <sup>†</sup>	0.1 <sup>†</sup>	0.1 <sup>†</sup>	0.0 <sup>†</sup>	0.0 <sup>†</sup>

<sup>a</sup>Impact of threat: \*\*, high; \*, medium; <sup>^</sup>, low; <sup>†</sup>, negligible.

<sup>b</sup>Threats likely to cause fluctuations in populations are given the same weighting as those causing slow significant declines.

We also calculated research achievement (RA) and management achievement (MA) such that

$$RA_{xt} = \frac{I_{xtc} \times MU_{xt}}{MU_{(\max)}}, \quad (3)$$

and

$$MA_{xt} = \frac{I_{xtc} \times MI_{xt}}{MI_{(\max)}}. \quad (4)$$

### Taxon Scores

Where multiple threats affect a taxon, effects can be additive, antagonistic (one threatening process inhibits another) or synergistic (impact is magnified [Côté et al. 2016]). As there is no universal rule on how threat impacts combine, we calculated overall research needs or achievements in managing all known threats to a taxon by summing the taxon-specific research needs or achievements for a given threat and then dividing by the maximum possible score for each threat to provide a measure that can be compared among threats. Hence, the research need (RN<sub>x</sub>) and management need (MN<sub>x</sub>) for a given taxon (x) are

$$RN_x = \frac{\sum_{t=1}^j RN_{xt}}{I_{l(\max)} \times MU_{(\max)} \times t_{j(\max)}}, \quad (5)$$

and

$$MN_x = \frac{\sum_{t=1}^j MN_{xt}}{I_{l(\max)} \times MI_{(\max)} \times t_{j(\max)}}, \quad (6)$$

where *j* is the number of threats facing a taxon, *I<sub>l(max)</sub>* is the maximum weighting for threat impact (i.e., 63.0) (Table 2), and *t<sub>j(max)</sub>* is the number of IUCN threat types coded to the lowest (i.e., most specific) level operating on any taxon which, for Australian threatened birds, is 25 (the number of threats affecting the Orange-bellied Parrot [*Neophema chrysogaster*]).

The research achievement (RA<sub>x</sub>) and management achievement (MA<sub>x</sub>) for a given taxon across all threats are similarly

$$RA_x = \frac{\sum_{t=1}^j RA_{xt}}{I_{l(\max)} \times MU_{(\max)} \times t_{j(\max)}} \quad (7)$$

and

$$MA_x = \frac{\sum_{t=1}^j MA_{xt}}{I_{l(\max)} \times MI_{(\max)} \times t_{j(\max)}}. \quad (8)$$

### Threat Scores

We calculated overall research needs or achievements in managing threats to Australian birds by summing the basic metrics RN<sub>xt</sub>, MN<sub>xt</sub>, RA<sub>xt</sub>, or MA<sub>xt</sub> then dividing them by the total threat score for all threatened Australian bird taxa such that

$$RN_t = \frac{\sum_{x=1}^j RN_{xt}}{\sum_{t=1}^j \sum_{x=1}^k RN_{xt}}, \quad (9)$$

$$MN_t = \frac{\sum_{x=1}^j MN_{xt}}{\sum_{t=1}^j \sum_{x=1}^k MN_{xt}}, \quad (10)$$

$$RA_t = \frac{\sum_{x=1}^j RA_{xt}}{\sum_{t=1}^j \sum_{x=1}^k RA_{xt}}, \quad (11)$$

and

$$MA_t = \frac{\sum_{x=1}^j MA_{xt}}{\sum_{t=1}^j \sum_{x=1}^k MA_{xt}}, \quad (12)$$

where *k* is the number of taxa.

### Percent Threat Reduction

The overall threat impact was calculated by summing the impact scores across all *j* threats for taxon *x*, both with management (*I<sub>xta</sub>*) and without management (*I<sub>xte</sub>*):

$$I_{xta} = \sum_{t=1}^j (I_{ta}) \quad (13)$$

and

$$I_{xte} = \sum_{t=1}^j (I_{te}), \text{ respectively.} \quad (14)$$

Because threat impact can be lower only when management has been applied, *I<sub>xta</sub>* is only less than *I<sub>xte</sub>*,

where  $MA \geq 4$  (i.e., management must have reached at least stage “v. solutions are enabling achievement but only with continued conservation intervention” [see Table 1]). Management that has had perverse outcomes (e.g., mesopredator release after apex predator control, Ritchie & Johnson 2009) is accounted for by defining such outcomes as threats (invasive and other problematic species for mesopredator release).

