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ABSTRACT

Monitoring of threatened species and threatened ecosystems is critical for determining population trends, identifying urgency of management responses, and assessing the efficacy of management interventions. Yet many threatened species and threatened ecosystems are not monitored and for those that are, the quality of the monitoring is often poor. Here we provide a checklist of factors that need to be considered for inclusion in robust monitoring programs for threatened species and threatened ecosystems. These factors can be grouped under four broad themes – the design of monitoring programs, the structure and governance of monitoring programs, data management and reporting, and appropriate funding and legislative support. We briefly discuss key attributes of our checklist under these themes. Key topics in our first theme of the design of monitoring programs include appropriate objective setting, identification of the most appropriate entities to be measured, consistency in methodology and protocols through time, ensuring monitoring is long-term, and embedding monitoring into management. Under our second theme which focuses on the structure and governance of monitoring programs for threatened species and ecosystems, we touch on the importance of adopting monitoring programs that: test the effectiveness of management interventions, produce results that are relevant to management, and engage with (and are accepted by) the community. Under Theme 3, we discuss why data management is critical and highlight that the costs of data curation, analysis and reporting need to be factored into budgets for monitoring programs. This requires that appropriate levels of funding are made available for monitoring programs, beyond just the cost of data collection – a key topic examined in Theme 4. We provide examples, often from Australia, to highlight the importance of each of the four themes. We recognize that these themes and topics in our checklist are often closely inter-related and therefore provide a conceptual model highlighting these linkages. We suggest that our checklist can help identify the parts of existing

monitoring programs for threatened species and threatened ecosystems that are adequate for the purpose or may be deficient and need to be improved.

KEYWORDS: Endangered species, threatened ecosystems, biodiversity conservation, monitoring design and implementation, threatening processes, Australia

1. INTRODUCTION

Monitoring in ecology is sometimes termed the "Cinderella science"; shunned, forgotten, and unsupported (Nisbet, 2007). When monitoring programs are established, they are often poorly designed and badly implemented and many eventually fail (Lindenmayer and Likens, 2018): i.e., they do not fulfil their purpose and contribute to their own unpopularity. This is a significant problem for threatened species and ecosystem conservation as monitoring is essential for quantifying trends in populations of species, documenting the condition of ecosystems, and determining the direction and effectiveness of management interventions (such as invasive animal and plant control, species reintroductions, and vegetation restoration) (Reynolds et al., 2016; Legge et al., 2018).

Monitoring programs are particularly important for understanding the status of threatened species and threatened ecosystems, and for managing the factors affecting them (Legge et al., 2018). However, in many jurisdictions, such as Australia, most threatened species and ecosystems (termed 'ecological communities' in Australian environmental law) remain unmonitored or poorly monitored (Scheele et al., 2019). Monitoring threatened species can be particularly challenging for a range of reasons, including that such species are often difficult to detect (Garrard et al., 2014), populations can fluctuate erratically, and are often at very low densities. This can limit statistical power to detect trends and preclude or constrain some kinds of studies such as experimental interventions (e.g. manipulation of habitat) (Legge et al., 2018). Furthermore, our experience indicates that there is a perception in some agencies responsible for threatened species that available funding should be prioritized to management actions (i.e. 'doing something') rather than to monitoring of populations and their response to management action, which may not in itself deliver short-term benefits. This is a problematic perspective because it leads to an ongoing lack of evidence about the effectiveness of, and return on, investment from conservation actions. This can create a perception that conservation actions are not effective or represent poor value for money. A general rule of thumb for management programs is that approximately 10% of the budget should be dedicated to monitoring the effectiveness of management activities, including the responses of species to those actions (Franklin et al., 1999; Lindenmayer and Likens, 2018).

Some of the same deficiencies in monitoring programs for threatened species also exist for threatened ecosystems. For example, there can be few opportunities to manipulate some rare and highly spatially-limited ecosystems to improve their extent, condition or both (e.g. mound springs ecosystems in rangelands Australia). There is increasing global recognition of the need for ecosystem conservation and management (Keith et al., 2013). Several countries, including Australia, maintain listings of, and commitments to conserve, threatened ecosystems. Many of the principles of monitoring for threatened species apply also to monitoring of threatened ecosystems, but there also may be a need to consider additional components including condition, species composition, areal extent, fragmentation and disturbance history (Keith et al., 2018).

