Biodiversity and Conservation Science

Summary of knowledge for six faunal species that are Matters of National Environmental Significance in the Pilbara, Western Australia

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Cover image (left to right): Greater bilby (*Macrotis lagotis*) © John Lawson; Northern quoll (*Dasyurus hallucatus*) © Judy Dunlop; Pilbara leaf-nosed bat (*Rhinonicteris aurantia*) © Stewart Ford; Ghost bats (*Macroderma gigas*) © Carly Bishop; Pilbara olive python (*Liasis olivaceus barroni*) © David Pearson; Night parrot (*Pezoporus occidentalis*) © Steve Murphy.

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Background

To build on existing fauna research and on-ground conservation management in the Pilbara, Western Australia, the Department of Water and Environmental Regulation (DWER) propose to develop a fauna investment plan for the Pilbara Environmental Offsets Fund (PEOF) to guide the delivery of offset investment. The Department of Biodiversity, Conservation and Attractions (DBCA) was contracted by DWER to undertake a review of existing information on six Pilbara fauna species that are classified as Matters of National Environmental Significance (MNES) by the Australian Government (DoE, 2013): the greater bilby (*Macrotis lagotis*), northern quoll (*Dasyurus hallucatus*), Pilbara leaf-nosed bat (*Rhinonicteris aurantia* Pilbara form), ghost bat (*Macroderma gigas*), Pilbara olive python (*Liasis olivaceus barroni*), and the night parrot (*Pezoporus occidentalis*).

This information will provide DWER with a comprehensive understanding of the work conducted to date and provide a clear picture on the conservation priorities for MNES fauna in the Pilbara, so that duplication can be avoided, investment leveraged and conservation outcomes for these species maximised.

Focusing on Pilbara populations, this report:

- Summarises current knowledge relating to each species (i.e., general overview, distribution, habitat requirements, threatening processes, conservation status, population status, and genetic structure)
- Identifies future research directions based on gaps in knowledge, and
- Identifies potential management actions based on the outcomes of research already undertaken.

A list of publications and grey literature associated with each species (from at least 2012) is provided separately.

1 Greater bilby (*Macrotis lagotis*; Reid, 1837)

Order Peramelemorphia; Family Thylacomyidae

1.1 Summary of current knowledge

1.1.1 General overview

The greater bilby (*Macrotis lagotis*; henceforth referred to as the bilby), is a medium-sized, nocturnal burrowing marsupial and the sole remaining member of the Thylacomyidae family (Lynch, 2008). This iconic and culturally significant native Australian mammal (Abbott, 2001; DCCEEW, 2023f) is distinguished by its large rabbit-like ears, silky blue-grey fur, and long black tail with a furred white tip (Johnson, 2008). Weighing between 800-2500 g and measuring up to 550 mm in length (head and body), bilbies have strong forelimbs for digging and construct complex burrow systems for shelter (Johnson, 2008). The bilby is considered an ecosystem engineer (Fleming *et al*., 2014), with their foraging enhancing soil health and plant productivity (Chapman, 2013) and their (used/disused) burrows providing important refuge sites for other fauna (e.g., Hofstede and Dziminski, 2017).

Capable of breeding throughout the year, bilbies typically raise between 1-2 young, which remain attached to the teat for approximately 80 days prior to deposition in a burrow. Young stay in the burrow for around two weeks before weaning (Johnson, 2008). Bilbies are cryptic and generally solitary (Bradley *et al*., 2015), with reported low site fidelity (Southgate *et al*., 2007). In the wild, bilbies are relatively short-lived, with a generation length of approximately four years (Woinarski *et al*., 2014). Bilbies can be highly mobile with variable home ranges, particularly males (Bradley *et al*., 2015).

1.1.2 Distribution

Prior to European settlement, the bilby formerly occurred over approximately 70% of the Australian mainland (Southgate, 1990), occupying several habitat types within Australia's arid and semi-arid zones (Woinarski *et al*., 2014). Like many other small to medium-sized terrestrial species, bilby populations suffered severe declines due to the direct or combined impacts of introduced non-native animals (i.e., predation and competition), landscape modification and altered fire regimes following European colonisation (Bradley *et al*., 2015; Woinarski *et al*., 2015). The bilby is now patchily distributed within less than approximately 20% of its former range (Southgate, 1990; Bradley *et al*., 2015), with the species' distribution believed to be contracting northwards in response to threatening processes (DCCEEW, 2023f). Remnant, naturally occurring populations now only persist within central and northern Western Australia (WA), the Northern Territory (NT), and an isolated area in southwestern Queensland (Qld) (Bradley *et al*., 2015). Within WA, wild bilby populations are restricted to the Pilbara, Kimberley, and central desert and rangelands regions (Page, 2015; Lohr *et al*., 2021).

Within the Pilbara bioregion, which supports the north-western extent of the species range, the bilby is largely distributed across the eastern half (48%), with recent and historical records indicating the western boundary of the species' range lies roughly 50 km west of Port Headland and continues south-east of Newman (Dziminski *et al*., 2020b) (Figure 1). Beyond the Pilbara, the species' range extends east and south-east into the Great Sandy, Little Sandy and Gibson Deserts, south into the Gascoyne, and northwards into the south-western Kimberley region (Dziminski *et al*., 2020b) (Figure 1).

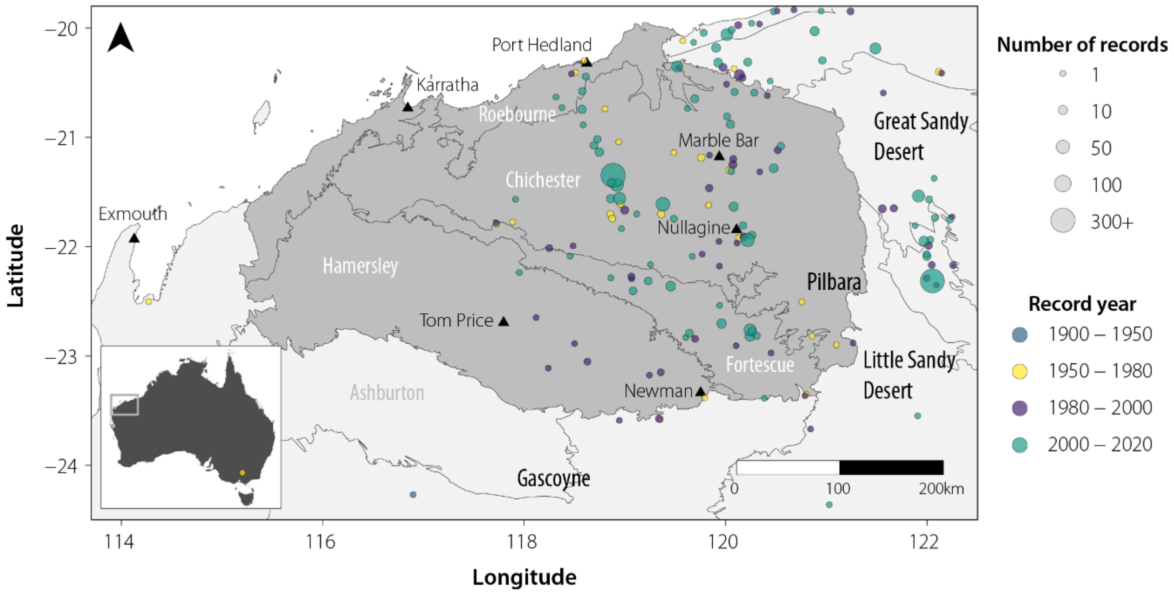

Figure 1 *Map of the Pilbara region with the locations of greater bilby (Macrotis lagotis) records from the Western Australian Department of Biodiversity, Conservation and Attractions' NatureMap database from 1990-2021 (https://naturemap.dbca.wa.gov.au, downloaded July 2021). Point size represents the number of NatureMap records reported within a 20 km radius for each collection year period (specified by colour). The darker grey represents the Pilbara IBRA region, with map borders showing IBRA subregions.*

1.1.3 Habitat requirements

In the north of WA, bilbies inhabit a wide range of substrate and vegetation types, including residual, fluvial and sand plain landforms with typically low shrub cover of *Acacia* spp. with hummock (*Triodia* spp.) and tussock grasses (Cramer *et al*., 2017). The presence of soil substrate suitable for burrow construction is critical (Dziminski and Carpenter, 2016). Using presence data, DBCA commenced habitat modelling in 2017 using physical habitat characteristics (i.e., topography, geology and soil properties). Preliminary results (Dziminski and Carpenter, 2017) identified elevation, and soil type and depth as key predictor variables contributing to habitat suitability for the bilby.

Using publicly available species occurrence data, Cadenhead *et al*. (2015) mapped the habitat suitability and distribution of four Pilbara MNES species using MaxEnt (Phillips *et al*., 2006). For the bilby (n = 46), '*mean diurnal temperature range, seasonal* *temperature variation, precipitation of the driest period, amounts of clay in the soil and the mean temperature of the driest quarter*' were the most important parameters predicting the distribution of bilbies in the Pilbara. Predictive species habitat modelling has also been conducted by environmental consults and mining proponents for environmental impact assessment (EIA) processes (e.g., Eco Logical, 2015; for the BHP iron ore mining in the Pilbara strategic assessment); bilbies were '*strongly associated with hotter regions of the eastern part of the Pilbara bioregion, with lower, flatter and sandier areas identified as higher potential habitat*' (BHP, 2016).

Bilbies are omnivores with an opportunistic dietary strategy and exploit a wide range of food types including invertebrates and their eggs/larvae, and seeds, bulbs, roots, fungi, and fruit (Southgate, 1990; Gibson, 2001; Johnson, 2008). In the Pilbara, *Acacia* stands provide a major food resource, cossid moth larvae (grubs), from their root systems (Southgate *et al*., 2019). *Acacia bivenosa*, *A. colei*, *A. dictyophleba*, *A. melleodora*, *A. stellaticeps* and *A. trachycarpa* [including dwarf variant described in Maslin *et al*. (2010)] are all known to host root-dwelling (Cossidae) insect larvae in the Pilbara (Southgate *et al*., 2019). Associations with other plant species in the Pilbara (e.g., *Senna notabilis*) were also identified (Southgate *et al*., 2019).

1.1.4 Threatening processes

Key threats to the bilby in the Pilbara include predation by the introduced red fox (*Vulpes vulpes*) and feral cat (*Felis catus*); competition with introduced herbivores [especially grazing livestock and the European rabbit (*Oryctolagus cuniculus*)]; habitat loss, fragmentation and degradation (secondary to grazing and other human-mediated activities such as land clearing, mining, infrastructure development and large scale pivot irrigation agriculture); inappropriate fire regimes; and climate change (Bradley *et al*., 2015; Cramer *et al*., 2017; DCCEEW, 2023f). Outside of conservation reserves, mineral exploration and pastoral leases impact the vast majority of bilby habitat within the Pilbara, and formal conservation protection within the region is lacking (Gardner, 2013).

Weeds such as buffel grass (*Cenchrus ciliaris*; Burrows, 2019) are considered a potential indirect threat in the Pilbara due to their influence on fire patterns and competition with native plant species (Bradley *et al*., 2015; DPaW, 2017); though bilbies have been observed in areas invaded by buffel grass (M. Dziminski pers. obs.). Mortality from vehicle and/or train collisions, and the emission of artificial noise and light may also pose a threat (Gardner, 2013; BHP, 2016). Numerous road mortalities have been reported over the past decade, and the medium to long term impacts on local bilby populations are unknown (DCCEEW, 2023f). The small and fragmented nature of bilby subpopulations may reduce population resilience and genetic fitness enhancing susceptibility to local extinction (DCCEEW, 2023f). Importantly, there are significant and complex interactions between threats (e.g., introduced predators, grazing pressure and fire; McGregor *et al*., 2014), which require further evaluation (DCCEEW, 2023f).

1.1.5 Conservation status

The greater bilby is currently classified as ‘Vulnerable’ under the WA *Biodiversity Conservation Act 2016* (Government of Western Australia, 2016), the Commonwealth *Environment Protection and Biodiversity Conservation (EPBC) Act 1999* (DCCEEW, 2023d), and on the International Union for Conservation of Nature (IUCN) Red List of Threatened Species (Burbidge and Woinarski, 2016). The bilby was also selected as one of the 21 priority mammal species in the Threatened Species Action Plan 2022-2032, although the Pilbara was not listed as one of the 20 priority places targeted for threatened species management (DCCEEW, 2022). Under the *EPBC Act*, the presence of bilbies and bilby habitat is a key environmental factor in mining and infrastructure project evaluations in northern WA (Cramer *et al*., 2017).

1.1.6 Population status

Recent assessment by the IUCN (Burbidge and Woinarski, 2016) estimates that the global bilby population consists of fewer than 10,000 mature individuals, however uncertainty is relatively high (NESP TSRH, 2018). Some natural subpopulations are considered to be in decline (Woinarski *et al*., 2014). During recent bilby population monitoring in the Pilbara, the Pardoo and McPhee Creek populations became locally extinct after very large wildfires (Dziminski *et al*., 2020a). Population monitoring in the Pilbara, Kimberley and central desert regions indicates that wild bilby populations are small, comprising roughly 2-15 individuals (DBCA, 2018; Dziminski *et al*., 2020a; DBCA, 2021b); wild populations in the Pilbara are isolated and distinct (Dziminski *et al*., 2020a).

There are currently no bilby populations on islands or mainland fenced exclosures capable of excluding cats and foxes (safe havens) in the Pilbara (Legge *et al*., 2018). The bilby has benefited from management programs elsewhere in WA, with a successful reintroduction at Matuwa Kurrara Kurrara National Park for example, under a regime of intensive large-scale introduced predator management (NESP TRSH, 2018; Lohr *et al*., 2021). Bilby populations also occur in fenced safe havens outside of the Pilbara region in WA (e.g., Australian Wildlife Conservancy’s Mount Gibson Wildlife Sanctuary; NESP TSRH, 2018).

1.1.7 Genetic structure

Until recently, knowledge regarding the genetic structure within and between bilby populations was limited to a handful of studies (Southgate and Adams, 1994; Moritz *et al*., 1997; Smith *et al*., 2009). It is now accepted that the Qld, NT and WA sub-populations are genetically similar (Smith *et al*., 2009), and should be managed as a single meta-population (Bradley *et al*., 2015; DCCEEW, 2023f). A meta-population management plan, which acknowledges one national genetic management unit is currently being drafted (DCCEEW, 2023f).

Genome-wide diversity across the national fenced bilby meta-population was recently characterised (Brandies, 2021; C. Hogg pers. comm.). DArT sequencing data obtained from Brandies (2021) was used as the basis to develop an individual-based single nucleotide polymorphism (SNP) array for repeatable genotyping of bilby scats on the MassArray automated SNP genotyping platform (R. Sun pers. comm.). This methodology is now being implemented in monitoring projects in WA (e.g., DBCA, 2023; Moore *et al*., 2023c) and the NT (H. Geyle pers. comm.) as a replacement of the microsatellite-based approach developed by Dziminski *et al*. (2020a). DBCA are currently using SNP genotypes to identify individuals, their sex and kinship patterns. Individual genetic ‘capture’ records are entered into a georeferenced database to examine individual movement patterns through space and time. Associated kinship estimates may be used to infer dispersal of individuals and their descendants. As SNP genotypes accumulate from projects in the Pilbara and elsewhere in WA and the NT, broader analyses of the genetic relationships amongst regional populations can be undertaken (K. Ottewell pers. comm.).

Recent analysis of scat and tissue samples from the Pilbara (Brandies, 2021) showed that the Pilbara bilby population exhibited low levels of genetic diversity relative to the managed (safe haven) populations (SNP H_E = 0.16) and high levels of inbreeding (F_{IS} = 0.205), though relatedness was low (0.19). These results likely reflect the reduced range, low density and isolated nature of bilby populations within the Pilbara (Dziminski *et al*., 2020a; 2020b), although further comparison with other wild populations would place the Pilbara population in appropriate context. A similar trend has been observed for other Pilbara MNES species (e.g., the northern quoll and Pilbara olive python; see below).

