Pilbara Northern Quoll Research Program

2024 Annual Report

Natasha Harrison, Harry Moore, Mitchell Cowan, Judy Dunlop,
Daniel Bohorquez Fandino, Lesley Gibson

February 2025

GOVERNMENT OF
WESTERN AUSTRALIA

Department of **Biodiversity,
Conservation and Attractions**

Department of Biodiversity, Conservation and Attractions
Locked Bag 104
Bentley Delivery Centre WA 6983
Phone: (08) 9219 9000
Fax: (08) 9334 0498

www.dbca.wa.gov.au

February 2025

This report/document/publication was prepared by Natasha Harrison.

Questions regarding the use of this material should be directed to:
Dr Natasha Harrison
Research Scientist, Animal Science Program
Biodiversity and Conservation Science
Department of Biodiversity, Conservation and Attractions
Locked Bag 104
Bentley Delivery Centre WA 6983
Phone: 0435 305 512
Email: natasha.harrison@dbca.wa.gov.au

The recommended reference for this publication is:
Harrison, N., Moore, H., Cowan, M., Dunlop, J., Bohorquez Fandino, D., Gibson, L., 2025, *Pilbara Northern Quoll Research Program 2024 Annual Report*, Department of Biodiversity, Conservation and Attractions, Perth.

Cover image: A northern quoll detected at Millstream National Park in 2024

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Acknowledgements

This project is currently supported by environmental offsets provided by Roy Hill, API Management and Onslow Iron.

Work from Mitch Cowan's and Chloe McAuley's PhDs included in this report was funded by Charles Sturt University in collaboration with DBCA, Roy Hill and Consolidated Minerals. We are grateful to Dale Nimmo, Judy Dunlop, Samantha Setterfield, Damien Michael and Peter Speldewinde for co-supervising these two students. Dale and Judy also contributed to collaborative projects.

This report includes data from studies that were designed and conducted by the DBCA Cane Toad Strategy Program. We are grateful to Theo Campbell and Clare Forward for their contributions.

Field work was conducted on the lands of the Ngarluma, Yindjibarndi, Yaburara, Mardudhunera, Banjima, Kariyarra, Kuruma Marthudunera, Nyamal, Palyku, Puutu Kunti Kurrama, Martu, and Pinikura peoples. We acknowledge and respect the traditional custodians of these lands and their ongoing connection to the land, water, and culture.

Field work was conducted in collaboration with Martu, Kariyarra, Palyku, Nyamal, Murujuga, Budadee, Yindjibarndi, Dambimangari and Wilinggin Indigenous ranger groups.

The northern quoll, as drawn by a student at Warralong Community School

Summary

The northern quoll (*Dasyurus hallucatus*) is a medium-sized, omnivorous marsupial that was once prevalent across northern Australia. However, since the arrival of Europeans, the species has experienced significant declines in its range and population fragmentation. One of the primary causes of these declines is lethal ingestion of the toxic, non-native cane toad.

The Pilbara population of northern quolls is considered to be of high conservation significance as it is genetically distinct and has not yet been impacted by cane toads. Despite this, the population still faces threats from habitat loss due to intensive mining development and predation from feral cats and dogs. Historically, efforts to conserve this population were hindered by a lack of information about the species' ecology, distribution, and key threatening processes. To address this, the Pilbara northern quoll research program (PNQRP) was established with research priorities originally identified in 2013 (Cramer *et al.* 2016) and later updated in 2016 (Cramer and Dunlop 2018) and 2023 (Gibson *et al*., 2023) as new information was obtained. This offset-funded program aims to gather crucial information to inform conservation management of the species.

During 2023 and 2024, the PNQRP made significant progress in its research efforts, including:

- The continuation of a camera trap-based Pilbara-wide (30 sites) northern quoll monitoring program.
- A document that compiles best-practice monitoring techniques and impact mitigation for northern quolls in the Pilbara, advocating for consistent sampling regimes (Dunlop *et al.* 2024).
- An analysis of northern quoll temporal activity revealing two main peaks of activity during the night (Moore *et al.* 2024a).
- An analysis that examined the influence of fire attributes on northern quoll occurrence in the Pilbara bioregion (Moore *et al.* 2024c).
- An analysis of the home range of two northern quolls following a large wildfire (Cowan *et al.* 2024b).
- The development of a collaborative PhD project with Charles Sturt University exploring the effect of fire on northern quoll movement ecology.
- Preliminary findings from an observational study of northern quoll fitness and population demography following fire in the absence of introduced predators.
- An initial evaluation of a conditioned taste aversion trial aimed at buffering northern quolls in the Kimberley against the cane toad invasion.
- Development of a project that will predict the dispersal of cane toads to Pilbara offshore islands, to inform potential translocations to establish northern quoll insurance populations.
- An analysis that used GPS, VHF, and accelerometer data to measure the activity and spatial ecology of northern quolls in a mining landscape, revealing their fine-scale movements and interactions with mining-disturbed habitats (Cowan *et al.* 2024a).
- A simulation study evaluating the impact of mining on landscape connectivity.

Introduction

The northern quoll (*Dasyurus hallucatus*) is a medium-sized (300-800g; Oakwood 1997), omnivorous marsupial. Once common across northern Australia (Braithwaite and Griffiths 1994), the species has suffered significant range contractions and population fragmentation since European colonisation (Moore *et al.* 2019). Owing to such declines, the northern quoll is now listed as Endangered by the IUCN and Australian federal government (Oakwood *et al.* 2016; DCCEEW 2021) as well as by the Western Australian *Biodiversity Conservation Act 2016*.

A major contributor of population decline in this species across northern Australia has been lethal ingestion of the toxic introduced cane toad (*Rhinella marina*) (Moore *et al.* 2021a). This has led to complete collapse of some northern quoll populations in Queensland and the Northern Territory (Burnett 1997; Oakwood 2003; Woinarski *et al.* 2008). In addition to cane toads, several other ecological factors are contributing to the decline of quolls, including predation by feral cats and wild dogs/dingoes, habitat degradation caused by altered fire regimes and grazing pressure by introduced herbivores, as well as direct habitat loss and fragmentation (Moore *et al.* 2021a).

The Pilbara population of northern quolls has been identified to be of high conservation significance for the species given it is genetically distinct (von Takach *et al.* 2022) and remains the only population yet to be impacted by cane toads. However, Pilbara northern quolls remain under threat from habitat loss associated with intense mining development (Cramer *et al.* 2016), as well predation from feral cats and dogs (Cowan *et al.* 2020b; Moore *et al.* 2021a).

Conservation of Pilbara northern quolls has previously been restricted by limited information relating to the species' ecology, distribution, as well as key threatening processes. The Pilbara northern quoll research program (PNQRP) is an offset funded research program led by the Western Australian Department of Biodiversity, Conservation and Attractions that seeks to address these knowledge gaps, so as to inform conservation management of the species. The PNQRP is guided by a set of overarching research priorities that were first identified in 2013 (Cramer *et al.* 2016) and later refined as part of 2016 workshop involving industry, government, and species experts (Cramer and Dunlop 2018). These include:

1. Assess and refine survey and monitoring protocols (combined priorities 1 & 2)
2. Improve our understanding of fine-scale habitat use to identify areas of critical habitat
3. Population dynamics and structure
4. Assessing the impacts of introduced predators
5. Understanding the spread and impact of cane toads
6. Interactions with infrastructure and built environments
7. Other research opportunities including understanding the influence of interacting threats

Progress against these priorities was reviewed in 2023 (Gibson *et al.* 2023). Reporting of these topics is structured in line with the above priorities. Prior reports on the research program can be found at library.dbca.wa.gov.au. This report serves as a progress update between 2023- 2025.

1 Assess and refine survey and monitoring techniques

1.1 Monitoring program

1.1.1 Background

Baseline data collection for northern quoll populations not currently co-occurring with cane toads is recognised as a priority in the national recovery plan for northern quolls (Hill and Ward, 2010). The Pilbara northern quoll monitoring program aims to provide such data, documenting region-wide trends in the Pilbara population.

Since 2022, the monitoring program has been conducted using camera traps as the primary survey method, as opposed to live traps. This change was prompted by results from a recent power analysis (Moore *et al.* 2023), which indicated a camera trapping approach using five cameras per site was superior to previous live trapping designs in both statistical power and financial cost. Despite methodological differences, comparisons in occupancy between sites that were surveyed before this updated camera approach (2014-2019) are still feasible given both methods have near perfect detectability when the prescribed number of occasions are used (Moore *et al.* 2023).

Aside from reduced effort and cost and improved animal welfare, an additional benefit of the camera trap-based monitoring design is that it is less technically demanding, creating opportunity for increased involvement from partners including Traditional Owners, industry and non- for-profit organisations. This involvement assists in building monitoring capacity in the groups, such that potential exists for them to initiate their own northern quoll monitoring programs which can contribute to the existing program. In 2023 and 2024, partners that participated in northern quoll monitoring included the Yindjibarndi, Budadee, Murujuga, Nyamal and Kanyirninpa Jukurrpa Indigenous ranger teams, Warralong Community School, Roy Hill, Australian Premium Iron, Indee Station, Yarrie Station, Mardie Station, Mallina Station, Mount Florence Station, Water Corp, as well as regional DBCA staff.

1.1.2 Method

A total of 24 and 30 sites were surveyed as part of Pilbara northern quoll monitoring program in 2023 and 2024, respectively (Figure 1.1-1), including the majority of sites monitored in previous years (access permitting). This is slightly below the optimum of 33 sites but given that initial occupancy in the Pilbara is generally above the conservative 80% used in the power analysis by Moore *et al.* (2023) (based on data from this monitoring program), statistical power for measuring changes in occupancy is predicted to be above 80%. The final suite of sites comprised a spectrum of habitat suitability values (Figure 1.1-2) that should facilitate correlative analyses between northern quoll occupancy and both habitat quality and threatening processes.

Sites were monitoring using five downward orientated camera traps (each separated by ~200m) which were deployed for a minimum of 30 nights between May and October. Cameras were fixed to either a tree or wooden post 1.5m above the ground and were baited with canned tuna (Figure 1.1-3). Detection histories for each site were assembled by pooling detections across all traps within a site (i.e., detections pooled across five trap units deployed at each camera trap site) into a single measure of detection/non-detection for each trap night. Detectability was then estimated using occupancy models that were fit using the unmarked package (Fiske and Chandler 2011) in R version 3.6.2 (R Core Team 2019).

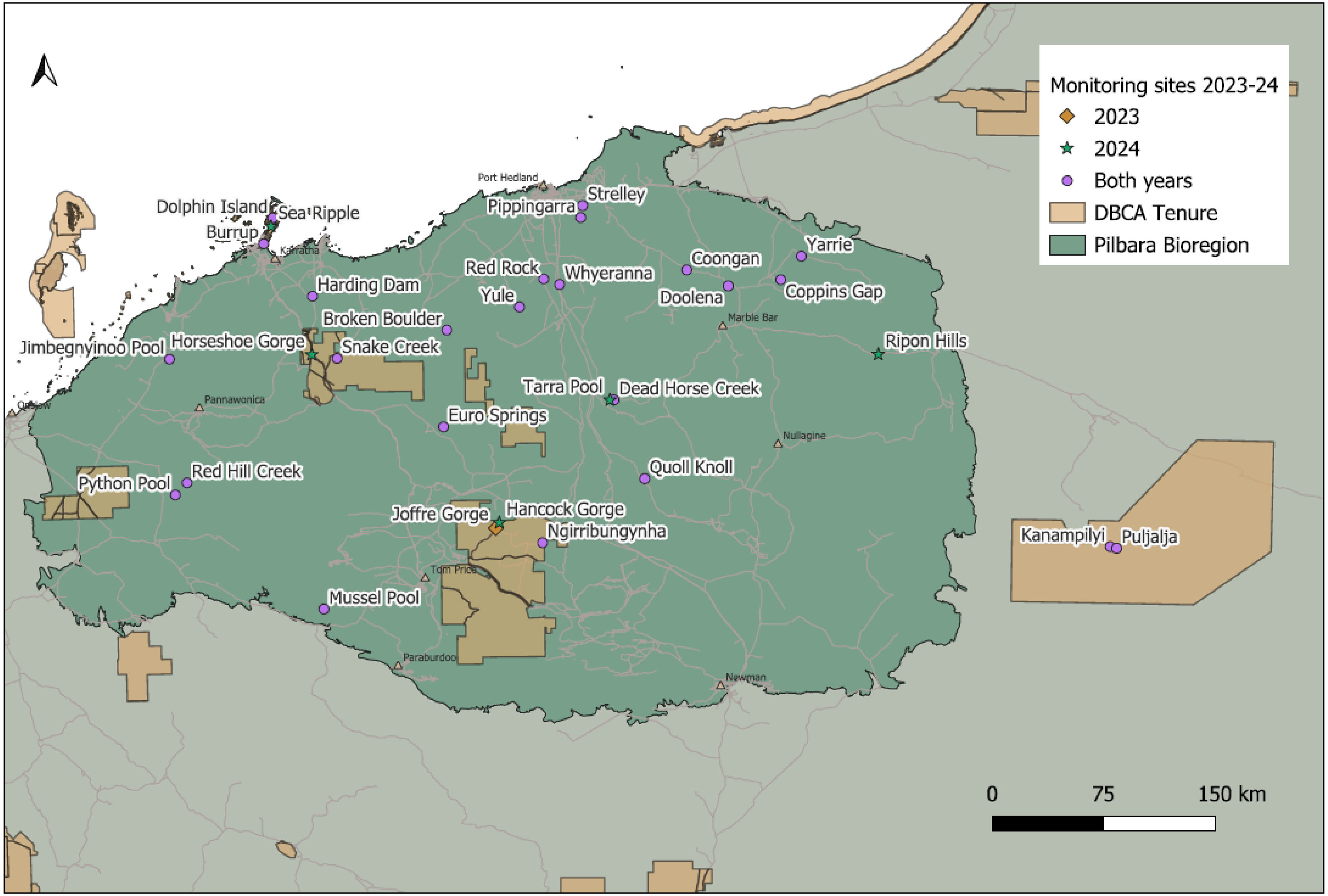


Figure 1.1-1– Northern quoll monitoring sites established as part of the Pilbara regional monitoring program in 2023 and 2024.

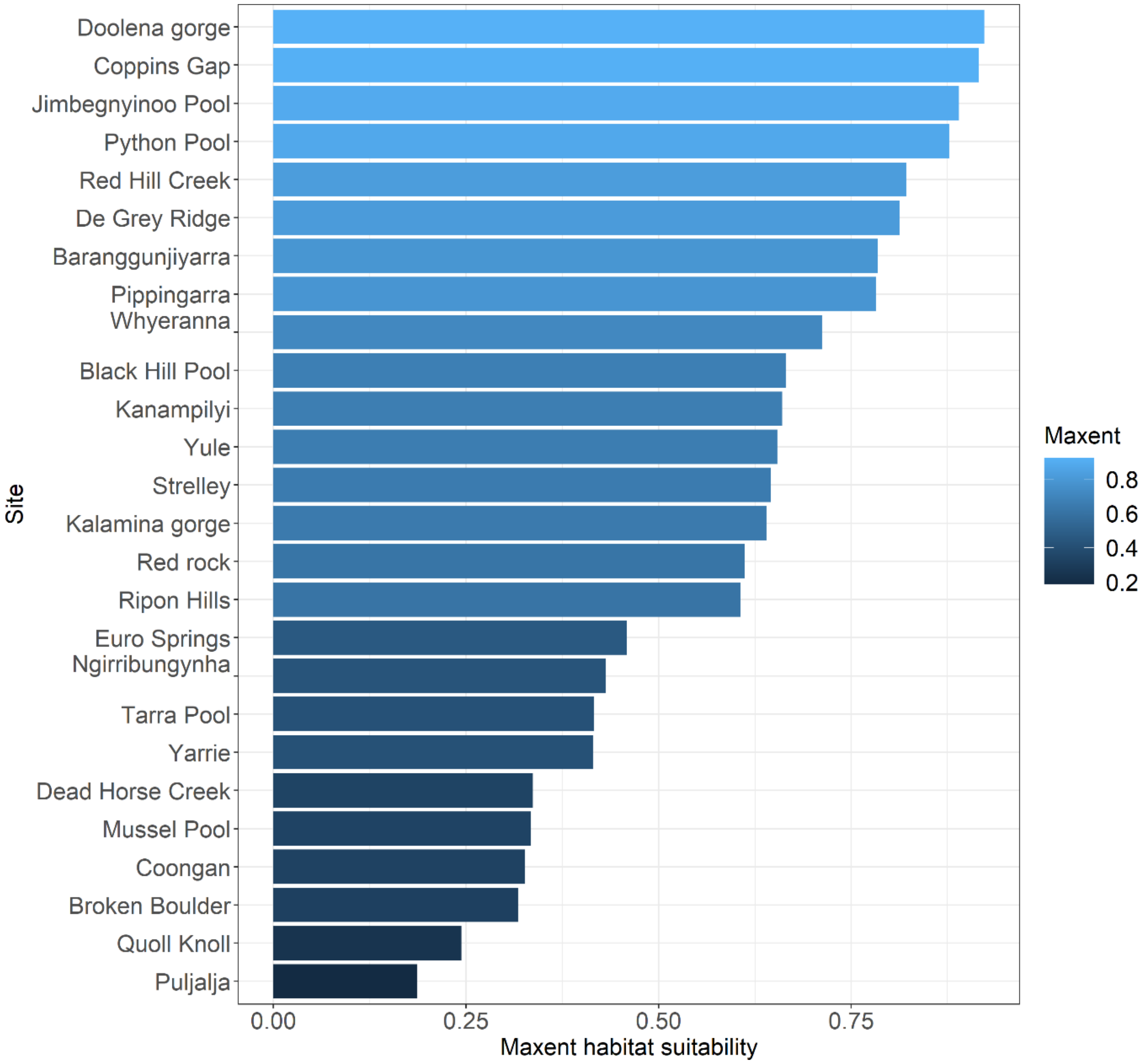


Figure 1.1-2 – Northern quoll monitoring sites ranked according to maxent habitat quality, as derived from maps produced by Moore *et al.* (2019). Note: no habitat suitability estimates were available for Dolphin Island and the Burrup.

