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Adaptive management informs conservation and monitoring of Australia's threatened malleefowl

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Abstract

Monitoring is an essential component of adaptive management, and a carefully designed program is needed to ensure high-quality data and inferences over realistic time scales. Co-operation among agencies and incorporating citizen science may help enhance learning whilst reducing the financial costs of monitoring. We seek to realise this potential while conserving the Australian malleefowl (*Leipoa ocellata*). An established network of citizen scientists provide low-cost, sustainable annual monitoring data, yet the most effective actions for conserving malleefowl remain highly uncertain. The continent-wide species' distribution presents significant challenges, including multiple environmental strata to sample and numerous management jurisdictions. We outline an adaptive management framework that aims to unify malleefowl conservation priorities nationally, and target monitoring efforts. We elicited a model structure for the drivers of, and threats to, malleefowl persistence in a workshop with land managers and advocates. We parameterised 80 uncertain interactions within this structure using novel ensemble modelling techniques and identified the effectiveness of predator control as a critical uncertainty affecting malleefowl persistence. We developed a classical, spatially replicated experimental design to test whether malleefowl breed more frequently where predators are suppressed. The proposed monitoring design will rely on the contributions of several dozen land managers and 200-300 citizen scientists annually. We have developed a broad stakeholder base, a proactive communication strategy, and an agile approach to accessing resources to foster resilience and longevity in the monitoring program. If malleefowl conservation successfully adapts in response to monitoring outcomes, it will become one of the largest adaptive management programs on the planet.

Keywords: citizen science, *Leipoa ocellata;* feral predator; structured decision making; stakeholder engagement; ensemble modelling; statistical power

1 Introduction

A key challenge within the science of conservation biology is assessing the relative importance of the various threats to species and ecosystems, and consequently identifying the actions that will most effectively conserve those species and ecosystems. Approaches such as structured decision-making (Gregory et al. 2012) and management strategy evaluation (Bunnefeld et al. 2011) offer a logical way of deconstructing and assessing this problem to arrive at a preferred course of action. While these approaches can accommodate a range of knowledge formats, such as field measurements, system models, stakeholder preferences and expert opinion, it is also prudent to specify what inevitably remains uncertain. Adaptive management is a specific form of structured decision-making that allows the most effective actions to be identified in the presence of uncertainty (Walters 1986, Lyons et al. 2008).

Adaptive management was initially applied within the context of natural resource management (Walters 1986), where uncertainty in population growth and carrying capacity was accounted for in the management of fisheries (e.g. Smith & Walters 1981). Waterfowl hunting across North America has been guided by adaptive management for three decades (Johnson et al. 1997), in the face of uncertainty around individual survival rates and the strength of density dependence in recruitment. Applications of adaptive management to conservation have taken longer to develop (Runge 2011). These have included predator control (Innes et al. 1999, Parkes et al. 2006, Whitehead et al. 2008), weed suppression (Gannon et al. 2013), habitat management (Aldridge et al. 2004, Nicol et al. 2015), fire management (Moore et al. 2011), and reintroductions (Armstrong et al. 2007).

Embarking on adaptive management is particularly relevant if uncertainty is present, if learning (i.e. reducing uncertainty) is feasible on a management-relevant time-scale, and where there are opportunities to adjust management as a response to learning (Doremus 2010). Quantitative methods for planning adaptive management are well developed (Chadès et al. 2017). These methods require the specification of management objectives and performance measures, characterisation of uncertainty as multiple alternative models of how actions could influence performance, and a monitoring program design (Lyons et al. 2008). Past adaptive management programs have typically identified a small set of uncertainties (often just one or two) that crucially affect the optimal choice of action (e.g. Walters & Hilborn 1976, Johnson et al. 1997, although see Armstrong et al. 2007 for an exception). Value-of-information analysis can be used to evaluate the benefits of resolving uncertainty in terms of the management objective (Walters 1986). Quantitative analysis can guide how actions should be adjusted as a response to learning (often using control theory and other optimisation approaches; Walters 1986), although socio-political factors are also important (Walters 2007).

The broad philosophy of adaptive management is participatory and collaborative, extending to the person(s) with the authority to make decisions and take actions and the many other stakeholders concerned with the consequences of those actions (Allen & Gunderson 2011, Hopkinson et al. 2017). It is important that their range of perspectives are represented in the management objectives (Susskind et al. 2012). Stakeholders, researchers and other system experts may propose a diverse range of actions and system models for consideration. Leaders or champions, facilitators, researchers and system experts without a stake in management decisions are needed to direct the process and ensure all voices are heard (Allen & Gunderson 2011, Susskind et al. 2012). Similarly, ‘bridging organisations’ can be crucial for facilitating communication and holding participants accountable during planning, action and monitoring (Allen et al. 2011, Hopkinson et al. 2017). Engaging and sustaining such a diverse team is difficult, and a common barrier to successful adaptive management (Allen & Gunderson 2011, Susskind et al. 2012)

Monitoring provides essential feedback within adaptive management (Lyons et al. 2008), and a lack of sustained funding for monitoring is a widespread barrier to programs' success (Walters 2007, Westgate et al. 2013). Recruiting citizen scientists has been proposed as a low-cost and participatory monitoring approach, and it requires commitment from program managers to engage and motivate participants (Aceves-Bueno et al. 2015). Citizen science programs must be rigorous and carefully targeted to meet the requirements of adaptive management.

In this study, we outline our approach to designing a large-scale adaptive management program for the threatened malleefowl (*Leipoa ocellata*). Actions that influence malleefowl persistence are taken by a range of land managers including government agencies, mining companies, Traditional Owners, farmers and other private landholders and leaseholders. Furthermore, the various levels of government have varying authority over different tenures and legislation designed to protect species and habitats (see Appendix A for a summary). A National Malleefowl Recovery Team (henceforth the 'recovery team') is responsible for providing recommendations to these land managers. Their task is hampered by significant uncertainty about which threats and conservation actions most strongly influence malleefowl persistence (Benshemesh et al. 2007, Bode & Brennan 2011, Walsh et al. 2012). The recovery team therefore called for a unified adaptive management framework that integrates the interests and capabilities of varying stakeholders across jurisdictions, and prioritises conservation actions in the presence of uncertainty. The recovery team already supported co-ordinated citizen science monitoring of malleefowl breeding mounds as a potential foundation for program monitoring (Benshemesh et al. 2018). A key challenge to overcome was that prominent methods within adaptive management were not suitable for eliciting and analysing the multiple threats and uncertainties present in the mallee system.

In this paper, we describe the extension and adjustment of adaptive management practices to develop a unified malleefowl conservation plan. In collaboration with the recovery team, we acted as a 'bridging organisation' that engaged and co-ordinated regular communication among land managers, technical experts, and the existing citizen science program. We introduced ensemble modelling as a technique for representing and analysing multi-dimensional uncertainty. We addressed the challenge of sustaining monitoring by building on the existing citizen science program. The effectiveness of our proposed monitoring design was evaluated using a general power analysis structure that was tailored to management priorities.

2 An adaptive management framework for malleefowl conservation

2.1 Management context

The malleefowl is an iconic megapode that spans the Australian continent (3.3 million km^2, BirdLife International 2010; Figure 1). It is nationally listed as vulnerable, and endangered in the eastern states of Australia. Malleefowl have experienced substantial range contraction from their pre-European distribution, following large-scale habitat clearance for agriculture (Benshemesh 2007). Although clearance has slowed considerably in recent decades, it is uncertain if populations continue to decline (Benshemesh et al. 2007). In addition to historic habitat clearance, malleefowl persistence may be threatened by predation from introduced and native species and changing fire regimes (Benshemesh 2007). There is significant uncertainty about which threats and conservation actions most strongly influence malleefowl persistence (Benshemesh et al. 2007, Bode & Brennan 2011, Walsh et al. 2012).