Good monitoring programs for threatened species and ecosystems are usually characterized by several key foundational attributes of governance and communication, links to management and policy, design, and data management (Legge et al., 2018; Robinson et al., 2018; Scheele et al., 2018). Here we provide a summary checklist of attributes that we consider should be part of a robust and effective monitoring program for a threatened species or threatened ecosystem. These attributes of effective monitoring programs can be grouped under four broad themes – the design of monitoring programs, the structure and governance of monitoring programs, data management and reporting, and appropriate funding and legislative support. We briefly discuss key attributes of our checklist under these four themes. Our checklist is based on the collective experience of the authors in designing, establishing and maintaining monitoring programs both for threatened species and in ecological monitoring *per se*. It is also based on antecedent work that collated the experiences and views on monitoring programs for threatened biodiversity across many practitioners (Legge et al., 2018; Robinson et al., 2018; Scheele et al., 2018), and that developed a framework for guiding monitoring of threatened species (Woinarski, 2018). We support the various elements in our checklist with examples from threatened biodiversity monitoring programs, primarily in Australia. We recognize that some of the items in our checklist will be familiar to scientists and the managers of threatened species and threatened ecosystems. However, we conclude with commentary on some ways in which the checklist might be used to improve existing monitoring programs and design new programs for threatened species and threatened communities.

2. PROGRAM DESIGN

2.1 Objective setting

Setting clear objectives is a fundamental component of all successful conservation and resource management programs (Muir, 2010; Wintle, 2018). Monitoring programs for threatened species and threatened ecosystems are not different in this regard and are more likely to be effective when they set clear objectives at the outset (Legge et al., 2018). For example, it is important to be transparent about whether the objective of monitoring is to quantify population trends or status trends, determine the effectiveness of a given management intervention (e.g. invasive plant control), or quantify the magnitude of a particular threat (e.g. the extent and impacts of an exotic disease), and in many cases, multiple objectives exist. The choice of objective will also have flow-on effects on how, where, and when monitoring should occur (Wintle, 2018). Clear objectives are best documented in a written form that is developed with, and available to, all parties with an interest in the conservation and management of a given threatened species or threatened ecosystem, but particularly by those agencies or groups that are most accountable for the recovery of the species or ecosystem and the management of its threats. As a general principle, the design and objectives of a monitoring program should be embedded within, and contextualized by, a broader plan of recovery for that species or ecosystem, such that monitoring and management are intricately and explicitly linked (Lindenmayer et al., 2013). Many conservation management programs have overarching objectives of recovering a species or ecosystem such that it is no longer threatened, and monitoring is a key requirement to measure staged progress towards that broad objective.

2.2 Good design, fit for purpose

The experimental design that underpins a monitoring program for a threatened species or ecosystem is a fundamental factor that can influence success or failure of the monitoring program and of the recovery efforts more broadly. Clear design, and its justification, is also necessary to identify the resources needed to meet the monitoring objective, or to help tailor the monitoring program to be most effective within available resources (Southwell et al., 2019).

Some threatened species are highly localized and reduced to very small populations, such that monitoring of the entire population may be tractable and affordable. Other than for highly localized species that are consistently detectable, most monitoring designs will entail some kind of sample of the total population. In order that an unbiased estimate of population change and to help understand where and how particular actions are working to increase the population or area of occupancy, stratification of sampling across the environment (for example by climate, attributes of habitat suitability, management regimes or some other measure) will be required. In many cases, some sites (e.g. a seabird breeding colony supporting most of the species' total population) will have more leverage and significance than others, and hence represent priorities for the establishment of monitoring sites. Experimental designs based simply on geographic space – such as regular spacing of sites a set distance apart (e.g. every 25 km apart) – will rarely be successful, except in the case where a species is very evenly distributed across the environment, the area of occupancy is confined to a small area, or the whole environment can be monitored due to a relatively large investment in monitoring effort (e.g. the biodiversity monitoring program in Switzerland; Federal Office for the Environment, 2017). Automated approaches to simplify the problem of stratifying samples across environmental and management gradients, or across varying levels of habitat suitability described by a species distribution model, exist in freeware statistical software packages (e.g. Southwell et al. 2019).

2.2.1 Detectability

Threatened species are often rare, randomly dispersed such that not all suitable habitat is occupied, and/or cryptic and therefore difficult to detect. Therefore, it is important to distinguish whether a given species is actually occupying a site but observers failed to detect it, or if it is truly absent from an area. Quantifying detection-occupancy patterns (*sensu* McKenzie et al., 2003) can be critical for threatened species monitoring in a range of ways, such as informing how long to spend surveying a site to reduce false-absences and identifying locations where organisms have a very high probability of long-term persistence (and hence where to target management actions) (Garrard et al. 2014). Comparing detectability rates for alternative sampling methods can also inform monitoring cost-effectiveness (Southwell et al., 2019). Advances in the use of dynamic detection-occupancy models means that it is now possible to quantify key attributes of population dynamics including local extinction and colonization of sites (Latif et al., 2016; Maphisa et al., 2019). The utility of dynamic occupancy modelling is well demonstrated through programs for large carnivores that are amongst the most threatened mammals in the world, range over large areas, and require long temporal scales to detect trends. Modelling of data from animal signs and camera traps for example, can offer reliable and efficient means for identifying source populations and drivers of decline across large spatial scales (Karanth et al., 2011; Steenweg et al., 2016).

