



Minerva Access is the Institutional Repository of The University of Melbourne

Author/s:

Robinson, NM;Scheele, BC;Legge, S;Southwell, DM;Carter, O;Lintermans, M;Radford, JQ;Skroblin, A;Dickman, CR;Koleck, J;Wayne, AF;Kanowski, J;Gillespie, GR;Lindenmayer, DB

Title:

How to ensure threatened species monitoring leads to threatened species conservation

Date:

2018-09-01

Citation:

Robinson, N. M., Scheele, B. C., Legge, S., Southwell, D. M., Carter, O., Lintermans, M., Radford, J. Q., Skroblin, A., Dickman, C. R., Koleck, J., Wayne, A. F., Kanowski, J., Gillespie, G. R. & Lindenmayer, D. B. (2018). How to ensure threatened species monitoring leads to threatened species conservation. *Ecological Management and Restoration*, 19 (3), pp.222-229. <https://doi.org/10.1111/emr.12335>.

Persistent Link:

<https://hdl.handle.net/11343/284629>

1 **How to ensure threatened species monitoring leads to threatened species conservation**

2 Natasha M. Robinson, Ben C. Scheele, Sarah Legge, Darren M. Southwell, Oberon Carter, Mark
3 Lintermans, James Q. Radford, Anja Skroblin, Chris R. Dickman, Jessica Koleck, Adrian F. Wayne, John
4 Kanowski, Graeme R. Gillespie, David B. Lindenmayer.

6 **Authors contact block**

7 Natasha Robinson, Ben Scheele, Sarah Legge and David Lindenmayer are researchers with the
8 Fenner School of Environment and Society, Building 141, Linnaeus Way, The Australian National
9 University, Canberra ACT 2601 Australia, Tel: +61 413 687 675 Email: natasha.robinson@anu.edu.au.

10 Darren Southwell and Anja Skroblin are researchers with the Quantitative and Applied Ecology
11 Group, School of Biosciences, University of Melbourne, Parkville, VIC 3010 Australia.

12 Oberon Carter is a Senior Conservation Management Officer with the Department of Primary
13 Industries, Parks, Water & Environment, PO Box 44, Hobart, TAS 7001 Australia.

14 Mark Lintermans is a researcher with the Institute for Applied Ecology, University of Canberra, ACT
15 2601 Australia.

16 James Radford contributed to this paper whilst at Bush Heritage Australia. He is now a researcher
17 with the Research Centre for Future Landscapes, Department of Ecology, Environment and
18 Evolution, La Trobe University, Bundoora, VIC 3083 Australia.

19 Chris Dickman is a researcher with the School of Life and Environmental Sciences, University of
20 Sydney, NSW 2006 Australia.

21 Jessica Koleck contributed to this paper whilst at WWF Australia. She is now with the Australian
22 Wildlife Conservancy, Subiaco, Perth WA 6008 Australia.

23 Adrian Wayne is a Senior Research Scientist with Biodiversity and Conservation Science, Department
24 of Biodiversity, Conservation and Attractions, Locked Bag 2, Manjimup, WA 6258 Australia.

25 John Kanowski is the National Science and Conservation Manager at the Australian Wildlife
26 Conservancy, PO Box 642, Herberton QLD 4887 Australia.

27 Graeme Gillespie is the Director Terrestrial Ecosystems, Flora and Fauna Division, Department of
28 Environment and Natural Resources, CSIRO Complex, 564 Vanderlin Drive, Berrimah NT 0828
29 Australia.

31 **Acknowledgements**

This is the author manuscript accepted for publication and has undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process, which may lead to differences between this version and the [Version of Record](#). Please cite this article as [doi: 10.1111/emr.12335](https://doi.org/10.1111/emr.12335)

This article is protected by copyright. All rights reserved

32 Funding from the Australian Government's National Environmental Science Programme through the
33 Threatened Species Recovery Hub facilitated the workshop and preparation of this paper. The figure
34 was developed with assistance from Claire Foster.

Author Manuscript

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28

DR. NATASHA MAREE ROBINSON (Orcid ID : 0000-0003-0421-8683)

PROF. DAVID B LINDENMAYER (Orcid ID : 0000-0002-4766-4088)

Article type : Review article

How to ensure threatened species monitoring leads to threatened species conservation

Summary

Monitoring is essential for effective conservation and management of threatened species and ecological communities. However, more often than not, threatened species monitoring is poorly implemented, meaning that conservation decisions are not informed by the best available knowledge. We outline challenges and provide best-practice guidelines for threatened species monitoring, informed by the diverse perspectives of 26 conservation managers and scientists from a range of organisations with expertise across Australian species and ecosystems. Our collective expertise synthesised five key principles that aim to enhance the design, implementation and outcomes of threatened species monitoring. These principles are: 1) Integrate monitoring with management; 2) Design fit-for-purpose monitoring programs; 3) Engage people and organisations; 4) Ensure good data management; and 5) Communicate the value of monitoring. We describe how to incorporate these principles into existing frameworks to improve current and future monitoring programs. Effective monitoring is essential to inform appropriate management and enable better conservation outcomes for our most vulnerable species and ecological communities.

Key words: adaptive management; conservation management; knowledge transfer; management cycle; monitoring and evaluation; threatened species, populations & communities; translating science

29 **Introduction**

30 The world is losing species at an alarming rate (Butchart et al. 2010, Waldron et al. 2017), far higher
31 than background rates through geological time (Ceballos et al. 2017). Australia, especially, is
32 experiencing ongoing species declines and extinctions (Cresswell and Murphy 2017, Waldron et al.
33 2017). Many extinctions may have been avoided if adequate knowledge of declines existed, and if
34 this knowledge triggered actions to halt declining species trajectories (Martin et al. 2012,
35 Lindenmayer et al. 2013, Woinarski et al. 2016). In this regard, the application of effective
36 monitoring is central to informing management and preventing species extinctions (Martin et al.
37 2007). Monitoring is the process of collecting and analysing repeated observations or measurements
38 to identify changes and evaluate progress of management towards stated aims. In the context of
39 threatened species conservation, monitoring is essential to detect trends in abundance and
40 distribution through time, measure the impacts of threatening processes, and evaluate the
41 effectiveness of management responses (Legge et al. 2018). It is also important for informing
42 legislative protection and securing investment in management, and is a powerful communication
43 tool that allows for meaningful engagement with a broad range of stakeholders. Despite these
44 imperatives, the current contribution of monitoring to the conservation and management of
45 threatened biodiversity in Australia is severely deficient (Legge et al. 2018).

