A critical review of survey techniques and perceived threats for the threatened Pilbara ghost bat (*Macroderma gigas*)

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ABSTRACT

Ghost bats of Western Australia's Pilbara region are widespread, although patchily distributed, and are threatened with local extirpation, largely in part due to the expanding mining footprint across the region. The extensive data collected to inform environmental impact assessments for mineral exploration projects, however, provides a key source of information to inform ghost bat policy and management. At present, the effectiveness of this resource is limited by accessibility. To help bridge this gap, we conducted a comprehensive review of the grey literature on ghost bats, summarising strategies for survey techniques, perceived threats, and threat mitigation strategies. Numerous threatening processes were identified as impacting ghost bats, with habitat loss and the cumulative impacts of mining most reported. Survey techniques were found to often include a combination of indirect and direct methods, although the suitability of different techniques is reliant on the context of the study. For this reason, it is important for future environmental assessment reports to include a detailed method rationale to support better data comparability and population estimation across the Pilbara. Overall, comprehensive and comparable research outputs will help to better assess and understand extinction risks, and to develop effective conservation management plans for this threatened species.

KEYWORDS: Abandoned mines, ecology, ghost bat, microbat, survey, threat mitigation

[**Editors' Note**: "Grey"-literature references are marked by * and cited in Appendix with link to website or library catalogue number]

INTRODUCTION

The ghost bat (*Macroderma gigas*) is Australia's only carnivorous bat and largest of the microchiropteran group (Strahan 1995; Start *et al*. 2019). Individuals weigh approximately 130 grams in the Pilbara (Guppy & Coles 1988), with a wingspan of approximately 60 centimetres (Walldorf & Mehlhorn 2014), and have pale grey to light brown fur, large ears that connect over the head, and a prominent but simple nose leaf (Tidemann *et al.* 1985). Ghost bats belong to a monotypic, endemic genus (Churchill & Helman 1990), and after a significant historic range contraction (Worthington Wilmer *et al.* 1999), are now limited to a small number of non-interbreeding populations across northern Australia, from the northwest of Western Australia to Rockhampton in Queensland (Churchill & Helman 1990; Hoyle *et al.* 2001). They are protected under both state (*Biodiversity Conservation Act 2016**; Vulnerable, Schedule 1) and federal (*Environment Protection and Biodiversity Conservation Act 1999**; Vulnerable) legislation. Pilbara populations are geographically widespread and discontinuous (Armstrong & Anstee 2000; McKenzie & Bullen 2009; Fig. 1), bordered by desert to the north and east (Bat Call 2017*). Due to geographic isolation from other extant ghost bat populations, the Pilbara population is recognised as genetically distinct at the regional level (Worthington Wilmer *et al.* 1994, 1999).

The distribution of ghost bats is limited by the presence of appropriate roosting sites, which can include both natural cave systems and disused mines, provided they have the required conditions for resting and breeding and permit access to suitable foraging habitat (Cramer *et al*. 2022). Presently, population size estimation for ghost bats in the Pilbara is between 1300 to 2000 individuals (TSSC 2016*; Ottewell *et al.* 2017*). Much of the Pilbara ghost bat population is limited to stronghold colonies roosting in disused copper and gold mines in the eastern Chichester subregion (approximately 70% of all ghost bats in the region; TSSC 2016*). Most of these roosting sites are at risk of collapse from age or from destruction by mining ventures (TSSC 2016*; Bat Call WA 2021*). Prior to conservation listing of the ghost bat under the *Environment Protection and Biodiversity Conservation Act 1999** in 2016, it was anticipated that many of the known Pilbara ghost bat roosts would be lost within 30 years in the absence of strategic intervention (Woinarski *et al.* 2014).

The Pilbara region is a hotspot for mining development and is of substantial economic importance to the rest of the state (Government of Western Australia 2014*), generating about 40% of Western Australia's gross domestic product (PEOF Overview 2019*). Almost 92% of the Pilbara IBRA (Interim Biogeographic Regionalisation for Australia) region is under mining and exploration tenure (Government of Western Australia 2014*). Consequently, mining activity and development pose a primary threat to ghost bat persistence (Cramer *et al.* 2022). There is a significant body of grey literature from decades of surveys conducted for Environmental Impact Assessment (EIA) of mining and mineral exploration projects, representing a major source of knowledge for the biodiversity in this region (Government of Western Australia 2014*). However, a limitation of this knowledge resource is a lack of communication between proponents and the absence of an easily accessible, central source of reporting and information (Government of Western Australia 2014*; Cramer *et al.* 2016). Failure to coordinate regional conservation initiatives and research can waste limited conservation funding and impede successful conservation outcomes (Pilbara Conservation Strategy 2017*).

