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Conserving the Pilbara leaf-nosed bat: directions for future research and management

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ABSTRACT

The Pilbara leaf-nosed bat (*Rhinonicteris aurantia* 'Pilbara form') is a threatened insectivorous microbat endemic to the Pilbara region of Western Australia. It is at risk of significant population decline, particularly due to habitat loss from mining. To address its key threats, stakeholders from a range of backgrounds collectively listed and prioritised research actions in 2013. This exercise was repeated in 2022 to evaluate and update progress of the research priorities. We conducted a review of scientific and grey literature (2013–2023) to: (1) identify the work undertaken to date that addressed the research priorities identified in the 2013 stakeholder workshop; (2) identify the current knowledge gaps in Pilbara leaf-nosed bat ecology, conservation, and threatening processes; and (3) highlight how these gaps relate to the newly ranked 2022 priority list for both research and management outcomes. We found that the 2013 research priorities were largely unaddressed, with most publications and unpublished industry reports in the review period primarily reporting presence or monitoring data around areas of interest to the resources sector, with minimal focus on the species' conservation or management directly. Therefore, the knowledge gaps identified in 2013 were still largely relevant in 2022. Further targeted research is required to meet the 2022 priorities and better understand the habitat characteristics, movement ecology, disturbance buffer requirements, and cumulative impacts of mining on Pilbara leaf-nosed bat colonies. Overall, targeted research beyond traditional mining outputs, changes to regulatory procedure, and collaborative, adaptive management, are key to supporting the long-term persistence of Pilbara leaf-nosed bats.

Keywords: cumulative impacts, ecology, management, microbat, mining, Pilbara, *Rhinonicteris aurantia*, roosts, threatening processes.

Introduction

The Pilbara leaf-nosed bat (*Rhinonicteris aurantia* Pilbara form; Yinpterochiroptera: Rhinonycteridae; Armstrong 2006*a*) is a geographically isolated and divergent population of the orange leaf-nosed bat (*R. aurantia*) that is separated from the Kimberley and Northern Territory population by the Great Sandy Desert (Armstrong 2001, 2002, 2003, 2006*b*; Armstrong and Coles 2007). Colonies of Pilbara leaf-nosed bats are scattered across the Pilbara region; however, their distribution is influenced by the availability of suitable roost sites in geological terrains that form relatively deep caves or have been the focus historically of underground mining (i.e. adits) (Armstrong 2001). They have an obligate requirement for roost microclimates that are relatively warm and humid, and their selection of such roost sites is a consequence of their physiological limitations (Churchill *et al.* 1988; Churchill 1991; Armstrong 2001). The species is unable to enter torpor or regulate their body temperature for extended periods when exposed to relatively cool temperatures and low humidity, and they have one of the highest rates of water loss measured for any mammal species (Kulzer *et al.* 1970; Baudinette *et al.* 2000).

Pilbara leaf-nosed bats are considered threatened with local extirpation and are protected under Western Australian State (*Biodiversity Conservation Act 2016* (BC Act); Vulnerable) and Commonwealth (*Environment Protection and Biodiversity Conservation*

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Act 1999 (EPBC Act); Vulnerable) legislation. The primary threat for the species is the destruction and disturbance of roost habitat, both directly via encroachment on natural caves and historical underground mine adits by open cut mining, and indirectly through deterioration of and flooding within mine adits (Armstrong 2001; Woinarski *et al.* 2014; Bat Call WA 2021). There is no Recovery Plan or Threat Abatement Plan adopted for this species (Department of Climate Change, Energy, the Environment and Water 2022), which has contributed to a lack of accountability for stakeholders to engage in active management, although, due to the imposition of some Commonwealth approval conditions, some resource companies have committed to relatively intensive studies; however, these have only had a localised focus on stakeholder project areas (e.g. Bat Call WA 2020; Blast It Global 2020). Limited coordinated effort and communication between neighbouring stakeholders with Pilbara leaf-nosed bat habitat on their tenure also impedes effective conservation (Cramer *et al.* 2023). If mining activity were to continue without appropriate controls, Woinarski *et al.* (2014) predicted a population decline of >30% in the next 15 years (from publication date, 2014–2029) and a loss of most roosting sites in the next 30–50 years (from publication date, 2014–2044/2064), which would likely result in an increase of the species' threatened status.

To address this issue and foster a sense of ownership over the research effort needed to understand the ecological and conservation requirements of Pilbara leaf-nosed bats, the (then) Western Australian Department of Parks and Wildlife initiated a stakeholder consultation workshop in 2013 (Cramer *et al.* 2016). Attendees represented environmental consultancies, mining companies, research institutions and government agencies responsible for environmental approvals and regulation of mining proposals, and collectively determined and ranked research priorities for the Pilbara leaf-nosed bat, summarised in Table 1 (Cramer *et al.* 2016).

Subsequently, nearly a decade since the 2013 workshop, a second stakeholder workshop was held in April 2022, following a similar workshop process (Cramer *et al.* 2016). Attendees discussed the degree to which research priorities from 2013 had been addressed and, via elicitation, identified current research priorities. Research priority themes that emerged at the 2022 workshop were similar to those from 2013; however, their relative priorities differed. In 2022, priorities were consolidated into four themes to better capture the range of key tasks and questions (Table 2). The importance of management was also highlighted at the workshop, with attendees developing and ranking a list of priority management actions.

To evaluate the level of research progress on the Pilbara leaf-nosed bat that has occurred since 2013, a comprehensive survey was conducted of the literature that included peer-reviewed journals and grey literature (including local magazines and, environmental consultancy and government reports). The aim of the literature review was to: (1) identify the work undertaken to date that addressed the research priorities identified in the 2013 stakeholder workshop; (2) identify the current knowledge gaps in Pilbara leaf-nosed bat ecology, conservation, and threatening processes; and (3) highlight how these gaps relate to the newly ranked 2022 priority list for both research and management outcomes. Through these three aims, we identify the best way forward for a collective effort for the study and long-term protection of the Pilbara leaf-nosed bat.