The problem of detectability applies equally to abundance estimators and occupancy estimators of populations and trends. In the case of occupancy estimators, imperfect detectability indicates that not every time that an observer monitors an occupied site will they detect the species they are looking for, even if it is present at the time of survey. The monitoring state variable measured in a monitoring program based on occupancy surveys is the change (over time and between treatments) in the proportion of sites occupied. Imperfect detectability impacts abundance or density observations and estimators because not every individual of a species can necessarily be observed on every occasion, leading to counts that are an underestimate of true abundance. Various methods have been developed to adjust for individual level detectability when estimating site-level abundance including capture-mark-recapture analysis (Lebreton et al., 1992)and n-mixture modelling for repeated counts of unmarked organisms (Royle, 2004), each of which has useful freeware statistical packages to support analyses (Laake et al., 2013).

In some cases, a combination of methods may be required to establish site occupancy and, in turn, clarify population sizes and trends. A good example is the Giant Panda (*Ailuropoda melanoleuca*) where direct observations and DNA sampling of scats was used to show that populations were somewhat larger than previously recognized (Zhan et al., 2006). Indeed, more recent work, based on multiple methods to establish site occurrence, has suggested that the species is recovering and might be a candidate for down-listing (Swaisgood et al., 2018).

The use of multiple survey methods can be important when monitoring threatened ecosystems or suites of threatened species. Different methods may produce the same overall estimates of species richness, but each can miss vital details of occupancy or abundance for any given species in the community. This dilemma was evident in survey methods used to monitor macro-invertebrate communities in Great Artesian Basin springs (Rossini et al., 2016). Comparisons of three methods revealed similar estimates of family and species-level richness, but species-specific measures of abundance were sensitive to method choice. The design of any monitoring program, based either on occupancy, abundance or other population parameters (e.g. birth rate) requires understanding and measurement of detection performance associated with each candidate field sampling method for each species of interest (Rossini et al., 2016)(Southwell et al. 2019).

2.2.2 Periodicity

Conventional thinking in monitoring programs is that all sites in a given program should be visited at a particular pre-determined frequency (e.g. annually). However, the most cost-effective frequency will vary according to species' life history attributes and generation time, and to the stability or otherwise of environmental covariates as well as threats. In addition, monitoring programs using more sophisticated, statistically-based experimental designs can be highly effective, such as where there is a large area over which inference is sought, but logistical and cost constraints preclude the complete census of all sites in, for example, a given year. As an example, a rotating sampling approach has been developed by statisticians for monitoring groups such as seabirds (Welsh et al., 2000). Rotating sampling involves making a statistically-based selection of a subset of sites in a population of sites that are targeted in a monitoring program. Thus, for example, in any given year, a sample of the population is surveyed, with the sample varying between years so that over time (e.g. five years) all sites are visited at least once. Such a design has been adopted in a monitoring program for arboreal marsupials (including threatened species like Leadbeater's Possum [*Gymnobelideus leadbeateri*] and the Greater Glider [*Petauroides volans*]; (Lindenmayer et al., 2003)), and in a monitoring program for a declining guild (small mammals) in northern Australian (Legge et al., 2019). Importantly, these designs enable many sites to be surveyed (thereby increased the strength of inferences that can be made) but at the same time overcoming the logistical constraints associated with visiting all sites in a given year.

2.2.3 Sufficient power to detect change

A key part of all threatened monitoring programs is the capacity to detect change (and especially the extent of response to a change in a threat or to management intervention), and determining the amount and intensity of monitoring required for such an objective. Such questions are typically explored using a power analysis (e.g. Taylor and Gerrodette, 1993; Hatch, 2003). As an example, recent work has focused on modifying a long-term monitoring study in northern Australia, including Kakadu National Park, aimed at strengthening the design to better quantify trends in biodiversity, including threatened species. In this work, the power of the existing monitoring program for detecting future trends in birds, mammals and reptiles was assessed using species distribution models and spatial simulation (Southwell et al., 2019). The location of sites, as well as the frequency and intensity of monitoring, was modified to maximize power given the total available monitoring budget (Einoder et al., 2018).