For each threat, overall impact of management ( $TI_{ta}$ ; existing threat impact) was calculated by summing threat impact for each taxon affected by the threat such that

$$TI_{ta} = \sum_{x=1}^{kt} (I_{ta}), \quad (15)$$

where  $k_t$  is the number of taxa affected by threat  $t$ .

Overall impact without management (potential threat impact [ $TI_{tc}$ ]) was also calculated by summing threat impact for each taxon affected by the threat, but because progress in MU and MI for each threat for each taxon is unique,  $TI_{tc}$  is also equal to the sum of the threat impacts of each category of MU or MI such that

$$TI_{tc} = \sum_{x=1}^k (I_{tc}) = \sum_{MU=1}^6 \sum_{x=1}^k (I_{tn}) = \sum_{MU=1}^7 \sum_{x=1}^k (I_{tc}). \quad (16)$$

Actual reductions in threat impact were calculated as the percent difference between the estimated rate of decline from a threat and the rate that could be occurring had there been no management (percent threat reduction [ $PTR_x$ ]) such that

$$PTR_x = \frac{(I_{xtc} - I_{xta}) \times 100}{I_{xtc}}. \quad (17)$$

We also calculated overall progress in reducing the impact of each threat proportional to its impact on all taxa without management such that

$$PTR_t = \frac{(I_{tc} - I_{ta}) \times 100}{I_{tc}}. \quad (18)$$

A worked example for 3 taxa that includes all formulas is provided in the Supporting Information.

### Geographic Distribution

Summaries for each metric were calculated for each Australian marine and terrestrial bioregion (Commonwealth of Australia 2006; Department of Sustainability, Environment, Water, Population and Communities 2012) to determine the location of threats and where research or management is either most urgent or has been most effective.

### Analyses

We correlated the 5 metrics (response variables) against one another (using Spearman's Rank-Order Correlation),

first normalizing all scores to 100. We repeated this step with 11 potential predictor variables (Supporting Information) to test for collinearity (finding no correlation coefficients  $>0.7$ ). We then used generalized linear modeling (multiple linear regression) to examine the effect of each of the 11 predictors on each metric. We examined a large set of models representing all possible combinations of the 11 predictors for each response variable (total of 5 sets, corresponding to each metric). For percent threat reduction, we only modeled the 130 taxa for which  $PTR > 0$ , as the primary interest was to understand factors influencing management interventions that had at least started to be effective.

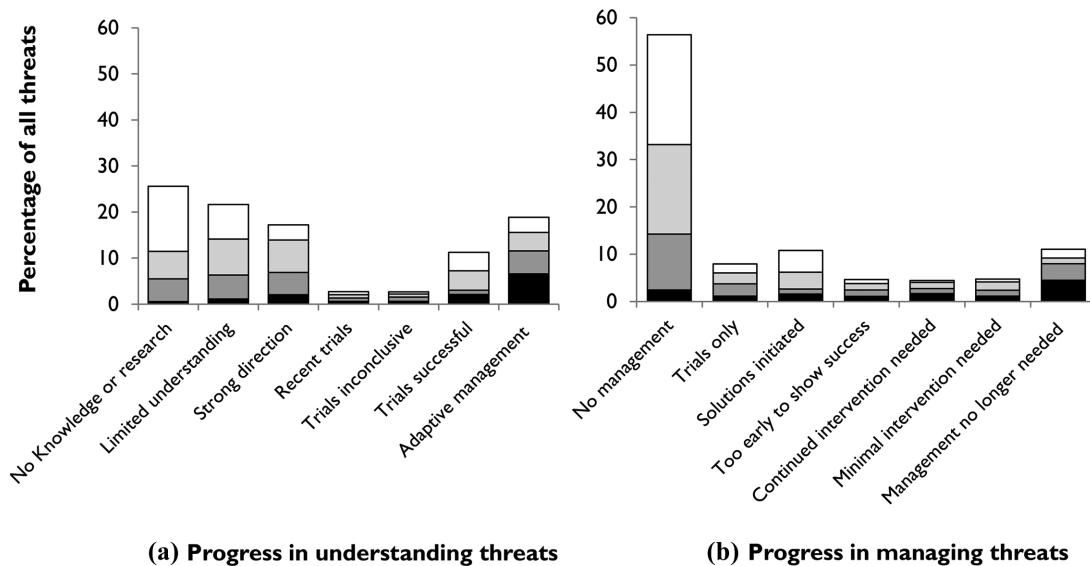
We then used a second-order form of Akaike's information criterion ( $AIC_c$ ) (Burnham & Anderson 2002) that is suitable for small sample sizes to rank and identify the best performing models in each set. A subset of models was chosen within 2 Akaike units from the best model (candidate set) because those at a greater distance have much less support for explaining the observed data. The final model used for inference was based on multimodel averaging of the entire candidate set. Analysis took place using the lme4 package in R version 3.3.1.

