Threatened Species Recovery Hub

National Environmental Science Programme

Securing the kowari in South Australia

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Arid Recovery

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Cover image: Kowari. Image: Ariana Ananda

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Executive summary

Similar to many Australian mammal species, the kowari (*Dasyuroides byrnei*), a marsupial 'micro-carnivore' restricted to the gibber plains of central Australia, persists under the threat of extinction. The kowari has experienced a significant contraction from its historical range and is now extinct in the Northern Territory, with scattered populations persisting in South Australia and Queensland. Recent estimates suggest the kowari has a 20% chance of extinction within the next 20 years, prompting an application to up-list the species to Endangered at the federal level on the schedules of the Environment Protection and Biodiversity Conservation Act (submission pending).

This project seeks to further develop our understanding of the temporal and spatial dynamics of the kowari and the processes that threaten its survival. These aims incorporate both modelling and field-based investigations to determine changes in the kowari's distribution from its historic range, and movement patterns, habitat use, interactions with predator/prey species, diet, and genetics.

This report provides an update on project progress. In particular, we have found that the kowari now occupies only 28% of its former geographical range, having suffered one of the largest contractions in area occupied of any currently extant arid-dwelling mammals. Hypotheses that have been generated to explain the precipitous decline in range include predation from introduced species, competition or habitat loss due to cattle grazing, climate change and interactions among these factors. Patterns uncovered to date reveal negative spatial associations between the kowari and cattle and between the kowari and dingoes. Intriguingly, however, no kowari remains have been detected in small numbers of predator scats that have been examined to date or in a large sample of pellets from the barn owl. Trapping records and camera images show that kowari numbers have recently responded on one of the two main study grids due to improved rainfall conditions that have also seen a surge in the numbers of co-occurring small mammals such as the long-haired rat (*Rattus villosissimus*). Both long-term live-trapping and camera-studies indicate an association of kowari with gibber plain, suggesting that this habitat provides refuge for sheltering or foraging. Attempts to radio-track kowari have so far yielded little information (tail-mounted tags have had limited success), but use of a drone is expected to increase areal coverage and improve understanding of movements. Due to extensive delays caused by government-mandated restrictions to crossing the NSW/SA border (March – November 2020; recently re-instated in June 2021) and extreme weather events (March 2021), this project will continue longer than initially anticipated and help to inform proposals to translocate the kowari if translocation is approved.

Kowari at entrance to burrow. Image: Ariana Ananda

Introduction

Australia's biodiversity extinction crisis is severe, with the loss of >30 mammal species since 1788 contributing 35% to the world's modern-day total of mammal extinctions (Woinarski et al. 2015). Of particular concern is the loss of ecologically important keystone predators that play a major role in structuring ecosystems and maintaining native species biodiversity (Brüniche-Olsen et al. 2014). It is suspected, though unconfirmed, that the kowari is a keystone species in the gibber plain ecosystem, meaning that its removal or continued decline may have deleterious consequences for desert biota via flow-on effects down the food chain. Hence the kowari may be instrumental in promoting native species diversity as do other similar-sized relatives in arid Australia (Greenville et al. 2017). If the kowari were to decline further or become extinct, the Australian landscape would also lose a species that has the potential to act as an icon in the push to achieve sensitive and sustainable use of the stony desert rangelands (Canty & Brandle 2008).

Concern about the status of the kowari has been long-standing. The population in the Northern Territory — that provided the type specimen for *D. byrnei* — became extinct in the first half of the 20th century (Finlayson 1961). In 1979, Archer (1979) identified the kowari as being in continuing decline from causes unknown, and the species has been listed as Vulnerable under federal legislation since 1992. Subsequent work has suggested that rainfall influences the size of local populations via its effects on primary productivity, and has identified invertebrates, rodents and other small vertebrates as major components of the diet (e.g., Woolley 1971; Fisher & Dickman 1993; Greenville et al. 2018). Despite increased attention, the kowari has continued to fare poorly. Canty & Brandle (2008) estimated that there were some 24 known populations of the kowari, but also noted that some had disappeared recently. One of these populations, on Sandringham Station in south-western Queensland, was the subject of considerable study in the 1960s and 1970s and provided the initial stimulus for curiosity-driven research on Australia's desert fauna (Dickman & Robin 2014). This population went extinct during the 1970s. The cause of the species' extirpation is not known, but MacMillen & MacMillen (2009) speculated that overgrazing by cattle was likely to have contributed. The best studied and still extant populations of kowari now occur in north-eastern South Australia where they have been subject to study by Robert Brandle, Peter Canty and colleagues (South Australian Department of Environment and Water) since 2000.

Context

The South Australian populations of kowari are restricted mostly to gibber habitats, although sparsely vegetated sand dunes may also be used if these occur within the broader gibber landscape (Canty & Brandle 2008; Canty 2012; Greenville et al. 2018). Sand-spread habitats may occur on depressions in gibber and, while thin, support plant growth but appear to be too shallow for burrowing by kowari or other mammals. Deeper sand lenses seem to provide suitable conditions that allow burrow construction. Kowaris have been captured rarely on gibbers dominated by large (> 5 cm) stones, perhaps because these are poor habitats for burrowing and poor habitats also for the detection and avoidance of predators (Baker 2015).

Detailed observations of kowari at two focal study sites in South Australia by Robert Brandle and Peter Canty indicate that cattle may deflate sand lenses and compromise the integrity of kowari burrows. The effects of cattle may be exacerbated if watering points are constructed near sites of kowari activity. The capacity of kowaris to repopulate sites from which they have been extirpated appears to be low, despite their occupation of individual ranges that may cover as much as 20 km^2 (Canty 2012). It is possible that dispersal and site-recolonisation are facilitated by heavy rains when prey resources are more reliably available across the landscape, but this possibility has not been tested. The two focal kowari populations in South Australia have declined over a 16-year period, despite increases in reproduction from periods of rainfall-induced productivity increases (Greenville et al. 2018). This project sought to provide an overview of the extent of kowari decline and return to the two focal populations to track their status, explore threats and provide recommendations for future management.