Materials and methods

Literature was sourced from database searches and provided by members of industry, consultancies, and government agencies. Database searches involved searching for the terms 'Pilbara leaf-nosed bat' or '*R. aurantia*' on Scopus, Web of Science and Google Scholar (until April 2023). Relevant industry and consultant reports and applications were searched for using the Index of Biodiversity Surveys for Assessments website, the Government of Western Australian Environmental Protection Authority Referral website, and the EPBC Act Referrals list Basic Portal. Literature that referred to populations of *R. aurantia* outside the Pilbara region and those that only used the species name as a referenced example rather than a primary study focus were eliminated from the analysis. Reports were treated as a single document (including reports in the Supplementary material), unless only the report in the Supplementary material was supplied or sourced on its own. Repeat reports (the Biologic Environmental Survey report in the Supplementary material of Stantec 2016*a* and Stantec 2018*b*) was not repeated in the analysis of the latter report.

Table 1. Research priorities for the Pilbara leaf-nosed bat determined by the 2013 stakeholder workshop (Cramer *et al.* 2016).

Research priority	Summary
1. Pilbara leaf-nosed bat records	Collate existing data contained within unpublished environmental surveys.
2. Natural roosts	Clarify and better characterise the number and distribution of day roosts.
3. Habitat requirements	Better understand habitat requirements, particularly foraging habitat, and the movement of bats between roosts.
4. Pilbara leaf-nosed bat colonies	Provide more robust estimates of total population and colony size, and improve understanding of social behaviour.
5. Management decisions	Investigate appropriate buffers in a range of mining contexts and protocols for artificial roost construction.

Table 2. Research priorities for the Pilbara leaf-nosed bat determined by the 2022 stakeholder workshop.

Rank	Theme	Research priority	Key tasks/questions
1	Ecology	Dispersal	• Determine when and how dispersal occurs • Determine how breeding-related dispersal occurs • Understand how habitat corridors facilitate dispersal • Investigate the physical and/or ecological limitations to dispersal
		Breeding	• Define breeding seasons • Better understand breeding ecology
		Demographics	• Monitor population size and movements over time • Understand social behaviour and demographics • Determine the demographic composition of colonies • Continue surveying population and colony sizes • Better understand and monitor population trends
2	Threatening processes	Mining/infrastructure/other land uses	• Increase knowledge of appropriate buffer requirements for mining activities • Investigate and determine artificial roost protocols • Investigate the potential for mortality from wind turbines • Better understand secondary impacts of mining • Determine their resilience to different types of disturbance
		Predators/disease	• Predator dietary analysis • Determine the potential for impact of white-nosed syndrome
		Climate change	• Create population viability models • Develop a long-term multidisciplinary research focus • Investigate how climate change will impact the viability of roost sites
3	Records/data	Collate data	• Collate and analyse existing data • Develop a genetic database of individual genotypes • Include incidental data from non-Pilbara leaf-nosed bat studies in database • Increase collaboration and data sharing • Develop a standard monitoring methodology
4	Habitat	Roosts	• Clarify number and distribution of diurnal roosts • Characterise the structure and conditions in natural roosts • Determine what happens when roosts are deserted • Utilisation and movement between (at regional scale) • Investigate the fidelity of individuals to roosts • Determine the role of a nearby water source in roost site viability • Investigate the required roost microclimate conditions • Determine the utility of environmental DNA for monitoring
		Foraging/critical habitat	• Characterise and map foraging habitat and its use • Understand patterns of movement among roosts and the role of foraging resource availability

A total of 119 documents relevant to the species published between 2013 and 2023 were collated. Of those, 92% were 'grey literature' ($n = 110$) and the rest ($n = 9$) comprised of peer-reviewed scientific literature, including one book chapter and eight journal articles. Documents were assigned a binary classification ('yes' or 'no') as having addressed or considered the five key research questions from the 2013 stakeholder workshop (Table 1). Question 1 (the collation of unpublished data) was considered achieved for documents that published results in a format accessible by the public (book chapter or scientific publication). Question 2 (the distribution of diurnal roosts) was considered in studies that monitored or confirmed the presence of bats at a roost or investigated the presence at a potential roost site. Question 3 (habitat requirements) was addressed if monitoring or surveys mentioned the habitat type used or was potentially used by the species, or if surveys assessed the movement of groups or individuals. Question 4 (population and colony size and social behaviour) was addressed by literature that surveyed or monitored the number of individuals, or discussed or surveyed for social behavioural characteristics. Question 5 (disturbance buffers and artificial roosts) was considered addressed if either disturbance buffer distance or the use of artificial roosts was mentioned in the literature.

Results and discussion

We summarised the state of research addressing each of the research priorities from 2013 (below) and assessed whether research targets had not been met, were partially met or fully met in the literature in intervening years. We found that none of the priority research themes listed in the 2013 stakeholder workshop had been adequately addressed in

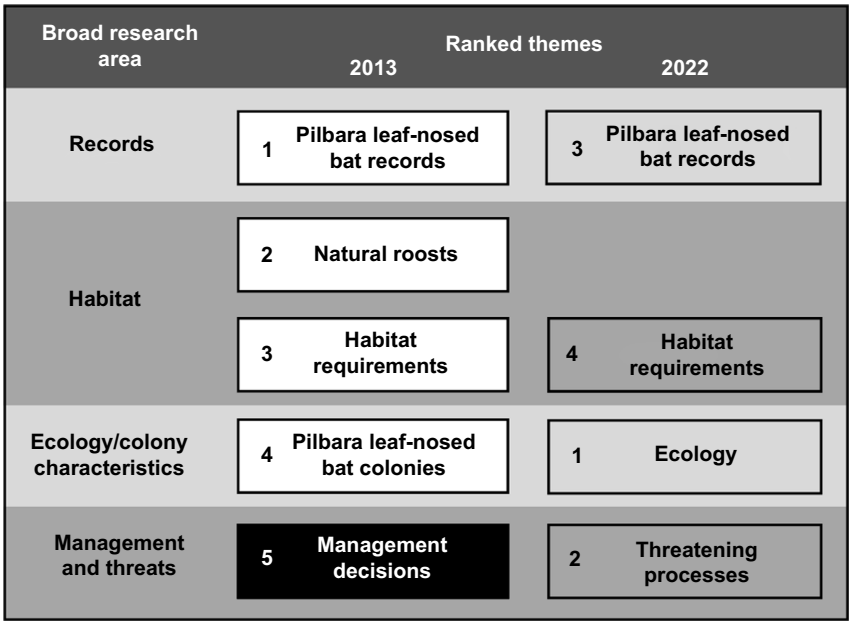

Fig. 1. The ranked research themes according to stakeholder discussion at the Pilbara Leaf-nosed Bat Workshop in 2013 and 2022. White boxes represent research targets partially met and the black box represents research targets largely unmet between 2013 and 2023. Numbers represent priority ranking.

the literature since 2013 (Fig. 1). Following review of the literature, we articulate the outstanding research gaps and how they relate to 2022 research priorities.