1.2 Identification of research priorities

Until recently, knowledge regarding the status and ecology of bilbies in the northwest of WA was lacking, with studies limited to general and targeted survey work to establish bilby presence (Cramer *et al*., 2017). With intensifying pressure from key threats in the Pilbara, in particular the rapid growth of the mining industry over the past two decades (DPaW, 2017), the then Department of Parks and Wildlife (now DBCA) hosted a series of workshops in 2013 for several Pilbara MNES species (including the bilby), to review existing knowledge and identify key research priorities to inform conservation management, through a facilitated process involving scientists, environmental consultants, mining proponents and State and Federal government agencies.

Focusing on the bilby, five key areas or ‘themes’ for future research effort were identified and ranked according to priority (Cramer *et al*., 2017). For each theme, research priorities and key questions were defined (see Cramer *et al*., 2017 for key questions associated with each priority). Research priorities for the bilby aimed to:

1. Refine survey methods.
2. Improve understanding of habitat use.
3. Improve understanding of the genetic structure of bilby meta-populations.

4. Improve understanding of the threats posed by introduced predators and herbivores.
5. Improve understanding of how fire regimes affect bilby conservation.

In partnership with universities and other stakeholders, including consultancies, CSIRO and traditional owners, DBCA (i.e., the Biodiversity and Conservation Science - Bilby Research Program) has been conducting bilby research focusing on the five key research areas identified above. Progress against each of the research priorities between 2013 and 2023 was recently reviewed (Northover *et al*., 2023). Options to guide future research and the ongoing conservation management of the bilby in the Pilbara are summarised below.

1.3 Future research directions and management actions

1.3.1 Future research directions

To improve knowledge and enhance the conservation management of the bilby in the Pilbara, we propose a revised set of research directions for the bilby (Table 1) based on a review of existing knowledge and progress made-to-date (Northover *et al*., 2023).

***Table 1** Future research directions for the bilby (Macrotis lagotis) in the Pilbara, ranked high, medium or low (modified from Northover et al., 2023).*

Priority	Topic	Research directions
High	Survey and monitoring – baseline occupancy survey of the Pilbara	• Conduct a large-scale survey to compare bilby occupancy with other regions where this approach has been undertaken (e.g., Fitzroy River catchment) and establish a baseline to compare occupancy in the future. • Selection of sites should include areas where there is a high level of uncertainty of bilby presence (e.g., zone B in Figure 1, Dziminski *et al*., 2020b). • **Outcome**: Estimates of occupancy in the Pilbara will help to inform conservation planning including environmental impact assessments to better protect bilby populations.
High	Survey and monitoring – establishment of long-term monitoring sites	• Based on the occupancy survey above, and previously monitored populations, establish long-term monitoring at selected populations, and resurvey at regular intervals, to better understand population trends and changes in distribution over time. • Concurrent monitoring of introduced herbivores and predators, and habitat condition, would also enable the identification of potential factors influencing changes in bilby abundance and distribution. • **Outcome**: Improved understanding of long-term population trends of the bilby in the Pilbara will help to identify changes in conservation status, the potential cumulative effects of developments, and effectiveness of threat mitigation.

Priority	Topic	Research directions
High	Habitat requirements – undertake habitat suitability modelling to identify important habitat	• Using both historical information and data collected from the occupancy survey above, produce a habitat suitability model to identify important bilby habitat. • Combined with genetic data, population connectivity (gene flow) and genetic diversity hotspots across the Pilbara could also be examined (e.g., Shaw *et al*., 2023). • **Outcome**: Identification of areas important for targeted conservation management to support bilbies in the Pilbara.
High	Habitat requirements – association of key food resources and fire	• Identify the association of root-dwelling invertebrate larvae favoured by bilbies with their host *Acacia* (or other) spp. and the relationship between these plant species and fire (e.g., re-seeders/re-sprouters), including interactions with other flammable vegetation (e.g., *Spinifex,* buffel grass). • Include other attributes such as rainfall. • **Outcome**: Fire management strategies that promote food resources for bilbies and maintain/promote suitable habitat.
High	Threat mitigation – threat interactions and their management	• Better understand how multiple interacting threats influence bilby populations (e.g., introduced predators, grazing pressure and fire) by using established survey and monitoring protocols and a network of paired managed and unmanaged bilby populations. • **Outcome**: Effective integrated threat management to better protect bilbies.
High	Habitat requirements – influence of spatial and temporal fire attributes on bilby habitat	• Using existing information on the distribution of the bilby across the Pilbara, combined with satellite-derived spatially explicit fire data, investigate the influence of multi-scale fire attributes on bilby presence. • This could be further refined following the baseline occupancy survey that would also include data on introduced predator and herbivore occupancy. • **Outcome**: Fire management strategies that promote/protect bilby habitat.
Medium	Threat mitigation – resilience of bilbies to feral cat density/activity thresholds	• Interrogate the survey and monitoring data to determine the density threshold of feral cats below which bilbies can persist to inform targeted feral cat management. • **Outcome**: Identification of a feral cat management strategy that facilitates the persistence of sustainable bilby populations.
Medium	Threat mitigation – cumulative impacts of mining	• Better understand the cumulative impacts of mining on bilby populations and habitat connectivity. • Identify potential barriers to gene flow such as railway lines and roads. • **Outcome**: Improved understanding of the influence of mining disturbance and strategies to mitigate these.

Priority	Topic	Research directions
Medium	Population dynamics – understanding population shifts	• Develop and test a long-term satellite tag and attachment system to enable long-term tracking (6+ months) of individual bilbies, to better understand what triggers populations to shift location across the landscape. • Validate the use of scat DNA to track individuals/descendants as a complementary approach. • **Outcome**: Management strategies that enhance population connectivity.
Medium	Population structure – understand genetic diversity and gene flow in the Pilbara relative to other wild populations	• Continue to refine genomic sequencing techniques based on scat DNA (e.g., DArTcap, Feutry *et al*., 2020; Hohwieler *et al*., 2022) to understand the broader genetic structure of wild populations. • **Outcome**: Accurate measurement of population genetic parameters to inform management.
Low	Threat mitigation – influence of invasive buffel grass on habitat suitability	• The interaction of introduced buffel grass, grazing and wildfire has been identified as a potential threat to bilbies by hindering or altering fire management. • Research to improve knowledge on the complex interactions between buffel grass, fire and introduced herbivores will help to inform threat mitigation. • **Outcome**: Threat mitigation strategies effective for management of buffel grass to ensure suitability of bilby habitat is maintained.
Low	Survey and monitoring – continue to investigate broadscale survey techniques	• Continue trialling the development and optimisation of aerial survey techniques including remotely piloted aircraft, and if technology becomes more cost effective, reinvestigate very high-resolution light detection and ranging (LiDAR) over large areas to detects burrows and diggings. • Evaluate trade-offs between accuracy, efficiency and cost-effectiveness per area covered of new technology compared to plot and/or transect-based methods. • **Outcome**: Improvement in survey extent including previously inaccessible areas of the Pilbara to better understand bilby distribution.
Low	Habitat requirements – trial environmental DNA (eDNA) approaches to further evaluate diet using scats	• Develop (or refine existing) DNA barcode libraries of potential dietary items and match DNA extracted from scats to provide a more comprehensive understanding of dietary requirements (e.g., Dawson *et al*., 2021). • **Outcome**: Provision of a comprehensive understanding of bilby diet and habitat requirements.
Low	Threat mitigation – influence of climate change	• Undertake a climate change vulnerability assessment (e.g., Foden and Young, 2016) for the bilby that considers interactions with threats (e.g., distribution and abundance of) introduced predators).

Priority	Topic	Research directions
		• **Outcome**: Improved understanding of the influence of climate change on bilby populations in the Pilbara to inform adaptation strategies.

1.3.2 Management actions

Threat management may be implemented at a local or regional level and prioritised based on factors such as ecological cost-effectiveness (e.g., Carwardine *et al*., 2019). Using a structured elicitation approach, Carwardine *et al*. (2014) prioritised threat management for Pilbara species of conservation significance including the bilby. Seventeen management strategies were agreed upon and prioritised based on their estimated average expected benefits, average costs and cost-effectiveness. Feral ungulate and domestic herbivore management, fire management, and feral cat management (including combined management strategies) ranked highest. In the absence of management intervention, the bilby was one of 13 species at high risk of being lost from the region over the next 20 years.

The Pilbara Conservation Strategy (DPaW, 2017) describes a landscape-scale approach to biodiversity conservation across the region and provides strategic direction for on-ground management actions to enhance conservation outcomes in partnership with State and Commonwealth governments, mining industry, traditional owners, natural resource management groups, pastoralists, local government, non-government organisations, community groups and research institutions. While landscape-scale threat management may be desirable, this is not always achievable, with on-ground actions often tailored to suit local conditions, resources and capacity, which may vary over time (DCCEEW, 2023f). Management on a smaller scale (no less than ~10,000 ha), focusing on local bilby populations and/or key habitat, is also beneficial, and cumulatively over time and space, may eventually result in a landscape-scale program (DBCA, 2021b).

Based on current knowledge of the bilby and associated threats, we provide a number of options to guide management that are most likely to benefit and facilitate the persistence of bilbies in the Pilbara (Table 2). These options closely align with the proposed on-ground strategies listed in the National Bilby Recovery Plan (DCCEEW, 2023f) and for other bilby populations in WA that face similar threats (e.g., Dziminski and van Leeuwen, 2019; DBCA, 2021b).

***Table 2** Threat management options for the bilby (Macrotis lagotis) in the Pilbara (DBCA, 2021b; Northover et al., 2023).*

Threat	**Population-scale actions** (i.e., applied to an area ~10,000 ha surrounding the population)	Landscape-scale actions
Introduced predators	• Implement localised, strategic aerial and/or ground baiting (e.g., Doherty and Algar, 2015) using *Eradicat*® in managed populations and surrounding buffer zones, in conjunction with supplementary methods such as trapping (e.g., Lohr	• Implement annual, strategic aerial *Eradicat*® baiting (Algar and Burrows, 2004; Algar *et al*., 2013; Comer *et al*., 2020). The bilby has benefited from large-scale introduced predator management using baits and supplementary control methods

Threat	**Population-scale actions** (i.e., applied to an area ~10,000 ha surrounding the population)	**Landscape-scale actions**
	and Algar, 2020) and shooting (CoA, 2015b). • Consider trialling Felixer™ feral cat grooming traps, which show potential as an effective complementary tool for targeted feral cat control (Dunlop *et al*., 2020; Moseby *et al*., 2020).	elsewhere in WA (e.g., Matuwa, Lohr and Algar, 2020; Lohr *et al*., 2021). • *Eradicat*® baiting (and wild dog baiting operations on pastoral lands) will also opportunistically target foxes.
Inappropriate fire regimes	• Implement localised, ground-based (hand) patch mosaic burning in and around managed populations and establish firebreaks around managed areas (Burrows, 2019) to prevent large wildfires destroying habitat and food resources (Wright and Clark, 2007) and facilitating predator access (McGregor *et al*., 2014; McGregor *et al*., 2016). • The fire management plan developed for the Warralong Bilby Land Management Area (Burrows, 2019) can be used as a template to be applied to other bilby populations in the Pilbara.	• Implement adaptive fire management across selected large areas of the Pilbara with suitable bilby habitat (DBCA, 2021b).
Introduced herbivores	• Opportunistic ground culling of feral herbivores and unmanaged livestock (DBCA, 2021b). • Negotiate the closure of artificial water points within managed bilby populations (DBCA, 2021b). • Exclude introduced herbivores from bilby habitat using livestock fencing (DBCA, 2021b).	• Consider aerial culling of feral herbivores and unmanaged livestock over large areas of suitable bilby habitat (DBCA, 2021b). • Consider fencing to exclude livestock (DBCA, 2021b).
Land clearing	• Avoid clearing habitat near key bilby populations (DBCA, 2021b).	• To reduce the impacts of land clearing, conserve large tracts of connected suitable habitat to support wild bilby populations (DBCA, 2021b). • Create formal conservation reserves within the established range of the bilby (DBCA, 2021b).
Threat interactions	• Introduced predators and fire: Implement localised fire management (as above) and concurrent targeted ground *Eradicat*® baiting and trapping/shooting within managed sites and surrounding buffer zones (DBCA, 2021b).	• Implement fire management across selected large areas of the Pilbara with suitable bilby habitat, with concurrent aerial *Eradicat*® baiting and targeted trapping/shooting (DBCA, 2021b).

Threat	**Population-scale actions** (i.e., applied to an area ~10,000 ha surrounding the population)	**Landscape-scale actions**
Loss of genetic diversity	• Consider genetic supplementation of populations (e.g., translocations) with low levels of genetic diversity.	• Promote habitat integrity and connectivity to facilitate dispersal and enhance gene flow across the Pilbara. • Establish and maintain a bilby meta-population that preserves genetic diversity and evolutionary potential (DCCEEW, 2023f).
Mining associated infrastructure and disturbance	• Avoid clearing habitat near key bilby populations where possible (DBCA, 2021b). • Consider wide culverts/underpasses under railway lines and roads in the proximity of bilby populations. • Introduce dusk to dawn speed limits near bilby populations.	• Consider the cumulative impacts of mining operations in areas of bilby habitat e.g., habitat surrounding salt lakes where there is increasing development of mineral sand, rare earth and lithium mining.
Weeds	• Targeted management of buffel grass and habitat restoration.	
Road mortality	• Limit the construction and upgrading of roads in areas where there are bilbies. • Introduce dusk to dawn speed limits near bilby populations. • Consider wide culverts/underpasses under roads in the proximity of bilby populations.	
Population decline	• Reintroduce free ranging bilbies, and the beneficial ecosystem services they provide, to areas where they were locally extirpated, without the need of high-cost predator exclusion fencing (e.g., replicate the success of Matuwa, Dziminski *et al*., 2020b; Lohr *et al*., 2021). This would require management of introduced predators and herbivores, and fire as above.	

2 Northern quoll (*Dasyurus hallucatus*; Gould, 1842)

Order Peramelemorphia; Family Thylacomyidae

2.1 Summary of current knowledge

2.1.1 General overview

The northern quoll is a solitary, medium-sized, predatory marsupial endemic to northern Australia (Oakwood, 2008). Smallest of Australia's four quoll species, the northern quoll has reddish brown fur with characteristic white spots over the back, rump and head, and a long tail with black fur at the tip. Weighing between 240-1120 g and measuring up to 370 mm in length (head and body), the northern quoll is sexually dimorphic, with males larger than females (Oakwood, 2008). Northern quolls breed annually (July-August in the Pilbara), exhibiting synchronous reproduction, and are the largest mammal to undergo post-mating male die-off (Oakwood, 2008; Woinarski *et al*., 2014). The species' is short-lived, with an average life expectancy of up to two years in the wild (Holz, 2008). Predominantly nocturnal, northern quolls take refuge and raise young in dens, particularly small caves and crevices in rocky outcrops and mesas that adequately buffer the extreme ambient temperatures in the Pilbara (Cowan *et al*., 2020; Moore, 2021). Females raise six to eight young (born late August/early September in the Pilbara, Woinarski *et al*., 2014; Hernandez-Santin *et al*., 2019), which are carried in a pouch prior to deposition in the den at eight to nine weeks of age. Young are weaned at approximately six months old (Oakwood, 2008). Males disperse widely (up to 30 km) during the breeding season, whereas females are highly site philopatric (Oakwood, 2002).