There is no current over-arching regional management plan for the protection of Pilbara ghost bats (Armstrong 2010; Cramer *et al.* 2022). Growing interest amongst stakeholders to achieve conservation outcomes for threatened species in the Pilbara led to the launch of a workshop in March 2021 to identify research priorities for the Pilbara ghost bat (Cramer *et al.* 2022). A lack of data sharing due to confidentiality constraints and fragmented biodiversity data management systems

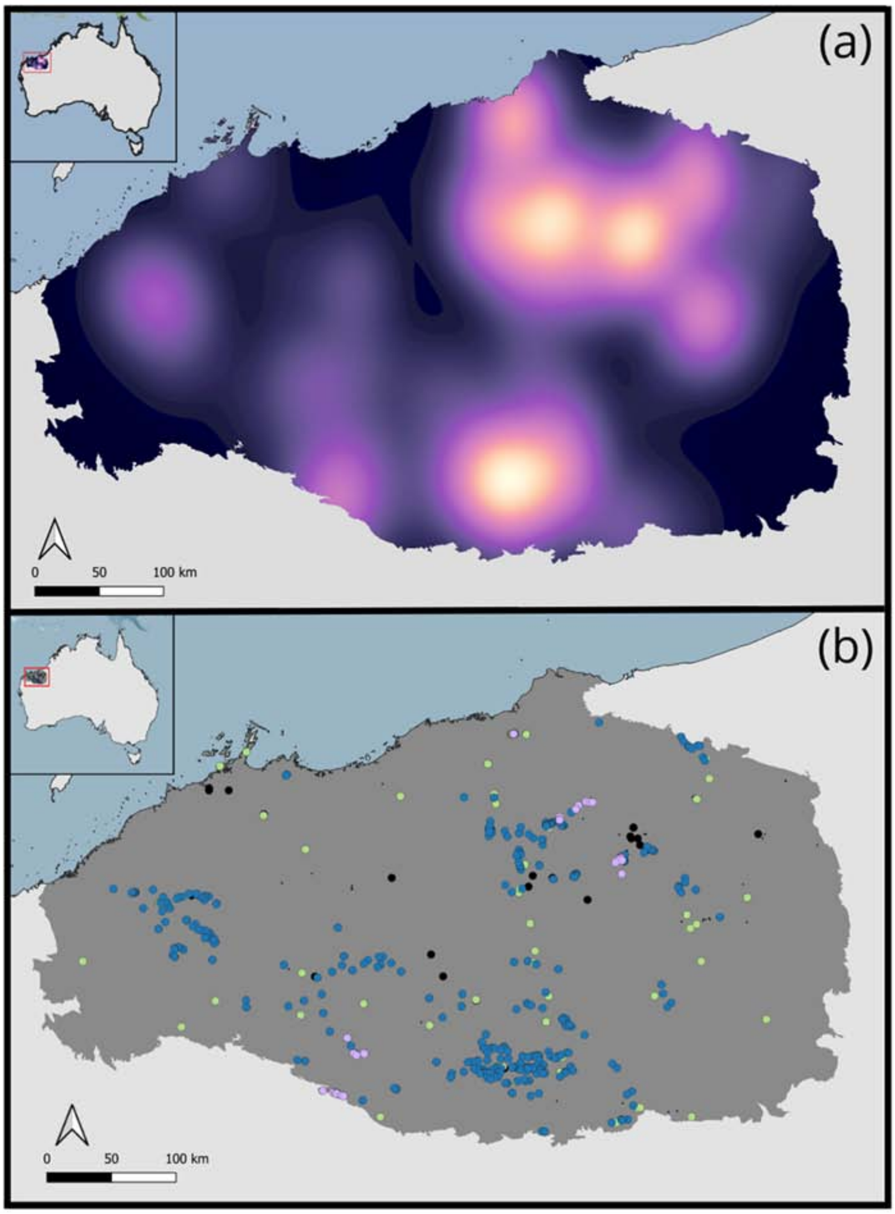

Figure 1. (a) Heatmap of ghost bat occurrence records across the Pilbara. Locations are taken from scientific and grey literature records of sightings/evidence collected between 1854 and 2022; and **(b)** occurrence records for the Pilbara ghost bat, as collected from the grey and scientific literature. Occurrence records are grouped as: black (pre-2000), green (2000–2010), blue (2010–2020), and purple (2020+), highlighting the general increase in recordings over the last decade.

and processes was identified as a major barrier to conservation planning for the species. To address this issue of largely scattered and inaccessible survey data, we collated a database of grey literature from sources ranging from multinational mining companies to sole trader consultancies. We conducted a comprehensive review of the grey literature, to: (i) identify and quantify the types of survey approaches and their frequency of use and (ii) identify the major perceived threats reported for ghost bat populations. Through recognition of these key trends and strategies, we aim to help facilitate best practice management and the ongoing conservation and recovery of the Pilbara ghost bat.