46 Threatened species monitoring and management in Australia is not of a standard and
47 comprehensiveness commensurate with the nation's wealth, scientific capacity and stable
48 governance structure (McDonald et al. 2015, Waldron et al. 2017, Legge et al. 2018). A recent
49 assessment of Australia's threatened species and ecological communities has revealed inadequacies
50 in the quantity and quality of monitoring, with a lack of monitoring for many threatened species and
51 communities (Legge et al. 2018). An estimated 24 – 46% of threatened vertebrate species receive no
52 monitoring at all, and a high proportion of monitoring programs that do exist are poorly designed
53 with not enough statistical power to detect changes in population trends. More worryingly, Legge et
54 al. (2018) also identified poor coordination between monitoring programs, inadequate data
55 management and reporting, and limited integration between monitoring and management. These
56 issues are not unique to Australia, with inadequacies in monitoring being documented globally (Legg
57 and Nagy 2006, Lindenmayer and Likens 2010).

58 Resource constraints are often cited as a fundamental reason for not being able to monitor
59 effectively (Lindenmayer et al. 2012, Environment and Communications References Committee
60 2013). Consequently, there have been calls to prioritise monitoring and management choices and

61 increase efficiency (Joseph et al. 2009). Yet, overall we need more resources, not simply better
62 allocation. Indeed, the Australian Government falls short on delivering adequate resources for
63 biodiversity by both national (Cresswell and Murphy 2017) and international standards (Waldron et
64 al. 2013). This is despite threatened biodiversity facing increasing pressures, and despite the
65 inclusion of an explicit target to develop a national monitoring program in Australia's Biodiversity
66 Conservation Strategy (2010–30) (Natural Resource Management Ministerial Council 2010). We note
67 that, at present, monitoring is not mandatory even for critically endangered species. We advocate
68 that adequately resourced monitoring programs be developed for priority threatened species, in line
69 with nations such as United States of America, where biennial monitoring of threatened species
70 population trend is mandated via funded recovery plans (U.S. Endangered Species Act of 1973).
71 Further improvements in monitoring can be made through enhancing existing capacity such as
72 through greater engagement, effective partnerships, and increased coordination and integration of
73 programs.

74 Other reasons for inadequate monitoring, however, are more concerning than resource limitations.
75 These include a growing disregard for science (Lindenmayer et al. 2015, Sutherland and Wordley
76 2017), de-valuing of evidence-based management (Russell-Smith et al. 2015), competing interests
77 that undervalue biodiversity or erode ecological integrity (Ritchie et al. 2013), wilful obstruction
78 towards receiving bad news (Woinarski et al. 2016), and hesitation to act on information (Martin et
79 al. 2012). Such attitudes and behaviours are attributed to limited understanding of the value of
80 threatened species monitoring by scientists, governments, industry and the broader public, along
81 with a culture of pessimism that considers extinction inevitable (Garnett and Lindenmayer 2011).
82 Under-appreciation of biodiversity values and defeatism, however, can be transformed into
83 empowerment to act, by promoting both intrinsic and extrinsic biodiversity values (Keith et al.
84 2017), inspiring hope (Garnett and Lindenmayer 2011, Balmford 2012, Garnett et al. 2018), and
85 demonstrating how effective monitoring can inform decision-making and management to enhance
86 threatened species conservation (Lindenmayer et al. 2013).

87 Biodiversity monitoring is challenging; there are many variables, interacting factors and ecological
88 surprises that can confound our understanding of species, ecosystems and processes (Lindenmayer
89 and Likens 2018). Threatened species monitoring is, however, even more challenging than
90 monitoring non-threatened taxa. Attributes such as rarity, low or variable detectability, and narrow
91 habitat niches present challenges with design and logistics (Martin et al. 2007, Crates et al. 2017).
92 There are restrictions in the use of experimental methods due to ethical issues of working with
93 threatened species and a greater requirement to avoid negative consequences (e.g. the use of

94 biotelemetry tools, Cooke 2008). The fragile existence of threatened species further demands that
95 monitoring has adequate precision and sensitivity to detect subtle changes in populations to inform
96 important decisions and future management without delay (Martin et al. 2007, Martin et al. 2012).

97 Although the overall state of threatened species monitoring in Australia is inadequate (Legge et al.
98 2018), this is not universally the case. For example, shorebird monitoring in Australia is a successful
99 long-term collaboration between citizen scientists, governments and researchers that has yielded
100 large-scale robust information on shorebird demographics, habitats and threatening processes to
101 enable effective, coordinated recovery efforts (Hansen et al. 2018). Much can be learnt from
102 evaluating good monitoring programs (e.g. Bayraktarov et al. 2018), and using existing frameworks
103 that have been developed to guide monitoring. Here, we collate personal experience in what makes
104 monitoring difficult, learn lessons from good examples and synthesise the academic literature to
105 draw out key principles that lead to better monitoring.

106 ***Essential principles for making the monitoring of threatened biodiversity count***

107 Our principles are the product of a two-day workshop in 2016 on threatened species monitoring in
108 Australia, involving 26 practitioners from government, non-government organisations,
109 environmental consulting companies and academic institutions. Participants had expertise in
110 monitoring that encompassed threatened flora and fauna across all major Australian biomes; they
111 shared their knowledge and experience in threatened species monitoring via pre-workshop surveys
112 (Robinson et al. 2018), individual presentations and targeted group discussion. The workshop
113 culminated in focused discussion on how to improve threatened species monitoring. Within small
114 groups, ideas and insights were shared then, as a collective, these were collated and distilled into
115 five essential principles for monitoring; these being: 1) Integrate monitoring with management; 2)
116 Design a fit-for-purpose monitoring program; 3) Engage people and organisations; 4) Ensure good
117 data management; and 5) Communicate the value of monitoring. These principles complement
118 existing guidelines for developing monitoring programs (e.g. Reynolds et al. 2016), and monitoring-
119 management frameworks (e.g. Williams 2011, Schwartz et al. 2012). Central to all these frameworks
120 is a holistic and cyclical view of improving monitoring and management through learning, evaluating
121 and applying new knowledge. We outline how our principles fit with such frameworks with the
122 specific aim of improving conservation actions for threatened species (Fig. 1). Our principles,
123 although designed to address monitoring of threatened species, are equally applicable to the
124 monitoring of threatened ecological communities.

125 ***Principle 1. Integrate monitoring with management***

126 Threatened species monitoring is often poorly integrated with management, even for species with
127 dedicated monitoring programs (Legge et al. 2018). Failing to explicitly link the two limits the
128 potential to positively influence conservation outcomes and document the effectiveness of actions
129 (Martin et al. 2012). A threatened species monitoring program should complement a recovery plan
130 (or analogous process) with clearly articulated management responsibilities and accountabilities.
131 These monitoring and management plans should be publicly available (e.g. online reports, published
132 management plans) to ensure transparency in process and accountability for actions, and be
133 regularly reviewed and updated.