2.1.2 Distribution

Previously inhabiting most of northern Australia from the Pilbara to southern Qld (Oakwood, 2008), the range of the northern quoll has contracted in an east-to-west progression since European colonisation, with the most recent and ongoing decline coinciding with the spread of introduced cane toads (*Rhinella marina*) (Moore *et al*., 2019). Other threats including predation by introduced predators, altered fire regimes, livestock grazing, and habitat loss and disturbance (e.g., secondary to mining) have also contributed towards the species' dramatic decline (Moore *et al*., 2022a). The northern quoll now persists in four disjunct populations: the Pilbara (including Dolphin Island) and Kimberley (including islands) regions of WA, the top end of the Northern Territory (including islands) and Queensland (Moore *et al*., 2019). The Pilbara, which is considered an important stronghold for the northern quoll (Gibson *et al*., 2023), has suffered less range contraction and niche reduction compared to other regions (Moore *et al*., 2019), which is likely attributed to the (current) lack of cane toads and topographic ruggedness of the region (Cramer *et al*., 2016b). Within the Pilbara, the prevalence of northern quolls is highest within complex rocky areas in the north, west and central Pilbara (Cramer *et al*., 2016b; Shaw *et al*., 2023) (Figure 2).

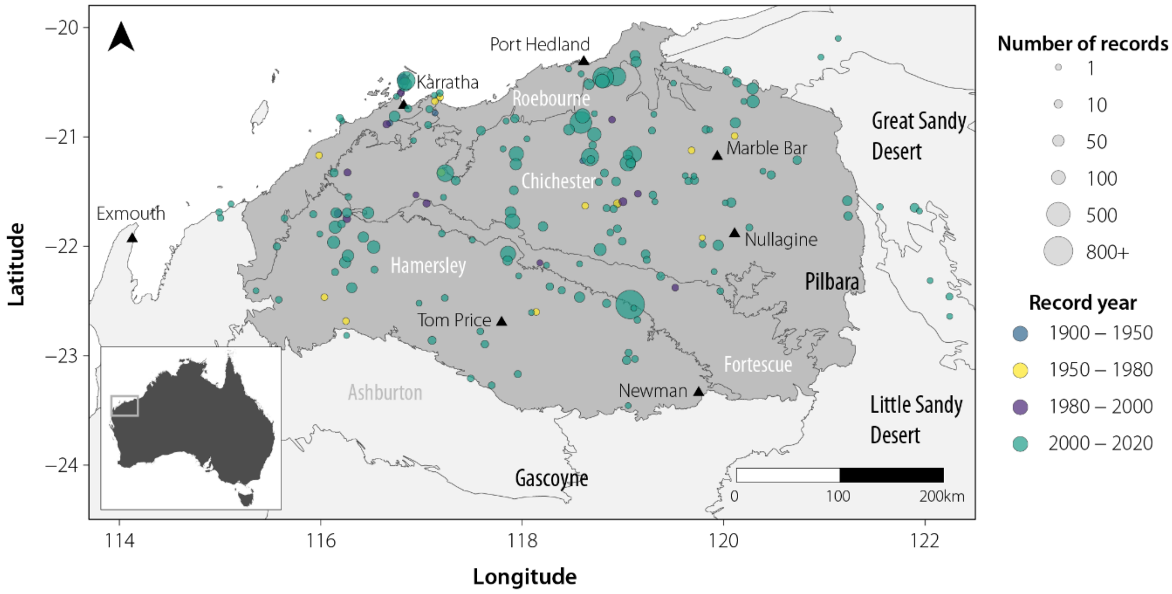

***Figure 2** Map of the Pilbara region with the locations of northern quoll (D. hallucatus) records from the Western Australian Department of Biodiversity, Conservation and Attractions' NatureMap database from 1990-2021 (https://naturemap.dbca.wa.gov.au, downloaded July 2021). Point size represents the number of NatureMap records reported within a 20 km radius for each collection year period (specified by colour). The darker grey represents the Pilbara IBRA region, with map borders showing IBRA subregions.*

2.1.3 Habitat requirements

Northern quolls can be found in a variety of habitats, particularly males during the breeding season, but show a preference for complex rocky areas in the Pilbara (Molloy *et al*., 2017; Moore *et al*., 2021; Cowan *et al*., 2022; Gibson *et al*., 2023; Shaw *et al*., 2023). Complex, rocky landforms often in close proximity to permanent water are considered critical habitat as they provide refuge from predators (Hernandez-Santin *et al*., 2016) and other threats (e.g., fire; Cook, 2010), access to food (Dunlop *et al*., 2017), and shelter for denning (Braithwaite and Griffiths, 1994; Hernandez-Santin *et al*., 2022). Watercourses facilitate connectivity for dispersal and foraging (Cowan *et al*., 2022; Shaw *et al*., 2023), while areas with high silt or clay content (i.e., alluvial, coastal, and hardpan plains) may impede dispersal (Shaw *et al*., 2023).

Moore *et al.* (2022b) determined that the spatial configuration of rocky habitat was more important than habitat amount, with quoll occupancy and abundance decreasing as fragmentation increased. Within rocky habitat, quolls favoured patches with higher vegetation cover and den availability, less edge habitat relative to patch size, and greater rocky habitat extent (Moore *et al*., 2021). Cadenhead *et al*. (2015) found that '*topographical roughness, precipitation and mean temperature of the warmest period*' best described the distribution of northern quolls (n = 305) in the Pilbara; though finer-scale environmental layers that capture preferred habitat (i.e., mesas or rocky outcrops) were not examined. While northern quolls largely avoid spinifex sandplain, probably due to the risk of predation (Hernandez-Santin *et al*., 2016), GPS tracking has shown that quoll activity increases with higher percentage cover in these areas (Cowan *et al*., 2022). In the Robe River valley, northern quolls increased their use of spinifex plains in response to broadscale feral cat baiting (Palmer *et al*., 2021). Relaxed predation pressure from feral cats potentially facilitates improved access to new prey resources and allows for safer dispersal.

Within the Pilbara, northern quolls have a highly opportunistic dietary strategy, characterised by a broad and variable omnivorous diet (predominantly insects, vegetation, small mammals and reptiles; Dunlop *et al*., 2017). Preliminary analysis of quoll diets in an area where feral cats were baited revealed a gradual dietary shift to rodent prey away from protein-poor food sources such as fruits (Palmer *et al*., 2020). Whereas northern quoll diets were stable at the neighbouring unbaited reference site, suggesting that feral cat control may benefit quoll populations indirectly by improving their access to richer prey sources in high-risk open habitats.

2.1.4 Threatening processes

In the Pilbara, key threats to the northern quoll include inappropriate fire regimes; predation by, and competition with, feral cats and foxes (and potentially dingoes); and habitat loss, fragmentation and degradation, particularly from mining and infrastructure development, but also pastoralism. The threat of dingoes (*Canis familiaris*) to Pilbara northern quolls is unknown (Gibson *et al*., 2023). While dingoes are known to predate radio-collared northern quolls in Qld and the NT, they are less likely to occur in topographically rugged, rocky terrain (Hernandez-Santin *et al*., 2016; Moore *et al*., 2022a). The occurrence of northern quoll remains in dingo scats (3 in 395 scats; 0.8%) was low compared to feral cats (17 in 135 scats; 12.6%) in the Robe and Cane River valleys (Palmer *et al*., 2020).

The future invasion of cane toads from the Kimberley may threaten Pilbara quolls with cane toads predicted to colonise the Pilbara by 2037-2046 (Tingley *et al*., 2013; Southwell *et al*., 2017). Poisoning from the ingestion of cane toads is the primary cause of the species' current decline across other parts of northern Australia as northern quolls lack immunity to cane toad (bufonid) toxins (Gibson *et al*., 2023). Local extinctions have occurred following the advent of cane toads in Queensland (Burnett, 1997) and the NT (Oakwood, 2004). Strategies to mitigate the spread of cane toads from the Kimberley are being investigated (e.g., Tingley *et al*., 2013; Phillips *et al*., 2016; Southwell *et al*., 2017).

Other potential threats to the northern quoll in the Pilbara include mortality from road and/or rail traffic collisions, the emission of noise and light, and climate change (BHP, 2016). Research to evaluate how multiple interacting threats impact northern quolls is required, particularly interactions between predation, fire, and grazing (Gibson *et al*., 2023).

2.1.5 Conservation status

The northern quoll is listed as 'Endangered' under the WA *Biodiversity Conservation Act 2016* (Government of Western Australia, 2016), the Commonwealth's *EPBC Act 1999* (DCCEEW, 2023a), and on the IUCN Red List of Threatened Species (Oakwood *et al*., 2016). Like the bilby, the northern quoll was selected as one of the 21 priority mammal species in the Threatened Species Action Plan 2022-2032 (DCCEEW, 2022) and northern quoll presence and/or habitat is a key environmental consideration in mining project and strategic environmental assessments in the Pilbara (Cramer *et al*., 2016b).

2.1.6 Population status

There are no reliable estimates of the population size of northern quolls in the Pilbara, or for the species as a whole (Woinarski *et al*., 2014), though the number of mature individuals is thought to be decreasing (Oakwood *et al*., 2016). Recent advances in survey and monitoring techniques, whereby remote camera trap images can be used to identify individuals based on their unique spot patterns, will enable more robust estimates of population size (Moore *et al*., 2020, 2021, 2023b). Male population size fluctuates seasonally (i.e., lowest in September at the end of the breeding season) and the number of quolls may vary between sites dependent on habitat quality (Hernandez-Santin *et al*., 2019). Population viability analyses by Moro *et al*. (2019) indicate that increased juvenile mortality rates above current levels could result in '*a projected decline in population size of 22-54%, with a moderate-to-high chance (20-96%) of local extinction within 20 years*.'

2.1.7 Genetic structure

Analysis of the genetic diversity and population structure of the Pilbara northern quoll population revealed that it is homogenous and genetically distinct from the Kimberley and NT populations (How *et al*., 2009; Spencer *et al*., 2013; Hohnen *et al.*, 2016; von Takach *et al.*, 2022). Further analyses of local Pilbara populations using microsatellite markers showed heterozygosity across mainland northern quoll subpopulations was high (~70%) and there was no evidence of recent or historic genetic bottlenecks (Cramer and Dunlop, 2018; Dunlop *et al*., 2019). Within the Pilbara, there was no evidence of genetic structuring across the mainland meta-population, however genetic diversity of the Dolphin Island population was comparatively low (Dunlop *et al*., 2019). While northern quolls have a highly random and promiscuous mating pattern, mate choice was evident on Dolphin Island, with females selecting smaller males (Chan *et al*., 2020).

In a recent study that examined connectivity and patterns of genetic structure in northern quolls in the Pilbara using high-resolution SNP markers (Shaw *et al*., 2023), a weak northeastern-southwestern split was identified, though low genetic structuring suggests a lack of major physical barriers to dispersal within the Pilbara. Shaw *et al*. (2023) however, detected lower genetic diversity in isolated areas with low connectivity (e.g., Dolphin Island and eastern Hammersley coldspots), potentially placing these subpopulations at risk of inbreeding depression and reduced adaptive potential.

2.2 Identification of research priorities

While preserving quolls within the Pilbara is recognised as a national priority (Hill and Ward, 2010), targeted ecological research focusing on the Pilbara northern quoll population was lacking prior to 2014 (Cramer *et al*., 2016b). Research priorities for the northern quoll were initially determined in a workshop hosted by DBCA in 2013 (Cramer *et al*., 2016b), and further refined in a revisionary workshop held by DBCA in 2016 (Table 3; Cramer and Dunlop, 2018). Over the past decade, northern quoll research has focused on the priorities identified at both workshops. In 2023, a review of progress of the Pilbara Northern Quoll Research Program, including key outcomes, was undertaken (Gibson *et al*., 2023) to identify future research directions to inform the ongoing investment of funds to support northern quoll conservation in the Pilbara.

2.3 Future research directions and management actions

2.3.1 Future research directions

Proposed future research directions for the Pilbara northern quoll (Table 3; Gibson *et al*., 2023) are categorised according to the research priorities identified by Cramer and Dunlop (2018).

Table 3 *Future research directions for the northern quoll (Dasyurus hallucatus) in the Pilbara (modified from Gibson et al., 2023).*

Rank	Topic	Research directions
1	Survey and monitoring – assess and refine survey and monitoring protocols (Priority 1 and 2 combined)	• 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, including Indigenous Rangers, to better understand long-term population trends. • Investigate emerging technologies (e.g., artificial intelligence cameras) to improve effectiveness and efficiency of monitoring approaches. • **Outcome**: More effective and efficient survey and monitoring protocols to better understand population trends and management effectiveness.
2	Habitat requirements – improve 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.

Rank	Topic	Research directions
		• **Outcome**: Improved understanding of habitat use to identify areas of critical habitat requiring protection.
3	Population dynamics – improve 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. • **Outcome**: Improved understanding of population viability to identify conservation actions that promote sustainable populations.
4	Key threats – assess 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 (i.e., aerial and targeted ground baiting using *Eradicat*®, and/or trapping) and the subsequent response of northern quolls. • Investigate dietary overlap between northern quolls and feral cats. • **Outcome**: Effective feral cat control to facilitate the persistence of northern quolls.
	Key threats – understand the spread and impacts of cane toads	• Investigation of the uptake and potential longer-term conditioned taste aversion of nausea inducing thiabendazole-laced cane toad sausages or non-lethal juvenile toads by northern quolls and non-target species in the Pilbara. • Identify 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). • **Outcome:** Improved understanding of the likely impacts of cane toads in the Pilbara.
5	Recolonisation of restored or artificial habitat – 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 resources and predator abundances) influence the movement and behaviour of northern quolls.

Rank	Topic	Research directions
		• Better understand the cumulative impact of habitat loss due to mining in relation to northern quoll distribution and habitat connectivity. • **Outcome:** Improved understanding of the influence of mining disturbance and strategies to mitigate these.
6	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. • **Outcome:** Integrated threat mitigation strategy to facilitate northern quoll persistence.

2.3.2 Management actions

Management actions that are most likely to benefit and facilitate the persistence of northern quolls in the Pilbara are those that promote habitat integrity and connectivity, maintain/increase vegetation cover, and maximise the survival of juvenile quolls (Gibson *et al*., 2023). As for the bilby, threat management may be implemented at a local or regional scale (Table 4). Annual, strategic aerial *Eradicat*® baiting is considered to be the most effective and efficient landscape-scale method for controlling feral cats (Algar and Burrows, 2004; Algar *et al*., 2013; Comer *et al*., 2018; Comer *et al*., 2020). However, the operational use of *Eradicat*® is currently not permitted in areas where northern quolls are present, as the risk to this species in the wild had not been assessed at the time the bait was registered in WA (Palmer *et al.* 2021). The studies of Palmer *et al.* (2021) and Cowan *et al.* (2020) indicate baiting with *Eradicat*® poses a low poison risk to northern quolls, which will help to inform the future use of this bait now that it is being assessed for national registration.

In the meantime, feral cat *Eradicat*® baiting can occur in locations supporting northern quolls providing a site-based research permit is issued by the Australian Pesticides and Veterinary Medicines Authority (APVMA). Research and any associated non-target monitoring must be provided to the APVMA on completion of such projects. Ongoing population monitoring using a cost-effective, standardised framework is recommended to measure the effectiveness of management interventions and adapt future actions (see Moore *et al*., 2023a).