An extensive malleefowl mound monitoring program has developed over the past three decades, growing from a handful of sites in the early 1990s to more than 150 sites in 2016 (Figure 1b). Initially monitoring was often performed by government agencies and consultants. Recruitment of citizen scientists occurred gradually in most areas as locals interested in the species were casually invited to participate in monitoring, and in some cases undertook monitoring of their local site. As word of the program spread through volunteer and friendship networks, the citizen scientist component grew and the program was adapted accordingly to ensure data accuracy. As funding became scarce, citizen scientists increasingly played a pivotal role in the monitoring program. Their involvement has led to substantial cost savings and reduced the program's reliance on continuous funding (Benshemesh et al. 2018).

Historic malleefowl monitoring has focused on annual observations of nesting activity at known breeding mounds, because this is generally regarded as the most feasible and accurate method of measuring trends in the species' conservation trajectory. Adult malleefowl breed most years except following winter drought (Booth & Seymour 1984). Current and past malleefowl breeding mounds are identified via ground searches or remote sensing techniques, such as photogrammetry (Thompson et al. 2015) and LiDAR (Saffer & Peake 2014). Malleefowl pairs occasionally abandon old mounds to create new ones, and so the recovery team recommends that these searches are repeated every 10 years to identify new mounds. Known mounds are visited annually by citizen scientists to observe signs of breeding and predator activity (evidenced by tracks or scats).

More recently, motion-triggered cameras have also been piloted as a means of monitoring malleefowl, their predators, and competitors (Benshemesh 2013). Citizen scientists retrieved data cards from camera traps and sorted through the resulting tens of thousands of photographs. Benshemesh (2013) found that volunteers were readily available, accurate, timely and enthusiastic for these tasks.

While the recovery team had already developed recommendations and established monitoring practices with the co-operation of diverse land managers and citizen scientists (Benshemesh et al. 2018), there was a need to prioritise multiple threats and conservation actions to effectively protect malleefowl populations. In the project outlined in this paper, we addressed most stages of the adaptive management cycle (Figure 2) and established a plan for co-ordinated malleefowl conservation among land managers. First, we engaged malleefowl advocates and land managers in framing the conservation problem (2.2). Using their conceptual models of cause and effect, we characterised and prioritised uncertainty across multiple dimensions (2.3). We designed a monitoring program targeting the highest priority uncertainty, taking advantage of spatial replication (2.4). Conservation action and monitoring rely on the co-operation of many land managers, so we explicitly addressed the challenges of leadership and long-term engagement, communication, and sustained funding (2.5).

2.2 Problem framing

We convened a workshop and used structured decision-making (Gregory et al. 2012) to frame the malleefowl conservation challenge, understand the current state of knowledge, and identify relevant issues for future prioritisation. The 24 attendees included: community advocates and citizen scientists; state government staff responsible for research integration, for environmental management planning and for park management; federal government staff responsible for threatened species support; and university researchers with expertise in structured decision-making, adaptive management, and/or mallee ecosystems.

There was broad agreement among workshop participants that their fundamental objective was to foster the long-term persistence of a self-sustaining malleefowl population. The spatial extent of the population was left unspecified, acknowledging that there has been substantial historic range contraction and there may be future range shifts as a response to climate change. Three indicators were nominated as the quantitative means for assessing this fundamental objective: adult abundance, juvenile abundance, and population occupancy/range. Given the population fluctuations that malleefowl typically exhibit as a response to fluctuating resources, participants noted that high values for these indicators need not be achieved every year in order to fulfil the fundamental objective.

In smaller independent teams, participants developed lists and cause-effect diagrams of the drivers and threats that influence the three indicators. These, in combination with potential management actions, formed the foundation of our system models. While numerous influences were collated, four were broadly agreed-upon as drivers of malleefowl population dynamics: predation, rainfall, grazing and fire. Predation by foxes, cats, dingoes, dogs, raptors and goannas were predicted to directly reduce adult and juvenile malleefowl abundance. Rainfall, grazing and fire potentially interact to affect habitat structure, which provides food, nesting materials, and cover from predators. Herbivores (rabbits, goats, sheep and kangaroos) may compete directly with malleefowl for food, and also deplete the understorey vegetation that is thought to protect malleefowl from predation and provide nesting materials. Fire was expected to cause direct mortality and dramatically alter habitat structure, reducing food availability and exposing malleefowl to predators. Malleefowl have rarely been observed to breed in recently (< 15 years) burned areas and thus broad-scale fires could affect the population's range.

Actions (which can be grouped into strategies or alternatives; Figure 2) were proposed to address threats to malleefowl persistence, including reduction of grazing pressure (e.g. by closing water points or erecting fencing strategically), reducing the density of grazers and predators, strategic fire management, influencing land change and protection, malleefowl translocation, habitat revegetation, supplementary feeding, and erecting road signs. Participants contributed knowledge and located documents that could help characterise the cause-and-effect relationships that affect malleefowl persistence. The relative importance of the identified threats, and our capacity to address them, was not resolved in the literature and so there was substantial uncertainty to characterise through an adaptive management approach.

2.3 Characterising and prioritising uncertainties

The initial workshop (2.2) revealed a complex array of interacting environmental and biotic factors and potential conservation actions influencing malleefowl persistence. We focused on one participant group's causal ecosystem model (Figure 3a), which included 80 interactions between 14 ecosystem components (Bode et al. 2017). While each interaction was captured qualitatively, it was not feasible to specify the interaction strengths quantitatively. Faced with a model with this complexity: (1) participants were unlikely to know about all possible interactive responses, (2) representing uncertainty and differing opinions among stakeholders was difficult, and (3) eliciting all interactions would have placed an excessive burden on participants.

The quantitative strength of each interaction in the ecosystem, i.e. 80 parameters, formed the set of uncertainties for the adaptive management problem. We used a single ecosystem model structure, prescribing an equation for each of the 14 ecosystem components (e.g. malleefowl density, fox density, rainfall quantity, see Figure 3a for full list) that included density dependence and responses to every other model component via an interaction parameter (Appendix B). Assuming that we knew only the direction of the interaction (positive, negative or zero; indicated in Figure 3a) from workshop participants, we generated 10^9 different plausible parameterisations of the ecosystem model (Bode et al. 2017). This finite, discrete ensemble of model parameterisations formed a more tractable expression of uncertainty than a set of 80 interaction parameters with continuous probability distributions (Chadès et al. 2017).

We subsequently refined the set of plausible parameterisations by excluding models that contradicted what was known about and had been observed in the system. First, if the long-term equilibrium of a given parameterisation included the extinction of any ecosystem components, it was removed from the set, given that all model components are currently observed in the system. Second, we engaged malleefowl experts via a second workshop and elicited more detailed, quantitative predictions of how the ecosystem would respond to perturbations in each component. Participants described the range of possible component trajectories over 5 years following a perturbation, e.g. changes in fox population density as a response to 3 years in which herbivores occurred at double their long-term average density. We selected the 5% (~10^5) of the remaining ecosystem parameterisations that aligned most consistently with participants' responses (Bode et al. 2017).

Using this reduced ensemble capturing plausible ecosystem dynamics, we predicted the consequences of candidate management actions (Recovery plan interventions; Benshemesh 2007) addressing six threats: disease and inbreeding; fire intensity and severity; predation by introduced cats; predation by introduced foxes; competition by herbivores; and habitat loss and fragmentation (see Appendix B for more details). For each action and each parameterisation in the ensemble, we simulated all components for 5 years and recorded the final malleefowl abundance. We also simulated each parameterisation in the absence of management action, and thus calculated the predicted change in malleefowl abundance arising from each management action. Five of the six actions had the potential to positively or negatively affect malleefowl abundance; addressing disease and inbreeding was very likely to positively affect malleefowl abundance (Figure 3b). Actions addressing fox and cat predation included possibilities for the largest malleefowl population increases, while addressing fox predation and fire intensity included possibilities for the most rapid population declines. Other studies have similarly highlighted uncertainty surrounding the roles of fox predation and control in malleefowl population dynamics (Benshemesh et al. 2007, Bode & Brennan 2011, Walshe et al. 2012). Thus, understanding fox predation and control emerged as a top research priority, with cat predation and fire management also warranting consideration.