2.3 Identification of the most appropriate population attributes to be measured

Many threatened species monitoring studies are (appropriately) focused on counts of the number of individuals in a population or set of populations. Sometimes, however, other variables may be more appropriate to measure. This may be particularly true for long-lived animals or plants where the current persistence of adults may mask key problems with long-term population viability such as a failure of juvenile recruitment (e.g. in the case of some Orca [*Orcinus orca*] populations (Desforges et al., 2018) and extremely long-lived plants [e.g. *Borderea chouardii*] (García, 2003)). In the case of Australian temperate woodland birds (including a range of species of conservation concern), recent studies have indicated that counts of individuals in remnant and restored patches may not be a good surrogate for long-term population trajectory; rather breeding success may be a better indicator (Belder et al., 2018; Belder et al., 2019). Other potential parameters that may be insightful to monitor include health or disease prevalence, sex ratio, mortality rates and causes, age structure, incidence and impacts of threats (Legge et al., 2015). By documenting sex ratios in Kakapo (*Strigops habroptilus*), Clout et al. (2002) demonstrated that supplementary feeding produced a male-biased offspring sex ratio that could have deleterious long-term effects for recovery of the species. Likewise, carefully targeted monitoring revealed a far more rapid (and consequential) decline in genetic variability than in population size for a population of the Critically Endangered Mountain Pygmy-possum (*Burramys parvus*) at a site in Victoria, Australia, prompting a novel management intervention (Weeks et al., 2017) (see section 3.1 below).

The phenology of threatened species may be especially important now that many are at risk of being decoupled from broader ecosystems by climate change. For example, detecting the early stages of separation in co-dependent pollinators and plants may signal impending declines in either (Robbirt et al., 2014). In many cases, a considered mix of population parameters, rather than for example counts of individuals or breeding success alone, will provide most insight into management needs and success.

Much monitoring of threatened species is specifically tailored to report on trends in individual species. However, there may be cost-efficiencies and opportunities for further insights if monitoring considers multiple co-occurring species that may be responding to similar threats and management actions. For example, a multi-species monitoring program has demonstrated marked recovery of many breeding colonies of seabirds, and of threatened plants, on Macquarie Island following eradication of introduced cats, rabbits and rodents (Springer, 2018).

For threatened ecosystems, monitoring should include consideration of a different but parallel suite of attributes, including successional stage, extent, connectivity and fragmentation, species composition (with particular focus on diagnostic or ecologically significant species), and threats (e.g. Burns et al., 2015; Taylor and Lindenmayer, 2019).

2.4 Consistency in methodology and protocols through time

A fundamental tenet of all effective ecological monitoring, including monitoring of threatened species, is the maintenance of the integrity of long-term datasets (Lindenmayer and Likens, 2018). Breaches of integrity can lead to irreparable breaks in a time series and cause monitoring programs to fail. Consistency in the methods used to gather field data is the best way to maintain the integrity of long-term data and maximise power to infer trends and drivers (Likens, 1989). However, monitoring may benefit from new approaches and improved tools: for example, camera trapping has radically increased our capacity to detect many species and enhanced the logistical efficiency of sampling for many threatened animal species. Similarly, eDNA (environmental DNA) can be obtained from, for example, samples of soil and water rather than the species itself and allow for rapid and cost-effective monitoring for many species, including highly cryptic taxa (Day et al., 2019).

A challenge for many long-established monitoring programs is to consider how to make use of new approaches without compromising the program's continuity and integrity. Typically, this is done through a period of calibration. An example comes from the long-term ecological monitoring program at Booderee National Park, where logistical challenges made it impossible to maintain long-term pitfall trapping, with it being replaced by the deployment of artificial substrates. The two approaches were maintained side-by-side for two full years of monitoring before pitfall trapping was discontinued. Statistical analyses of the resulting data identified those species for which changes in methodology significantly influenced counts and, in turn, affected inferences about population trajectories (e.g. for the Small-eyed Snake *Cryptophis nigrescens*) (Welsh et al., unpublished data).

2.5 Ensuring monitoring is long-term

Monitoring programs will often need to be maintained for prolonged periods to be effective. This is because it can take many years for species and ecosystems to recover, there is often high natural variability in ecological systems, or the status of species (or the incidence and impacts of threats) may change. Changes in threat status can occur unexpectedly, demanding new forms of action sometimes with the need for very rapid response; e.g. the Woylie (*Bettongia penicillata*) in south-western Australia (Marlow et al. 2015; Wayne et al. 2015, 2017). This long-term continuity of monitoring can be critical when new threats emerge, species and ecosystems rapidly deteriorate, and/or threatened species and ecosystems that had ostensibly recovered may again be at risk. For example, the Tibetan Antelope (*Pantholopos hodgsonii*) in western China recovered strongly from previous low populations caused by poaching, but is now again threatened by the indirect impacts of climate change (Pei et al., 2019). Unforeseen benefits of long-term monitoring have been shown to be very high in many instances, including the rapid corroboration (and implementation of recovery actions) of hypothesized impacts of Tasmanian Devil Facial Tumor Disease (Wintle et al., 2010).