## Results

Across all 238 taxa considered, there were 181 separate threats with an average of 7.8 threats per taxon. The 1847 combinations of threat by taxon represents 5541 opportunities for management to have affected threat timing, extent or severity, but there was no reduction for over 85% of these threat impact parameters. For 52% of threat by taxon combinations, research is providing at least strong direction on what needs to be done to manage them, although that means that there is little or no understanding of the remainder (Fig. 1a). About 43% of the threat by taxon combinations had some management under way, with one-third of those in the high-impact category no longer needing active management (Fig. 1b).

Despite being derived from the same data sets, correlation among the 5 metrics (research need, management need, research achievement, management achievement, and percent threat reduction) for the different taxa was generally low, with nonsignificant relationships between research need and research or management achievement (Supporting Information). The highest correlations were between research and management need (0.92) and between research and management achievement (0.73).

No individual model was clearly superior in explaining the observed data (Supporting Information), but certainty surrounding each effect (i.e. whether or not the confidence intervals include 0) changed only slightly among



**Figure 1.** Level of progress in (a) understanding and (b) managing threats to Australian birds relative to the percentage of all threats identified for different taxa and the impact they are having on the birds (black, high-impact threats, population declines of  $\geq 50\%$ ; dark gray, medium, 10–50%; light gray, low, 2–10%; white, negligible,  $< 2\%$ ).

alternative models, and overall direction and effect size (regression coefficients) remained the same, justifying a model averaging approach. Furthermore, all highly significant predictors (i.e., those where  $p < 0.01$ ) (see predictors in Fig. 2 that do not overlap 0) remained so in each alternate model and in most cases were present in the entire candidate set (Supporting Information).

### Correlates with Taxon Scores

Research need was significantly influenced by range, geography, taxon type, status under the EPBC Act and conservation planning (Fig. 2a) (see Supporting Information for top-performing taxa). Research need was lower for taxa with larger ranges, for birds on islands compared with mainland birds and for taxa with a current recovery plan—a legislative instrument for which there are ministerial obligations—but higher for shorebirds compared with passerines and taxa listed as threatened under the EPBC Act.

Research achievement was significantly influenced by quality of monitoring, estimated detectability, range size, and taxonomic grouping and status under the EPBC Act (Fig. 2b). As might be expected, the better it was monitored, the greater the understanding of how to manage threats facing a taxon, though the link is not necessarily causal. High research achievement scores were also evident for birds with larger ranges, shorebirds, and those listed as endangered and critically endangered. Lower levels of research achievement were apparent among taxa that are easy to detect and for nonpasserines other than seabirds, shorebirds or parrots.

Although research need and management need were correlated, the type and influence of explanatory variables differed. Management need was significantly influenced by range size, geography, taxon grouping, and EPBC listing (Fig. 2c). Management need was greater for taxa that have larger ranges and are EPBC listed but lower for birds on islands, seabirds, and passerines.