Research priority 1: ecology

Dispersal patterns

The research priority of highest importance identified in the 2022 stakeholder workshop was to better understand the capacity, triggers, and limitations to dispersal for the Pilbara leaf-nosed bat (Table 2). This aligns with the third priority listed in the 2013 workshop, which specified the need for a better understanding of bat movements between roosts (Cramer *et al.* 2016). We found that 31% (37/119) of the literature in the past decade considered or investigated the habitat and movement patterns of the Pilbara leaf-nosed bat (Fig. 2). This is likely because 92% (110/119) of the literature were industry/consultant reports containing surveys assessing/monitoring the use of areas by Pilbara leaf-nosed bats as a compliance requirement for mine approvals. The literature largely noted the presence of bats within different habitat types from ultrasonic recorders, and some literature directly tracked the movements of individual bats; however, data was often limited to few individuals in a non-replicable manner (i.e. inconsistent sampling and tracking techniques or equipment). Thus, the observations documented to date might be unrepresentative generally of their dispersal patterns because of the influence of the local landscape, small sample size, as well as bias from the capture and handling involved in transmitter attachment. Despite this, due to the relatively poor understanding of the species' dispersal patterns, the collection of any data is considered valuable for informing better management and mitigation measures for the species at a local and/or regional scale.

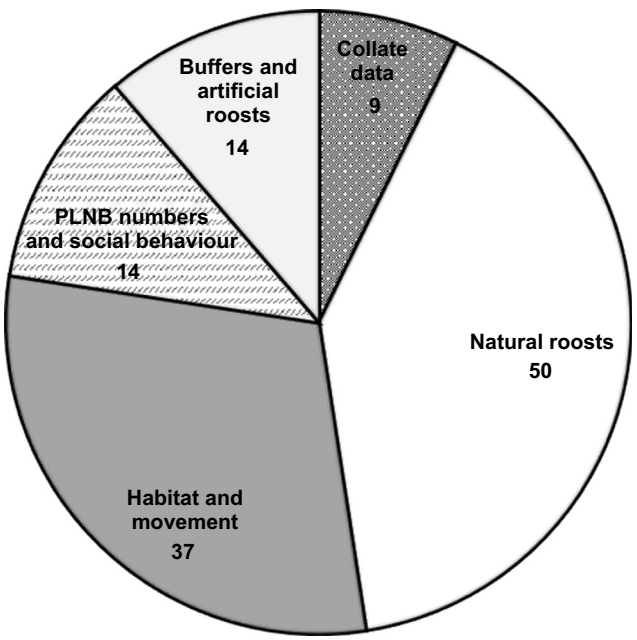

Fig. 2. The proportion of literature (years 2013–2023; 119 documents) that considered each of the five research priorities (not mutually exclusive) as listed in the 2013 workshop (Cramer *et al.* 2016). PLNB, Pilbara leaf-nosed bat.

Knowledge of Pilbara leaf-nosed bat movements has improved in the past decade from the targeted use of technology such as ultrasonic recorders, very high frequency (VHF) trackers and radio frequency identification (RFID) transmitters (Biologic Environmental Survey 2019*a*; Bullen and Reiffer 2020, 2021; Reiffer 2022). RFID tagging has been shown useful to record long-distance dispersal events

(Bullen and Reiffer 2020), and smaller scale movements such as nightly, monthly, and seasonal variations in the frequency and timing of foraging bouts (Bullen and Reiffer 2021). However, many studies are still in their infancy or are unpublished, and further studies are recommended to build upon pilot sample sizes in the grey literature. Stakeholders also expressed the importance of further understanding the timescale of colonies returning to abandoned sites (natural and/or disturbed), and the likelihood of such a return. Understanding the species' movements regionally, and how foraging and roosting habitats and/or disturbance buffers facilitate and/or influence these movements, will assist with appropriate protection of suitable areas to maintain and promote colony persistence and survival.

Breeding and demographics

From a broad perspective, the workshop attendees determined that it is important to: (1) better understand the demography and social behaviour of colonies; (2) better define breeding seasons and behaviour; (3) increase the collective survey and monitoring effort across the region in a consistent manner to determine and monitor population trends; and (4) generate an accurate estimation of the regional population size. These topics align to a key task of Priority 4 from the 2013 workshop: to provide more robust estimates of total population and colony size and improve understanding of social behaviour. Only 12% of the literature (14/119) considered or addressed these factors in the past decade, and largely focused on estimating or monitoring the colony sizes at known roost sites. Two estimates of regional population size have recently been suggested based on recorded colony size estimates and echolocation data (Bat Call WA 2021). In 2016, the Pilbara leaf-nosed bat population was estimated to be approximately 30,000–35,000 individuals (Bullen 2019, cited in Bat Call WA (2021)), but based on recent and ongoing surveys it was suggested that the population has declined to 10,000–15,000 individuals, with speculation involving a bust-cycle period associated with drought or inconsistent annual rainfall (B. Bullen, pers. comm., 2023). However, a more intensive empirical study with modern methods is required to confirm the current population size and any change that might occur, ideally using acoustic bat detector recordings and incorporating video or other approaches so that counts can be properly validated and errors rates estimated.