Methodology

Animal trapping

Two 4 × 4 km live-trapping grids (WAL and PAN), 30 km apart, were surveyed once a year from 2001 to 2004, then in 2006 (Fig. 1). Uneven and reduced sampling effort occurred on the grids in 2007, 2009, 2011, 2013, 2015, 2018, 2020 and 2021. The last two years of trapping form part of a PhD project by William La Marca. These two sites were chosen after a preliminary broadscale survey during 1999 (>800 trap-nights per site × 5 sites) spanning the Sturt Stony Desert and 100 km south of the Cooper Creek (R. Barratt & P. Canty unpublished). The preliminary study found that the study sites on Clifton Hills cattle station had the highest trapping rates for the kowari. The distance (30 km) between sites was chosen to ensure independence: no marked animals have been recorded to move between the two sites. At each grid, Elliott traps were spaced 100 m apart on five 4-km lines that were 1-km apart (200 traps per grid). Traps were opened from 1 to 4 nights depending on weather conditions and available resources, baited with dog biscuits soaked in fish oil, and checked each morning at first light. The sex of each individual was determined along with measurements of mass, pes length, head length, and indicators of reproductive activity including testis width, pouch condition (developed or not developed) and number of pouch young present. Each animal was marked with a unique microchip from 2000 to 2004, and 2020-2021 to identify individuals, and with paint marks on the tail during the later, less-frequent visits to identify same-session recaptures.

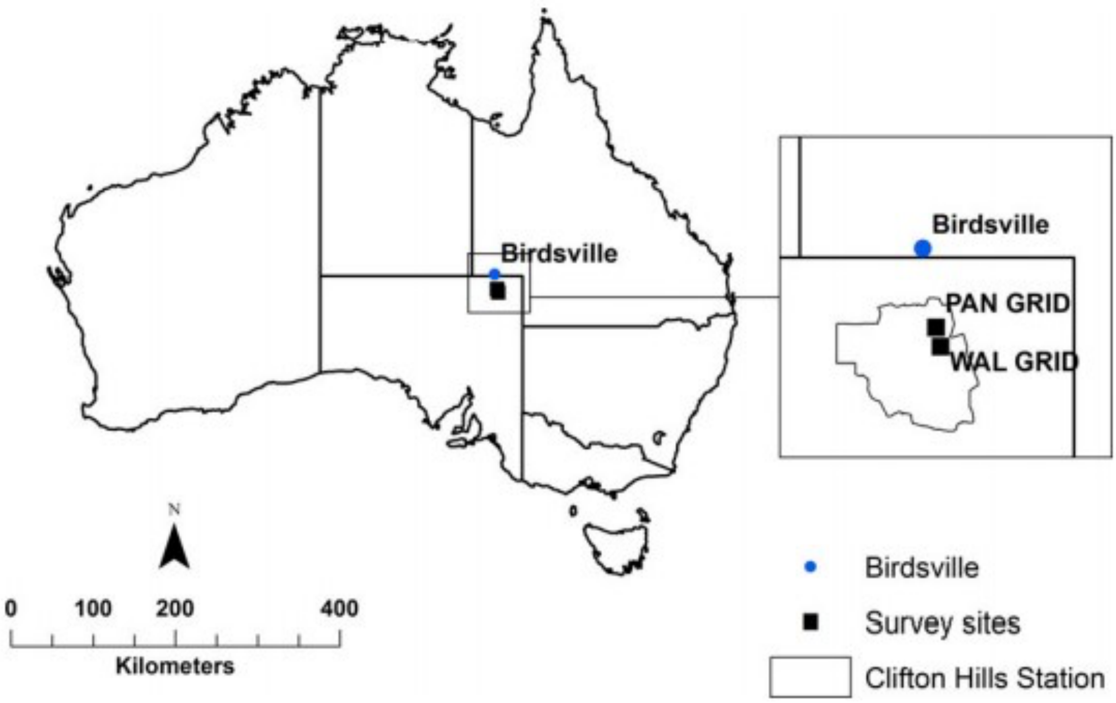


Figure 1: *The study region in the Sturts Stony Desert, and location of the long-term live-trapping grids for the kowari,* Dasyuroides byrnei*, in South Australia.*

Temporal dynamics

To assess the long-term temporal dynamics, we used Bayesian multivariate autoregressive state-space (MARSS) models. Live-trapping data were standardized for effort by calculating numbers of captures (excluding recaptures) per year per 100 trap nights and log + 1 transformed, as MARSS models use log space. We based the MARSS models on the Gompertz growth model and assumed that sub-population growth rate varied exponentially with sub-population size and that metapopulations were closed to immigration and emigration (Hinrichsen & Holmes, 2009). The MARSS framework is hierarchical and allows modelling of different spatial population structures and parameters such as growth rates, while including both process (state) and observation variability. To allow model convergence, each model was fitted with three Markov chains, each with 100 000 Markov chain Monte Carlo (MCMC) iterations, thinning of 25 and the first 60 000 iterations discarded, leaving 4800 iterations saved (see Greenville et al. 2018 for description of priors, model formation, and JAGS code). Analyses were conducted in R 4.3. (R Core Team 2020) and JAGS 4.3.0 (Plummer 2016a), using the R2jags 0.6– 1 (Su & Yajima 2015) and RJAGS 4–10 (Plummer 2016b) packages.

To provide a useful tool to monitor the temporal trends in kowari captures, a web-based application was built that allows stakeholders to add capture data from South Australia and calculate population estimates and growth rates. In addition, the tool can forecast the estimated mean population size up to 10 years since the last captures. The population model is based on the Bayesian multivariate autoregressive state-space (MARSS) models above, following the methods described in Greenville et al. (2018). The application is programmed using Shiny package in R and is hosted by the University of Sydney. Code will be made open-sourced and published on GitHub.

Spatial dynamics

To determine the change in extent of occurrence, records for kowari and an additional 38 arid-zone mammal species (including subfossil deposit records) were collated and vetted for duplications, mis-identifications, and inadequate geographical precision. Where possible, museum specimens were examined to avoid common mis-identification problems with *Dasycercus* species. Occurrence records were used to calculate alpha hull polygons of historic and modern ranges. This analysis is in the process of being expanded, as part of a PhD project to test different hypotheses about the factors that have caused declines or shifts in distributions. To investigate habitat suitability, the records above of the kowari were combined with a suite of 24 environmental and bioclimatic variables to formulate Maxent models of environmental suitability for the kowari within its known distribution. Model outputs allow us to better understand the likely extant distribution and inform survey efforts to uncover hidden populations.