Figure 1.1-3 – Downward facing camera trap design used as part of the Pilbara northern quoll monitoring program. Cameras were mostly mounted to trees at a height of 1.5m. Where suitable trees were not available, wooden posts were bolted into the ground, and cameras were mounted to posts, following (Moore *et al.* 2021b).

1.1.3 Outcome

In 2023, 24 sites were deployed for a mean duration of 67 days. In 2024, 30 sites were deployed for a mean of 51 days. At the time of writing, the 2024 data along with 4 sites from 2023 are yet to be processed so the results presented here only include 20 sites monitored in 2023.

Northern quolls were detected at 95% (19/20) of monitoring sites (Figure 1.1-4). This includes all sites where northern quolls have been recorded as part of live trapping conducted since 2015 (Dunlop *et al.* 2019), suggesting it is unlikely northern quoll occupancy has declined in the Pilbara over this time.

Northern quoll nightly detectability was high (32.6%), and thus confidence in quoll absence after 30 nights was very high (99.9%) (Figure 1.1-5). Predicted occupancy was equal to the naïve occupancy measure of 95%.

In addition to northern quolls, 47 other species were recorded on camera traps. This included feral cats (*Felis catus*; 45% of sites), common rock rats (*Zyzomys argurus*; 25%), dingoes (*Canis familiaris*; 45%), red fox (*Vulpes vulpes*; 10%) and Rothschild's rock wallaby (*Petrogale rothschildi*; 50%) (Figure 1.1-6). Notably, naïve occupancy of rock rats in 2023 (25%) has declined considerably from 2022 (85%).

There were not enough detections to run models with single night occasions for cats, so occasions were set to 7 days. Predicted occupancy of cats was lower than previous years at 45.6%, but still indicative of considerable overlap in habitat with northern quolls.

1.1.4 Status

Ongoing in 2025.

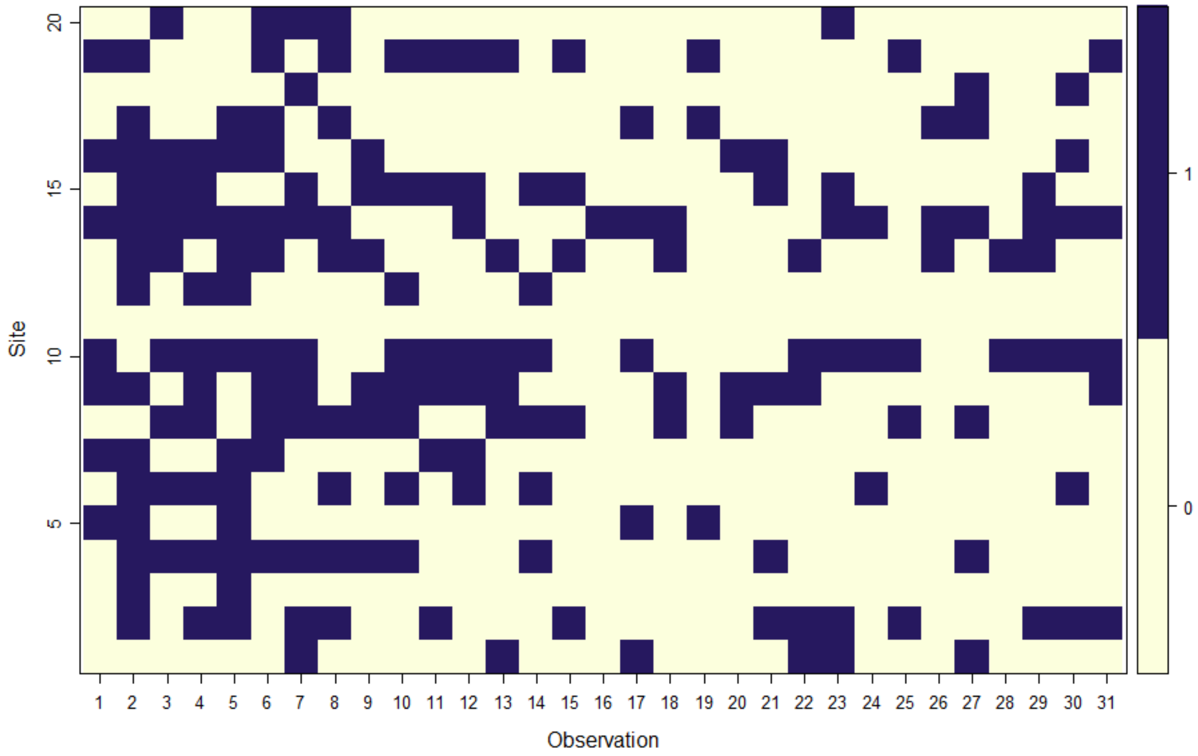


Figure 1.1-4 – Northern quoll detection histories across the 20 monitoring sites in 2023 from which data have been processed.

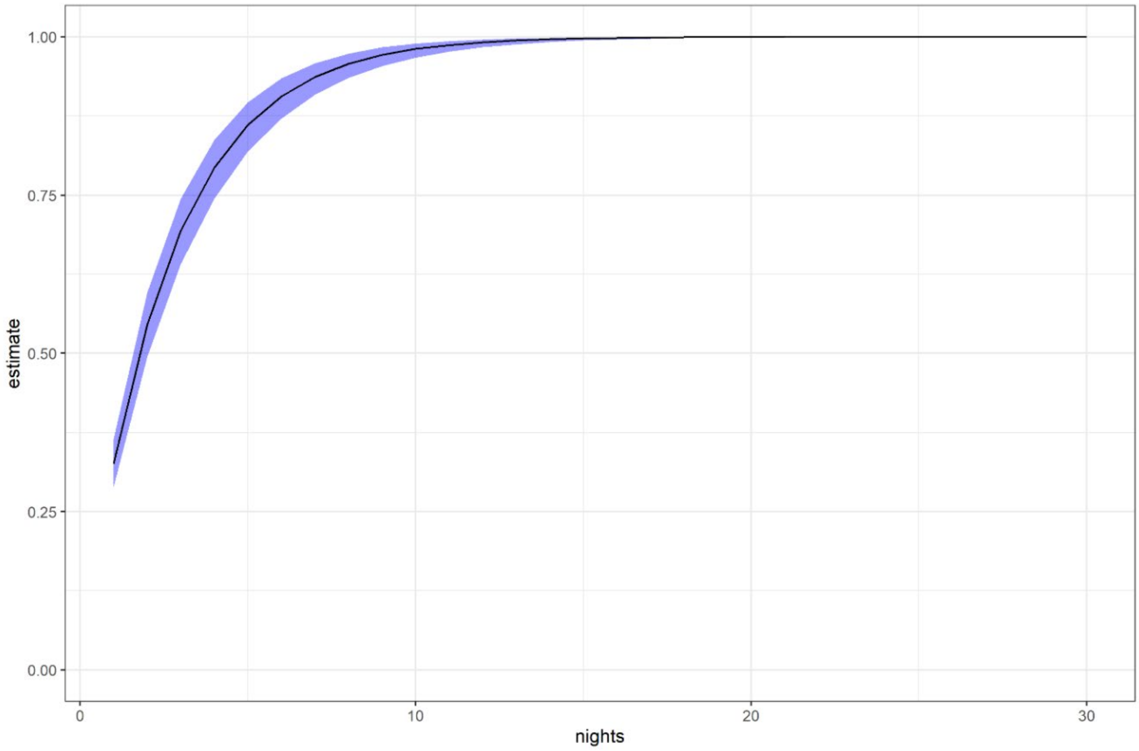
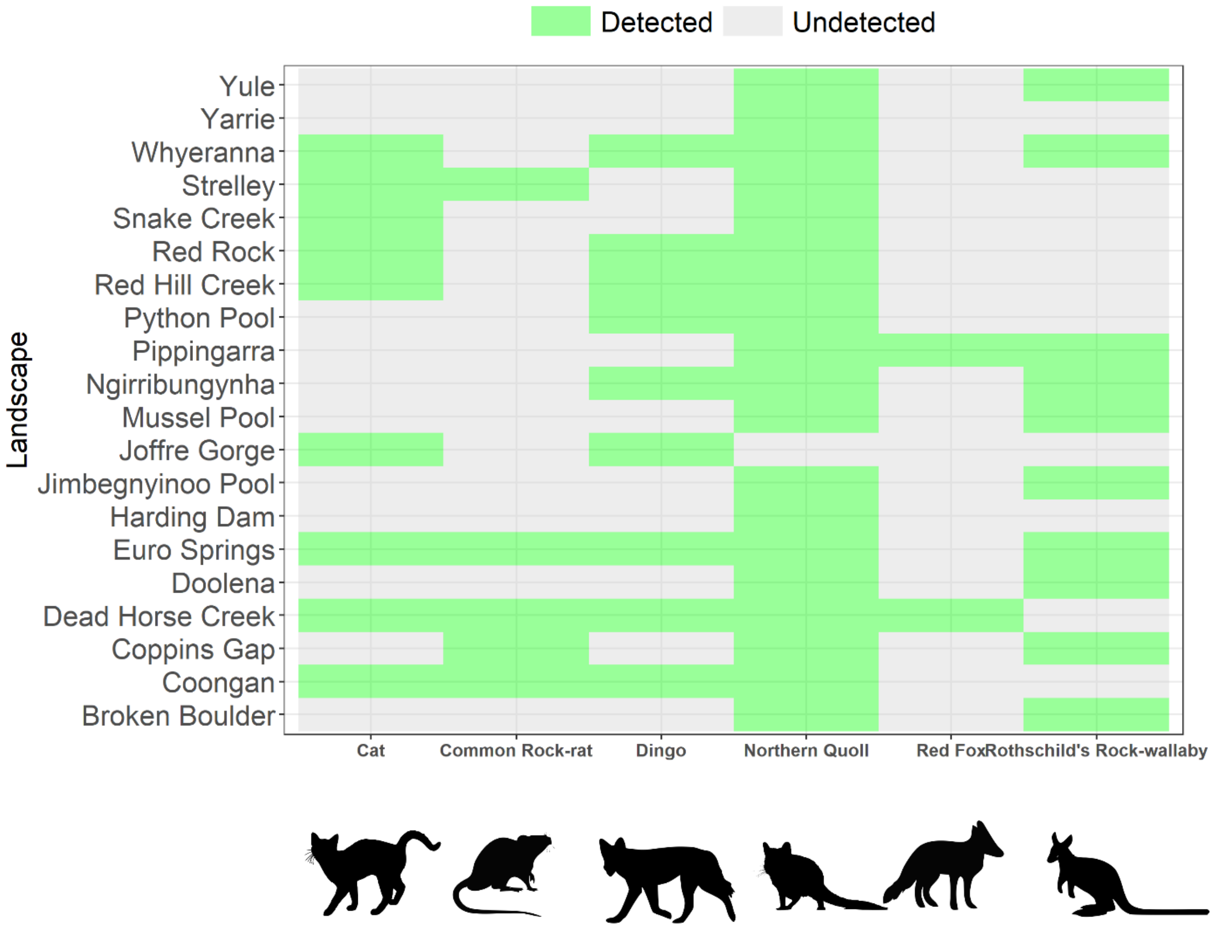


Figure 1.1-5 – Northern quoll detection probability increases with increasing number of deployment days.



🟩 Detected ⬜ Undetected

Landscape	Cat	Common Rock-rat	Dingo	Northern Quoll	Red Fox	Rothschild's Rock-wallaby
Yule	⬜	⬜	⬜	🟩	⬜	🟩
Yarrie	⬜	⬜	⬜	🟩	⬜	⬜
Whyeranna	🟩	⬜	🟩	🟩	⬜	🟩
Strelley	🟩	🟩	⬜	🟩	⬜	⬜
Snake Creek	🟩	⬜	⬜	🟩	⬜	⬜
Red Rock	🟩	⬜	🟩	🟩	⬜	⬜
Red Hill Creek	🟩	⬜	🟩	🟩	⬜	⬜
Python Pool	⬜	⬜	🟩	🟩	⬜	⬜
Pippingarra	⬜	⬜	⬜	🟩	🟩	🟩
Ngirribungynha	⬜	⬜	🟩	🟩	⬜	🟩
Mussel Pool	⬜	⬜	⬜	🟩	⬜	🟩
Joffre Gorge	🟩	⬜	🟩	⬜	⬜	⬜
Jimbegnyinoo Pool	⬜	⬜	⬜	🟩	⬜	🟩
Harding Dam	⬜	⬜	⬜	🟩	⬜	⬜
Euro Springs	🟩	🟩	🟩	🟩	⬜	🟩
Doolena	⬜	⬜	⬜	🟩	⬜	🟩
Dead Horse Creek	🟩	🟩	🟩	🟩	🟩	⬜
Coppins Gap	⬜	🟩	⬜	🟩	⬜	🟩
Coongan	🟩	🟩	🟩	🟩	⬜	⬜
Broken Boulder	⬜	⬜	⬜	🟩	⬜	🟩

Figure 1.1-6 – Species presence and absence across 23 monitoring sites in 2023. From left to right, species are feral cats (*Felis catus*), common rock-rats (*Zyzomys argurus*), dingoes (*Canis familiaris*), northern quolls (*Dasyurus hallucatus*), red foxes (*Vulpes vulpes*) and Rothschilds rock wallabies (*Petrogale rothschildi*).

Figure 1.1-7 – In 2023 and 2024, PNQRP staff travelled to Karlamilyi National Park to deploy two long-term northern quoll (Wiminyji) monitoring sites with Martu Kanyirninpa Jukurrpa rangers. The northern quoll population at Karlamilyi is of high ecological importance given it represents the most easterly populations with the species Pilbara range. A combined total of more than 100 participants were involved in the deployment of camera traps at sites.

Figure 1.1-8 – In 2023 and 2024, northern quoll monitoring sites were deployed within Murujuga National Park, on the Burrup Peninsula and Dolphin Island. Cameras were deployed in collaboration with regional DBCA staff and Murujuga Indigenous rangers. Dolphin Island is only the only island occupied by northern quolls within the Pilbara bioregion, and thus provides an important insurance population, particularly in the context of a future cane toad invasion.

Figure 1.1-9 – In 2024, PNQRP staff met with regional DBCA staff at Millstream National Park to demonstrate how we monitor for quolls and discuss how the resulting data might be used to inform future research surrounding fire practices in Millstream Chichester National Park. This contributed to the development of a new PhD project exploring the effect of fire on quoll movement ecology (see Section 7.3).

Figure 1.1-10 – Imagery collected at northern quoll mointoring sites in 2023-24. The top two images depict northern quolls, the middle left is a Rothchild's rock wallaby (*Petrogale rothschildi*), the middle right is a spiny tailed monitor (*Varanus acanthurus*), and the bottom images show two feral cats (left; *Felis catus*) and a red fox (right; *Vulpes vulpes).*

1.2 Advocating for consistency in survey techniques

1.2.1 Background

Effective conservation policy and management actions for ensuring the survival of a species requires reliable methods of detecting and monitoring populations. Unreliable detection methods can produce erroneous estimates of conservation status, habitat requirements, and population trends.

Surveys of northern quoll populations may be undertaken for several purposes: (1) to detect whether the species is present or absent in an area of habitat (e.g., for an impact assessment); (2) to determine if it is an ‘important population’ (relating to dispersal corridors, density, subject to conservation activities and outside of cane toad occurrence; see DOE 2016); and (3) to monitor population change over time in response to disturbance (e.g., mining, cane toads) or management actions (e.g. rehabilitation, feral cat baiting, artificial refuges). Surveys for northern quolls typically use one or a combination of four methods: habitat surveys, sign surveys, camera trapping, and/or live trapping (DOE 2016). However, evidence from the rapidly growing catalogue of Pilbara grey literature suggests there is a lack of consistency in the application of these methods by on-ground users, including mining proponents, environmental consultants, and Indigenous ranger groups. This inconsistency diminishes the collective value of survey data for both research and management purposes and presents a challenge in understanding the species’ population trajectory.

1.2.2 Method

A collaborative publication reviewed the application of techniques in surveying the northern quoll, including the effort required to be 95% confident of detecting presence and monitoring change in population trends in the Pilbara bioregion (see Dunlop *et al.* 2024). The outlined protocols indicate best practice for effective and efficient northern quoll monitoring, ensuring animal welfare is upheld, and are relevant to Environmental Protection and Biodiversity Conservation Act requirements. Suggestions are also provided for mitigating impacts of disturbance to animals and habitat, future directions and emerging techniques for the monitoring of northern quolls.

1.2.3 Outcomes

The review collated information surrounding habitat surveys (including suitable habitat and critical denning habitat), sign surveys, camera trapping, live trapping, and options for impact mitigation (structure retention, movement corridors, preventing habitat degradation, rehabilitation) (Dunlop *et al.* 2024). This collation of information communicates best-practice monitoring techniques to stakeholders interested in monitoring northern quolls, including consultants, Traditional Owners and land managers. It is a valuable resource that works to ensure that monitoring of this species is conducted in an efficient and accurate manner by all stakeholders. By advocating for the use of robust and consistent methodology, this resource will ensure that monitoring data collected on this species is meaningful and comparable across the region. Such data will contribute to improving our understanding of northern quoll population trends, and their drivers.