2.4 Monitoring design

As we reviewed and expanded the malleefowl monitoring program in this project, we focused on our capacity to learn more about and act to address the threats of fox and cat predation. Learning about the effect of predator control on malleefowl persistence could be accelerated further by spatially replicating management across the species' range (Walters 1986). We investigated a control-impact design by identifying clusters of unmanaged ('control') and predator-managed ('impact') sites with similar characteristics, such as habitat quality and rainfall patterns. Each site within the cluster was expected to experience similar temporal fluctuations in environmental conditions, thus constraining random spatial variation, and enhancing our ability to estimate the effect of predator management.

Even with the advantage of spatial replication, multiple years of data are required from each cluster to effectively distinguish local population dynamics from any global responses to predator management. The monitoring program does not have consistent long-term funding and staffing to guarantee that uncertainty will be resolved by a control-impact experiment (Hopkinson et al. 2017), so it was important that the benefits of implementing adaptive management were assessed over realistic time frames and resource constraints (Walters 2007, Doremus 2010, Allen et al. 2011). We developed a statistical power analysis to evaluate the capacity of the malleefowl monitoring program to resolve uncertainty around the benefits of fox (and potentially feral cat) management.

2.4.1 Statistical power analysis for a predator control experiment

The power analysis estimated the probability that a spatially-replicated control-impact experiment could detect a pre-set range of improvements in malleefowl mound activity arising from predator management (Figure 4). The analysis used historic mound activity data to estimate temporal and spatial fluctuations in the number of active mounds at monitoring sites, and simulated data collection from multiple control-impact two-site clusters occupied by malleefowl (see Appendix C). An experiment of five years duration comprising 36 or more sites (in 18 two-site clusters) had an 89% probability of detecting a 22% increase in mound activity. Mound activity is expected to be proportional to adult malleefowl abundance (and mediated by rainfall). Thus, the ensemble modelling suggests effect sizes of 0-100% are possible (i.e. no effect up to a doubling of malleefowl abundance; Figure 3b). Population viability analysis has previously suggested that smaller effect sizes of 0-35% are plausible (Bode & Brennan 2011). After reviewing the power analysis, the recovery team aspired to engage 40 sites for control-impact monitoring over five years.

We are now in the process of identifying suitable control and impact sites for targeted monitoring. Land managers are advising us of which neighbouring malleefowl sites have comparable habitat and contrasting predator management. In some cases the paired control-impact design will be extended to a cluster of three or more sites grouped together and assigned the same spatial random effect (Appendix C). While grouping near neighbours strengthens our inference in the face of spatial variation, it conflicts with our need to ensure that the malleefowl populations respond to the action implemented in their site and not actions in neighbouring sites (e.g., through dispersal of malleefowl or predators). Thus, we will set buffers of predator control around monitored impact sites, and minimum distances between control and impact sites.

A five-year control-impact experiment might not detect an effect of predator control on malleefowl mound activity, even if it exists. This could occur if mound activity were below the nominated average across most sites, if the effect of predator control were weaker than estimated, or if the spatial or temporal variation were larger than estimated. Finally, the nature of the power analysis is such that, even under ideal conditions, we accept some probability of failing to detect a significant effect of management even though it is present (i.e. type II error). This probability is estimated to be less than 0.1% if malleefowl mound activity doubles in the presence of predator control (effect size 101%, Figure 3), but is as high as 76% if predator control only induces a 10% increase in mound activity.

Alternatively, the implemented predator control may not increase malleefowl mound activity. This could arise if: (a) the implemented predator control does not successfully reduce predator activity, or (b) reduced predator activity does not increase malleefowl mound activity. Distinguishing between these cases would be beneficial for adaptive management. If the implemented actions do not reduce predator activity, then alternative predator control methods may still be worth exploring for the potential benefit of malleefowl and other native prey. However, if malleefowl breeding activity is found not to improve under reduced predator activity, then predator control can be abandoned as a malleefowl management action. We proposed supplementary monitoring at the experimental sites to test whether hypothesis (a) is true.

2.4.2 Supplementary monitoring of predator activity

We aimed to distinguish whether predator management at ‘impact’ sites reduces predator activity below the predator activity observed at predator-unmanaged ‘control’ sites. We proposed installing an array of solar-powered camera traps at the sites included in the predator control experiment (van Hespen et al. in press) to estimate predator activity as a count of fox or cat photos from each camera. We performed a second power analysis to estimate the number of camera traps that would be required at each site to distinguish control-impact differences in predator activity from random variation.

To parameterise our analysis, we used data from 16 camera traps collected by Benshemesh (2013) at Wandown Nature Reserve, a 20 km^2 patch of remnant mallee vegetation not subject to fox control and surrounded by agricultural land. From these data we estimated spatial and temporal variation in fox photo counts. The model structure closely resembled the power analysis of mound activity (Appendix C), although the spatial and temporal scales had higher resolution (in terms of between-camera variation and monthly variation, respectively). The power analysis estimated the difference in mean photographic trapping rate between a 'control' and an 'impact' site, and we deemed the difference to be statistically significant at the customary $\alpha = 0.05$ significance level (van Hespen et al. in press). If predator control efforts reduce fox activity by 75% from an unmanaged density of 2 foxes/km^2, we estimated that 6 cameras per site would be sufficient to achieve an 96% probability of detecting the difference in fox densities over 12 months (Figure 5a).

Stakeholders queried whether more expensive cameras with broader detection zones would generate higher quality data to support this experiment. The power analysis indicated that it is more important to capture the high estimated spatial variation in photo counts than to increase the number of fox detections from each camera. Consequently, a fixed budget would be more effectively spent on a larger number of cheaper cameras with reduced detection zones (Figure 4b).

2.5 Strategies for collaboration and commitment

Effective monitoring and conservation of malleefowl relies on continued co-operation among stakeholders and land managers. We evaluate our co-operative approach using Aceves-Bueno et al.'s (2015) three stakeholder criteria for using citizen science within adaptive management. They propose that: (1) stakeholders must be identified and engaged, (2) managers must provide appropriate motivation and incentives to participants, and (3) decision-makers must be accountable to stakeholders.

First, we have identified and engaged community stakeholders. The recovery team communicates, shares knowledge and trains volunteers continuously. Researchers join them annually to conduct workshops for participants and potential participants in the predator control experiment. The first of these workshops focused on a project design that was feasible and would allow for meaningful inference, and guided the monitoring design outlined in this article. Subsequent workshops have been used to maintain the momentum of the project, by assessing progress, sharing knowledge and solving logistical challenges collaboratively (Allen et al. 2011). As sites submit data in the future, workshops will expand to presentation of analyses, reflecting on what has been learned, and potentially developing adjustments to management and monitoring protocols.

Second, there are incentives and motivation for participation. For land managers, there is an opportunity to adopt a rigorous national standard of data collection. In the medium term, managers will receive trend analyses that exceed their local capacity and in the long term, they expect to learn more about the role of predator control in malleefowl conservation, drawn from the co-operation of many participants. The value of this information should not be underestimated. Many land managers have expressed frustration at not having resources to test the efficacy of their predator control programs. Furthermore, they often have other external motivations to monitor and report their predator control and malleefowl conservation activities (e.g. state directives, reports to NGO sponsors); we worked with managers to develop protocols that align with these other motivators.