METHODS

To compile the database, we sourced available grey literature relating to ghost bat surveys and research. We limited our search to ghost bats within the Pilbara region of Western Australia as a unique management unit, due to their geographic and genetic isolation and the concentrated survey effort within this region**.** Literature was sourced from searches of databases, and from members of industry, government agencies, and consultancies. Searches of databases included Google Scholar, Web of Science (all databases, 1950–2021), and Scopus (all documents including secondary documents, all years; last searched March 2021), with additional publications sourced from the bibliographies of published literature. Searches of databases comprised any combination of the terms: 'ghost bat', or '*Macroderma gigas*', AND 'Western Australia', or 'Pilbara', AND 'behaviour', 'ecology', 'population', 'physiology', 'management', or 'conservation'. Grey literature included unpublished data such as government reports, environmental impact assessments, management plans, information posters, bulletins, and consulting surveys and reports; however, sourcing of grey literature was largely restricted to provision by members of industry and government due to difficulties accessing this data (Corlett 2011; Cramer *et al.* 2016). Only literature containing specific mention of ghost bats and a form of technology/method for their detection was included. Although published literature from across Australia has been referenced throughout this review to provide context, the reported statistics and trends relate only to our Pilbara-specific grey literature database, as our target questions (survey techniques and threat mitigation strategies) relate to management and policy, rather than research designed to answer a specific scientific question.

A total of 55 documents from the grey literature (from the years 2000-2022) were analysed to determine trends in the types of techniques and technologies used to survey ghost bats in the Pilbara (Fig. 2). Distribution records (between years 1899-2019) provided from the state government (Department of Biodiversity, Conservation and Attractions), were included for mapping purposes, as well as coordinates provided in the scientific and grey literature (Fig. 1). As numerous reports referred to previous survey work or surveys conducted by a different organisation, we considered survey techniques and threats those which were 'referenced' within a document.

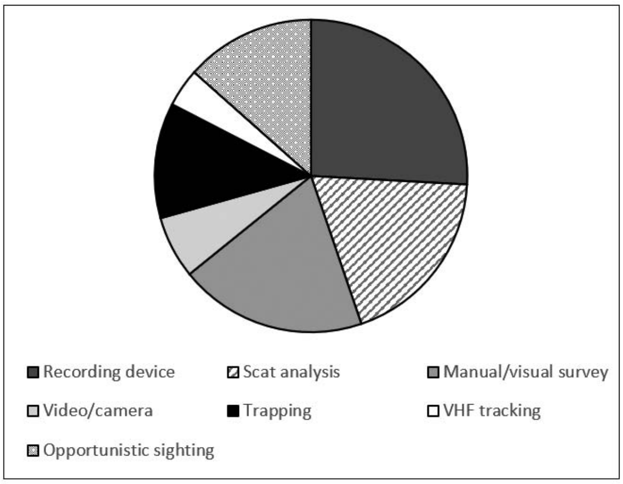

Figure 2. The relative proportions of techniques referenced for surveying ghost bats (*Macroderma gigas*), grouped according to acoustic and ultrasonic recording devices, scat analysis, manual/visual searches, video and camera devices, physical trapping of bats, VHF tracking, and opportunistic sightings. Reference to survey techniques was not mutually exclusive.

RESULTS

Survey techniques

We found that survey techniques generally aligned to a three-step process: (i) the determination of potential roost sites and habitat; (ii) confirmation of bat presence and cave usage; and (iii) more detailed studies into population dynamics such as genetic health and colony connectivity. Overall, the use of recording devices was mentioned most often in the grey literature (26% of the total times techniques were reported; n = 52/203), followed by manual/visual searches (19%; n = 39/203) and scat analysis (19%; n = 38/203; Fig. 2).

RECORDING TECHNOLOGY

Review of the grey literature revealed most documents (84%; n = 46/55) referred to a form of acoustic or ultrasonic recording technology, with Song Meters (full spectrum detectors by Wildlife Acoustics Inc., USA) the most referenced (54%; n = 25/46), followed by AnaBat devices (early detectors by Titley Electronics, Australia; 33%; n = 15/46; Fig. 3). The type of ultrasonic recorder deployed was not specified or different in 24% (n = 11/46) of documents. Only 4% (n = 2/55) of documents referred to non-ultrasonic recording devices as a complementary recording method to the traditional ultrasonic methods.

Song Meters and AnaBat devices were the recording technologies with the highest reported use (Fig. 3); however, Song Meters have been steadily increasing in use, whereas AnaBat equipment has slowly decreased in use with time (Fig. 4). Only one report referenced a different recording technology (handheld Echo Meter; Biologic Environmental Survey 2019c*). Of the documents which used an ultrasonic recording technology (n = 37/55), only 16% (n = 6/37) justified why this technology

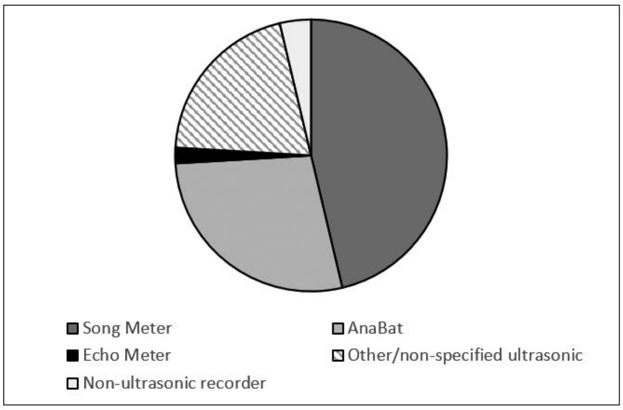

Figure 3. The relative proportions of recording equipment referenced for surveying ghost bats (*Macroderma gigas*), within documents which referenced a form of recording technology. Reference to recorder types was not mutually exclusive.

was selected. As Song Meter technology was more recently developed than AnaBat technology (Biologic Environmental Survey 2014*), justification was only relevant in later years (Song Meters appeared in the grey literature after 2009). However, justification was only present in 15% (n = 6/41) of documents dated as released after 2009 and referenced a form of acoustic or ultrasonic technology (n = 41).