134 Many monitoring-management frameworks have been devised to help plan, design and implement
135 an integrated monitoring-management plan (e.g. Schwartz et al. 2012, Reynolds et al. 2016). These
136 frameworks vary, but all begin by defining and scoping the problem (or problems) affecting a species
137 (Fig. 1). These initial steps focus on developing compatible conservation monitoring and
138 management aims and outlining existing and potential management actions and strategies.
139 Collaboration and integration at this early stage facilitates greater uptake and implementation of
140 new knowledge by managers later in the management cycle (Nichols and Williams 2006). An
141 understanding of the management context further helps to identify priority areas for monitoring
142 based on management needs and knowledge gaps (Nichols and Williams 2006). Clarifying
143 relationships between threats, actions and species persistence helps to prioritise management
144 actions and refine what monitoring is required to improve our understanding and management.
145 Sometimes limited knowledge of these relationships can stall decisions on how to act. In such
146 situations, Value of Information, in combination with expert elicitation, can help quantify the
147 benefits of resolving uncertainty through monitoring and refine what data are required (Runge et al.
148 2011). For example, Bode et al (2017) used expert elicitation along with ecosystem modelling to
149 illustrate the links between threats to Malleefowl (*Leipoa ocellata*) and effective management
150 action; this process has subsequently helped guide management and monitoring needs. In other
151 cases, critical management decisions may need to be made in the absence of certainty or monitoring
152 data. However, monitoring the outcomes of such management decisions is essential (Radford et al.
153 2018).

154 Integration with management is also important during the monitoring design phase. To encourage
155 management accountability and action, the monitoring design should outline decision triggers
156 (Lindenmayer et al. 2013) and identify who is responsible for management intervention. Decision
157 triggers indicate critical stages along a species' population trajectory, or a level of impact from
158 threatening process, where an action is required (Lindenmayer et al. 2013, Addison et al. 2016, Cook

159 et al. 2016). Often, immediate and decisive action is necessary to avert negative outcomes or
160 prevent extinction (Martin et al 2012). For example, decisive action by the Orange-bellied Parrot
161 (*Neophema chrysogaster*) recovery team in response to critically low numbers of wild individuals
162 triggered a captive breeding program that averted extinction of the wild population (Martin et al
163 2012). Conversely, indecision and opaque accountability meant that the Christmas Island Pipistrelle
164 (*Pipistrellus murrayi*) was monitored to extinction (Martin et al 2012). Decision triggers should be
165 identified early to minimise indecision, and enforce action and accountability in a timely fashion
166 (Martin et al. 2012), yet such triggers are rarely defined during the design phase of monitoring
167 programs.

168 The next two phases of the monitoring-management cycle focus on evaluating monitoring data (i.e.
169 learning) and improving future management decisions (Fig. 1). Evaluation and reporting ensures that
170 monitoring results inform management and other stakeholders, enabling responsive action (e.g. via
171 decision triggers) and adjustments to ongoing monitoring and management action. Evaluation
172 should occur at multiple levels. At the species or population level, analysing monitoring data can
173 quantify trends in distribution and abundance, which can inform future projections of species or
174 population trends, and be used to review listing status under threatened species legislation. For
175 example, ongoing monitoring of Woylies (*Bettongia penicillata*) tracked initial population increases
176 followed by subsequent unexpected declines which prompted a re-listing of the species (Groom
177 2010). At the program level, evaluation reveals the effectiveness of management actions, suitability
178 of methodological approach, efficiency of resource allocation, and explains how well the program is
179 meeting conservation objectives. For example, review of a long-running vertebrate monitoring
180 program in Northern Australia revealed that statistical power to detect further declines in occupancy
181 was low. This prompted a re-design of the program and changes to the location, timing and
182 frequency of monitoring (Einoder et al. 2018). Evaluation, and subsequent program improvement,
183 ensures effective and efficient threatened species monitoring and management.

184 *Principle 2: Design a fit-for-purpose program*

185 Threatened species monitoring can rarely be a by-product of generic biodiversity monitoring (i.e.
186 'surveillance' monitoring). It needs to be targeted, question-driven and scientifically robust, to be
187 able to detect and quantify causes of decline and evaluate management effectiveness (Lindenmayer
188 and Likens 2018). The design of a threatened species monitoring program (i.e. where, when, what
189 and how to survey) must address the monitoring objectives and questions, be tailored to suit the
190 specific attributes of the target species and have adequate statistical rigour with respect to the

191 monitoring objective (Lindenmayer and Likens 2018). Failure to consider these design issues could
192 result in a costly data collection exercise that is unable to detect causes and effects, and ultimately a
193 waste of resources that could otherwise be spent on management (Legg and Nagy 2006).

194 The design of a monitoring program for threatened species is usually more challenging than for non-
195 threatened taxa. Species rarity can invoke particular sampling and detection challenges. For
196 example, the Regent Honeyeater (*Anthochaera Phrygia*) is rare and highly mobile (Crates et al.
197 2017), making it difficult to know where to locate monitoring sites to confidently detect population
198 changes given low and variable occupancy over time. Monitoring design should be informed by the
199 type and quantity of data required, what analyses are to be conducted, the variability in the
200 dynamics of the species or system (e.g. spatial coverage, irruptive species), and the probability of
201 detection (Block et al. 2001, Martin et al. 2007). Power analysis is required to ensure that sufficient
202 effort is allocated towards monitoring to detect variation in populations should a change occur (e.g.
203 Einoder et al. 2018). At the most basic design level, sampling methods must be able to adequately
204 represent the abundance of target species or life history stages (e.g. new recruits, Lintermans 2016).
205 Monitoring-program design should also consider the level of skill or training needed, timing and
206 duration of data collection, and opportunities for new technologies. Design and methodology need
207 to also consider cost-effectiveness, ethics, longevity and feasibility of the monitoring program.

208 To meet rigorous design criteria, threatened species monitoring programs can be at risk of becoming
209 extremely expensive and / or logistically unfeasible. Innovative approaches could be investigated
210 that enable more cost-effective and or data-specific methods. For example, advancements in drone
211 technology can facilitate greater precision in data capture (Hodgson et al. 2016) and eDNA has
212 proven to be an effective tool in monitoring some endangered species or threats (Thomsen et al.
213 2012); both techniques promise benefits in cost effectiveness. Similarly, citizen science projects such
214 as the web-based Wildlife Spotter (DigiVol 2018) have increased data processing capacity of camera
215 trap images with high accuracy of species identification (Koleck 2018).

216 *Principle 3. Engage people and organisations*

217 Successful engagement ensures that a monitoring program is valued, integrated in decision making,
218 and has financial and popular support from institutions, partner agencies and across the broader
219 community (Dickman 2013). Effectively engaging with people and organisations means that all
220 relevant stakeholders are involved or consulted appropriately throughout the monitoring process
221 (Burbidge et al. 2011, Ens et al. 2012, Ives and Kendal 2014). Engagement can promote knowledge

222 exchange, develop common or compatible goals, raise awareness, generate political support and
223 create change.

