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Pilbara Northern Quoll Research Program: a review of progress (2016-2021)

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Pilbara Northern Quoll Research Program: a review of progress

(2016-2021)

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Summary

The Pilbara is currently an important stronghold for the endangered northern quoll (*Dasyurus hallucatus*), given that the invasion of the poisonous cane toad (*Rhinella marina*) elsewhere in northern Australia has seen dramatic declines in once locally abundant quoll populations. Northern quolls are listed as Endangered under both the Commonwealth's *Environment Protection and Biodiversity Conservation Act 1999* and the Western Australian *Biodiversity Conservation Act 2016*. A dearth of information on the ecology of the northern quoll in the Pilbara highlighted a need to improve on this knowledge to better inform conservation management of the species in this region.

A research plan guiding the implementation of priority future actions for the northern quoll in the Pilbara was developed in 2010 and updated in 2013, following a workshop with scientists, environmental consultants, mining proponents, and state and federal government agencies. The Department of Biodiversity, Conservation and Attractions (DBCA) has been undertaking research on Pilbara northern quolls focusing on the key directions determined by the research plan (i.e., the Pilbara Northern Quoll Research Program), which was refined following a second workshop held in May 2016. Here, we review the progress against the key research priorities for the northern quoll in the Pilbara determined at this latter workshop (i.e., the 2016-2020 Research Plan). We also provide future directions to guide ongoing research and investment.

The Pilbara Northern Quoll Research Program has made significant progress in better understanding the status and ecology of this endangered species in the Pilbara. In summary:

- Surveys for new populations increased the number of known northern quoll records (Dunlop *et al.,* 2019a) and enabled the development of a species distribution model that accounted for sampling bias (Molloy *et al.*, 2017; Moore *et al.*, 2019; Shaw *et al.,* 2023).
- Data from camera traps and standardised cage trapping indicated the efficacy of survey and monitoring protocols could be improved due to the dynamic nature of northern quoll populations (Dunlop *et al.,* 2019a, Moore *et al.,* 2020, 2023a,b).
- Investigation of habitat use at multiple scales has helped to identify critical habitat with complex topography (Moore *et al.,* 2021a, 2022; Cowan *et al.,* 2022).
- A dietary analysis of northern quolls across the region indicated a flexible omnivorous strategy (Dunlop *et al.,* 2017).
- Sequencing of more than 1800 tissue samples uncovered a lack of genetic structure and a high level of female promiscuity within the Pilbara population (Dunlop *et al.,* 2019; Chan *et al.,* 2020).
- Population viability analyses indicated species persistence may be compromised by juvenile mortality, highlighting the importance of reducing threats to dispersing males, including predation by feral cats (Moro *et al.,* 2019).
- Knowledge of the demographics of northern quoll populations in the Pilbara has been improved (Henandez-Santin *et al.,* 2019).
- Trials of Felixer™ feral cat grooming traps indicated they were safe to use in the presence of northern quolls, and they were effective at identifying feral cats as targets (Dunlop *et al.,* 2020; Edwards and Nelson, 2022).

- The identification of female northern quoll dens used during breeding showed that they used deeper and cooler dens than other available rocky crevices, and this can help to inform artificial habitat creation (Cowan *et al.,* 2020b).
- Investigation of the influence of other threats and their management, such as the impending cane toad invasion and mining activities is ongoing.
- Further research on the influence of interacting threats on northern quolls such as introduced predators, fire and grazing is also recommended (Moore *et al.*, 2021b).
- A review on the progress of the Pilbara Northern Quoll Research Program was also published (Gibson *et al.*, 2023).

Introduction

The northern quoll (*Dasyurus hallucatus*) is a medium-sized carnivorous marsupial, the smallest of Australia's four species of Dasyurus (Oakwood, 2002). Once widely distributed in northern Australia, the species has suffered a significant range contraction since European settlement (Braithwaite and Griffiths, 1994; Hill and Ward, 2010; Moore, 2021b). The primary cause of the most recent decline across northern Australia has been attributed to the spread of the toxic introduced cane toad (*Rhinella marina*). Poisoning resulting from predation attempts on cane toads has resulted in the complete collapse of some northern quoll populations in Queensland and the Northern Territory (Woinarski *et al.*, 2010, 2015). Cane toads are yet to reach the Pilbara but are predicted to eventually invade this region from the Kimberley (Kearney *et al.*, 2008; Tingley *et al.*, 2013; Southwell *et al.*, 2017).

Several other factors have been attributed to the decline of the northern quoll, including competition with and predation by introduced predators, altered fire regimes, grazing pressure by introduced herbivores, habitat loss and fragmentation, and the various interactions between these threats (Braithwaite and Griffiths, 1994; Hill and Ward, 2010; Woinarski, 2014; Moore *et al.*, 2021b). While northern quolls inhabit a range of habitat types across northern Australia (Moore *et al.*, 2021b), in the Pilbara they tend to prefer topographically complex rocky habitats (Hernandez-Santin *et al.*, 2016; Moore *et al.*, 2021a). As the iron-ore rich rocky areas also tend to be the focus of mining operations, habitat loss from mining and infrastructure development is considered an added threat unique to the Pilbara population (McKenzie *et al.*, 2009). Given their rapid decline coupled with this range of threats, northern quolls are listed as Endangered under both the Commonwealth's *Environment Protection and Biodiversity Conservation Act 1999* and the Western Australian *Biodiversity Conservation Act 2016*.

Until recently, there was a dearth of information available on the ecology of the northern quoll in the Pilbara (Cramer *et al.*, 2016). We know that the Pilbara population is genetically distinct, being separated from the nearest Kimberley population by approximately 500 km of the arid Great Sandy Desert, with no evidence of contemporary gene flow (Spencer *et al.*, 2013; Hohnen *et al.*, 2016). To better inform conservation management of the Pilbara northern quoll population, a need was identified to improve our knowledge of the species in this region.

Key directions for northern quoll research were determined at a workshop hosted by the Department of Biodiversity, Conservation and Attractions (DBCA) in 2013 (Cramer *et al.*, 2016), and further refined in a subsequent workshop in May 2016 (Cramer and Dunlop, 2018) wherein the research priorities for northern quolls in the Pilbara were identified. These included:

1) Assessing and refining survey and monitoring protocols (combination of the first two priorities).
2) Improving our understanding of fine-scale habitat use to identify areas of critical habitat.
3) Improving our understanding of population dynamics and structure.
4) Assessing the impacts of introduced predators.
5) Understanding the spread and impacts of cane toads.
6) Understanding interactions with infrastructure and built environments.
7) Other research priorities (threat interactions).

In collaboration with universities and other stakeholders, DBCA has been undertaking northern quoll research guided by the above priorities under the Pilbara Northern Quoll Research Program (PNQRP), with funding from the mining industry (including offsets) and other development proponents. Collaborative projects with universities have supported several student projects that have addressed many of the research questions identified. Much of this research has been published and summaries are provided here. Progress reports on the PNQRP are available at library.dbca.wa.gov.au (Cook and Morris, 2013; Department of Parks and Wildlife, 2014; Dunlop *et al.*, 2016, 2018, 2019a; Dunlop, 2017; and Appendix A for other outputs). This review is an overarching summary of progress from 2016, and it also provides suggestions for future research to ensure the ongoing persistence of the northern quoll in the Pilbara. A scientific paper resulting from this review was also published (see Gibson *et al.,* 2023).

Assess and refine survey and monitoring protocols

Context

Survey and monitoring information underpins assessments of northern quoll distribution and allows presence and abundance within a defined area to be determined. Long-term regional scale monitoring (i.e., Pilbara-wide) of northern quoll populations helps us understand natural fluctuations in population size and provides context for monitoring at the local scale (e.g., within a small distinct location). One important consideration for the northern quoll is that most males die after their first year of a largely synchronous breeding season (i.e., semelparity; Oakwood, 2000); hence the timing of surveys needs careful consideration depending on the aim of the survey.

Dunlop *et al.* (2014) revised and implemented a survey and monitoring protocol for several Pilbara sites with known northern quoll populations, with the aim to obtain detailed information on population ecology, demographics, and trends in abundance across these sites. Although this monitoring program was not established to implicitly measure management effectiveness, it does provide baseline data that may be useful for such studies. Cramer and Dunlop (2018) identified a need to further refine survey and monitoring protocols, principally focusing on:

1) The extent to which the existing survey guidelines can be enhanced using emerging technologies, to ensure that they provide the most cost-effective and robust protocols for use at a regional level.
2) Consideration of detectability, and hence more robust estimation of appropriate sampling effort (and protocols) to reliably demonstrate presence or absence.
3) Further refinement of sampling procedures that can provide estimates of density and local population size.

Baseline data

Since its inception, the Pilbara Northern Quoll Research Program (PNQRP) has contributed more than 1700 northern quoll records to historical data (Dunlop *et al.*, 2019a). The majority of these are recent with only 313 records dating back further than 2009 (Figure 1). Over time, surveys in new areas under the PNQRP have significantly expanded knowledge on the distribution of the northern quoll in the Pilbara. Historically, survey effort has typically been focused in mining areas for environmental impact assessment, and hence have been highly spatially biased. Using an expanded data set of northern quoll presence and adjusting for this bias, a predictive species distribution model was produced by Molloy *et al.,* (2017).