Fieldwork components for the PhD project – which form the bulk of the project – have faced extensive setbacks, and fieldwork therefore is ongoing. Fieldwork initially scheduled for March 2020 was cancelled due to restrictions put in place to prevent the spread of COVID-19, and field sites thus could not be accessed by the Sydney research team until November 2020. However, Rob Brandle (South Australian Department for Environment and Water) and Catherine Lynch (SA Arid Lands Landscapes Board) were able to install remote cameras on the focal study sites in June 2020. A subsequent trip in March 2021 was impacted by >50 mL of rainfall that bogged the field team *in situ* and made data collection impossible. Despite these setbacks, progress has been made. Live-trapping has continued on the two focal study grids. Wildlife camera grids have been deployed across the two study sites – PAN and WAL grids – with 30 cameras at each site arranged in a 6 x 5 grid which overlays the historical trapping lines. Preliminary analyses of images during the period June – November 2020 have been undertaken to examine the occurrence relationships between the kowari and other species, with spatial analyses to be incorporated upon the creation of orthomosaic images of the grid sites.

The population of kowaris at the Clifton Hills study site is again being PIT tagged to enable individual identification. In total, 56 individuals have been marked with individual IDs to inform ongoing research into population dynamics. Scat samples from both kowaris and potential predator species have been collected, and predator scat samples have been analysed for their contents. Genetic samples have been taken from all individuals captured. These will be combined with historic samples from South Australia and Queensland for utilisation in population genetic analyses. Current plans centre around the sequencing of the kowari's genome and single nucleotide polymorphism (SNP) analyses to determine the level of population sub-structuring across the kowari's total extant range.

Given the nature of the unexpected delays, several research aspects remain ongoing. Analysis of kowari movement patterns and the determination of home range sizes are scheduled to be undertaken in August 2021 (COVID-19 restrictions permitting) using drone technology to more effectively radio-track individuals, a task that has proven difficult using traditional "manual" efforts (see Lim 1998; these difficulties were also confirmed through our trials). Similarly, burrow use and occupancy will be examined using both drone technology and – in future trips – the deployment of detection dogs which are in the process of being trained by Skylos Ecology to detect kowari scent and scats. A study to determine the efficacy of detection dogs in revealing kowari presence and active burrow sites is planned and may have implications for the methods used to track kowaris in proposed translocation events (i.e., the efficacy of detection dogs vs. radio-tracking/traditional trapping methodologies).

Findings

Temporal dynamics

Previous analysis of kowari captures (2000–2015) from South Australia revealed a negative population growth rate with high uncertainty (U = -0.08, 95% credible interval -0.28 to 0.10; Greenville et al. 2018). An updated analysis that added data from 2018 to 2021 has produced a similar result (U = -0.036, 95% credible interval: -0.18 to 0.1; Fig. 2). Our results indicate that the kowari is still at risk from stochastic extinction in the studied sub-populations.

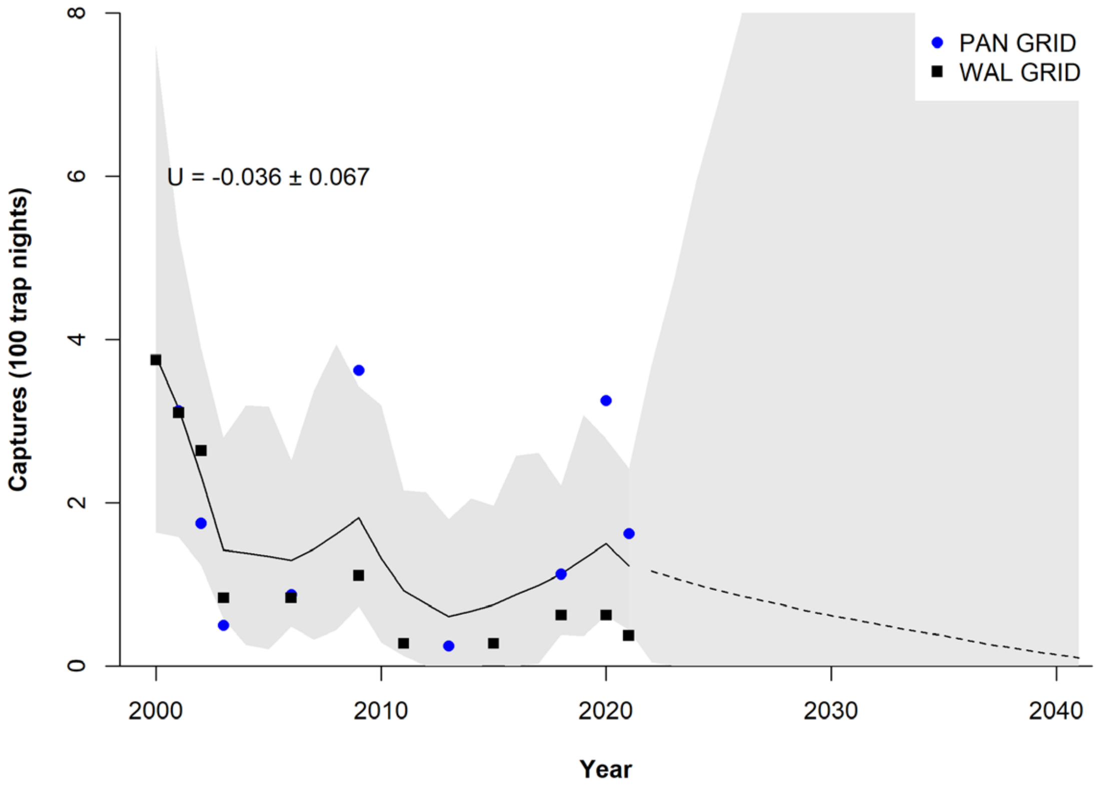
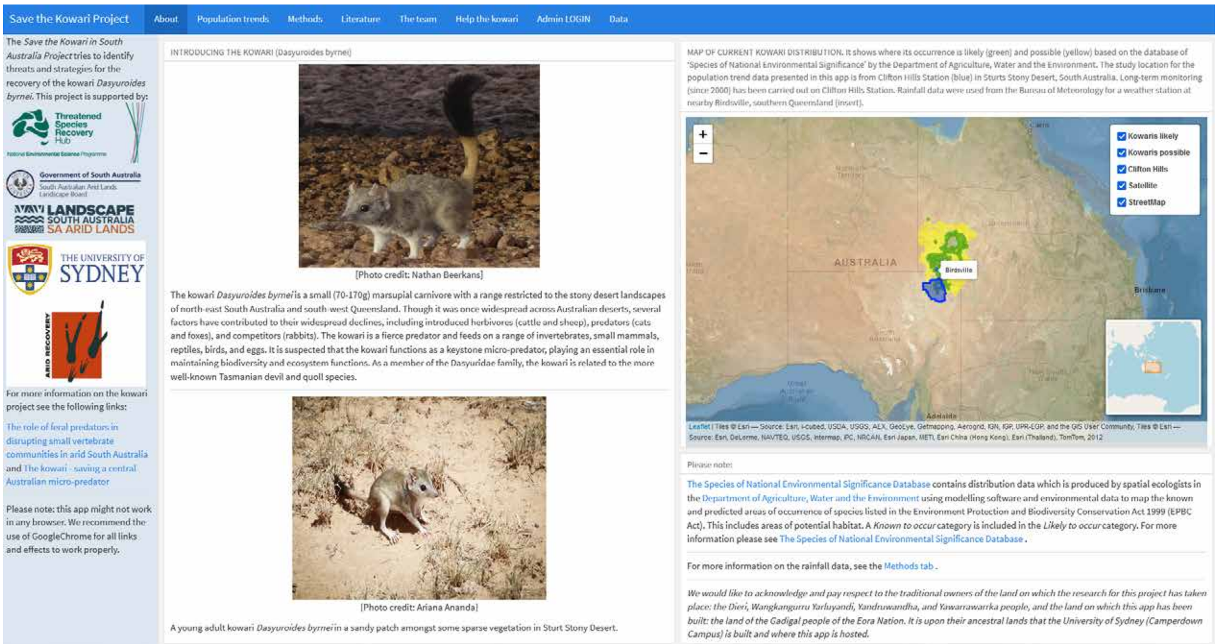