***Table 4** Threat management options for the northern quoll (Dasyurus hallucatus) in the Pilbara (largely based on research outcomes discussed in Gibson et al., 2023).*

Threat	Population-scale actions	Landscape-scale actions
Introduced predators	• Consider trialling Felixer™ feral cat grooming traps for targeted feral cat control (Dunlop *et al*., 2020; Moseby *et al*., 2020) in the vicinity of critical habitat, feral cat sources or sinks, or dispersal corridors (e.g., watercourses; Shaw *et al*., 2023). • Targeted shooting and trapping (CoA, 2015a).	• *Eradicat*® baiting pending national registration (see Section 2.3.2). • While this process remains underway, feral cat baiting projects in areas supporting northern quolls require a site-specific research permit from the APVMA.
Inappropriate fire regimes	• Implement targeted (i.e., dispersal routes and grasslands surrounding rocky areas) and ecologically appropriate fire regimes to maximise vegetation cover and reduce predation risk.	• Implement adaptive fire management across selected large areas of the Pilbara with suitable northern quoll habitat to reduce the incidence of large, intense, and frequent wildfire.
Introduced herbivores	• Opportunistic ground culling of feral herbivores and unmanaged livestock. • Consider fencing to reduce livestock grazing in critical habitat (e.g., along watercourses).	• Consider aerial culling of feral herbivores and unmanaged livestock over large areas of northern quoll habitat; target riparian areas, which are subject to overgrazing and degradation (McKenzie *et al*., 2009).
Habitat loss, fragmentation and degradation	• Protect large areas of topographically complex rocky habitat, in particular female denning sites, by targeted actions such as introduced predator/herbivore control and fire management to reduce incidence of large, intense and frequent wildfire. • Maximise vegetation cover within and surrounding rocky patches preferred by quolls to reduce predation risk and increase food availability (Moore *et al*., 2021) by managing herbivores and fire, and restoring habitat.	• Safeguard large tracts of connected suitable habitat to facilitate male dispersal and promote connectivity between fragmented populations via large herbivore and fire management. • Restore areas surrounding core habitat, including recently burnt areas and drainage lines, to facilitate range expansion and meta-population connectivity (Shaw *et al*., 2023).
Threat interactions	• Implement targeted fire management and concurrent feral cat/herbivore control (as above) in and surrounding core habitat (i.e., topographically	• Implement large herbivore and fire management in the broader landscape.

Threat	**Population-scale actions**	**Landscape-scale actions**
	complex rocky habitat and along watercourses).	
Loss of genetic diversity	• For isolated populations with lower genetic diversity (e.g., Dolphin Island, Shaw *et al*., 2023), targeted intervention may be required (e.g., translocations to mix populations).	• Management actions to increase connectivity (as above) will enhance gene flow across the Pilbara.
Cane toads	• Should cane toads arrive in the Pilbara, establish biosecurity and surveillance programs, particularly on Dolphin Island to prevent cane toad incursion (Woinarski *et al*., 2014).	• Implementing broad-scale avoidance ‘training’ of quolls prior to their incursion has been recommended (Woinarski *et al*., 2014), however further research is required to determine its effectiveness (Indigo *et al*., 2023).

3 Pilbara Leaf-nosed Bat (*Rhinonicteris aurantia* Pilbara form; Gray, 1845)

Order Chiroptera; Family Rhinonycteridae

3.1 Summary of current knowledge

3.1.1 General overview

The Pilbara leaf-nosed bat (PLNB) is a distinct form of the orange leaf-nosed bat (*Rhinonicteris aurantia*) endemic to the Pilbara region. Weighing between 8-10 g and measuring 41-47 mm in length (head and body), *Rhinonicteris* spp. range in colour from bright orange to yellow, white and brown and have a distinctive noseleaf (Armstrong, 2008). Yet to be formally classified (Cramer *et al*., 2016a), the PLNB is distinguished by its unique echolocation call frequency (116-122 kHz, Armstrong and Coles, 2007; McKenzie and Bullen, 2013) and skull morphology (Armstrong, 2002). The PLNB is a ‘high-energy’, insectivorous bat with high food intake requirements (Bullen and McKenzie, 2004; Salt, 2022). Catching prey on the wing, the diet of the PLNB has not been studied, though *R. aurantia* from the NT selectively forages for Lepidoptera and Coleoptera species, and Isoptera when abundant (Churchill, 1994). The PLNB is an obligate deep-cave roosting species (Bullen and Reiffer, 2020). As the PLNB cannot enter torpor and has a limited capacity to conserve water or energy (Kulzer *et al*., 1970; Baudinette *et al*., 2000), it’s area of occupancy is defined by the availability of diurnal roost sites with high humidity and stable temperatures to minimise energy expenditure (Baudinette *et al*., 2000; Cramer *et al*., 2016a).

Mating occurs in July and females give birth to a single pup in late December/early January, and young are weaned and independent by late February/March (Churchill, 1995; Armstrong, 2001). The PLNB is known to travel large distances (e.g., up to 45 km from diurnal roosts to forage; Bullen, 2023) with one male travelling more than 170 km over 12 months (Bullen and Reiffer, 2020). Genetic studies have identified some evidence of female philopatry (Armstrong, 2006; Umbrello *et al*., 2022). The PLNB is relatively long-lived, with an estimated life span of eight to ten years (Umbrello *et al*., 2022).

3.1.2 Distribution

Rhinonicteris aurantia occurs within the Pilbara region of WA, and from the Kimberley across the Top End of the NT (including islands) to north-western Qld (Armstrong *et al*., 2021a). The PLNB (*R. aurantia* Pilbara form) occurs within the Pilbara region (Armstrong, 2008) and three satellite locations surrounding the Pilbara (Barlee Range Nature Reserve of the upper Gascoyne region, Mt Vernon Station, and the rocky uplands of the Karlamilyi National Park; Bat Call WA, 2021b). While historical records prior to 1995 are scarce (Armstrong, 2001), it is estimated that the Pilbara and Kimberley PLNB populations have been separated by the Great Sandy Desert for over

30,000 years (Armstrong, 2006; 2008). Permanent diurnal roosts have been detected throughout most of the Chichester and Hamersley subregions of the Pilbara, with a small number also found in the nearby Ashburton (south) and Little Sandy Desert (east) bioregions (Bat Call WA, 2021b) (Figure 3).

With the widespread use of automated acoustic recorders over the past decade, detection of the species' distinctive echolocation call frequency has enabled their current range and extent of occurrence to be mapped (Bat Call WA, 2021b). While the PLNB has been detected across much of the Pilbara (Figure 3), the species' area of occupancy is estimated to be less than 1000 ha (excluding foraging habitat) given their specific roosting microhabitat requirements (Cramer *et al*., 2016a). Suitable diurnal roosts are patchily distributed and often occur in mineral-bearing strata of economic interest (Cramer *et al*., 2016a).

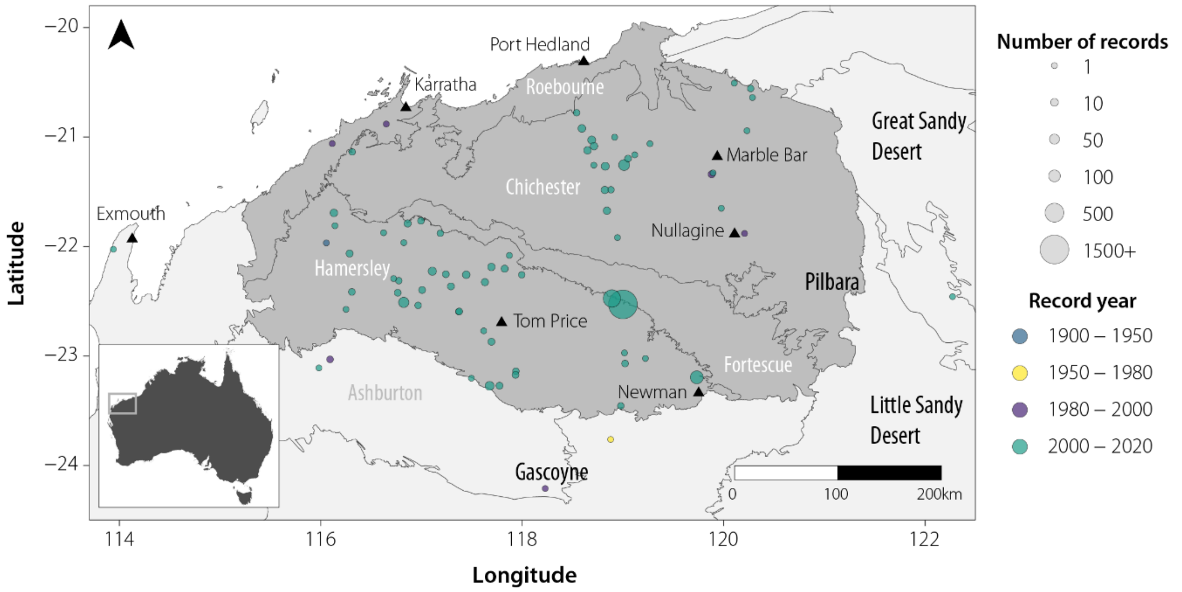

Figure 3 *Map of the Pilbara region with the locations of Pilbara leaf-nosed bat (Rhinonicteris aurantia Pilbara form) records from the Western Australian Department of Biodiversity, Conservation and Attractions' NatureMap database from 1990-2021 (https://naturemap.dbca.wa.gov.au, downloaded July 2021). Point size represents the number of NatureMap records reported within a 20 km radius for each collection year period (specified by colour). The darker grey represents the Pilbara IBRA region, with map borders showing IBRA subregions.*

3.1.3 Habitat requirements

Foraging in a variety of habitats including the characteristic *Triodia* hummock grasslands of the Pilbara, the PLNB favours the highly productive and structurally complex riparian zones where water is permanently available and insect biomass is sufficiently high (Armstrong, 2001; McKenzie and Bullen, 2013). Females are highly dependent on foraging habitat within close proximity to maternal roosts, especially during lactation (Woinarski *et al*., 2014). As such, diurnal roost sites (deep caves within banded ironstone strata and disused underground copper/gold mines; McKenzie and Bullen, 2013) are typically located within flying range (i.e., 5-7 km) of permanent water

(Bullen, 2023), though longer linear distances between roost sites and natural water sources have been documented (e.g., 8.7 km from the Kalgan Creek Roost; Bat Call WA, 2021b). Seasonal variation in intra-regional presence, corresponding with lower temperatures and higher humidity (i.e., April/May), has also been documented with bats travelling > 20 km from permanent diurnal roosts to occupy non-permanent roost caves (Bat Call WA, 2021b).

Given the species' limited capacity to conserve water or energy, diurnal roost site suitability is governed by strict temperature (28-32°C) and humidity (85-100%) requirements (D'Rozario, 2022), which are typically provided by the presence of ephemeral pools or waterfalls at roost entrances, or seeps and groundwater pools deeper inside caves (Armstrong, 2001; BHP, 2016). Rates of water loss in *R. aurantia* in the NT were more than double that of other bats (including *Macroderma gigas*) and roost temperatures of at least 30°C were required to maintain thermoneutrality (Baudinette *et al*., 2000), highlighting the species-specific microclimate requirements. Critical habitat, as defined by Bat Call WA (2021b), includes permanent diurnal (categories 1 and 2) roosts that are essential for the daily and long-term survival of the PLNB; semi-permanent diurnal (category 3) roosts that are essential for the long-term survival of the PLNB; and any permanent pools close to permanent diurnal roosts.

Research to characterise the geological uniqueness and importance of natural roosts is ongoing. Temperature, humidity and bat activity was monitored in a 2019-2020 cave study in the Chichester area (D'Rozario, 2022) and the characteristics of natural cave diurnal roosts have been described (Bat Call WA, 2021b). Other factors (e.g., causes of humidity fluctuation in caves) require further evaluation (Bat Call WA, 2021b; D'Rozario, 2022). Species distribution modelling by Cadenhead *et al*. (2015) indicated that '*the proportion of cells classified as valley bottoms (erosional), slope, precipitation and mean temperature in the driest quarter*' were the most important parameters predicting PLNB distribution, though sample size was small (n = 41 records).

3.1.4 Threatening processes

Threats to the PLNB were recently reviewed at a 2022 workshop and include feral cat predation; climate change (potentially reduced rainfall); cumulative impacts; disturbance and destruction of roosts (includes secondary impacts of mining such as vibration, dewatering, light, noise and blasting); degradation and fragmentation of foraging habitat; inadequate buffer zone implementation; hydrological change (i.e., loss of permanent water and reduction in water quality/pollutants); and interactions with wind turbines (Bat Call WA, 2021b; Salt, 2022). The PLNB's characteristic low-to-ground zigzag flight pattern also makes the species' highly susceptible to mortality from vehicle strike (Armstrong, 2008; BHP, 2016).

The destruction and disturbance of category 1 and 2 roosts (i.e., natural caves and historical underground mine adits in mineral-bearing strata) associated with current/future mining operations, and the deterioration, flooding or collapse of disused mine sites (e.g., Chichester region), is recognised as the greatest threat to the PLNB

(Armstrong, 2011; Woinarski *et al*., 2014; Bat Call WA, 2021b). There is concern that the estimated population size of the PLNB could decline by > 30% over the next 15 years, and in the absence of management intervention, it is predicted that the majority of roost sites will be destroyed over the next 30-50 years as they tend to occur in ore-bearing strata (Woinarski *et al*., 2014).

Feral cat predation is a newly identified threat to the PLNB (D'Rozario, 2022). Feral cats may impact bats directly (i.e., via predation) or indirectly (i.e., via disturbance) at roosting sites (R. Bullen, unpubl.), though the full impact of feral cats is unknown. Cave roosting bats elsewhere have been shown to be more vulnerable to cat attacks when they are pregnant or when young bats were present in the roost (Ancillotto *et al*., 2013). Once located, individual cats are known to specialise on bats at roosts (Ancillotto *et al*., 2013). The PLNB is also susceptible to predation by other native species (e.g., ghost bat, Start *et al*., 2019; northern quoll, Palmer *et al*., 2020; and pythons, R. Bullen pers. comm.).

3.1.5 Conservation status

The PLNB is listed as 'Vulnerable' under the WA *Biodiversity Conservation Act 2016* (Government of Western Australia, 2016) and the Commonwealth *EPBC Act 1999* (DCCEEW, 2023g). Conservation Advice exists for the PLNB under the *EPBC Act* (TSSC, 2016c), although no formal recovery plan is currently in place (DCCEEW., 2023g). *Rhinonicteris aurantia* is listed as 'Least Concern' by the IUCN due to its widespread distribution, and presumably large population size, across northern Australia; '*the species as a whole is considered to be secure*' (Armstrong *et al*., 2021a).

3.1.6 Population status

At present, there is no reliable estimate of population size (Woinarski *et al*., 2014) and the number of bats occupying roost sites can vary widely (e.g., < 20 to > 10,000) in response to climatic (e.g., rainfall) and seasonal variation (Bat Call WA, 2021b). The use of infra-red lighting video to provide colony headcounts has been shown to correlate well with ultrasonic echolocation recordings (Bat Call WA, 2021b); the PLNB population estimate was 30,000 to 35,000 individuals in 2017 but has subsequently declined due to poor rainfall over successive years (Salt, 2022). Recent genotyping of bat samples obtained from seven diurnal roosts between 2017 and 2019 from the Pilbara suggests an effective population size of 3000 to 3900 individuals (Umbrello *et al*., 2022). There are ~ 50 known natural roost caves that support permanent PLNB bat colonies in the Pilbara (Bullen, 2023); 10 are under immediate threat and 30 face possible future threat due to mining development (Salt, 2022).

3.1.7 Genetic structure

Research using mitochondrial DNA (mtDNA) markers and reduced representation genomic sequencing (DArT) of tissue samples collected from seven diurnal roost sites located in the Hamersley and Chichester subregions of the Pilbara (Umbrello *et al*., 2022), found high levels of gene flow and low geographic population structure (i.e., low genetic differentiation between roosts and subregions, especially for males), indicating one panmictic (or randomly mating) population. Results from mtDNA, which is maternally inherited, provided some evidence of female philopatry and potential male-mediated dispersal. Overall, the PLNB had consistent levels of genetic diversity across the sampled populations and low levels of inbreeding (Umbrello *et al*., 2022).

3.2 Identification of research priorities

Research priorities for the PLNB were first identified in a workshop hosted by DBCA in 2013 (Cramer *et al*., 2016a). These aimed to:

1. Collate and analyse existing unpublished literature/data and capture in an appropriate data repository.
2. Clarify and better characterise the number and distribution of day roosts.
3. Characterise and map foraging habitat, better understand movement patterns between roosts and the role of resource availability.
4. Provide estimates of metapopulation and local colony size and improve understanding of social behaviour.
5. Increase knowledge of appropriate buffer requirements for mining activities and develop protocols for artificial roost construction.