As a result of the increased survey effort, an isolated population of northern quolls was discovered in Karlamilyi National Park in 2012 (Turpin and Bamford 2015; eastern-most records in Figure 1). In partnership with Kanyirninpa Jukurrpa (KJ) Martu Rangers, additional surveys (trapping, cameras, and scats) undertaken between 2016 and 2018 detected further records of the species in this area (Dunlop *et al.*, 2019a). Consistency of detections over the past few years indicates that marginal desert habitat on the eastern edge of the Pilbara can support a low-density population of quolls.

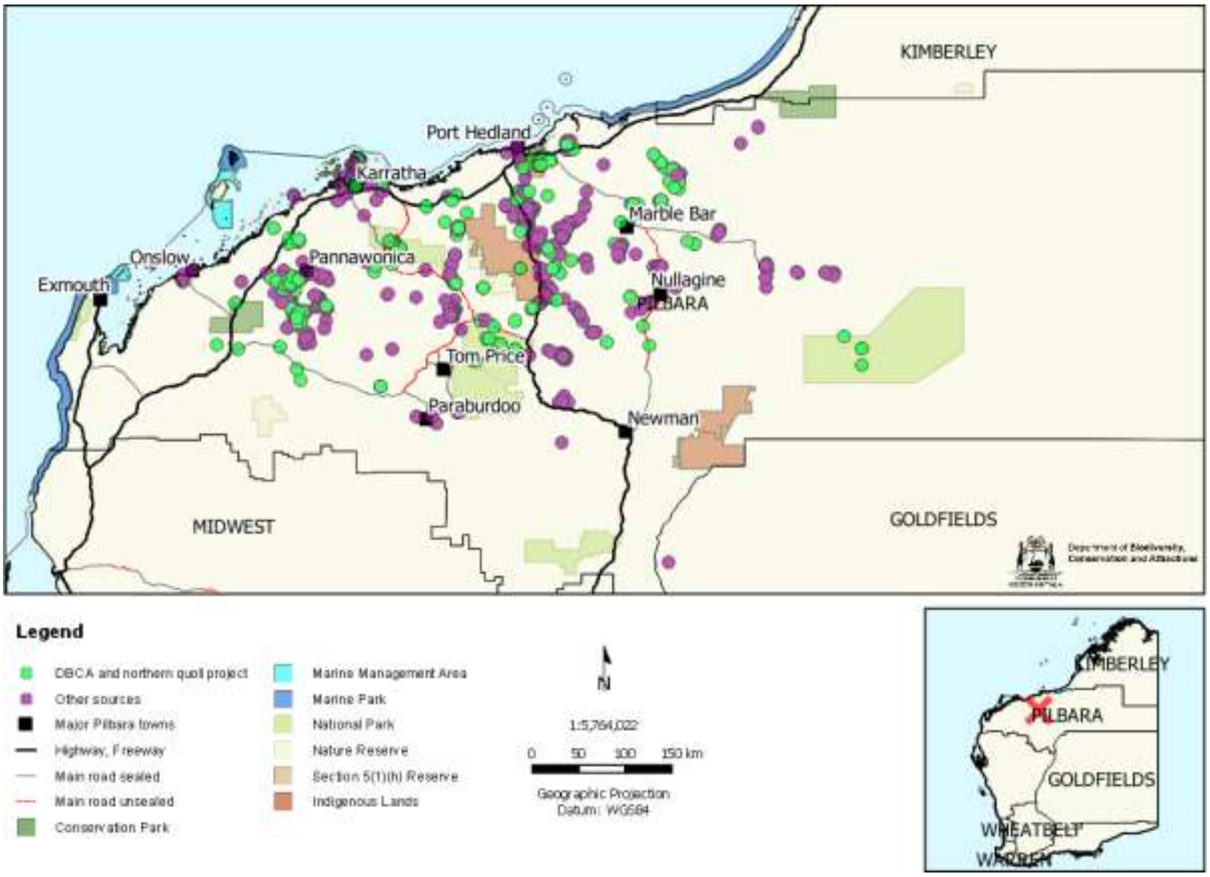

***Figure 1** Location of northern quoll records in the Pilbara between 2011 and 2019 (from Dunlop et al., 2019a). Records collected by the PNQRP are shown in green while those collected by universities, biological consultants, or other sources are shown in purple.*

Sampling effort

Understanding the likelihood of detecting northern quolls using a given survey technique is particularly important to determine the effort required for adequate detection in areas with low density populations (Dunlop *et al.*, 2019a). Standardised survey and monitoring procedures were revised in 2014 (Dunlop *et al.*, 2014); these cover methods for cage trapping, scat searches, and camera trap detection. Using this approach, annual surveys of northern quolls were undertaken in the Pilbara from 2014 to 2019 (Table 1; Figure 2). Additional sites were also monitored as a component of Roy Hill's Northern Quoll Research Plan targeting the Chichester Ranges (see Cowan and Dunlop, 2020; Appendix B).

Preliminary analyses based on the live trapping data from this annual survey program (i.e., six trapping sessions from 2014-2018) using spatially explicit capture-recapture analyses were undertaken to estimate population size (Dunlop *et al.*, 2019a; Table 1).

Table 1 *Total capture (above) and individual capture (below) statistics for northern quolls at all monitoring sites in the Pilbara (adapted from Dunlop et al., 2019a). *Indicates survey effort was conducted through remote camera deployment, and individuals are estimated numbers (below). CR = Conservation Reserve, CP = Conservation Park, NP = National Park.*

Site	2014	2015	2016	2017	2018	2019	Total	Trap nights	Captures/100 traps
Cane River CR	1	0	0	-	-	-	1	600	0.17
Dolphin Island	43	61	19	17	18	17	175	1200	14.58
De Grey Station	4	-	-	-	-	-	4	200	2.00
Hooley Station	*	0	0	*	*	*	0	400	0.00
Indee Station	65	81	30	41	124	55	396	1200	33.00
Karijini NP	0	0	12	*	12	1	25	1000	2.50
Karlamilyi NP	0	-	1	*	*	-	1	240	0.42
Mallina Station	14	26	0	*	-	*	40	600	6.67
Meentheena CP	-	1	-	-	-	-	1	200	0.50
Millstream-Chichester NP	26	2	3	7	0	1	39	1000	3.90
Mt Florance Station	18	10	10	*	*	*	38	600	6.33
Poondano	-	8	5	-	-	-	13	400	3.25
Red Hill Station	5	14	7	-	-	-	26	400	6.50
Roy Hill Rail	-	1	0	5	-	3	9	300	3.00
Yarrie Station	18	12	4	*	*	*	34	600	5.67
Grand Total	194	216	91	70	154	77	802	8940	8.97

Site	2014	2015	2016	2017	2018	2019	Total	Trap nights	Individuals/100 traps
Cane River CR	1	0	0	-	-	-	1	600	0.17
Dolphin Island	22	17	8	11	11	10	79	1200	6.58
De Grey Station	3	-	-	-	-	-	3	200	1.50
Hooley Station	-	0	0	3*	1*	2*	0	400	0.00
Indee Station	22	26	12	23	32	9	124	1200	10.33
Karijini NP	0	0	4	4*	5	1	10	1000	1.00
Karlamilyi NP	0	-	1	-	6*	-	1	240	0.42
Mallina Station	6	14	0	8*	-	-	20	600	3.33
Meentheena CP	-	1	-	-	-	-	1	200	0.50
Millstream-Chichester NP	9	1	1	3	0	1	15	1000	1.50
Mt Florance Station	6	5	3	12*	8*	2*	14	600	2.33
Poondano	-	5	3	-	-	-	8	400	2.00
Red Hill Station	3	6	5	-	-	-	14	400	3.50
Roy Hill Rail	-	1	0	2	4	1	8	300	2.67
Yarrie Station	7	6	3	8*	6*	-	16	600	2.67
Grand Total	79	82	40	39	52	21	313	8940	3.50

However, due to the low recapture rate at many of the sites, only estimates of density could be determined for two sites (i.e., Dolphin Island and Indee Station). This analysis also excluded males due to an inadequate sample size.

The density estimate was 0.29 females ha^{-1} (95% CI: 0.22, 0.40) at Dolphin Island and 0.23 females ha^{-1} (95% CI: 0.18, 0.28) at Indee Station, which remained largely stable across the six trapping sessions. The probability of detection if a trap was placed at the centre of an animal's home range was estimated to be 0.29 (95 % CI: 0.22, 0.40) at Dolphin Island and 0.22 (95% CI: 0.17, 0.28) at Indee Station. The results indicated that live trapping using the standard 50 traps for four nights (Dunlop *et al.*, 2014) would be sufficient to calculate the population size of female northern quolls when they occur at relatively high densities, but more effort would be required for low density populations. The live capture rates for northern quolls at most of the selected monitoring sites were relatively low (Table 1), therefore, further refinement of the monitoring program in terms of selected sites and methodology should be considered.