Management achievement was significantly influenced by monitoring quality, detectability, taxon grouping, EPBC status, and conservation planning (Fig. 2d). It was greatest among taxa with high-quality monitoring and among EPBC listed taxa but lowest among highly detectable species, shorebirds, and those with an old recovery plan.

Threat reduction had been achieved in over half of all taxa (55%;  $n = 130$ ). Percent threat reduction was particularly high for threatened birds on continental islands but low for critically endangered taxa (Fig. 2e).

### Correlates with Threat Scores

Invasive species comprised the major threat class with the highest scores for all need and achievement metrics (Fig. 3), particularly cats (*Felis catus*) and black rats (*Rattus rattus*) (Supporting Information). Urban development, agriculture, biological resource use, and natural system modification all had moderate scores. Pollution and climate change or extreme weather measures (particularly more intense or frequent droughts) have high need scores but almost no achievements for either research or management.

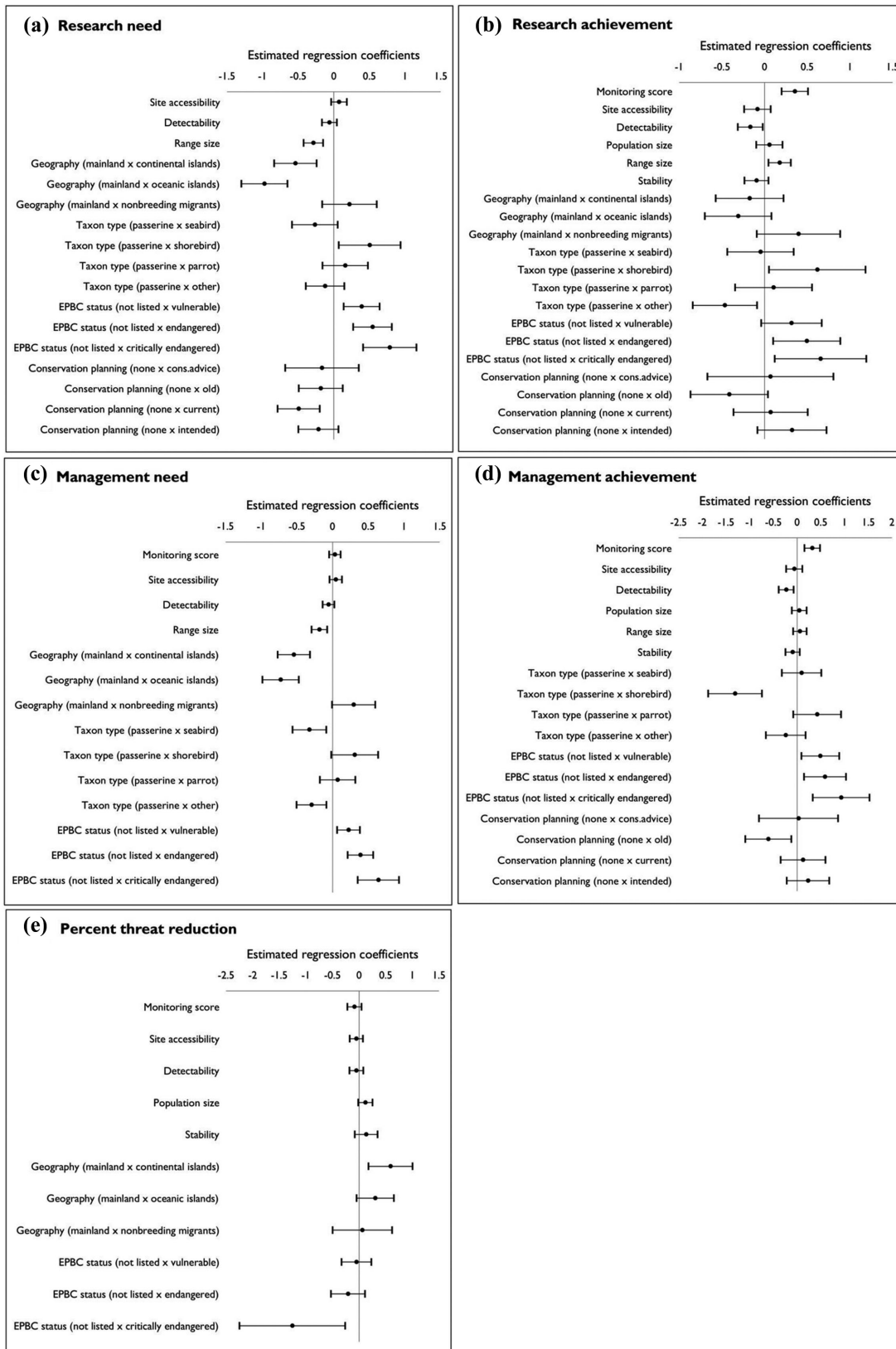