Long-term monitoring is especially important where hyper-variable inter-annual conditions can drive large fluctuations in populations, making it challenging to distinguish long-term trajectories from annual variation. The need to consider and interpret such temporal variability in monitoring data and hence the need for long-term monitoring programs is especially marked in arid and semi-arid Australia where rainfall conditions are erratic (Edwards, 2013; Dickman et al., 2014), but the issue is also relevant in temperate areas. For example, in south-eastern Australia, monitoring of the Greater Glider (*Petauroides volans*) showed evidence of between-year drought effects (Lindenmayer et al., 2011), but long-term monitoring has been important to establish major declines in populations over the past 20 years (Lindenmayer and Sato, 2018).

3. STRUCTURE AND GOVERNANCE

3.1 Embedding monitoring into management

No species, including threatened species, should be monitored passively until they go extinct (Martin et al., 2012). Monitoring should be embedded in management, informing both when management is working, and also when changes to that management are required. Embedded monitoring allows not just assessment of the efficacy and cost-effectiveness of management action, but also reporting on that action to the wider community of policy-makers and the public. Embedded monitoring also allows triggers for pre-emptive action to be set, so that rapid research and management responses can be catalyzed once a problem is first evident, and before major problems occur (such as precipitous declines or even global extinction) (Lindenmayer et al., 2013). An example is where monitoring results show rapid decline of a species in the wild such that continuation of the trend would rapidly result in the population becoming unviable and all management responses compromised. In such cases, monitoring results could support a decision to intervene and, for example, supplement in-situ populations with individuals from other populations and thereby boost genetic variability and population performance. This occurred in populations of the Mountain Pygmy-possum in Victoria, Australia (Weeks et al., 2017). In other cases, monitoring data may indicate a need to remove animals from the wild and commence captive breeding as a prelude to later reintroduction programs. This occurred after the rediscovery of a small wild population of the Black-footed Ferret (*Mustela nigripes*) in the mid-west of the USA with a subsequent reintroduction and spectacular recovery of the species (Santymire et al., 2014). In an Australian context, there are many similar cases of such interventions to remove animals from the wild and commence *ex-situ* conservation actions (Sheean et al., 2012). Examples include the Orange-bellied Parrot (*Neophema chrysogaster*) (Stojanovic et al., 2017), the Mala (*Lagorchestes hirsutus*) (Langford and Burbidge, 2001; Woinarski et al., 2014) and Christmas Island Blue-tailed Skink (*Cryptoblepharus egeriae*) (Andrew et al., 2018).

3.2 Management efficacy and management relevance

Although monitoring provides the mechanism to determine the effectiveness of management interventions, it is remarkable how seldom this is done. One example in which the ecological effectiveness of interventions has been quantified is the control of the invasive plant Bitou Bush (*Chrysanthemoides monilifera monilifera*) in Booderee National Park in Jervis Bay Territory, in coastal eastern Australia. The area invaded by Bitou Bush supports populations of the endangered Eastern Bristlebird (*Dasyornis brachypterus*) as well as threatened ecosystems such as Coastal She-Oak Woodland. Significant amounts of the management budget for Booderee National Park are dedicated to controlling Bitou Bush. Monitoring has determined which combination of spraying and burning is the most ecologically effective treatment not only for removing the species, but also for stimulating the recovery of both native vegetation cover and the Eastern Bristlebird. Data on management costs have also helped determine that the most ecologically effective treatment regime is also the most cost-effective form of invasive species management (Lindenmayer et al., 2017). Another compelling example of the value of long-term monitoring in determining management effectiveness is the use of long-term citizen Malleefowl mound monitoring in determining the effectiveness of fox baiting in improving Malleefowl populations (Hauser et al. 2019). Possibly the highest profile example of monitoring for determining population management (harvesting quotas) and learning about the impacts of hunting on species is the North American Mallard adaptive management program (Johnson and Williams, 1999).

An important part of monitoring the effectiveness of management interventions is that the monitoring program needs to be management relevant. In the USA, threatened species monitoring and reporting is a legislated requirement, considered part of the recovery program requirements for agencies responsible for managing species listed under the US Endangered Species Act (United States Fish and Wildlife Service, 1973). Similarly, monitoring is also mandatory for agencies responsible for threatened species and threatened habitats in Europe under the Birds and Habitats Directives (Kramer, 2013). Monitoring programs that are not relevant to management are at risk of failing (Lindenmayer and Likens, 2018). A good example of a monitoring program that has passed the test of management relevance through being strongly connected to applied management interventions, is the program thathas documented the pre-management state and subsequent recovery of seabird colonies and vegetation following the eradication of exotic predators, rabbits and rodents on sub-Antarctic Macquarie Island (Springer, 2018). Garnett et al. (2018) and Legge et al. (2018) provide numerous other examples of Australian threatened species monitoring, management and recovery.

A key requirement for the successful integration of monitoring within a broader management context is that monitoring results are analyzed and reported in a timely fashion, that these results are communicated and interpreted frankly to the responsible management agencies, and that those management agencies are appropriately responsive to such information.