224 Identifying stakeholders and the significance of their role to the success of the monitoring is
225 important at the outset (Fig. 1). Similar to managers of threatened species, there may be
226 stakeholders whose involvement or activities may significantly affect the monitoring and / or the
227 threatened species or ecosystems of interest. These may include users of the threatened species or
228 their habitat (e.g. recreational users and extractors / harvesters of water, minerals, timber, flowers,
229 food, etc.) and adjacent land users whose activities may impact the threatened species (e.g. source
230 of invasive species such as introduced predators). Such stakeholders may be better identified as
231 integrated partners in the monitoring program, because if they 'own it' they are more likely to be
232 part of the solutions and remedial actions if they are required. Other stakeholders whose roles may
233 be more supportive than integral, remain important but may be better engaged differently (e.g.
234 consultation or participation as assistants more so than partners). In the case of the Lord Howe
235 Island Stick Insect (*Dryococelus australis*), early engagement with the local community meant that
236 the recovery of the species was supported from the outset. Soon after its rediscovery, it was listed
237 and a recovery plan that involved the community was produced (Carlile et al. 2009). Recovery of the
238 species has subsequently inspired an ambitious Black Rat (*Rattus rattus*) eradication program that
239 was possible only with strong community support (Carlile et al. 2009). Without some level of
240 consensus between stakeholders on issues of management and recovery approach, monitoring
241 efforts may be hampered.

242 During the design and implementation stages, people with expertise or those closely involved with
243 or conducting the monitoring should be consulted (Fig. 1). Researchers and statisticians are
244 particularly valuable in the design stage to draw out key monitoring questions, highlight limitations
245 in monitoring approaches, and give advice on appropriate methods, data requirements, and data
246 analysis (Lindenmayer et al. 2012). Conversely, field staff and land managers can provide valuable
247 insights to what is happening on the ground, and outline constraints to implementation (Burbidge et
248 al. 2011). Engagement across jurisdictional boundaries (regions, states) facilitates coordinated 'big
249 picture' management and monitoring approaches and multijurisdictional recovery teams play a key
250 role (Lintermans 2013). Regular interaction with those implementing the monitoring (e.g. via training
251 and project updates) ensures problems are quickly resolved, maintains consistent application of
252 methods and data collection, improves morale, and, in the case of volunteers, can lead to greater
253 commitment to the project (Koleck 2018).

254 Inadequate acknowledgement and involvement of stakeholders throughout the monitoring process
255 can, conversely, undermine the capacity of the program to properly address monitoring objectives,
256 and exclude potential supporters. In the case of the nationally vulnerable Baudin's Cockatoo
257 (*Calyptorhynchus baudinii*), limited representation and ad hoc engagement with the fruit growing
258 and timber industries effectively ignored links between these industries and the primary threats (e.g.
259 illegal shooting, insufficient tree hollows) (Holmes et al. 2017). Consideration of additional
260 stakeholder values, beyond that of monitoring threatened species, may further require development
261 of compatible goals, or the design of multi-objective programs. For example, monitoring programs
262 on Indigenous lands should be developed in partnership with Indigenous communities and aim to
263 integrate values and objectives from both Indigenous and non-Indigenous perspectives (Ens et al.
264 2012). Indigenous groups often place importance on integration of environmental outcomes with
265 cultural, social and economic outcomes, and aim to bring together Indigenous knowledge (in
266 culturally-appropriate ways) with western science, which influences both the design and execution
267 of monitoring and management programs (Bohensky et al. 2013, Ens et al. 2015). In North America,
268 the incorporation of Indigenous ecological knowledge is often required in threatened species
269 recovery planning, adding value and improving knowledge outcomes (Polfus et al. 2014). In cross-
270 cultural collaborations, ample time should be provided to understand perspectives, develop trust
271 and build relationships, define the governance structure, and establish intellectual property
272 agreements (Ens et al. 2012, Bohensky et al. 2013). Investing time and energy to develop good
273 stakeholder relationships and develop compatible objectives early in the process can provide long-
274 term benefits such as financial support (Bush Heritage Australia 2017), community advocacy
275 (Ainsworth et al. 2016) and institutional commitment to projects (Burbidge et al. 2011).

276 *Principle 4. Ensure good data management*

277 Data management is an essential component of developing and maintaining effective monitoring
278 programs. Good data management will identify data needs, maintain data integrity, and enable early
279 detection of species trends allowing managers to act quickly (e.g. Groom 2010). However, data
280 management is often neglected and its value apparent only when it fails (Caughlan and Oakley
281 2001). For example, if data analysis requirements are poorly estimated during program design, there
282 may be a failure to make reliable inferences about threatened species (Houston and Hiederer 2009).
283 Similarly, budget blow-outs resulting from a lack of accounting for the cost of data management
284 (Caughlan and Oakley 2001), or data loss resulting from insufficient data security (Whitlock 2011)
285 highlight the need for good data management practices. Data management should be considered
286 throughout the life of a monitoring program and be properly costed at the start of the project. Data

287 management plans assist by outlining how data will be organised, stored, processed and analysed.
288 Such plans further detail responsibilities for who maintains the database, and who can use the data
289 (Vos et al. 2000).

290 An example of a well maintained database for a single species is the National Malleefowl Monitoring
291 Database (Benshemesh et al. 2018). This central data repository was custom designed to enable
292 consistent data collection, accessibility to users, stakeholders and contributors, and facilitate regular
293 reporting. Data are collected and loaded onto the database by volunteers and screened by experts
294 before being analysed; this process streamlines data collation whilst ensuring data quality. Not all
295 monitoring programs, however, are as well coordinated or their data as accessible. Monitoring data
296 from small scale or short term projects are largely unavailable, or difficult to access. A national
297 review of conservation activities for threatened freshwater fish reported that >80% of on-ground
298 actions had associated monitoring, but there were no national databases to store and curate such
299 datasets (Lintermans 2013), making learning from previous monitoring approaches problematic.
300 Emerging web-based technologies are, however, opening up possibilities for online data storage and
301 synthesis, allowing for better integration and access of disparate databases, and powerful tools for
302 processing and modelling (Vitolo et al. 2015).

303 During initial problem framing, it is important to consider what data are required and already
304 available (Fig. 1). Australia's Long Term Ecological Research Network (LTERN 2018), until recently,
305 maintained a large database of species observation records that was available for broader use.
306 Unfortunately, its recent decommission now jeopardises the future of associated monitoring and
307 reporting (Lindenmayer 2017). Other data requirements may be met by collaborating with related
308 monitoring projects to integrate and share data. The development of Australia's first threatened
309 species index relies on collating data from multiple sources (Bayraktarov et al. 2018). Data sharing
310 arrangements can minimise unnecessary monitoring, reduce costs, and value-add to existing data.
311 However, the sensitive nature of threatened species data and the concern for abuse of knowledge
312 (e.g. poaching, interference of habitat) will require that certain data restrictions be considered to
313 protect sensitive species location data (Lindenmayer and Scheele 2017).