Figure 2. Standardized regression coefficients and 95% CIs for predictors of (a) research need, (b) research achievement, (c) management need, (d) management achievement (for all  $n = 236$  threatened Australian birds), and (e) percent threat reduction (for all  $n = 130$  threatened Australian birds with percent threat reduction  $> 0$ ).



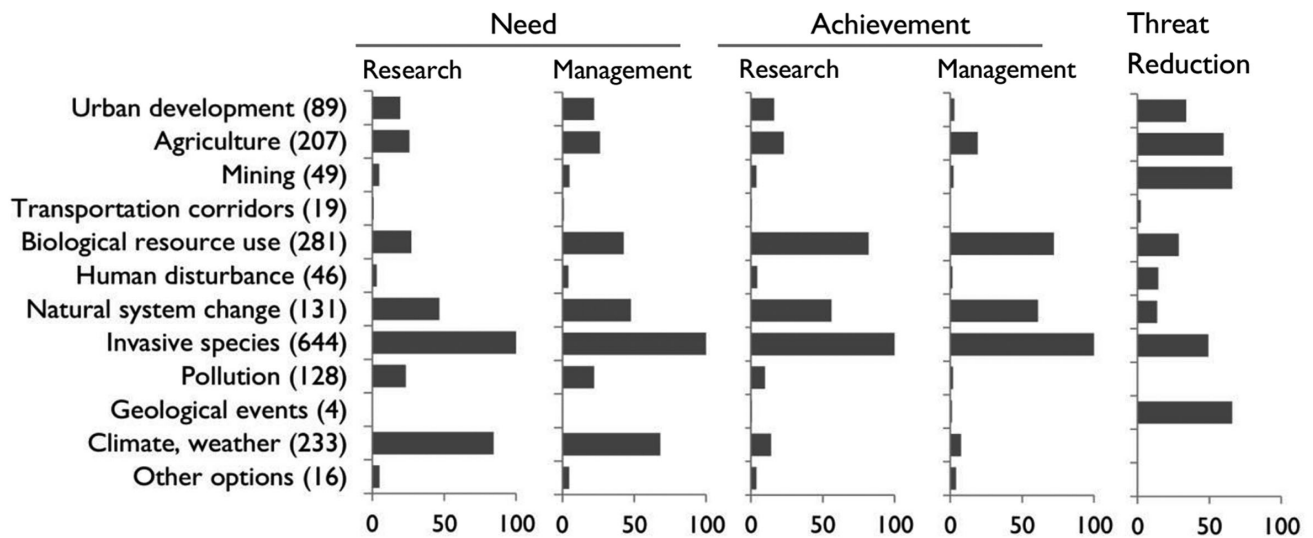


Figure 3. Normalized values of performance for research and management needs and achievements and percent threat reduction for the 12 major threat classes affecting Australian threatened birds (the total number of bird taxa affected by each threat class in parentheses).

The highest percent threat reduction as a result of management since 1900 has been from mining, followed by geological events then agriculture, largely because critical habitat that could have been cleared was reserved for the purpose of conservation. The almost equally high score for geological events was an artifact of a small sample size; in this case, translocation of Hutton's Shearwater (*Puffinus buttoni*) to spread risk to breeding sites was remarkably timely (McSweeney 2016). Moderately high percent threat reduction scores were achieved for urban development, biological resource use and invasive species. No threat reduction was achieved for pollution, climate change, or extreme weather.