3.3 Community engagement and acceptance

Monitoring programs, including those for threatened species, are more likely to persist and be effective when they have strong community support, including community involvement in aspects of the monitoring. Meaningful partnerships with communities and other stakeholders usually means involving them in key components of monitoring programs such as identifying objectives, developing field protocols, and establishing an appropriate governance structure. In an Australian context, Indigenous communities are custodians of the land supporting a large proportion of the country's threatened species (Renwick et al., 2017), and genuine cross-cultural partnerships are an essential underpinning for collaborative work.

There are many examples of monitoring programs with strong community engagement and robust citizen science support (e.g. Jackson et al., 2015; Torre et al., 2019). These range from the Breeding Bird Survey in the USA to targeted programs such as those for the Greater Bilby (*Macrotis lagotis*) on Martu lands in north-western Australia (NESP, 2019; Skroblin et al., 2020). Another example is the monitoring program for the Malleefowl (*Leipoa ocellata*) which is taking place across many parts of the Australian continent (Hauser et al., 2019). In the case of Malleefowl, the involvement of citizen scientists has drastically reduced survey costs; has increased the spatial and temporal resolution of sampling; and has sustained monitoring over three decades of uncertain funding. The choice of metric to monitor has been crucial to the program's success: monitoring nest/mound activity (in this species, nesting mounds are long-lasting and conspicuous features) rather than the abundance or survival of individuals, is relatively cheap, requires no specialist skills or experience, and can be easily repeated over space and time by volunteers (Benshemesh et al., 2018).

4. DATA MANAGEMENT AND REPORTING

All effective monitoring programs, including those for threatened species, are dependent on reliable, dedicated and high quality curation of the datasets that are collected. This ensures that errors can be corrected, and robust analyses can subsequently be completed in a timeframe relevant for management response. The costs of curation and data management (including the provision of well-described meta-data so that others can access datasets) can be non-trivial (Caughlan and Oakly, 2001). These costs need to be factored into the overall budget for a monitoring program. Some funding bodies such as the National Science Foundation in the USA make it mandatory to curate datasets gathered in initiatives like the Long-term Ecological Research program soon after field data are gathered.

Monitoring data can have limited value for management and policy if it remains unanalyzed and unreported (Møller et al., 2010). Monitoring data and their interpretation also should be publicly accessible. In many cases, the public directly or indirectly funds the monitoring program or management efforts in which the monitoring is embedded, so the public should know what their investments are achieving. Accessibility to the results from monitoring also helps generate community interest in, and support for, conservation efforts and the monitoring programs within them. Public reporting of monitoring information may also help raise financial contributions. Dixon et al. (2019) showed that when monitoring data are stored in a publicly available database, they are more likely to be used to inform management. In Australia, an excellent example of well-curated and readily accessible datasets that include records of threatened species is the work of the Desert Research Group in western Queensland (LTERN, nd).

5. APPROPRIATE FUNDING AND LEGISLATIVE SUPPORT

Threatened species monitoring has costs and will not occur, or will be ineffective, without adequate funding and other resources. In a small number of countries (such as Switzerland), sufficient funding is dedicated to ensuring that a nationwide biodiversity monitoring program is maintained, including for a range of threatened species (Federal Office for the Environment, 2017). In contrast, nations such as Australia dedicate an order of magnitude **less** funding than required to recover threatened species, including inadequate funding for effective monitoring (Wintle et al., 2019).

A mandate for regular reporting can be the stimulus to ensure monitoring data continue to be gathered, analyzed, and then presented (Kramer, 2013). For example, the nationwide biodiversity surveys conducted annually in Switzerland must, by legislative decree, be formally reported every three years (Federal Office for the Environment, 2017). In Australia, there is comparably mandated 5-year State of Environment Reporting, but these documents have rarely included time series data (Lindenmayer et al., 2015), especially for threatened species and ecosystems.

One mechanism to help ensure legislative support and highlight the need for and role of monitoring within an overall recovery effort is to explicitly include a monitoring prospectus and program within the broader recovery plans that frame conservation management for threatened species (e.g. Woinarski et al., 2017). In Australia, such recovery plans have some legislative clout (albeit less so than for the USA), but are not necessarily funded, and are developed for only a minority of threatened species.

Monitoring programs, including those for threatened species and ecosystems, are typically the last items funded and the first to be cut, under the constrained budgets that characterize environmental management in most jurisdictions globally (Lindenmayer and Likens, 2018). Budget constraints significantly impede effective biodiversity conservation worldwide (Waldron et al., 2017), including in Australia (Wintle et al., 2019). To have any chance of sustained funding, monitoring programs for threatened species and ecosystems will need to demonstrate that they are cost-effective, provide good return on investment, and have community support (Garnett et al., 2018). Relatively few quantitative examples exist to show this. One is the Environmental Stewardship Program in endangered Box-Gum Grassy Woodlands in south-eastern Australia where a novel rotating sampling approach was used to sub-sample sites to reduce costs but maintain a robust experimental design that underpinned the monitoring work (Lindenmayer et al., 2012).