314 *Principle 5. Communicate the value of monitoring*

315 Multiple values are inherent in threatened species monitoring, including tracking changes in
316 populations, evaluating management performance and effectiveness, and contributing to improved
317 biodiversity conservation. Extrinsic values, such as empowering local communities (Ens et al. 2012),
318 creating social connections between diverse people and groups (Holmes et al. 2017), and

319 highlighting health, economic and societal benefits (Keith et al. 2017), may not be the primary
320 reason to monitor but can be important for other parts of society and contribute to conservation
321 initiatives (Ives and Kendal 2014). These diverse values are often lost in the overwhelming tide of
322 negative stories about the future of threatened species and ongoing extinctions. Continuous
323 reminders of dire situations can lead to a sense of hopelessness and inevitability, and a lack of
324 motivation to work towards solutions; this only serves to reinforce undesirable outcomes (Garnett
325 and Lindenmayer 2011). Instead, messages need to be framed around solutions to the threatened
326 species crisis, and examples of how monitoring has improved conservation trajectories. These
327 messages need to be communicated broadly and creatively to inspire participation and support of
328 threatened species monitoring (Fig. 1).

329 The telling of success stories is an important tool in inspiring activism and engagement, and
330 promoting the value of monitoring. Several authors have done this eloquently, compiling a list of
331 conservation success stories to inspire optimism (Balmford 2012, Garnett et al. 2018). Support,
332 especially in the form of funding, can be further encouraged by spruiking novel and unusual
333 elements of a species' biology, and innovative monitoring methods or management approaches. For
334 example, the Lord Howe Island Stick Insect has achieved widespread fame and support, a rare feat
335 for an insect, due to a creative campaign capitalising on quirky aspects of the species biology (large
336 size), the charm of its rediscovery (an adventurous tale of rock climbing on an isolated sea spire),
337 and the diverse use of media and educational tools (e.g. books, film, school programs) (Carlile et al.
338 2009). Similarly, the Difficult Birds Research Group (DBRG 2018) have used original messaging (e.g.
339 cartoons) to communicate their innovative management approaches and successfully attract crowd
340 funding for several threatened bird species.

341 Conservation success stories and messages of hope may, however, not appeal to all members of
342 society due to different underlying values. In such circumstances, messaging that speaks to different
343 values can be more useful. For example, the old growth forests of Mountain Ash (*Eucalyptus*
344 *regnans*) in the Central Victorian highlands are home to a range of species, including the critically
345 endangered Leadbeater's Possum (*Gymnobelideus leadbeateri*), and vulnerable Greater Glider
346 (*Petauroides volans*). The forest ecosystem is also listed as critically endangered by the IUCN (Burns
347 et al. 2015). Despite clear and longstanding promotion of these conservation values, one of the main
348 threatening processes (clear-fell timber harvesting) continues (Burns et al. 2015). This has prompted
349 researchers and advocates to diversify their messaging. Environmental accounting is being used to
350 put an economic value on the range of natural values of these forests (e.g. water provisioning,
351 carbon sequestration, cultural and recreational services) (Keith et al. 2017). This message draws in

352 other elements of society, such as those interested in employment, health benefits and economic
353 growth. Communicating the value of monitoring through creative messaging can foster broad(er)
354 support among stakeholders, secure funding and facilitate uptake and integration of monitoring into
355 management (Ives and Kendal 2014, Lindenmayer and Likens 2018).

356 The value of threatened species monitoring can be further communicated through education and
357 engaging conservation champions to teach people of all ages about the value of threatened species
358 and the role of monitoring. Mulligan's Flat, a conservation reserve in the Australian Capital Territory,
359 has successfully motivated people to be interested in the conservation of several threatened
360 species, through visits to schools and community events, showcasing animals such as the Eastern
361 Bettong (*Bettongia gaimardi*). Conservation champions can influence and strengthen values, and
362 drive species recovery. Local champions, in particular, can lend credibility to conservation initiatives,
363 and mobilise action, exemplified by the conservation trajectories of two almost morphologically
364 identical, equally threatened birds (Ainsworth et al. 2016). In the first instance, local advocacy led to
365 strong emotional attachment to the Capricorn Chat (*Epthianura crocea macgregori*), resulting in
366 increased awareness, government funding and effective conservation actions. In contrast, the
367 Alligator River Chat (*Epthianura crocea tunneyi*) had no local support; it subsequently received no
368 dedicated funding, was infrequently monitored, and no recovery program was implemented. Social
369 values are influential in determining conservation effort, thus it is important to understand what
370 motivates people in order to effectively engage and promote positive action.

371 **Conclusion**

372 Effective threatened species monitoring can make an important contribution to improved
373 conservation outcomes. We outline five principles designed to improve threatened species
374 monitoring. They serve as a reminder of key elements to consider when planning, designing,
375 implementing and reviewing monitoring programs. First, monitoring must be integrated with
376 management with clear objectives, transparency and accountability. Second, a fit-for-purpose
377 monitoring design is required to address specific monitoring questions. Third, inclusive, respectful
378 engagement with a broad range of stakeholders is necessary for shaping monitoring objectives and
379 securing the future of the program. Fourth, data management needs to be comprehensive and
380 considered early in the design phase. Lastly, the value of monitoring must be enthusiastically and
381 creatively communicated to ensure that its contribution to threatened species conservation, and
382 broader societal values, is understood and supported. Implementation of these principles will not
383 prevent species extinctions. However, when conservation actions and decisions are underpinned by

384 good processes and knowledge, declines due to inaccurate or irrelevant data, inefficient or
385 ineffective management actions, poor knowledge transfer and communication, and lack of support
386 or awareness can be avoided. As practitioners in this space, we need to promote the value of
387 monitoring and increase its efficacy to enable informed management and enhanced conservation of
388 our threatened biodiversity.

389

390 **Acknowledgements**

391 Funding from the Australian Government's National Environmental Science Programme through the
392 Threatened Species Recovery Hub facilitated the workshop and preparation of this paper. The figure
393 was developed with assistance from Claire Foster.