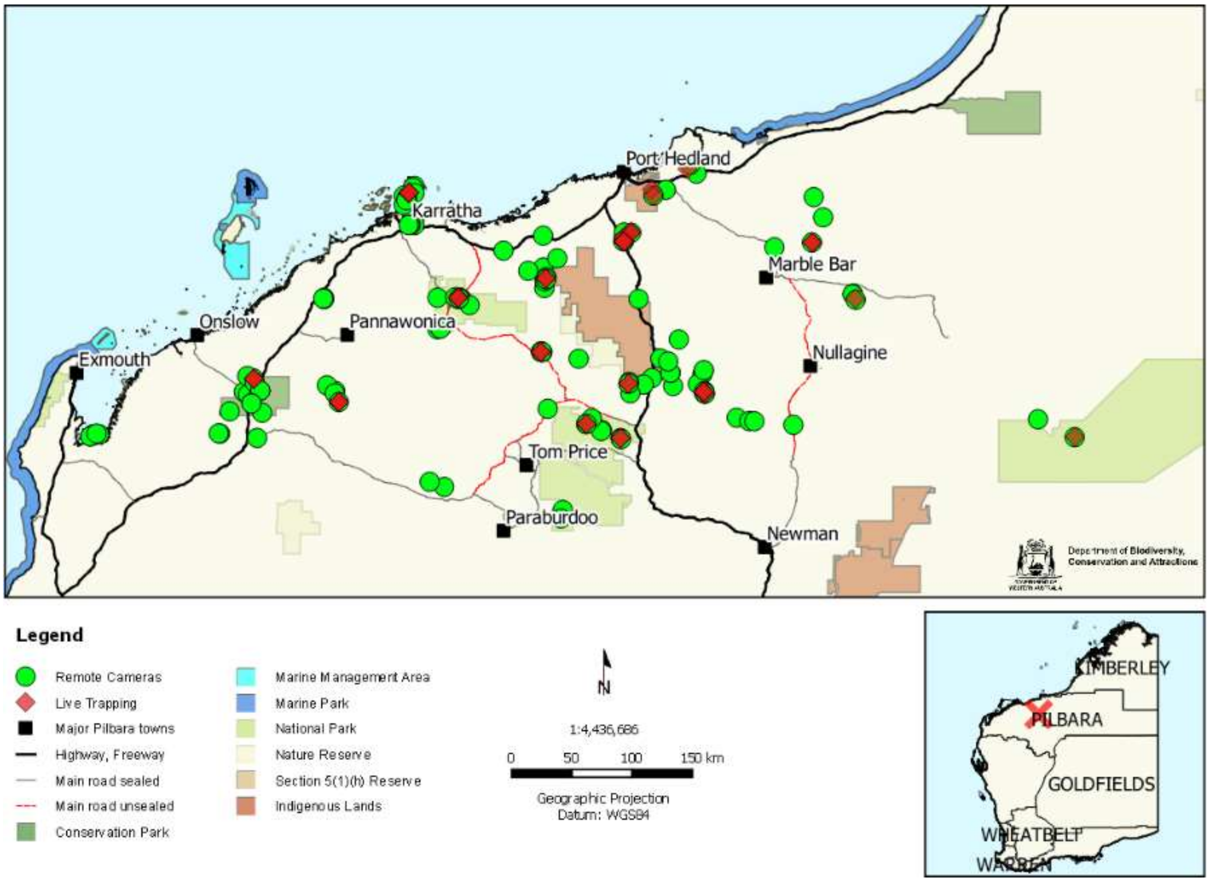

Figure 2 *Location of monitoring sites for northern quolls via camera and cage trapping in the Pilbara region, 2011-2019 (from Dunlop et al., 2019a).*

Improving detection rate

An increasingly popular alternative to live trapping is the use of camera traps. When applied to a species where individuals can be recognised via unique markings, camera traps can be used to estimate abundance (e.g., Hohnen *et al.*, 2013). In the Pilbara, the potential for remote cameras to accurately identify individual northern quolls based on their spot pattern was examined by placing 110 vertically orientated (downward facing) cameras across 23 landscapes within a 6000 km^2 study area (Moore *et al.*, 2021a). Results indicated that vertically orientated cameras were effective at capturing images suitable for individual identification, with over 70% of images allowing for quolls to be identified (Moore *et al.*, 2021a).

Moore *et al.* (2020) examined the sampling effort required using horizontally or vertically orientated cameras to reliably detect northern quolls in the Pilbara. Given the reduced field of view of vertically orientated cameras, it was assumed that this may reduce the detection rate. A total of 46 arrays consisting of paired horizontally and vertically orientated cameras were deployed across the same 23 landscapes as above, with two arrays in each landscape (Figure 3). Landscapes varied in predicted quoll abundance, ranging from 0 to 71 individuals (Moore *et al.,* 2022). Both cameras in each orientation operated for 200 days, although detection probabilities were analysed using only the first 60 nights. Results showed camera orientation was not a significant factor in influencing northern quoll detectability, with slightly less survey effort required using horizontal cameras to be 95% confident of northern quoll absence at a site (i.e., 24 compared to 32 nights).

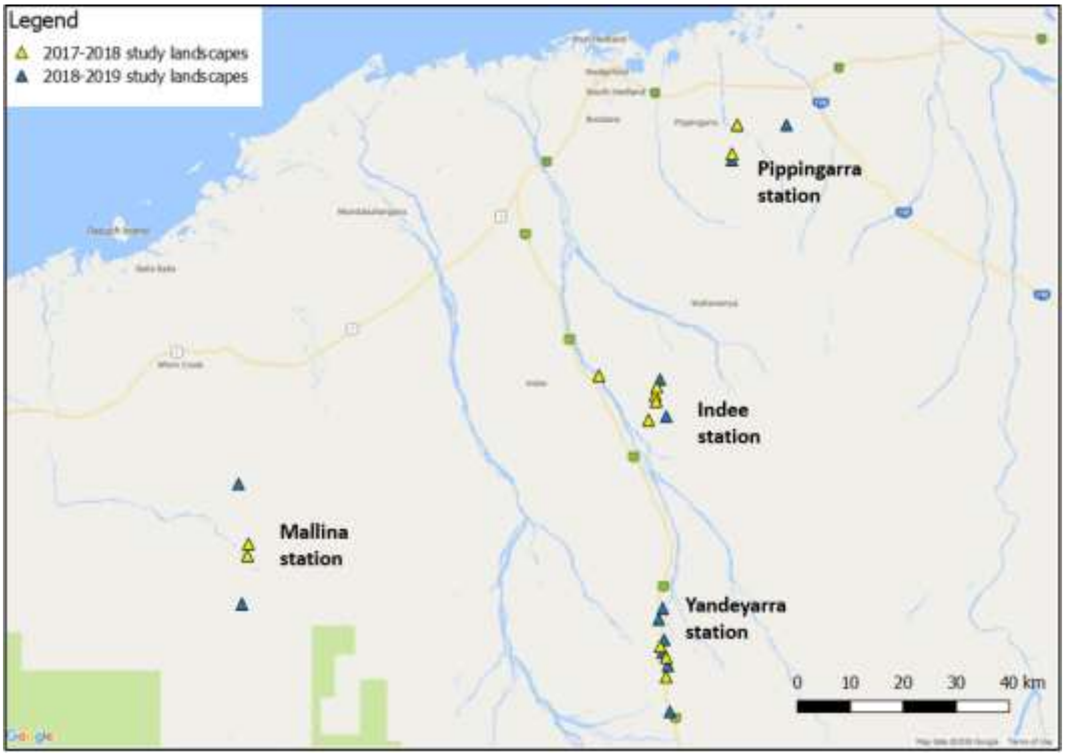

Figure 3 *Locations of the 23 study landscapes for both 2017-2018 and 2018-2019 sampling periods (from Dunlop et al., 2019a). Study landscapes were distributed across four pastoral stations: Mallina, Indee, Pippingarra and Yandeyarra.*

Cost effectiveness – live trapping versus camera trapping

Data from the Pilbara northern quoll annual survey program, collected from sites which varied in estimated quoll abundance (Moore *et al.,* 2022), was used to compare the cost effectiveness of using either live trapping or vertically orientated camera traps to detect changes in northern quoll occupancy with 80% confidence (Moore *et al.,* 2023a). Regardless of whether the monitoring program aimed to detect a 30, 50 or 80% change in quoll occupancy, a program using camera traps was always cheaper and more efficient than one using live trapping. The cost differential between the two monitoring methods increased as the program aimed to detect smaller changes in occupancy. While the most cost-effective camera designs used a similar number of sites to the most cost-effective live trap designs, camera trap designs were able to accrue greater survey effort by operating for longer periods of time at very little cost.

Overall, these results suggest that monitoring using camera traps is a cheaper and more efficient method than using live trapping, particularly for detecting smaller magnitudes of decline.

Outcomes

- Improved understanding of the distribution of the northern quoll in the Pilbara.
- Improved understanding of the application of capture-recapture techniques to estimate density based on standardised live trapping data, indicating that further refinement is required.
- Identification of the sampling effort required using either horizontally or vertically orientated cameras to detect northern quolls with a pre-specified level of confidence, with either orientation producing a similar result.
- Identification of the cost-effectiveness of monitoring programs using either vertically orientated camera traps or standard live trapping; with camera traps being a more cost-effective option.

Future directions

1) Update existing survey and monitoring protocols to include recommendations regarding a program based on camera traps, individual identification and capture-recapture or occupancy analytical approaches.
2) Provide a guiding framework for regional monitoring of northern quolls that can be used by multiple stakeholders to better understand long-term population trends.
3) Investigate emerging technologies (e.g., artificial intelligence cameras) to improve effectiveness and efficiency of monitoring approaches.