Citizen scientists' motivations may be less tangible, primarily focused on individuals' connections to nature and fellow malleefowl enthusiasts. They may rely on leadership from one of numerous community 'champions' (Garnett et al. 2018). Malleefowl are much loved in the regional communities where they persist, perhaps because their maintenance of 1m tall nest mounds has earned them a reputation as one of the hardest working birds in the world (Department of the Environment and Energy 2006). The program offers flexibility in involvement at several levels: the difficult physical work of monitoring in remote locations with harsh climates (earning the catch phrase 'bushwalking with a purpose'), organising equipment and volunteers, managing and verifying data, and classifying the images captured by camera traps. Ensuring ongoing citizen science involvement is a major challenge, and it is important that citizen scientists see that their contributions are valued and influential. To this end, the recovery team engages volunteers by co-hosting community training days (up to 11 sessions across regional Australia in one year, attracting over 250 participants); providing online access to the national database; disseminating newsletters covering news, personal stories and research findings from the program; and holding a National Malleefowl Forum every 3-4 years.

The third stakeholder criterion is that decision-makers must be accountable to stakeholders (Aceves-Bueno et al. 2015). The network of agencies with the authority to decide on malleefowl conservation actions is diffuse. Within the predator control experiment, none of them have been called on to change their actions. Malleefowl monitoring is within the remit of participants, and we aimed to build a culture of accountability within the annual workshops. In this way the recovery team has acted as a 'bridging organisation', despite its lack of regulatory authority or funding to incentivise particular management actions (Allen et al. 2011).

Many other studies cite a need for strong leadership or a 'champion' to drive successful adaptive management (Gregory et al. 2006, Allen & Gunderson*.* 2011, Walters 2007). The malleefowl project has these leaders. First, there is a leading malleefowl ecological expert with a long-term commitment to the species' conservation and excellent communication skills. Second, the recovery team created paid National Co-ordinator and Engagement Officer roles with explicit responsibilities for progressing adaptive management and monitoring. The co-ordinator and engagement officer are facilitators: organised, enthusiastic and persistent, and not expected to drive the scientific research design (Walters 2007). These leaders are supported by a project team with a shared vision and purpose, initially negotiated and articulated in a joint co-funding proposal, with varied and complementary skills and knowledge to contribute.

Sustaining funding is a common challenge in adaptive management (Allen et al. 2011, Walters 2007) that applies to the malleefowl program. Characteristic of long-term research projects, the recovery team has drawn funding from a variety of sources. The initial research plan was launched via an Australian Research Council Linkage grant with supplementary funding from one state government agency and one environmental offsetting program, mediated via a citizen scientists' group. Researcher salaries and annual workshop expenses have been secured through universities, large environmental management, and threatened species research centres. The recovery team has financially supported the stakeholder co-ordinators and database managers. Members of the recovery team have facilitated small grant applications to NGOs seeking the equipment and training needed at individual sites participating in the predator control experiment. Future data collection relies on the in-kind support of numerous professional agencies and community groups. This wide-ranging strategy demonstrates that the recovery team can be proactive and flexible in its resource acquisition. While this can be daunting, we hope that the approach will prove robust, freeing the program from reliance on the long-term financial commitment of any one agency.

3 Discussion

We have established the minimum conditions needed to justify adaptive management for malleefowl conservation: uncertainty is present, learning (i.e. reducing uncertainty) is feasible on a management-relevant time-scale, and there are opportunities to adjust management as a response to learning (Doremus 2010). We have developed an adaptive management framework and communication strategy that facilitate and formalise collaboration among the numerous agencies and community groups concerned with malleefowl conservation. The adaptive management framework has steered their monitoring efforts towards a better understanding of the uncertain effects of predator control. Nevertheless, the ensemble model structure and regularly scheduled workshops offer some flexibility for future management choices and learning priorities. If malleefowl conservation successfully adapts in response to the new monitoring data we expect to collect, it will become one of the largest adaptive management programs on the planet, both in terms of geographic extent and the number of jurisdictions and citizen scientists involved.

Our project was well aligned with more general frameworks for adaptive management in conservation (Runge 2011; Figure 2). We posed and structured the malleefowl conservation challenge clearly in collaboration with experts and stakeholders (2.2). Our approach to evaluating consequences and uncertainties was new to the adaptive management context (2.3), and we designed a rigorous, feasible monitoring program (2.4). However, some components of the framework were less thoroughly addressed, and we discuss these here.

3.1 Evaluating consequences and critical uncertainties to identify the preferred alternative

We introduced ensemble modelling into the adaptive management space, as a means of representing and prioritising a large number of uncertainties (i.e. 80 interactions between mallee system components; Figure 3a). The consequences of six candidate management actions (Appendix A) were predicted for malleefowl abundance, including all associated uncertainty. However, we did not construct an objective function or use any optimisation methods to derive a preferred conservation action. We identified critical uncertainties informally by inspecting the range of plausible malleefowl responses to each candidate action, and prioritising actions with broad uncertainty and high possible benefits. A more formal value-of-information analysis using an objective function could estimate the expected benefits of resolving uncertainty. However, there were barriers to using these more traditional analyses. Any combination of the six modelled conservation actions could theoretically be pursued simultaneously, but it was unclear which combinations of agencies were responsible for implementing actions and not all agencies could afford all possible action combinations (as it was, some could only be involved as control sites). We focused instead on how targeted monitoring could help resolve the highest priority uncertainty identified by the literature and the ensemble modelling: the effect of fox and cat predation on malleefowl persistence.

3.2 Implementing action

We have collaborated intensively with land managers to identify suitable control and impact sites for the project. Under the proposed experimental design, participants continue to implement their current predator control action. Predator and malleefowl populations are expected to already occur at their equilibrium densities with respect to their assigned management action. The experiment therefore poses no extra risk of negative outcomes than status quo management. However, stronger statistical inference would arise from random allocation of actions to sites (e.g. Lyons et al. 2008). As it stands, there may be systematic reasons why predator control has been selected by managers *a priori* for some sites and not others. These reasons are confounded with malleefowl's response to predator control in the proposed design.

3.3 Monitoring

Our experimental monitoring design calls on numerous agencies to standardise and share their monitoring data, much of it collected by citizen scientists. The proposed program sets a foundation for fulfilling the four monitoring criteria set by Aceves-Bueno et al. (2015) to successfully utilise citizen science within adaptive management. First, the historic mound monitoring program and camera trap pilot program have demonstrated that monitoring can be achieved. Monitoring in the first predator control experiment clusters is underway, and there are strategies in place to continue engaging participants (2.5). Second, the monitoring design is relevant and rigorous. Power analyses of malleefowl mound monitoring and camera trapping of predators have helped us build evidence that an experiment can generate meaningful inference regarding an important uncertainty over feasible temporal and spatial scales (40 sites in 20 control-impact pairs/clusters monitored for five years each; Figure 3) with realistic resourcing (e.g. Figure 4).

Third, we have strived for cost-effectiveness, although we have not performed a value-of-information analysis that could directly weigh the benefits of the experimental design against its costs. Using remote sensing to locate new mounds and cameras for monitoring predators are notable financial costs that exceed status quo management. Camera installation was not a mandatory requirement for participation, and the recovery team has worked with site managers to secure funding where assistance was needed. The monitoring program has been structured to 'piggy-back' on existing initiatives wherever possible (Westgate et al. 2013), harnessing volunteer efforts and spreading costs among many participants (Walters 2007).

Fourth, monitoring will accommodate multiple temporal and spatial scales. It is not expected that all site clusters will commence monitoring in the same year. Rather than planning an experiment that will conclude in five years, we expect staggered involvement of various site clusters, each having a goal of at least five years' participation. Learning the range-wide malleefowl response to predator control over five-to-ten years is the overarching goal of the experiment, but data and feedback can also be examined at finer resolutions. Malleefowl mound and predator activity data will be collated at each site annually (with predator activity measured as monthly photo counts), and the recovery team can deliver annual cluster-specific reports.

3.4 Updating and learning

If participants collect and submit the proposed data to the recovery team, we anticipate opportunities to update knowledge and share learning at a number of scales. These range from refining our definition of predator control, to opportunistically learning about uncertainties beyond predation, and reprioritising the critical uncertainties.