Figure 2: *Long-term (2000–2021) dynamics of two sub-populations of kowari,* Dasyuroides byrnei, *on PAN and WAL grids, Sturts Stony Desert, South Australia. Size of the population as estimated by the synchronous MARSS model (sub-populations combined), expressed as captures per 100 trap nights per year (black line), and forecast population (dashed line). Grey shaded area represents 95% credible intervals. Points indicate captures for WAL (black square) and PAN (blue circle) grids. Years without points indicate no survey occurred. U = population growth rate ± SD. Note that low capture rates in 2020 and 2021 on the WAL grid have been significantly impacted by high capture rates of the long-haired rat* Rattus villosissimus.

To allow stakeholders to run population models for the kowari in South Australia, a web-based app was written (Fig. 3a) that included a simple data entry interface. Capture data can be entered, and the population model runs and updates the plots and growth rate for the kowari (Fig. 3b).

(a)



(b)

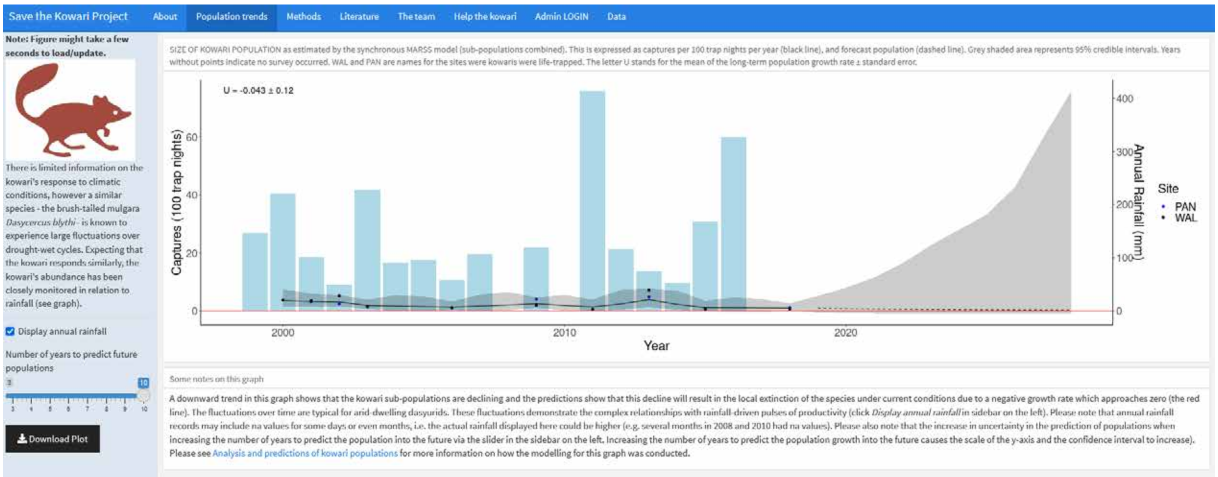


Figure 3: (a) : Home page of the Save the Kowari app. (b)Temporal population plot for the kowari, Dasyuroides byrnei*, on PAN and WAL grids, Sturts Stony Desert, South Australia (2000-2018) and 10 year forecast trend (± 95% credible interval) generated from the Save the Kowari app. Size of the population as estimated by the synchronous MARSS model (sub-populations combined), expressed as captures per 100 trap nights per year (black line), and forecast population (dashed line). Stakeholders can update population model as new data are obtained. Note U is the population growth rate (±SD).*

Spatial dynamics

Preliminary results from the multispecies analysis utilising alpha hull polygons reveal that the kowari has one of the lowest percentages of its historic range remaining occupied (28.16%; Fig. 4), well below the average for the other 38 species considered (78.46%). Among dasyurid marsupials, only the red-tailed phascogale (*Phascogale calura*) has fared more poorly, having declined to just 14.57% of its former range. By comparison, the mulgaras (*Dasycercus* spp.), which are ecologically most similar to the kowari, have declined over less than 5% of their original geographical ranges. As different hypotheses for these declines are incorporated into the analysis, we will gain understanding as to the specific factors that have caused the kowari's range to recede so severely compared to other arid zone mammal species. The hypotheses being considered are that the modern range represents a refuge for/from productivity, predation, competition, climate change, or interactions thereof, similar to McDonald et al. (2015) on critical weight range species that have declined but remain extant in the Northern Territory.