A second workshop hosted by Curtin University was held in April 2022 to review progress against the priorities identified by Cramer *et al*. (2016a) and define areas for future research effort (Salt, 2022).

3.3 Future research directions and management actions

3.3.1 Future research directions

At the 2022 PLNB workshop, it was acknowledged that most of the research priorities identified at the 2013 workshop (Cramer *et al*., 2016a) were inadequately addressed, and therefore still applicable today. Table 5 summarises the future research directions identified at the 2022 workshop, listed in order of priority (Salt, 2022).

Table 5 *Future research directions for the Pilbara leaf-nosed bat (Rhinonicteris aurantia Pilbara form) in the Pilbara (modified from Salt, 2022).*

Rank	Topic	Research directions
1	Ecology – dispersal, breeding, and population size	• Improve knowledge of dispersal patterns, including the influence of season and limitations to dispersal (physical and/or ecological). • Better understand seasonal breeding patterns. • Strengthen understanding of natural fluctuations in colony size, and the factors influencing those changes (e.g., season, breeding, social behaviour). • Assess changes in meta-population size (region-wide) and factors influencing those.

Rank	Topic	Research directions
		• **Outcome:** Improved understanding of factors influencing movement and population growth/persistence to inform conservation management.
2	Threats	• Better understand the influence of mining activities (including indirect impacts) within the vicinity of roosts, and the effectiveness of mitigation strategies (e.g., buffer requirements). • Improve knowledge of the characteristics of natural roosts to inform artificial roost construction. • Strengthen understanding of other potential threats such as feral cat predation (e.g., camera monitoring at roost entrances, predator diet analyses), wind turbines, climate change and disease (white-nosed syndrome), and mitigation strategies to address these. • **Outcome**: Threat mitigation strategies that facilitate persistence of the PLNB in the Pilbara.
3	Data collation, survey and monitoring	• Encourage submission of PLNB records to existing data repositories such as via the Biodiversity Information Office (Dandjoo/Boranga). • Develop a genetic database of individual genotypes. • Develop/implement standard monitoring methodology e.g., approach outlined in Bat Call WA (2021b). • Determine the utility of scat DNA for monitoring. • **Outcome**: More efficient and effective survey and monitoring protocols to measure population trends and management effectiveness.
4	Habitat use – roosts and foraging habitat	• Use existing data to generate a habitat suitability model that considers foraging habitat. • Clarify number and distribution of diurnal roosts. • Improve knowledge on characteristics of natural roosts such as microclimate and the influence of changes in humidity, and the role of a nearby water source in roost site viability. • Better understand the spatial relationship between day roosts and foraging habitat, including the influence of seasonal variation in resource availability. • Landscape features that support seasonal movements require further evaluation, including the mechanisms driving this movement. • Consider non-invasive DNA metabarcoding (eDNA) analysis of faecal pellets (e.g., Arteage Claramunt *et al*., 2019) to determine dietary requirements. • **Outcome**: Identification of critical habitat requiring protection.

3.3.2 Management actions

Clearly, there is still much to be learnt about the PLNB, including the likely influence of a range of factors including anthropogenic disturbances on this species. Ongoing monitoring of PLNBs in relation to their use of roosts and foraging habitat, and associated movements, is likely to be critical to improving this understanding. At the 2022 PLNB workshop, implementing a collaborative, adaptive and integrated management program was proposed (Salt, 2022). To ensure the future conservation of the PLNB in the Pilbara, proposed management options are provided in Table 6.

Table 6 *Management options for the Pilbara leaf-nosed bat (Rhinonicteris aurantia Pilbara form) in the Pilbara (modified from Salt, 2022).*

Theme	Management actions
Habitat protection	• Preservation of known roosting sites and core foraging habitat.
Habitat restoration	• Evaluate the effectiveness of artificial roosts, in particular usage (i.e., numbers of bats, timing of use, breeding) and longevity of use. • Develop a protocol for artificial roost construction. • Evaluate time lag and associated impacts on local populations between the establishment of restored habitat and the delivery of expected environmental services to the PLNB.
Mining disturbance	• Provision of information and advice on new mining proposals on the preferred habitats and ecological requirements of the PLNB so that planning to mitigate impacts can be undertaken. • Develop guidelines and implement/evaluate known buffer best-practice and ensure formal requirements evolve as related research progresses. • Monitoring of indirect impacts on roosts (i.e., vibration, dewatering, light, noise, and blasting). • Establish and apply agreed industry standards to manage indirect impacts of mining.
Collaboration and adaptive management	• Establish agreed reporting standards for new projects to facilitate the development of meaningful, sharable datasets across the Pilbara. • Identify barriers to data sharing and creation of software tools to navigate and collate data relevant to the management of PLNB in the Pilbara. • Implement adaptive management to enable further improvements to best practice techniques.
Introduced predator control	• Targeted feral cat control at important roosts sites (e.g., using Felixer™ feral cat grooming traps at category 1 and 2 roost entrances) may be beneficial. • Feral cat baiting using *Eradicat*® may also be an option, which could be applied by hand at the local scale or aerially at the broad scale targeting foraging habitat.

4 Ghost Bat (*Macroderma gigas*; Dobson, 1880)

Order Chiroptera; Family Megadermatidae

4.1 Summary of current knowledge

4.1.1 General overview

The ghost bat (or false vampire bat) is a large, carnivorous bat endemic to Australia (Richards *et al*., 2008). Measuring 100-130 mm (head and body length) and weighing 140-165 g, ghost bats prey upon insects and small vertebrates, including other bats (e.g., PLNB; Start *et al*., 2019). Characterised by their large eyes, long conjoined ears, simple noseleaf, pale ventral fur and lack of tail, ghost bats locate and capture prey using a combination of sight, sound and echolocation (Kulzer *et al*., 1984; Richards *et al*., 2008; TSSC, 2016a). The ghost bat is an obligate troglodyte, and survival is critically dependent on finding natural roosts in caves, crevices, deep overhangs and artificial roosts such as abandoned mines (Hall *et al*., 1997). The species has a fission-fusion social system where individuals of both sexes gather during the winter mating season and segregate afterwards, with dispersal being male-mediated (Worthington Wilmer *et al*., 1999). Females congregate in regionally centralised maternity roosts during parturition and rearing of young, typically giving birth to a single pup in spring (October/November) (Hoyle *et al*., 2001; Richards *et al*., 2008), with young weaned by March (Hoyle *et al*., 2001). Ghost bats have low fecundity and survival (Hoyle *et al*., 2001); generation time is estimated to be eight years (Woinarski *et al*., 2014).

4.1.2 Distribution

Currently patchily distributed across northern Australia, including Qld, the NT, and the Kimberley and Pilbara regions of WA (Woinarski *et al*., 2014), the ghost bat previously inhabited southern and central Australia (Richards *et al*., 2008). The species' northwards range contraction has been associated with the historic onset of more arid conditions and more recently the impacts of European colonisation (Churchill and Helman, 1990; Cramer *et al*., 2022). Ghost bats have been recorded across most of the Pilbara, including all four IBRA subregions (McKenzie and Bullen, 2009; Bat Call WA 2021a; Cramer *et al*., 2022) (Figure 4). The largest colonies are currently known from four abandoned gold and copper mines (Bamboo Creek, Comet, Klondyke Queen, and Lalla Rookh) in the Chichester sub-region of the eastern Pilbara (Bat Call WA, 2021a). Other smaller colonies (typically < 15 individuals) are known from natural caves and relatively small adits across the Pilbara, particularly the Hamersley subregion (Armstrong and Anstee, 2000; Bat Call WA, 2021a). Ghost bats have been recorded on West Intercourse Island (R. Bullen pers. comm.). As for the PLNB, the species' area of occupancy is limited by the number of diurnal roost sites that are capable of supporting either maternity colonies or high numbers of bats (Cramer *et al*., 2022).

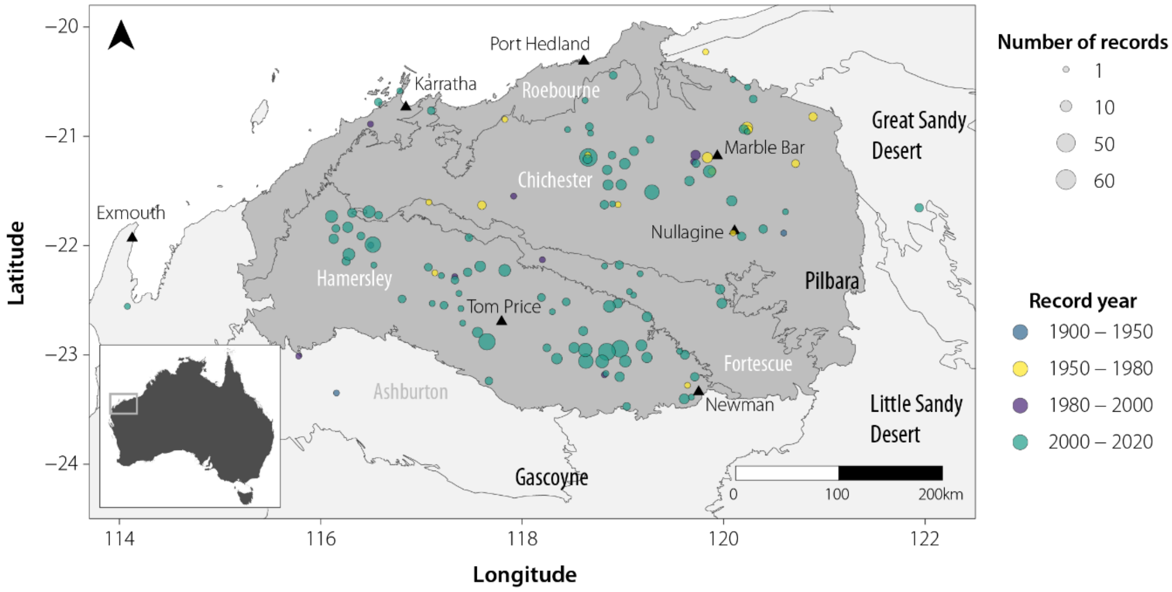

Figure 4 *Map of the Pilbara region with the locations of ghost bat (Macroderma gigas) records from the Western Australian Department of Biodiversity, Conservation and Attractions' NatureMap database from 1990-2021 (https://naturemap.dbca.wa.gov.au, downloaded July 2021). Point size represents the number of NatureMap records reported within a 20 km radius for each collection year period (specified by colour). The darker grey represents the Pilbara IBRA region, with map borders showing IBRA subregions.*

4.1.3 Habitat requirements

Ghost bats forage by either ambushing passing prey, or gleaning surfaces while in flight (TSSC, 2016a). Within the Pilbara, the species' is known to forage in productive habitat including '*drainage lines and along riparian corridors, on alluvial plains supporting mulga woodland and tussock grassland, sparse woodland along ridge lines, as well as cave entrances where other bats are hunted'* (Cramer *et al*., 2022). In areas with a moderate (30-70) percentage of bare ground, sparsely wooded areas of Mulga, other *Acacia* or Eucalypt spp. or linear woodland features (e.g., riparian area) were favoured during foraging (Bullen *et al*., 2023). Ghost bats have also been documented taking birds from nests in tree canopies and will hunt opportunistically in cleared agricultural land and along edges of crop circles (Augusteyn *et al*., 2018; Bullen, 2023). While their diet varies depending on availability (TSSC, 2016a), a recent study suggests that small mammals and birds make up the majority of their diet in the Pilbara, with reptiles and amphibians consumed less often (Arteage Claramunt *et al*., 2019). Foraging areas tend to be located less than 5 km from diurnal roost sites (TSSC, 2016a); though larger distances are being reported using VHF and GPS/satellite tracking technologies (Augusteyn *et al*., 2018; Bat Call WA, 2021a; Bullen *et al*., 2023). Recent studies in the Pilbara (Bullen *et al*., 2023) documented nightly flight path distances in excess of 40km. Ghost bats are known to move periodically from roost to roost in response to season or local prey availability (Bat Call WA, 2021a; Bullen, 2023).

Although ghost bats inhabit a variety of roost sites, the species' is reliant upon permanent underground roosts with a warm (23-28°C) and humid (50-100%) microclimate, especially in more arid environments such as the Pilbara (TSSC, 2016a; Armstrong *et al*., 2021b); though the species is heavily dependent on stable ambient temperatures to maintain homeostasis, rather than humidity (Baudinette *et al*., 2000). Critical habitat, as defined by Bat Call WA (2021a) and Bullen (2023), includes Category 1 maternity/diurnal roost sites with permanent occupancy, which are essential for the daily and long-term survival of ghost bats; Category 2 maternity/diurnal roost caves with regular diurnal occupancy that make up an 'apartment block' grouping to support the daily and long-term presence of ghost bats; and Category 3 roost caves with occasional occupancy when adjacent to Category 2 caves, as these are considered to be a part of an 'apartment block' and therefore critical habitat to support reproducing females and ensure the ongoing presence of ghost bats in the area (Bat Call WA, 2021a).

Non-invasive genetic monitoring using SNP genotyping (see Section 4.1.7) suggests that ghost bats in the Pilbara typically roost in small groups (< 10 individuals) and show site fidelity to roost clusters within 10 km of each other (DBCA, 2021a; Ottewell *et al*., 2022; Prada *et al*., 2023), though longer flight distances between roost clusters (25-130 km; R. Sun pers. comm.) have been recorded. Hence, the viability of ghost bats in the Pilbara appears to be linked to the maintenance of interconnected roosts in the landscape.

4.1.4 Threatening processes

Philopatric roost sites in the Pilbara are associated with underground mines and natural caves in banded ironstone strata (Woinarski *et al*., 2014). Therefore, loss of roosting sites and degradation of foraging habitat due to mining and infrastructure development are considered the greatest threats to ghost bats in the region (Cramer *et al*., 2022). Few maternal roost sites have been identified (Richards *et al*., 2008) and of those that have, most are not protected and are at risk of being lost (Woinarski *et al*., 2014; TSSC, 2016a). Several large colonies in the Chichester subregion are subject to nearby mining activities and others have been lost to development (e.g., Bulletin mine at Bamboo Creek; Bat Call WA, 2021a). The development of BHP's Mining Area C will result in the disturbance of 36 known ghost bat roosts and over 14,000 ha of foraging habitat, while 27 roosts will be retained at the site (BHP, 2022a).

Other threats to ghost bats include the entanglement of ghost bats in barbed wire fences; the future invasion of cane toads; the cumulative impacts of disturbance and environmental change; the impact of climate change on prey availability and cave microclimate; human disturbance of roosts; secondary impacts of mining (i.e., noise, vibrations and dust from drilling blasting and machinery movement, artificial lighting and vehicle traffic); and competition with, and predation by, feral cats (Cramer *et al*., 2022). Large-scale wind farms have been identified as an emerging threat (Bullen, 2023).

Concerningly, the species extent of occurrence continues to decline behind the cane toad front (TSSC, 2016a; White *et al*., 2016), which is predicted to reach the Pilbara by 2037-2046 (Southwell *et al*., 2017). Ghost bats lack resistance to bufonid toxins (Shine *et al*., 2016) and cane toads have been implicated in the decline of ghost bat colonies elsewhere (White *et al*., 2016), however, the potential impacts of cane toads on ghost bats in the Pilbara is unknown (Cramer *et al*., 2022).

As for the PLNB, there is evidence that interactions with feral cats may threaten ghost bats. Feral cats and piles of discarded ghost bat remains (wings) have been observed at known roosting sites (e.g., Klondyke Queen; Bat Call WA, 2021a), which is consistent with cat predation events on bats elsewhere (Welch and Leppanen, 2017). Large ghost bat colonies have temporarily abandoned permanent roosts in the presence of feral cats (Bullen, 2023), though the level of threat feral cats pose at the population level is unknown.