OBSERVATIONAL SURVEYS

Targeted manual/visual surveys are the most common observational study method, reported in 71% (n = 39/55) of documents. Manual/visual surveys included inspections of suspected roosting sites and bat counts at cave entrances at dusk during bat emergence times (Molhar 2006*), plus aural surveys of bat calls (Bat Call WA 2013*). Both infrared cameras and motion-activated camera devices were used for bat surveys; and were evenly reported within the grey literature (infrared = 9%, n = 5/55 of documents; motion capture technology = 9%, n = 5/55 of documents).

TRAPPING & SCAT ANALYSIS

Trapping of bats using harp trapping or mist netting was referenced in 44% (n = 24/55) of documents. Collection of scats was one of the most common survey methods for ghost bats (69% of documents; n = 38/55).

Threats

For this review, perceived threats to ghost bats were reported in numerous documents (n = 42/55), with several highlighting more than one threat. The cumulative impacts from mining were reported in 98% (n = 41/42) of documents which referenced threats, and loss of habitat in 83% (n = 35/42) of those documents. Habitat modification was referenced in 74% of documents which referenced threats (n = 31/42), with feral predators (33%; n = 14/42), collisions with barbed wire fencing (29%; n = 12/42), and cane toads (17%; n = 7/42) the least often reported threats from these categories.

DISCUSSION

Survey techniques

Review of the grey literature determined a range of different techniques employed to survey and monitor Pilbara ghost bats. Acoustic and ultrasonic recorders were the survey technique used most often, followed by targeted searches and scat observation/collection. However, more novel or developing technologies such as VHF tracking for movement studies have been adopted in more recent years. The following discusses the use and context of the different survey techniques pertinent to the ongoing monitoring and management of Pilbara ghost bats.

ACOUSTIC & ULTRASONIC RECORDERS

Acoustic and ultrasonic recording is a method used to determine if caved areas are likely to be occupied by ghost bats, or to confirm presence at a particular cave site. It was the most frequently reported survey technique within the grey literature over the review period. This is likely because 95% (n = 52/55) of the documents which reported survey techniques were consultant or industry reports, primarily designed to meet a compliance requirement for the mining approval process. Determining the presence or use of an area by ghost bats is required prior to approval for mineral extraction in the Pilbara, and the deployment of ultrasonic and acoustic recorders can be a simple mechanism to survey ghost bat presence which allows the passive collection of data over consecutive days. It is also a method recommended under the Environmental Protection Authority's Technical Guidance for terrestrial vertebrate fauna surveys from environmental impact assessment in Australia (EPA 2020*).

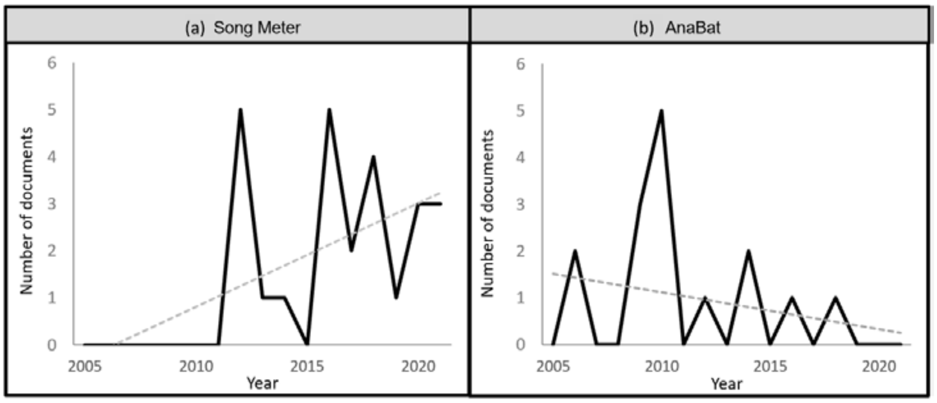

Figure 4. The number of documents (out of 55) specifying the use of (a) Song Meter devices and (b) AnaBat devices, between the years 2005 and 2021. Trendline is depicted in grey.

The collective distribution information provided by the acoustic and ultrasonic sampling data could be key to the continued regional monitoring of the Pilbara ghost bat population due to being the most feasible technology to be used at scale. However, different detectors can capture varied information (e.g., zero-crossing recordings do not capture amplitude or harmonic information; EPA 2020*) and can give different results, which impacts the comparability of results across the region and highlights the importance of reporting detector type and selected settings (Adams *et al*. 2012). The timing of the survey is also important to report, as seasonality can impact survey findings. For example, late summer when adult bats return, or the onset of winter when the population reassembles in the warmest caves, may be the most favourable times to conduct targeted colony counts, as bats will be congregated together (Toop 1985). Understanding the context of different surveys will help more accurately compare and collate population estimates across the region (Cramer *et al.* 2022).