#### Geographic Spread of Research and Management Need and Achievement

Geographically the highest density of threatened taxa occurs in seas off southern Australia, particularly southeast of Tasmania, whereas the terrestrial bioregions with the highest numbers of threatened taxa are in the coastal parts of northern and eastern Australia. Research need is greatest around the coasts of mainland Australia, reflecting the urgency in understanding how to contain the threats to migratory shorebirds (Fig. 4a). In contrast, research achievement (Fig. 4b) appears to reflect progress in understanding the threats facing southern seabirds. Management need (Fig. 4c) remains high in the southeastern marine zone as well as for coastal birds whereas management achievement (Fig. 4d) has been greatest for Macquarie Island, which is also where the greatest overall percent reduction in threat impact has been achieved (Fig. 4e).

#### Discussion

Used appropriately, these metrics can provide an overview for an entire class of animals for a whole continent, the needs for research and management for each threat to each taxon, the achievements to date in alleviating those threats and the percent change in impact on the ground. This information can be generated for any taxon or group of taxa, any threat or group of threats and at any geographical scale, allowing prioritization of action and reporting.

While acknowledging the need for caution and, preferably, triangulation in employing the analyses to determine priorities at a taxon level rather than between taxa, we see 4 main merits in our approach.

The relative ease with which assessments of progress can be completed. Understanding which threats pertain to a taxon and their impact, based on threat timing, extent and severity, are recommended to be assessed as part of any standard IUCN Red List assessment (IUCN 2013). To calculate our metrics requires only 3 further judgments for each threat—an assessment of the impact of a threat had no management occurred, the level of understanding of how to manage each of the threats affecting a taxon, and the extent to which that knowledge is being applied.

The metrics allow, for the first time, evidence-based prioritization of research or management within or between taxa. Within a taxon, ranking of research and management needs for different threats can potentially contribute to recovery planning. Comparisons among taxa or threats can indicate where investments are most likely to have an impact. Amelioration of a threat that affects multiple taxa could have higher priority because