4.1.5 Conservation status

The ghost bat is listed as 'Vulnerable' under the WA *Biodiversity Conservation Act 2016* (Government of Western Australia, 2016), the Commonwealth's *EPBC Act 1999* (DCCEEW, 2023c) and on the IUCN Red List of Threatened Species (Armstrong *et al*., 2021b). Recent changes to the species' EPBC status reflect population declines of > 30% across their contemporary range, including the loss of roost sites (abandoned mines) in the Pilbara (TSSC, 2016a). Of the six largest colonies in the eastern Pilbara, two have been destroyed, while the remaining four are showing signs of collapse, flooding and/or disturbance (Cramer *et al*., 2022). Conservation Advice exists under the *EPBC Act* (TSSC, 2016a), but there is no formal recovery plan for the ghost bat (DCCEEW, 2023c).

4.1.6 Population status

The global population is estimated to be less than 10,000 individuals, with the species currently exhibiting a decreasing population trend (Armstrong *et al*., 2021b). Woinarski *et al*. (2014) predicted an ongoing decline of > 10% over three generations (24 years) and raised concern that maternity roosts in the Pilbara could potentially be mined-out over the next 30-50 years, with the majority of roost sites destroyed over coming decades. Well known major roost sites within the Pilbara have since shown evidence of collapse, flooding and/or human disturbance, including active mineral exploration (TSSC, 2016a). An estimated 1300-2000 ghost bats now inhabit the Pilbara region (TSSC, 2016a).

Emerging genetic approaches, for example scat DNA-based genotyping of individuals using polymorphic microsatellite loci (e.g., Worthington Wilmer *et al*., 1999; Augusteyn *et al*., 2018; Ottewell *et al*., 2020) or SNP loci (e.g., Ottewell *et al*., 2021, 2022; Prada *et al*., 2023), combined with SECR analyses can now be used to estimate ghost bat abundance more precisely. Such technology can also be used to identify individuals, their sex and kinship patterns, examine individual movement patterns, and conduct population genetic analyses (Carroll *et al*., 2018).

4.1.7 Genetic structure

The ghost bat comprises several genetically distinct subpopulations, including the Pilbara and Kimberley populations in WA (Worthington Wilmer *et al*., 1994, 1999). Within the Pilbara, genetic clusters have been identified in each of the subregions (Chichester, East Hamersley and West Hamersley), with further sub-structuring evident in the East Hamersley population (Ottewell *et al*., 2017). Overall, however, genetic structuring is weak and there is evidence of admixture, consistent with high levels of (presumably male-biased) dispersal providing genetic connectivity within and between subregions (Ottewell *et al*., 2017). While genetic diversity is consistently high amongst subregions and there is no evidence of recent genetic bottlenecks (Ottewell *et al*., 2017), observed heterozygosity was lower (Ho = 0.68) than previously reported (Ho = 0.81; Worthington Wilmer *et al*., 1999), which may reflect recent population declines. The complete mitochondrial genome of the ghost bat was also recently sequenced (Zandberg *et al*., 2021).

Similar to the bilby, an individual-based SNP array has been developed for repeatable genotyping of ghost bat scats (R. Sun pers. comm.) and is currently the method of choice for monitoring populations in the Pilbara (Ottewell *et al*., 2021; DBCA, 2021a). This methodology is also being implemented in the NT (N. Hanrahan pers. comm.) and Qld (Ottewell *et al*., 2023). DBCA are currently using SNP genotypes to identify individuals, their sex and kinship patterns to understand spatial and temporal patterns of cave use. Individual genetic ‘capture’ records are entered into a georeferenced database to enable mark-recapture analysis and to examine individual movement patterns and cave use. As SNP genotypes accumulate from projects in the Pilbara and elsewhere in WA, the NT and Qld, broader analyses of the genetic relationships amongst regional populations can be undertaken (K. Ottewell pers. comm.).

4.2 Identification of research priorities

Curtin University hosted a workshop in March 2021 to review current knowledge and research being undertaken on ghost bats across Australia to identify knowledge gaps and prioritise future research in the Pilbara (Cramer *et al*., 2022). The research priorities outlined below aim to fill current knowledge gaps that will help to inform environmental impact assessments and maximise conservation outcomes for ghost bats in the Pilbara (Cramer *et al*., 2022).

4.3 Future research directions and management actions

4.3.1 Future research directions

At the 2021 workshop, five research themes (ranked according to priority), and associated research priorities and key tasks/questions, were identified for the ghost bat (Cramer *et al*., 2022; summarised in Table 7). These priorities closely align with those of the PLNB.

***Table 7** Future research directions for the ghost bat (Macroderma gigas) in the Pilbara (modified from Cramer et al., 2022)*

Rank	Topic	Research directions
1	Habitat use – identifying critical diurnal roosts and foraging habitat	• Better understand which individual roost sites and/or roost complexes are critical to survival, including seasonal influences. • Improve knowledge on the influence of disturbance on roost sites/complexes in relation to movement, survival, and breeding success. • Better understand the relationship between diurnal roosts and foraging habitat, including the influence of seasonal variation in resource availability. • Determine the key characteristics of foraging habitat and the influence of disturbances on those. • **Outcome**: Identification of critical habitat requiring protection.
2	Distribution, movement and dispersal	• Determine the distribution of ghost bats in the Pilbara, including outside of active mining areas. • Improve understanding of roost residency, local movement, and long-distance dispersal, including the influence of season, sex, and age cohort on movement patterns. • Landscape features that support movement require further evaluation, including the mechanisms driving this movement. • **Outcome**: Improved understanding of factors influencing movement to inform conservation management.
3	Population size, persistence and long-term trends	• Assess changes in population size (region-wide) and factors influencing those. • Increase knowledge of age structure and recruitment rates to inform population persistence. • Ongoing data collation, establishment of survey and monitoring protocols and implementation of a Pilbara-wide monitoring program would assist in establishing baseline population trends for the ghost bat. • **Outcome**: Improved understanding of factors influencing population persistence to inform conservation management.
4	Impacts from mining, infrastructure development and other human activities	• Better understand the local and cumulative indirect impacts of mining activities within the vicinity of roosts, including variability among sex and life stage (e.g., lactating females). • Improve knowledge on the characteristics of natural roosts (microclimate, chamber architecture, spatial arrangement in landscape) to inform artificial roost construction/placement and assess their effectiveness. • **Outcome:** Improved understanding of the influence of mining disturbance and strategies to mitigate these.
5	Research for adaptive	• Strengthen understanding of other potential threats such as entanglement in barbed wire fences, cane toads and feral cat

Rank	Topic	Research directions
	management of other threats	predation (e.g., camera monitoring at roost entrances, predator diet analyses), and mitigation strategies to address these. • **Outcome**: Threat mitigation strategies to facilitate persistence of the ghost bat in the Pilbara.

4.3.2 Management actions

The lack of a comprehensive regional management plan has been implicated as an impediment to the successful conservation of ghost bats in the Pilbara (Armstrong, 2010; 2011). Given that few ghost bat colonies are currently monitored or managed, and there is no formal integration between mining projects (Cramer *et al*., 2022), regular collaboration and data sharing were advocated as supportive strategies to conserve ghost bats in the Pilbara at the 2021 workshop (Salt, 2021a). Management options to promote the ongoing survival of the ghost bat in the Pilbara were also briefly discussed at the workshop and are summarised in Table 8 below.

Table 8 *Management options for the ghost bat (Macroderma gigas) in the Pilbara (modified from Salt, 2021a, 2021b).*

Theme	Management actions
Habitat protection	• Preservation of known roosting sites and core foraging habitat.
Habitat restoration	• Evaluate the effectiveness of artificial roosts, in particular usage (i.e., numbers of bats, timing of use, breeding) and longevity of use. • Evaluate time lag and associated impacts on local populations between the establishment of restored habitat and the delivery of expected environmental services to ghost bats.
Mining disturbance	• Provision of information and advice on new mining proposals on the preferred habitats and ecological requirements of ghost bats so that planning to mitigate impacts can be undertaken. • Develop guidelines and implement/evaluate known buffer best-practice and ensure formal requirements evolve as related research progresses. • Critical habitat buffers (i.e., 50 m from cave extremities during pre-mining phases, and larger buffers 150-250 m or greater during mining operations) have been proposed for category 1 and 2 roosts (Bullen, 2023), however long-term monitoring is needed to determine their effectiveness at eliminating/minimising disturbance.
Collaboration and adaptive management	• Establish agreed reporting standards for new projects to facilitate the development of meaningful, sharable datasets across the Pilbara. • Identify barriers to data sharing and creation of software tools to navigate and collate data relevant to the management of ghost bats in the Pilbara.

Theme	Management actions
	• Implement adaptive management to enable further improvements to best practice techniques. • Design/implement standardised survey and monitoring techniques.
Predator control	• Targeted feral cat control at important roosts sites (e.g., using Felixer™ feral cat grooming traps at category 1 and 2 roost entrances) may be beneficial. • Feral cat baiting using *Eradicat*® may also be an option, which could be applied by hand at the local scale near roosts or aerially at the broad scale targeting foraging habitat.
Barbed wire fence elimination	• Introduce incentives for the replacement of existing barbed wire fences in the region. • Trialling alternative fence types such as plain wire strands with high visibility broad tape (as for night parrots; Section 6.1.4); or bat deflectors (Bat Call WA, 2021b) in the vicinity of ghost bat habitat could also be considered.

5 Pilbara Olive Python (*Liasis olivaceus barroni*; Smith, 1981)

Order Squamata; Family Pythonidae

5.1 Summary of current knowledge

5.1.1 General overview

The Pilbara olive python (POP) is a distinct subspecies (*barroni*) of the olive python (*Liasis olivaceus*) endemic to the Pilbara and northern Gascoyne regions in WA (Smith, 1981; Pearson, 1993; Storr *et al*., 2002). It was distinguished from *L. olivaceus* by Smith (1981) on the basis of scale counts [fewer (58-63) midbody scale rows and more (374-411) ventrals]. The POP is reputed to grow up to 6.5 m long (Shine,1991), but typically reaches 3 to 4 m in length (Pearson, 2007). The body is unpatterned with a dull olive-grey or red-brown upper surface and creamy-white belly (Smith, 1981; Storr *et al*., 2002). Cryptic in nature, the POP is a non-venomous, nocturnal top-order predator inhabiting rocky environments and riparian vegetation at relatively low densities (Pearson, 2007). Habitat preferences and prey selection are believed to vary markedly between differently sized cohorts. Females are capital breeders (Pearson, 2013), mating during the cooler dry season (June to August), probably laying in September/October and incubating eggs until hatchlings emerge from the nest in late December/early January (Pearson, 2007). Males may travel large distances (up to 3 km) in search of females during the breeding season (Pearson, 2007).

5.1.2 Distribution

The POP occurs throughout the Pilbara at all elevations within its range (including islands; Pearson *et al*., 2013), with the species distribution extending south into the Gascoyne bioregion of WA at least as far south as Yinnetharra Station (Pearson, 2007) (Figure 5).

5.1.3 Habitat requirements

Defining habitat critical for the survival of the POP is difficult due to a lack of research on habitat use and life history. For instance, habitats that juveniles use remain unknown. Likewise, sites that are important for reproduction in adults are poorly understood as only two nesting sites have ever been located in rocky hills away from river systems. Nonetheless, a ‘default’ definition has emerged based on the description of common habitat characteristics where people tend to encounter this species. That being rocky gorges, gullies, and permanent waterholes (BHP, 2022a).

Pilbara olive pythons are typically encountered in riparian areas during the warmer months (e.g., gorges and around waterholes, D. Pearson pers. comm), and in rocky habitats (e.g., rock crevices, Rayner *et al*., 2016) at other times of the year (Doughty *et al*., 2011). However, further research using radio-tracking to trace movements is required to determine the seasonal habitat preferences of the taxon. In Millstream-Chichester National Park, POPs are relatively inactive during the winter, although mating occurs at this time. Adult males may move considerable distances in the cooler months to locate receptive females (Pearson, 2007, unpubl.).

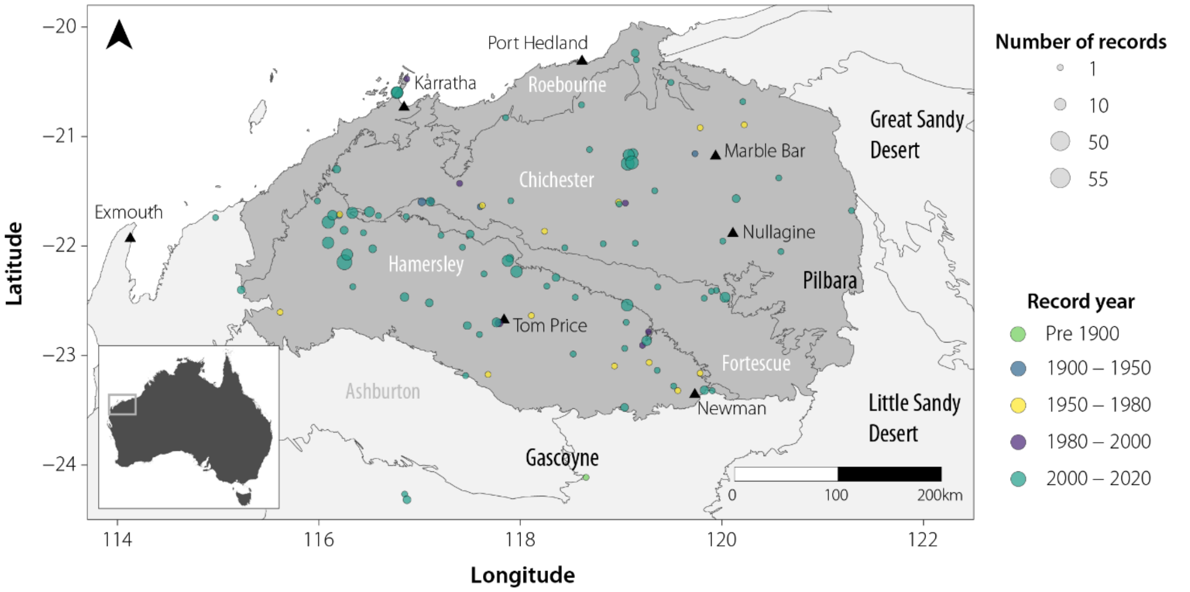

Figure 5 *Map of the Pilbara region with the locations of Pilbara olive python (Liasis olivaceus barroni) records from the Western Australian Department of Biodiversity, Conservation and Attractions' NatureMap database from 1990-2021 (https://naturemap.dbca.wa.gov.au, downloaded July 2021) and R. Palmer (unpubl.). Point size represents the number of NatureMap records reported within a 20 km radius for each collection year period (specified by colour). The darker grey represents the Pilbara IBRA region, with map borders showing IBRA subregions.*

Radio-tracking has shown that the POP occupies discrete home ranges on the Burrup Peninsula in the Pilbara (from 87 to 449 ha; Tutt *et al*., 2004), visiting favourite shelter and ambush sites repeatedly (Rayner *et al*., 2016); males generally have large home ranges, but there is a wide range of variation in size (Pearson, 2007). The seasonal use of different areas may be separated by several kilometres (e.g., in Millstream-Chichester National Park; D. Pearson pers. comm.). Species distribution modelling by Cadenhead *et al*. (2015) identified '*slope, the proportion of cells classified as valley bottoms (erosional), and three parameters describing temperature*' as the most important variables predicting POP distribution, though sample size was small (n = 37). Potential habitat predicted by Eco Logical (2014) was '*most heavily concentrated in the ranges of the southern and central areas of the Pilbara bioregion; however potential habitat was also predicted in association with river plains in the north and the ranges and outcrops of the east*'. Modelling has been limited by the lack of records across the known range of the species and the probable bias towards summer records in riparian areas.