Non-ultrasonic recorders can be used to complement ultrasonic recording surveys. The social calls of ghost bats are low pitched and range from 5-15 kHz, which is audible to humans and can be recorded on both non-ultrasonic recorders and ultrasonic recorders (Guppy *et al.* 1988; Hanrahan *et al.* 2021). As ghost bats often use visual detection to hunt (Tidemann *et al*. 1985), they are not always reliant on making ultrasonic calls (McKenzie 2016*; Outback Ecology 2012a*). New research in the Northern Territory indicates that recording social vocalisations can assist in the identification of maternity behaviours and roosting sites in a semiautomated and less invasive way than other methods which require entry into caves (Hanrahan *et al*. 2021). As many caves are not used by ghost bats, this application of the non-ultrasonic recording technology is most relevant to a secondary, detailed analysis of a site once colony occupation has been confirmed.

OBSERVATIONAL SURVEYS

Bat census surveys can confirm occupancy of a cave after selection as a potential roost site following cave assessment and acoustic surveying (Bat Call WA 2021*). Colony size can be estimated through direct observation and counts, and remote monitoring through use of video recordings can be used to conduct simultaneous assessments at multiple roost sites (e.g., Biologic Environmental Survey 2015*; 2020c*). Targeted searches and assessment of ghost bat usage of potential roost sites was the second highest reported technique among grey literature which reported survey methods. As in the acoustic surveys, this is likely an outcome of consultant and industry experimental designs targeted to assess ghost bat presence or absence for the mining approval process.

Despite the popularity of this method, a conservative approach must be taken to prevent stress to females with young or causing a colony to vacate a roost (Bat Call WA 2021*). Assessment of caves according to required roosting characteristics will help determine sites for further surveying and confirmation of ghost bat presence (Bat Call WA 2021*). A species distribution model is currently under development (K. Ottewell, pers. comm., 2022) and will also assist with targeting survey effort in the future, to gain a more comprehensive understanding of roost usage across the region. Additionally, visual inspection of bats in person and on camera can be useful to determine the presence of juveniles to confirm cave use as a maternity site (Biologic Environmental Survey 2015*). Confirmation of maternity roosting sites or critical caves is important, as these Category 1 and 2 caves (Bat Call WA 2021*) are protected for their regional significance, due to the comparative rarity of these caves with complex and stable internal structure and microclimate characteristics, in contrast to other short-term roosts (Biologic Environmental Survey 2014*).

TRAPPING

As ghost bats are easily disturbed and driven away from roosting sites, the disturbance of bats through physical entry of caves and trapping (e.g., harp trapping and mist netting) are not recommended on a repeated basis (TSSC 2016*; Ecoscape 2018*; Bat Call WA 2021*). To reduce the impact to pregnant and lactating females and their young, entry and trapping in caves should be avoided from mid-December to mid-March (Bat Call WA 2021*). Trapping should only serve a particular purpose, such as tissue collection or tracking studies (Bat Call WA 2021*). For example, tissue collection has allowed insight into the physiological resistance of ghost bats to toad toxins (Shine *et al.* 2016), an important step in prioritising and managing the threat of cane toads in the Pilbara. Capture of individuals to attach trackers for VHF tracking (e.g., Biologic Environmental Survey 2019c*; 2020d*) or GPS satellite tracking (Augusteyn 2018; Bullen *et al.* 2023) has also allowed greater insight into habitat use and likely areas of foraging, which can assist with optimising management and protection.

SCATS

The scats and middens produced by ghost bats are distinctive as they are almost twice the size of those produced by other cave-dwelling bats in the region (Biologic Environmental Survey 2020e*), and fresh scats can indicate current occupancy of a cave (Greenhall & Paradiso 1968). One limitation of this method is it relies on bats defecating directly above a ground sheet (Biologic Environmental Survey 2020e*). However, visual inspection of scat freshness away from the ground sheet can provide an indication of recent activity, although it is not possible to specify the time-period of activity (Biologic Environmental Survey 2015*). Scat presence can indicate site usage by ghost bats regardless of sampling season, as older scats can indicate historical use of a roost site and can be collected at any time. This is compared with other methods, such as acoustic recording which relies on active ghost bat presence at a site, which can be difficult given low site fidelity (Biologic Environmental Survey 2012*).