394 **References**

- 395 Addison, P. F. E., Cook, C. N., and de Bie, K. (2016). Conservation practitioners' perspectives on
396 decision triggers for evidence-based management. *Journal of Applied Ecology* **53**:1351-1357.
- 397 Ainsworth, G. B., Aslin, H. J., Weston, M. A., and Garnett, S. T. (2016). Do social values influence
398 levels of conservation effort in threatened species? The case of two Australian chats. *Oryx*
399 **50**:636-645.
- 400 Balmford, A. (2012). *Wild hope: on the front lines of conservation success*. University of Chicago
401 Press, Chicago.
- 402 Bayraktarov, E., Ehmke, G., Tulloch, A., Driessen, J., O'Connor, J., Barnes, M., Woinarski, J., Garnett,
403 S., McRae, L., Lindenmayer, D. B., Avery-Gomm, S., Morgain, R., Nguyen, H., Watmuff, J.,
404 MacGregor, N., Byrne, M., Hardie, M., Joseph, L., Mokany, A., Bennison, K., Brazill-Boast, J.,
405 Carter, O., Chauvenet, A., Guru, S., Hill, B., Hodgson, J., Holewa, H., Kark, S., Kitchin, M., Kutt,
406 A., La Salle, J., Latch, P., Legge, S., McDonald-Madden, E., Moorrees, A., Nicholls, M.,
407 Robinson, J., Rogers, D., Turak, E., Vardon, M., and Possingham, H. (2018). *A Threatened
408 Species Index for Australia: Interim Report Part 1 – Birds*. National Environmental Science
409 Program's Threatened Species Recovery Hub.
- 410 Benshemesh, J., Southwell, D. M., Lahoz-Monfort, J. J., Hauser, C. E., Rumpff, L., Bode, M., Burnard,
411 T., and Wintle, B. A. (2018). The national malleefowl monitoring effort: citizen scientists,
412 databases and adaptive management. Pages 389-398 *in* Legge, S., Lindenmayer, D. B.,
413 Robinson, N. M., Scheele, B. C., Southwell, D. M., and Wintle, B. A., editors. *Monitoring
414 threatened species and ecological communities*. CSIRO publishing, Melbourne.

- 415 Block, W. M., Franklin, A. B., Ward, J. P., Ganey, J. L., and White, G. C. (2001). Design and
416 Implementation of Monitoring Studies to Evaluate the Success of Ecological Restoration on
417 Wildlife. *Restoration Ecology* **9**:293-303.
- 418 Bode, M., Baker, C. M., Benshemesh, J., Burnard, T., Rumpff, L., Hauser, C. E., Lahoz-Monfort, J. J.,
419 and Wintle, B. A. (2017). Revealing beliefs: using ensemble ecosystem modelling to
420 extrapolate expert beliefs to novel ecological scenarios. *Methods in Ecology and Evolution*
421 **8**:1012-1021.
- 422 Bohensky, E. L., Butler, J. R. A., and Davies, J. (2013). Integrating Indigenous Ecological Knowledge
423 and Science in Natural Resource Management: Perspectives from Australia. *Ecology and*
424 *Society* **18**:20.
- 425 Burbidge, A. H., Maron, M., Clarke, M. F., Baker, J., Oliver, D. L., and Ford, G. (2011). Linking science
426 and practice in ecological research and management: How can we do it better? *Ecological*
427 *Management & Restoration* **12**:54-60.
- 428 Burns, E. L., Lindenmayer, D. B., Stein, J., Blanchard, W., McBurney, L., Blair, D., and Banks, S. C.
429 (2015). Ecosystem assessment of mountain ash forest in the Central Highlands of Victoria,
430 south-eastern Australia. *Austral Ecology* **40**:386-399.
- 431 Bush Heritage Australia. (2017). Annual Report 2016-2017. Bush Heritage Australia, Melbourne.
- 432 Butchart, S. H. M., Walpole, M., Collen, B., van Strien, A., Scharlemann, J. P. W., Almond, R. E. A.,
433 Baillie, J. E. M., Bomhard, B., Brown, C., Bruno, J., Carpenter, K. E., Carr, G. M., Chanson, J.,
434 Chenery, A. M., Csirke, J., Davidson, N. C., Dentener, F., Foster, M., Galli, A., Galloway, J. N.,
435 Genovesi, P., Gregory, R. D., Hockings, M., Kapos, V., Lamarque, J.-F., Leverington, F., Loh, J.,
436 McGeoch, M. A., McRae, L., Minasyan, A., Morcillo, M. H., Oldfield, T. E. E., Pauly, D.,
437 Quader, S., Revenga, C., Sauer, J. R., Skolnik, B., Spear, D., Stanwell-Smith, D., Stuart, S. N.,
438 Symes, A., Tierney, M., Tyrrell, T. D., Vié, J.-C., and Watson, R. (2010). Global Biodiversity:
439 Indicators of Recent Declines. *Science* **328**:1164-1168.
- 440 Carlile, N., Priddel, D., and Honan, P. (2009). The recovery programme for the Lord Howe Island
441 Phasmid (*Dryococelus australis*) following its rediscovery. *Ecological Management &*
442 *Restoration* **10**:S124-S128.
- 443 Caughlan, L., and Oakley, K. L. (2001). Cost considerations for long-term ecological monitoring.
444 *Ecological Indicators* **1**:123-134.
- 445 Ceballos, G., Ehrlich, P. R., and Dirzo, R. (2017). Biological annihilation via the ongoing sixth mass
446 extinction signaled by vertebrate population losses and declines. *Proceedings of the National*
447 *Academy of Sciences* **114**:E6089-E6096.

448 Cook, C. N., de Bie, K., Keith, D. A., and Addison, P. F. E. (2016). Decision triggers are a critical part of
449 evidence-based conservation. *Biological Conservation* **195**:46-51.

450 Cooke, S. J. (2008). Biotelemetry and biologging in endangered species research and animal
451 conservation: relevance to regional, national, and IUCN Red List threat assessments.
452 *Endangered Species Research* **4**:165-185.

453 Crates, R., Terauds, A., Rayner, L., Stojanovic, D., Heinsohn, R., Ingwersen, D., and Webb, M. (2017).
454 An occupancy approach to monitoring regent honeyeaters. *The Journal of Wildlife*
455 *Management* **81**:669-677.

456 Cresswell, I., and Murphy, H. (2017). Australia state of the environment 2016: biodiversity,
457 independent report to the Australian Government Minister for the Environment and Energy.
458 Australian Government Department of the Environment and Energy, Canberra.

459 Dickman, C. R. (2013). Human community ecology: making connections for conservation. *Pacific*
460 *Conservation Biology* **19**:312-319.

461 Difficult Bird Research Group. (2018). <https://www.difficultbirds.com/about-us>. Australian National
462 University.

463 DigiVol. (2018). <https://volunteer.ala.org.au/wildlife-spotter>. Australian Museum.

464 Einoder, L. D., Southwell, D. M., Gillespie, G. R., Fisher, A., Lahoz-Monfort, J. J., and Wintle, B. A.
465 (2018). Optimising broad-scale monitoring for trend detection: review and re-design of a
466 long-term program in northern Australia. Pages 271-280 *in* Legge, S., Lindenmayer, D. B.,
467 Robinson, N. M., Scheele, B. C., Southwell, D. M., and Wintle, B. A., editors. *Monitoring*
468 *threatened species and ecological communities*. CSIRO Publishing, Melbourne.