Budgets sufficient for long-term maintenance of adequate monitoring programs for threatened species are rarely available and hard won. Many monitoring programs rely on insecure funding subject to the short-term whims of changing governments. A key challenge for monitoring of threatened species and ecosystems is to attempt to grow and better secure the funding pool: this may be progressed through the use of philanthropy, incorporation of individual or collective monitoring programs as integral components of high-level state-of-the-nation or comparable reporting, legislative requirements, or through long-term commitments to monitoring from development-offset programs. Monitoring design also will need to be tailored to cost-effectiveness, as many ideally designed monitoring programs have failed once an initial sufficient source of funding has been exhausted. A common challenge of monitoring design is to find the optimal design of an adequate and informative monitoring program within the context of resourcing that can be sustained over a time period relevant to the recovery of a threatened species.

Table 1. Checklist of considerations in developing robust monitoring programs for threatened species and threatened ecosystems.

<u>Theme #1 The design of monitoring programs</u>

- Appropriate objective setting
- Identifying the most appropriate attributes to be measured
- Maintaining comparability in methodology and protocols through time
- Ensuring monitoring has sufficient statistical power for its purpose and is long-term

<u>Theme # 2 The structure and governance of monitoring programs</u>

- Embedding monitoring into management
- Testing the effectiveness of management interventions

- Producing results that are relevant to management
- Engaging with the community groups and other stakeholders

Theme #3 Data management, analysis and reporting

Theme #4 Appropriate funding and legislative support

6. GENERAL DISCUSSION

We have outlined what we consider to be some of the critical attributes of effective monitoring programs for threatened species and threatened communities. We recognize that many of these attributes are fundamentally inter-related (Figure 1). For example, the amount of available funding will clearly affect the size and scale of a monitoring program and hence influence many key aspects of design, including its effectiveness and sensitivity. Similarly, whether monitoring is legislated as part of threatened species recovery programs (and therefore mandated) will influence not only levels of resources but also whether it is likely to be successful. Indeed, we argue that robust monitoring programs should be mandated as part of all species and ecosystem recovery efforts and be explicitly identified (and appropriately funded) as a key action in all planning documents such as Threat Abatement Plans, Action Statements, Conservation Advices and Recovery Plans.

There is a long history of poorly designed and poorly implemented monitoring programs (Thompson et al., 1998; Gardner, 2010; Lindenmayer and Likens, 2018). In some cases, it may be possible to resurrect an initially poorly designed monitoring program guided by some of the attributes identified here. This process can be deemed to be Adaptive Monitoring (*sensu* Lindenmayer and Likens, 2009) in which an existing monitoring program is altered in response to the need to address new questions, the development of new technologies, or other issues (such as the rapid decline of a target threatened species).

We are acutely aware that not all effective monitoring programs for threatened species are necessarily characterized by all of the attributes identified in the checklist in Table 1. However, some items in Table 1 will typically be more important than others, although which ones will likely be context-dependent. For example, while levels of funding can often be critical, they may not be so important where active community groups can volunteer their time and personal funds to cover a shortfall from more conventional government sources. However, we argue that community groups should not be expected to cover the costs of threatened species monitoring simply because of inadequate support by governments.

An outstanding unresolved issue is whether all threatened species and threatened communities should be targeted for monitoring. For example, monitoring and reporting is required for all species listed under the US Endangered Species Act (United States Fish and Wildlife Service, 1973) and this has, in part, led to such programs generally being robust. Such requirements demand appropriate levels of resources to ensure that suitable monitoring programs can be designed, implemented, and maintained. An alternative approach might be to prioritize threatened species and threatened for monitoring. However, it remains unclear what the best parameters would be for guiding which species and communities should be selected and which should remain unmonitored. Indeed, a decision to not monitor a particular species or communities is one taken with considerable risk as such neglect can have significant effects on the likelihood of successful recovery, as demonstrated a wide-ranging reviews of threatened species and ecosystems in an Australian context (Garnett et al., 2018; Legge et al., 2018).

7. CONCLUDING COMMENTS

With appropriate legislative, funding and governance attributes in place, it is crucial that monitoring is embedded in a management program by the accountable agency that is working towards the recovery of a given threatened species or threatened ecosystem. To achieve recovery, monitoring can: **(1)** provide the evidence base that identifies the relative impacts of putative threats; **(2)** measure the effectiveness of management directed towards the control of those threats; **(3)** determine the level of urgency needed to take such action; **(4)** provide the capability to detect unexpected issues; **(5)** identify the component of the population that most needs (or can respond most substantially to) management attention; **(6)** provide a mechanism for reporting to, and engaging with, a wide community of interests; and **(7)** ultimately chart the progress towards recovery. We argue that these benefits of monitoring will be far more likely to be achieved if the monitoring program is well designed with clearly articulated objectives, with due attention to the attributes that have been described in this article.