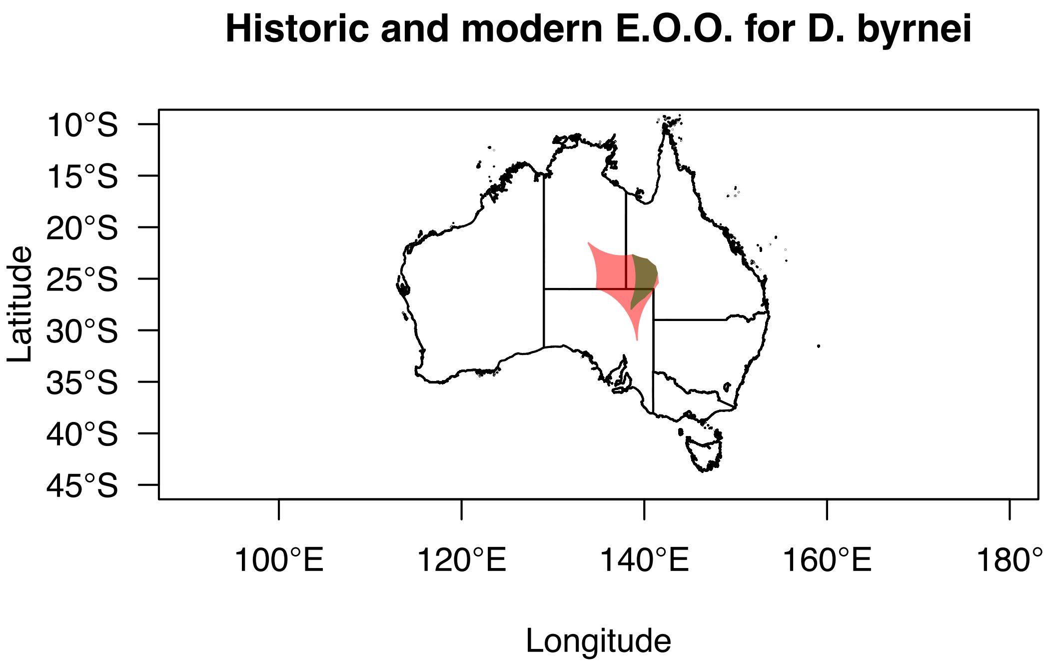


Figure 4: Extent of Occurrence (EOO) of kowari, Dasyuroides byrnei*, historic range (pink) and current range (grey).*

The current Maxent model of environmental suitability (Fig. 5) predicts occurrences extremely well on both training data (AUC = 0.99) and held-out test data (AUC = 0.99). By far the most important predictor variable was habitat suitability (areas of gibber plain as defined by satellite and on-ground surveys) with a percentage contribution of 65.1%. Other variables considered important by the current model were the temperature annual range (6.1%), mean temperature of the warmest quarter (5.2%), soil type (3.7%), and mean temperature of the driest quarter (3.2%). Given the iterative nature of modelling processes, we expect these to shift as new layers are developed using expert knowledge and incorporated.

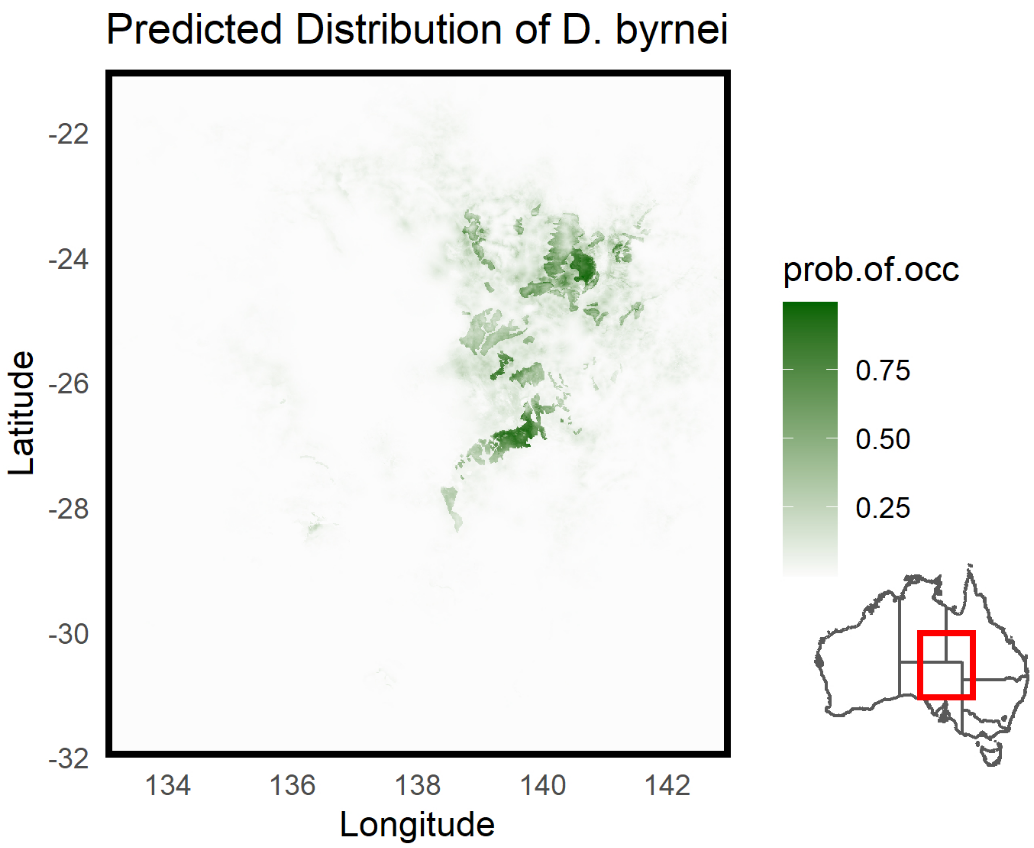


Figure 5: Probability of occurrence for the environmental suitability for the kowari, Dasyuroides byrnei*, generated using a Maxent model.*

Preliminary analyses of trapping data show that of all the potential predator species (dingoes, cats, foxes, and numerous bird/reptile species), kowari presence is most negatively correlated with dingo presence across both trapping grids (occurrence correlations: -0.16 PAN grid and -0.13 WAL grid, perhaps as a consequence of behavioural avoidance or predation pressure). Nonetheless, these correlations are not strong, and live-capture results since 2016 indicate that kowari numbers have responded to recent rainfall events (Fig. 2).

A stronger negative response to cattle presence was recorded on the historically lesser-grazed WAL grid (occurrence correlation: -0.2) compared to the PAN grid (occurrence correlation: -0.01), which has been subject to a higher grazing intensity both historically and in contemporary times. One hypothesis for this disparity is that individuals on the PAN grid have selected for burrow sites that have proven resilient to cattle presence (i.e. trampling) over time. Co-occurrence was observed with the fawn hopping mouse (*Notomys cervinus*) and kultarr (*Antechinomys laniger*) across both trapping grids and the long-haired rat (*Rattus villosissimus*) on the WAL grid only, potentially due to the extremely high numbers of *R. villosissimus* at this site (La Marca, unpublished PhD data). In contrast to the live trapping rates, higher densities of kowari captures were obtained via camera traps on the WAL grid (Fig. 6, right: captures per location ranged from 0 to 10) than on the PAN grid (Fig. 6, left: range 0-3). This is likely due to the extremely high number of *R. villosissimus* present on the WAL grid (n = 400) in comparison to the PAN grid (n = 63) during the November 2020 trapping period. On both grids there is a strongly evident association of camera-captures with gibber habitat (brown substrate in the figure), although activity clusters are close in all cases to small patches of sand as well as to floodplains.