Our power analyses treat predator control as a binary action with a common response across all managed sites, but this is unlikely to be the case for at least three reasons. First, predator control is applied differently across Australia, involving baiting at varying frequencies and densities, trapping and/or fencing. Second, foxes and cats occur at different densities and in different ratios across malleefowl's range and they respond differently to the same control action. Third, malleefowl populations may respond differently to the same reduction in predator density, for example depending on the shelter from predators provided by a site's vegetation structure. All three phenomena could be assessed through the planned camera trapping to estimate predator (fox or cat) activity. After data have been collected, the method of predator control may be included as a more nuanced covariate in analyses, and other variables that mediate the response of malleefowl to predator control could also be included as interaction terms. Thus, the power analysis was designed to provide only a rough guide to the realised statistical power.

An upcoming technical challenge will be updating the ensemble models (Bode et al. 2017) over a relevant time frame in response to the predator control experiment findings and other malleefowl monitoring data. Further refinement of the ensemble model set should consider the reliability of the new data (e.g. via sample size or confidence/credible intervals). The model set represents uncertainty in 80 parameters with a common model structure, and we expect that this could be updated numerically using Bayesian methods (Chadès et al. 2017). More research is needed to evaluate tools for representing this kind of multi-dimensional uncertainty within adaptive management, including ensemble modelling and Bayesian belief networks (Nyberg et al. 2006, Rumpff et al. 2011).

Regardless of whether reducing fox and cat predation is feasible and beneficial to malleefowl persistence, fire and grazing management may warrant exploration (Figure 2b). The targeted monitoring and power analysis design described in this article could be transferred and tailored to these issues. However, we anticipate slow ecosystem responses and land manager commitments far beyond the five years nominated in the predator control experiment. Furthermore, making strategic changes to fire and grazing management may be even more difficult than altering predator control. Scenario planning may be a preferable alternative to adaptive management in these cases (Allen et al. 2011).

There will be some capacity for opportunistic learning about the role of fire and grazing management within the current design. Our understanding of the mallee system can potentially be updated with more than just malleefowl mound activity and predator photo counts. Identifying other species among the photographs collected can also provide supplementary information, including malleefowl, predators such as cats and dogs, and potential competitors such as kangaroos, goats and rabbits. Successful fox control has the potential to influence the abundance of these other malleefowl predators and competitors (e.g. Figure 3a), and thus indirectly affect malleefowl persistence. We expect to collect other supplementary data, such as rainfall (which affects food availability) and fire history (which affects mortality, food availability and cover from predators). These could all potentially be used as covariates in a model of mound activity (based on the equations in Appendix C) and also to refine the ensemble model set. However, learning is expected to be slow and erratic in the absence of a targeted monitoring design.

Successful adaptive management makes space for uncertainty, complexity, reflection and critical discussion (Allen & Curtis 2005, Gregory et al. 2006, Scarlett 2013). Over the five-to-ten years needed to undertake the predator control experiment, funding, policy, personnel and agency priorities are all likely to undergo changes. Extreme natural events may occur. It is possible, even probable, that the data generated in the predator control experiment will include surprises, generating new doubts and questions. The philosophy of adaptive management welcomes these events as opportunities for learning, generating new hypotheses and collaboration. An effective recovery team will consciously create a culture of openness and constructive debate to address these upheavals, and allow for revisions of the program strategy and design (Allen & Gunderson 2011).

3.5 Can adaptive management of malleefowl succeed?

If the uncertainties in malleefowl conservation are effectively resolved, it remains to be seen whether management can be shifted accordingly. Conservation actions such as fox and cat suppression, strategic fire management, reducing grazing pressure, and reducing land clearing have implications for other valued native species, ecological communities and economic interests. The recovery team and surrounding community of malleefowl advocates must engage with broader processes of decision-making, identifying trade-offs within the malleefowl-specific actions and among malleefowl and other land use priorities. A rigorous monitoring program will form an important foundation of evidence as these trade-offs are investigated. By focusing first on the management actions already taken by participants and the monitoring established with citizen scientists, the program can build co-operation and credibility, and prepare for future changes.

Acknowledgements

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(a)

(b)

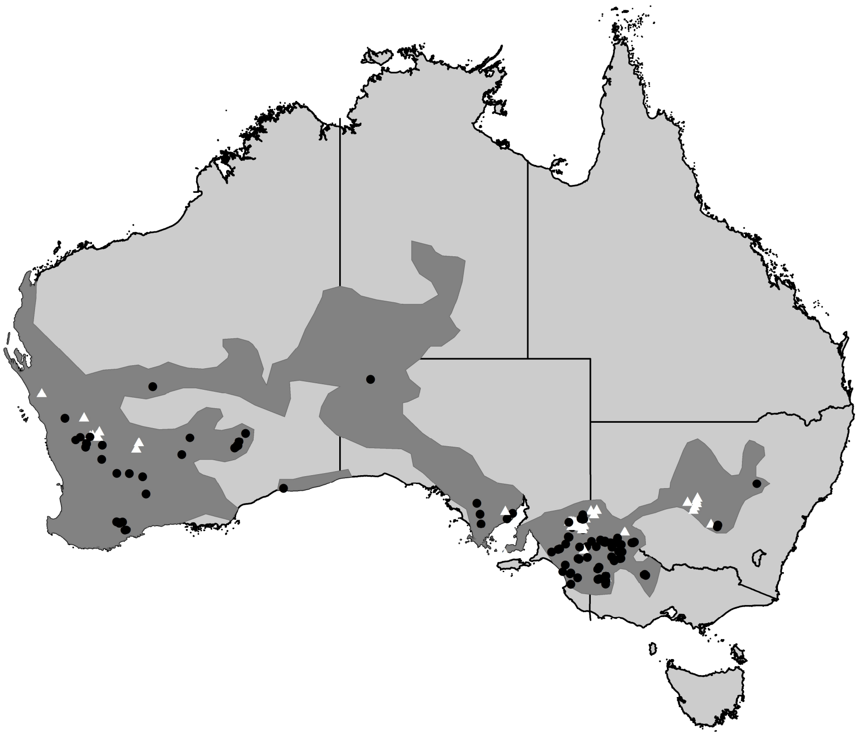

Figure 1. (a) An adult malleefowl in the wild, photographed by Graeme Tonkin. (b) The presumed original distribution of malleefowl across Australia, based on historical records (dark shading), with locations of long-term monitoring sites (black circles), and locations of candidate sites where monitoring data will support the predator control experiment (white triangles).