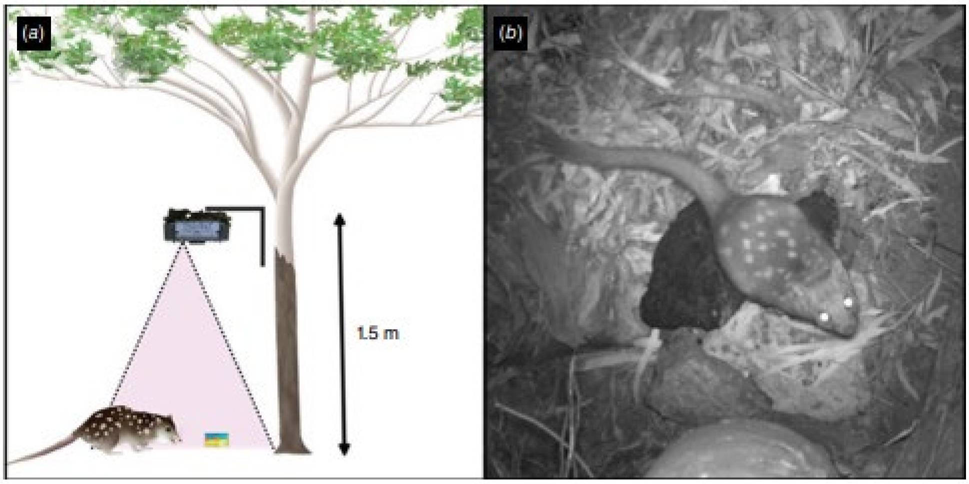


Figure 1.2-1 – a) The recommended camera trap orientation for surveying northern quolls in the Pilbara. The purple triangle represents the camera's field of view. (b) A typical image recorded of a northern quoll, showing unique spot patterning located on dorsal surface, taken using the vertical camera orientation shown in panel (a). Figure modified from Dunlop *et al*. (2024).

1.2.4 Status

Published in *Australian Mammalogy*:

Judy Dunlop, Harry Moore, Mitchell Cowan, Natasha Harrison (2024) Survey techniques and impact mitigation for the Endangered northern quoll (*Dasyurus hallucatus*) in the semi-arid landscapes of the Pilbara. *Australian Mammalogy* 46, AM24003.

2 Define critical habitat

2.1 Northern quoll movement and habitat interactions in a mining landscape

2.1.1 Background

Drill and blast mining throughout the northern quolls' range destroys complex rocky outcrops, displacing quolls and increasing the amount of simple habitat in the landscape—potentially leading to increased movement between rocky refuges, and likely, higher predation risk (Cowan *et al.* 2022). However, mine sites can also create complex infrastructure, such as waste rock piles and mine pits. In some instances, some individuals have been found to persist in mining landscapes (Henderson 2015), but their movement and behavioural responses to mining are relatively unknown (Cramer et al. 2016). Further, mine sites may expose animals to novel disturbances such as artificial light and noise pollution. An understanding of how quolls interact with mining landscapes in a movement sense, could lead to conservation interventions that enhance persistence of quolls within the footprint of mining tenements.

We used GPS collars equipped with VHF antennas and accelerometers to measure the activity and spatial ecology of northern quolls in a mining landscape, to reveal their fine-scale movements and how they interact with mining disturbed habitat. GPS units and accelerometers are widely accepted as leading methods to measure both the long-term and fine-scale activity of animals. Due to the need to avoid predators, we hypothesise that northern quolls will avoid structurally simple habitats at the mine (e.g., cleared areas, roads) where predators such as feral cats are more successful hunters (McGregor *et al.* 2016), and instead, primarily utilise the limited complex habitats available (e.g., waste rock piles, mine pits) which provide greater protection. Further, we predict that when quolls do traverse such environments in the mining landscape, their movements will be more rapid than those in natural habitats.

2.1.2 Method

Fieldwork took place at the Woodie Woodie mine, a manganese mine managed by Consolidated Minerals, 400 km SE of Port Hedland on the far eastern edge of the Pilbara and bordering the Great Sandy Desert. We captured a total of five northern quolls during the breeding season in 2021 and five during the non-breeding season in 2022 (n = 10) which were large enough for us to attach one LiteTrack 20 GPS collar (Lotek, North Havelock). All but one of the quolls collared were male. Quolls were collared for one month with GPS collars set to take fixes every 30 minutes between 6pm and 6am, and recorded the vectorial sum of dynamic body acceleration (VeDBA) every 5s, 24 hours a day. VeDBA is often used as a proxy for energy expenditure and relates to speed of movement, when quolls are mostly active (Qasem *et al.* 2012).

Specific details on the statistical analysis used in this study can be found in Cowan *et al.* (2024a). Briefly, to investigate how northern quolls interact with mining disturbance, as well as with other environmental variables at the fine scale, we used integrated step selection functions (iSSFs) (Avgar *et al.* 2016). Step selection functions involve a form of conditional logistic regression where each '*observed* step' (path connecting two consecutive observed locations of the individual) is compared with a set of '*available* steps' with a strata term (step ID) which pairs *observed* steps with their respective *available* steps (Thurfjell *et al.* 2014). Integrated step selection functions take this further, by including animal movement and resource selection parameters in the model, reducing bias, and allowing further estimation and simulation of habitat selection. For each *observed* step, we generated five random *available* steps with turning angles drawn from a von Mises distribution and step lengths drawn from a gamma distribution (Thurfjell *et al.* 2014). For each *observed* and *random* step, we extracted covariates from the four landscape maps at the end of the step. We constructed separate models for the breeding and non-breeding seasons due to differences in northern quoll behaviour during these periods (Oakwood 2002).

To examine the influence of mining disturbance and other landscape features on mean VeDBA (i.e., energy expenditure), we combined spatial and accelerometry data, using a piecewise structural equation modelling (PSEM) approach. We did this with the 'psem' function from the "piecewiseSEM" package in R (Lefcheck 2016). PSEMs are a statistical approach used to analyse multiple complex interacting variables by uniting them into a single model. They are useful for investigating direct and indirect effects of multiple predictor variables on response variables, and for examining causal relationships in ecological systems. Unlike classical SEMs, where global estimation is used to construct a model, the piecewise approach allows each response variable to be modelled separately as simultaneous generalised linear mixed-effects models (GLMMs). We fit a separate PSEM for each environmental variable, which were the proportions of each habitat type, the median topographic ruggedness index (TRI), the mean distance from disturbance, and the mean distance from rocky habitat, for each *observed* step.

2.1.3 Outcomes

In total, 12 northern quolls were tracked across two seasons at Woodie Woodie and of these, 9 individuals were suitable for analysis: four from the breeding season and five from the non-breeding season.

Northern quoll observed movement ranges had a higher proportion cover of rocky habitat compared to the available landscape, and all other habitats were used in proportion to their availability (Figure 5.1-1). Movement ranges were located in the most topographically rugged areas of the landscape, and were, on average, closer to rocky habitat and disturbed mining habitats relative to the available landscape (Figure 5.1-1).

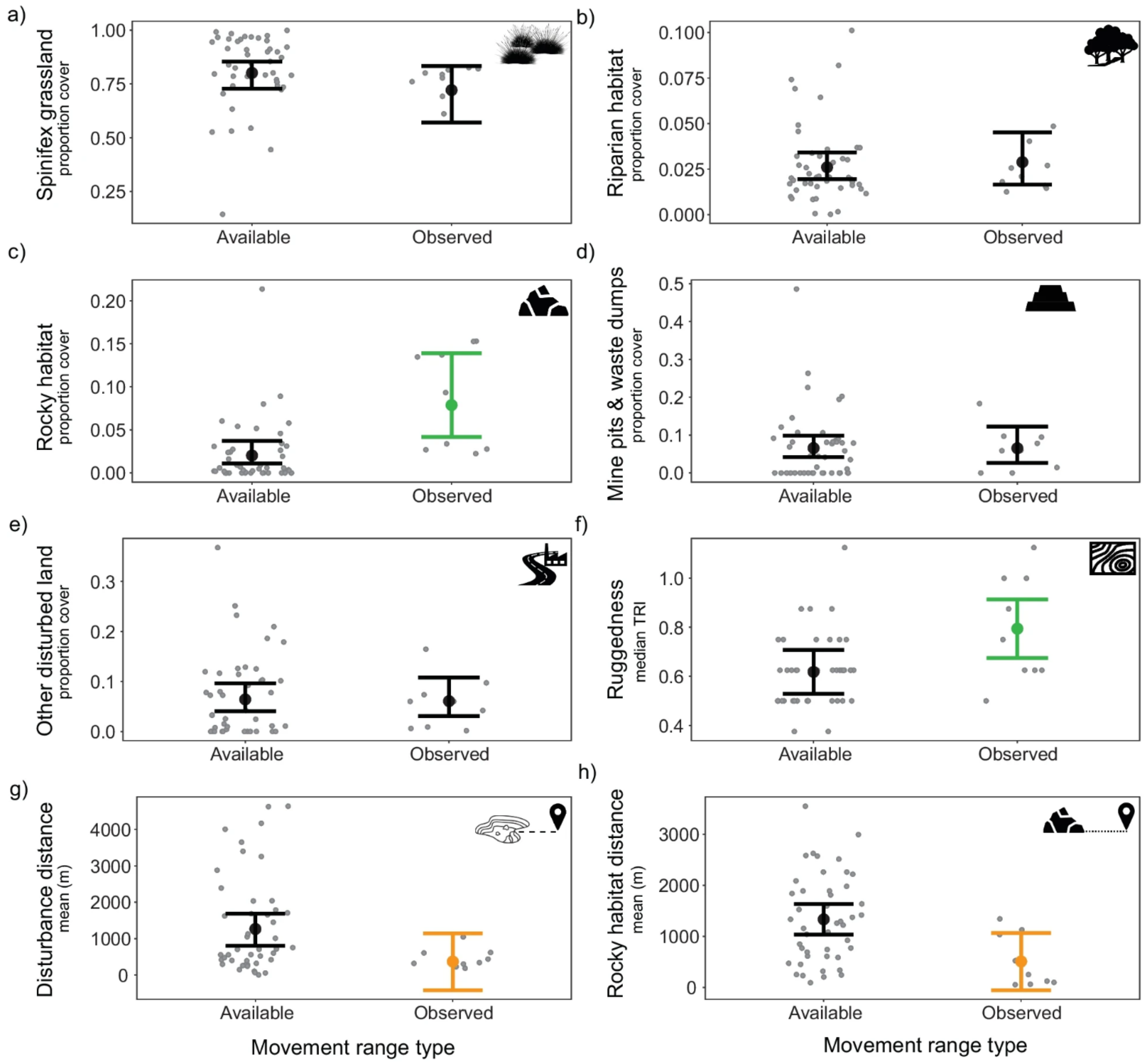


Figure 2.1-1 - Conditional effects plots for all models analysing the influence on broad scale northern quoll movement ranges by the proportional cover of **a** spinifex grassland, **b** riparian habitat, **c** rocky habitat, **d** mine pits and waste dumps, and **e** other disturbed land, as well as the **f** median topographic ruggedness index, **g** mean distance from disturbance, and **h** mean distance from rocky habitat. Small grey points indicate raw data, large points indicate the conditional effect for each model, and bars indicate the 95% CIs. Green bars indicate a significant positive relationship for *observed* compared to *available* movement ranges, orange bars indicate a significant negative relationship for *observed* compared to *available* movement ranges, and black bars indicate a non-significant relationship. Figure from Cowan *et al.* (2024a).

The global iSSF model for breeding season suggests that, within their movement range, northern quolls were significantly less likely to use mining habitats, spinifex grassland, and riparian habitat compared to rocky habitat. However, the global iSSF model for the non-breeding season suggests that, within their movement range, northern quolls used both mining habitats and riparian habitat at a similar rate to rocky habitat, but used spinifex grassland significantly less (Figure 5.1-2).

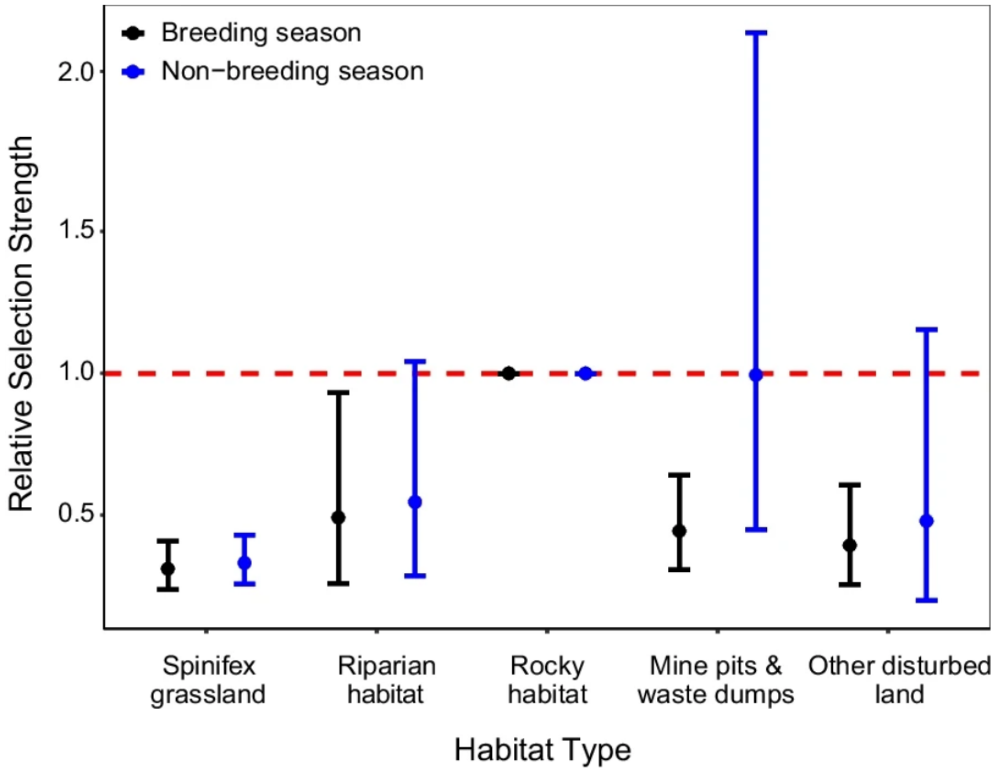


Figure 2.1-2 - The relative selection strength (RSS) for northern quolls in breeding and non-breeding season, where the selection of spinifex grassland, riparian habitat, mine pits and waste dumps, and other disturbed land is compared relative to selection for rocky habitat. Points reflect the RSS and bars reflect the 95% CIs. Black points and bars reflect selection in breeding season while blue points and bars reflect selection in non-breeding season. The red dashed line reflects the relative selection strength for rocky habitat and a significant difference is observed if CIs do not cross this line. Figure from Cowan *et al.* (2024a)

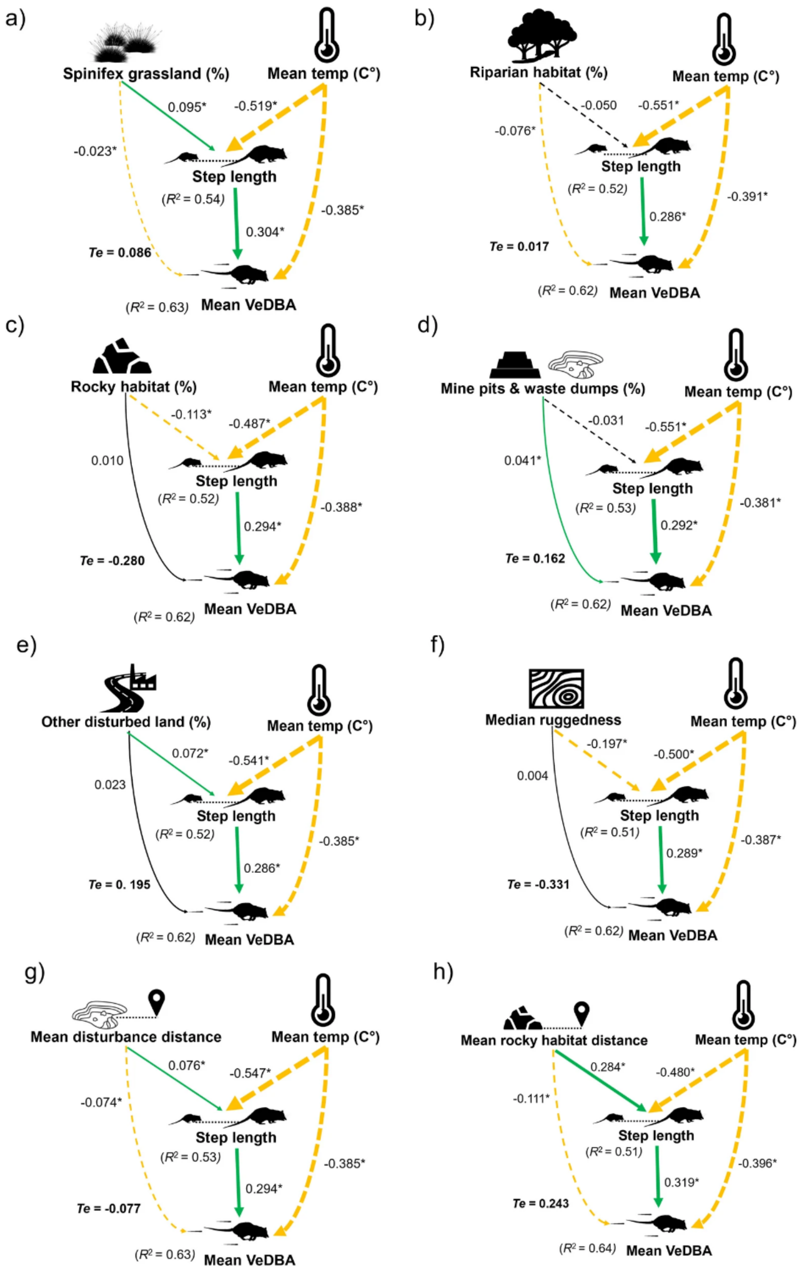


Figure 2.1-3 - Relevant range coefficients for step length and mean VeDBA (a proxy for energy expenditure) related to the influence of mean temperature and the proportion used of **a** spinifex grassland, **b** riparian habitat, **c** rocky habitat, **d** mine pits and waste dumps, **e** other disturbed land, as well as **f** median ruggedness, **g** mean distance from disturbed land, and **h** mean distance from rocky habitat. Dashed arrows represent a negative relationship and solid arrows represent a positive relationship. Arrow colour represents significance ($p = < 0.05$) with green representing significant positive relationships, orange representing significant negative relationships, and black representing a non-significant relationship. Arrow width reflects the size of the effect, with wider arrows representing a larger effect. An asterisk on relevant range coefficients also signifies that the relationship is significant and the conditional R^2 value for step length and mean VeDBA is listed for each model, outlining the variance explained by the predictor variables. *Te* represents the total effect coefficient of each environmental variable on mean VeDBA, both directly and mediated through step length. Figure from Cowan *et al.* (2024a)

This study evaluated the habitat selection and energy use of the endangered northern quoll in an active mining landscape. As predicted, we found that at the broad scale, quolls preferred rugged, rocky habitat, and used spinifex grassland, riparian habitat, and disturbed mining habitats in proportion to their availability. At the fine scale, quolls used all habitats less than rocky habitat during the breeding season, but used mining and riparian habitats at similar amounts to rocky habitat during the non-breeding season. Moving through mining habitat increased energy expenditure (mean VeDBA), suggesting that these areas may impose higher energetic costs than natural habitats. This supports existing concerns for quolls regarding the continued expansion of large-scale mining disturbance in the Pilbara and highlights the sub-lethal threats to species living in human-altered landscapes.