In addition to signifying cave habitation, analysis of DNA from the outer surface of ghost bat scats enables identification and tracking of individuals for mark recapture analysis and simultaneously provides information on the genetic 'health' of the population. Genotyping of DNA from scat samples creates a unique genetic fingerprint, a form of 'molecular tagging' that is used to survey individual bats in mark-recapture analyses to estimate population sizes. Molecular Tagging can be used to collect information on the temporal and spatial movements of individual ghost bats in a local area, for example to detect resident versus transient individuals and to identify 'recaptures' across years (Ottewell *et al.* 2018*; DBCA 2019*). Sex-linked markers are also available to identify sex of individuals which can assist in determination of population sex ratios, identification of maternity caves and monitoring of sex-based differences in dispersal and other behaviours. It is the only survey method currently available, besides live trapping, to provide resolution at the level of an individual. In addition to approaches using telemetry, genotyping of DNA from scat samples can provide insight into ghost bat movement patterns, including medium to long-distance dispersal events (e.g., Ottewell *et al*. 2019*) and the size of the spatial genetic neighbourhood (e.g., Ottewell *et al.* 2017*).

MOVEMENT STUDIES

Further surveying is required to understand both the presence and absence of ghost bats across the Pilbara landscape, and their basic ecology and movements (Claramunt *et al*. 2018; Cramer *et al*. 2022). Some previous studies have focussed on using VHF tracking to determine movement patterns, using VHF towers to determine relative importance of habitat areas (e.g., Biologic Environmental Survey 2019c*; 2020d*). However, as technology improves with the decrease in size of GPS tags (e.g., Weller *et al.* 2016; Conenna *et al.* 2019) and the development of satellite tags with data that can be downloaded remotely (e.g., Randhawa *et al.* 2020; Bullen *et al*. 2023), assessments of habitat usage and movement can be easier to conduct and with greater detail. The use of high-resolution GPS/satellite or VHF radio tracking can assist in identifying how movement is influenced by landscape features at various scales, such as whether long distance flights are facilitated by 'stepping-stones' of roosting sites (Cramer *et al*. 2022). A greater understanding of local movements and long-distance dispersal will enable identification of priority areas for management and conservation, and suitable buffer zones (e.g., from active mining) to assist in population conservation and management (e.g., as recommended in Biologic Environmental Survey 2016*; Bat Call WA 2017b*; Biologic Environmental Survey 2021d*).

Overall, ghost bats are a cryptic, evasive, and nocturnal species, and can be difficult to study (McKenzie 2016*). Surveying often requires a combination of techniques, including indirect and direct methods, for an effective assessment of occupancy and population size (McKenzie 2016*). We recommend the inclusion of a detailed method rationale in survey reporting to become standard practice, to support better comparability of data across the Pilbara, and generate a more accurate regional population estimation and consistent classification of roost habitat. Improved population estimation will require a substantial and coordinated effort which will be important for the assessment of regional and localised declines and inform policy and target management efforts.

Threats & mitigation management

Ghost bats are at risk of local extirpation across the Pilbara, largely due to habitat loss, the cumulative impacts of mining, collisions with barbed wire fencing, habitat modification, and competition and predation by feral predators with poisoning from cane toads an emergent risk. These are perceived threats, as it is difficult to obtain quantitative data on actual threat levels. Research priorities to quantify some of these threat levels are discussed in Cramer *et al.* (2022). The March 2021 stakeholder workshop (Cramer *et al*. 2022) identified each of these threats as a priority for mitigation to ensure the ongoing survival of ghost bats in the Pilbara, with climate change the only perceived threat not directly referenced in any of the literature. Although these perceived threats are not a novel insight and have been previously published within the scientific literature (e.g., Armstrong & Anstee 2000; Hoyle *et al.* 2001; Woinarski *et al.* 2014), our following summary can help discern if the same perceived threats are also prevalent within the grey literature.

HABITAT & ROOST LOSS

The most immediate threat to Pilbara ghost bats is the destruction of habitat from mining and other development activity (Woinarski *et al*. 2014; Cramer *et al*. 2022). Over the last decade, ghost bats were listed in the top ten threatened species in Australia to lose the most potential habitat (Ward *et al.* 2019). Without stronger protection or a change to current mining trends, many Pilbara roosting sites are predicted to be destroyed from mining activity within the next 30 years (Woinarski *et al*. 2014). The conservation of both roosting caves and foraging habitat, such as riparian corridors and productive plains with sparse, mature woodlands over *Triodia* spp. (Bat Call WA 2021*), is crucial for the long-term survival of ghost bat populations (Armstrong & Anstee 2000; Biologic Environmental Survey 2019c*; Cramer *et al*. 2022).

In addition to the protection of current habitat assets within the Pilbara, another mitigation strategy to prevent further population decline is the rehabilitation of degraded roosting sites. Ghost bats often rely on abandoned mine shafts as roosting sites, particularly in the East Pilbara (Churchill & Helman 1990; Armstrong & Anstee 2000; Woinarski *et al*. 2014). However, many abandoned underground mining structures are degraded and collapsing (Woinarski *et al*. 2014; TSSC 2016*). As there is a large backlog of rehabilitation work to fix these degraded roosting sites (Woinarski *et al*. 2014; TSSC 2016*), a strategic assessment of the regional significance of different roosting sites and an inventory of disused mines will be important to plan and prioritise rehabilitation efforts (NSW National Parks and Wildlife Service 2001*; Thomson *et al.* 2015). Under this approach, the highest value conservation assets should be protected first. A mitigation plan will also be required to limit or manage the disturbance to in situ bat populations during rehabilitation works.