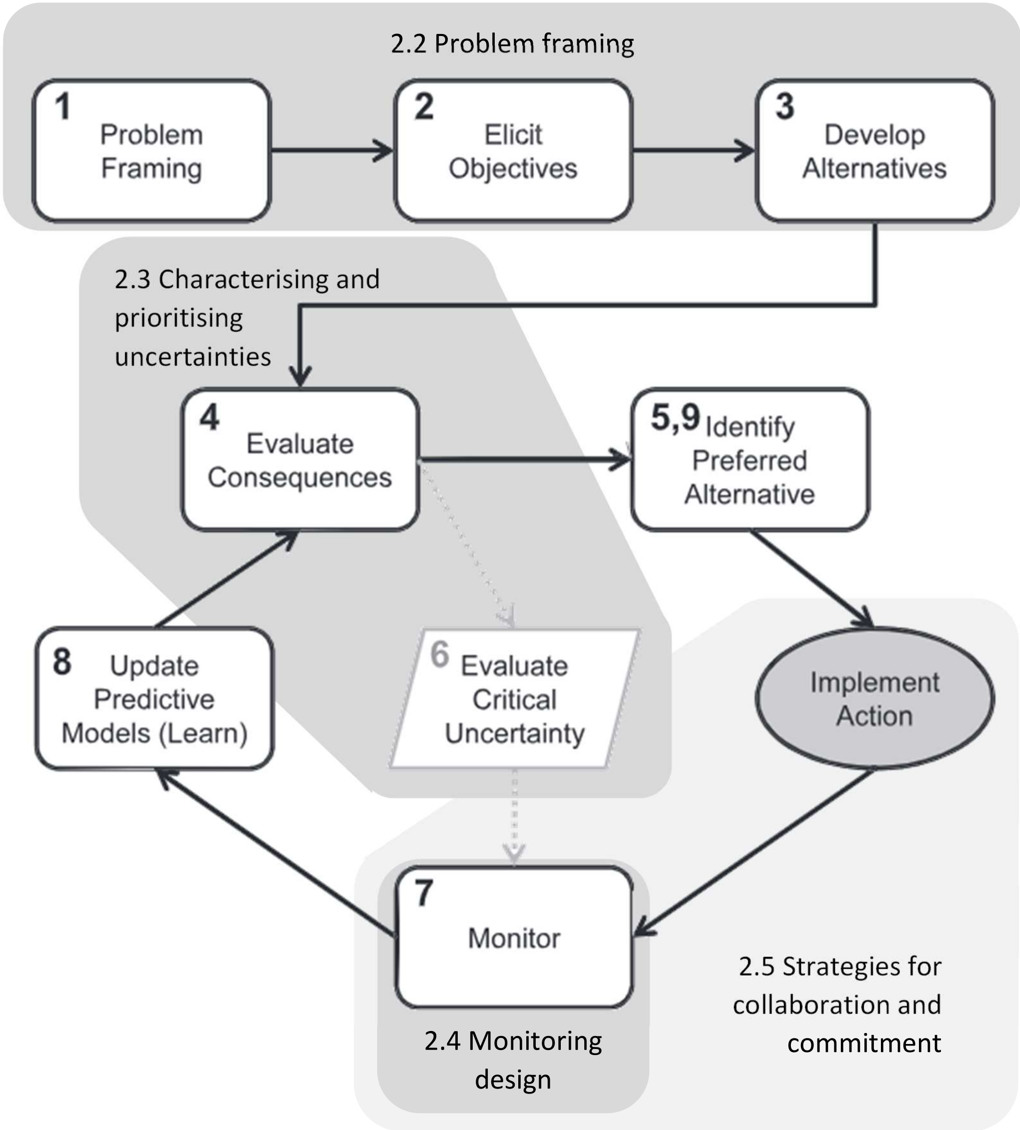

Figure 2. A schematic of adaptive management, originally published by Runge (2011), including the contributions that this paper makes to adaptive malleefowl conservation. We developed the problem framing, conservation objectives and alternative management options with stakeholders (2.2); developed a network model and identified critical uncertainties (2. 3); designed a monitoring program to address the critical uncertainty (2.4); and formulated strategies for collaboration that support conservation action and monitoring (2.5). We have not yet formally identified preferred conservation actions, nor developed a plan for updating the network model.

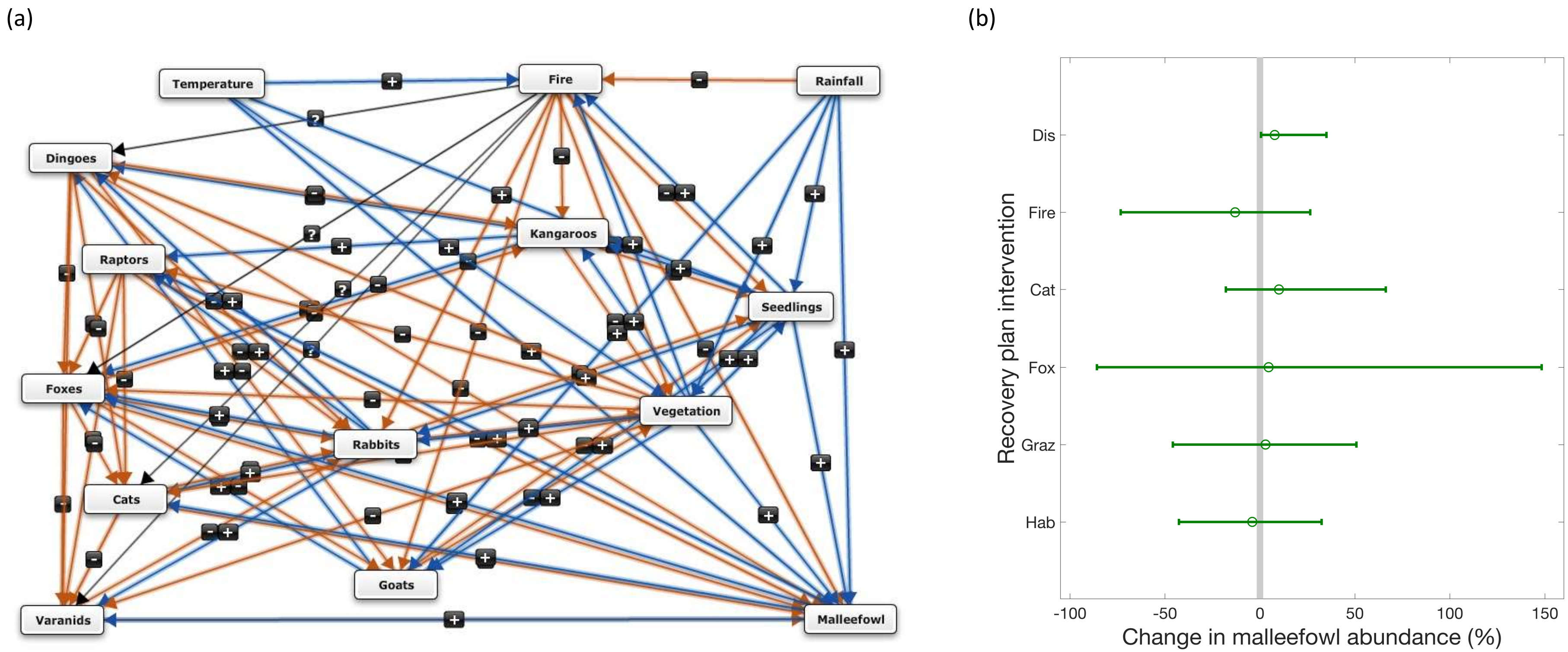

Figure 3. (a) The malleefowl ecosystem model structure developed for ensemble modelling. Arrows indicate the direction of influence, with the sign label indicating the direction of influence (see Appendix A for associated equations); absent connections between components indicate that there is no direct influence. (b) 95% credible intervals on predicted malleefowl population change as a response to a Recovery plan intervention (respectively: Dis = disease and inbreeding, Fire = fire intensity and severity, Cat = predation by cats, Fox = predation by foxes, Graz = competition from grazing herbivores, Hab = habitat loss and fragmentation). Diagrams adapted from Bode et al. (2017).