The POP has a variable and opportunistic dietary strategy, capitalising upon prey species of various size as would be expected from a gape-limited predator. The POP is a proficient swimmer and will ambush prey at waterholes (Pearson 2007) but has also been observed on euro (*Osphranter robustus*) trails in ambush positions several kilometres from free water (Tutt *et al*., 2004) and ascending date palms to capture fruit bats (D. Pearson pers. comm.). POPs are known to prey upon macropods, fruit bats and birds, particularly corellas and ducks (Pearson, 2007; Ellis, 2013; Ellis and Johnstone, 2016). Ellis *et al*. (2021) detected the remains of several mammal species, a reptile and a feral cat from eight faecal pellets presumed to be those of adult POPs from the central and eastern Pilbara regions. In a separate study that utilised a DNA metabarcoding approach to investigate the diet of the POP in the Robe River valley (Biologic, unpubl.), birds were the only prey species identified (n = 4 samples), including two previously unknown prey species (*Aythya australis* and *Fulica atra australis*). POPs are known to predate other Pilbara MNES species including northern quolls (Palmer *et al*., 2020). Predation of the Pilbara leaf-nosed bat is also suspected based on observation and video evidence (R. Bullen pers. comm.).

POP scats cannot be differentiated from other sympatric predators based on scat morphology alone, as there are a number of other sympatric species that produce similar scats. In addition, the taxonomic resolution to which remains can be identified is often poor. DNA metabarcoding may be useful for dietary analysis (e.g., Swinehart *et al*., 2023) and can be used to confirm both the identity of the predator species that produced the scat, and the prey consumed. This non-invasive tool could be used to evaluate the diet of both juvenile and adult POPs. Collecting scats from POPs when handled during research work is also an easy way to obtain dietary data and has the advantage that the size of the python can also be obtained.

5.1.4 Threatening processes

Threats to POPs are poorly understood and most are speculative. The destruction of habitat (blasting, removal, flattening of rock shelters) during mining processes and infrastructure development are likely to have profound impacts on resident POP populations. Some possible threats to the POP include habitat fragmentation and degradation due to resource development and pastoralism that results in the loss or reduction of habitat quality, shelter sites and/or prey resources. Local populations near transport corridors may also be impacted by vehicle collisions (Pearson, 1993).

Predation by, and competition with, introduced predators (Pearson, 2007; Chapple *et al*., 2019) may also impact on populations. Loss or suppression of prey species is a potential threat where introduced predators occur, or where other factors are impacting prey populations such as habitat change linked to pastoralism or mining activities. Foxes have a predominantly coastal distribution in the Pilbara and are believed to have caused the decline of Rothschild's rock-wallaby (*Petrogale rothschildi*) on the Burrup Peninsula as well as the loss of the Black-flanked rock-wallaby (*P. lateralis*) on Depuch Island (Kinnear *et al*., 1984; Pearson and Kinnear, 1997). Rock-wallabies are known prey for the POP. The loss of important prey items may delay POP maturation and breeding frequency, especially in females.

Due to their broader distribution in the Pilbara, feral cats may pose a greater predation risk to juvenile POPs than foxes. One feral cat study found unidentified snake material in five of 135 feral cat scats (3.7%) examined from the Robe River valley (Palmer *et al*., 2020). Wild canids (foxes and wild dogs) have been reported to kill large adult carpet pythons (*Morelia spilota*) when encountered in open environments (Heard *et al.* 2006) so their potential impact also needs to be considered and clarified.

Other generalised potential threats to the POP include altered fire regimes (Burbidge, 2004); the emission of noise and light; climate change; and the future invasion of cane toads (BHP, 2016; Booth *et al*., 2021). Within riparian zones, overgrazing and trampling by domestic and introduced livestock, may particularly reduce important shelter and ambush sites of juveniles (D. Pearson pers. comm.). Mining associated dewatering can alter regional hydrology by lowering water tables or drying waterholes/springs (e.g., Weeli Wolli Spring in the Fortescue River Basin; Booth *et al*., 2021), and could reduce foraging habitat for the POP (BHP, 2016). Dewatering can also lead to increased and constant flows (e.g., Robe River) that could alter the use of some ambush and shelter sites. Deliberate road kills and the public killing POPs when misidentified as poisonous snakes (Pearson, 2007), and tourism-related disturbance (e.g., public visitation of waterholes; Pearson, 2003) can pose a threat to local populations.

It is unknown whether cane toads will impact the POP. While some terrestrial snake species have declined following the invasion of toads (i.e., from death due to lethal toxic ingestion; Phillips *et al*., 2003), other snake species may be unaffected (Shine, 2010) or even benefit from the presence of toads (e.g., due to declines in other apex predators; Brown *et al*., 2020). Cane toads may cause the death of juvenile POPs, but the extent of any impact is unknown.

5.1.5 Conservation status

The POP is listed as 'Vulnerable' under the WA *Biodiversity Conservation Act 2016* (Government of Western Australia, 2016) and the Commonwealth's *EPBC Act 1999* (DCCEEW, 2023b). A Conservation Advice Notice has been written for the POP under the *EPBC Act* (DEWHA, 2008), however no recovery plan is currently in place. The olive python *Liasis olivaceus* is listed as 'Least Concern' on the IUCN Red List of Threatened Species (Doughty *et al*., 2017).

5.1.6 Population status

Currently there is insufficient data to reliably estimate population size, however the species is considered susceptible to decline (Booth *et al*., 2021). It is difficult to monitor POPs given the species is highly cryptic, relatively untrappable using conventional techniques, and does not usually trigger camera traps (Booth *et al*., 2021). Monitoring of a prey species (Rothschild's rock-wallaby) as a surrogate for POP abundance was trialled (Morris *et al*., 2016), however it is unlikely to be indicative for a generalised predator.

Radio-tracking at various sites in the Pilbara has provided vital information about POP ecology and their habitat use (e.g., Pearson, 2003; Tutt *et al*., 2004; Pearson, 2007). BHP, in collaboration with Helix solutions, Biota Environmental Sciences, and the eDNA Frontiers Laboratory at Curtin University are currently implementing a POP monitoring program using a combination of radio-tracking and eDNA extraction techniques from water samples to trace movements and gather data on the genetic characteristics of the POP (BHP, 2022b).

An eDNA test for the POP was developed by EnviroDNA, and in collaboration with Spectrum Ecology (EnviroDNA, 2021), targeted eDNA sampling was successfully trialled in the field (Ellis *et al*., 2022). Mousavi-Derazmahalleh *et al*. (2023) demonstrated that a metabarcoding assay developed for reptiles (West *et al*., 2021) could successfully detect the presence of POP eDNA from rock pool water samples. However further research is needed to evaluate other substrates (e.g., soil) and examine spatial and temporal variation in DNA persistence (Mousavi-Derazmahalleh *et al*., 2023). For instance, it is not known if individual POPs were present in pools hours or weeks prior to water sampling.

5.1.7 Genetic structure

A genetic survey of olive pythons using nuclear microsatellite and mitochondrial markers obtained from scale clips (Pearson *et al*., 2013) showed that olive pythons from the Pilbara and Kimberley regions comprise two Evolutionary Significant Units, such that it may warrant the POP being recognised as a separate species from the northern olive python population. This study found no evidence of genetic bottlenecks in either population, however, the POP population had half the genetic diversity of the Kimberley population and showed little phylogeographic structure; though sample sizes were small (n = 25 and n = 22, respectively) and Millstream was over-represented compared to other sites. Further comparison with other populations would help to provide more context. A collaborative eDNA genomics study (BHP, 2022b) is seeking to generate the first olive python reference genome and conduct analyses to better understand population genetic structure, genetic diversity and inbreeding.

5.2 Identification of research priorities

Research priorities for the POP were identified at a workshop hosted by DBCA in 2013 (Salt, 2013a). Research outputs were not published but aimed to:

1. Undertake a literature review.
2. Develop survey and monitoring techniques (combination of priorities 2 and 3).
3. Better understand habitat requirements.
4. Understand the breeding biology.
5. Better understand prey relationships.
6. Better understand predator relationships.

There have been no further workshops to review progress and re-evaluate the POP research agenda since this time. Ellis and Coppen (2014) compiled a bibliography containing information from 1923 to 2014.

5.3 Future research directions and management actions

5.3.1 Future research directions

A revisionary workshop would help to refine future research and management priorities for the POP. Until such time, based on existing knowledge, we propose a number of research directions ranked as high, medium or low (Table 9).

Table 9 *Future research directions for the Pilbara olive python (Liasis olivaceus barroni) in the Pilbara, ranked high, medium or low.*

Priority	Topic	Research directions
High	Distribution	• Collate verified location records, and relevant environmental spatial information, to generate a species distribution model. • **Outcome**: Better understanding of the distribution of the POP in the Pilbara to guide future surveys and inform management decisions to protect critical habitat.
High	Habitat requirements and breeding biology	• Build on existing ecological information to identify habitat requirements. • Better understand reproductive biology using radio telemetry to locate critical mating and nesting sites. • Clarify reproductive potential of females and the dispersal and habitat use of neonates and juveniles. • Consider genetic studies to determine if the POP is polygamous. • **Outcome**: Better understanding of habitat use and reproductive requirements to identify critical habitat requiring protection.
High	Survey and monitoring	• Review methods already used to survey and monitor POPs and other similar species. • Investigate the effectiveness of known or novel survey techniques (e.g., Walkup *et al*., 2023) to locate POPs. • Trial monitoring techniques at the site of a known population to determine an optimal monitoring design (timing and intensity). • Develop monitoring protocols and identify suitable monitoring sites. • **Outcome**: More effective and efficient survey and monitoring approaches to measure population trends and management effectiveness.
High	Threats	• Investigate the impacts of planned and unplanned fires with radio telemetry of individual pythons, and their prey. • Monitor POP populations at mine sites (from early stages to completion) to determine sources of mortality, changes to demographics and habitat use.

Priority	Topic	Research directions
		• Better understand the impact of grazing animals on habitats that are thought to be significant for juvenile POPs (e.g., riparian forests and swamplands). • Examine introduced predator impacts by examining changes to populations of important prey items. • Investigate the impacts of translocation on individual pythons e.g., do they survive and establish new home ranges? • **Outcome**: Improved understanding of threats and mitigation strategies to reduce impacts.
Medium	Population genetics and structure	• Improve existing knowledge on the genetic diversity and structure of populations across the Pilbara through analysis of blood, tissue or scat samples (existing and targeted sampling). • **Outcome**: Increased understanding of the genetic structure of POP populations and impacts of fragmentation to inform management strategies that facilitate population connectivity.
Low	Dietary requirements	• Trial non-invasive DNA metabarcoding of field collected scats to further evaluate the diet of both juvenile and adult POPs. • **Outcome**: Improved knowledge on habitat requirements in relation to resource availability.

5.3.2 Management actions

Given that the nature and relative severity of potential threats faced by POPs is poorly understood, relevant research is needed to determine their importance. Clearly, complete habitat removal during mining operations of ironstone ranges will directly impact local POP populations. The role of other possible threats is less clear. It is suspected that neonate and juvenile POPs are more susceptible to environmental change due to overgrazing and inappropriate fire regimes, and most vulnerable to predation (Pearson, 2013). As for other Pilbara MNES species, management actions that promote habitat integrity and connectivity may benefit the POP, in particular targeting areas or populations of high conservation priority (DEWHA, 2008). While there is no available information on the impact of predators on POPs, their ongoing control will at least benefit a number of their prey (and other MNES) species. Threat management options for the POP are summarised below in Table 10.

Table 10 *Threat management options for the Pilbara olive python (Liasis olivaceus barroni) in the Pilbara.*

Threat	Management actions
Habitat disturbance during mining and infrastructure construction	• Provision of information and advice on new mining proposals on the preferred habitats and ecological requirements of POPs so that planning to mitigate impacts can be undertaken. • This may include siting roads, camps, etc, away from known or suspected POP habitat and limiting mining of critical habitat where possible.

Threat	Management actions
Habitat alterations due to landscape scale impacts	• Consider fencing around important gorges or known habitat (e.g., rock holes or springs) to exclude cattle and feral herbivores. • Landscape control of feral herbivores (e.g., aerial culling). • Establish alternative water sources to avoid cattle using natural gorges or areas where riparian vegetation will be damaged by their activities. • Implement fire management in POP habitat to prevent direct mortality during fires; avoid the removal by fire of large areas of contiguous vegetation in suitable habitat; avoid hot fires around cliff edges that may result in the mortality of rock figs (*Ficus* spp.), important for shelter and ambush sites.
Predation by introduced species and their impacts on preferred prey	• Undertake control of introduced predators impacting on the diversity and abundance of prey used by POPs. • Species such as Rothschild's rock-wallaby and the northern quoll may be especially important for some POP populations.
Direct human-induced mortality	• Encourage the inclusion of POP information in the induction of mine/ infrastructure staff. • Recommend avoidance at night of tracks and roads that cross POP habitat or if this is not possible, institute road speed restrictions and consider the installation of fauna crossings (e.g., underpasses). • Provision of information to the general public, especially residents of Pilbara towns, about POPs and the dangers of driving at night for both this species and other Pilbara wildlife. • Alert residents of Pilbara towns via councils and tourist information centres about snake removal services (to avoid their deliberate killing) and if translocation is required; make those translocations to nearby suitable habitat. Consider post-translocation monitoring to determine outcome.

6 Night Parrot (*Pezoporus occidentalis*; Gould, 1861)

Order Psittaciformes; Family Psittaculidae

6.1 Summary of current knowledge

6.1.1 General overview

The night parrot is a small (~ 100 g), elusive, ground-feeding and ground-nesting parrot endemic to remote arid and semi-arid Australia (Higgins, 1999; Leseberg, 2021). Once presumed to be extinct, an extant population was discovered in south-western Qld in 2013 (NESP TSRH, 2019). Nocturnal and highly cryptic in nature, the night parrot measures about 22-25 cm in length and is distinguished by its green plumage with mottled black and yellow markings, yellow belly and short tail (DBCA, 2017). Night parrots occur at low densities, taking refuge in roost tunnels constructed in low, dense vegetation during the day and emerging at night to feed (Leseberg, 2021). Relatively sedentary, night parrots inhabit roost sites continuously over several years (Murphy *et al*., 2017b) and breeding follows significant rain, rather than being strictly seasonal (Jackett *et al*., 2017; Murphy *et al*., 2017a). Clutch size typically ranges between two and four (Higgins, 1999; Murphy *et al*., 2017a).

6.1.2 Distribution

The night parrot is currently known from at least eight sites in northern WA (Figure 6) and a single site in south-western Qld (Leseberg *et al*., 2021b; A.H. Burbidge, unpubl.). Prior to European colonisation, the night parrot occurred throughout arid and semi-arid Australia (Higgins, 1999), with probable records from all mainland states and territories except NSW and the ACT (Leseberg *et al*., 2021a). The severe decline and consequent range contraction of the night parrot has coincided with the spread of pastoralism and its accompanying threats (Leseberg, 2021), although feral cat predation and altered fire regimes have likely compounded the decline (Leseberg *et al*., 2021a). It is estimated that the night parrot has now been extirpated from 61% of its former potential habitat and has also suffered a 36% decrease in mean patch size (Ward *et al*., 2022).

In WA, there have been a small number of purported sightings in the centre and north of the state since 1912 (including the Pilbara, see Davis and Metcalf, 2008: Figure 1; Olsen, 2018), however, it was not until 2017 that night parrots were confirmed (via photograph) in the East Murchison bioregion of WA (Jackett *et al*., 2017). The night parrot has since been identified at several other sites in northern WA (NESP TSRH, 2021; A.H. Burbidge, unpubl.), including the Pilbara, with most records obtained during acoustic surveys using autonomous recording units (ARUs) (see robust and repeatable survey protocol developed by Leseberg *et al*., 2022). Only a few of these records are from long-term stable roost sites, with the remainder being records of birds that are foraging, or moving between sites (Leseberg, 2021). Central and northern WA is now considered the stronghold for the species (Leseberg, 2021; Leseberg *et al*., 2021a).