Improve our understanding of fine-scale habitat use to identify areas of critical habitat

Context

As discussed above, based on the available occurrence data of northern quolls in the Pilbara, a predictive habitat suitability model was developed by Molloy *et al.* (2017; Figure 4). Moore *et al.* (2019) added to this work by expanding species distribution modelling to include the entire species' range. While these models provide regional context for potentially suitable habitat for northern quolls, further studies to identify refugial areas, and the spatial distribution of these, that provide protection from threats and are suitable for breeding, were considered a priority by Cramer and Dunlop (2018). Genetic studies show minimal genetic divergence among subpopulations in the Pilbara, suggesting that a high level of dispersal occurs between geographically separated populations (Spencer *et al.*, 2013). As such, an understanding of the location of dispersal corridors, to facilitate ongoing gene flow, is also likely to be important. Adequate protection of these critical habitats is vital for the long-term persistence of Pilbara northern quolls, particularly given the ongoing and increasing pressure of mining developments.

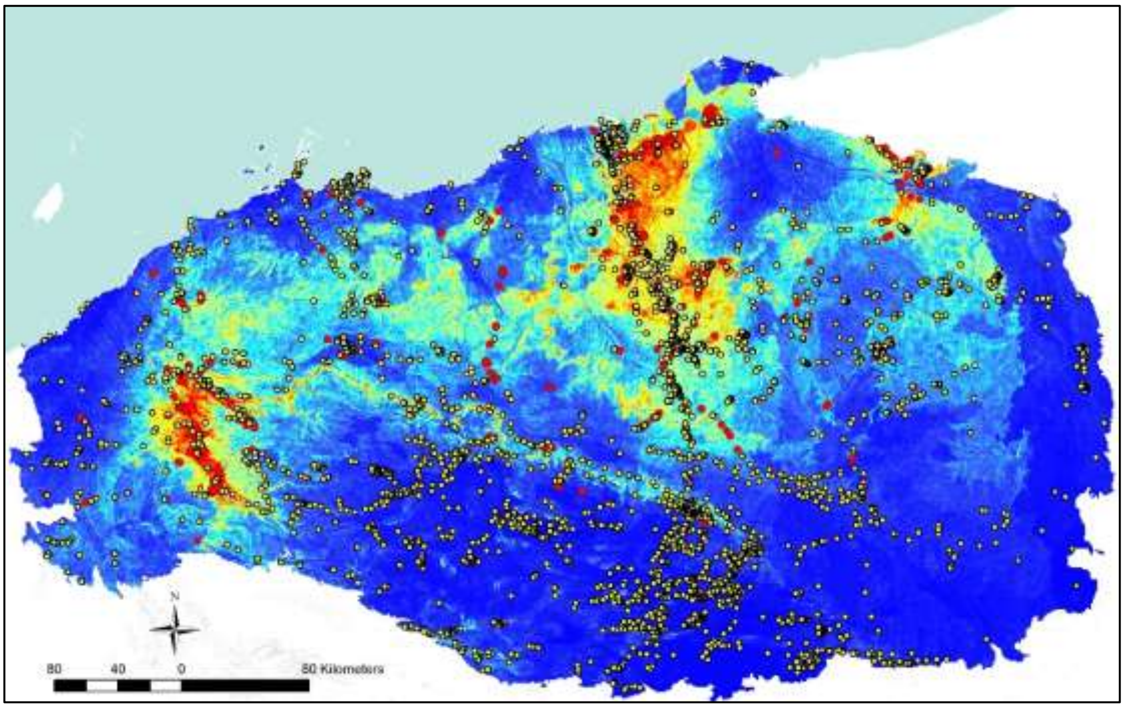

Figure 4 *Likelihood of northern quoll presence in the Pilbara bioregion created from the final MaxEnt species distribution model (adapted from Molloy et al., 2017)*

Cramer and Dunlop (2018) suggested that autecological studies are required to better understand detailed habitat use, with a particular focus on defining those factors that are most significantly associated with female den sites. Where possible, such studies should consider the time frame (preferably longer term) and, areas where a range of management scenarios have been applied, to assess site fidelity by northern quolls. The timing of studies should consider questions related to home range use and dispersal across all seasons by both sexes.

Habitat use

Moore *et al.* (2022) investigated the influence of habitat amount and habitat configuration on northern quolls across 22 landscapes in the Pilbara, each measuring 75 ha in size (Figure 3). Landscapes consisted of a matrix of rocky outcrops and spinifex grassland in various proportions and varied in terms of the degree to which they were naturally fragmented. Data was collected using vertically orientated camera traps (five of each deployed at each landscape) and analysed using a series of occupancy and n-mixture models. Results indicated spatial configuration of rocky habitat was more important than habitat amount in terms of predicting northern quoll occupancy and abundance; northern quoll occupancy and abundance both declined with increasing fragmentation. This response was likely driven primarily by predation risk. Habitats with a high edge density consist of many small patches and quolls need to move between these patches to find all the resources they require. Moving between patches involves moving through spinifex plains where predation risk is highest (Hernandez-Santin *et al.*, 2016). In addition, northern quoll abundance increased with increasing topographical ruggedness and previous wet season rainfall, supporting the results of species distribution modelling (Molloy *et al.,* 2017; Moore *et al.,* 2019).

Moore *et al.* (2021a) built on the results above, by examining northern quoll responses to habitat at the patch, and within-patch scale, using the same set of landscapes. Results indicated northern quolls preferred rocky outcrops that also had greater vegetation cover <0.5 m and a higher number of den crevices (within-patch), had smaller amounts of edge habitat relative to patch area (patch) and were embedded in a landscape with more rocky outcrops (landscape). Female northern quolls require deep rocky dens that sufficiently buffer extreme ambient temperatures to raise young (Cowan *et al.*, 2020b). Quolls were scarce in the surrounding grassland but when they used it, they remained close to the rocky habitat and preferred areas of high vegetation cover (i.e., less affected by fire). These results indicate that critical habitat for northern quolls constitutes large areas of concentrated, complex rocky habitat. Management actions that facilitate habitat connectivity (e.g., predator control) and maximise vegetation cover (e.g., reduced grazing and fire) are likely to be important for protecting this critical habitat.

Cowan *et al.* (2022) examined the habitat use of 12 GPS-collared northern quolls in the Pilbara, using data from four studies conducted between 2014 and 2018 (Biologic, 2016; Cowan *et al.*, 2020a; Hernandez-Santin *et al.*, 2020; Moore, unpubl. data). They investigated the proportional use of four habitat features (rocky habitat, spinifex sandplain, Acacia stands and riverbed) and topographic ruggedness and the influence of these on the space use of northern quolls. Northern quolls selected areas that were more topographically rugged and with a higher percentage cover of rocky habitat and riverbed than the surrounding landscape. Quolls avoided selecting areas with a higher percentage cover of spinifex sandplain than the surrounding landscape. The size of their activity area also increased with increased cover of the non-preferred spinifex sandplain, suggesting that individuals must move further to access resources within rocky habitat (e.g., food, shelter) in areas where it is in low abundance, potentially increasing predation risk by feral cats which are most common in spinifex sandplain (Hernandez-Santin *et al.,* 2016). These results further support those studies mentioned above which indicate that rugged rocky areas provide critical habitat for the Pilbara northern quoll by providing both sufficient resources and protection from threats such as predation. This study also highlights the importance of riverbeds which are likely dispersal pathways for northern quolls.

A complementary study (from an alternative funding source) used occurrence records post-2000 and spatial-environmental data to generate a contemporary species distribution model (Shaw *et al.,* 2023). Using a landscape genetics approach, the same environmental data was combined with genomic data to identify potential dispersal pathways. Again supporting the studies above, and like Molloy *et al.* (2017), habitat suitability was strongly associated with terrain ruggedness, while dispersal was facilitated by proximity to watercourses (see Appendix C).

Diet

Dunlop *et al.* (2017) undertook a dietary analysis of 498 scats collected across 325 locations in the Pilbara. Dietary composition and niche breadth were modelled against environmental factors, and pairwise comparisons of diet groups were used to evaluate regional dietary differences. Northern quolls were omnivorous, with up to a three-fold difference in dietary niche breadth across study landscapes. Invertebrates made up most of their diet, although they also consumed at least 23 species of vertebrates (mammals, birds, reptiles, frogs), as well as molluscs, carrion, and plant material (e.g., seeds, fruits and flowers). Volume of insects consumed decreased as the volume of rodents increased, potentially indicating a preference for the latter. There were no clear environmental drivers of their diet. Northern quolls demonstrated a broad dietary niche, suggesting an opportunistic dietary strategy, where food items are consumed according to their availability.

Outcomes

- Identification of the spatial configuration of suitable habitat that is likely to afford protection from threats such as introduced predators i.e., relatively contiguous rocky patches.
- Improved understanding of fine-scale habitat use of northern quolls indicating the importance of well-connected and vegetated rugged rocky outcrops and riparian areas as critical habitat.
- Improved knowledge of the diet of northern quolls across the region revealing a broad omnivorous dietary niche suggestive of an opportunistic dietary strategy.