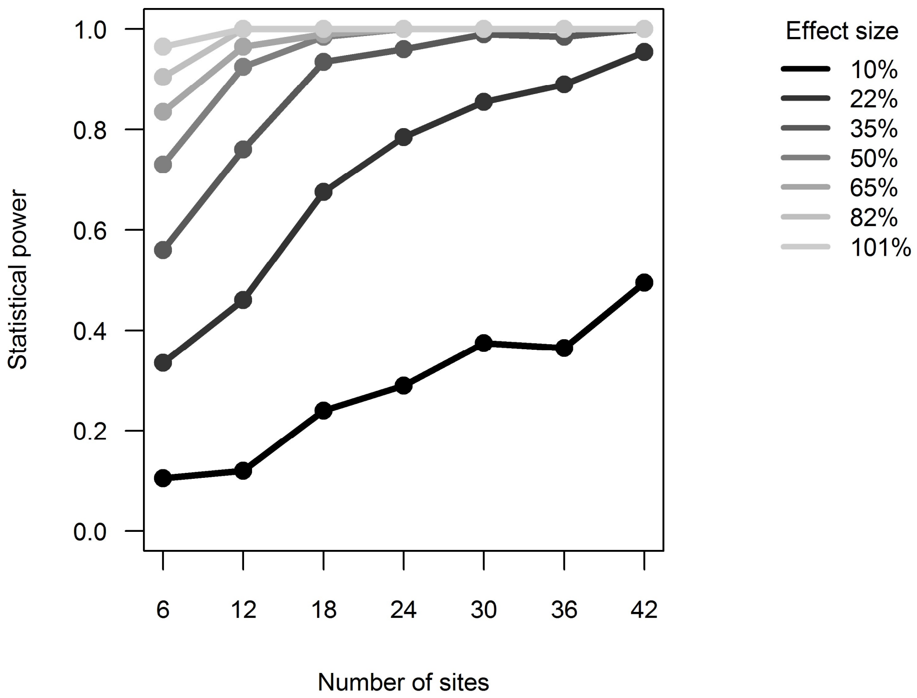

Figure 4. Statistical power to detect a proportional change in malleefowl mound activity, over 5 years of monitoring, given the total number of unmanaged and managed sites included in the study and assuming a type I error rate of 0.05. Lines indicate the power to reject a null hypothesis of no change based on mound activity effect sizes ranging from a 10% to a 101% (i.e. two-fold) increase. See Appendix for details of model construction.

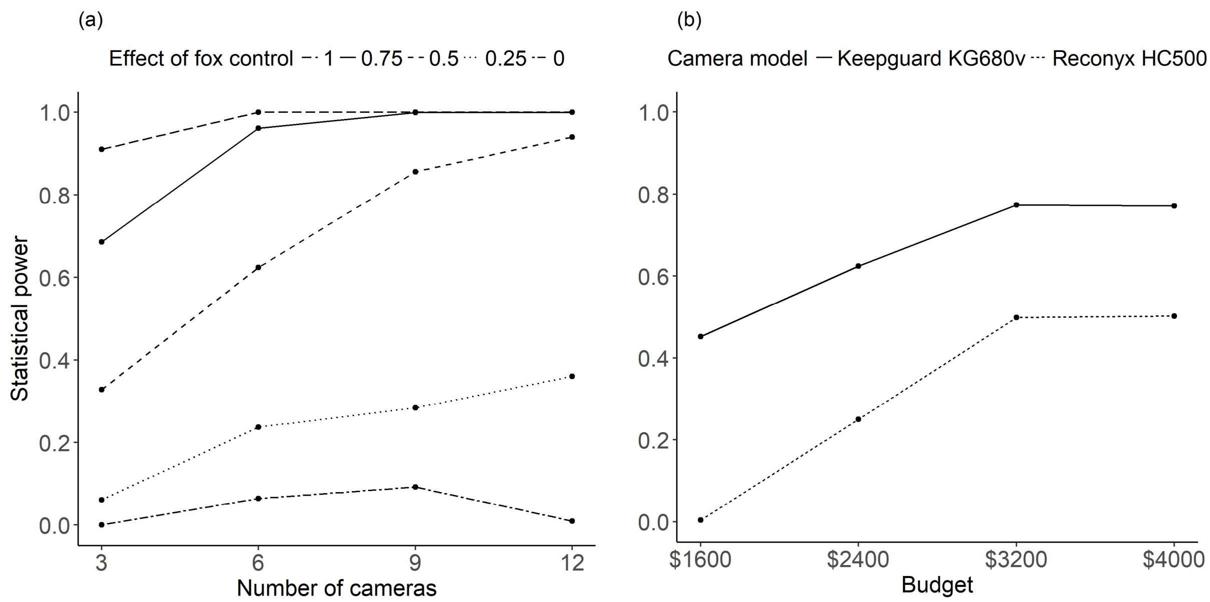

Figure 5. Power to detect a difference in predator activity (baiting effect) between a pair of control and impact sites, (a) given the number of cameras allocated to each site over a 12-month period, and (b) given the camera budget at each site for two alternative camera models. Images adapted from van Hespen et al. (in press).

Supplementary Material

Appendix A: Summary of roles and responsibilities for malleefowl conservation

Table A1. A list of agencies involved in the conservation of malleefowl and/or other land management that is likely to influence malleefowl persistence. State abbreviations are: Western Australia (WA), South Australia (SA), Victoria (Vic) and New South Wales (NSW). Other common abbreviations are: Natural Resource Management (NRM), Catchment Management Authority (CMA), Local Land Service (LLS), and Indigenous Protected Area (IPA). While substantial efforts have been made to engage broadly, this may not form a comprehensive account of all agencies concerned with malleefowl conservation.

Role	*Agency names*	*Responsibilities*
Federal government	Department of the Environment and Energy (DOTEE)	Listing of threatened species under the Environmental Protection and Biodiversity Conservation (EPBC) Act 1999 Establishing a recovery team for listed species
Species recovery team (National Malleefowl Recovery Team)	National Malleefowl Recovery Team (NMRT, the 'recovery team' in this manuscript)	Developing a recovery plan Advising land managers of preferred management actions to conserve target species
State government	WA Department of Biodiversity Conservation and Attractions (DBCA); SA Department of Environment and Water (DEW), Parks Victoria (PV), Vic Department of Environment, Land, Water and Planning (DELWP), NSW Office of Environment and Heritage (OEH), NSW National Parks and Wildlife Service (NPWS)	Predator control in state and national parks Control of pest species, e.g. rabbits, goats Weed management Habitat restoration (revegetation) Fire management on public and private land Land clearing permits across all land types Implementing the Flora & Fauna Guarantee Act 1986 (FFG, Vic), Threatened Species Conservation Act (NSW) Malleefowl mound monitoring across all land types
Local area coordinators of land management	WA: South West Catchment Council, Northern Agriculture Catchment Council, Wheatbelt NRM, South Coast NRM, Rangelands NRM. SA: Eyre Peninsula NRM, Northern and Yorke NRM, Arid NRM, Alinytjara Wilurara NRM, South East NRM, SA Murray Darling Basin NRM. Vic: Mallee CMA, Wimmera CMA , North Central CMA NSW: Western LLS, Riverina LLS, Central West LLS	Implement actions from the recovery plan utilising federal funding under the National Landcare Partnerships program (17 projects with primary or secondary benefits for malleefowl worth AU$24.8m over 2013-2023) Land clearing permits on private land (NSW)

Traditional Owners	Aboriginal Corporations: Maralinga Tjarutja (SA)*, Anangu-Pitjantjatjara- Yankunytjatjara (SA)*, Pila Nguru (WA), Ngaanyatjarra (WA) Indigenous Protected Area: Ninghan (WA), Mawonga (NSW), Walalkara (SA)*, Watarru (SA)* Other: Rick Farley Reserve (NSW)	Predator control on the IPA Malleefowl mound monitoring on Indigenous managed lands Camera monitoring predators on Indigenous managed lands
Non-government organisations (NGOs)	Bush Heritage Australia, Australian Wildlife Conservancy, Great Victorian Desert Biodiversity Trust, Gondwana Link, Gunduwa Regional Conservation Association	Predator control on NGO land Fire management on NGO land aligned with state government directives Malleefowl mound monitoring on NGO land Camera monitoring predators on NGO land
Community volunteer groups	Victorian Malleefowl Recovery Group (VMRG), WA Malleefowl Recovery Group, National Malleefowl Recovery Group, Kalgoorlie Field Naturalists, Dubbo Field Naturalists, Mid Murray Field Naturalists	Malleefowl mound monitoring as permitted across all tenures
Mining companies	Wiluna Uranium mine, St Ives mining, Mount Gibson Iron Limited Extension Hill Operations, Cliffs Resources, Cameco Yeelirrie	Predator control on leased land Malleefowl mound monitoring on leased land Camera monitoring predators on NGO land
Universities	Federation University, Melbourne University, La Trobe University	Research Predator control on leased land Malleefowl mound monitoring on leased land Camera monitoring predators on NGO or leased land??
Private property	Many individuals	Predator control on private land Malleefowl mound monitoring on private land Camera monitoring predators on private land Weed control and habitat restoration on private land

** Aboriginal people of the Great Victoria Desert in SA and WA.*

Appendix B: Ensemble model structure and analysis

The ecosystem model (Figure 3a) followed the Lotka-Volterra structure:

$$\frac{dN_i}{dt} = r_i N_i + \sum_{j=1}^{C} a_{ij} N_i N_j$$

for ecosystem components $i = 1, 2, \ldots, C$. $N_i(t)$ was the quantity of component i at time t years (the abundance or density of a population, volume of rainfall, etc.), and $C = 14$ was the number of components in the ecosystem. The intrinsic growth rate of component i was r_i, and the per-unit effect of component j on each unit of component i was a_{ij} (Bode et al. 2017).