Overall, the lack of progress towards understanding fundamental aspects of the species' biology likely reflects the predominance of consultant reports supporting environmental approvals and/or addressing compliance requirements, as opposed to biological research. Thus, it was identified that future research effort should be directed towards understanding the population size and trends, dispersal patterns, and breeding dynamics of the Pilbara leaf-nosed bat, beyond establishing baseline presence/absence, single colony size counts and short-term monitoring at a localised and individual project scale. This will require ongoing, collaborative and focused field studies since establishing patterns and cycles of animal behaviour requires many years of research and significant resources. A comprehensive understanding of population ecology is critical, as effective conservation management generally requires a range of interventions at a population- to ecosystem-level scale (Brussard 1991).

Research priority 2: threatening processes

A key outcome of the 2022 stakeholder workshop was collating and prioritising key threats to Pilbara leaf-nosed bats (Table 3). Identified threats included feral cats, climate change, cumulative impacts, roost disturbance/destruction, habitat degradation and fragmentation, and inadequate implementation of buffer zones on critical habitat (i.e. roosts). Factors contributing to each threat were also discussed by workshop participants (Table 3). Of these factors, mining and infrastructure, cumulative impacts, predation, climate change, and understanding disease were selected as priorities for targeted research.

Mining and infrastructure

Disturbance buffers and artificial roosts. One of the major threatening processes identified for the Pilbara leaf-nosed bat was mining and associated anthropogenic disturbances, which aligns with Priority 5 from the original workshop, which focused on disturbance buffer requirements and artificial roost construction protocols (Cramer *et al.* 2016). Since 2013, only 9% (11/119) of the literature directly investigated specific buffer requirements relating to Pilbara leaf-nosed bats and 3% (3/119) of the literature directly trialled or monitored the success of artificial roosts, with some reports repeating discussion of the same roosts (six separate in total; Bat Call WA 2021; Biologic Environmental Survey 2022). Additionally, 3% (3/119) of the literature referenced other documents that specified buffer requirements or stated a buffer distance without providing a rationale, and 2% (2/119) referenced other artificial roost studies or provided mention of an artificial roost with no details. This indicates that the research gap has only been partially addressed in the past 10 years and is still a research priority for ongoing conservation and management. However, a lack of reporting could be due to the need to only investigate buffer requirements once at a location, that studies are ongoing, or else the exclusion of information from public reporting, rather than a lack of consideration. Nonetheless, we advocate for greater transparency in documenting the reasoning for determining buffer distances. Bat Call WA (2021) provides recommendations in relation to disturbances such as noise and ground borne vibration, advising a buffer distance of several hundred metres from the roost entrance; however, further studies are required to assess the suitability of buffer distances in relation to specific impacts. It is also recommended that further evidence be gathered to support this guidance (Bat Call WA 2021). Contextual studies, surveys or calculations are required to understand the surrounding cave geology and susceptibility

Table 3. The greatest threats to the Pilbara leaf-nosed bat, as nominated at the 2022 stakeholder workshop.

Priority	Threat	Relevant factors
1a	Feral cat predation	• Current lack of recognition as a significant threat for management and policy
1b	Climate change	• Potentially reduced rainfall
2a	Cumulative impacts	• Hydrological changes: loss of permanent water and reduction in water quality • Vehicle strikes • Inappropriate fire regimes • Diseases • Lack of life/ecology knowledge during all life phases • Lack of data sharing • Future mining of ironstone formations • Renewables projects
2b	Disturbance and destruction of roosts	• Future mining of ironstone formations and old adits • Renewables projects
3a	Degradation and fragmentation of foraging habitat	• Inappropriate fire regimes • Wind turbines • Future mining of ironstone formations • Renewables projects • Hydrological changes: loss of permanent water and reduction in water quality • Climate change (potentially reduced rainfall)
3b	Inadequate buffers	• Lack of information about critical habitats and the impacts of nearby activities and the thresholds (e.g. distances and extent) of these • Lack of knowledge of life cycle/ecology during breeding phase

Priorities were divided in two (a and b) when the same priority weighting was assigned by workshop participants.

for structural failure, the particle velocity from vibration, the potential for fly rock, and the appropriate distance or vibration threshold required to prevent disturbance or cave abandonment by Pilbara leaf-nosed bats (Blast It Global 2020). Therefore, selection of buffer distances needs to be calculated on a case-by-case basis, recognising the specific site characteristics. To increase transparency and aid information gathering, specifying the reasoning for determination and implementation of buffer sizes should be provided. Where supporting data is not available or influence of potential impacts are unknown, a precautionary approach should be taken, and increased buffer sizes implemented.

The distinct spatial overlap in concentrated iron ore, gold deposits and Pilbara leaf-nosed bat habitat highlights a direct conflict for land use and management, and a major threat to the species (Armstrong 2010; Bullen and Creese 2014). Due to this conflicting land use, there is a clear need to understand the impacts of mining and the viability of creating artificial roost sites to offset destruction of habitat. Abandoned mining adits effectively represent artificial roost habitat that has provided refuge and a focus for breeding for many decades; however, the collapse and/or flooding of these adits is considered a major threat to Pilbara leaf-nosed bats colonies (Armstrong 2001; Woinarski *et al.* 2014). This is primarily attributed to their instability (Donnelly and McCann 2000; Gonsalves *et al.* 2021), and extensions to ore bodies beneath these structures being accessed for further mining that may influence natural water tables. In addition to advocating for the protection of natural roosts, the recommended focus of research into artificial roosts is, therefore, to create viable additional roosting sites with greater longevity and structural stability than abandoned mining adits.

Despite being a research priority since 2013, investigation into the usefulness of specifically designed artificial roosts for Pilbara leaf-nosed bats appears to be only a recent undertaking by mining proponents. Within the past decade of literature, only five reports could be sourced that discussed or referenced concept for the design of artificial roosts, and those that detailed actioned trials were from 2021 or later (Bat Call WA 2021; Biologic Environmental Survey 2022). As installations of these artificial roosts has been only undertaken recently (in 2017, 2018, and 2019) there has not been sufficient time for monitoring to indicate whether these structures provide suitable roosting habitat for the Pilbara leaf-nosed bat (Atlas Iron Limited 2021; Bat Call WA 2021). Further monitoring and design trials are required to determine which techniques and materials are the most appropriate for artificial roost construction, if they are used at all or reliably by Pilbara leaf-nosed bats, and if they are an appropriate mitigation tool to reduce colony loss in the event of habitat destruction. Due to the unknown feasibility of artificial roosts for habitat, it must be noted that conservation of the natural roost sites must be the first priority, and artificial roost development should only be planned as an additional management technique when preservation of natural roosts is not achievable.