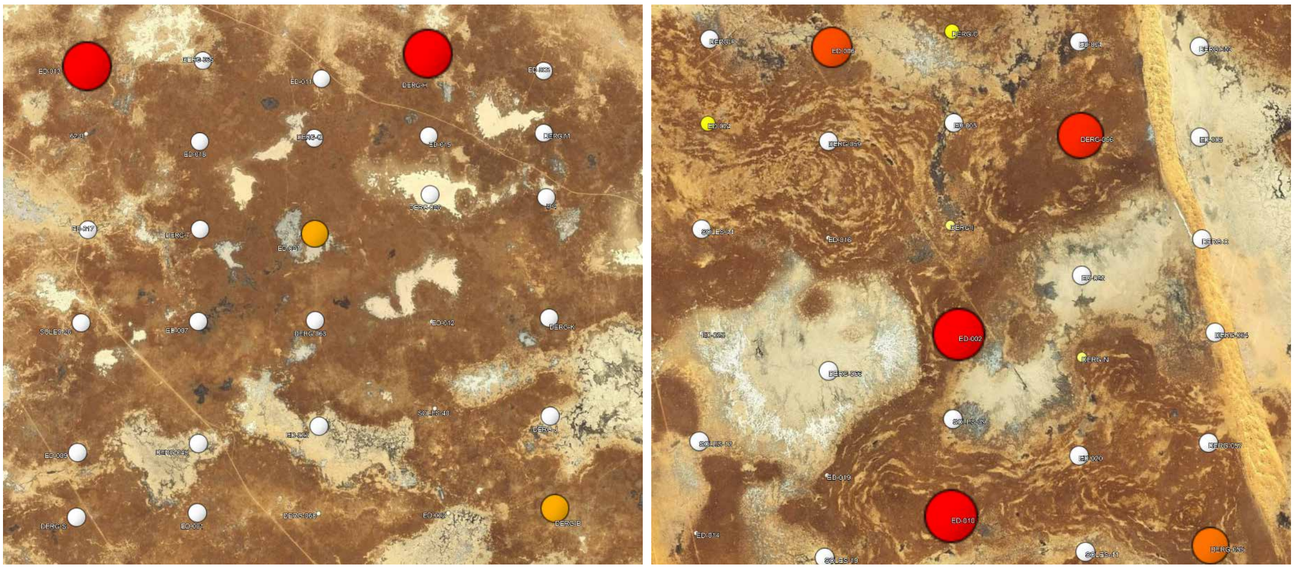


Figure 6: *Relative kowari densities captured by two camera grids (PAN and WAL grids, left and right, respectively) across the initial 6-month period. Point sizes scale with the number of triggers for each location in the Sturts Stony Desert, South Australia. PAN: 0-1 triggers = white, 2 = orange, 3 = red; WAL: 0-1 triggers = white, 2-3 = yellow, 8 = orange, 9-10 = red (no trigger values were between 4 and 7)*

Analysis of the mammalian (n = 10) and reptilian (n = 2) predator scats collected to date reveal an absence of kowari remains, indicating that the predation threat for kowaris may be low (La Marca, unpublished PhD data). This is consistent with the recent findings of Vernes et al. (2021) who found significant numbers of both cat (n = 43) and dingo (n = 204) scats throughout the Stony Desert bioregion, but with no traces of kowari remains. Similarly, analysis of barn owl (*Tyto delicatula*) pellets examined to date (n >100) revealed no traces of kowari remains, although many of the collected barn owl pellets remain unexamined (La Marca, unpublished PhD data).

Trials of distance testing using the Wildlife Drones radio-receiver system have demonstrated efficacy up to 1600 metres horizontal distance given a flight altitude of 95 m (Fig. 7). This indicates that by simply launching the drone 95 m into the air and rotating the directional antenna to listen for all tag signals simultaneously, a total of 804 hectares (8.04 km^2) can be surveyed in 2–3 minutes. In actual tracking scenarios this distance will increase substantially as the drone pilot will operate the drone across the grid sites during each ~20 minute flight survey. Tracking radio-tagged kowari is planned for August 2021, pending border restrictions.

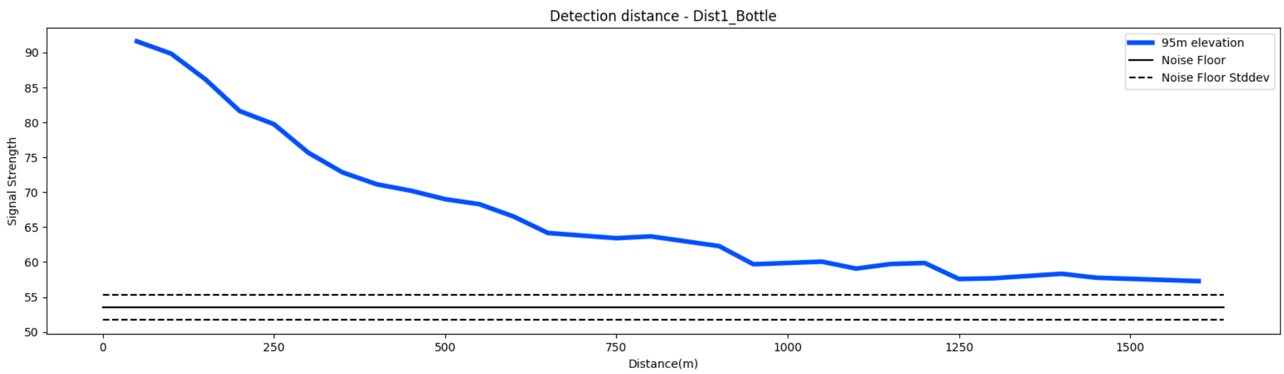


Figure 7: *Detection distance testing of Kowari tags, situated at ground level, using the Wildlife Drones radio-tracking system (flight altitude 95 m), reproduced from Saunders & Keaton (2021) with permission.*

A collaboration with Skylos Ecology has commenced the training of a detection dog on kowari scent and scat samples. Proposed research will utilise the detection dog to identify active burrows sites for burrow-usage analyses and will be structured to test the efficacy of detection dog services in contrast to traditional survey methods for identifying burrow sites (e.g., radio-tracking).