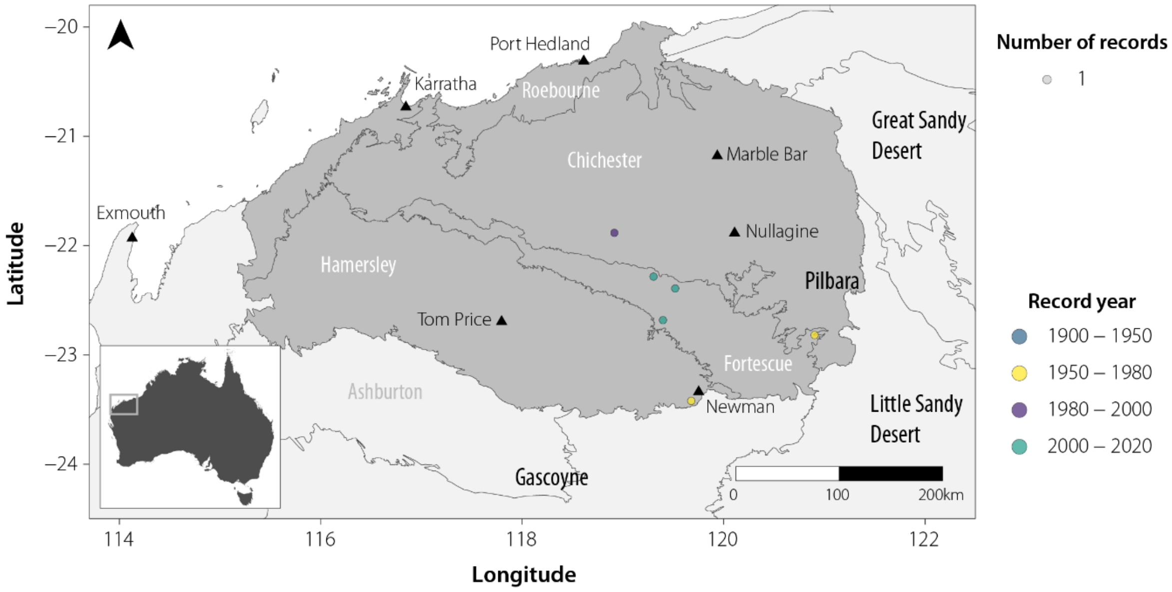

Figure 6 *Map of the Pilbara region with the locations of probable and confirmed night parrot (Pezoporus occidentalis) records from Leseberg et al. (2021) and A.H. Burbidge (unpubl.). Uncertain reports are not included. Point size represents the number of records reported within a 20 km radius for each collection year period (specified by colour). The darker grey represents the Pilbara IBRA region, with map borders showing IBRA subregions.*

6.1.3 Habitat requirements

There is still much to be learnt about night parrot habitats but known key attributes have been described by the Night Parrot Recovery Team (2020). Night parrots inhabit semi-arid grasslands, roosting and nesting in long-unburnt spinifex hummocks (ring-forming *Triodia* spp., particularly *T. longiceps* and *T. infesta* (formerly known as *T.* aff. *plurinervata*; Jackson *et al*., 2018). All contemporary roosting observations have been from *Triodia* dominated habitats, but historically night parrots have also been reported from chenopod-dominated shrublands during the day (Leseberg, 2021; Leseberg *et al*., 2021b; NESP TSRH, 2021). In WA, almost all high probability and confirmed records are associated with drainage lines, particularly paleodrainage lines (Burbidge and Hamilton 2013; Jackett *et al*., 2017; A.H. Burbidge, unpubl.). Guidelines for determining the likely presence of night parrot (*Pezoporus occidentalis*) in Western Australia are currently being drafted by DBCA (A.H. Burbidge pers. comm.).

At night, night parrots are known to travel large distances to open floodplains, waterholes and run-off areas to feed on key seed-producing flora (e.g., grasses, herbs and forbs). Foraging habitat tends to be open, typically on flat or gently sloping ground, and highly productive and floristically diverse (Murphy *et al*., 2017b; Leseberg, 2021). Known foraging habitat in WA includes alluvial flats and chenopod dominated systems, especially *Sclerolaena* (Jackett *et al*., 2017; Jackson *et al*., 2018), but there are no detailed data on foraging in WA. The diet of night parrots in WA is unknown.

6.1.4 Threatening processes

Threats to the night parrot include predation by introduced predators (particularly feral cats); habitat degradation, loss and fragmentation (i.e., from potash mining and livestock overgrazing/trampling, particularly cattle); inappropriate fire regimes that leave little or no unburnt roosting habitat; rabbit grazing; and climate change (i.e., increased frequency or length of droughts and rising temperatures/heat waves) (NESP TSRH, 2019; Leseberg *et al*., 2021b). Overgrazing by kangaroos (*Osphranter* spp.) is also recognised as a threat (NESP TSRH, 2019), particularly when numbers are high. Mortality from fence collisions may impact local or dispersing birds, though fences also serve to exclude livestock from high quality feeding habitat (NESP TSRH, 2019). Plain-top wire and high visibility broad tape fencing was installed at Pullen Pullen Reserve in 2016 and is being monitored for its effectiveness in stock exclusion and bird collision. Anecdotally, it seems there are fewer fence strikes on the tagged fence, but there are too few data yet to test statistically (Murphy *et al*., 2018; N. Leseberg pers. comm.). A king brown snake (*Pseudechis australis*) has been documented preying upon night parrot eggs at Pullen Pullen Reserve in Qld (Murphy *et al*., 2017a).

6.1.5 Conservation status

The night parrot is listed as 'Endangered' under the Commonwealth *EPBC Act 1999* (DCCEEW, 2023e; currently under threatened listing assessment, due 30-Oct-2024), and 'Critically Endangered' under the WA *Biodiversity Conservation Act 2016* (Government of Western Australia, 2016) and on the IUCN Red List of Threatened Species (BirdLife International, 2022). The Action Plan for Australian Birds recommends that the species be listed as Critically Endangered (Leseberg *et al*., 2021b). The night parrot was also selected as one of the 22 priority bird species in the Threatened Species Action Plan 2022-2032 (DCCEEW, 2022). While Conservation Advice has been established under the *EPBC Act* (TSSC, 2016b) there is no formal recovery plan for the night parrot (NESP TSRH, 2019).

6.1.6 Population status

Remnant populations in WA and Qld are small (Murphy *et al*., 2022). While it is inherently difficult to estimate the population size of an enigmatic and cryptic species with a large potential range, targeted ARU surveys across Australia have detected no more than 30 individuals since 2013 (Leseberg *et al*., 2021b). Furthermore, many such searches have failed to find any birds (Leseberg *et al*., 2021b).

Despite some improvement in detecting vocalisations, the number of night parrots in WA is unknown. As of May 2023, no new night parrot locations have been confirmed and announced from within the Pilbara IBRA region, beyond the occurrences in the Fortescue Marsh.

6.1.7 Genetic structure

The genetic structure within and between night parrot populations is currently unknown (Leseberg *et al*., 2021b). Some progress is being made in this area in a current project being funded under the Australian Threatened Species Initiative (L. Joseph and J. Austin, pers. comm.).

6.2 Identification of research priorities

DBCA hosted a workshop in 2013 to identify research priorities for the night parrot (Salt, 2013b). While research outputs were not published, significant research has since been conducted at Pullen Pullen Reserve in Queensland, providing vital information about night parrot physiology, breeding behaviour, habitat use, nocturnal movements and calling behaviour (see Kearney *et al*., 2016; Murphy *et al*., 2017a, 2017b). Far less is known about night parrots in WA, though observations by Jackett *et al*. (2017) and Hamilton *et al*. (2017) provide some information. In other work, recent studies on skull morphology (Iwaniuk *et al*., 2020; Shute *et al*., 2023) have provided insights into the visual and auditory capacities of the species. Additionally, Leseberg *et al*. (2020; 2022) provides guidelines for detecting night parrot calls in acoustic surveys.

Large knowledge gaps remain for the night parrot in WA. Research priorities were presented at the 2018 Goldfields Environmental Management Group Workshop to better focus conservation efforts and target threats (Jackson *et al*., 2018; A.H. Burbidge unpubl.). Research priorities for the night parrot in WA aim to:

1. Determine night parrot distribution (i.e., continue to model and survey potential new locations).
2. Estimate population size (e.g., genetic analysis to estimate population size and structuring; Leseberg *et al*., 2021b).
3. Better understand habitat use, in particular roosting and nesting habitat.
4. Characterise foraging habitat.

6.3 Future research directions and management actions

6.3.1 Future research directions

The research priorities identified by Jackson *et al*. (2018) are still largely relevant today, particularly within the Pilbara. Other research priorities have been identified since the 2018 workshop. Collectively, these have been captured in Table 11, with priorities ranked as high, medium or low. As for the POP, a revisionary workshop would help to refine future research priorities for the night parrot in the Pilbara.

***Table 11** Future research directions for the night parrot (Pezoporus occidentalis) in the Pilbara ranked high, medium or low.*

Priority	Topic	Research directions
High	Survey and monitoring	• Improve knowledge on the distribution of the night parrot in the Pilbara by targeted survey (ARUs). • Establish long term monitoring at selected locations to better understand population size and trends. • **Outcome**: Identification of areas important for targeted conservation management to support night parrots in the Pilbara.
High	Habitat requirements	• Better characterise roosting, nesting and foraging habitat. • Determine key food plant species. • **Outcome:** Identification of critical habitat requiring protection.
Medium	Population dynamics and structure	• Investigate the genetic structure within and between night parrot populations (Leseberg *et al*., 2021b). • **Outcome:** New knowledge on the genetic diversity and connectivity of night parrot populations to inform conservation management.
Medium	Threat mitigation – fencing, climate change and predators	• Identify fencing that will prevent cattle incursions onto habitat but prevent mortality from fence collisions (NESP TSRH, 2019). • Explore the potential threat of climate change, including the response of night parrots to extreme heat or drought (NESP TSRH, 2019). • Evaluate the role of dingoes in reducing feral cat, fox and macropod numbers in ecosystems occupied by night parrots (see Murphy *et al*., 2018; NESP TSRH, 2019). • **Outcome**: Identification of appropriate threat mitigation strategies in relation to fencing, climate change and introduced predators/competitors to facilitate night parrot persistence.
Low	Population dynamics	• Identify limitations to recruitment by examining sub-adult dispersal and mortality (Leseberg *et al*., 2021b). • **Outcome**: Implementation of appropriate threat mitigation strategies to facilitate night parrot recruitment.
Low	Threat mitigation – feral cats and weeds	• Identify tolerable feral cat densities (Leseberg *et al*., 2021b; Murphy *et al*., 2022). • Investigate the impact of invasive weeds such as buffel grass (NESP TSRH, 2021), including the complex interactions between buffel grass, fire and introduced herbivores. • **Outcome**: Identification of appropriate threat mitigation strategies in relation to feral cats and weeds to facilitate night parrot persistence.

6.3.2 Management actions

Prioritising and implementing management actions is challenging in the absence of sound knowledge of the basic biology and ecology of the night parrot. However, based on a rigorous expert elicitation process involving key researchers and others familiar with arid zone ecology and management, NESP TSRH (2021) and Leseberg *et al*. (2023) have provided relative cost estimates and recommendations for prioritising management actions for night parrots in two different types of sites ('intact' and 'degraded') containing known or potential night parrot habitat.

To support the basic ecological needs of night parrots in WA, management actions that target threats and promote habitat integrity and connectivity are most likely to benefit and facilitate the persistence of the night parrot (Table 12).

Table 12 *Threat management options for the night parrot (Pezoporus occidentalis) in the Pilbara.*

Threat	Management actions
Inappropriate fire regimes	• Fire management is critical for the retention of night parrot roosting and breeding sites and may enhance food production (Jupp *et al*., 2015). • Prescribed burning regimes should aim to reduce the risk of high-intensity fires destroying whole habitats and populations, while still retaining areas of long unburnt roosting habitat preferred by night parrots, by increasing heterogeneity of fire classes in suitable habitat (Leseberg *et al*., 2021b). • Small-scale mosaic burns using both aerial and ground-based approaches conducted during the cool season (e.g., Jupp *et al*., 2015) are likely to benefit the night parrot in the Pilbara (Jackett *et al*., 2017; Leseberg *et al*., 2023) • Although fire management practices are somewhat variable, the Indigenous Desert Alliance 10 Deserts Project regional fire management approach (https://10deserts.org/project/fire-management/), with input from DBCA, is highly relevant and could be used as a template to guide fire management in the Pilbara.
Introduced predators	• Feral cat control is considered a critical conservation action given the life history traits (e.g., ground nesting and foraging) of night parrots (Murphy *et al*., 2022) and should be implemented at known sites, guided by quantitative management targets (Leseberg *et al*., 2021b). • Intensive feral cat control using Felixer™ grooming traps and indigenous hunters was identified as the most beneficial single management strategy for the night parrot (Leseberg *et al*., 2023). • Localised, strategic aerial and/or ground baiting in core habitat, in conjunction with supplementary methods such as trapping or shooting (e.g., Comer *et al*., 2020) are also advocated (Leseberg *et al*., 2023). • Strategic aerial *Eradicat*® baiting is considered to be the most effective and efficient landscape-scale method for controlling feral cats (Algar and Burrows, 2004; Algar *et al*., 2013; Comer *et al*., 2018; Comer *et al*., 2020).

Threat	Management actions
Introduced herbivores	• Reduce the impact of grazing and trampling where appropriate (Leseberg *et al*., 2021b) and protect habitat (e.g., fencing to exclude livestock; Leseberg *et al*., 2023). • Restore degraded land (NESP TSRH, 2021); though this is considered the least effective and most expensive conservation option (Leseberg *et al*., 2023).
Land clearing	• Ensure pre-approval surveys are undertaken at potential development sites and impose controls as appropriate (NESP TSRH, 2019; Leseberg *et al*., 2021b). • Avoid clearing habitat near known night parrot populations.
Threat interactions	• Implement feral cat control and fire management (as above). • Protecting and actively managing existing intact habitat via combined management of grazing, introduced predators and fire is predicted to offer the greatest conservation benefits to night parrots (Leseberg *et al*., 2023).

7 Conclusions

Progress against the research priorities identified at stakeholder workshops has been variable among the six MNES fauna species summarised in this report. Unsurprisingly, there has been a strong focus on survey and monitoring protocols for all species which has seen new and novel approaches being developed, notably non-invasive techniques such as the use of scat DNA, camera traps and ARUs. The resulting information has provided a good understanding on the distribution of each species in the Pilbara, and with significant advancements in genomic technologies, has also allowed for an improved understanding of connectivity between subpopulations across the region. Tracing movement patterns using GPS-tracking, VHF tags and genotyping individuals using scat DNA has provided similar information at the local scale. Perhaps the night parrot is the exception here, given the few discoveries of this species in the Pilbara.

Identification of habitat critical for survival is better known for some species (e.g., northern quoll) than others (e.g., Pilbara olive python), although knowledge gaps remain for all six species. For example, the creation of artificial habitat, as has been proposed for some species (e.g., northern quolls and bats), still requires sound knowledge of the key characteristics of natural habitat/refuges and how to replicate these.

While there has been some research related to the influence of single threats on these MNES species, threat mitigation is likely to be more effective if the synergistic interactions among them are better understood, and they are managed collectively under an adaptive framework. For example, integrated management of fire, introduced predators and herbivore grazing is likely to provide benefits to all six species. The cumulative impacts of resource developments on each species is another area of concern requiring further attention. A high level of uncertainty also exists in relation to the potential impact of the cane toad given its imminent invasion of the region.

A clear message that was expressed at the workshops was the need for a collaborative approach whereby data is shared freely to enable a Pilbara-wide understanding of the population status of each species, and the management actions being undertaken to improve their conservation outlook.

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