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Figure legend

Figure 1. Conceptual diagram highlighting the inter-relationships between key attributes of effective threatened species monitoring programs.

Figure
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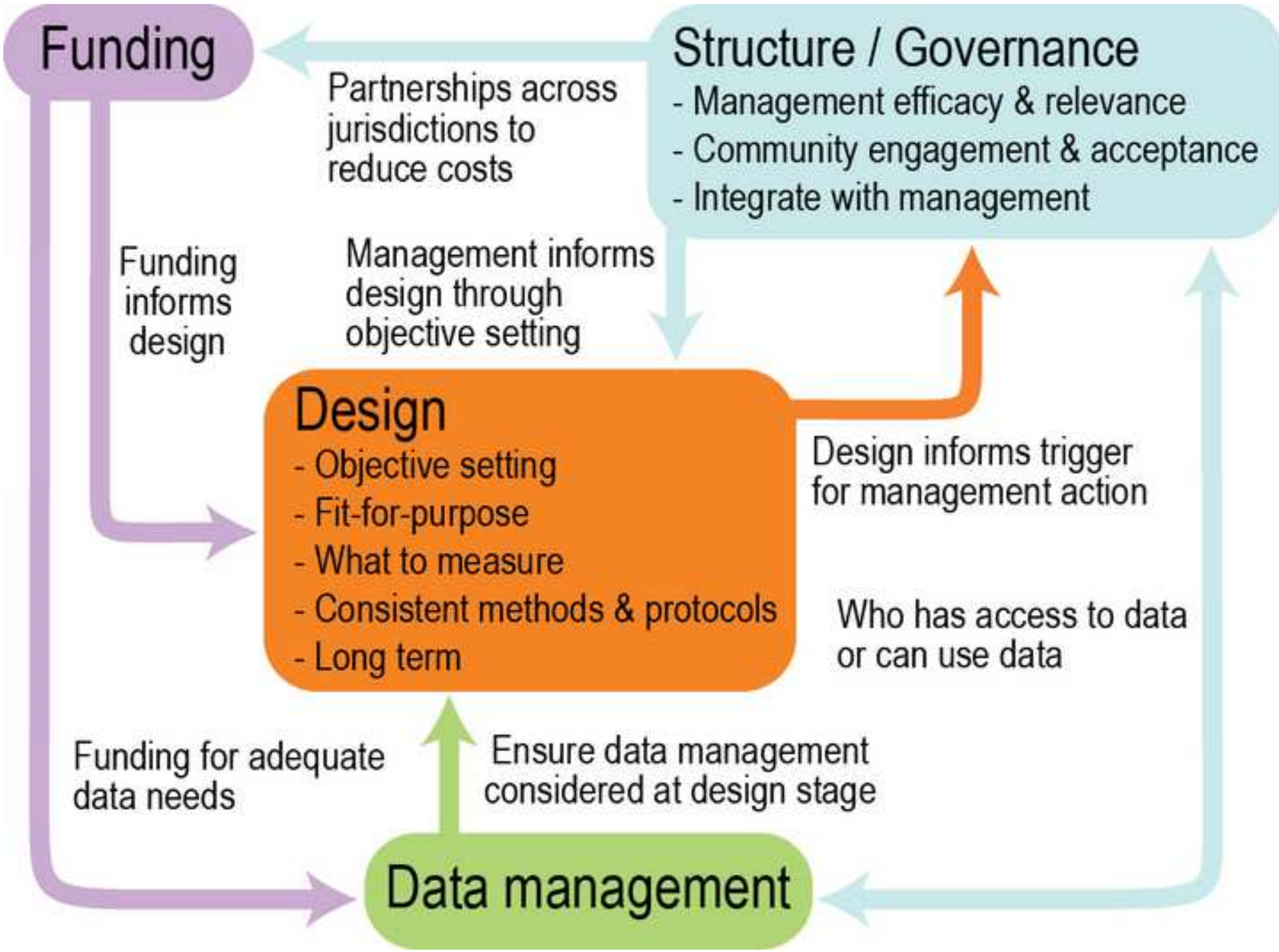

***Declaration of Interest Statement**

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

***Credit Author Statement**

CRediT author statement

David Lindenmayer: Conceptualization; Writing - original draft; Writing - review & editing. John Woinarski: Writing - review & editing. Sarah Legge: Writing - review & editing. Darren Southwell: Writing - review & editing. Tyrone Lavery: Writing - review & editing. Natasha Robinson: Writing - review & editing. Ben Scheele: Writing - review & editing. Brendan Wintle: Writing - review & editing