2.1.4 Status

This research forms part of Mitchell Cowan's PhD thesis and is Published in *Movement Ecology*:

Mitchell Cowan, Judy Dunlop, Lesley Gibson, Harry Moore, Samantha Setterfield, Dale Nimmo (2024). Movement ecology of an endangered mesopredator in a mining landscape. *Movement Ecology* **12**, 5. https://doi.org/10.1186/s40462-023-00439-5

3 Population dynamics and ecology

3.1 Northern quoll bimodal temporal activity

3.1.1 Background

Understanding the daily activity patterns — known as diel patterns — of animal species is a fundamental component of ecology. These patterns govern key aspects of an animal's life, including access to food, exposure to predators, and interactions with other species. Recent advancements in ecological monitoring technology, particularly remote cameras and telemetry, offer a mechanism for obtaining large volumes of data on species' diel patterns. Traditionally used to monitor wildlife populations, camera traps are increasingly capturing time-stamped data that reveals important details about species' behaviour. This information is crucial for understanding species' basic ecology and niches. One realisation emerging from the new generation of diel data is that traditional and broad categorisations of diel patterns, such as "diurnal", "nocturnal", and "crepuscular", do not adequately capture the complexity of species' diel patterns. Rather than simply being active by day or night, animals show clear peaks and troughs over the diel period, sometimes with multiple periods of heightened activity (Aschoff 1966).

Like most marsupials, northern quoll diel patterns have traditionally been categorised as primarily nocturnal. However, there is emerging evidence to suggest that northern quoll temporal activity patterns may be more complex than previously thought. For example, Hernandez-Santin *et al.* (2016) and Cowan *et al.* (2020) found that northern quolls in the Pilbara exhibited bimodal peaks of activity with a distinct lull occurring around midnight. A similar bimodal pattern was identified from accelerometers attached to northern quolls on Groote Eylandt (Gaschk *et al.* 2023). Here, as a part of a collaborative study, we build on these observations by comparing northern quoll temporal activity patterns across their contemporary distribution, using data collected from time-stamped camera trap images as well as accelerometers that were attached to animals (see Moore *et al.* 2024). In doing so, we aimed to more accurately describe diel patterns used by northern quolls across their range, while also considering the influence of location, seasonality, and lunar phase.

3.1.2 Method

Data collection

Temporal activity data were collected from time-stamped camera trap imagery captured between 2013 and 2022. Imagery was sourced from five northern quoll populations spanning most of the extent of northern quolls' contemporary distribution: the Pilbara, the Kimberley (Mornington Wildlife Sanctuary, Adolphus Island), Groote Eylandt, and Cape York. Camera-trap models used included Reconyx HC550 (white flash), Reconyx HC600 (infrared flash), Reconyx PC900, Scoutguard 560DF (dual flash), and Scoutguard 565F (white flash). Cameras were mounted to a tree or post either 1 or 1.5 m above the ground and oriented vertically (facing downward), so as to capture unique spot patterning located on the dorsal surface of animals (Diete *et al.* 2017; Moore *et al.* 2020; Indigo *et al.* 2023; Trewella *et al.* 2023). All cameras were baited (fish, peanut butter, or sesame oil) and left active for between 2 and 150 days at a time. To mitigate the impact of clustering within data associated with an animal spending prolonged periods in front of the camera, thus generating many detections in close succession, the data were condensed into "independent detections events", which we defined as detections separated by 15 mins following Diete et al. (2017). To corroborate camera trends, we obtained accelerometer data from a different northern quoll study in the Pilbara (Cowan *et al.* 2024a). Collars containing GPS loggers and accelerometers were deployed on nine individuals (F = 1, M = 8) for between 13 and 30 days in 2022 and 2023. Accelerometers recorded data at 5-second intervals for 24 h a day. Four individuals were collared during part of the breeding season (September–October) and five during part of the non-breeding season (June–July). Both periods occurred in the Pilbara dry season. No similar data were available from the wet season.

Statistical analysis

To estimate the probability density of quoll activity over the 24-h diel period, we fitted non-parametric kernel-density curves using the 'overlap' package (Ridout and Linkie 2009) in R version 4.2. (R Core Team 2021). We used the default smoothing parameter of 0.8 in our analysis, as recommended for small sample sizes (Ridout and Linkie 2009). We assessed seasonal activity variations by generating distinct density curves for "wet" and "dry" seasons in each population. At Mornington, Adolphus Island, and Cape York, the wet season was defined as December–March; in the Pilbara, January–March; and on Groote Eylandt, November–April, according to average rainfall. The corresponding dry seasons were April–November, April–December, and May–October, respectively. Moon phase has been shown to influence the activity patterns of some marsupial species (Linley *et al.* 2020). To investigate the influence of moon phase on northern quolls, we assigned moon phase data to each temporal observation using the lunar package (Lazaridis 2022). We then fit separate kernel curves for full moon and new moon observations for each population. We chose the full moon and new phases because they represent the range of lunar brightness, potentially affecting quoll activity in different ways.

Accelerometer data were cleaned to avoid times when a quoll was in a trap. Raw acceleration data (g) were converted to the vector of the dynamic body acceleration (VeDBA)—previously used to investigate northern quoll behaviour on Groote Eylandt (Gaschk *et al.* 2023). See Qasem et al. (2012) for the detailed methods we followed to calculate VeDBA. VeDBA is a good proxy for energy expenditure and deals well with variation in data caused by potentially rotating collars (Qasem *et al.* 2012). To deal with the large data size (and for purposes required by the other study), VeDBA was converted to 30-min averages (henceforth mean VeDBA). We then fit a generalized additive mixed model (GAMM) to examine the relationship between mean VeDBA and time of day (hour), while accounting for the effects of season and the random effect of individual. We used the "gamm4" function from the "gamm4" package in R (Wood and Scheipl 2017) to fit the GAMM, with a smooth term for hour and a fixed effect of season. The "by" argument in the smooth term allowed the smoothness of the relationship between VeDBA and hour to vary by season (Wood and Scheipl 2017). Results were then plotted for visualization of the mean hourly VeDBA (or energy use).

3.1.3 Outcome

Bimodal diel patterns, that is, two peaks in activity separated by a trough, were observed in the Pilbara and Groote Eylandt across both wet and dry seasons. Similar bimodal peaks were also observed in the Mornington wet season data and the Cape York dry season data. No bimodal activity was observed in either the wet or dry season for Adolphus Island (Figure 3.1-1).

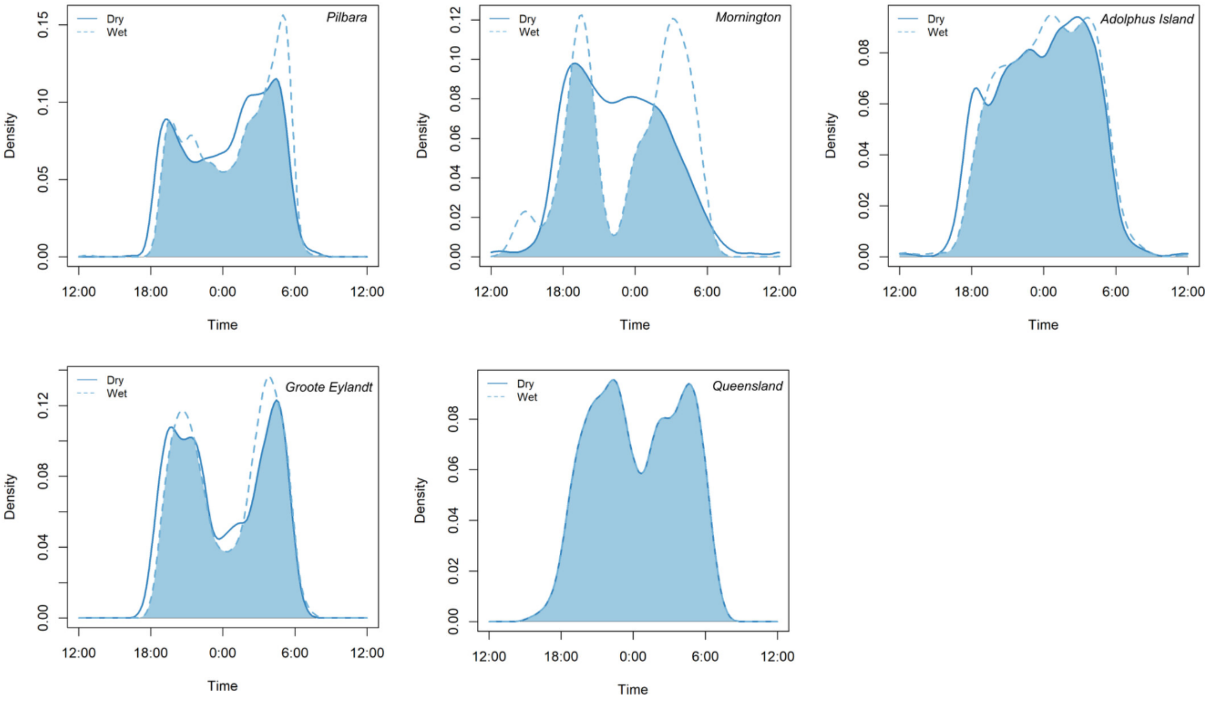


Figure 3.1-1 – Density plots depicting patterns of northern quoll temporal activity across the five study populations, in both the wet and dry seasons. Figure from Moore *et al.* (2024a).

Bimodal peaks occurred mostly within the 3 hours prior to midnight, as well as within the 3 hours following midnight. Lulls in activity separating these peaks mostly overlapped with midnight. This was supported by accelerometer data from the Pilbara, where mean VeDBA showed twin peaks with lower energy use around midnight in both the breeding and non-breeding seasons (Figure 3.1-2).

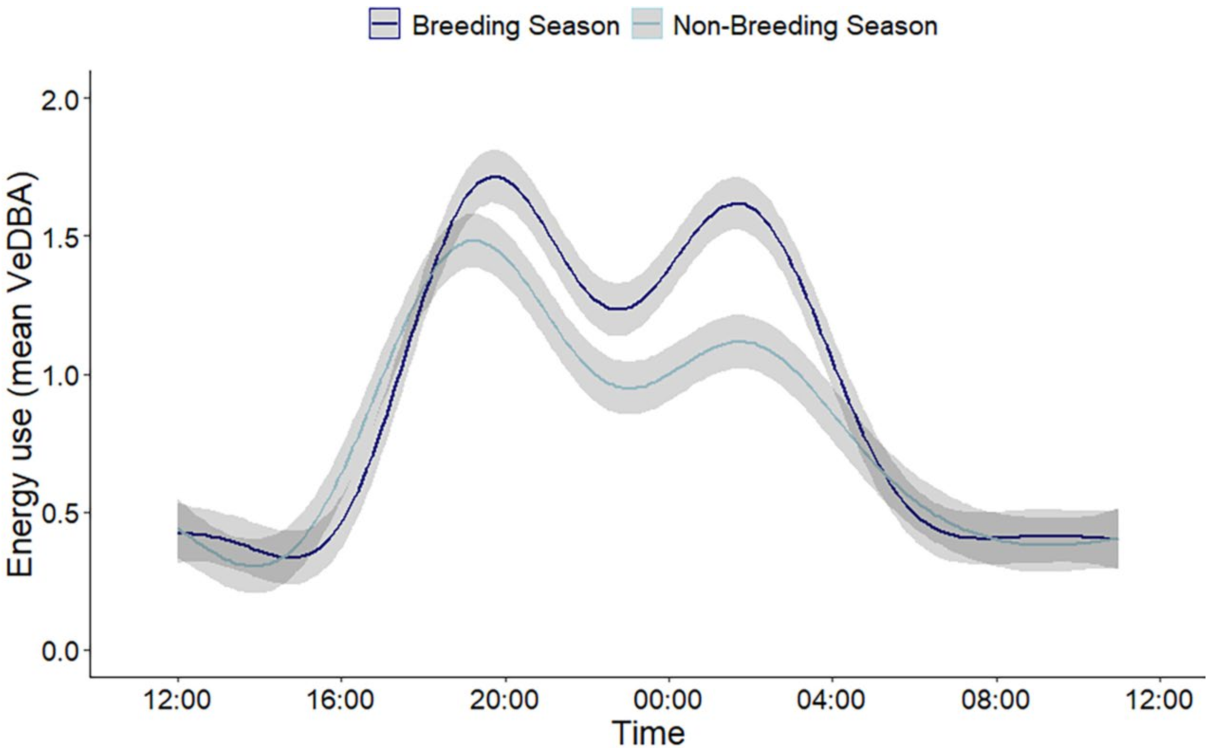


Figure 3.1-2 – Graph depicting modelled mean VeDBA (Vector of Dynamic Body Acceleration) across a 24-h diel cycle for northern quolls during breeding and non-breeding seasons in the Pilbara. Figure from Moore *et al.* (2024a).

The results from our study align with a growing body of research that suggests the diel patterns of marsupial predators, including the northern quoll, can be more complex than previously assumed.

3.1.4 Status

Published in *Austral Ecology:*

Harry Moore, Rebecca Diete, Naomi Indigo, Mitchell Cowan, Gavin Trewella & Dale Nimmo (2024) Midnight siesta: Bimodal temporal activity observed in an endangered marsupial predator. *Austral Ecology*, 49, e13521. Available from: https://doi.org/10.1111/aec.13521

4 Assessing the impact of introduced predators

4.1 Northern quoll responses to fire in the absence of predators

4.1.1 Background

Fire is a fundamental part of many ecosystems, but the frequency and intensity of fires has changed substantially in contemporary times. This is largely owing to land-use changes, climate change (Pausas and Keeley 2009; Armenteras and Retana 2012), and in the Australian context, the cessation of burning by Aboriginal people (Burrows and Christensen 1990; Hoffman *et al.* 2021).

Our understanding of how fire impacts the northern quoll is advancing (Moore *et al.* 2021a). Across their range, quolls have been negatively associated with recently burned areas (Andersen *et al.* 2005; Hernandez-Santin *et al.* 2022; Moore *et al.* 2024c; Cowan *et al.* 2024b) and increasing fire frequency (Radford *et al.* 2015; Ondei *et al.* 2021). Populations have been documented declining following fire (Kerle and Burgman 1984; Oakwood 1997), and fire is suggested to disrupt breeding and reduce recruitment (Begg 1981; Griffiths and Brook 2015). There are multiple instances, however, where fire appears to have had minimal impact on quoll populations. Cook (2010) and Cowan (2024) have found that quolls may continue to utilise burned areas, and in some cases, quolls have been more abundant in association with fire (Woinarski *et al.* 2004; Radford *et al.* 2020). Considerable variation can be seen in the responses of northern quolls to fire, indicating that they are likely to be context specific (Moore *et al.* 2021a), yet the mechanisms driving these observed responses remain unclear.