Future directions

1) Incorporate spatial information into new population viability analyses to further improve accuracy.
2) Identify the characteristics of habitats that reduce predation risk for northern quolls during dispersal events.

Population dynamics and structure

Context

Cramer *et al.* (2016) indicated that information on the number of subpopulations of northern quolls in the Pilbara, the stability of these over time, and the dynamics of source and sink populations was lacking. Demographic data to inform robust population viability analyses (PVA) at the subpopulation level was also limited. A genetic study undertaken by Spencer *et al.* (2013) showed that the Pilbara population is a single genetic cluster, with a similar level of genetic diversity between locations implying widespread dispersal across the sampled region. However, Spencer *et al.* (2013) also state that sampling was biased to the northeast of the northern quolls' distribution in the Pilbara, and that additional sampling in its western distribution would build on their results.

Further studies to obtain demographic and genetic data to better understand the population dynamics and structure of Pilbara northern quolls were identified as a priority by Cramer and Dunlop (2018). Such information would help to inform conservation actions for northern quolls at both the sub- and metapopulation level.

Population demographics

The PNQRP was one source of information for a Population Viability Analysis (PVA) that simulated the trajectories of a northern quoll population under a range of scenarios (Moro *et al.,* 2019). Under current conditions the PVA model predicted a 99% probability that northern quoll populations would persist in the Pilbara over the next 20 years. The mean annual population growth rate was estimated at 0.37 ± 0.35. Reducing or increasing adult mortality (before breeding) had little effect on the viability of the population. In contrast, population viability was sensitive to increases in juvenile mortality, with immediate declines in population size predicted with increases in juvenile mortality as low as 5%. The important implication here is that management actions that maximise survival of juvenile northern quolls are likely to facilitate the persistence of this species in the Pilbara.

Knowledge of the demographics of northern quoll populations in the Pilbara has also been improved through the study of Hernandez-Santin *et al.* (2019); a collaborative project undertaken prior to 2016. Focused at two sites in the Pilbara, Indee Station and Millstream-Chichester National Park (2013-2015), results showed that apparent survivorship for both males and females varied primarily between seasons, with variation between years being of a smaller magnitude. This study also showed that the probability of an individual entering the population, which is a combination of immigration and juvenile recruitment, varied with season and between males and females but not between years. The difference between sexes is likely due to male-biased dispersal rather than differing juvenile recruitment. These data can be used to estimate annual median mortality rates for young Pilbara northern quolls which may improve the accuracy of PVA models. Hernandez-Santin *et al.* (2019) also found that the population size at Indee Station was much larger than at Millstream-Chichester National Park and the population size of females was larger than the males. At both sites, male population size increased from April to June and then reached their lowest point in September (Hernandez-Santin *et al.*, 2019).

Population structure

Genotyping of additional tissue samples collected between 2012 and 2018 to fill gaps in coverage was undertaken to build on the analyses reported in Spencer *et al.* (2013). Genetic analysis of 1844 samples in the Pilbara region, and 660 samples from the Kimberley and 164 from the Northern Territory (Figure 5), confirmed that Pilbara northern quolls formed a homogeneous group (Dunlop *et al.,* 2019a). Within the Pilbara, there was no obvious genetic structuring across the mainland meta-population, although the Dolphin Island population was moderately differentiated from those on the mainland. Individuals from the recently discovered isolated population in Karlamilyi National Park grouped with other mainland Pilbara populations. None of the mainland subpopulations showed sign of recent or historical population bottlenecks and heterozygosity was high (~70%), though it was 38% for the Dolphin Island population. Genetic composition of mainland populations showed that mating was essentially random, whereas on Dolphin Island there was some evidence of mate selection (see below). Genetic relatedness between populations indicated that dispersal occurred over mostly 1-2 km for females and up to 30 km for males. These results reflect findings of other studies which show that females are highly site philopatric and stay within a relatively small home range whereas males disperse widely in the breeding season (e.g., Oakwood, 2000; Henderson, 2015).

Interestingly, an albino northern quoll was discovered in 2018 with eight pouch young (Dunlop *et al.,* 2019b). It is not known if any pouch young shared the albinism mutation, but another albino northern quoll was captured 7.8 km from the study site ten years earlier.

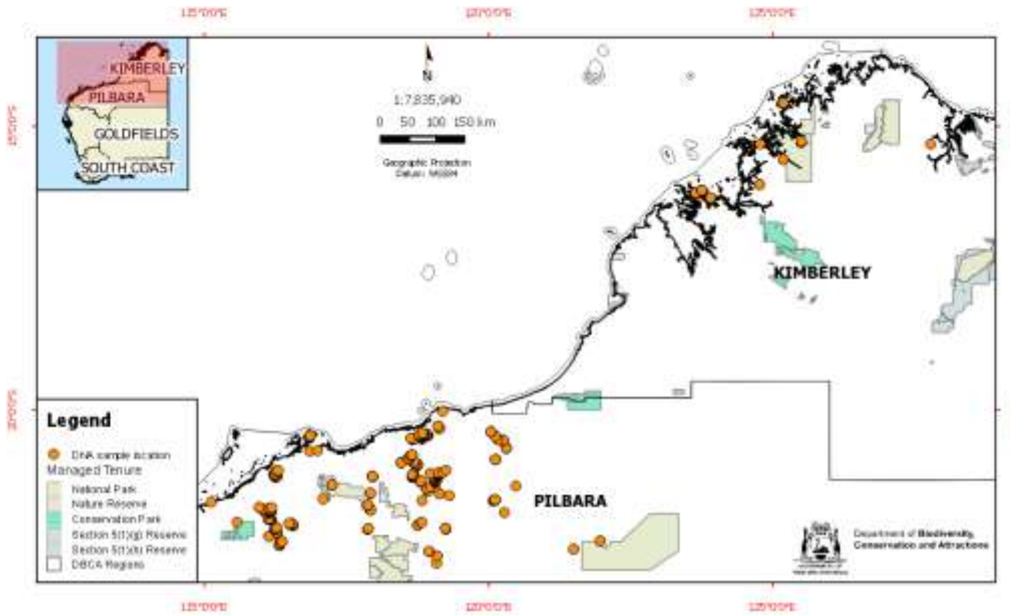

***Figure 5** Spatial distribution of northern quoll tissue sample locations in the Kimberley and Pilbara regions (from Dunlop et al., 2019a).*

Shaw *et al.* (2023) also explored genetic structure in Pilbara northern quolls (including tissues samples collected by the PNQRP) and identified only a weak east-west split. Results suggested limited barriers to dispersal, although silt/clay plains showed the highest resistance (see Appendix C).

Paternity and mate choice

Chan *et al.* (2020) compared paternity of litters and mate choice of northern quolls between Dolphin Island and Indee Station on the mainland. Multiple paternity was evident regardless of location, with the young from every litter having multiple fathers. In some litters, everyone had a different father. Such a competitive mating strategy is likely to enhance the fitness of offspring and may explain the selection for die-off of males after their first breeding season (Fisher *et al.*, 2013). The number of male sires per litter did not differ between Dolphin Island (3.78: range 2-6) and Indee Station (4.57: range 2-8), however, pattern of female mate choice did. On Dolphin Island, fathers weighed significantly less (~20%) than those not identified as a father. Whereas, at Indee Station, there was no difference between the two male cohorts. This indicates that females on Dolphin Island are selectively mating with smaller males. A further difference is that females on Dolphin Island consistently have six nipples, whereas they have eight on the mainland. These differences are likely to be driven by limited resources on islands (Lawlor, 1982). Investment in fewer and smaller offspring mean a smaller requirement for resources. These results have important implications for sourcing animals for translocations. Given the high level of multiple paternity, a male-biased sex ratio may be preferential. The preference of female northern quolls for smaller males on islands also has implications in terms of the body weight of selected males, at least for island translocations.

Outcomes

- Population viability analyses indicated increased mortality of juvenile northern quolls may compromise the persistence of the species.
- Improved population demographics information is now available to improve PVA models.
- Confirmation that there is no obvious genetic structuring across the mainland meta-population of northern quolls with results of genetic relatedness indicating widespread dispersal of males.
- Genetic analyses identified reproductive strategies likely to maximise fitness of offspring, such as multiple paternity of northern quoll litters, and island females preferentially choosing smaller males, which has implications in terms of sourcing animals for translocations.

Future directions

1) Refine population viability analyses using improved information, such as survivorship rates of juveniles.
2) Identify source and sink populations of northern quolls in the Pilbara using fine-scale demographic information.

Assessing the impacts of introduced predators

Context

Cowan *et al.* (2020c) provided evidence of the impact of feral cats on northern quolls in the Pilbara with cats killing 8 of 41 radio-collared individuals over a period of approximately four months, and another 20% killed by other introduced predators (dogs/dingoes or foxes). Feral cats are also likely to compete with northern quolls for resources such as food and dens, and may limit juvenile dispersal (Cramer *et al.*, 2016). In the Pilbara, foxes are largely confined to the coastal plain, dispersing some distance inland along river systems (Carwardine *et al.*, 2014), so are likely to pose a more moderate threat than feral cats (Woinarski *et al.*, 2014). The threat of wild dogs or dingoes to Pilbara northern quolls is unknown, although evidence from the Northern Territory and Queensland suggests dogs/dingoes do predate northern quolls (Moore *et al.,* 2021b). As top predators, dogs/dingoes may also play a role in regulating both feral cat and fox populations (Hernandez-Santin *et al.*, 2016).