All ecosystem component quantities $N_i(t)$ were scaled to lie between 0 and 1; plausible values for the interaction parameters a_{ij} fell between -1 and 1. In the first instance, we used workshop participants' knowledge to restrict parameters to [-1, 0) when the interaction between components was thought to be negative (red lines in Figure 3a), 0 when there was no interaction between components, and (0, 1] when the interaction between components was thought to be positive (blue lines in Figure 3a). We assigned uniform prior distributions over the above ranges to describe parameter uncertainty in component interactions. We assigned inverse uniform distributions to the intrinsic growth rates, i.e. $1/(r_i + 1) \sim \mathrm{U}(0, 1)$. We used Latin hypercube sampling to generate 10^9 plausible parameterisations of the ecosystem model.

Following the refinement of the model set described in 2.2 we developed six candidate actions or interventions, with each one designed to address a threat to malleefowl that had been identified in the National Recovery Plan (Benshemesh 2007):

1. *Disease and inbreeding:* the specific management action was unclear, but the result of successful management was predicted to be a 10% increase in malleefowl population growth.
2. *Fire intensity and severity:* the management action and component response was a 50% increase in the area burned by fire.
3. *Predation by introduced cats:* baiting that targeted cats was predicted to reduce cat populations by 85%.
4. *Predation by introduced foxes:* baiting that targeted foxes was predicted to reduce fox populations by 95%.
5. *Competition by herbivores:* Mustering feral goats was predicted to reduce their population by 30%, and baiting rabbits was predicted to reduce their population by 30%.
6. *Habitat loss and fragmentation:* Active restoration was predicted to increase seedling and vegetation components by 15%.

Appendix C: Power analysis of control-impact monitoring on malleefowl mound activity

In developing an initial power analysis, we assume clusters of two sites each with similar characteristics (e.g. climate, vegetation), that can be used as a 'control' site (no predator management) and an 'impact' site (intense predator control). To ensure that predator activity around the monitored mounds reflects the chosen management, we have recommended that predator management be uniformly applied to a 10000 ha area surrounding the mounds as a 'buffer'. To limit the possibility that predators travel between unmanaged and managed sites, we also recommend that sites be placed at least 8km apart (and often more, depending on the location of tracks).

For each site, the response data is the *number of active mounds* in a given year. We assume a common average mound activity with superimposed temporal and spatial fluctuations. The paired nature of the experiment (and consequent model structure) helps disentangle the long-term (average) effect of predator management on malleefowl breeding, from the spatial and temporal fluctuations, as:

1. some sites consistently show higher nesting activity than others, due to e.g. more suitable habitat for breeding. Pairing together similar sites, that are 'consistently high' or 'consistently low', helps to isolate the effect of predator management from the effects of breeding activity due to local habitat quality.
2. some malleefowl breeding seasons will be 'better' or 'worse' than average across the entire range. This influences how we view the impact of predator management, e.g. we are less likely to attribute a breeding activity increase to predator management if it occurs in both control and impact sites.

The purpose of this power analysis is to determine – in advance of data collection – the probability that a control-impact experiment would correctly recognise the benefits of predator management, assuming it has a given effect size.

Model specification

For each site s and year t, the number of active mounds (random variable a) can be described with a Poisson distribution with year- and site-specific mean $\lambda_{s,t}$:

$$a_{s,t} \sim Pois(\lambda_{s,t}).$$

We model the mean number of active mounds λ as a log regression with time and cluster-specific variation as:

$$log(\lambda(s,t)) = \beta_0 + \varepsilon_S(s) + \varepsilon_T(t) + b \cdot c(s)$$

where β_0 is the average log-rate (intercept), ε_S is a site-level random term (spatial variation), ε_T is a year-specific random term (temporal variation) and b is the effect of predator management (the indicator covariate $c(s)$ is 1 for 'impact' sites and 0 otherwise). The random effects are described as normally distributed with zero mean and variances:

$$\varepsilon_S \sim N(0, \sigma_S^2)$$

$$\varepsilon_T \sim N(0, \sigma_T^2)$$

Note that the site random effect $\varepsilon_S(s)$ is shared by each cluster of control-impact sites.

Simulation parameters

We analysed historical mound activity data in the state of Victoria from the National Malleefowl Monitoring Database (http://database.malleefowlvictoria.org.au/Start.aspx) to obtain values to parameterise realistic simulation of mound activity data. The analysis was based on the model above (without the predator management term $b \cdot c(s)$). In particular, we estimated:

- long-term **average mound activity**: λ=3.07 active mounds per site (equivalent to β_0=1.123).
- spatial variation in mound activity across sites: σ_S=1.172
- temporal variation (sample variance) in mound activity, from year-to-year: σ_T=0.411

We investigated the amount of monitoring effort that would be needed to draw scientifically rigorous conclusions under several different predator management responses (i.e. different 'effect sizes'), from no effect (b = 0; average active mounds λ = 3.07 at both sites) to doubling the average number of active mounds (b = 0.7; from λ = 3.07 mounds at a control site to λ = 6.19 mounds at an impact site; Table A1).

Power analysis simulations

We performed a power analysis on the above defined control-impact experiment, for scenarios defined by the number of sites S, number of years T and an effect size b using the following steps:

1) Simulate a data set of mound activity observations (active/inactive) using the model above (assumed as the reference "truth")
2) Analyse the simulated data set using the same model structure
3) Determine whether the estimation of the existing effect of predator control ($\hat{b}$) is found to be statistically significant at the customary $\alpha = 0.05$ significance level (i.e. whether the 95% Credible Interval does not include the value zero)[1].
4) Repeat steps 1 to 3 for 200 iterations
5) Estimate the statistical power G for each scenario as the percentage of simulations in that scenario in which the assumed effect of predator management is detected.

The simulation study was conducted using the software R (R Core Team 2015, version 3.2.0). To fit the model specified above to each data set in step 2, we performed Bayesian Markov chain Monte Carlo sampling in the rjags package (Plummer 2016) and monitored the effect of predator control (*b*, step 3). Note that for each site cluster, the proportional increase in activity between control and impact sites depends on the number of active mounds per site, because λ includes site- and time-specific random effects. Therefore the percentage increases in mound activity in Table A1 are accurate only at the landscape level, and the parameter b is the true underlying difference that is used directly in the model.

Table C1. Conversions of effect size b to mean number of active mounds λ and percentage increase in mound activity between unmanaged and managed sites. The % increase compared to no management is only valid for the mean of $\lambda = 3.07$, and is shown here to provide an intuitive idea of the effect size.

effect size (b), log scale	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7
corresponding average λ	3.07	3.40	3.75	4.15	4.59	5.07	5.60	6.19
% increase in managed site above unmanaged site	---	10.5%	22.1%	35.0%	49.2%	64.9%	82.2%	101.4%

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[1] The 5% significance level implies that there is a 5% chance of declaring that an effect exists when in fact it does not; a trade-off exists between this error and statistical power, so that lowering that probability of falsely detecting an effect implies a lower power to detect a true effect.