Discussion

This study confirms that the kowari has declined dramatically across time and geographical distribution, and indeed appears to have suffered a greater decline than most other extant small and mid-sized mammal species in arid Australia. These results confirm the results of other syntheses (e.g., Woinarski et al. 2014), but also provide both a quantitative estimate of the extent of decline and a ranking of where the kowari stands in comparison to other species. The kowari is now restricted to gibber habitats in South Australia and Queensland, having once occurred more broadly, albeit patchily, in surrounding sandy habitats. The current restriction of kowaris to gibber habitat may suggest that this is the species' preferred habitat and that its former presence elsewhere simply reflects small or ephemeral populations that failed to persist as the climate or environment changed. Alternatively, kowaris may persist in gibber because this habitat has been less subject to disturbance than most other habitats. The only other mammal species that is currently restricted largely to gibber is the fawn hopping-mouse (*Notomys cervinus*); notably, our work shows that this species now persists in only 20.13% of its former distribution. Gibber habitats are generally less subject to heavy grazing from cattle, and constitute environments that are too harsh for persistent activity by introduced predators. Low levels of these potential threats may best account for the persistence of kowari (and species such as the fawn hopping-mouse) to the areas of gibber habitat. In support of this, our spatial association analyses implicate disturbance from cattle as a key factor in reducing the local activity of kowaris, especially where grazing is recent and there is potential for fresh damage to burrows or other habitat components. We have not found evidence of predation upon kowari by dingoes or introduced predators, although a weak inverse spatial association between kowaris and dingoes suggests that predation may yet emerge as an explanatory factor when further diet samples have been obtained and network analyses have been completed. However, the population growth rate for populations that occur in the gibber of South Australia remain negative and are highly variable. Taken together, the geographic decline and temporal decline in South Australia place the kowari at risk of local stochastic extinction, with little ability to recover from surrounding populations.

Separation of the effects of cattle grazing and predation can be made by examining the diets of predators and collecting temporal as well as spatial data on the association between cattle and kowari. However, inferences garnered from association analyses are unlikely to be definitive; experiments will be needed to gain strong inference about causal factors driving kowari decline. Intriguingly, Archer (1979) singled out the kowari as in particular need of research experiments to identify range-limiting factors and nominated translocations to other areas where particular threats were absent as a useful way to progress this. We take up this possibility further overleaf.

Kowari being released by volunteer Lily Mackintosh. Image: Ariana Ananda

Application of research (to-date and anticipated)

Because data collection and analysis are ongoing, applications of our research need to be drawn cautiously. Nonetheless, on the basis of findings to date, management of cattle grazing and predation from introduced predators should be key considerations for conservation of the kowari.

Observations on one of the study grids (PAN) show that kowari can persist in the presence of cattle, but the negative association between cattle and kowari on the lightly grazed WAL grid suggests that kowari populations may be initially impacted when cattle first disturb previously ungrazed sites. An implication from this is that expansions in cattle grazing, such as may occur with the creation of new watering points, will be damaging for kowari for at least the initial period of co-occurrence. Ideally, cattle-free areas should be ensured in critical kowari habitat or, at the least, key habitat components such as established burrows in sand patches should be identified and fenced to prevent damage from cattle trampling.

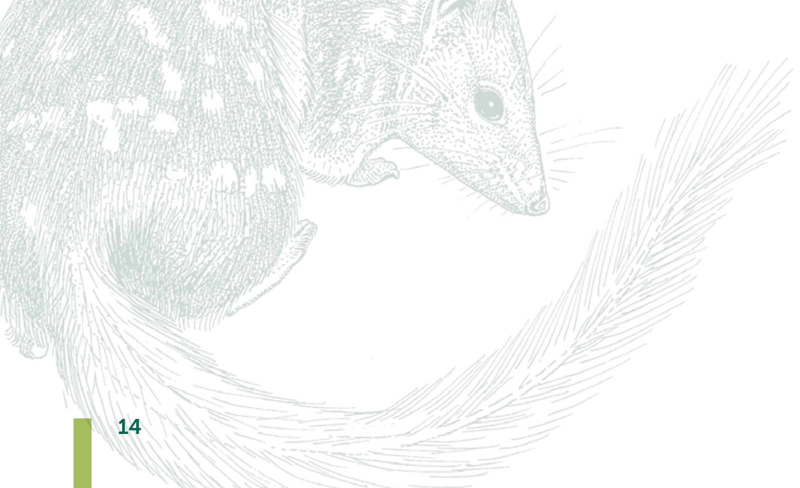
Kowari remains have not been found in feral cats, foxes or dingoes in our study area, and we recorded only weak inverse spatial associations between kowari and dingoes on the two grids. However, our sample sizes to date are small, and comparative data from dietary studies of similar-sized mulgaras suggest that the three predator species take small but significant numbers of individuals, especially during the decline phase of population irruptions when *per capita* predation is most intense (Spencer et al. 2017). Alternatively, co-occurring predators may compete for food, decreasing the survival of individuals. Invoking the precautionary principle, control of predators should be a goal for management and could be implemented most effectively in priority population sites for kowari and at times when *per capita* predation is likely to be most detrimental to population persistence.

Impact of the research (to-date and potential in future)

The research has been carried out and supported by the South Australian Department for Environment and Water, with additional funding provided by the Australian Government through SA Arid Lands NRM and now Landscapes Boards, and forms part of the Department's long-term monitoring and management of the state's kowari populations. The long-term temporal dynamics of the focal study populations in South Australia revealed the kowari sub-populations act in synchrony and have undergone a population decline (Greenville et al. 2018). The development of a shiny app for the addition of field monitoring data and analysis of population size will assist in real time interpretation of kowari population trends and help to quickly identify times when management intervention is urgent. As research is ongoing and will comprise the PhD thesis and publications to be completed by Mr William La Marca, further impacts of the research can be anticipated when data collection is finalised and the research findings are widely available. The results from the temporal and spatial dynamics have also contributed to the kowari being accepted for an up-listing review (from Vulnerable to Endangered) on the Environment Protection and Biodiversity Conservation Act; the review is set to take place in 2022. In addition, an informal kowari recovery group has been formed to discuss and implement conservation strategies to aid the kowari.

This project has also raised the public awareness of the kowari through the initiation of Team Kowari Incorporated (https://teamkowari.com.au/). Team Kowari aims to educate and organise a team of citizen scientists to conserve the kowari. It raises funds through donations and subscriptions to help undertake conservation work and will support the continued PhD project beyond NESP.

We anticipate that the ongoing work will generate findings applicable to translocation efforts proposed by both the South Australian Department for Environment and Water and the conservation initiative Arid Recovery. Similarly, the outputs of this research are expected to be applicable to the ongoing survey and management programs undertaken by South Australian and Queensland government agencies. Through Team Kowari and the informal recovery group, actions such as on-going education, public awareness, and scientific research will be implemented into the future.