469 Ens, E. J., Finlayson, M., Preuss, K., Jackson, S., and Holcombe, S. (2012). Australian approaches for
470 managing 'country' using Indigenous and non-Indigenous knowledge. *Ecological*
471 *Management & Restoration* **13**:100-107.

472 Ens, E. J., Pert, P., Clarke, P. A., Budden, M., Clubb, L., Doran, B., Douras, C., Gaikwad, J., Gott, B.,
473 Leonard, S., Locke, J., Packer, J., Turpin, G., and Wason, S. (2015). Indigenous biocultural
474 knowledge in ecosystem science and management: Review and insight from Australia.
475 *Biological Conservation* **181**:133-149.

476 Environment and Communications References Committee. (2013). Effectiveness of threatened
477 species and ecological communities' protection in Australia. Commonwealth of Australia,
478 Canberra.

479 Garnett, S. T., and Lindenmayer, D. B. (2011). Conservation science must engender hope to succeed.
480 *Trends in Ecology & Evolution* **26**:59-60.

481 Garnett, S. T., Woinarski, J., Lindenmayer, D. B., and Latch, P. (2018). Recovering Australian
482 threatened species : a book of hope. CSIRO Publishing, Melbourne.

483 Groom, C. (2010). Justification for continued conservation efforts following the delisting of a
484 threatened species: a case study of the woylie, *Bettongia penicillata ogilbyi*
485 (*Marsupialia:Potoroidae*). *Wildlife Research* **37**:183-193.

486 Hansen, B. D., Clemens, R. S., Gallo-Cajiao, E., Jackson, M. V., Kingsford, R. T., Maguire, G. S., Maurer,
487 G., Milton, D., Rogers, D. I., Weller, D. R., Weston, M. A., Woehler, E. J., and Fuller, R. N.
488 (2018). Shorebird monitoring in Australia: a successful long-term collaboration among citizen
489 scientists, governments and researchers. Pages 151-166 *in* Legge, S., Lindenmayer, D. B.,
490 Robinson, N. M., Scheele, B. C., Southwell, D. M., and Wintle, B. A., editors. *Monitoring*
491 *threatened species and ecological communities*. CSIRO Publishing, Melbourne.

492 Hodgson, J. C., Baylis, S. M., Mott, R., Herrod, A., and Clarke, R. H. (2016). Precision wildlife
493 monitoring using unmanned aerial vehicles. *Scientific Reports* **6**:22574.

494 Holmes, T. Q., Head, B. W., Possingham, H., and Garnett, S. T. (2017). Strengths and vulnerabilities of
495 Australian networks for conservation of threatened birds. *Oryx* **51**:673-683.

496 Houston, T. D., and Hiederer, R. (2009). Applying quality assurance procedures to environmental
497 monitoring data: a case study. *Journal of environmental monitoring* **11**:774-781.

498 Ives, C. D., and Kendal, D. (2014). The role of social values in the management of ecological systems.
499 *Journal of Environmental Management* **144**:67-72.

500 Joseph, L. N., Maloney, R. F., and Possingham, H. P. (2009). Optimal Allocation of Resources among
501 Threatened Species: a Project Prioritization Protocol. *Conservation Biology* **23**:328-338.

502 Keith, H., Vardon, M., Stein, J. A., Stein, J. L., and Lindenmayer, D. (2017). Ecosystem accounts define
503 explicit and spatial trade-offs for managing natural resources. *Nature ecology & evolution*
504 **1**:1683-1692.

505 Koleck, J. (2018). Community involvement in monitoring threatened species: a WWF perspective.
506 Pages 347-360 *in* Legge, S., Lindenmayer, D. B., Robinson, N. M., Scheele, B. C., Southwell, D.
507 M., and Wintle, B. A., editors. *Monitoring threatened species and ecological communities*.
508 CSIRO Publishing, Melbourne.

509 Legg, C. J., and Nagy, L. (2006). Why most conservation monitoring is, but need not be, a waste of
510 time. *Journal of Environmental Management* **78**:194-199.

511 Legge, S., Lindenmayer, D. B., Robinson, N. M., Scheele, B. C., Southwell, D. M., and Wintle, B. A.,
512 editors. (2018). *Monitoring threatened species and ecological communities*. CSIRO
513 Publishing, Melbourne.

514 Lindenmayer, D. (2017). Save Australia's ecological research. *Science* **357**:557-557.

515 Lindenmayer, D., and Scheele, B. (2017). Do not publish. *Science* **356**:800-801.

516 Lindenmayer, D. B., Blair, D., McBurney, L., and Banks, S. C. (2015). Ignoring the science in failing to
517 conserve a faunal icon – major political, policy and management problems in preventing the
518 extinction of Leadbeater’s possum. *Pacific Conservation Biology* **21**:257-265.

519 Lindenmayer, D. B., Gibbons, P., Bourke, M. A. X., Burgman, M., Dickman, C. R., Ferrier, S.,
520 Fitzsimons, J., Freudenberger, D., Garnett, S. T., Groves, C., Hobbs, R. J., Kingsford, R. T.,
521 Krebs, C., Legge, S., Lowe, A. J., McLean, R. O. B., Montambault, J., Possingham, H., Radford,
522 J. I. M., Robinson, D., Smallbone, L., Thomas, D., Varcoe, T., Vardon, M., Wardle, G.,
523 Woinarski, J., and Zerger, A. (2012). Improving biodiversity monitoring. *Austral Ecology*
524 **37**:285-294.

525 Lindenmayer, D. B., and Likens, G. E. (2010). The science and application of ecological monitoring.
526 *Biological Conservation* **143**:1317-1328.

527 Lindenmayer, D. B., and Likens, G. E. (2018). *Effective ecological monitoring*. CSIRO publishing,
528 Collingwood, Vic.

529 Lindenmayer, D. B., Piggott, M. P., and Wintle, B. A. (2013). Counting the books while the library
530 burns: why conservation monitoring programs need a plan for action. *Frontiers in Ecology*
531 *and the Environment* **11**:549-555.

532 Lintermans, M. (2013). A review of on-ground recovery actions for threatened freshwater fish in
533 Australia. *Marine and Freshwater Research* **64**:775-791.

534 Lintermans, M. (2016). Finding the needle in the haystack: comparing sampling methods for
535 detecting an endangered freshwater fish. *Marine and Freshwater Research* **67**:1740-1749.

536 Long Term Ecological Research Network. (2018). <http://www.ltern.org.au> Terrestrial Ecosystem
537 Research Network, University of Queensland.

538 Martin, J., Kitchens, W. M., and Hines, J. E. (2007). Importance of Well-Designed Monitoring
539 Programs for the Conservation of Endangered Species: Case Study of the Snail Kite.
540 *Conservation Biology* **21**:472-481.