Cumulative impacts of mining. The importance of understanding cumulative impacts of mining and the resilience of Pilbara leaf-nosed bats to these changes (Table 2) is important because multiple stressors can interact to cause

nonlinear impacts to the environment (Segner *et al.* 2014). Impacts from mining can occur at multiple trophic levels and cascading effects throughout ecological networks can produce disproportionate consequences to certain species (Segner *et al.* 2014). Threatened species are at particular risk from multiple threatening processes acting together. For example, the Pilbara leaf-nosed bat occurs throughout the tenure of numerous proponents, meaning they are not protected or managed by a single proponent, and the regulatory framework can be ambiguous in assigning responsibility (Vanderduys *et al.* 2016). The current national legislation in Australia has limitations to regulate the collective number of impacts that might be insignificant on an individual basis but represent a cumulative impact on Matter of National Environmental Significance (MNES) (Dales 2011). Biodiversity impact assessments under threatened species legislation regularly only consider a development/disturbance proposal in the context of a single location and a single species (Whitehead *et al.* 2017), which fails to recognise the combined and concurrent consequences of numerous approved developments. Therefore, the cumulative effect of multiple mining operations and anthropogenic disturbances across the Pilbara risks local extirpations of Pilbara leaf-nosed bats due to 'death by a thousand cuts' (Dales 2011; Tulloch *et al.* 2016). As a result of the potential pressure from the cumulative impacts of mining on the threatened status of Pilbara leaf-nosed bats, stakeholders at the 2022 workshop determined this to be a new research priority. Specifically, important areas of focus identified were: (1) the threatening processes associated with mining and other threats and how they might interact; (2) how the cumulative impacts of mining might directly influence (i) roosting habitat and (ii) foraging habitat; and (3) the proportions/combination of disturbance to each of these habitats might impact colony viability, leading to reduced population resilience. Detailed studies on the ecological requirements of Pilbara leaf-nosed bats, such as home range size, the landscape characteristics required to support long-distance movements, and the area and quality of foraging habitat required to support a colony, are crucial to inform how the cumulative impacts of mining may influence population resilience.

As Australia has committed to a net zero carbon emissions target by 2050 to reduce climate change impacts (Foerster *et al.* 2017; DCCEEW 2021), research into the cumulative impacts of renewable energy generation and associated infrastructure (i.e. wind turbines or solar farms) will also be key to ensuring persistence of Pilbara leaf-nosed bats. Bat mortality from wind energy infrastructure has been investigated extensively in northern hemisphere systems (e.g. Kunz *et al.* 2007; Hein and Schirmacher 2016; Richardson *et al.* 2021). Research questions such as the flight height of Pilbara leaf-nosed bats, movement routes through the landscape (for avoidance), and potential deterrents or warning systems to bats, might help to significantly reduce the likelihood of bat mortality from this infrastructure. Additionally, other renewable energy sources such as solar farms may also be of consideration. The influence of solar farms on bat activity, particularly in relation to large scale clearing of foraging habitats, is also gaining increased interest from researchers (Szabadi *et al.* 2023; Tinsley *et al.* 2023). Overall, there is an imperative to better understand the cumulative impacts on Pilbara leaf-nosed bats, including factors such as mining, infrastructure development, and pastoralism. In addition, how these factors interact spatially across the Pilbara and across both roosting and foraging habitat, and how this impacts Pilbara leaf-nosed bat resilience to local extirpation, will be key to ensuring their long-term conservation.

Predators, disease and climate change

The impact of predation and disease, and how this may be amplified with climate change, was a key research task highlighted by the 2022 stakeholder workshop. While predation by native predators such as northern quolls (*Dasyurus hallucatus*) and ghost bats (*Macroderma gigas*) were previously known (Dunlop *et al.* 2017; Start *et al.* 2019), the 2022 stakeholder workshop recognised that feral cats (*Felis catus*) can impose significant predation pressure on some Pilbara leaf-nosed bat roosts (D'Rozario 2022; Moyses *et al.* 2022). Further understanding of the impact of feral cats, and their influence on local extirpations or colony declines of the species, will be important for ensuring appropriate management and mitigation measures can be implemented.

The 2022 stakeholder workshop also considered the potential for impact of fungal disease similar to the white-nose syndrome caused by the *Pseudogymnoascus destructans* fungus (Lorch *et al.* 2011; Minnis and Lindner 2013) on Pilbara leaf-nosed bats. However, studies have suggested that Pilbara leaf-nosed bats, and the region more generally, are unlikely to be impacted by this fungus due to the species' behaviour and less favourable environmental factors such as temperature and humidity in the Pilbara region (Verant *et al.* 2012; Holz *et al.* 2019). Further investigation into predicted temperature and climate variation with climate change will be important to determine if there is a future risk from fungal infection to colonies. Modelling the cumulative impacts of climate change will also be important to understand the predicted impacts to roost suitability (through any changes to temperature, rainfall, and/or humidity), impacts to foraging habitat and prey populations, and other extreme events (i.e. fire) which might influence predator behaviour and Pilbara leaf-nosed bat breeding and colony persistence in parts of the Pilbara.

Research priority 3: records and data

The sharing and collation of data was listed as a priority both in the 2013 and 2022 stakeholder workshops. Review of the literature found a gradual increase in the number of occurrence records since listing at federal level of the Pilbara leaf-nosed bat as Vulnerable under the EPBC Act in 2001 (Fig. 3). The highest numbers of occurrence records were produced after 2013 when