Direct mortality from fire has not been observed in northern quolls (Moore *et al.* 2021a) and is assumed to be of relatively low risk given that they are highly mobile and inhabit rocky areas that should afford them shelter from most fires (Robinson *et al.* 2013; Moore *et al.* 2022; Shaw *et al.* 2023). Disentangling the relative impact of fire on resource availability and predation requires exploration of these threatening processes in isolation. Dolphin Island, a 3,300 ha island in the Dampier Archipelago in Western Australia is free from grazing cattle, and largely free of introduced predators (feral cats *Felis catus* and foxes *Vulpes vulpes*) (Dunlop *et al.* 2014; Dunlop and Birch 2018), providing a rare and valuable opportunity to study a northern quoll population in the absence of major threatening processes. Here, we use observational data to describe the response of the Dolphin Island northern quoll population and their prey (common rock-rat; *Zyzomys argurus*) to a large, island-wide fire in December 2013.

4.1.2 Method

Field methods

Population monitoring was conducted on Dolphin Island using cage traps between 2012 and 2019, during which, traps were set in the evening and checked the following morning within 3 hours of sunrise. Traps were spaced either 20 m (2012-13) or 50 m (all other years) apart and deployed for between two and four nights (see Table 1 for details). Captured northern quolls were inserted with a microchip for individual identification, and weight, sex, pes (hind foot) length and head length were recorded. Rock-rats, a popular prey item of northern quolls (Dunlop *et al.* 2017), were commonly caught as bycatch during this monitoring. In these instances, rock-rats were ear-notched to identify new or recaptured individuals and, in most cases, processed as above.

Table 4.1-1- Details of trapping regimes for northern quolls on Dolphin Island between 2012 and 2019. Session, date, duration of survey, number of traps, and spacing of traps are presented, as well as the minimum number of individuals known to be alive (MNKA).

Session	Start date	Duration (days)	Traps (#)	Spacing (m)	Individuals (MNKA)
1	27/06/2012	3	40	20	9
2	04/07/2012	2	40	20	7
3	06/07/2013	4	30	20	12
4	17/06/2014	4	50	50	22
5	13/06/2015	4	50	50	17
6	07/10/2015	4	50	50	18
7	14/06/2016	4	50	50	9
8	25/07/2017	4	50	50	11
9	12/06/2018	4	50	50	11
10	28/07/2019	4	50	50	9

Statistical analysis

We built two linear models with year (2013 pre-fire and 2014 post-fire) as a fixed effect to test its influence on body mass and body condition, while accounting for differences between sexes. Model fit was tested using the 'DHARMa' package (Hartig 2022) and the significance of each parameter was evaluated by conduction likelihood ratio tests between the full model with and without each respective variable.

The minimum number of individuals known to be alive (Krebs 1966) was calculated based on the number of unique individuals captured each session. To explore trends in local quoll abundance through time, we estimated the quoll population size at our trapping site in each session using a multi-session open population capture-recapture model ("JSSAN") from the package 'openCR' (Efford 2024). Quoll life history dictates considerable seasonal effects on the detectability and abundance of individuals. To avoid any confounding effects of season, we removed session 6 (October 2015) from this analysis so that all remaining data were collected in either June or July. We allowed population size (N) to vary between sessions, survival (φ) to vary by the interaction between sex and session, and detection probability (p) to vary by sex and trap spacing (a session-level covariate where sessions were assigned either 'a' if there was 20m between traps, or 'b' where there was 50m between traps). The best model was determined by comparing AIC values from models with varying combinations of these parameters, as well as with a null model. The model with the lowest AIC value was deemed to perform best.

Rock rat capture rate was calculated based on the number of captures per trap effort (traps x nights). The minimum number of individuals was also calculated based on the number of 'new' animals (those without an ear notch indicative of previous capture) captured throughout the session. To explore the fitness of rock rats, we built another linear model testing for the effects of year and sex on body mass. Only captures from the first night and 'new' animals were used in this analysis to avoid including multiple observations per individual. Model fit and the significance of each parameter were evaluated as above.

4.1.3 Outcomes

Between 2012 and 2019, there were 215 captures of 101 northern quoll individuals. All individuals were considered adults (based on the presence of fully formed testes or an active pouch), indicating they were a minimum of 1 year old (as northern quolls reach sexual maturity at 1). No males were recaptured between years. The median difference in time between a female's first and last capture event was 368 days (i.e., surviving approximately 2 years). There were three individuals recaptured after 719, 730 and 731 days respectively (i.e., surviving to 3 years of age). Sex ratios were male biased in 2013, 2014, 2015, and 2019 (Figure 4.1-1).

The best performing capture-recapture model allowed survival to vary by sex, population size to vary by session, and detection probability to vary by sex and trap spacing. Notably, models including session as a predictor of population size had substantially higher AIC values compared to the best model (ΔAIC = 11.7 and 21.3 for session as a fixed effect or as an interaction with sex respectively), providing no support for variation in survival between sessions. Estimates of local population size ranged from 8 to 24 individuals and increase post-fire although the confidence intervals considerably overlap (Figure 4.1-1). Apparent survival between sessions was estimated to be 0.0004 (± 0.002 S.E) for males, and 0.280 (± 0.067 S.E) for females. Males had slightly higher capture probability (0.376 ± 0.070 and 0.384 ± 0.045 at 20m and 50m spacing respectively) compared to females (0.297 ± 0.063 and 0.303 ± 0.043 at 20m and 50m spacing respectively).

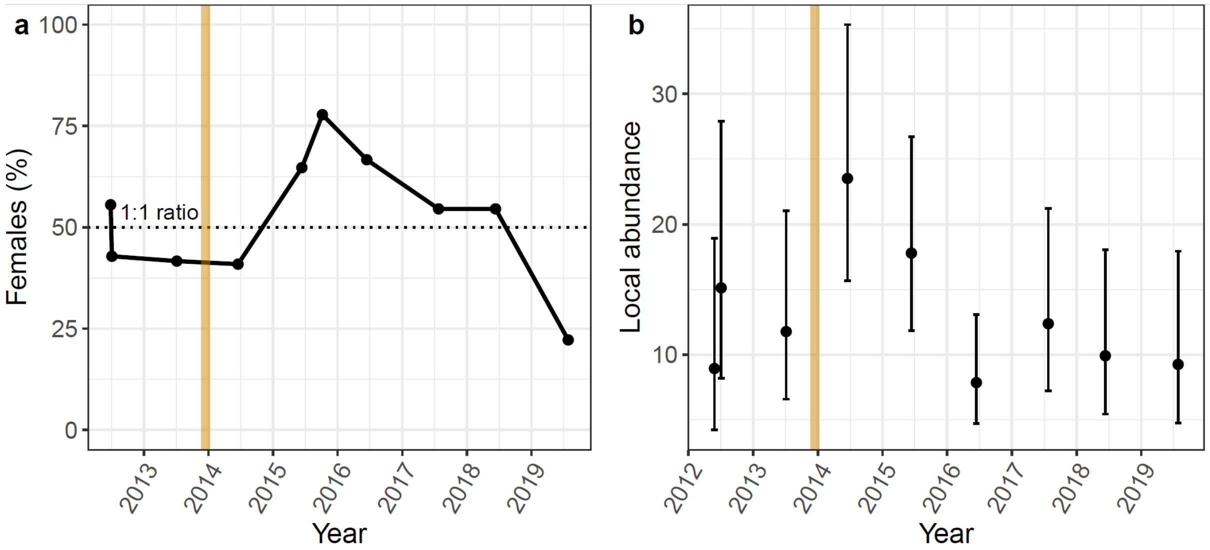


Figure 4.1-1 - (a) Sex ratios and (b) estimates of local population abundance of northern quolls on Dolphin Island between 2012 and 2019. Dotted horizontal line represents parity (50% females, 50% males) and orange column depicts the timing of the fire in December 2013 and error bars represent 95% confidence intervals.

Body measurements were recorded from 5 females and 6 males in 2013, and 9 females and 13 males in 2014. Males had higher body mass compared to females (mean = 400g and 330g respectively; Table 4.1-2) but there were no differences in quoll body mass between 2013 and 2014 (Figure 4.1-2). Similarly, males had higher body condition scores compared to females (mean = 5.9 and 5.1 respectively; Table 4.1-2), but there was no difference in body condition between years (Figure 4.1-2).

Table 4.1-2 - Effect of year and sex on northern quoll body mass and body condition on Dolphin Island. The slope, standard error (SE), and degrees of freedom (df) for each variable in the final model is reported (with levels of a particular variable indicated after the underscore), as is the p-value resulting from likelihood ratio tests of the final model with and without each respective variable.

	Body mass				Body condition			
Parameter	Estimate	S.E.	df	p-value	Estimate	S.E.	df	p-value
Intercept	336.07	23.94	-	-	5.18	0.28	-	-
Sex_Male	70.54	23.60	1	<0.01	0.81	0.28	1	<0.01
Year_2014	-13.89	24.76	1	0.58	-0.12	0.29	1	0.67

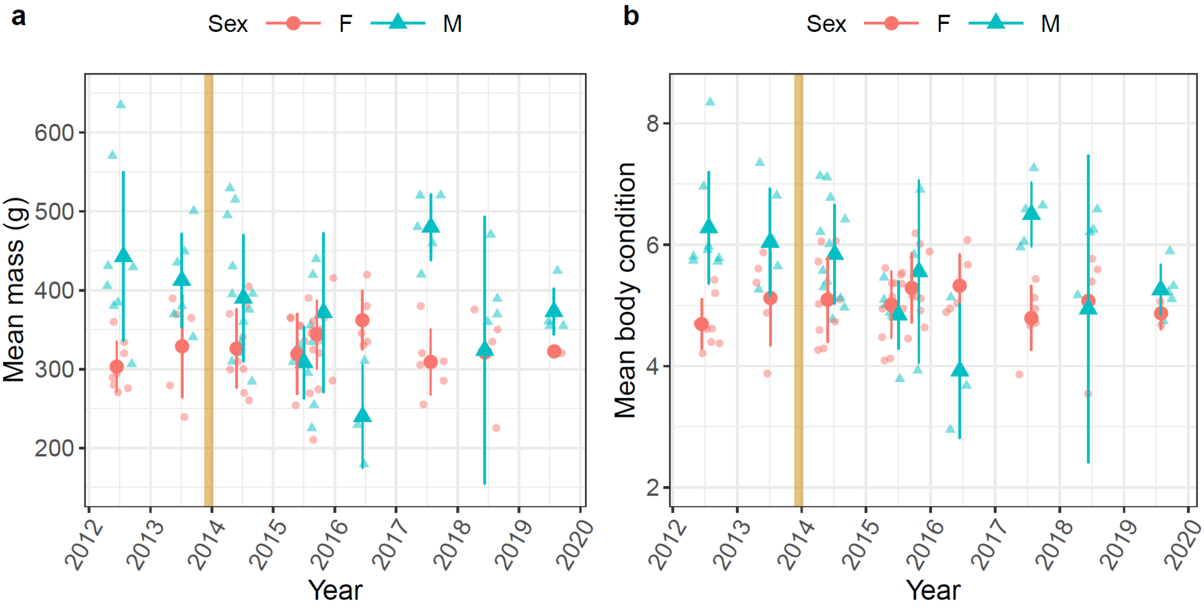


Figure 4.1-2 - (a) Mean body mass (g) and (b) body condition (body mass/head length) of male (blue, triangle) and female (pink, circle) northern quolls on Dolphin Island between 2012 and 2019. Orange column depicts the fire that occurred in December 2013 and error bars represent standard deviation.

The rock rat population declined substantially after the fire with the lowest capture rate and minimum number of individuals both occurring in 2014 (Figure 4.1-3). Rock rat body measurements were taken from 11 males and 15 females in 2013, and 3 males and 3 females in 2014. There was no difference in body mass between males and females (Table 4.1-3) or between years (Figure 4.1-3).

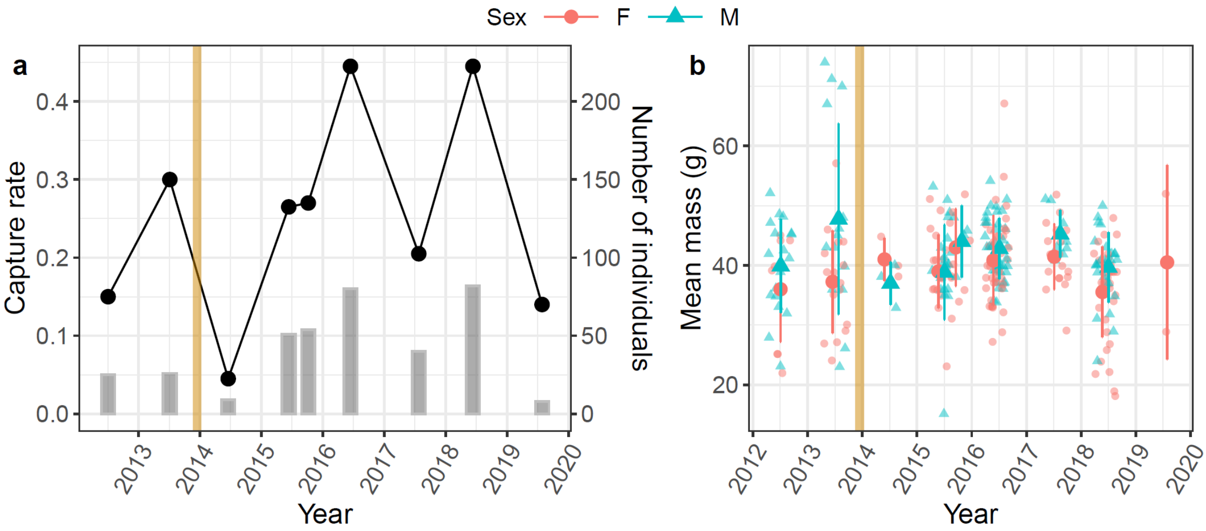


Figure 4.1-3 - (a) Capture rate (black points, left axis) and minimum number of individuals caught (grey column, right axis) as well as the (b) Mean body mass of male (blue, triangle) and female (pink, circle) rock rats on Dolphin Island between 2012 and 2020. Orange column depicts the large fire that occurred in December 2013 and error bars represent standard deviation.

Table 4.1-3 - Effect of year and sex on rock rat body mass on Dolphin Island. The slope, standard error (SE), and degrees of freedom (df) for each variable in the final model is reported (with levels of a particular variable indicated after the underscore), as is the p-value resulting from likelihood ratio tests of the final model with and without each respective variable.

Parameter	Estimate	S.E.	df	p-value
Intercept	37.75	2.67	-	-
Sex_Male	5.50	3.84	1	0.16
Year_2014	-1.5	4.89	1	0.76

In this observational study we find no substantial negative impact of the 2013 fire on a local population of northern quolls on Dolphin Island. Despite a reduction in prey availability, there were no differences in quoll body mass or condition following the fire. We found no evidence for variation in apparent survival between sessions, and estimates of population abundance demonstrate that the population remained relatively stable, even displaying signs of increase following fire. Overall, no population-level effects resulting from this fire could be detected. Dolphin Island is pristine northern quoll habitat, with a variety of prey items and lack of threatening processes. Taken together, these data suggest that in the absence of predation, quoll populations in high quality habitat can exhibit resilience to moderate fire regimes.

4.1.4 Status

Further interrogation of this data is currently being undertaken with a full manuscript expected in 2025.

5 Understanding the spread and impact of cane toads

5.1 Conditioned taste aversion to buffer northern quoll populations against cane toad invasions

5.1.1 Background

Introduced species are disrupting ecosystems globally. A particularly formidable invader that has colonised many countries is the cane toad (*Rhinella marina*). The northern quoll has suffered dramatically following the introduction of the cane toad, facing population declines across much of their range where cane-toads have invaded (Woinarski *et al.* 2010; Woinarski *et al.* 2011; Indigo 2020). Quolls are susceptible to cane toad toxins (Shine 2010), but can coexist with cane toads in some areas. Quolls that do persist in areas invaded by cane toads demonstrate adaptive behaviours that are likely to persist across generations (Kelly and Phillips 2017). However, there is considerable natural variation in quoll responses to cane toads (Kelly and Phillips 2017), and the challenge for conservation managers is sustaining viable populations long enough for them to exhibit desired responses. Often the impact of toads at the invasion front is so severe, it offers little opportunity for adaptation. Without intervention, we risk the extinction of numerous predator populations from the Australian landscape.

Conditioned taste aversion (Garcia *et al.* 1955) , herein CTA, is an adaptive, learned avoidance of food that induces nausea. Harnessing the principles of cognition, CTA has increasingly been employed in a conservation context. This includes combatting predator mortality through ingestion of toxic toads by ‘training’ wildlife to avoid predating them - pairing cane toad stimuli with nausea inducing chemicals (inducing the responses demonstrated by those quolls that persist with toads). The success of this method has been demonstrated in numerous Australian predator species including freshwater crocodiles (Ward-Fear *et al.* 2024), blue-tongued skinks (*Tiliqua scincoides intermedia)* (Price-Rees *et al.* 2013), goannas (*Varanus panoptes)* (Ward-Fear *et al.* 2016), and planigales (*Planigale maculata)*(Webb *et al.* 2008). In northern quolls, convincing behavioural shifts have been demonstrated in captive trials (Kelly *et al.* 2018; Indigo *et al.* 2018), and in multiple instances, “toad-smart” quolls trained in captivity have had higher survival than their naïve counterparts when exposed to cane toads in the wild (O’Donnell *et al.* 2010; Jolly *et al.* 2017).

In collaboration with the DBCA Cane Toad Strategy team, we aimed to evaluate the use of CTA to buffer northern quolls in the Kimberley region of Western Australia against the cane toad invasion. Three rounds of conditioned taste aversion baits at six sites across two broader areas were deployed between 2020 and 2022 and monitored (and paired controls) for four years (2020-2024). The effectiveness of this trial will be explored by investigating population-level effects of CTA baiting in northern quolls and other native predator species at these sites. The trial will be considered successful if the CTA baiting reduces the decline of quolls at treatment sites compared to the controls (i.e., the treatment had a significant effect on occupancy or detection rates).