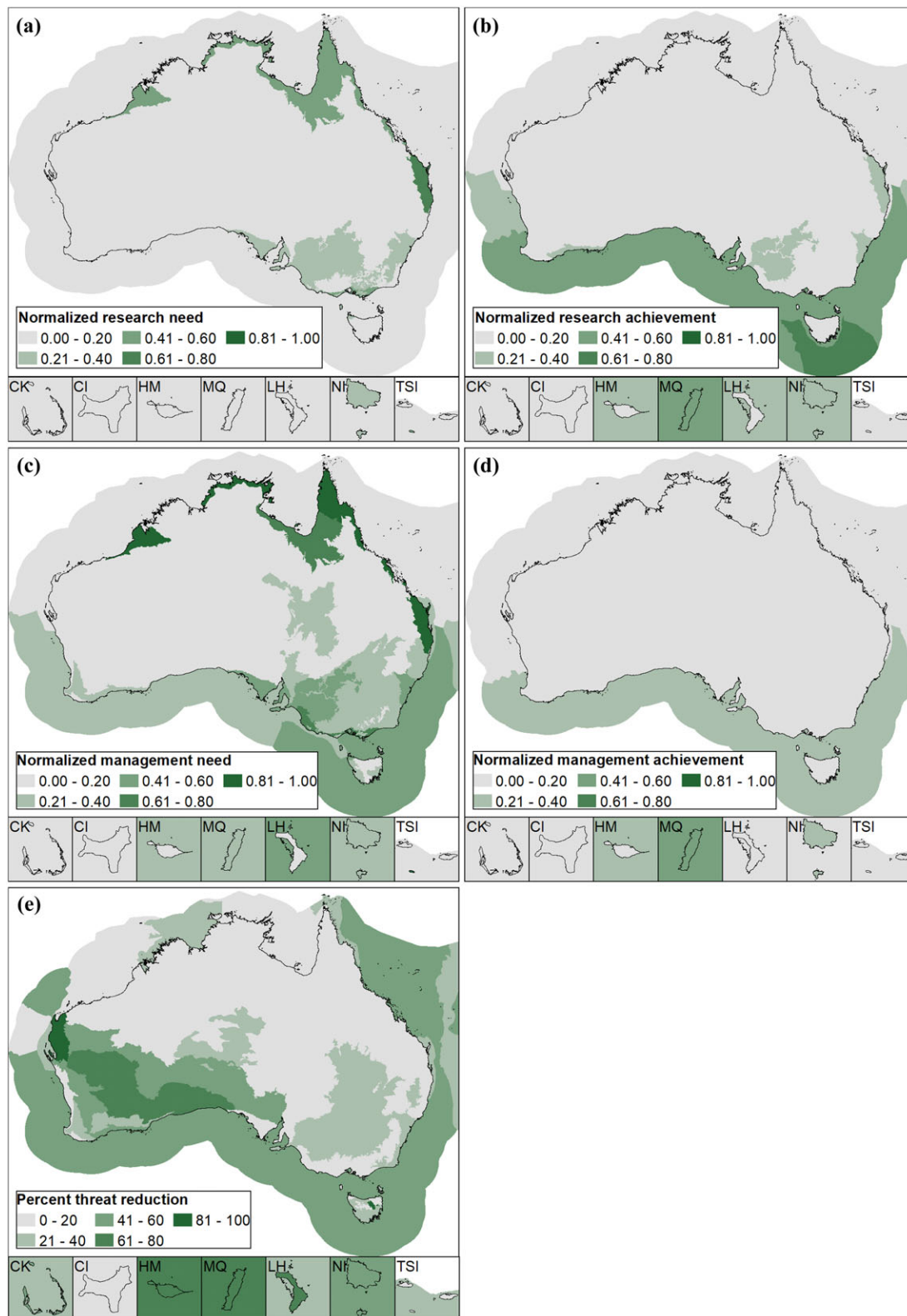


Figure 4. Normalized bioregional totals for predictors of (a) research need, (b) research achievement, (c) management need, (d) management achievement (for all  $n = 236$  threatened Australian birds), and (e) percent threat reduction (for all  $n = 130$  threatened Australian bird taxa with percent threat reduction  $> 0$ ) (CK, Cocos Keeling Islands; CI, Christmas Island; HM, Heard and McDonald Islands; MQ, Macquarie Island; LH, Lord Howe Island; NI, Norfolk Island; TSI, Torres Strait Islands).

knowledge of threat management should be transferable among similar taxa.

Incorporation of both needs and achievement in the same set of metrics can help practitioners balance the scale of problems ahead with what has been achieved: encouragement is critical to conservation advocacy (Garnett & Lindenmayer 2011). Our framework and others currently in development (i.e., the IUCN Green List of Species [Akçakaya et al. 2018]) explicitly incorporated this approach. It can be easy to forget how effectively hunting has been reduced as a threat in Australia, especially when compared internationally (Maxwell et al. 2016). Similarly, protected areas and legislation are limiting clearing of threatened taxon habitat, even if habitat loss continues to affect some threatened taxa.

The adoption of an explicit counterfactual approach allows for more comprehensive assessment of the impact of conservation. In a world where overall biodiversity declines are the norm, narratives of conservation success tend to focus on particular case studies. Our approach builds on and extends previous efforts to provide more systematic and quantitative metrics of the impact of conservation efforts across an entire group of taxa (Butchart et al. 2005; Hoffmann et al. 2010, 2015).

### Opportunities for Metric Development

There are many opportunities to refine or improve the method we have proposed. We adopted a simple linear approach to scoring progress in research and management, but there is potential to explore this more systematically to ensure each step is conceptually of equal significance. Rules could be developed to accommodate synergies or overlaps in threat impact. Sensitivity analyses could explore the impact of uncertainties in any of the parameters. Threat impacts could be weighted to reflect their reversibility. We prioritized minimizing threats across all threatened taxa by giving equal weight to all threats and all taxa with the same impact score. However, weighting taxa by IUCN Red List category of extinction risk could emphasize extinction minimization (see Supporting Information). A knowledge weighting could reduce potential bias arising from more threats being identified for the most closely studied taxa. Sometimes the process may need to be undertaken in several stages. While counterfactual assessments of threat impact, knowledge of how to manage threats and the extent to which that knowledge is being applied are reasonably easy to score for narrow ranging taxa or threats with narrow scope, wide-ranging taxa or large scope threats are more challenging. In such cases, spatial variation in the answers (e.g., between countries) may need to be assessed regionally then aggregated to the taxon level.