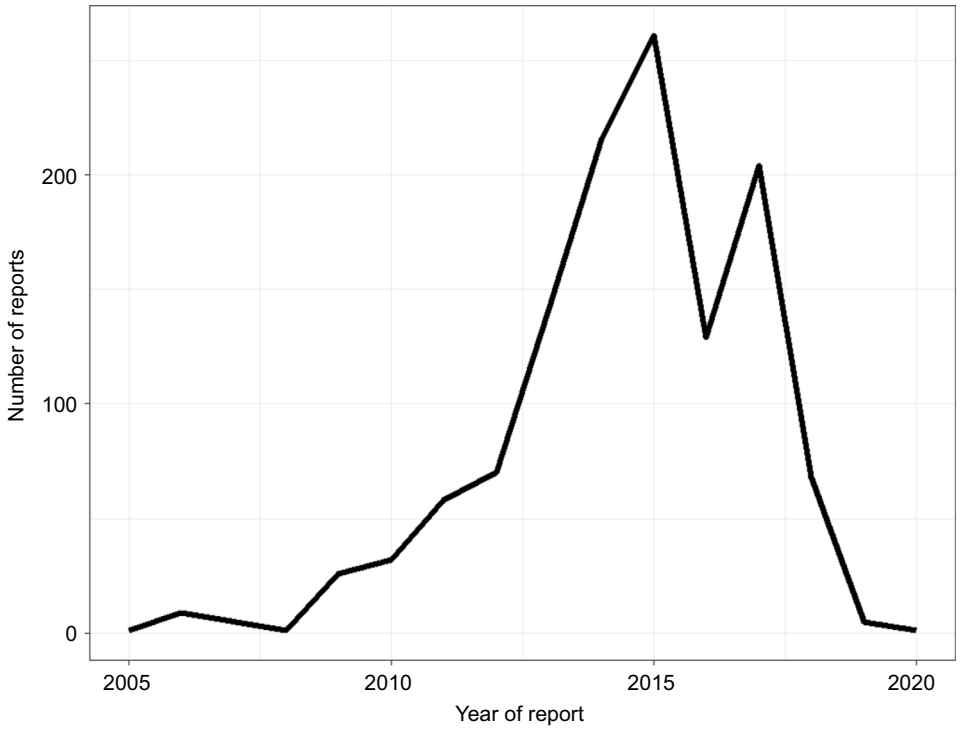

Fig. 3. The number of reported occurrence records between 2000 and 2022, as sourced from Department of Biodiversity, Conservation and Attraction records. The 16 records from 1925–2000 were excluded for ease of graph interpretation.

the first stakeholder workshop was held, and when there was the first call to action for the increased publication and dissemination of information as a research priority (Fig. 3). The general trend of increased occurrence records over time was also likely influenced by the increased sampling and survey effort following the listing of Pilbara leaf-nosed bats as a MNES, meaning that if disturbance is likely to have a significant impact on the species, such as through mining activity, a referral is required to be assessed and approved at the national level by the Australian Government Environment Minister (Department of the Environment 2013). The slight decrease in occurrence records since 2017 (Fig. 3) may not be a true reflection of a reduced level of reporting, as delays from the approval process can setback the timing of formal submission or public release of reporting, making these documents unavailable to the repositories used to source the grey literature for this review.

A significant number of the recent occurrence records for the Pilbara leaf-nosed bat come from the grey literature that is largely composed of mining and consulting reports. These reports are not commonly publicly available; therefore, it is possible that additional records have been missed. Further, these reports are predominantly written in the context of meeting environmental compliance for a single site, or specific to an environmental approval, rather than for the purpose of broadscale and/or systematic species survey suggesting that spatial gaps in distributional records are likely present. For this reason, despite substantial progress on this priority since 2013, we consider that this research priority has only been partially met. In future, it is essential that survey records from consultants, researchers and mining companies are added to appropriate publicly accessible state and national biodiversity databases and data repositories (e.g. Dandjoo Biodiversity Data Repository, which is managed by the Western Australian Department of Biodiversity, Conservation and Attractions; and Atlas of Living Australia, which is hosted by the Commonwealth Scientific and Industrial Research Organisation) that are accessible to inform further research and survey effort. Records may consist of observations (e.g. echolocation sound recordings, infra-red video, scats, visual observations) as well as capture records. Development of standardised survey and monitoring protocols through a 'standard operating procedure' could assist in ensuring that data is comparable and treated consistently over the Pilbara region, such as the recommended survey approach detailed in Bat Call WA (2021), although the development of such a procedure will need to be based on a broad level of input. Due to limited conservation funds and time, an improvement in collaboration, communication and data sharing will help fast-track the address of key knowledge gaps currently limiting the effective management and conservation of Pilbara leaf-nosed bats.

Research priority 4: habitat

Roosts and foraging habitat

A better understanding of habitat requirements was listed as a priority at both stakeholder workshops (Cramer *et al.* 2016). Our review of the literature found that 31% (37/119) of documents considered or mentioned habitat, at least through presence/absence records in certain habitat types or habitat features. In addition to presence records, VHF tagging of individuals can help analyse the time spent in different habitat types, distances travelled, and potential uses of different habitat and roost sites (Biologic Environmental Survey 2019*a*). For example, VHF tracking of Pilbara leaf-nosed bats using fixed towers in a 2018 pilot study used detection events to determine that the preferred foraging habitat of tagged bats was along drainage lines and ephemeral watercourses, highlighting the likely significance of surface water (Biologic Environmental Survey 2019*a*). The importance of water sources was also highlighted in other studies that directly tracked individuals (Biologic Environmental Survey 2019*b*, 2020), and 86% of the literature that mentioned habitat had survey results that supported (62%, n = 23/37) or mentioned (24%, n = 9/37) the importance of water or riparian habitat for foraging.

A more detailed comment on the importance/use of habitat types, and the activity levels of Pilbara leaf-nosed bats in habitat types, was recently summarised in Bat Call WA (2021), based on extensive echolocation monitoring data. It was found that the bats forage in almost all productive and semi-productive habitat types, with a preference for sites with permanent or semi-permanent water courses and complex vegetation structure (Bat Call WA 2021). This assessment helps to substantially address the knowledge gap discussed at both the 2013 and 2022 workshops. The omission of natural roost characterisation from the 2022 workshop (Priority 2 in the 2013 workshop; to further expand previous research of Armstrong (2000, 2001) also indicates that there has been a progression towards building a greater understanding of the components of a suitable roost such as humidity and temperature parameters, although there are still factors requiring further investigation, such as causes of humidity fluctuation in cave structure (Bat Call WA 2021; D'Rozario 2022).