Broader implications – for other places or species

Analysis of the ranges of the 38 other arid-dwelling mammal species considered in this study should yield insight into whether similar suites of factors are involved in limiting their distributions. If there are, management of a small number of defined threatening processes should maximise conservation benefits for the most species and increase the efficiency and effectiveness of resource allocation. If different factors emerge as important for dictating the ranges of individual species, management may need to be site-specific or focused on individual threats. In this instance, our ranking of the degree of range decline for each of the study species could be used as part of a ranking process for the allocation of management effort.

In the more specific case of the kowari, we anticipate that management actions imposed to ensure kowari population persistence would benefit co-occurring species such as the fawn hopping-mouse and kultarr.

Future research priorities

The kowari has declined across much of its former range, and priorities for future research therefore fall into three main categories. First, there is a need to identify key populations that remain extant in Queensland and South Australia and ensure that these are adequately protected. Species distribution modelling is an important first step in this process (Figure 5), but targeted field surveys will be critical to determine kowari population size in both known and any further identified localities. Second, when key populations have been identified, these will need to be monitored and factors that affect kowari population size and persistence determined. We elaborate further on necessary steps below. Third, in places where kowaris have disappeared, research that seeks to reintroduce them would be justified. This third step is crucial to help ensure the persistence of the kowari as a species, and to restore its functions as a culturally important species and as a potential keystone predator in arid landscapes.

We suggest that specific priorities to address these three research areas should include:

- Field surveys in areas identified by modelling as potential kowari hot spots.
- Testing of novel methods and technologies to improve the efficiency of field surveys. As foreshadowed above, use of drones and kowari-detection dogs are two such methods.
- Continued monitoring of known hot spot populations, such as those described in this report, to document the effects of heavy rains, droughts, increased temperatures and other manifestations of the changing climate.
- Targeted field experiments that quantify the relative importance of cattle and introduced predators. Such experiments could be carried out most readily by judicious use of fences to exclude cattle and predators from parts of the landscape. Ideally experiments should have an orthogonal and replicated before-after control-impact design, but more practically inferences could still be gained by fencing off parts of the landscape to exclude cattle or predators, or by targeted-area baiting to reduce feral cat and /or fox activity.
- Assessment of the dispersal capability of kowaris, especially in relation to their ability to repopulate sites from which they gone locally extinct. Radio-tracking via drones should assist with this, but is temporally limited and may not reveal individuals that are in the process of dispersing. SNP analysis of collected tissue samples should therefore be seen as a priority to gain insight into landscape level movements and the potential for dispersal.
- Identification of key habitat, food and shelter resources needed by kowari. This research is essential to ensure that currently extant populations do not become resource-limited due to environmental or climatic changes or changes in land use, and to better understand kowari requirements in the event that approvals can be gained for translocations to new sites or sites from which the animals have disappeared.
- Identification of sites to which kowari can be translocated. Two such sites, at Arid Recovery and Witjira National Park, have been identified already.

Data sets

Historic data and population data collected in ongoing monitoring will be stored by the South Australian Department for Environment and Water and on the shiny app developed for this project. In addition, we anticipate that thousands of camera images and focal datasets on kowari habitat use and movements will be produced. The core of such databases will be made available as Supplementary Material to future journal publications arising from this study.

Recommendations

Much of our understanding of kowari ecology and conservation requirements has come from long-term monitoring of populations in South Australia. We strongly support continuation of this program. In addition, we recommend identification of further kowari populations from elsewhere in the species current range and to initiate programs of long-term monitoring at these sites too. Sites in the Diamantina region in western Queensland have already been subject to survey for kowaris (J. Augusteyn, pers. comm.), and may be particularly suitable. The monitoring should be designed not only to assess the population trajectory of kowari, but also of other threatened species with which they occur. The monitoring should also evaluate the extent and intensity of identified threats, and of interactions among threats, and build in trigger points at which management interventions are likely to be most needed.

We recommend also that the seven dot point research priorities outlined above be considered for future implementation.

Conclusion

Our study confirms the kowari as a threatened species and identifies it as having lost more of its overall geographical range than most other extant arid-zone native mammals. Much of our current understanding of the species comes from targeted research on two local populations in north-eastern South Australia. This work emphasises the critical importance of long-term monitoring, and provides insight into threats such as cattle grazing (which impacts habitat and shelter sites) and predation (which potentially depletes populations). The downward spiral of the kowari can be stemmed, and here we outline a series of suggestions and recommendations to stabilise extant populations and restore others that have gone locally extinct.

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Ethics statement

Approval to carry out the field-based research was granted by the University of Sydney Animal Ethics Committee (approval no. 2019/1639).

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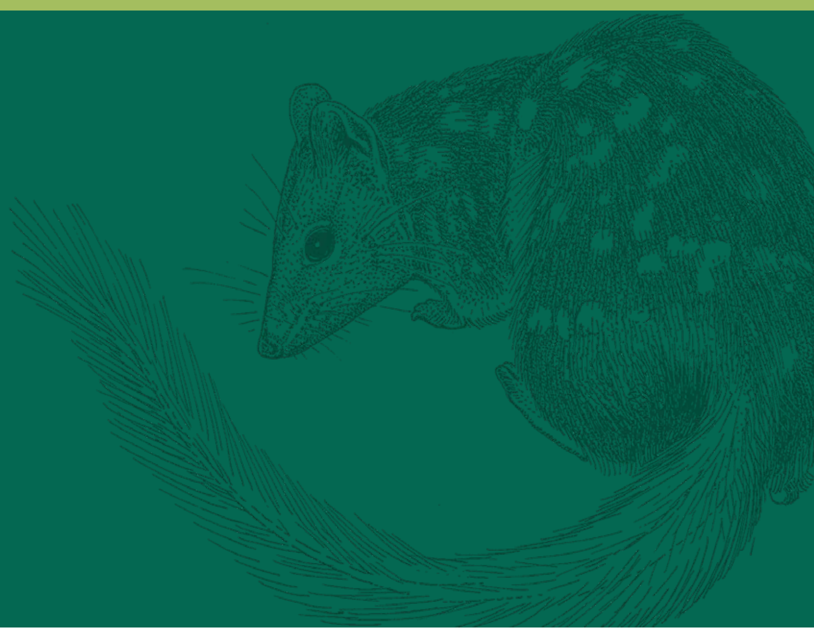

Further information:

http://www.nespthreatenedspecies.edu.au

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