5.1.2 Method

In this study, CTA baits were deployed at two broad areas: Mt Hart Station and Prince Regent National Park in the Kimberley. Baits were deployed via aircrafts to attempt broadscale (~250ha areas) aversion training in quolls in 2020 (immediately before the arrival of cane toads), 2021 and 2022. Each baited site (two at Mt Hart, four at PRNP), and a corresponding paired control site >2km away was monitored using five downward facing cameras baited with tuna (as per Dunlop *et al.*, 2024).

Dynamic occupancy models will be used to explore changes in quoll occupancy at treated and control sites between 2020 and 2023. Preliminary detection rates from this data can be seen in Figure 5.1-1 and show no obvious population effects of CTA treatments.

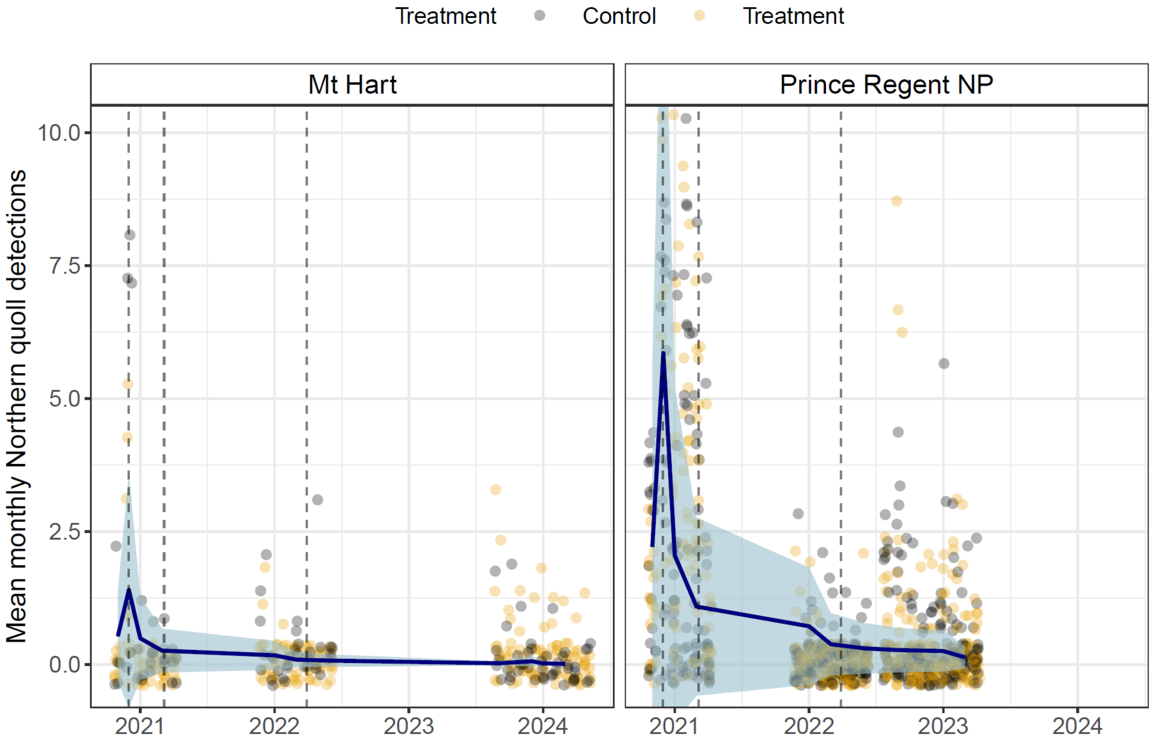


Figure 5.1-1. Mean monthly detections of northern quolls at sites treated with CTA baits (yellow) and control sites (black) at Mt Hart Station and Prince Regent National Park between 2020 and 2024. Dotted lines represent bait drops in 2020, 2021, and 2022.

5.1.3 Outcomes

The outcomes from this analysis will help to evaluate the suitability of aerial delivered CTA baits in buffering northern quoll populations from cane toad invasion, which could reach the Pilbara without intervention by as soon as 2035 (Tingley *et al.* 2013).

5.1.4 Status

Analysis of this data is underway, with a draft manuscript expected in 2025.

5.2 The suitability of Pilbara offshore islands for supporting insurance populations of northern quolls in the face of cane toad invasion

5.2.1 Background

Invasive species are a major threat to biodiversity, with many authorities ranking them second only to habitat destruction as a threatening process worldwide (Parker *et al.* 1999; Clavero and Garcia-Berthou 2005). Toxic cane toads (*Rhinella marina*) are particularly threatening for native frog-eating predators (Shine, 2010; Ujvari & Madsen, 2009). The introduction of the cane toad into Australia has had a devastating impact on native fauna, including northern quolls (Letnic *et al.* 2008; Doody *et al.* 2009; Jolly *et al.* 2015). Cane toads are yet to reach the Pilbara, but are predicted to arrive as soon as 2035 without intervention, and given that they are near-impossible to eradicate from the landscape, exclusionary strategies must be explored (Tingley *et al.* 2013).

Offshore islands can provide effective refuge as they provide a natural physical barrier to exclude invasive species (Moro *et al.* 2018; Ringma *et al.* 2018) and the Pilbara coastline hosts more than 600 islands with an approximate total land area of 500 km^2. However, irrespective of their distance from the mainland, islands are not guaranteed to remain free of cane toads. Cane toads have been documented travelling more than 30 km to offshore islands during major flooding events (e.g., Taylor et al. 2004) and human traffic can increase the movement of toads (Taylor and Edwards 2005).

In this study, we will use Bayesian Belief Networks informed with a variety of biological, climatic and anthropogenic parameters to predict the probability of cane toads dispersing to and establishing on 556 offshore Pilbara islands. We will then explore these findings in the context of the conservation and management of northern quolls. Using elements of the Structured Decision Making approach (Gregory *et al.* 2012; Fischer *et al.* 2022), we will assess the ecological suitability of Pilbara islands for supporting insurance of populations of northern quolls in light of their predicted future cane toad status. Ultimately, we aim to reveal the best candidate island(s) based on evaluations of quoll establishment and persistence probability, potential impacts on existing biodiversity, and the likelihood of each island remaining toad-free.

5.2.2 Method

Estimating future toad status

To estimate the probability of toads dispersing to and establishing on each island ten years after toads are present along the Pilbara coastline, we will use biosecurity Bayesian Belief Networks (BBN) developed by Lohr *et al.* (2017a). The Biosecurity BBN is an island pest risk mapping system built using a series of generic Bayesian Belief Networks (BBNs), which are linked by Java computing code and the freely available GeNIe application to automate the creation and computation of species- and site-specific biosecurity BBNs (Lohr *et al.* 2017a). The Biosecurity BBN generates estimates for each island of the number of individuals of one or more species arriving, the number of individuals using each dispersal pathway, and the annual risk of establishment for each species, despite uncertainty in data inputs.

The Biosecurity BBN has a hierarchical structure, with five sub-models representing dispersal pathways, including swimming/flying to an island, rafting on flood plumes, walking across temporary tidal land bridges, or being transported by industrial or recreational shipping. Each sub-model is created and run, via stochastic sampling (n=1000) and ultimately generates path-specific and an overall annual estimate of the probability of a species establishing a new population on an island.

The Biosecurity BBN is designed to predict biosecurity risk within one year. To predict the probability of cane toads 'island-hopping' throughout an archipelago over the course of 10 years we will take the annual estimated probability that cane toads may establish on each island from the Biosecurity BBN outputs for year 1 and re-enter it into the input spreadsheet describing the presence of cane toads on each island as a Bernoulli distribution for year 2. We will repeat this process for 10 subsequent years. Using a Bernoulli distribution allows uncertainty regarding the established presence of cane toads on an island to propagate through the biosecurity BBN, which influences the probability that toads are further dispersed.

Identifying candidate islands and evaluating suitability.

We will determine the minimum geographical suitability of islands to support quolls (>100 ha in size, >1,000m from the mainland) based on the results of previous quoll translocations (e.g., Griffiths, et al., 2017; Rankmore et al., 2008). A list of all islands located within the Pilbara Bioregion was retrieved from the Pilbara Island Biosecurity Database (Lohr *et al.* 2017b) and refined based on these criteria to give a list of candidate islands.

Following the structured decision-making framework (Gregory *et al.* 2012; Fischer *et al.* 2022), we will determine four fundamental objectives of a translocation of northern quolls to a Pilbara island (maximising quoll establishment probability, maximising quoll persistence probability, minimising the impact on local biodiversity, and minimising the probability that cane toads would arrive and establish) along with performance measures to quantify the suitability of each candidate island against each of these four objectives (draft measures can be found in Table 4.5-2). Each candidate island will be assessed against these criteria to determine its suitability for hosting an insurance population of northern quolls in the face of the impending cane toad invasion.

Table 5.2-1 - Fundamental objectives and performance measures to assess the suitability of Pilbara islands to support northern quolls in the face of cane toad invasion.

Fundamental Objective	Performance Measure	Justification	Data source
Maximise establishment probability of quolls	Ruggedness (Index)	Ruggedness is consistently one of the most important predictors of habitat suitability for northern quolls (Molloy *et al.* 2017; Moore *et al.* 2019; Shaw *et al.* 2023). Topographically complex rocky habitat	(Lohr *et al.* 2015)

		specifically provides important breeding habitat and shelter from fire, heat and predators (Hernandez-Santin *et al.* 2022; Shaw *et al.* 2023). Moreover, it has been linked to quoll fitness (Moore *et al.* 2024b).	
	Presence of eutherian predators	Feral cats (*Felis catus*) and foxes (*Vulpes vulpes*) predate quolls (Palmer *et al.* 2019; Cowan *et al.* 2020b) and may reduce their ability to establish and persist. Dingo predation has contributed to the failure of other quoll translocation programs (e.g., Jolly et al., 2017).	(Legge *et al.* 2018)
Maximise persistence probability of quolls	Estimated capacity	Larger populations are less likely to experience population collapse from stochastic events. We estimated a coarse measure of carrying capacity for each island using the following formula (modified from that used by Brook *et al.* 2004): $N = \frac{A}{HR_f * 0.5}$ Where N is the carrying capacity, HR_f is the average female 95% MCP home range for the Pilbara (19.8 ha; Cowan et al., 2020), and A is the total available habitat area on each island. Here we assume overlap in territories, and that the sex ratio of females to males is 2:1.	
	Island tenure	The Pilbara region is a multi-use landscape (Gibson *et al.* 2023), with only ~6% protected within the conservation reserve system (Government of Western Australia 2017). Conservation Reserve status can offer protection against land-use changes, offering a more secure future for any translocated populations.	(Lohr *et al.* 2015; Government of Western Australia 2017)
Minimise impact to local biodiversity	Presence of predator-susceptible mammals	Northern quolls are known to eat small mammals, reptiles, and invertebrates (Radford 2012; Dunlop *et al.* 2017) and have the potential to disrupt local	(Legge *et al.* 2018)

		populations of these species. We list any known potential prey species (terrestrial mammals between 35g and 5kg).	
	Presence of nesting turtles	Northern quolls display considerable dietary flexibility (Radford 2012; Dunlop *et al.* 2017) and may opportunistically predate eggs from the nests of sea birds or turtles.	(Fossette *et al.* 2021)
	Important Bird Areas	Birdlife has identified Important Bird Areas are places of greatest significance for the conservation of the world's birds, considered priorities for bird conservation (Dutson *et al.* 2009; Donald *et al.* 2019). Predation of birds or eggs by northern quolls at these sites may pose a disproportionately high impact to regional bird biodiversity.	Birdlife Australia
Minimise probability of cane toads arriving and establishing at site	Probability of cane toad establishment	Cane toads may disperse to some Islands in the Pilbara, which would compromise the persistence of quolls there. We will estimate the probability of cane toads dispersing to and establishing on each island as outlined above.	(Lohr *et al.* 2017b)

5.2.3 Outcomes

The presence of cane toads may have severe consequences for the local biodiversity on Pilbara islands, as may the presence of introduced northern quolls and this research will provide information for conservation managers to help inform decisions. By evaluating the ecological suitability of Pilbara islands to support northern quolls and remain free of cane toads, we will reveal which, if any of the 31 candidate islands could be considered for a translocation of northern quolls to protect them from a cane toad invasion, while minimising any impact to extant island species. While we will not evaluate whether translocation is the most appropriate action here, we will provide a valuable collation of information to aid in timely and informed decision making if translocation is to be pursued.

5.2.4 Status

Data collation and BBN modelling is currently being undertaken with a draft manuscript expected in 2025.

6 Interactions with infrastructure

6.1 Impact of mining on animal movement and landscape connectivity revealed through simulations and scenarios

6.1.1 Background

Landscape-scale disturbances, such as mining, alter habitat structure, introducing new stressors that can severely disrupt animal movement. Understanding how landscape modification impacts animal movement and landscape connectivity is vital for effective conservation in the Anthropocene. Here, we build on Section 5.1 and use movement simulations and 'landscape scenarios' to evaluate how mining influences northern quoll movement. We aim to determine the effects of different configurations of mining on the movement costs, habitat accessibility, and landscape connectivity of this species. We used GPS data collected from a mining landscape in the Pilbara region of Western Australia to assess temporally dynamic habitat selection. This then informed movement simulations across four landscape scenarios: current mining, dispersed mining, aggregated mining, and non-mining. We compared animal movements, energetic costs, and landscape connectivity across all landscape scenarios.

6.1.2 Method

We used movement data (observed and random steps from four male northern quolls tracked at Woodie Woodie mine during part of their breeding season in 2021) and environmental variable maps from Cowan *et al.* (2024a). These data were used to fit an integrated step-selection function (iSSF) (Avgar *et al.* 2016) to inform simulations of northern quoll movements and subsequent energetic costs across four constructed landscape scenarios: (1) the current mining landscape at Woodie Woodie, (2) a non-mining landscape, which represents the likely landscape structure prior to the establishment of Woodie Woodie, (3) a dispersed mining landscape (with fragmented mining disturbance across the landscape), and (4) an aggregated mining landscape (with consolidated mining disturbance in a localised area). Simulations had a memory function which allowed them to more closely reflect northern quoll home ranges, and included temporally-dynamic selection to account for the cyclic return to rocky dens by northern quolls (Forrest *et al.* 2024).

To compare habitat connectivity among landscape scenarios, we constructed a new set of simulations where we omitted the memory process to allow simulations to cover the entire landscape without being restricted to a home range. To locate movement corridors in each landscape scenario, we converted simulations into networks and calculated landscape betweenness (as per Hofmann *et al.* 2023). For specific details, see (Cowan 2024; Chapter 5).

6.1.3 Outcome

Mining created barriers to movement leading to greater distances and larger home ranges required to access preferred rocky habitat. The availability and connectivity of rocky habitats was also lower in mining landscapes as suggested by higher revisitations of the same rocky habitat patches (Figure 6.1-1). As a result, simulated movements in mining landscapes travelled through larger amounts of energetically costly mining habitat.

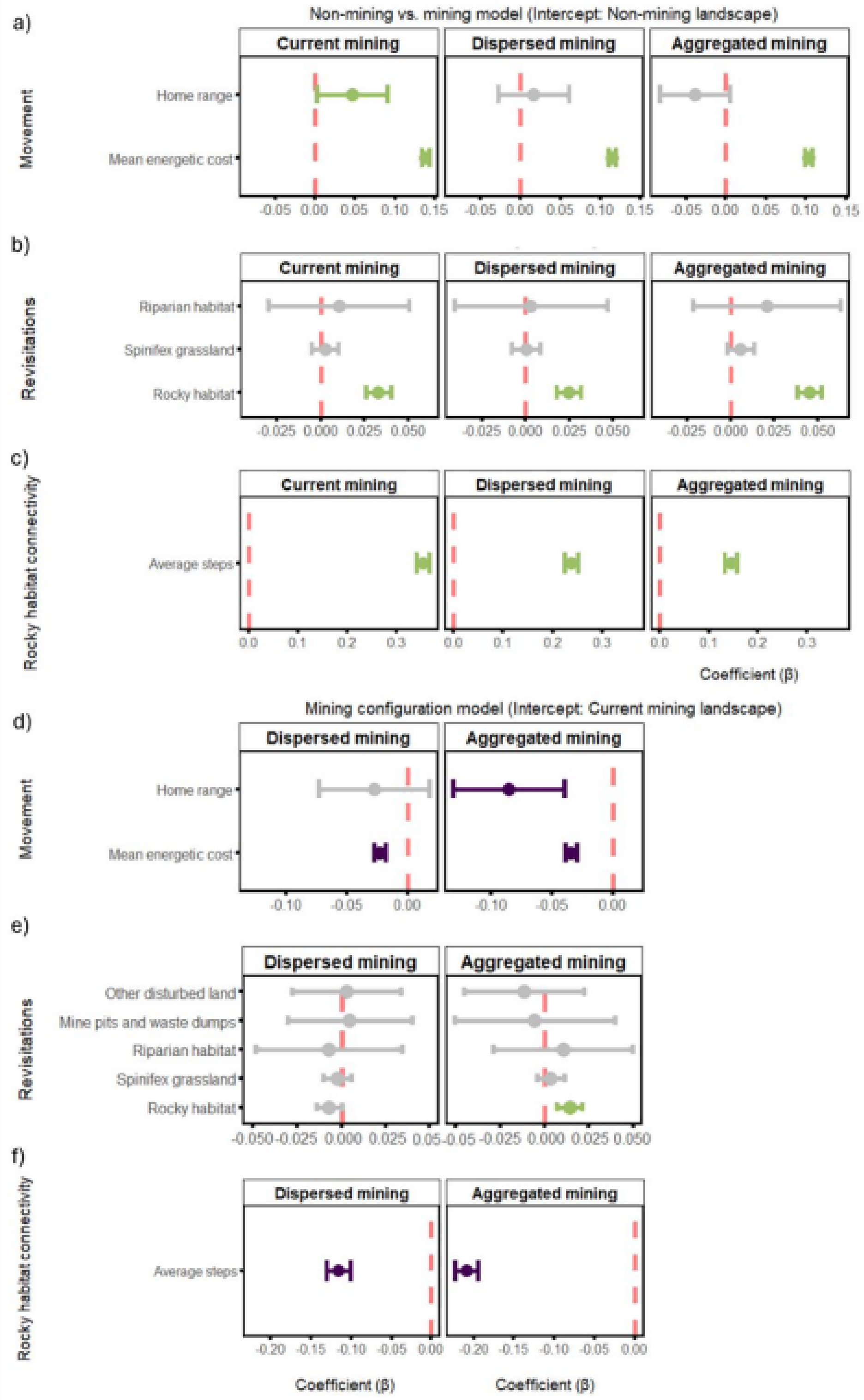


Figure 6.1-1 - Coefficients and 95% CIs of GLMMs comparing movement simulations among landscape scenarios. The non-mining vs. mining model is compared for a) home range and energetic movement costs, b) habitat revisitations, and c) average steps between rocky habitats, with the non-mining landscape as the reference category. The mining configuration model is compared for d) home range and energetic movement costs, e) habitat revisitations, and f) average steps between rocky habitats, with the current mining landscape as the reference category, and the non-mining landscape excluded. Clear relationships are considered when 95% CIs do not overlap zero (red dashed line). Positive relationships are shown in green, and negative relationships are shown in purple.