Management directions

The 2022 stakeholder workshop built upon the 2013 workshop by additionally discussing the management priorities required for the future conservation of the Pilbara leaf-nosed bat. Consultation with stakeholders revealed six major management priorities, relating to a series of key tasks and questions (Table 4).

Management priority 1: introduced predator management

Management of introduced predators, particularly feral cats, is a priority for the Pilbara leaf-nosed bat, with feral cats confirmed as a threat to the bats by stakeholder consensus and presenter findings (D'Rozario 2022; Moyses *et al.* 2022; J. Moyses, C. Grabham, K. N. Armstrong, C. Knuckey, B. D'Rozario, unpubl. data) at the 2022 workshop. Although not previously identified as a key threatening process for Pilbara leaf-nosed bat (Threatened Species Scientific Committee 2016; Bat Call WA 2021), bat predation by feral cats is known to occur on a broad range of species and cats are considered one of the most damaging invasive species on bat populations around the world (Ancillotto *et al.* 2013; Oedin *et al.* 2021). The impact of cat predation has contributed to numerous extinctions, particularly in Australia (Doherty *et al.* 2016, 2017), and predation by feral cats is listed as a broad threatening process for threatened species under the Australian EPBC Act. The Australian Government's Threatened Species Strategy 2021–2031 (DAWE 2021) lists 'mitigating new and established threats', including feral cats, as the top action fundamental to the recovery of threatened species in Australia. Therefore, the top management priority for the Pilbara leaf-nosed bat aligns with the same focus area for the recovery of threatened species more broadly throughout Australia.

Management and monitoring of feral cats is challenging, as they are cryptic and solitary, with large home ranges and often occur at low density across the landscape (Edwards *et al.* 2000; Fisher *et al.* 2015; Comer *et al.* 2018; Palmer *et al.* 2021). There is no current landscape-scale control method determined consistently effective for the management of feral cats (Webber 2020). Despite being declared a pest under the BAM Act, feral cats are in the 'unassigned control-category', meaning that individuals and agencies are not obligated to manage feral cats on their property (Webber 2020). Stakeholders at the 2022 workshop advocated for feral cat management to become a compliance requirement in the Pilbara (Table 3). Regulation of feral cat management in the Pilbara region could contribute towards a more coordinated management approach, leading to widespread and long-term testing of methods to help improve management techniques (Webber 2020). Management as a compliance requirement could also help reduce the likelihood of unmanaged neighbouring properties acting as a continued source of replacement individuals for those areas with active control. In addition, regulation could reduce low-level and *ad hoc* management practices, which can counter-productively lead to the immigration of more feral cats than were originally in the area, increasing predatory activity (Lazenby *et al.* 2014).

Management priority 2: local collaboration

Positive communication between proponents and organisations in the Pilbara will be critical for the widespread

Table 4. Management priorities for the Pilbara leaf-nosed bat identified in the 2022 stakeholder workshop.

Rank	Management priority	Key tasks/questions
1	Introduced predator control	(a) Feral cats • Extend existing programs • Make a compliance requirement • Conduct at a landscape scale (b) Other predators • Control food around campsites • Make a compliance requirement
2	Local collaboration	• Proponent collaboration on regional studies • Higher standards for new projects • Identify what is most effective • Tools above databases (e.g. to facilitate comparisons) • Include Traditional Owners and Indigenous rangers • Have targeted community engagement (including knowledge and incentives)
3	Artificial roosts	• Determine the methods that work • Determine the next steps required to make a viable management method • Protect and preserve known roost sites
4	Monitoring	(a) Secondary and cumulative impacts • Impacts include vibration, dewatering, light, noise, and blasting • Establish and apply agreed industry standards • Make post-mining assessment monitoring a compliance requirement (b) Colony and habitat characteristics • Long-term monitoring of population impacts to occur at a regional scale for a range of variables • Monitor at the population scale • Water/hydrology levels and quality
5	Buffer implementation	• Must be based on research
6	Regional consistency	(a) Consistent application of management regimes • Protocols document • Consistent guidance • Adaptive management for local conditions (b) Security for the future • Identify source of funding for ongoing management and monitoring • Determine whether there are there other/new offset options • Manage the Pilbara leaf-nosed bat as a panmictic population

sharing and advancing of management methods. Stakeholders emphasised the importance of proponent collaboration on regional studies to address broad questions, compared with past projects that were typically isolated to areas managed by a single proponent, and the results not communicated outside to separate organisations. The first study using microsatellite and mitochondrial (mtDNA) markers (K. N. Armstrong, unpubl. data), plus a recent conservation genetics study using mtDNA and nuclear single nucleotide polymorphism markers identified high levels of gene flow throughout Pilbara leaf-nosed bat colonies and that the population exists in a state of panmixia (Umbrello *et al.* 2022). Connectivity corridors are important to maintaining high gene flow between colonies and appropriate management will involve communication among proponents and land managers to facilitate continued dispersal events and prevent the establishment of barriers to gene flow (Armstrong 2001, K. N. Armstrong, unpubl. data; Umbrello *et al.* 2022).

Communication of the most effective methods and management under different circumstances will also increase the capacity for best-practice techniques to be followed across the Pilbara. Inclusion of Traditional Owner and ranger groups as part of ongoing discussions of Pilbara leaf-nosed bat conservation and management is also a priority highlighted by the 2022 workshop attendees, as well as targeted community engagement. The collaborative use of traditional ecological knowledge, particularly in combination with western science, to inform biodiversity conservation and natural resource management continues to be highlighted as an avenue for improving shared knowledge and achieving biodiversity protection and sustainable development of natural resources (Nabhan and Martinez 2012; Freitas *et al.* 2020; Sousa *et al.* 2020; Goolmeer *et al.* 2022; Goolmeer and van Leeuwen 2023). Overall, local collaboration and open communication will likely help improve or expedite achieving the other management and research priorities for the Pilbara leaf-nosed bat.