According to Hernandez-Santin *et al.* (2016), introduced predators influence the use of landscapes by northern quolls at small and large scales in the northern Pilbara, with quolls avoiding the flat and open habitats more frequently used by feral cats. They suggested that predator avoidance was a key reason for the contraction of the distribution of northern quolls to rocky areas across northern Australia. To better inform effective management of introduced predators, understanding spatio-temporal interactions between northern quolls and these predators was identified as a priority (Cramer *et al.*, 2016; Cramer and Dunlop, 2018).

Managing feral cats to benefit northern quolls

The aerial application of toxic baits is currently considered to be the most effective and efficient method for controlling feral cats at a landscape scale (Algar *et al.,* 2007). The efficacy of aerial baiting with the *Eradicat*® feral cat bait (i.e., sausage-style baits containing the toxin sodium fluoroacetate or 1080) within the Pilbara, specifically to benefit northern quolls, was examined by Palmer *et al.* (2021) in a complementary study (see Appendix D). A preliminary study prior to this provided evidence that the application of *Eradicat*® poses a low poison risk to northern quolls (Cowan *et al.*, 2020c).

As a component of the PNQRP, Dunlop *et al.* (2020) trialled an automated feral cat grooming trap (the "Felixer™") as a potential new complementary tool for feral cat management (see Read *et al.*, 2019; Moseby *et al.*, 2020). The unit has in-built algorithms that allow it to identify the shape and movement of a cat using an array of lidar sensors as it passes in front. Once a cat is detected, the unit ejects a lethal dose of toxic 1080 gel onto the fur of the feral cat. The premise is that the cat subsequently grooms itself and ingests a lethal dose of the poison. A photograph is also taken every time the detection beams are crossed. Northern quolls were identified as a potential non-target issue.

Three Felixer™ units (Model 3, Thylation, SA) were deployed in photo-only mode (non-toxic) at Indee Station (10 April to 1 November 2018), and then relocated to the Fortescue Metals Group Ironbridge Mine Site (North Star; 18 April to 11 January 2020). Northern quolls passed the Felixer™ units on 226 occasions and were all identified as non-targets (Figures 6 and 7). Of the 24 feral cat detections, 11 were identified as targets (Figures 6 and 8). Based on these results, a trial in toxic mode was undertaken at North Star from 29 January to 22 October 2021 (Edwards and Nelson, 2022). In total, 14 cats were detected (estimated 9 individuals), with six identified as targets (Figure 9). Two quolls were detected, and neither were identified as a target. While Felixer™ units appear to accurately target cats (and not quolls), reinvasion by feral cats from the surrounding area is likely to be an ongoing problem that confounds assessments of effectiveness (i.e., reducing cat abundance) at the local scale.

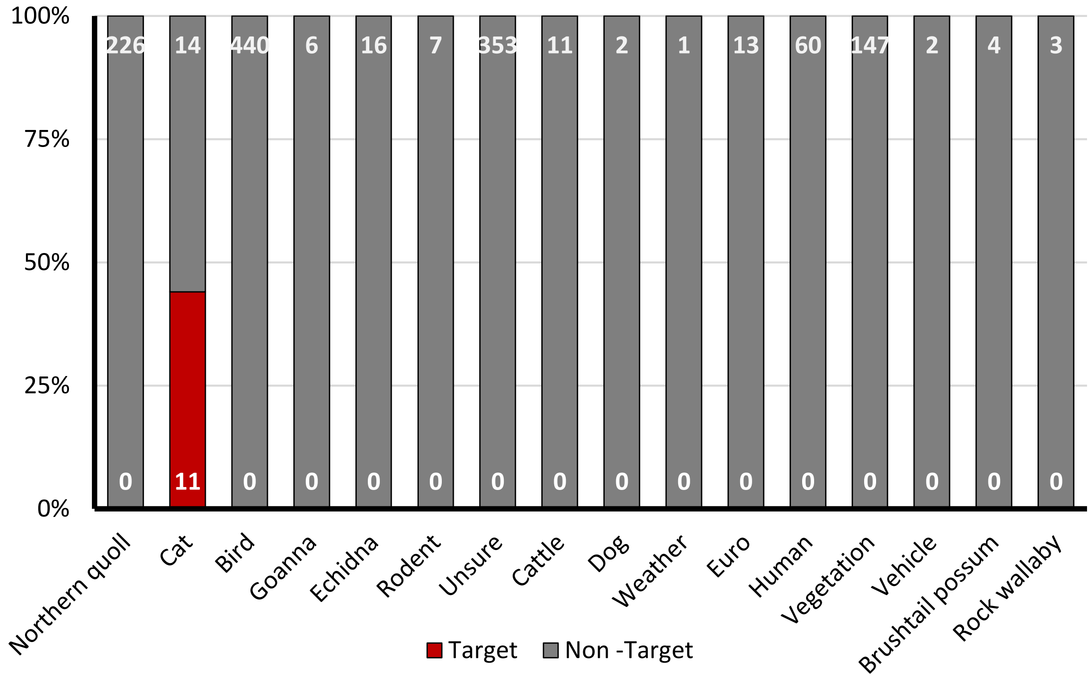

***Figure 6** A summary of the 1316 trigger events for the three Felixer™ units deployed in photo-only mode in northern quoll habitat in the Pilbara from April 2018 – December 2020. Non-targets are shown in grey and identified targets in red.*

***Figure 7** Northern quolls passing the Felixer™. No northern quolls were identified as a target.*

***Figure 8** Feral cat correctly identified as a target during the Pilbara Felixer™ trials.*

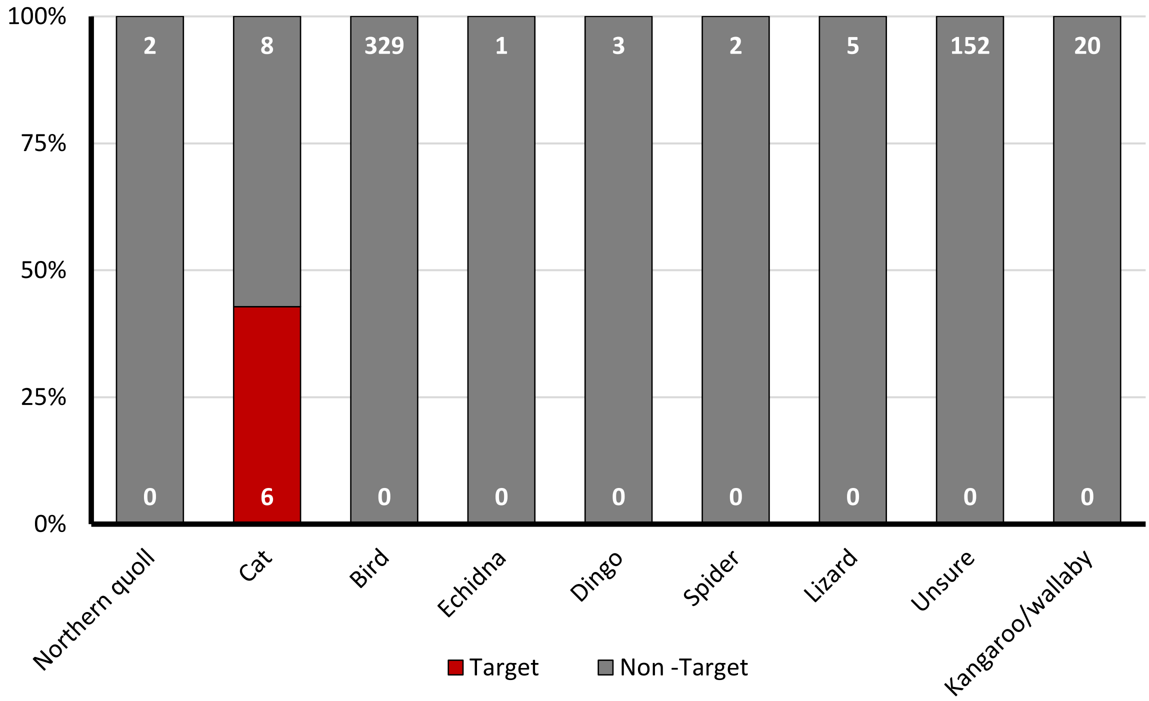

***Figure 9** A summary of the 528 trigger events for the three Felixer™ units deployed in toxic mode in northern quoll habitat in the Pilbara from January- October 2021. Non-targets are shown in grey and identified targets in red.*

Interactions between northern quolls and introduced predators

The PNQRP has continued to undertake surveys on Dolphin Island and on the adjacent Burrup Peninsula in the newly created Murujuga National Park (NP). Initial surveys conducted from 2012 to 2015 were followed with surveys from 2016 to 2018 (Birch and Dunlop, 2019). Live trapping and unbaited camera traps were used annually on Dolphin Island from 2016 to 2018 and camera traps with scented lures were installed in Murujuga NP in 2017 and 2018. Surveys on Dolphin Island captured between 8 and 11 individuals from 200 trap nights each year (Table 1) and there were numerous camera detections. Red foxes (*Vulpes vulpes*) were also recorded on Dolphin Island in each of the three years, but the number of detections was low (8 in 2016, 5 in both 2017 and 2018). No feral cats were detected on the island.