The application of these metrics can be extended. For example, the same methodology could be applied to locations or populations of a single taxon to clarify spatial

variation in performance of management interventions. Data on the level of investment applied to reduce the impact of each threat could allow calculation of cost-effectiveness in conservation investment, which can help with prioritization (Joseph et al. 2009). Metrics based on the same principles could be extended to the governance and social drivers of conservation performance and link threat management to the types of action taken to reduce those threats. The metrics presented here could also be used in tandem with other indicators to evaluate whether threat reduction is associated with changes in taxon status, for example, extinction risk (red list) and recovery (IUCN Green List of Species [Akçakaya et al. 2018]). With all refinements, the basic premise that metrics are indicative, not definitive, should not be forgotten.

### Implications for Australian Birds

The results show few threatened Australian bird taxa have had all threats reduced to a stage where they no longer need at least some form of ongoing management to persist. But there have been some remarkable successes, such as eradication of invasive species on some islands. Most results were unsurprising, but have never before been summarized in ways that allow comparison of performance across all of Australia's threatened birds. The success of several island conservation programs is well documented (Priddel & Carlile 2009; Frith 2013; Woinarski et al. 2016; Springer 2018), but their national context has not been fully appreciated. Our geographical summaries highlight the enormity of the achievement on Macquarie Island, the critical nature of quarantine to Heard Island and the importance of the research aimed at reducing the impacts of fishing on seabirds, although implementation of that knowledge has been challenging (Baker & Robertson 2018). These achievements contrast with the ongoing severe threats to migratory shorebirds, mainly outside Australia (Clemens et al. 2016) and the mounting evidence of the threat posed by cats (Woinarski et al. 2017).

Also unsurprising is the critical role played by monitoring in both research and management achievement, reinforcing pleas that monitoring be given increased attention and resourcing (Legge et al. 2018). Also, while intuitive, the link between research and management performance in conservation is rarely quantified (Cohen et al. 2002).

That listing under the EPBC Act was positively correlated with all metrics except percentage threat reduction (level of significance increased as severity of threat category increased) was expected and helps confirm the validity of the metrics. The results suggest that conservation effort has been greatest for the most threatened taxa, consistent with analyses by Garnett et al. (2003) who demonstrate the high costs per species for the most threatened taxa. The more threatened a taxon, the greater the need

for research and management but also the greater the effort that has been made to understand those threats and to alleviate them. Our results also suggest that performance of another element of the EPBC Act, listed key threatening processes and threat abatement plans (Department of the Environment and Energy 2018), warrant investigation with our approach once data are available on other faunal groups they are meant to benefit.

Notwithstanding the experimental nature of the metrics as presented here, the results from their application to Australian birds carry important messages. The first is that the contrast between current and counterfactual threat impacts suggests that the conservation status of Australian threatened birds is far better than it would be had there not been investment in research, management and policy over many decades, starting with hunting restrictions and the declaration of protected areas in the 19<sup>th</sup> century. In recent years there have also been some highly successful interventions to control or eradicate invasive species, particularly on some islands. Second, much remains to be done if extinctions are to be prevented and sustained conservation of Australian threatened birds is to be achieved. Given how much has been achieved, ongoing investment is warranted to complete the task. The metrics presented here can be used to measure that progress.

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## Supporting Information

A description of quality control of threat impacts and progress with understanding and managing threats (Appendix S1), weightings for threat impact scores (Appendix S2, S3), the RSPB progress framework (Appendix S4), data (Appendix S5), worked examples

(Appendix S6), a description of variables with which measures of progress in research or management were compared (Appendix S7, S8), metric correlation values and model outputs (Appendix S9, S10), ranked taxa according to highest scores for threats and performance in research and management (Appendix S11), highest scores for individual threats (Appendix S12), and weightings according to extinction risk (Appendix S13) are available online. The authors are solely responsible for the content and functionality of these materials. Queries (other than absence of the material) should be directed to the corresponding author.

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