Management priority 3: artificial roosts

Investigation into the suitability of artificial roosts is a research priority (Table 2) as well as a management

priority (Table 3) for the Pilbara leaf-nosed bat. Of first importance is determining the most effective artificial roost designs for Pilbara leaf-nosed bats. Once there is evidence for a design that is structurally sound and can successfully attract the focus of colonies over long-term monitored periods over multiple years or decades, then an optimised design and strategy can be promoted throughout the Pilbara. Although this is the final option in the mitigation hierarchy and will not compensate for the loss of natural roosts, installation of artificial roosts has successfully attracted and supported other bat species around the world (e.g. Kelm *et al.* 2008; Mering and Chambers 2014). This could be a useful approach for maintaining population size, colony connectedness and other conservation efforts that include other nearby roosts.

Management priorities 4–6: monitoring, disturbance buffers and regional consistency

Long term, targeted monitoring across the Pilbara region is a management priority for the Pilbara leaf-nosed bat. Standardised and consistent monitoring will help develop a better baseline dataset for characteristics relating to habitat use, as well as track responses to threatening processes (Legge *et al.* 2018), such as the cumulative impacts of mining. Analysis of monitoring records can help inform appropriate disturbance buffer sizes (e.g. Blast It Global 2020) to establish around roost sites and foraging habitat, which is also a priority area for research (Table 2). To achieve broad-scale monitoring for the Pilbara leaf-nosed bat, stakeholders from the 2022 workshop emphasised the need to make monitoring a compliance requirement. Workshop attendees also highlighted the need to establish and apply agreed industry standards, which will facilitate the development of meaningful, sharable datasets across the Pilbara to help inform best-practice management and achieve regional consistency (Management Priority 6).

Stakeholders at the 2022 workshop recommended that a guidance document be created to provide consistent guidance to land managers and ensure that appropriate management actions are implemented across the Pilbara. Development of this document is likely to require another collaborative stakeholder workshop with expert recommendations. Consistency is important across the region to ensure that all colonies are awarded appropriate protection; however, adaptive management is also important to achieve successful management in the context of local conditions. Adaptive management, with experimental trials of new methods or technologies, will facilitate further improvements to best practice techniques for the future (Haney and Power 1996; Kimball and Lulow 2019). Stakeholders at the 2022 workshop further recommended the need to identify a source of funding for the ongoing management and monitoring of Pilbara leaf-nosed bats to help understand patterns within and among colonies, and to provide information about possible population size changes. This will also be important to ensure that management regimes will continue to be implemented, as their longevity is key to providing the intended outputs of reliable datasets in the long term.

Conclusions and implications

As is evident from this literature review and the concerns raised at the 2022 Pilbara leaf-nosed bat workshop, there has only been partial progress towards addressing research priorities identified in the 2013 workshop (Cramer *et al.* 2016). Participants at the 2022 workshop identified the lack of an overarching framework, and the need for clear leadership structure or development of guidance documentation arising from the 2013 workshop as a barrier to developing the next steps for initiation and coordination of research programs. Participants were concerned that these risk factors are still present and may impact outcomes of the recent workshop, further hindering implementation of best management and conservation practices for the species.

Various efforts were made to investigate and answer the questions posed in Cramer *et al.* (2016); however, these investigations were largely isolated, in their infancy, were based on limited sampling, or with results mainly limited to release in the grey literature (or many studies likely not published at all), which can be difficult to access and contribute towards a shared knowledge. A clearly defined, detailed, and costed research strategy for Pilbara leaf-nosed bats based on outcomes from the workshop and stakeholder elicitation is necessary to guide and direct research activities and funding opportunities. A costed research strategy could act as a prospectus to facilitate the development of research partnerships between public, private and academic institutions, outlining the roles and contribution of each. Such a collaborative approach is currently employed by the Western Australian Biodiversity Science Institute and may provide a model for Pilbara leaf-nosed bats.

A key concern for stakeholders is the identification of source/s of ongoing funding to address research priorities, management activities and monitoring, particularly because the research targets are ambitious and require extended timeframes to address adequately. The key research questions for Pilbara leaf-nosed bats established in the 2013 stakeholder workshop were published in 2016 (Cramer *et al.* 2016), just after the sharp global decline in the price of iron ore (Bekiros *et al.* 2015), which is the primary industry of the Pilbara (Barratt and Ellem 2019). As evidenced by our literature review, progress on research priorities was largely restricted to grey literature reports by or for mining companies, thus a lack of spending by proponents outside of meeting regulatory requirements is likely to also have contributed to the impartial completion of the 2013 research targets.

Public–private co-funding models were the preferred approach raised at the workshop, and attendees discussed

leveraging funding through other sources such as the Pilbara Environmental Offset Fund. However, only a limited portion of the Fund is allocated towards research spending with the remaining focused on on-ground recovery actions (Government of Western Australia 2023). Allowance for greater research spending from the Fund to better understand species ecology prior to management intervention may help to improve the long-term conservation of the Pilbara leaf-nosed bat as well as other sympatric and ecologically similar species. This is of particular importance given the relatively limited expenditure on the species compared to other species that are not endemic to the region (i.e. northern quoll). The substantial expertise and good will present among workshop participants provide a strong foundation for the development of future collaborative approaches.

For the key management and research goals of the 2022 stakeholder workshop to be met, previous issues in the past decade relating to funding and allocation of responsibility will need to be addressed as a priority. Targets determined by stakeholders at the 2022 workshop provide guidance on research foci for the species and will need to be translated to specific, timely, and actionable goals when implementation is desired (i.e. furthering study on a particular aspect of the management and research goals identified herein), with a coordinated and collaborative effort among all stakeholders required to improve the likelihood of regional recovery for the Pilbara leaf-nosed bat more broadly overall. Experience since 2013 will help to direct and focus future research and management efforts, as well as highlight the clear gaps in strategy and policy to improve for the future. A research and management approach developed directly to address the priority targets, rather than indirectly through the current regulatory framework for mineral extraction and development in the Pilbara, will increase the likelihood of successfully completing the 2022 research and management targets. Overall, updated compliance regulations, coordinated funding, positive communication between proponents, and targeted research beyond simple survey measures, are critical for effectively meeting the targets highlighted in this review in the upcoming decade.

Supplementary material

Supplementary material is available online.

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Data availability. The grey literature that supports this review are available through the Government of Western Australia Department of Biodiversity, Conservation and Attractions Library Catalogue, Government of Western Australia Environmental Protection Authority proposal portal, Australian Government EPBC Act portal, plus other links provided in the Supplementary material.

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