In Murujuga NP, camera traps were placed in a grid array across the peninsula. No northern quolls were detected from these surveys despite 1200 camera trap nights over 2017 and 2018. The most recent record was of an individual sighted on the southern part of the peninsula in 2015. Numerous detections of black rats (*Rattus rattus*), feral cats and foxes were detected on the cameras. An introduced predator control program on the peninsula was recommended by Birch and Dunlop (2019) to prevent re-invasion by foxes and feral cats on Dolphin Island.

Outcomes

- Demonstration that Felixer™ feral cat grooming traps can be used safely in the presence of northern quolls, and that they correctly identify feral cats as targets.
- A complementary offset funded project demonstrated Eradicat® feral cat baits can be safely applied in the presence of northern quolls, and that aerial baiting using Eradicat® baits is beneficial to northern quolls.
- Increased knowledge of threats to an island population of northern quolls, indicating they can persist in the presence of a low density of foxes, and aerial baiting using Eradicat® on the nearby peninsula now undertaken.

Future directions

1) Investigate changes in habitat use by northern quolls with sustained introduced predator management.
2) Further investigate the efficacy of Felixer™ feral cat grooming traps in “aggressive” mode at targeted locations.
3) Further investigate the strategic management of feral cats using a combination of approaches (aerial and ground baiting using Eradicat®, trapping) and the subsequent response of northern quolls.

Understanding the spread and impacts of cane toads

Context

The Pilbara Northern Quoll Research Program is yet to invest in research questions in relation to cane toad impacts on northern quolls in the Pilbara. Training northern quolls to avoid cane toads through conditioned-taste aversion (CTA) (using a thiabendazole-laced sausage or non-lethal juvenile toad) prior to their reintroduction to an area has shown promise (Cremona *et al.,* 2017b; Jolly *et al.,* 2018). Field trials of the uptake of 'toad sausages' by northern quolls in the Kimberley were undertaken by Indigo *et al.* (2018, 2019). One study found that 61% of northern quolls consumed toad sausages when they first encountered them and that between 40 and 68% of these 'toad-smart' quolls avoided toad sausages subsequently (Indigo *et al.,* 2018). Another study estimated that 64% of a quoll population in the Kimberley would take toad sausages if they encountered them (Indigo *et al.,* 2019). A more recent study suggests that while CTA has potential to help mitigate impacts of cane toads on northern quolls, the method is highly dependent on the cultural transmission of toad avoidance behaviour (i.e., mother teaching offspring) being very high (Indigo *et al.,* 2021). Further testing of the delivery and uptake of CTA baits is required to elucidate the likely effectiveness of CTA methods in the Pilbara.

A further study used structured decision making to explore the optimal locations of barriers to the movement of cane toads into the Pilbara, and the costs of various water source management options (Southwell *et al.,* 2017). The practicality and feasibility of putting these into practice has raised some questions, particularly in relation to the confounding influence of land uses, such as irrigated agriculture, and widespread flooding associated with cyclones in the vicinity of the proposed barrier (D. Pearson pers. comm.). Clearly, much research is required to understand the spread and impacts of cane toads on northern quolls in the relatively arid and topographically complex landscapes of the Pilbara.

Future directions

1) Investigation of the uptake and potential longer-term aversion of cane toad sausages by northern quolls and non-target species in the Pilbara.
2) Identification of locations where northern quolls and cane toads are most likely to intersect to inform surveillance and targeted response (i.e., application of CTA).

Interactions with infrastructure and built environments

Context

Infrastructure associated with mining developments in the Pilbara has the potential to impact northern quoll populations. For example, direct mortality on roads or by impeding movement (e.g., railway lines) (Cramer *et al.*, 2016). Limited data on the use of existing culverts under railway lines identified further research was warranted (Henderson, 2015; Cramer and Dunlop, 2018). There is also evidence of northern quolls utilising other mining associated structures in the vicinity of accommodation villages, and raw material stockpiles such as rock quarries (Dunlop *et al.,* 2015), suggesting that quolls may use purpose built artificial habitat. Further research on the interactions of northern quolls with infrastructure and built environments was identified by Cramer and Dunlop (2018).

Use of railway line culverts/underpasses

A study by Henderson (2015), supported by the PNQRP, provided some limited data on the use of railway line culverts, indicating that while northern quolls were observed on camera in the vicinity of culvert openings, there was no evidence of movements through them. A more recent assessment on use of culverts/underpasses by northern quolls along Roy Hill's rail line in the eastern Pilbara was undertaken by an environmental consultancy (Ecoscape 2019). This study used motion-sensitive cameras placed inside, and at the mouth of, culverts of different sizes, as well as in adjacent habitat and on rail lines. Across all sites, quolls were detected 17 times at five sites with 16 detections at the mouth of culverts and a single detection inside a culvert, suggesting that northern quolls will use them.

Use of artificial habitat

Cowan *et al.* (2020b) investigated the characteristics of occupied natural dens, unoccupied natural crevices, and purposely built artificial refuges to identify the characteristics that made a den suitable for use by female northern quolls when raising young, and if current methods of artificial habitat creation were suitably replicating natural conditions. These characteristics included the physical, environmental, and thermal properties of the den as well as the availability of prey and visitation by quolls and other predators. They compared these variables among 10 examples of each den type and found that neither the dimensions nor number of den entrances differed between the three den types, but that occupied dens were significantly deeper than unoccupied crevices and artificial refuges. All den types buffered outside temperatures, but occupied and artificial dens were cooler than unoccupied crevices. There were no differences between occupied dens and unoccupied crevices in terms of the surrounding habitat. However, artificial dens had less cover of embedded rock and vegetation than the other two den types. Feral cat visitation was higher at artificial dens and less small mammal activity was observed compared to occupied dens. This study demonstrated the complexity involved in replicating natural northern quoll dens and highlighted the importance of the actual placement of artificial dens in the appropriate landscape setting (i.e., not just consideration of den properties). Northern quolls were observed with young at only two of the ten artificial refuges.

Further research is required to determine whether artificial or restored habitat provides for long-term sustainable populations of northern quolls. There are future opportunities in the Pilbara to conduct ‘natural’ experiments on the recolonisation of quolls after mining, including how to best design waste rock dumps so that habitat complexity and productivity is maximised by, for example, experimenting with the size and positioning of boulders, and their spatial arrangement in relation to surrounding landscape features (Cramer and Dunlop, 2018). Future management and creation of artificial habitats should employ extensive trials to determine their suitability as a conservation option (Cowan *et al.*, 2021, Watchorn *et al.*, 2022).

Influence of mining on northern quoll movement and ecology

A PhD study being undertaken by Mitchell Cowan as a part of a collaboration with Charles Sturt University, DBCA, Consolidated Minerals Ltd, University of Western Australia, Roy Hill and Fortescue Metals Group commenced in 2021 to investigate the influence of mining disturbance on the movement ecology and behaviour of northern quolls in the Pilbara. The project will specifically focus on the influence of infrastructure and habitat on movement and habitat use around mine sites.

Outcomes

- Indication that northern quolls will use culverts/underpasses and other disturbed habitat such as disused quarries.
- Identification of the characteristics of natural dens, indicating that northern quolls used natural dens which were cooler and deeper than other crevices available in the natural landscape.
- Indication that artificially created refuges were warmer than occupied natural dens, had less complex vegetation, lower detections of mammal prey, and higher detections of feral cats.

Future directions

1) Investigation into optimising the design of artificial refuges in relation to surrounding landscape features (e.g., size, spatial arrangement, surrounding habitat) and microclimatic attributes (e.g., material, internal temperature).
2) Investigate the use of artificial refuges by northern quolls in relation to breeding, survival, and recruitment and quantify risks of predation.
3) Undertake field trials to assess the influence of feral predator control and revegetation on northern quoll use of artificial refuges.
4) Determine how disturbances associated with mining influence the movement and behaviour of northern quolls.
5) Better understand the cumulative impact of habitat loss due to mining in relation to northern quoll distribution and habitat connectivity.

Other Research Opportunities: Understanding the influence of interacting threats

Context

Many of the studies undertaken as a component of the PNQRP have implications in terms of managing threats impacting on northern quoll populations in the Pilbara, but research specifically addressing the complexity of how multiple interacting threats influence northern quoll populations is currently lacking.

The lack of genetic structure of northern quolls across the Pilbara indicates a high level of dispersal (Spencer *et al.*, 2013). The movement of quolls through lower quality habitat, such as the lowland plains adjacent to rocky habitat, is likely to expose them to predators (Hernandez-Santin *et al.*, 2016). Extensive and frequent fires, along with overgrazing, is also likely to increase this exposure by reducing vegetation cover (Cremona *et al.*, 2017a; Jolly *et al.*, 2018). Introduced predators may actively make expeditions to hunt in areas that have been recently burnt by intense fires (McGregor *et al.,* 2015). Dispersal routes along watercourses (Shaw *et al.,* 2023) may be pinch points, particularly given these areas are often heavily grazed in the Pilbara (McKenzie *et al.,* 2009) and there is evidence that feral cats also favour riparian habitats (Williamson *et al.,* 2021; see Appendix D).