The configuration of mining influenced simulated movement and habitat connectivity differently, diverting movement corridors in each mining landscape from paths used in the non-mining landscape (Figure 6.1-2). These findings support existing concerns for northern quolls regarding the continued expansion of large-scale mining disturbance in the Pilbara (Moore *et al.* 2022a), and highlight the influence of altered habitat structure on the movement and habitat connectivity of animals in disturbed landscapes.

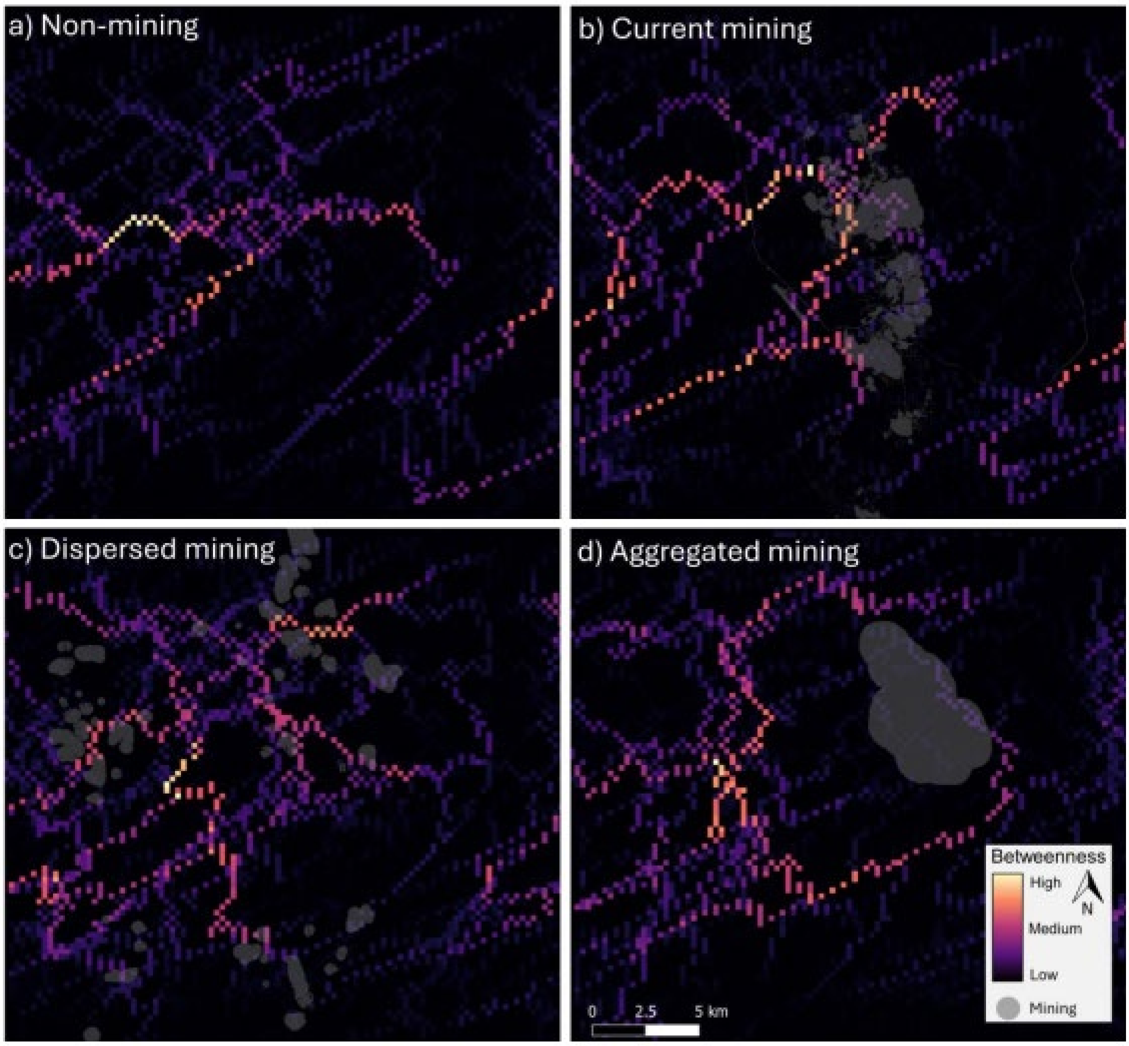


Figure 6.1-2 - Maps of landscape betweenness scores for each cell (257 x 257 m) in the a) non-mining landscape, b) current mining landscape, c) dispersed mining landscape, and d) aggregated mining landscape. A high betweenness score suggests high importance of that area in maintaining landscape connectivity. Transparent grey patches depict mining disturbance.

Our study demonstrates the significant influence of altered habitat structure on northern quoll movement and landscape connectivity, revealing negative ecological impacts associated with mining disturbance. Management strategies for active mines should prioritise the preservation and restoration of pre-disturbance habitat corridors, to enhance connectivity between rocky habitat patches and reduce the need for northern quolls to engage in energetically costly movements. Mining development that minimises sprawled contiguous disturbances which disconnect the landscape could mitigate some effects on northern quoll movement and habitat connectivity. However, dispersed and aggregated disturbances will still negatively affect both landscape connectivity and population persistence in different ways. Incorporating measures of animal movement and landscape connectivity into ecological impact assessments before disturbance is uncommon, but it is likely to lead to more positive biodiversity outcomes, including in mining. Given our small and exclusively male sample size here, future studies including female northern quolls would be useful.

6.1.4 Status

This analysis forms part of Mitchell Cowan's PhD thesis (chapter 5) and is currently under review in *Ecological Applications*.

Mitchell Cowan. (2024). Wildlife in mining landscapes: a case study of the endangered northern quoll (*Dasyurus hallucatus*). PhD Thesis. Charles Sturt University.

7 Interacting threats and future research opportunities

7.1 Effect of fire on northern quoll occurrence in the Pilbara

7.1.1 Background

Fire has been identified as a key threat to northern quolls in the Pilbara (Cramer *et al.* 2016), as well as across their broader range (Moore *et al.* 2021a). While there is some evidence to suggest that fires can have a negative impact on northern quoll populations (Begg 1981; Kerle and Burgman 1984; Oakwood 1997; Griffiths *et al.* 2015; Ondei *et al.* 2021), few studies have examined interactions between fire and northern quolls in the Pilbara — although see Hernandez-Santin *et al.* (2016).

Here, we used a large species presence database in combination with satellite-derived fire history data to assess the influence of fire attributes, including burn extent, frequency, and pyrodiversity, on the likelihood of occurrence of eight mammal species, including northern quolls, in north-west Western Australia.

7.1.2 Method

Northern quoll presence records

Northern quoll presence data was sourced from the Western Australian Department of Biodiversity, Conservation and Attractions (DBCA) dataset. The data set was cleaned to remove erroneous records and records with high uncertainty or missing collection dates. Only one record was retained for each 250m*250m pixel to limit the effect of clustering due to sampling bias. Records collected prior to the year 2011 were also removed, given this precedes the period for which we have access to long term fire data. Pseudoabsence records were also created to address sampling bias.

Environmental data

The environmental data used in this study comprised MODIS vector data available from the North Australia Fire Information service. Four fire attributes were calculated for each species presence record, including pyrodiversity, fire frequency, percent of early successional vegetation, and percent late successional vegetation (Table 7.1-1). All fire attributes were measured relative to the time a species presence records was collected. To ensure that fire metrics were assessed at scales ecologically relevant to each species, we utilised species movement data from the literature to generate “location buffers” of varying radii around each presence record and subsequently clipping the fire data to fit these location buffers. For northern quolls, we used a radius of 977 m, doubled to account for the possibility that the record was not in the centre of the animals’ home range. For further details, see Moore *et al.* (2024c).

Table 7.1-1 – Fire attributes used to examine the impact of fire on northern quolls.

Attribute	Method	Justification
% Recently burnt (< 3 years since last burn)	Calculated as the percent of vegetation within a location buffer that has been burnt within the previous three years.	Recently burnt vegetation was defined as vegetation which had burnt within three years. This is a period in which spinifex grassland cover and complexity is at its lowest in the Pilbara bioregion (Burrows *et al.* 2009).
% Long unburnt (> 10 years since last burn)	Calculated as the percent of vegetation within a location buffer that has not been burnt for at least 10 years.	Long unburnt vegetation was defined as vegetation which had not burnt for at least 10 years, given 10 years post fire is roughly the time at which *Triodia* cover peaks in the Pilbara and Western Deserts (Burrows *et al.* 2009). This definition aligns with the Martu definition *kunarka*, when spinifex becomes senescent (Bliege Bird *et al.* 2012). Late successional vegetation may be favoured by some small mammals given it provides increased protection from predators in the form of cover and complexity when compared to earlier successional stages (Radford *et al.* 2021).
Fire frequency (recent)	Calculated as the median number of times each cell within a location buffer has been burnt within the previous 10 years. Data was truncated to the previous 10 years to standardise fire history data available across records collected in different years.	Fire frequency can impact fauna by altering the availability of food and shelter which they rely on. Studies in northern Australia have demonstrated that increased fire frequency can lead to declines in abundance of small mammal populations (Andersen *et al.* 2005; Griffiths and Brook 2014; von Takach *et al.* 2020).
Pyrodiversity	Calculated using Shannon's diversity index, incorporating the three post-fire successional stages: early, mid, and late. The mid-successional stage is characterized by vegetation that has not burnt for 3 to 10 years.	Pyrodiversity refers to the diversity of fire regimes within a landscape. This diversity can be beneficial for small mammals by providing an array of habitats within areas suited to different needs (shelter, foraging areas).

To measure the effect of fire attributes on mammal occurrence, we fit binomial generalized linear models using the "*lme4*" package (Bates *et al.* 2014) in R. All fire attributes (extent recently burnt, extent long unburnt, pyrodiversity, fire frequency) were included in a global model for each species. These models were then compared using the "dredge" function in the "MuMIn" package (Bartoń 2013), fitting 16 models for each species. The most parsimonious model was selected based on AICc. This selected model was subsequently refit, and the contributions of the variables were assessed based on model estimates. Variables with $p < 0.05$ were considered to have a significant influence. Response curves were generated for fire attributes with significant effects using the "predict" function. Model performance was assessed using conditional R^2 values, calculated using the "r.squaredGLMM" function. Model predictions were calculated using the "predict" function.

7.1.3 Outcome

We found fire mosaic properties were strongly correlated with the occurrence of eight Pilbara mammal species. Northern quoll occurrence was positively associated with pyrodiversity, and negatively associated with increasing frequency of burn (Figure 7.1-1). Overall, our results indicate that a strategic fire management approach aimed at preventing large-scale wildfires is likely the most effective way to enhance habitat suitability for the eight Pilbara mammal species targeted in this study.

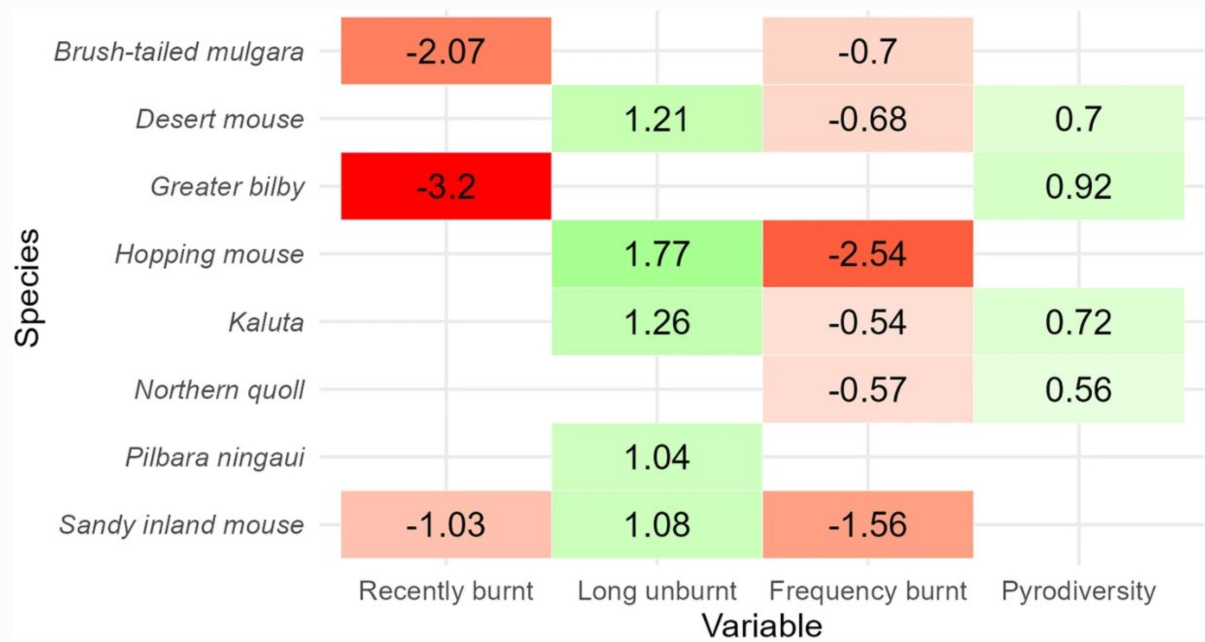


Figure 7.1-1 – Generalized linear model (GLM) estimates for significant ($p < 0.05$) fire attribute effects on Pilbara mammals. The colour intensity indicates the strength of the effect, with green representing positive effects and red representing negative effects. Figure adapted from Moore et al (2024b).

7.1.4 Status

Published in *Fire Ecology:*

Harry Moore, Lesley Gibson & Dale Nimmo (2024). The influence of fire mosaics on mammal occurrence in north-western Australia. *Fire Ecology* **20**, 84. https://doi.org/10.1186/s42408-024-00317-4

7.2 Movement patterns of two northern quolls after a large wildfire

7.2.1 Background

Fire plays a vital role in shaping ecosystems globally (Kelly *et al.* 2020). While animals often survive individual fire events (Jolly *et al.* 2022), post-fire population declines are common due to reductions in resources such as vegetative cover, which provides food resources and protection from predators (Doherty *et al.* 2022). Survival after fire is therefore dependent on animals navigating transformed landscapes (Nimmo *et al.* 2019). Given that fire regimes around the world are changing, understanding how fire affects animal movement is an urgent research priority (Nimmo *et al.* 2019).

7.2.2 Method

As part of a broader study by Cowan et al. (2024a), a 1-year-old male and 2-year-old female northern quoll were monitored for 15 and 14 days, respectively, using LiteTrack 20 RF GPS collars (Lotek, Havelock North) in 2022 at Ripon Hills, a rugged landscape on Nyamal country, in the Pilbara. The landscape is comprised of rugged rocky outcrops and cliffs scattered within spinifex grasslands, and vegetated riparian zones along creeks and gorges (Figure 4.2-1). This area experienced a large (~5000 ha), hot summer wildfire 7 months before the study, which burned the vegetation surrounding rocky outcrops, as well as vegetation on top of rocky outcrops in some cases (Figure 4.2-1). This resulted in simpler vegetation structure in burnt areas compared to unburnt areas (Figure 4.2-1). GPS collars contained accelerometers and recorded GPS fixes and mean vectorial dynamic body acceleration (VeDBA; a proxy for energy expenditure; Qasem *et al.* 2012) every 30 min from 6 PM to 6 AM, the northern quolls' active phase. Data were processed following Cowan *et al.* (2024a), and the fire scar was mapped using NDVI data from Sentinel 2 imagery from August 2022 (Figure 4.2-1). Rocky areas were digitised from satellite imagery and included exposed scarps or arrangements of rock that likely contain crevices.