The creation of new artificial roosting sites is being investigated as an additional management tool. Several factors are important to consider during the construction of artificial caves, including the physical and microhabitat requirements for the roost type. To maximise cost efficiency and minimise disturbance, the potential for conversion of an anthropogenic structure already in place (e.g., mine shafts), or addition of an adit to a preexisting cave should be considered first, particularly as natural caves are likely to have greater longevity than an artificial structure (Biologic Environmental Survey 2014*; 2016*). If an artificial roost is created from scratch, it should be adjacent to other known roost sites or disturbed roost sites, and of a size that would support a sustainable population size for the area (as ghost bats are a top-order predator, over-abundance in certain areas could impact prey populations; Biologic Environmental Survey 2014*). Trials are underway in the Pilbara testing the creation of roosting caves through placement of a concrete cave structure (with varied chamber sizes and rough roof material for bats to grip), buried into the side of a hill to avoid drill and blasting disturbance (GCM 2016*). Monitoring is ongoing to determine usage of these artificial sites by ghost bats (BHP 2017*). Overall, whilst rehabilitation of abandoned mine infrastructure and the installation of artificial roosting habitat can be useful mitigation measures, it must be emphasised that these are not an equivalent ecological replacement to the protection of natural roosting caves, which is the priority for the ongoing survival of ghost bats (L. Ruykys pers. comm. in Bat Call WA 2021*).

CUMULATIVE IMPACTS FROM MINING

There is a substantial knowledge gap regarding the impact of active mining operations and their proximity to ghost bats, and this is a research priority for the Pilbara (Bat Call WA 2021*; Cramer *et al*. 2022). Further research is required to determine the appropriate buffer zone size to prevent roost abandonment due to altered cave conditions after dewatering or excess water disposal from mining activity (Bat Call WA 2021*). It is unknown if ghost bats return to sites that have been abandoned, and the length of time this takes if they do return (Cramer *et al.* 2022). Determination of appropriate buffer zone size is important to protect bats from the direct and indirect effects of blasting, such as exposure to potential pollutants and irritants in the dust (Bat Call WA 2021*). The investigation of disturbance thresholds that trigger a significant response from ghost bats continues to be a considerable practical challenge (Cramer *et al.* 2022) and will be key to informing policy and management.

Current limitations to understanding the cumulative impacts of mining include the lack of transparent data sharing, no central information repository for survey and monitoring data, and no central information site on clearance approvals. Advice under the *Environment Protection and Biodiversity Conservation Act 1999** states that there are currently no adequate mechanisms in place to provide the high-level planning, prioritisation, and stakeholder support required to prevent further ghost bat declines (DoE 2022*). Therefore, in addition to further research, a collaborative effort to share and centralise information will be an important step towards effective conservation management. Formal protection of Pilbara roosting sites is required, alongside policy to enforce best practice as standard for mining proponents in the region (Armstrong & Anstee 2000; TSSC 2016*). We encourage a structured review of mitigation methods, particularly a cost-benefit assessment to understand which approaches are feasible, cost-effective and have the biggest impact on improving ghost bat survival. This process will likely require a further workshop with expert elicitation.

CANE TOADS & INTRODUCED PREDATORS

Cane toad poisoning is a risk to ghost bats, as the toads are of similar size to current prey items, and native frogs are already a component of the ghost bat diet (Manger *et al*. 2001; Barritt 2012*). The western cane toad invasion front has not yet reached the Pilbara but is predicted to be potentially facilitated by artificial water point 'stepping-stones' (Florance *et al.* 2011; Tingley *et al.* 2013; Southwell *et al.* 2017). There are not any effective tools available to significantly control cane toad numbers at a landscape scale within Australia (Shanmuganathan *et al.* 2010). As such, comparison of a species distribution model for ghost bats with a fundamental niche model for cane toads will help to identify areas the two species may overlap in the Pilbara and focus localised control measures (Cramer *et al*. 2022).

Ghost bats are the only carnivorous microbat in Australia, feeding on small mammals (including other bats), reptiles, birds, and large insects (Bat Call WA 2016d*). The nutritional value and water content derived from mammalian and bird prey is greater than from smaller insects, meaning ghost bats likely preferentially target larger prey in the arid Pilbara (Claramunt *et al.* 2018). Therefore, ghost bats are likely to be potential prey items themselves as well as compete for prey with other larger introduced predators such as the feral cat, fox, and wild dog (Duncan *et al.* 1999).

HABITAT MODIFICATION & ANTHROPOGENIC DISTURBANCE

Prevention of repeated entrance to roost sites is important, as repeated disturbances may lead to roost abandonment (Bob Bullen pers. comm. 2023). Broad-scale disturbances, such as livestock grazing and altered fire regimes, can also change the spatial and temporal productivity of the landscape, potentially decreasing the foraging quality for ghost bats (Cramer *et al.* 2022). Further research is required to provide definition of what is a significant impact to the foraging habitat of ghost bats (Cramer *et al.* 2022). Active protection of roost sites and foraging areas from degradation is considered a priority in the Pilbara (TSSC 2016*); however, there is currently no regional management plan in place to coordinate this effort (Armstrong 2010). Overall, further research, formalised policy, and the regional coordination of management is required to mitigate the degradation and modification of ghost bat habitat.