Northern quolls are likely to be most susceptible during the breeding season when males are ranging widely in search of females, and when young are dispersing (Hernandez-Santin *et al.*, 2016). At East Alligator River in the Northern Territory, late dry season fires reduced the available cover for juvenile quolls when they began foraging, with dog and dingo predation a major source of mortality (Cremona *et al.,* 2017a). As increases in juvenile mortality may lead to local extinction of populations (Moro *et al.*, 2019), better understanding the interactions between predation, fire and grazing may be critical to effectively conserving Pilbara northern quoll populations (Cramer and Dunlop, 2018).

Future directions

1) Understand the extent to which fire and grazing influences predation pressure on northern quolls.

2) Understand how interactions between threats influences habitat selection by northern quolls to inform threat mitigation.

3) Investigate the response of northern quoll occupancy and abundance to the management of interacting threats.

Conclusions

Ecological knowledge of the Pilbara northern quoll has been substantially improved as a result of the Pilbara Northern Quoll Research Program. Survey and monitoring techniques have evolved with technological and analytical advances, and many studies summarised in this review demonstrate the application of these emerging approaches. Data collated from remote sensing cameras has improved our understanding of the distribution, occupancy, and abundance of northern quolls in the Pilbara. In combination with spatially explicit GPS-tracking, genetic and environmental data, this has in turn allowed for assessments of habitat use from the regional to local scale, including the size, shape, and configuration of habitat. We now have strong evidence-based support that contemporary habitat critical for Pilbara northern quolls constitutes topographically complex, contiguous, and well vegetated rocky areas. Evidence also suggests riparian areas are equally important as dispersal corridors.

Monitoring data from several sites across the Pilbara indicate many subpopulations occur at apparently low density, although lack of genetic structure among them suggests widespread dispersal. As such, it appears northern quolls can move across suboptimal habitat such as the lowland plains surrounding rocky areas. Genetic studies also indicate male-biased dispersal and greater movements by males than female quolls, particularly during the breeding season. Given that high juvenile mortality is predicted to compromise the persistence of northern quolls, the importance of protecting dispersing young males is apparent.

Effective management of introduced predators, particularly feral cats and foxes where they are most prevalent, to facilitate movement and connectivity between fragmented populations is likely to be crucial to the persistence of northern quolls in the Pilbara. Targeting areas surrounding critical habitat, including along riparian areas, is likely to maximise outcomes, given that feral cats have also shown preference for the latter. Complementary research has demonstrated that northern quolls will expand their range in response to feral cat control. Strategic feral cat management using a combination of control options (e.g., targeted ground and aerial baiting, trapping) and focusing effort in areas of preferred feral cat habitat is likely to provide the most benefit.

Investigation of the influence of other threats, and their management, such as the impending cane toad invasion and mining activities is ongoing. It does appear that northern quolls will use artificial refuges, but more work is needed to assess their suitability as a long-term conservation tool. Another area requiring investigation is understanding how multiple interacting threats influence northern quoll populations in the Pilbara, particularly the synergistic threats of introduced predators, fire, and herbivore grazing.

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Appendices

Appendix A Outputs of the Pilbara Northern Quoll Research Program (2016-2023)

Journal articles

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Appendix B Roy Hill Northern Quoll Research Plan

Cowan and Dunlop (2020) summarised northern quoll targeted surveys in the Chichester Ranges undertaken by the Department of Biodiversity, Conservation and Attractions from 2014 to 2019 as a component of Roy Hill's Northern Quoll Research Plan. The purpose of these surveys was to identify long term monitoring sites for northern quolls and to provide further data to estimate the population size and distribution of quolls within the Chichester Ranges. A reconnaissance survey was undertaken in 2014, but regular monitoring was limited to Quoll Knoll, Wall Creek, Mesa 228, Python Pool, and Euro Springs.

Cowan and Dunlop (2020) concluded that the central extent of the Chichester Ranges had small and disjunct quoll populations, separated by several kilometres of unsuitable habitat, and that northern quolls have a dynamic and intermittent presence in the landscape which was likely influenced by predation, climate, and environment. Given the small and fluctuating populations in the Chichester Ranges, they identified the challenge of effectively tracking population trends and recommended a shift in research focus to other areas in the Pilbara with higher densities of northern quolls.

Appendix C Genetic connectivity of Pilbara northern quolls

Shaw *et al.* (2023) combined species distribution modelling (SDM) with landscape genetic approaches to provide a better understanding of landscape use of the northern quoll in the Pilbara. The SDM based on records post-2000 showed occurrence increased then plateaued with increasing terrain ruggedness and declined as both elevation and distance to water increased. Genetic analyses found only weak patterns of genetic structure, suggesting quolls have high dispersal capacity across the Pilbara. Dispersal was facilitated by proximity to water courses. There was limited evidence of major physical barriers to dispersal, although silt and clay plains, with low vegetation cover, appeared to show high resistance to dispersal.

The results of this study support the importance of topographically complex rocky habitat for northern quolls. It also identified watercourses as critical habitat for dispersal, and the likely vulnerability of quolls to predation while dispersing across more open and exposed habitats such as silt and clay plains. Management of threats such as feral cats and foxes, extensive and intensive fires and grazing pressure in these identified habitats used by northern quolls is likely to facilitate species persistence by maximising genetic connectivity and meta-population health.

Appendix D Benefits of landscape control of feral cats for Pilbara northern quolls

Palmer *et al.* (2021) explored the effectiveness of landscape scale feral cat baiting in the Pilbara and the benefits it provided to northern quolls. Camera traps were spaced across two adjacent cattle stations to monitor feral cats and quolls before and after winter baiting over four years (2016-2019). Yarraloola was aerially baited with *Eradicat*® and the adjacent Red Hill remained unbaited as a reference site. GPS radio-collars fitted to 15 feral cats were used to estimate mortality rates following baiting in 2018 and 2019. Although cat detections in each year did not differ between baited and unbaited sites, mortality of collared cats ranged between 18-33% at the baited site. There was a positive effect of cat baiting for northern quolls. Their detections at the unbaited site significantly decreased in all four years whereas quoll detections either increased or decreased to a lesser degree at the baited site. Quolls also expanded their range in response to baiting (Figure S1), which supports the suggestion that predators influence fine scale habitat use by northern quolls (Hernandez-Stantin *et al.,* 2016), and that rugged rocky habitat preferred by northern quolls in the Pilbara buffers them to some extent from cat predation (Williamson *et al.,* 2021; see below).

Palmer *et al.* (2021) also highlighted that baiting programs can result in cat populations that consist primarily of large, male, bait-shy cats, thus reducing the long-term efficacy of aerial baiting. They suggested that a more strategic method of controlling feral cats was required that used a combination of methods such as aerial and ground baiting, and leghold trapping to target bait-shy individuals to maintain the long-term efficacy of baiting programs.

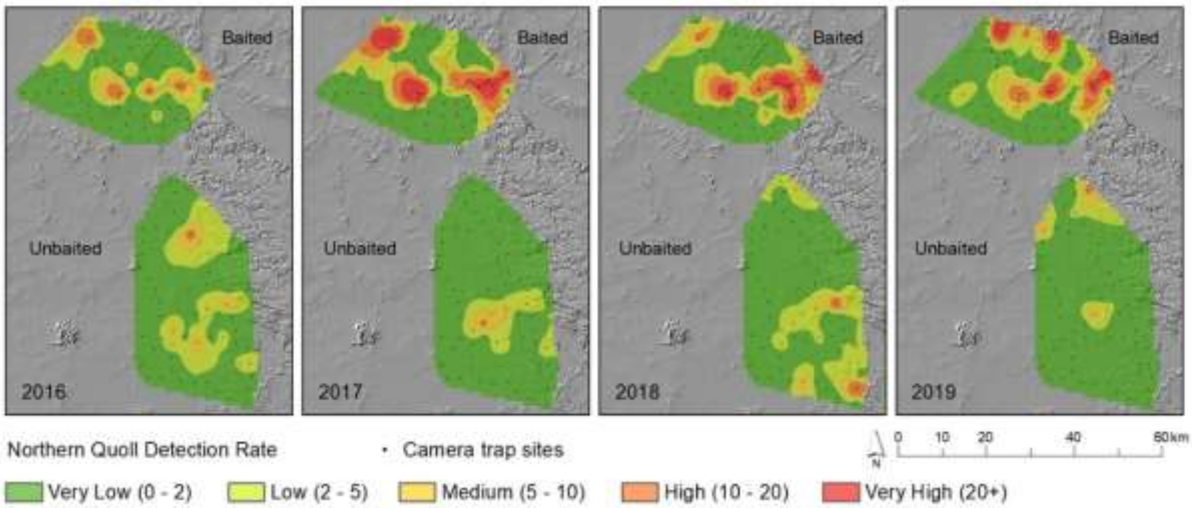

Figure S1. Spatial location of quoll detections in each of the four years of aerial cat baiting at the baited (top) and unbaited sites (bottom).

A recent study by Williamson *et al.* (2021) focusing on the same study location and using the data from the collared feral cats produced a species distribution model (SDM) using GPS-derived movement data to inform the SDM. Their results indicated a preference of feral cats for riparian habitats, and avoidance of topographically complex rocky habitats and areas recently burnt (i.e., < one year since last burnt). Fires in the study when the cats were being monitored were very hot, with little vegetation remaining post-fire.