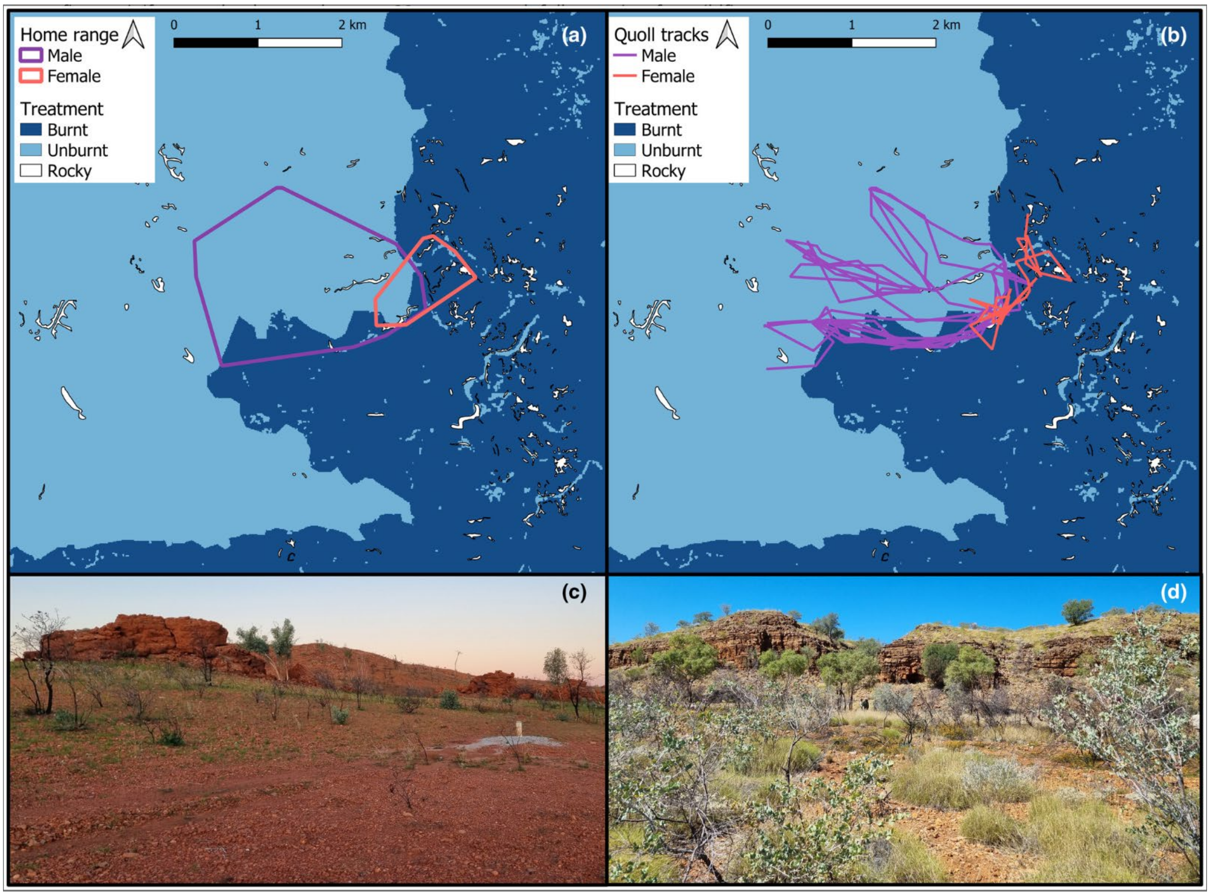


Figure 7.2-1 Maps showing burnt, unburnt and rocky areas with northern quoll (a) home ranges and (b) observed movement steps overlaid. Photographs show examples of (c) burnt areas and (d) unburnt areas, with rocky areas present in the background of each. Figure from Cowan *et al.* (2024b).

To investigate northern quoll movement across burnt, unburnt, and rocky areas, we determined home ranges by calculating 95% minimum convex polygons (MCPs) from GPS points for each individual (Hernandez-Santin *et al.* 2020), calculated the proportion of burnt, unburnt and rocky areas within each home range and converted GPS points to 'movement steps' (connecting subsequent GPS fixes). We standardised them for time and applied an integrated step selection function (iSSF) as per Cowan *et al.* (2024a), comparing northern quoll movement steps with five random potential steps—modelled using Gamma-distributed step lengths and von Mises-distributed turning angles (Avgar *et al.* 2016). Endpoints were categorized into burnt/unburnt and rocky/non-rocky. We fit separate iSSF models for the male and female northern quoll, with the step type as the response variable, and the endpoint type, the natural logarithm of step length, and the cosine of the turning angle included as categorical predictors. Step ID was used as a stratifying term to match observed and random steps. Models were fitted in the 'amt' package in R (Signer *et al.* 2019).

7.2.3 Outcome

Recently burnt areas covered 19.36% of the male northern quoll's home range and 63.09% of the female's home range, while rocky areas comprised 1.25% and 6.05%, respectively (Figure 4.2-1). The movement track of the male northern quoll suggested avoidance of the burnt area (Figure 4.2-1), and this was supported by the iSSF. According to the iSSF, the male neither preferred nor avoided rocky areas (Figure 4.2-2). The female northern quoll did not prefer or avoid the burnt area, but favoured rocky areas over non-rocky areas (Figure 4.2-2).

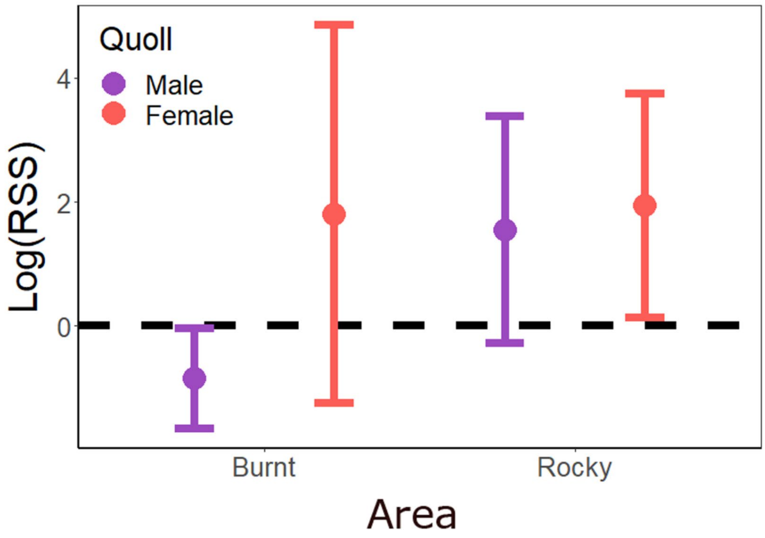


Figure 7.2-2 - The log relative selection strength (RSS) for burnt and rocky areas. Points reflect the RSS and bars reflect 95% CIs. The dashed line represents the intercept RSS for each model (unburnt/non-rocky areas). A clear difference between treatments is observed if CIs do not cross the intercept. Figure from Cowan *et al.* (2024b).

Here, we describe the movement of a male and female northern quoll in a post-fire landscape, exploring the potential influence of fire on their movement and energy use, highlighting intraspecific differences in the response to fire between sexes. The female's movement underscores the crucial role of rocky refuges in mitigating disturbance effects. Further research into northern quoll responses to fire, including tracking the movements of a much larger number of animals, is required to more robustly inform ecological fire management (Gibson *et al.* 2023).

7.2.4 Status

Published in *Austral Ecology*

Mitchell Cowan, Nyamal Rangers, Judy Dunlop, Harry Moore & Dale Nimmo (2024) Movement patterns of two northern quolls after a large wildfire. *Austral Ecology*, 49, e13569. Available from: https://doi.org/10.1111/aec.13569

7.3 Effect of fire on northern quoll movement ecology in the Pilbara

7.3.1 Background

Over the last ten years in Western Australia, the PNQRP has bridged many gaps in our understanding of the ecology and conservation needs of the northern quoll. A critical analysis of this program (Gibson *et al.*, 2023), along with another review on northern quoll conservation (Moore *et al.* 2021a), highlighted a lack of knowledge regarding how fire affects northern quolls and their predators as a remaining knowledge gap hindering northern quoll conservation. While some studies have explored quoll occurrence in relation to past fires, there has been no systematic, focused, on-ground assessment of how quolls are impacted by fire within the Pilbara. A new PhD project, a collaboration between DBCA and Charles Sturt University, aims to address this knowledge gap.

While fires might directly cause some mortality among northern quolls, indirect effects likely include changes in resource distribution, leading to altered movement patterns and energy expenditure. A key area of research is unravelling how fire interacts with other threats, especially predation by feral cats (*Felis catus*). It is hypothesised that fire events could heighten the risk of northern quolls to feral cat predation by reducing habitat cover. Better understanding the dynamics between quolls, fire, and predators is crucial, especially considering Western Australia's new Bushfire Risk Management Framework, which aims for precise fire management goals regarding the extent of burned areas and fire frequency.

Specifically, the PhD project aims to explore expand on section 4.2 to address four questions:

1. How does time since fire affect broad and fine scale movement of northern quolls in the Pilbara?
2. How does time since fire affect movement attributes and energy expenditure of northern quolls in the Pilbara?
3. How does time since fire influence spatiotemporal patterns of feral cat and northern quoll activity in the Pilbara?
4. How does the spatial configuration and location of fire impact simulated population connectivity of northern quolls in the Pilbara?

7.3.2 Method

This study will be centred within Millstream Chichester National Park, where a mosaic of fire histories is being created through the use of controlled, small-scale burns. To explore northern quoll movement ecology, quolls will be fitted with data-logging collars capturing GPS and accelerometer information. In complement to this collar data, large camera trap arrays (nine clusters of 3x3 grids, grid cameras spaced 200m apart, clusters spaced >2km apart) will be deployed annually to capture the spatial and temporal movement, and landscape use of northern quolls and feral cats. This data will be analysed to reveal how quoll movements are correlated with fire history and other environmental covariates. Ultimately, these findings will populate models that can simulate quoll movement (Figure 4.3-1) in relation to fire history, which can then contribute to scenario planning for fire management.

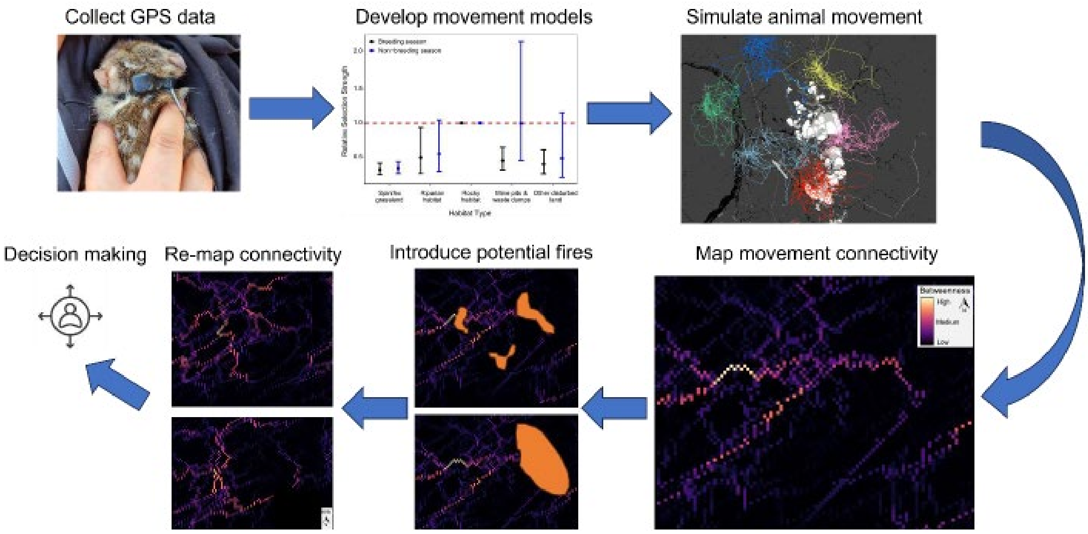


Figure 7.3-1 – Core steps for integrating northern quoll movement into fire management decisions. GPS data is used to develop step selection functions that are the basis for simulated quoll movements. These simulations can be run many times to generate a connectivity surface across a landscape. Yellow areas indicate regions of concentrated northern quoll movement, and darker areas indicate less movement. Landscapes can then be manipulated to see how different approaches to land management—in this instance fire management—would affect northern quoll movement.

7.3.3 Outcomes

In 2024, a PhD candidate (Chloe McAuley, Charles Sturt University) was appointed to this project. Approximately 100 camera traps have been deployed in Millstream Chichester National Park to begin exploring the utilisation of burn ages by northern quolls and feral cats (Figure 7.3-2).

7.3.4 Status

Collaring is anticipated to commence in 2025, and this project is planned to be completed by 2028.

Figure 7.3-2. PNQRP staff and CSU PhD candidate Chloe McAuley scope out sites for the deployment of camera trap arrays in Millstream Chichester National Park.

7.4 Review of progress and future research priorities

7.4.1 Background

DBCA facilitated workshops in 2013 and 2016 to identify research priorities for northern quolls occurring within the Pilbara bioregion. Workshops were attended by scientists, consultants, mining representatives, and government agencies. Outputs from these workshops are were reported and refined in a subsequent publications (Cramer *et al.* 2016; Cramer and Dunlop 2018), which guides the current Pilbara Northern Quoll Research Program. In 2022, we reviewed progress against the identified research priorities and identified future directions that either add value to research already undertaken or are based on the original priorities that have not been addressed (see Gibson *et al*. 2023).

7.4.2 Outcomes

The review demonstrated that research conducted as part of the PNQRP has significantly expanded our ecological understanding of the Pilbara northern quoll. Survey and monitoring techniques have evolved with advancements in technology and analysis (Moore *et al.* 2020). Camera traps, for example, have improved the ability to measure differences in occupancy (Moore *et al.* 2023) and abundance of northern quolls in the Pilbara (Moore *et al.* 2022). Combining this data with GPS-telemetry (Cowan *et al.* 2022) , dietary information (Dunlop *et al.* 2017), genetic and environmental data (Chan *et al.* 2020; Shaw *et al.* 2023), allows for assessments of habitat use at various scales, including the size, shape, and configuration of suitable habitat (DCCEEW 2021; Moore *et al.* 2023). Studies have shown that suitable contemporary habitat for Pilbara northern quolls includes topographically complex, contiguous, and well-vegetated rocky areas that are important for denning and riparian areas as important dispersal corridors.

Monitoring data from various sites across the Pilbara reveals that many subpopulations occur at low density, although the lack of genetic structure among them suggests widespread dispersal (Dunlop *et al.* 2019; Shaw *et al.* 2023). This suggests that northern quolls can move across suboptimal habitat such as 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 (Moro *et al.* 2019), the importance of protecting dispersing young males is apparent. The research also highlights the need to focus on protecting suitable habitat, and to consider the potential impacts of mining and cane toads, as well as other cumulative impacts on the population (Moore *et al.* 2021a).

Table 7.4-1. Proposed future research directions against each priority (Adapted from Gibson *et al.* 2023)

Research priority	Future directions
Assessing and refining survey and monitoring protocols	• Update existing survey and monitoring protocols to include recommendations regarding a program based on camera traps, individual identification and mark-resight or occupancy analytical approaches that are fit-for-purpose. • Provide a guiding framework for regional monitoring of northern quolls that can be used by multiple stakeholders to better understand long-term population trends. • Investigate emerging technologies (e.g., artificial intelligence cameras) to improve effectiveness and efficiency of monitoring approaches.
Improving our understanding of fine-scale habitat use to identify areas of critical habitat	• Incorporate spatial information into new population viability analyses (PVAs) to further improve accuracy. • Identify the characteristics of habitats that reduce predation risk for northern quolls during dispersal events.
Improving our understanding of population dynamics and structure	• Refine PVAs using improved information, such as survival rates of juveniles. • Identify source and sink populations of northern quolls in the Pilbara using fine-scale demographic information.
Assessing the impacts of introduced predators	• Investigate changes in habitat use by northern quolls with sustained introduced predator management. • Further investigate the efficacy of Felixer™ feral cat grooming traps in reducing the impact of feral cats on northern quolls. • Further investigate the strategic management of feral cats using a combination of approaches (aerial and targeted ground baiting using *Eradicat*®, trapping) and the subsequent response of northern quolls.
Understanding the spread and impacts of cane toads	• Investigation of the uptake and potential longer-term aversion of cane toad sausages by northern quolls and non-target species in the Pilbara. • Identification of locations where northern quolls and cane toads are most likely to intersect to inform surveillance and targeted response (i.e., application of cane toad taste aversion baits).
Understanding interactions with infrastructure and built environments	• 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). • Investigate the use of artificial refuges by northern quolls in relation to breeding, survival, and recruitment and quantify risks of predation. • Undertake field trials to assess the effectiveness of feral predator control and habitat restoration on northern quoll use of artificial refuges. • Determine how disturbances associated with mining (e.g., artificial light, altered resource and predator abundances) influence the movement and behaviour of northern quolls. • Better understand the cumulative impact of habitat loss due to mining in relation to northern quoll distribution and habitat connectivity.
Other research priorities (threat interactions)	• Understand the extent to which fire and habitat degradation influences predation pressure on northern quolls. • Determine how interactions between threats influence habitat selection by northern quolls to inform threat mitigation. • Investigate the response of northern quoll occupancy and abundance to the management of interacting threats.

7.4.3 Status

Published in *Australian Mammalogy:*

Lesley Gibson, Harry Moore, Mitchell Cowan, Michael Craig, Dale Nimmo, Judy Dunlop. (2023) A review of progress of a research program for the endangered northern quoll (*Dasyurus hallucatus*) in the multi-use landscapes of the Pilbara. *Australian Mammalogy* **45**, 251-263.

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