541 Martin, T. G., Nally, S., Burbidge, A. A., Arnall, S., Garnett, S. T., Hayward, M. W., Lumsden, L. F.,
542 Menkhorst, P., McDonald-Madden, E., and Possingham, H. P. (2012). Acting fast helps avoid
543 extinction. *Conservation Letters* **5**:274-280.

544 McDonald, J. A., Carwardine, J., Joseph, L. N., Klein, C. J., Rout, T. M., Watson, J. E. M., Garnett, S. T.,
545 McCarthy, M. A., and Possingham, H. P. (2015). Improving policy efficiency and effectiveness
546 to save more species: A case study of the megadiverse country Australia. *Biological*
547 *Conservation* **182**:102-108.

548 Natural Resource Management Ministerial Council. (2010). Australia's Biodiversity Conservation
549 Strategy 2010-2030. Australian Government, Department of Sustainability, Environment,
550 Water, Population and Communities, Canberra.

551 Nichols, J. D., and Williams, B. K. (2006). Monitoring for conservation. *Trends in Ecology & Evolution*
552 **21**:668-673.

553 Polfus, J. L., Heinemeyer, K., Hebblewhite, M., and Taku River Tlingit First, N. (2014). Comparing
554 traditional ecological knowledge and western science woodland caribou habitat models. *The*
555 *Journal of Wildlife Management* **78**:112-121.

556 Radford, J., Q., Wager, R., and Kerezszy, A. (2018). Recovery of the red-finned blue-eye: informing
557 action in the absence of controls and replication. Pages 377-387 *in* Legge, S., Lindenmayer,
558 D. B., Robinson, N. M., Scheele, B. C., Southwell, D. M., and Wintle, B. A., editors. *Monitoring*
559 *threatened species and ecological communities*. CSIRO Publishing, Melbourne.

560 Reynolds, J. H., Knutson, M. G., Newman, K. B., Silverman, E. D., and Thompson, W. L. (2016). A road
561 map for designing and implementing a biological monitoring program. *Environmental*
562 *Monitoring and Assessment* **188**:399.

563 Ritchie, E. G., Bradshaw, C. J. A., Dickman, C. R., Hobbs, R., Johnson, C. N., Johnston, E. L., Laurance,
564 W. F., Lindenmayer, D., McCarthy, M. A., Nimmo, D. G., Possingham, H. H., Pressey, R. L.,
565 Watson, D. M., and Woinarski, J. (2013). Continental-Scale Governance and the Hastening of
566 Loss of Australia's Biodiversity. *Conservation Biology* **27**:1133-1135.

567 Robinson, N. M., Morgain, R., Legge, S., Scheele, B. C., Lindenmayer, D. B., Southwell, D. M.,
568 Bennison, K., Benshemesh, J., Bickerton, D., Brooks, L., Carter, O., Dickman, C. R., Ehmke, G.,
569 Kanowski, J., Koleck, J., Lintermans, M., Marsh, H., Oliver, D., Paltridge, R., Radford, J.,
570 Skroblin, A., Wayne, A. F., and Woinarski, J. C. Z. (2018). Organisational perspectives on
571 threatened species monitoring. Pages 415-427 *in* Legge, S., Lindenmayer, D. B., Robinson, N.
572 M., Scheele, B. C., Southwell, D. M., and Wintle, B. A., editors. *Monitoring threatened*
573 *species and ecological communities*. CSIRO Publishing, Melbourne.

574 Runge, M. C., Converse, S. J., and Lyons, J. E. (2011). Which uncertainty? Using expert elicitation and
575 expected value of information to design an adaptive program. *Biological Conservation*
576 **144**:1214-1223.

577 Russell-Smith, J., Lindenmayer, D., Kubiszewski, I., Green, P., Costanza, R., and Campbell, A. (2015).
578 Moving beyond evidence-free environmental policy. *Frontiers in Ecology and the*
579 *Environment* **13**:441-448.

- 580 Schwartz, M. W., Deiner, K., Forrester, T., Grof-Tisza, P., Muir, M. J., Santos, M. J., Souza, L. E.,
581 Wilkerson, M. L., and Zylberberg, M. (2012). Perspectives on the Open Standards for the
582 Practice of Conservation. *Biological Conservation* **155**:169-177.
- 583 Sutherland, W. J., and Wordley, C. F. R. (2017). Evidence complacency hampers conservation. *Nature*
584 *ecology & evolution* **1**:1215-1216.
- 585 Thomsen, P. F., Kielgast, J. O. S., Iversen, L. L., Wiuf, C., Rasmussen, M., Gilbert, M. T. P., Orlando, L.,
586 and Willerslev, E. (2012). Monitoring endangered freshwater biodiversity using
587 environmental DNA. *Molecular Ecology* **21**:2565-2573.
- 588 Vitolo, C., Elkhatib, Y., Reusser, D., Macleod, C. J. A., and Buytaert, W. (2015). Web technologies for
589 environmental Big Data. *Environmental Modelling & Software* **63**:185-198.
- 590 Vos, P., Meelis, E., and Ter Keurs, W. J. (2000). A Framework for the Design of Ecological Monitoring
591 Programs as a Tool for Environmental and Nature Management. *Environmental Monitoring*
592 *and Assessment* **61**:317-344.
- 593 Waldron, A., Miller, D. C., Redding, D., Mooers, A., Kuhn, T. S., Nibbelink, N., Roberts, J. T., Tobias, J.
594 A., and Gittleman, J. L. (2017). Reductions in global biodiversity loss predicted from
595 conservation spending. *Nature* **551**:364–367.
- 596 Waldron, A., Mooers, A. O., Miller, D. C., Nibbelink, N., Redding, D., Kuhn, T. S., Roberts, J. T., and
597 Gittleman, J. L. (2013). Targeting global conservation funding to limit immediate biodiversity
598 declines. *Proceedings of the National Academy of Sciences* **110**:12144-12148.
- 599 Whitlock, M. C. (2011). Data archiving in ecology and evolution: best practices. *Trends in Ecology &*
600 *Evolution* **26**:61-65.
- 601 Williams, B. K. (2011). Adaptive management of natural resources—framework and issues. *Journal of*
602 *Environmental Management* **92**:1346-1353.
- 603 Woinarski, J. C. Z., Garnett, S. T., Legge, S. M., and Lindenmayer, D. B. (2016). The contribution of
604 policy, law, management, research, and advocacy failings to the recent extinctions of three
605 Australian vertebrate species. *Conservation Biology* **31**:13-23.

606
607 **Figure legends**

608 Fig. 1. The five essential monitoring principles (numbered) and how they fit within a four stage
609 monitoring-management cycle (grey boxes).

Monitoring-management cycle