BARBED WIRE

Over a quarter of the reviewed grey literature which specified threats to the ghost bat listed barbed wire as a perceived threat. However, despite the pervasiveness of this threat across the Pilbara, most ghost bat deaths from barbed wire entanglement are preventable. Barbed wire fencing is rarely essential and can be removed, replaced, or managed to reduce its impact (Little & Hall 2006*). The most effective solution to prevent entanglement deaths is to remove barbed wire completely and use alternative materials for fencing (Booth 2006*). As pastoral leases extend across more than 62 per cent of the Pilbara bioregion (PEOF Implementation Plan 2019*), the distribution of barbed wire for livestock management is likely extensive, and removal may first need to be targeted to areas with confirmed ghost bat roosting and

Figure 5. Example of a deceased ghost bat entangled in barbed wire fencing in the Pilbara region of Western Australia. 2005 Photograph by S. van Leeuwen.

foraging sites. An education and awareness program, such as those developed in Victoria (Maclean 2006*), may also be useful for the staged removal and replacement of barbed wire fencing by pastoralists. Some mining proponents, such as Atlas Iron Limited (2017)* and Roy Hill (2020)*, have committed to actively replacing or preventing the use of barbed wire for their projects. However, legal reforms and updated policy are required to make this mandatory for industry and land managers throughout the Pilbara (Booth 2006*).

In cases where the removal of barbed wire is not feasible, or the use of barbed wire is unavoidable, barbed sections may be covered with poly pipe, sheets of chicken mesh, or electric tape, particularly at entanglement hotspot sites (van der Ree 1999; Booth 2006*; Booth 2007*). Visible and audible additions to fences, including plastic flags, aluminium cans, metal tags, plates, and tape, may also increase the detectability of fences for bat avoidance (Booth 2006*; Booth 2007*). However, tags and flagging must be maintained or designed to be long-lasting due to deterioration in the elements and to withstand cyclonic events. Plastic options should be avoided for stock fencing as cattle (and likely other fauna) can consume plastic, which can lead to digestive problems and death (Booth 2006*; Anwar *et al.* 2013).

CONCLUSION

The extensive mining footprint across the Pilbara is a predominant threat to the ghost bat population (Cramer *et al.* 2022). However, the collective body of surveys produced as part of environmental impact assessments for mining proposals (K.N. Armstrong unpublished data cited in Armstrong 2010; Government of Western Australia 2014*) is a major source of knowledge for the biodiversity in this region (Government of Western Australia 2014*). At present, the grey literature is largely inaccessible, and the aim of this review was to collate a database of grey literature and synthesize trends in the survey techniques and perceived threats for Pilbara ghost bats. The complementary use of indirect and direct methods can be used to survey a range of factors relating to Pilbara ghost bats. The suitability of different techniques depends on the context of the study, highlighting the importance of reporting justifications for survey design. It is, therefore, recommended for future environmental assessment reports to include detailed method rationales to support better data comparability and population estimation across the Pilbara, which is important to inform policy and targeted management efforts.

Perceived threats to ghost bats are cumulative and varied, with habitat clearing and the cumulative impacts of mining often reported as perceived threats in the grey literature. Continued research and management trials will be important to develop optimal strategies for management. At present, most ghost bat surveys are conducted around mine sites, leading to a spatial bias in data collection. The grey literature consists of many once-off survey events that were the requirement for an environmental approval, leading to an *ad hoc* distribution of survey sites, and a lack of repeated assessments. There is a need for longer-term monitoring studies, plus an increased sample size of sites (particularly in under-sampled areas away from mined zones), to disentangle annual variation versus long-term trends in ghost bat ecology and population dynamics. Tenure issues may complicate the ability to select and secure long-term monitoring sites, although the Pilbara Environmental Offset Fund provides a framework and an avenue for collaboration to navigate these challenges (PEOF Implementation Plan 2019*).

While this review is an important step towards greater knowledge sharing and accessibility, the development of improved data capture systems will be important for optimised data sharing in the future. Across the world, the quantity of grey literature on some topics can far exceed that of the scientific literature (Corlett 2011), representing a vast, unexploited resource. Inclusion and analysis of grey literature studies to reviews and planning is important to help reduce the publication bias apparent in the scientific literature, where failed trials or null results are less likely to be published (Conn *et al*. 2003; Paez 2017). A more balanced understanding of the evidence (Paez 2017) is critical in a field such as threatened species management, where understanding the effectiveness of management actions is key to optimising techniques and standards. Development of a centralised data archive with free accessibility will contribute greatly to increasing visibility of the grey literature, and maximising data sharing (Corlett 2011). It is in the best interests of the scientific community to maximise the cumulative power of research, through the wider and more consistent dissemination of data (Conn *et al*. 2003), to improve conservation outcomes for threatened species, particularly those infrequently discussed in the published literature.

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APPENDIX

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